# Dredging of Reservoirs

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*Cover image:*
A grab dredge performing dredging works in the Luzzonne reservoir in Switzerland.
(*source: Liebherr (2016)*)

# Dredging of Reservoirs

by


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# Preface

This master thesis is written as a conclusion to the master of hydraulic engineering with a focus on dredging engineering at the faculty of Civil Engineering of the Delft University of Technology.

I want to thank everyone that has made it possible for me to write this thesis, for feedback in discussions and encouragement. Specifically I would like to thank Prof.dr.ir. C. van Rhee for entrusting me with the opportunity to investigate the interesting subject of the dredging of reservoirs.

Also I thank Dr. ir. C.J. Sloff and Dr. ir. G.H. Keetels for their feedback during committee meetings and individually, for motivating and inspiring me.

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*L. Elzinga*
*Delft, December 2017*

# Abstract


**Dredging of reservoirs**

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The main focus of this research is determining when dredging of reservoirs is feasible. First the main issues associated with the sedimentation of reservoirs are investigated. Most important are the loss of reservoir volume, sediment shortages downstream of the dam and possible blockage of water intakes. The sedimentation issues occur mostly in sediment laden rivers. Reservoirs close to the origin of the river, for instance in mountainous terrain usually do not suffer from severe sedimentation issues. A survey is held under authorities responsible for different reservoirs. Results indicate that not all reservoirs suffer sedimentation issues, but part of the worldwide dams and reservoirs does.

The most important conclusion is that sedimentation at this moment will only be dealt with if it is clearly affecting the function of a reservoir or if the function of a reservoir is threatened in the near future. The matter has to be urgent enough that owners are willing to spend funds on mitigating sedimentation issues. If added value can be gained through removing sediment this improves the business case of dredging. In the survey this is verified by the respondents.

Methods of dealing with reservoir sediment are discussed. Different dredging methods for the dredging of reservoirs are presented and investigated. The main advantages of dredging are found to be precise removal of sediment, avoiding large sediment flushes and no excessive loss of water. Using a 1-dimensional Sobek model, it is shown that part of the sediment entering the reservoir can be used for downstream river restoration.

Different factors that influence the feasibility of dredging are identified. The function of the reservoir is important. For the functions of irrigation, storage of hydro power, water supply and flood control the available volume is for example important. Sediment control is therefore important.

By modelling different shapes for reservoirs using Delft3D, it is found that the type of reservoir only partly determines the location of sediment in the reservoir. Other factors influencing the deposit location are sediment concentration and the type of sediment. The maximum reservoir depth is found to be linked to the dam height.

To determine if the dredging of reservoirs is feasible it has to be clear that the reservoir function or intake is threatened by sediment. Based on the function of the reservoir a business case can be made comparing costs and benefits. Benefits of extra reservoir volume are estimated. Possible added values are taken into account, such as the possible sale of dredged material. A dredging model is created to estimate the costs of reservoir dredging.

This model takes different parameters such as sediment composition, dredging depth, reservoir type and transport distance into account. Using this model for different scenarios it is shown that dredging prices can start as low as 1.01 euro. If the sediment is made up of soft and loose material this reduces the price of dredging. Furthermore the transport distance of the dredged material to shore has a large influence on the dredging costs. The transport distance for the dredged material must be kept small and the volume of material dredged must be over 25,000 $m^3$ to find a stable price. For all reservoirs these parameters are different, leading to a reservoir specific dredging price estimate.

Low dredging prices are possible under favourable conditions. At these prices, dredging can compete with other sediment management techniques. On top of that, the added benefits of dredging have to be taken into account: downstream river restoration, the possible sale of dredged sediment and increased downstream soil fertility. These benefits increase the feasibility of dredging a reservoir further. The dredging of certain reservoirs is seemingly beneficial. Reference reservoir dredging projects have to be performed to confirm that this

Further research into the deposition of sediment in different types of reservoirs is recommended. Also more investigations into the downstream return of sediment are recommended.

# Contents

# Acronyms

| | |
|---|---|
| BD | Backhoe Dredge |
| CSD | Cutter Suction Dredger |
| GD | Grab Dredge |
| GOH | Gross Operational Hours |
| GRanD database | Global Reservoir and Dam database |
| GUI | Graphical User Interface |
| ICOLD | International Commission on Large Dams |
| MAF | Mean Annual Flow |
| Mcbm | Million cubic meters |
| NOH | Net Operational Hours |
| RESCON | Reservoir Conservation |
| SP | Submersible Pump |
| TE | Trap Efficiency |
| TSHD | Trailing Suction Hopper Dredge |
| VOUB | Voortgezette Opleiding Uitvoering Baggerwerken [1] |
| WCD | World Commission on Dams |
| WID | Water Injection Dredge |
| WRD | World Register of Dams |

[1] Advanced Training in Dredging Works

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# 1 Introduction

Water is one of the most imported resources on the planet. Water is necessary to sustain life on earth, for some it even represents life. In order to control this necessary water, reservoirs are build all over the world. The definition of a reservoir used in this thesis is: a place where water is stored for future use (Sloff, 1991). Reservoirs are created by building a dam in a river, impounding a reservoir behind it. The first water reservoirs were already build more than five millennia ago (Jansen, 1983). Figure 1.1 is a good illustration of a reservoir.

Reservoirs have different purposes ranging from the harvesting of hydro power, flood control and irrigation to the storage of drinking water, navigation, recreation. Reservoirs can either have a single function or a combination of the previously mentioned functions.

Currently there are over 58,000 dams registered in the world (ICOLD (International Commission on Large Dams), 2016). These dams are higher than 15 $m$ or have reservoirs with volumes of at least 3 million cubic meters. Most of these dams and resulting reservoirs are used for irrigation purposes.

Figure 1.1: Example of a reservoir.

Reservoirs have become indispensable for today's society. Hydro power is seen as a clean source of energy. It is green power alternative to fossil fuels (Balat, 2007). This leads to hydro power as an attractive form of sustainable development. This is in compliance with millennium goal seven of the United Nations, stating that the world has to work toward ensuring environmental sustainability (UN, 2015).

Dams are also used for protection against floods, by intercepting the flood wave and slowly releasing the water, downstream floods are prevented. Reservoirs for drinking water and irrigation store river discharges of peak times. The stored water can be used over time. This is important in dry countries. Considering the influence of climate change, these reservoir functions will become more mandatory in the future (Annandale, 2013). Therefore reservoirs and reservoir related issues are important topics for today's society.

Reservoirs have a lot of advantages, but also come with big challenges. It can be hard to properly manage the water level in the reservoir in such a way that this will not lead to flooding. Recently problems occurred at the Oroville dam in the United States of America. Here a high water level of the reservoir lead to panic and the evacuation of roughly 180,000 people (Paul et al., 2017). On the other hand the construction of new reservoirs becomes more and more difficult since the favourable locations for reservoirs are running out.

Over the years many dams have been build all over the world. The number of dams build, grew steadily since 1900, had a small dip during the second world war and reached a peak in 1960. This follows from Figure 1.2, which was created using the ICOLD World register of dams database (ICOLD (International Commission on Large Dams), 1998). The building of new dams build is decreasing (blue line in Figure 1.2. The total reservoir storage in the world is stagnating (red line in Figure 1.2). It is important to note that the dams that are build after 2017 are dams that have been planned to be finished in the indicated year. The trend in reservoir storage volume across the globe is that it is declining. The estimate for this decline in global reservoir volume is 0.8% reservoir volume loss per year (ICOLD Sedimentation Committee, 2009). The reservoir volume compensated for this yearly volume loss is presented by the green line in Figure 1.2.

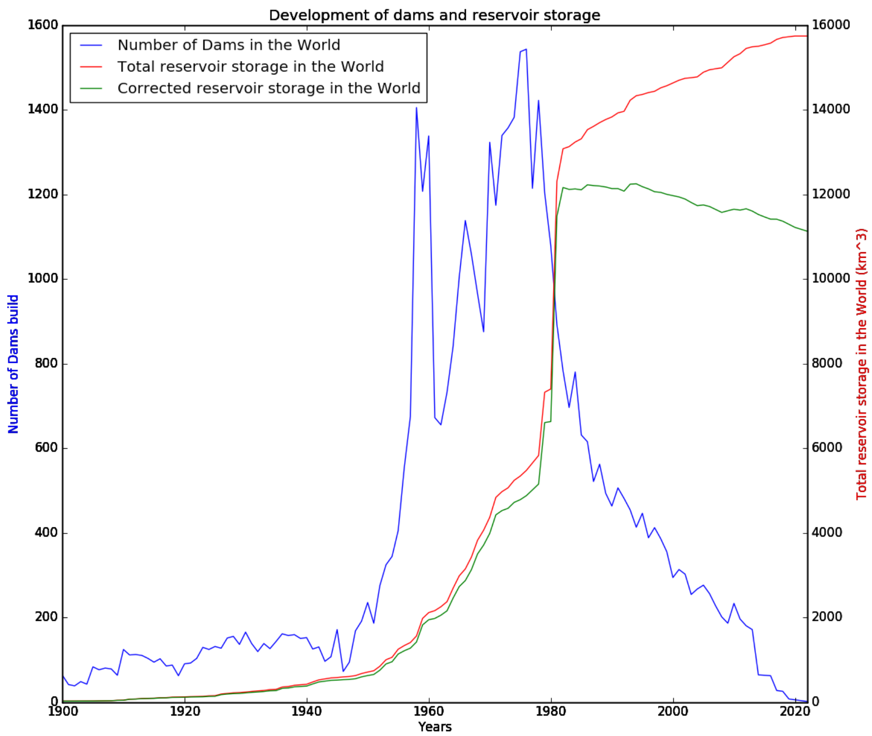



Figure 1.2: Development of dams and reservoir storage between 1900 and 2022, according to the ICOLD database.

## 1.1. Sedimentation in reservoirs

Rivers transport all sorts of material, from their origin in the mountains, to their final destination: the sea. The material that ends up in the river originates from abrasion of rock in the mountains, soil washed into the river or sand scoured of the river bed. The river transports all these different materials in different ways. The different transport methods are illustrated in Figure 1.3. Light material is suspended in the water and is called dissolved load. The heavier material moves along the bed of the river, by rolling sliding and saltation, it is called bed load.

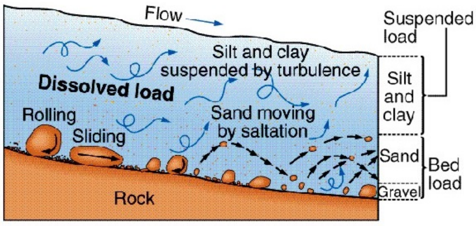



Figure 1.3: Process of sediment transport in a river, modified figure (Clement, 2002).

Building a dam to create a reservoir leads to blocking of the river. The natural result of blocking a river is a decrease of the velocity of the water. The sediment transport capacity of the river becomes smaller as the water is slowed down resulting in settling of the sediment particles. The existing literature gives large numbers for the cost sedimentation in reservoirs annually. In a technical paper of the World Bank in 1987 the yearly replacement costs of reservoir storage lost to sedimentation is estimated at \$6 billion dollar (Mahmood, 1987). These are the costs for only replacing the storage volume lost to sedimentation using a fixed price per $km^3$. In 2003 the annual replacement costs of lost storage were estimated to be \$ 13 billion (Palmieri et al., 2003). The storage loss is estimated to be between 0.5% and 1.0%.

It is clear that reservoir storage in the world is declining. The costs are based on 300 fictional dams, that could replace the lost storage until that year and these costs divided over each year. However, it is hard to find accurate cost calculations for sedimentation in this report. Possible explanations are that the costs of sedimentation are not only limited to the reservoir itself, but are also spread along the up and downstream reaches of the in and out flowing river. The total costs will thus be spread over different organizations, leading to scrambled costs. Also the global scale on which the reservoirs are build, makes it hard to get a indication of the problems associated with each reservoir.

Investigations into reservoir management have shown that the paradigm is shifting from building a reservoir with a finite lifespan to designing reservoirs which are future proof by attempting to manage reservoirs in a way that they can be continued to be used (Palmieri et al., 2001). The remaining costs at the end of the reservoir life are taken into account from the design phase onward. This study does however not result in clear costs associated with the sedimentation of reservoirs. The question arises whether or not the sedimentation of reservoirs is actually seen as a large problem, or that it is ignored till the reservoir function is threatened.

## 1.2. Dredging of sediment

In theory the sedimentation of reservoirs is an issue and dealing with this issue is necessary. There are different methods for the removal reservoir sediment. This research focuses on the removal by dredging. There have already been some investigations into the dredging of reservoir sediment, for instance in South Africa (Basson & Rooseboom, 1999). This investigation focused on different dredging methods. However it is striking that there are few investments in the dredging of reservoirs, even 18 years after this investigation. Dredging techniques have improved over the years, while the building of new reservoirs has slowed down, as shown in Figure 1.2.

New research into the dredging of reservoir sediment is therefore appropriate. Advantages and disadvantages of dredging sediment, available techniques that have been developed and the disposal of dredged material are investigated.

## 1.3. Feasibility

Dredging is a financially attractive solution for sediment removal. It could prove to be a viable solution to the reservoir sedimentation problem. The reservoir function could be restored and the downstream ecology could be improved as well.

The financial feasibility however has to be evaluated based on the dredging costs and the potential benefits expressed in monetary value. Added value which can not be expressed directly in a monetary value has to be taken into account in an economic evaluation.

## 1.4. Research questions

The above mentioned issues of reservoir sedimentation and the potential benefits of dredging reservoirs have let to the following main question for this thesis:

When is dredging of reservoir sediment feasible?

To answer this question a number of sub questions is formulated:

1. What are the current issues associated with reservoir sediment?
2. What classification can be made for reservoirs to indicate whether dredging is beneficial?
3. What are the advantages of dredging reservoir sediment?
4. What are recommendations for dealing with sediment in future reservoir design?

The last question, concerning recommendations for future reservoir design is more of an extra question, if results lead to recommendations they can be elaborated here. This will mainly be constrained by the time that is available for the completion of this study.

## 1.5. Research approach

The questions mentioned above will be investigated and answered in this thesis. Each chapter starts with the current state of knowledge on the subject, the performed research and a conclusion. The basic report structure is described here.

In Chapter 2 the issues that are associated with reservoir sediment are investigated. A literature study is performed into these issues and the build up of reservoir sediment.

Chapter 3 describes how different owners of reservoirs are contacted to investigate if they acknowledge sedimentation issues and how they are dealing with these issues. Furthermore their attitude towards a dredging solution is investigated.

The next chapter, Chapter 4, an attempt is made to investigate what reservoir properties have an influence on the suitability of dredging. The reservoir function is investigated, the reservoir size and depth as well. Furthermore the influence of the shape of the reservoir on the sediment deposition location is investigated. Modelling in Delft3D is used as part of this investigation

In Chapter 5 an overview of different methods to remove sediment from a reservoir is given. The dredging solution is further investigated. Different types of dredging equipment are explained in detail. The advantages and disadvantages of dredging are identified. Reservoir dredging experience of different dredging contractors is included as well. The production of the different types of dredging equipment is shown as well. An investigation into the deposit of dredged material is included as well. A case study is performed to investigate if sediment can be used to restore river downstream. This is done by modelling the release of sediment into the Neosho river downstream of the John Redmond dam.

In Chapter 6 the feasibility of dredging is determined. General considerations for the feasibility are given. Furthermore the costs of dredging reservoir sediment are estimated by setting up a quick estimation model for these costs.

In Chapter 7 the answers to the research questions are given. The overall conclusion on the feasibility of reservoir dredging is presented.

In the final chapter, Chapter 8, recommendations that come forth from the performed research are presented. Recommendations for the building of future dams are presented. Furthermore additional research topics are indicated.

# 2

# Reservoir sediment

Sedimentation in reservoirs is in theory a problem; sediment replaces the available water volume, which in time leads to loss of the reservoir function. What is surprising however is that research into this issue is not abundantly found. Attention for reservoir sedimentation is increasing. This increase is stimulated by the World Bank, which finances reservoirs worldwide. The results are a study by Mahmood, which indicates the costs of reservoir sedimentation for the first time. In the book "Reservoir sedimentation" (Annandale, 1987), the author makes a first attempt to describe issues related to reservoir sedimentation. The reservoir sedimentation handbook (Morris & Fan, 1998) is also a result of this movement of investigating sedimentation of reservoirs.

The construction of a reservoir, disturbs the sediment transport in a river. The sediment settles in the reservoir and in the downstream river reach unused transport capacity of the river, leads to erosion. This is not only an issue of river morphology change, but also the ecosystem is affected. To investigate the current state of knowledge on these issues, it is necessary to review what already has been written and researched on the subject. Therefore existing literature is reviewed.

## 2.1. Reservoir definition

As mentioned in Chapter 1 the definition of a reservoir used in this thesis is: a place where water is stored for future use (Sloff, 1991). A reservoir can be subdivided into three volume parts:

- Active storage
- Maximum storage
- Dead storage

The different storage parts are indicated in Figure 2.1. In the figure the water intake used for abstracting water from the reservoir to perform the function is indicated by 'bottom outlet'. The excess water in the reservoir is drained using the 'spillway'.

The active storage is confined between the bottom outlet of the dam and the spillway. The active storage contains the water that is used to perform the reservoir function. The water level in the active part of the reservoir fluctuates when water is used. If sedimentation occurs in the active storage part of the reservoir, the active storage volume decreases. Resulting in less space available for the storage of water.

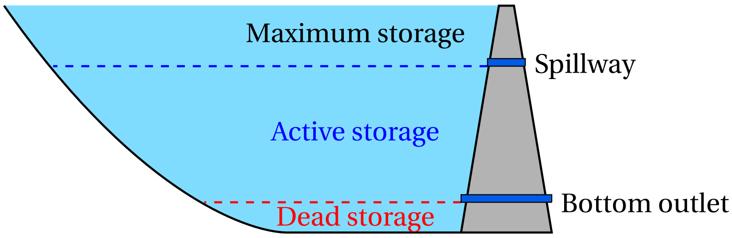



Figure 2.1: The different storage volumes in a reservoir.

The maximum storage is the active storage part of the reservoir combined with the height of the dam. The maximum storage is used to store a flood wave in the reservoir. The reservoir level is temporarily raised, but will be lowered using the spillway to the maximum active storage level. The extra water can therefore not be used to perform the reservoir function.

The dead storage is located beneath the lowest outlet of the reservoir. Water in this part of the reservoir can only be drained using pumps. It can thus not be used to perform the reservoir function. If sedimentation would occur in this part of the reservoir the reservoir function is thus not affected.

## 2.2. Reservoir sediment processes

One of the first studies that is performed into the trapment of reservoir sediment is done by Brune in 1953. The trap efficiency (*TE*) of 44 reservoirs in the United States is investigated. Brune defined trap efficiency as in Equation 2.1.

$$TE = (\frac{V_{trapped}}{V_{entered}}) * 100 \tag{2.1}$$

In which $V_{trapped}$ is the volume of sediment that is trapped in a reservoir over a certain time period. The total volume of sediment which has entered the reservoir in that time period is represented by $V_{entered}$. These volumes can for example be calculated using surveys of the reservoir at different times or by doing load measurements in the river upstream of the reservoir and downstream of the dam.

The conclusion of the research by Brune is that the *TE* is related to the reservoir volume and the inflow of water into the reservoir. Furthermore he concluded that this gives a better representation of the *TE* than the method previously proposed by Churchill, relating the *TE* capacity of the reservoir to the water outflow. Brune analyzed the data for 44 American reservoirs and defined a fitted curve, that relates the capacity-inflow ratio to the percentage of sediment trapped in the reservoir.

The Brune curve is shown in Figure 2.2. It contains a median curve (green curve) and an envelope (blue curves), in which most of the normal American reservoirs are included. The desilting and semi-dry reservoirs cause outliers. That is the reason that they are excluded from the Brune curve. The Brune relation is based on the median curve. The Brune curve is used to determine the *TE* for a certain reservoir with a known capacity and volume of water flowing into the reservoir annually. If the volume of sediment flowing into the reservoir is known, using the *TE* a rough estimate of the volume of sediment retained in a reservoir can be given. This relation is still used as a quick indicator for the *TE* of reservoirs today. In most cases an equation is fitted based on the median line of the Brune curve. That equation is than used to perform calculations for reservoirs worldwide (Ward, 1980; Vörösmarty et al., 2003; Kummu et al., 2010).

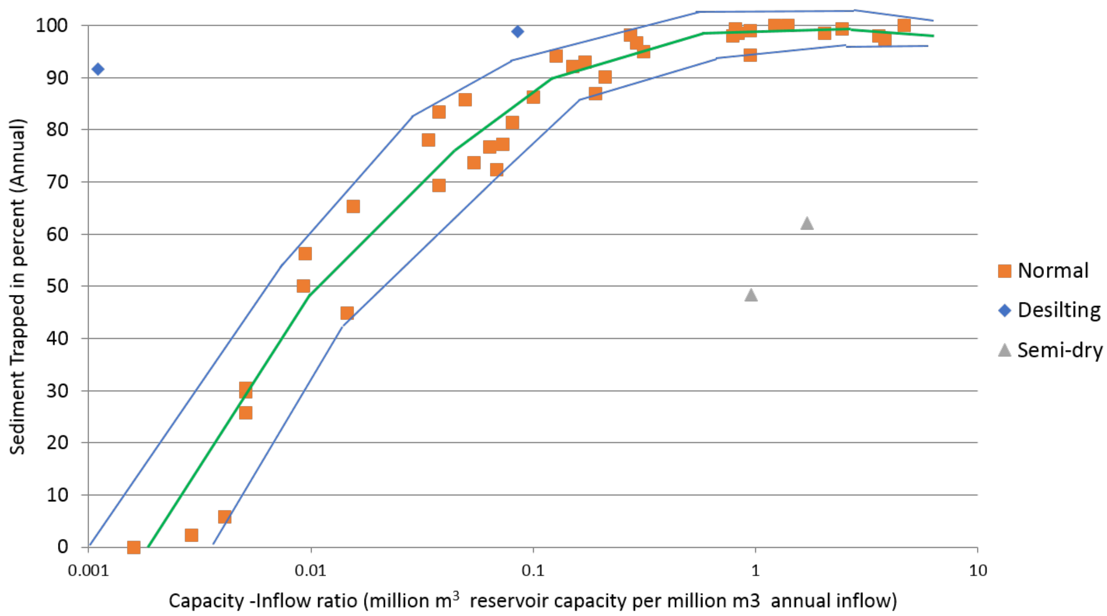



Figure 2.2: The Brune curve, linking the sediment trapped to the capacity inflow ratio (Brune, 1953).

It is important to note however that the use of the Brune curve can lead to an overestimate of the *TE* for reservoirs in climates characterized by water inflows with great variability in sediment concentration (Lewis et al., 2013). The precision of the Brune method is however low, which has led to underestimates of the sediment volumes trapped in reservoirs. This has resulted in viability issues for certain dams (McCully, 2001). The Brune method is used to provide a coarse estimate of the *TE* when limited data is available. It is important to keep in mind that the results are based on long term averaged values of reservoirs in the United States (Morris & Fan, 1998) when applying this method to reservoirs worldwide. If used for reservoir sediment volume estimations the decrease in *TE* due to decreasing reservoir volume has to be taken into account.

The most recent empirical model has been developed by van Rijn in 2013. The *TE* is described using the following formula:

$$TE = 1 - \exp\frac{-A_{vr} * L * (h - h_0)}{h^2} \tag{2.2}$$

The parameters in this formula are defined as follows. $A_{vr}$ is a deposition parameter, including the settling velocity a mean bed-shear velocity and a coefficient. The parameter $L$ is the length of the reservoir. The parameter $h_0$ is the flow depth at the upstream reservoir boundary and $h$ is the mean flow depth of the reservoir.

The trapping efficiency can than be used in combination with the inflow of sediment into the reservoir to determine the deposited sediment. By schematizing the reservoir in different compartments and calculating the *TE* for different sediment fractions, using the sediment volume balance, the deposit of each sediment fraction is calculated for these different parts of the reservoir. This gives an indication for what fractions in what magnitude can be found at certain locations in the reservoir.

The general consensus is that sediment is trapped in reservoirs all over the world. The exact *TE* differs for each reservoir, but the general trend is that a larger reservoir volume coincides with a higher *TE*. As shown in Section 1.1, rivers carry all sorts of different sediment which can be deposited in the reservoir. It has to be determined in what location in the reservoir this sediment will be deposited.

When water enters the reservoir, the water is slowed down because the reservoir is wider than the river. First the heavy coarse sediment particles settle. The lighter fine sediment particles are transported much further into the reservoir. This process leads to the formation of a delta in the reservoir. This delta formation process is reported by Sloff; Morris & Fan; Annandale et al.. This delta can progress into the upstream river reach, thus above normal reservoir level due to backwater effects.

If the river enters the reservoir transporting large volumes of sediment, density currents can occur. These currents are basically a thick mud, thus heavier than water. They flow over the reservoir bed and can make it all the way to the reservoir dam. If the density current can not pass the dam they will settle into a muddy pond. The above mentioned processes are schematized in Figure 2.3.

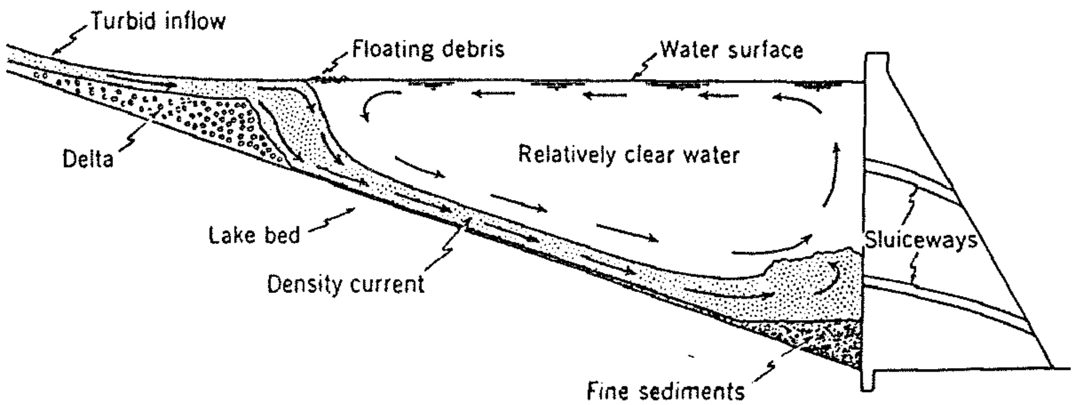



Figure 2.3: Different locations for settlement of particles in a Reservoir (Sloff, 1991)

Borland & Miller found that the deposition of sediment in reservoirs is related to the shape of the reservoir. They found an empirical relation between the reservoir depth and the deposited sediment, for four different types of reservoirs. These reservoirs are distinguished by the factor '$M$', which is defined as the reciprocal of the slope of the line plotting reservoir depth on the vertical axis and the reservoir volume on the horizontal axis. Both axes have to be plotted on a log-scale. The M-value is used as an indication of the reservoir shape. The following four types of reservoirs are distinguished:

- Type I; Lake type; $M = 3.5 - 4.5$ Characterized by the greater portion of sediment in the upper part of the reservoir.
- Type II; Floodplain-foothill type; $M = 2.5 - 3.5$
- Type III; Hill type; M = 1.5 – 2.5
- Type IV; Gorge type; M = 1.0 – 1.5 Characterized by the greater portion of sediment in the dead storage of the reservoir.

In the gorge type of reservoir, which is narrow and deep, reservoir volume is mostly dependant on the depth. The result is a steep slope of the depth-volume curve. This results in a small value of $M$ and vice versa for the lake type reservoir. The distribution of the sediment over the depth for each type of reservoir is given in Figure 2.4. The graph by Borland and Miller gives an idea of the difference that the shape of the reservoir makes for the distribution of the deposited sediment. It is important to note that no information on the sediment size and type is given for the graph in Figure 2.4.

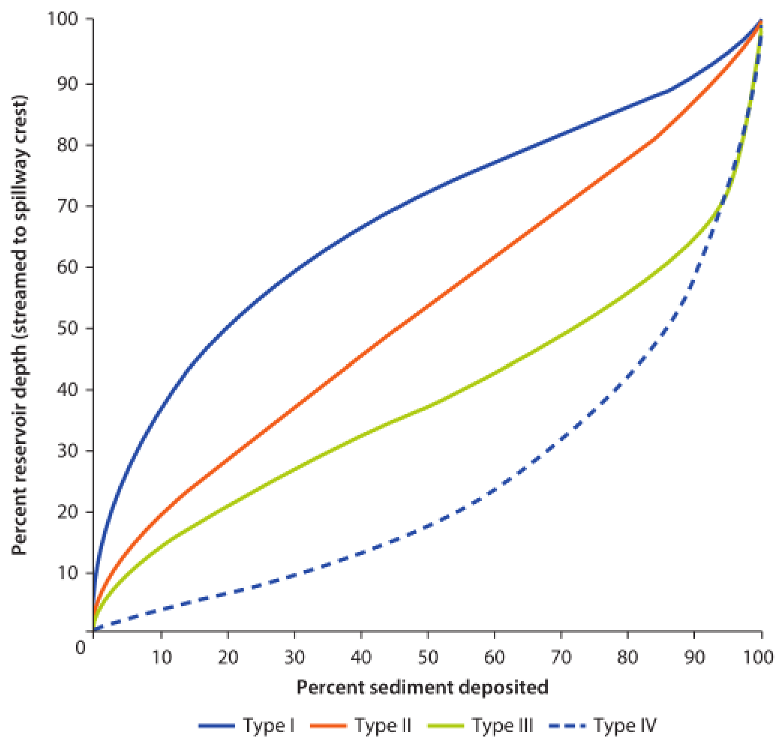



Figure 2.4: Different sediment distributions, for different reservoir types (Borland & Miller, 1960 as presented in (Annandale et al., 2016)).

To determine the value of $M$ an area-capacity curve of the reservoir under investigation is needed. This curve, relating the depth of the reservoir to the volume of water that is stored in the reservoir at that depth, has to be obtained using a bathymetric survey. The unavailable for most reservoirs. In order to obtain the M-value using fewer parameters Kaveh et al. developed a 'reservoir coefficient' ($N$), which is defined as follows:

$$N = \frac{2 * V_m}{y_m * A_m} \tag{2.3}$$

Where $A_m$ is the reservoir surface at the maximum normal water level, $y_m$ is the maximum depth of the reservoir and $V_m$ is the maximum reservoir capacity at maximum depth. These parameters are more readily available for different reservoirs. The 'reservoir coefficient' can be linked to the value $M$ of the reservoir using equation 2.4 (Kaveh et al., 2013).

$$M = \frac{2}{N} \tag{2.4}$$

The described empirical formulae show the deposition of sediment in the reservoir. This deposition is different for each reservoir. The above described methods can be used to obtain an indications of the sediment deposition in the reservoir. To find a more accurate distribution of sediments in the reservoir, a 2 or 3 dimensional model, like for instance Delft3D, can be used to solve the sediment balances (Annandale et al., 2016). For the setup of these models however detailed information is required. This information is not readily available, therefore the empirical formulae requiring less data input are not superfluous.

## 2.3. Problems due to reservoir sediment

In Chapter 2.2 it is shown how sediment is deposited in a reservoir. The resulting question is if this sediment deposition leads to problems in the reservoir. Furthermore, if problems do occur, what these problems are.

### 2.3.1. Loss of storage volume

Sediment deposition in the active storage has a direct impact on the reservoir storage capacity. All water volume in the active storage replaced by sediment can not be used to fulfill the reservoir function. If the reservoir is completely filled with sediment the function can no longer be performed. Figure 2.5 is an example of a completely silted up reservoir. Depending on specific reservoir parameters as total volume of the reservoir and the inflow of water and sediment, the reservoir the sedimentation rate is low or high. Each reservoir is unique and therefore the time before the reservoir function is impacted is also different.

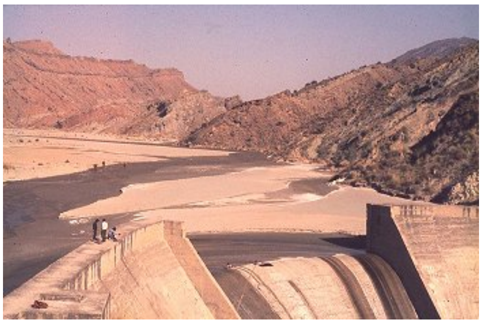


Figure 2.5: A reservoir which has lost most of the active reservoir capacity due to sedimentation (Butler, 2001).

The loss of storage occurs faster than expected in some reservoir. This leads to cases where the dam function was lost within years after construction and thus the design lifetime of the dam was not achieved. Evidence of this storage loss is found in the following cases:

- Welbedahct dam
- Sanmenxia dam
- Bachenthal dam
- Hiraoka dam

The Welbedacht dam in South Africa lost 32% of its reservoir capacity within the first three years of operation. This increased to 86% after 23 years (Batuca & M.Jordaan, 2000). Currently it is filled by sedient for 95% (Jacobs, 2017). The Sanmenxia dam in China lost 96% of its reservoir capacity within 4 years of completion. The Bachenthal dam in Austria lost 72% of its reservoir capacity in 23 years and the Hiraoka dam in Japan lost 96% of its reservoir capacity to sediment in only 12 years (Batuca & M.Jordaan, 2000). In Chinese reservoirs an average storage loss of 2.3 percent annually is reported, this is the highest percentage in the world. Most of the sediment deposition is the result of sediment carried in flood season (Jiang & Fu, 1997). .

The capacity loss due to reservoir sedimentation in the world in 1987 is estimated to be 1% per year. The very rough cost estimation to replace this lost storage is $6 billion (Mahmood, 1987). These are the costs for replacing the storage volume lost to sedimentation using a fixed price per $km^3$. In 2003 Palmieri et al. estimated the annual replacement costs of lost storage at $ 13 billion. Storage loss is estimated between 0.5% and 1.0%. A more recent investigation of the Sedimentation Committee of the ICOLD in 2009 estimated the total amount of storage lost to sedimentation to be slightly lower and in the order of 0.8% per year. The total annual cost of lost storage is estimated at $18.6 billion by determining the costs of replacing the entire reservoir storage volume on a yearly basis. (ICOLD Sedimentation Committee, 2009). In this value the downstream impacts of reservoir storage are not even included. The large cost estimates confirm that reservoir sedimentation is indeed a serious issue. Therefore a solution to reservoir sedimentation problems has to be found.

*Climate change*
As shown in Chapter 1 in Figure 1.2 the total reservoir volume is stagnating. This is only the sum of all initial volumes of the dams and reservoirs found in the World Dam database (ICOLD (International Commission on Large Dams), 1998). If the decline in reservoir capacity due to sedimentation of reservoirs is taken into account the worldwide reservoir volume is declining (green line in Figure 1.2. Taking into account the continuous growth of the world population (United Nations, 2017), the available volume of reservoir storage per capita is declining even further. This is striking, since the impact of climate change will lead to greater variability in precipitation and drought. In order to store enough water to be able to anticipate this, the storage volume of most reservoirs will have to increase (Annandale et al., 2016) to guarantee continued performance.

Another issue associated with climate change is that due to heavier rainfall in shorter periods, more sediment from the catchment area is washed into the river entering the reservoir. Resulting in higher sedimentation rates in the reservoir (UNESCO International Sediment Initiative, 2011). The example in the introduction of a dam using it's emergency overflow for the first time in history, is proof of changing conditions for reservoirs in the world.

### 2.3.2. Structural failure & Blockage of intake

If the density currents mentioned in Section 2.2 can not pass the dam. They will settle right in front of the dam, leading to clogging of the bottom outlet. This can lead to structural integrity issues, which can lead to collapse of the dam. In 1970, the Frias Dam in Argentina collapsed after it had to withstand a day of continuous rain. The reservoir overflowed and that led to the dam collapse. Sedimentation of the reservoir had led to reservoir volume decrease and it was suspected that outlets were clogged as well. This case is thus an example of reservoir sedimentation leading to dam collapse (Jansen, 1983). In 1975 the Banqiao and Shimantan and a series of smaller dams collapsed in China after a period of heavy rainfall. Water was let out of the reservoir via bottom outlets. Due to the blocking of the outlets by sediment, not enough water could be released to reduce the water level enough. A dam collapse could therefore not be prevented (Qing et al., 1998).

Not only the clogging of bottom outlets can lead to structural failure. The flood capturing volume of the reservoir can be reduced by sedimentation. This leads to less room for capturing flood peaks. The surplus of water can lead to a substantial overflow of the reservoir, if flood peaks are not anticipated. This happened at the IVEX Dam in Ohio in 1994. In this case 86% of the reservoir capacity was lost to sedimentation. The result was overflow and piping of the dam, leading to dam collapse(Evans et al., 2000).

Since submerged sediment is heavier than water, sedimentation against the dam leads to an increase of pressure on the dam. In case of an earthquake this can result in additional pressure on the dam (Chen & Hung, 1993), which in turn can lead to collapse of the dam. The collapse of a dam must be prevented at all times, since the impact of a big flood wave, full of sediment would have disastrous effects downstream.

Complete blockage of water intakes will render the dam useless, since the reservoir function can no longer be performed if the stored water can not be accessed. Partial blockage of the intakes will reduce the flow as well and thus lead to a reduction in the amount of water available for irrigation, production of hydro power or drinking water.

### 2.3.3. Hydro power dams

Hydro power dams are a special kind of reservoirs. In hydro power reservoirs water is stored to create a hydraulic head difference. This head difference is the height between the top of the bottom intake and the reservoir level. The potential energy stored in the water, is transformed into electric power. Water enters the powerhouse through the intake, via the penstock. The water flows through the penstock into a turbine. The flow of water through the turbine leads to spinning of the turbine. The resulting energy of the rotating turbine is transformed into electricity, using a generator. This process is illustrated in Figure 2.6.

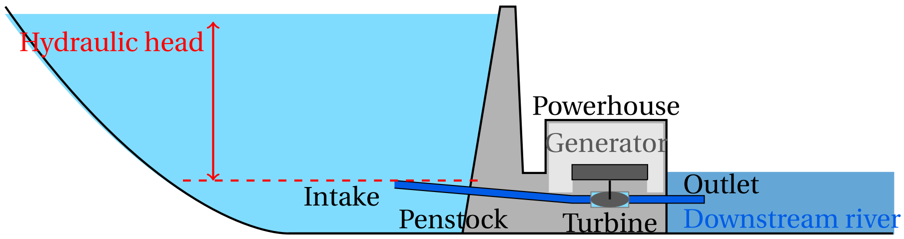



Figure 2.6: Basic overview of a hydro power dam.

There are two different types of hydro power reservoirs: storage reservoirs and run-of-river reservoirs. In the storage reservoir, the volume of active reservoir storage is much larger than the inflow of water into the reservoir. Water in the reservoir is used during peak demands for electricity. By increasing the flow through the turbines, the extra reservoir capacity is used to generate extra electricity. Another function of these storage reservoirs is the delivering of electricity year round. This is the case in regions river hydrograph shows large fluctuations throughout the year. Power generation is guaranteed by storing enough water to fulfill the energy demand year round, even if the inflow of water into the reservoir is low.

For run-of-river reservoirs, the hydraulic head is created by the dam as well. The biggest difference is that the active storage part of the reservoir is small. The river flow is guided through the turbines directly to generate power. Excess water passes the dam via the overflow and is thus not used for electricity production. This type of reservoir has a much smaller volume than a storage reservoir (van Duivendijk, 2007). The active storage is large enough to mitigate power peaks on an hourly or at most daily basis.

Hydro power reservoirs deal with the above mentioned general issues of reservoirs, but suffer specific sedimentation issues as well. The flow of sediment through the turbines will lead to abrasion of the turbine blades. This makes the turbines less effective, leading to an economical loss. Furthermore the maintenance of the turbines will increase, resulting in higher costs and more downtime (Morris & Fan, 1998; Annandale et al., 2016). The amount of damage to the turbines depends on the type of sediment passing the turbines. Sediment like silica, which is hard, causes a lot of damage. Softer material like calcium rarely has an impact on the turbines. Research into coatings to protect the turbines against sediment related wear is ongoing (*personal communication, J. Velasco, 21-6-2017*).

A study in Japan into the effect of sedimentation in hydro power reservoirs found that it is more important to manage sedimentation in the run-of-river type of reservoir than in the storage type of reservoir. This is the result of the relatively small size of these reservoir. Which are located in the downstream reach of a river. Here more sediment is present. Furthermore run-of-river reservoirs can barely be drawn down, since the active storage part of the reservoir is small. Therefore sedimentation occurs at higher water levels (Okumura & Sumi, 2012). The same study also found that loss of reservoir volume leads to a decrease in electricity production. It is concluded that sediment has to be managed in order to prevent losing too much power generation capacity.

### 2.3.4. Upstream impacts

The sediment deposition has an effect in the river upstream of the reservoir. The formation of the delta, as mentioned in Section 2.2, leads to an increased amount of sediment at the beginning of the reservoir. This delta slows down the incoming water even further, leading to extra sedimentation and this leads to increased delta formation. Due to the delta, the water level at the beginning of the reservoir is higher, leading to an upstream raise of the water levels, this is reinforced by backwater curves. The increased water level leads to an increase of the groundwater level and it also increases the risk of flooding upstream (Annandale et al., 2016; Morris & Fan, 1998). On top of these effects, aggradation of sediment can influence upstream engineering works like bridges and make navigation impossible. The higher water levels will lead to a reduced navigation clearance near bridges (Batuca & M.Jordaan, 2000).

### 2.3.5. Downstream impacts

The water and sediment captured in the reservoir lead to downstream impacts as well. These impacts become more noticeable the further a dam and reservoir are located downstream in a river reach (Annandale et al., 2016). The main effects are described here.

#### *Sediment effects*

The sediment that settles in the reservoir is not available for the river downstream anymore. The clear water that is released through the dam can also be referred to as 'hungry water' (Kondolf, 1997). This 'hungry water' has a capacity to carry sediment, but there is no sediment available. Sediment will therefore be taken from the river bed. Leading to incision of the river bed. For example a lowering of the river bed of 4 meters was reported at the Colorado river (McCully, 2001)). Other impacts mentioned in literature are: widening of the bed, coarsening of the bed material and erosion of the downstream delta is reported. The downstream delta erosion occurs is created by the sea which is eroding the coast, while the sediment that was replenishing the coast is no longer delivered (Annandale et al., 2016; Morris & Fan, 1998; Kondolf, 1997; Kondolf et al., 2014; Williams & Wolman, 1984; ICOLD Sedimentation Committee, 2009). Furthermore foundations of bridges and other hydraulic structures can be endangered by these effects. To reduce the impact of 'hungry water' the sediment shortage has to be compensated. The best way to reduce these negative impacts is by making sure that the sediment can pass the dam. In that case there will be less sedimentation in the dam and downstream impact is reduced (Kondolf et al., 2014; Kondolf, 1997).

#### *Discharge effects*

The water that passes the dam is discharged in a controlled fashion. In almost all cases this means that the flood peaks that existed before the dam was build, do not occur anymore. In general the low flow duration is increased and the flood peaks are absorbed by the reservoir. For hydro power dams the outflow of water usually fluctuates even more. If power demand peaks, more water is put through the turbines to produce more power and vice versa, these outflow peaks are called power peaks. Power peaks have for instance lead to peaks of water outflow in wintertime in the La Grande river and the reduction of flow in springtime. Since power consumption is highest in the low flow period in the winter. This is completely opposite to the natural hydrograph. This is an example of the complete change in discharge in the river on a seasonal basis, however also short time daily and hourly fluctuations occur. These fluctuations can lead to extra erosion of the river banks (McCully, 2001). The maximum transport capacity of a river coincides with the water velocities occurring during a flood. If floods become lower, velocities in the river will become lower and thus less material will be transported. The change in flow regime is also one of the causes of the growth of vegetation in the river channel. Vegetation can, due to this new flow regime grow closer to the bank, creating a rougher and more solid river bank. This increases the roughness of the riverbank, which leads to higher flood levels, thus to increased risk of flooding (ICOLD Sedimentation Committee, 2009).

The distance over which the changes appear, depends on the site specific conditions. The change in flow regime has to be considered when sediment is deposited downstream to replenish the river. If not done properly, the added sediment can block the river entirely (Kondolf, 1997). The impact downstream of a reservoir is reach from a few kilometers to more than hundreds of kilometers, depending on the local conditions of the river and the river basin. The river will try to reach a new equilibrium condition, up to the point that this equilibrium is reached, the river will continue to change, possibly leading to additional undesired downstream impacts.

***Impact on the ecosystem***

The main environmental impacts of dams are related to morphological changes, changes in water quality, water temperature change and to the dam itself. One of the effects of the blocking of sediment transport by the dam is the armouring of the river bed. This means that bigger stones form the top layer of the bed, which are heavier than the stones that formed the original river bed. The effect of bed armouring is that fish like salmon become unable to spawn (Kondolf, 1997). Another effect is that the water quality changes due to the presence of a dam, the amount of oxygen in the water becomes lower (ICOLD Sedimentation Committee, 2009) and the water flowing through the dam carries sediment along, leading to more turbid water (Morris & Fan, 1998). The temperature of water that is released into the downstream river becomes lower. This is the case when water is let out of the bottom outlets of a dam. The colder water is heavier than warmer water. The warmer water floats on top of the cold water. When water is released at the bottom of the dam, this creates a cold water flow into the downstream river. Making the river colder then before the dam, thus leading to a change in the ecosystem (World Comission of Dams, 2000). Furthermore the dam acts as a barrier for fish, it cuts an ecosystem in two parts, making migration of the species very difficult to impossible. For instance salmon has big issues related to this. Part of the obstacle can be mitigated by building fish ladders, however, it takes way longer for salmon offspring to reach the sea. Greatly affecting the transition from fresh water fish to a salt water fish (McCully, 2001). This is however a direct result of the dam itself and not a result of the sedimentation in the reservoir. It is thus out of the scope of this thesis.

## 2.4. Knowledge gap

Examples of dams affected by reservoir sedimentation have been presented abundantly in this chapter. An additional example of poorly functioning reservoirs are the Inga I & II dams and reservoirs in Congo. Sedimentation of the intake channel has let to a reduction in power production of 30 %, however instead of restoration of the old dams, a new dam (Inga III) is proposed (Sanyanga, 2017). These demonstrate the there is indeed a need for methods to restore reservoir capacity.

Although the ICOLD Sedimentation Committee concludes that the costs of reservoir sedimentation are significant, investments into solutions to reservoir sedimentation problems are small. Dealing with the issues is thus postponed and will have to done by future generations. More research into the subject is justified, especially since the new dams that are build, are build in locations with high sedimentation rates, like South East Asia and South America. In the future dam design does not only have to be economically optimized, but also has to be optimized for sustainability. A better understanding of sedimentation problems, will lead to better solutions. Management of sediments is often not implemented at dams, detailed studies are performed in the design phase of a dam, however this knowledge is not transferred for use during the actual operation of the dam, bathymetric surveys of reservoirs are scarce and the surveys that are available often date back to the 1980's. (ICOLD Sedimentation Committee, 2009).

Reservoirs should not be designed for a finite life, where the sediment is not really taken into account. The should be designed for an infinite life. This can be achieved by coming up with sediment management solutions (Annandale et al., 2016; Kondolf et al., 2014; Palmieri et al., 2003; Morris & Fan, 1998). The main focus in the coming years in the area of water reservoirs has to be taking the influence of sediment into account in the design of new dams and manage it accordingly and meanwhile deal with sedimentation issues in the current reservoirs. Measures have to be applied to raise awareness among the general public of the sedimentation issue. Climate change and the role of reservoirs in a changing climate and adaption to that climate have to be investigated as well. Worldwide collaboration on the research into sedimentation of reservoirs is needed to further understand the sedimentation process. A global database including sediment data would be a big help for this (Schleiss et al., 2016).

In discussions new insights came forward as well. For instance the possibilities of dredging seem to be mostly unknown to the owners of dams (*personal communication, K. de Graaf, 26-6-2017*). This means that the reservoir owners are mostly unaware of possible dredging solutions to their sedimentation problems. Furthermore new dams seem more attractive than projects for the rehabilitation of older, not fully functioning dams. The promotion of new dams is strong in the world, while there is gap between the owners of dams and the engineers providing possible solutions for the sedimentation problems. This gap leads to overestimation of the costs of dredging, making it appear as an expensive solution to issues associated with reservoir sedimentation (*personal communication, L. op de Beek, 6-7-2017*). These are all reasons to further investigate the possibility of dredging of reservoirs.

The focus of this thesis will be investigating when dredging of reservoirs is a feasible solution for the sustainable use of reservoirs. The awareness of reservoir owners to the sedimentation problems in reservoir is investigated. Dredging as a sediment management tactic will be investigated as well. Furthermore the deposition of sediment in the river downstream of the dam is investigated as well. The negative effects of sediment, in the upstream reach, the reservoir and the downstream reach have been shown. The disposal of dredged material to mitigate these negative effects will be investigated as well.

# 3
# Survey

The literature study confirms that sedimentation of reservoirs causes large problems. These problems occur in three locations: upstream of the reservoir, downstream of the reservoir and in the reservoir. However the reviewed literature shows that reservoir owners effectively dealing with the issue of reservoir sediment are scarce. Only a limited amount of projects dealing with reservoir sediment are described. Even fewer projects of dealing with reservoir sediment by means of dredging are described.

A survey is conducted among the owners and managers of reservoirs for several reasons: to determine if sedimentation is experienced as an actual problem; to investigate if dredging is perceived as viable solution; and to gain more insight into the general knowledge of reservoir owners on the subject.

## 3.1. Survey set-up

The survey starts off with basic questions about the respondent to the survey and the the concerning reservoir. Reservoir parameters as water inflow, sediment inflow and reservoir volume are asked. This information can possibly be to determine the possibility of dredging later on. Furthermore the availability of bathymetric surveys of the reservoir is asked. This in order to confirm whether or not there is indeed a lack of survey material. The value of the trap efficiency *TE* of the reservoir is requested to determine to what degree reservoir owners are familiar with this term.

The next section is the core of survey. The respondents are asked to indicate whether sedimentation of the reservoir has caused any problems. It is requested to indicate whether sedimentation of the reservoir is experienced as a problem or not. The next question is to elaborate on the fact that sedimentation is or is not perceived in the concerning reservoir.

Then awareness to downstream effects of the reservoir is asked. This in order to decide whether the reservoir managers are aware of downstream effects related to the dam, feel responsible for these effects and are willing to mitigate negative effects related to the dam.

The last part of the survey is on measures that are already in place. This gives an indication of the effects which are already mitigated, thus showing the seriousness of the sedimentation issue. The remaining questions are on the dredging of sediment. Would that be considered? How much are owners willing to spend on the dredging of sediment? What added values of dredging can they indicate? An implicit question here is whether the feasibility of dredging is purely an economical consideration or if the mitigation of downstream effects and a sustainable solution for the reservoir are taken into account as well.

The final question concerning the reservoir is whether or not environmental flows have to be produced. This is an indication for the degree of regulation already implemented by the local government. This is seen as an indicator for the importance of downstream river stakeholders.

The complete questionnaire used for conducting the survey is presented in appendix A.

## 3.2. Conducting the survey

The survey was conducted by picking 10 dams and reservoirs across the globe using the GRanD database. These reservoirs were picked based on geographic location and size. If a reservoir name had come up somewhere in the research that was an extra motivation to include that reservoir in the survey. Information on the authority managing the dam and reservoir was collected by searching for them on the internet. The survey was send by email or online contact form, including a link to the online survey. By sending the survey out to a few owners first, errors in the survey could be solved before spreading the survey on a larger scale.

The first round of sending out emails to the owners of 10 dams across the globe did not have the desired effect. The response rate was low and it was difficult to reach the appropriate person responsible for the management of the reservoir. Slow response to the survey was also related to the trajectory that the survey had to pass, starting at the receptionist working up to the final person who has to fill in the survey. Gathering data that the respondent needed to fill in the survey took longer than anticipated as well.

To speed up the process of getting in contact with owners and for a more direct approach, the contacting method was switched to calling respondents and getting approval to send an email first. Using this approach the response rate increased.

The online form of the survey lead to some issues, companies that had policies regarding emailed links were unable to complete the survey using this method. To mitigate this problem a PDF version of the survey was created. The PDF could be filled in digitally and returned by email. This also lead to an increase in response rate.

Conducting the survey led to new insights. Including all reservoirs in the world gives the survey a very wide scope, thus a wide variety in response. The structure of the survey focused on specific individual dams, however often multiple dams are owned by one company. To find the responsible person for one specific dam is in that case almost impossible. Especially for hydro dams the fact that one company owns multiple dams, leads to a general answer or approach to the sedimentation issue.

Another difficulty experienced is related to the communication with different countries. If a country was addressed where the main language was a form of English, the response was usually good. The purpose of the survey could be explained and questions answered accordingly. If however the English capabilities of a land or telephone operator were low, the survey goal became hard to communicate and often no answer was received. Examples of countries were this was an issue are: France, Iraq, Indonesia, Japan and China.

The time difference between countries lead to some midnight phone calls, but did not result in further problems. However there are quite a lot of companies that advertise phone numbers which are out of service or go unanswered.

The last issue that came up was that the statement 'owner of the reservoir' was hard to define.

Can the responsible engineer for a dam be qualified as an owner, or can a responsible research scientist be identified as an owner. To deal with this, the spread of 'owner' was taken very wide. Ranging from scientist, to responsible engineer, to asset manager.

Despite these issues, there are at least 14 people who have responded to the survey, for which I am grateful. Also the knowledge gained by in depth interviews with specific parties is of great help and is used in the rest of this thesis.

## 3.3. Sedimentation issues in practice

During the survey it became clear that it is really hard to connect to the appropriate person regarding each specific dam. In total 18 surveys have been completed regarding specific dams across the world. These surveys have been filled in by 14 different respondents. As shown in Appendix B the chance of sedimentation problems is at least 16%. However the band with in answers is due to the low response rate large.

In addition to the survey also different organizations which are connected to the dam industry have been contacted, including different owners of multiple dams under the responsibility of one owner. Some of these companies have been spoken to by phone or face to face. This leads to a more complete view of the problem.

Interesting results came forward out of these talks. Sedimentation is not considered as an issue in reservoirs located in areas with low sediment transport in the river. This low sediment transport is often the result of the surrounding terrain. This is the case in for instance East Canada, Norway and Germany.

Another interesting fact is that there are reservoirs which are not located in rivers, but are formed by natural lakes, up in the mountains. This is the case for a lot of reservoirs in East Canada. Sedimentation is less of an issue here since the reservoirs are located at the beginning of the river, where the sediment load of the river is low. If a reservoir is large enough, thus having a turnover time of the water of multiple years, the sediment that comes in is not considered to be a problem, since the remaining capacity will be large enough for the coming centuries.

In Africa, big issues regarding sediment have occurred in for instance the Welbedacht dam (ICOLD Sedimentation Committee, 2009). However sedimentation in African reservoirs has not led to problems in other parts of Africa like Malawi and Zambia, is the experience of experts (*personal communication, J. Velasco, 21-6-2017*). A special phenomenon in Zambia and surrounding countries are Dambo's. A Dambo is a form of wetland, acting like a giant sponge in case of rainfall. This sponge retains sediment, thus the rain water that reaches the actual river is relatively clear and hardly any sediment is carried. This is an interesting phenomenon that could indeed prove to be very useful in preventing the inflow of sediment into the river and thus into the reservoir. It has to be taken into account however, that these are very local effects.

In Indonesia the Mrica dam is heavily silted. In the Philippines and in St. Lucia sedimentation is also causing issues in reservoirs. The large amount of sediment in the reservoir in St. Lucia is attributed to a special event. In these cases a typhoon and an earthquake. These events are very hard to predict, making the sedimentation issues hard to predict.

In the state Kansas, almost all reservoirs are man made. They are put in the river ecosystem and are slowly silting up. The John Redmond reservoir was dredged in 2016. Key factors that helped to initiate this dredging process quickly were a recent drought, depleting the reservoir to 30% remaining capacity and the fact that cooling water for a nuclear power plant was taken downstream of the reservoir. Since the demand was predicted to exceed the supply in the near future, it was decided to start a dredging project to guarantee water supply beyond the year 2045 (*M. Unruh, personal communication, 21-6-2017*).

The results of the survey, are in accordance with the ICOLD report (ICOLD Sedimentation Committee, 2009). Sedimentation is indeed causing smaller issues in Canada, due to the very large reservoirs and low sediment load. The problems are larger in Asia, a example is Indonesia. The sedimentation rate in Germany is very low compared to the rest of Europe, at $0.17 \frac{\%}{year}$ (ICOLD Sedimentation Committee, 2009)) , which coincides with no sedimentation problems over there.

What has to be taken into account as well, is the effect of non-response bias. The survey has been sent out to over 50 different reservoir owners. The response has been from only 14 individual respondents. The resulting response is obtained from Africa, North America and Europe and also a response was obtained concerning Asia. The respondents have roughly been indicated on the world map in Figure 3.1.

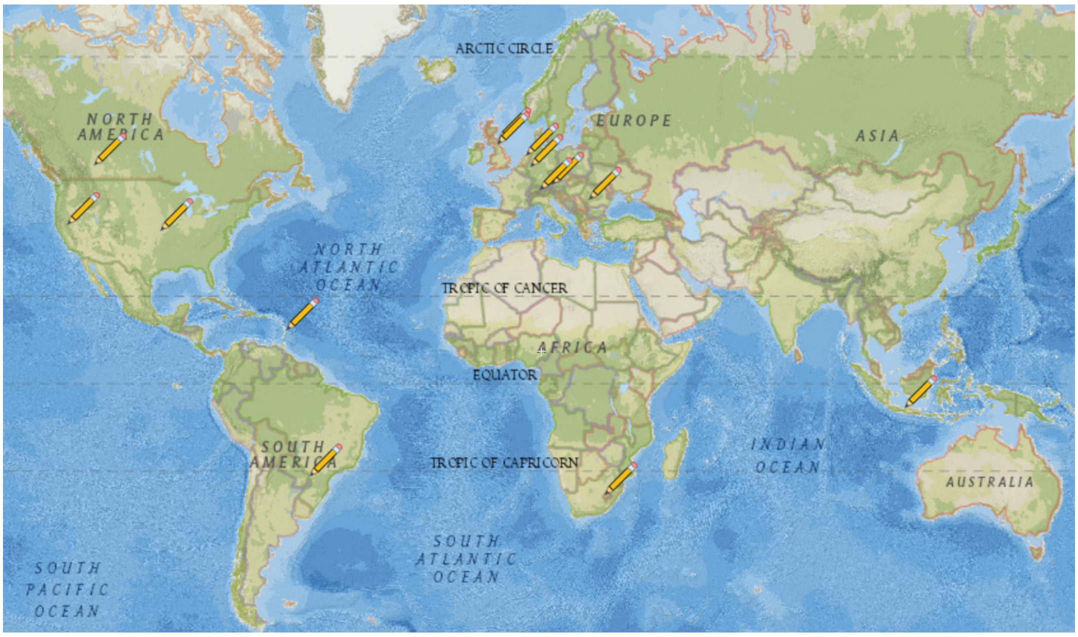



Figure 3.1: Indication of the location of the dams for which the survey has been completed.

Large countries like Russia and China and countries in South America are hard to engage, due to language barrier. The same goes for the middle Eastern countries. This has to be taken into account when the results of the survey are interpreted. The total scale of the issue is hard to determine using only input from English speaking countries. There is barely response received for non English speaking countries, the reservoirs in non English speaking countries can therefore not be taken into account. This creates bias in the results. This is especially difficult for countries where sedimentation problems are expected, based on the discussions with experts, like China, Algeria, Morocco and more. These problems are hard to verify, if communication is not possible.

## 3.4. Survey Results

The survey conducted among the owners of different reservoirs brought some insight into the challenges and also the operation and managing of dams and reservoirs all over the world. Even though the response rate was small, insight was gained. The general conclusions on sedimentation issues are discussed below.

### 3.4.1. Sedimentation issues

Using the response to the survey, more insight into the issues of sedimentation in reservoirs is obtained. Interesting is the difference in interpretation of issues associated with sediment by different reservoir owners. The answers to two questions are shown in Figure 3.2.

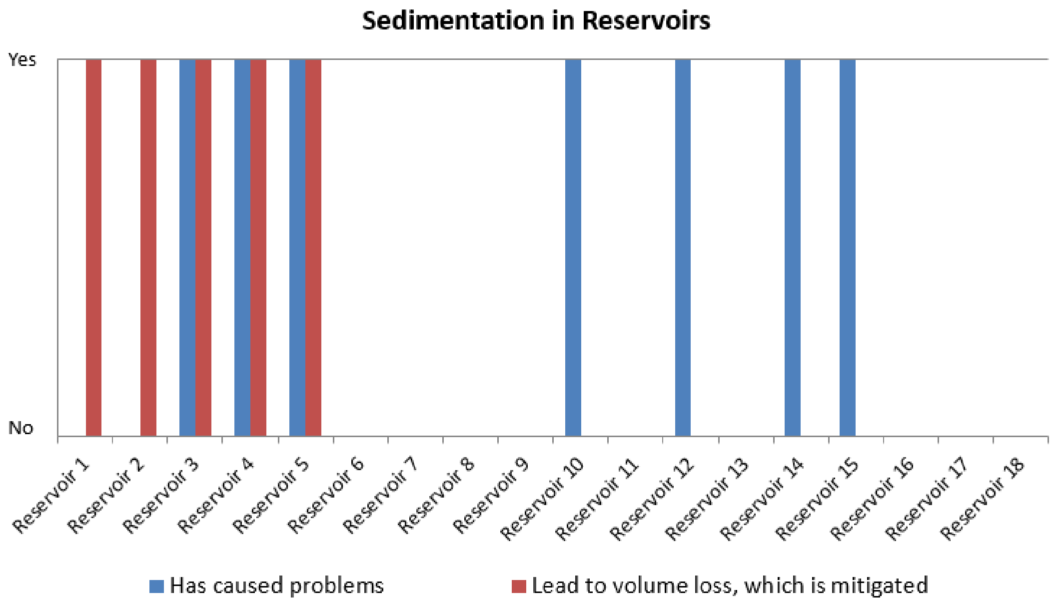



Figure 3.2: Responses to question 17 and 24 of the survey for the 18 different reservoirs.

Only for 3 out of the 18 reservoirs sedimentation problems occur and volume loss is mitigated at the same time. In all these cases the reservoir function: flood control or drink water supply was affected. Therefore the reservoir sedimentation lead to reservoir volume issues. The mitigation measures are either stringent control measures or proposed dredging to create more reservoir volume.

For 4 out of the 18 reservoirs sedimentation is causing problems, which are not yet mitigated. Described problems are blockage of the water intakes, increased flood levels, shipping channels being filled with sediment or erosion of the banks into the reservoir. Part of these problems are indeed associated with volume loss. The mentioned issues are in accordance with the issues associated with reservoir sediment, as mentioned in literature.

In two reservoirs however, sedimentation is not mentioned as a problem, but volume loss due to sedimentation is mitigated. Sedimentation apparently is not perceived as a problem, since the issue of sedimentation is already dealt with. The mitigation in these cases consists of flushing the reservoir when possible in combination with dredging. It is clear that if sediment would remain in the reservoir, it would cause problems. Apparently these problems are large enough to deal with them pro-active.

The sedimentation rate per year can be calculated for 9 out of the 18 reservoirs. The initial volume and completion year are known for each reservoir. However, only for 9 out of the 18 reservoirs the current reservoir volume is given. Negative values are neglected, since the enlargement of a reservoir is not a natural process and can not be taken into account for the sedimentation rate in the reservoir. The difference between original and current volume is calculated, divided by the number of years that has passed since start of operation till now. This gives an average of 0.896% volume loss per year. This number is even higher than the 0.8% mentioned in Chapter 2.

### 3.4.2. Bathymetric surveys

For 12 out of the 18 reservoirs a bathymetric survey has been carried at some point. For only 6 reservoirs, a bathymetric survey is conducted regularly. Apparently the bathymetric surveys are not as scarce as mentioned in literature, but not standard practice for all reservoirs either. From the bathymetric surveys carried out, 8 of 12 have been carried out within the last 4 years.

### 3.4.3. Trap efficiency

The term Trap Efficiency is highly unknown to the managers and operators of reservoirs. Only 5 out of the 14 respondents knew what the term Trap Efficiency meant. For the reservoirs for which the *TE* was known, all reported *TE* are higher than 80%, they have either decreased over time or stayed the same. This is in accordance with the expectation for the *TE*, as mentioned in Chapter 2. The volume loss due to sedimentation leads to a lower *TE*. For only 8 of the 18 reservoir the sediment inflow is known. It can be concluded that only part of the reservoir owners are considering sediment inflow as a possible problem.

### 3.4.4. Environment

Environmental flows have to be produced by 12 out of the 18 reservoirs and for one reservoir the backwater curve is kept at a constant level. This shows that there is indeed attention in most of the respondents countries for the downstream effects of the dam.

### 3.4.5. Dredging of the reservoir

In total 8 out of 14 respondents would be willing to invest in dredging their reservoir. In the case of a 'Yes' dredging projects were ongoing or being implemented. Dredging the reservoir leads in this case not necessarily to extra return, but is considered to be the best solution available. For other reservoirs dredging is only considered when a sustainable solution can be achieved where the reservoir can continue operating. While for other reservoirs dredging is only considered if extra financial benefits can be generated, thus if the gain exceeds the costs. The exact distribution of the response is shown in Figure 3.3.

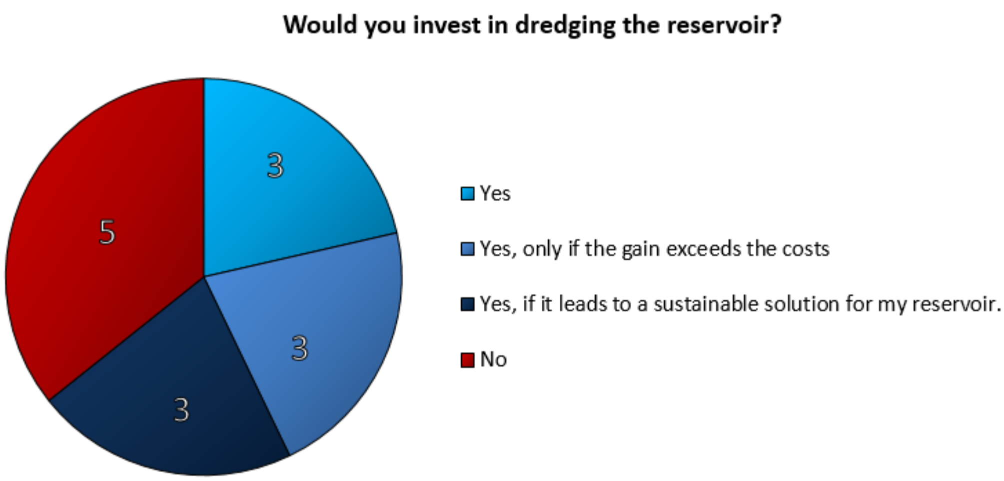



Figure 3.3: Response of individual respondents to question 26 of the survey: 'Would you invest in dredging the reservoir?'

The 5 respondents unwilling to invest in dredging of their reservoir, either could not give their opinion since it was the responsibility of someone else to decide over the investments or did not experience problems. In one case a detailed report proved that a dredging operation would not be beneficial.

Respondents asked what amount they were willing to invest into the dredging of reservoirs gave values ranging from \$3 to \$40 per $m^3$ up to millions for the a complete project.

Points of extra value regarding a dredging plan that are mentioned are: continuous operation of the reservoir; creating extra volume in the reservoir to be able to store (drinking) water; regain lost storage; optimize the economic performance of the reservoir; or restoration of the river downstream of the dam.

Specific remarks that followed from the survey are that reservoir sedimentation is becoming a more and more important subject all over the world. Also in the Alpine regions this is the case. Sustainable solutions have to be found to mitigate the negative effects of reservoir sedimentation, to increase lifespan of reservoir without affecting operations.

## 3.5. Conclusion

There are more than 58,000 dams in the world, but the small sample that is surveyed showed that not every dam and reservoir is dealing with sedimentation problems. This differs for each reservoir.

The surrounding terrain can be a big influencing factor, this is for instance the case in mountainous regions like Norway. Boulders might be moved along the bottom of the river and reservoir, but they are relatively easy kept out of the turbines. While in sediment laden rivers the sedimentation issues are indeed present, examples are known in Indonesia and United States of America.

Different criteria seem to be playing a role towards acting on the sediment problem. In for instance Kansas a dredging project was carried out due to the future safety of the drinking water supply and the cooling of a nuclear power plant. In Austria dredging projects were performed to clear sluicing gates and to make a reservoir future proof.

On the other hand, there are clear choices to delay acting on sedimentation till the effects of sediment form an actual influence on hydro power production, this is the case for a reservoir in the Philippines. Another option is to wait with acting on sedimentation problems, till a sustainable solution is developed, which is the case for the Welbedacht dam in South Africa.

The overall conclusion is that sedimentation will only be dealt with if it is recognized to influence the reservoir function. Added impulses to quickly deal with the sedimentation problems are threats to vital functions. Examples are: cooling water to a nuclear plant (*Kansas*); drinking water for a large population (*St. Lucia*); or loss of power supply.

The survey showed that the sedimentation issues are indeed real. In most cases, if the respondents had the authority, they indicated that investments in reservoir dredging would be considered if sedimentation issues were suffered. Therefore the rest of this thesis will focus on the potential of dredging as a solution to the sedimentation problems in reservoirs.

# 4

# Reservoir classification

The conclusion of Chapter 2 is that sedimentation in reservoirs indeed results in different issues. In Chapter 3 it is proved that these issues do occur in practice as well. Besides it is also concluded that dredging could indeed be a feasible solution to the reservoir sedimentation issues.

It would be useful to use a few reservoir parameters to quickly determine if dredging of a reservoir could be a feasible solution. In this chapter, reservoir parameters that are useful are identified. Using literature and common sense, parameters are reviewed that can possibly be used for the classification of reservoirs and the indication whether dredging is beneficial or not. Specific parameters relevant for dredging are taken into account.

To start off, the database used for data on existing dams and reservoirs is explained. The function of reservoirs is evaluated. Then factors influencing the seriousness of the sedimentation problem and factors influencing dredging are explored. The influence of the reservoir shape on the sediment location is investigated and finally a model for the evaluation of reservoirs is introduced.

## 4.1. Dam and reservoir databases

The databases used for the data on the current dams in the world are the Global Reservoir and Dam *GRanD* database and the World Register of Dams *WRD*. The GRanD database is set up to pinpoint geographic locations of dams and their reservoirs globally. The goal of the database is to bundle data on reservoirs in the world to make studying these reservoirs easier, now and in the future. Currently, version 1.1 of this database contains 6,862 records of dams and their associated reservoirs (Lehner et al., 2011a).

The data is build up using different data sets of Universities and other institutions across the globe. The location of the dams is relatively accurate, the volumes of the recorded reservoirs are reported, but have not been verified using bathymetric surveys. If multiple values for the reservoir volume are given all values are reported. These values are reported in the following order: the most representative volume, the maximum volume and the minimum value. This leads to a smaller degree of certainty on the reservoir volume.

Missing reservoirs surfaces are estimated using an empirical formula. The database contains for each dam and reservoir an identification number, the name of the dam, the closest city, the country it is in, the year the dam was build or commissioned, some dimensions, the most reliable estimates of reservoir capacity the main and secondary use of the dam and more (Lehner et al., 2011b).

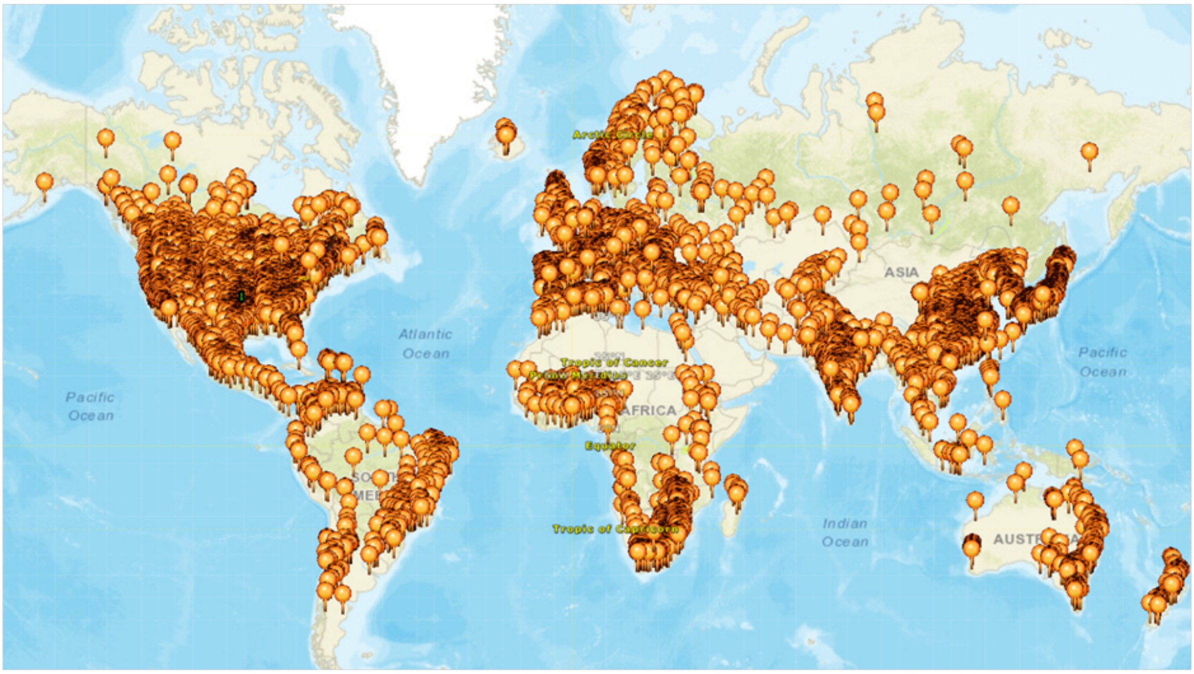



Figure 4.1: The GRanD database, pin-pointed on the map of the World. *(Screenshot)*

The database itself consists of two layers. The first layer contains pinpoints for each dam that is in the database. The second layer contains polygons, which have the shape of the reservoirs, that are enclosed by each dam. An overview of the database is given using ArcGIS (Geographic Information System) explorer and can be found in Figure 4.1.

If for instance the focus is placed on the W.A.C. Bennett Dam in the province of British Columbia in Canada. First the reservoir created by the dam, becomes visible, in this case thus the Williston Reservoir (Figure 4.2. By clicking the icon of the dam, all the information about the W.A.C. Bennett Dam present in the GRanD database, is shown on the map. This is shown in Figure 4.3.

The WRD is set up by the ICOLD (*International Commission on Large Dams*), it is maintained by processing input from all national ICOLD committees. It contains both smaller and larger dams (dams higher then 15 m or dams between 5 and 15 m, impounding more than 3 million cubic meters). There are currently 58,518 dams in the database (ICOLD (International Commission on Large Dams), 1998).

The dams included in the GRanD database can also be found in the WRD. However location data is not presented in the WRD database. There is however detailed information given on the dam dimensions, the function of the adjoining reservoirs, their construction type, and so forth.

The GRanD database was last updated in 2010. The ICOLD database is continuously updated by a special ICOLD comittee.

In their vision paper, Schleiss et al. are pleading for a global database on sedimentation. The GRanD database was a good start but has to be expanded by including all dams in the world and for instance sedimentation data for each reservoir. It would be great if the WRD and GRanD database could be combined and be freely accessible to everyone. That could prove to be a helpful tool for global research on dams, reservoirs and reservoir sedimentation.

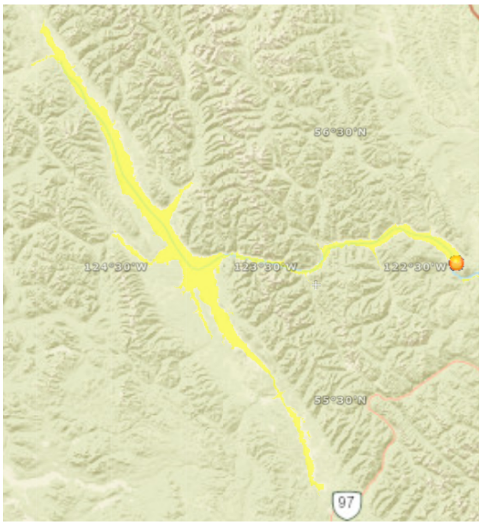



Figure 4.2: The Williston reservoir Polygon of the GRanD database. *(Screenshot)*

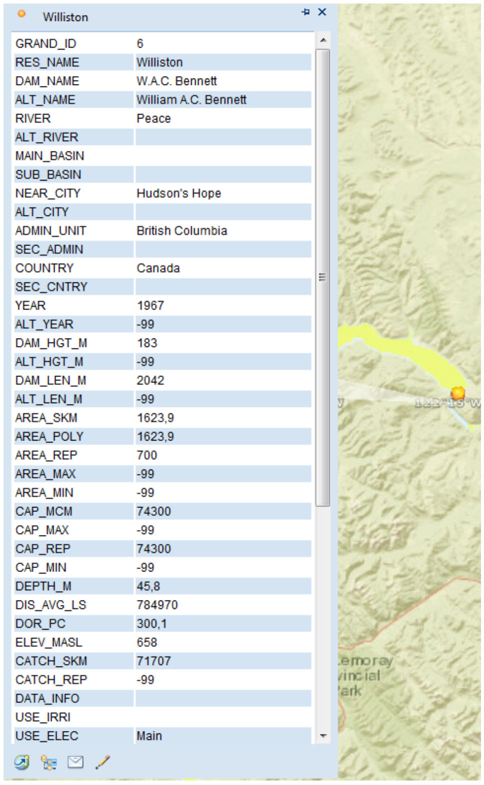



Figure 4.3: The details of the W.A.C. Bennett dam. *(Screenshot)*

## 4.2. Reservoir function

An important difference between reservoirs is the function of each reservoir. The GRanD reservoir contains 6,862 entries of dams and their attributing reservoirs. Of those 6,862 entries, for 1,577 dams their primary function is not known. For 3,048 entries a single purpose is given for the reservoir. The given reservoir functions are: Irrigation, Hydro electricity, Water supply, Flood control, Recreation, Navigation, Fisheries and other functions, like pollution control and the feeding of life stock.

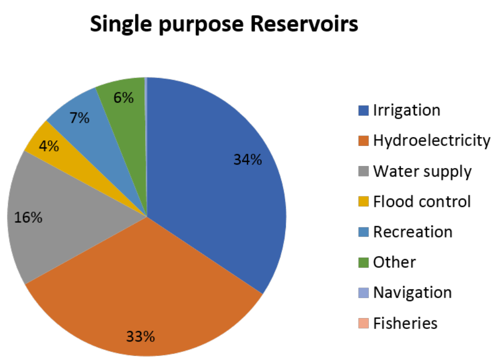



Figure 4.4: Single purpose reservoirs in the GRanD database.

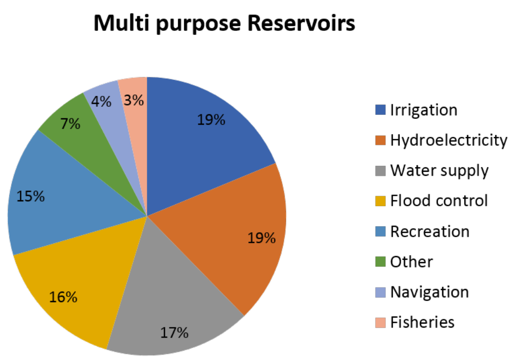



Figure 4.5: Multipurpose reservoirs in the GRanD database.

Using Microsoft Excel the function of each dam and reservoir in the database is visualized. The reservoirs fulfilling only one of the given functions are given as a percentage of the total number of single purpose reservoirs and can be found in Figure 4.4. For 2,237 dams and reservoirs, the main function is given, but also secondary functions of the dam and reservoir are included. In Figure 4.5 all the different functions are combined and given as a percentage of the total number of multipurpose reservoirs.

In the WRD the function is registered for 38,000 dams. In figure 4.6 the reservoirs for which only one function is registered in the WRD are displayed as a percentage of the total number (28,614) of single purpose dams. The multi purpose dams in the WRD are displayed in Figure 4.7 and shown as a percentage of the total number of multi purpose dams in the WRD (9,930).

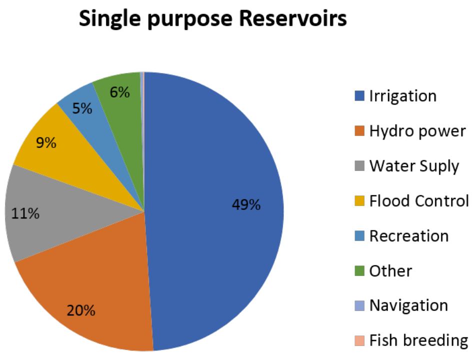



Figure 4.6: Single purpose reservoirs in the WRD.

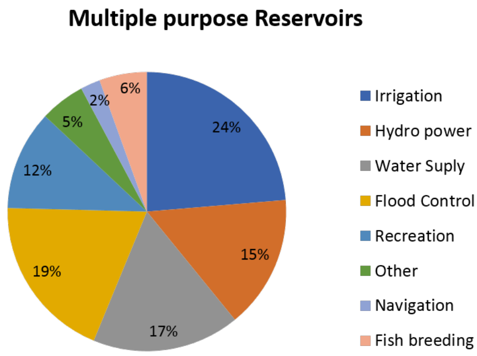



Figure 4.7: Multipurpose reservoirs in the WRD.

Both the Figures (4.4 & 4.6 and Figure 4.5 & 4.7), both from the GRanD database and the WRD show a good match. The part of single purpose dams in the WRD used for irrigation is larger, than for hydro power dams, when compared to the GRanD database.

From the comparison of the single and multipurpose reservoirs the following can be concluded. More than two thirds of the single purpose reservoirs are designed for irrigation and the generation of hydro power. If water supply is taken into account, 83% of all single purpose dams are covered. There are barely any single purpose dams having a function for navigation or fisheries. When multipurpose reservoirs are considered navigation and fisheries both increase from negligible to 4 and 3%. This means that both navigation and fisheries are most likely to be considered only in combination with another reservoir purpose.

The function of the reservoir is important, because it determines the importance of a reservoir. It is not hard to imagine that irrigation is an important function, because for food production enough water has to be available. However, drinking water supply would be more important than irrigation, since it would affect people more direct if water is for consumption would become unavailable. If the volume of water stored becomes to small, problems arise.

Electricity is very important, people can hardly do without electricity anymore. If thus no more power can be generated due to sedimentation, this leads to urgent problems. If a hydro power dam is the only source of energy, the problems become even more urgent.

Flood control can be an important function of the reservoir, however, the design flood of a flood retention reservoir does not occur every year. It occurs at a much lower frequency. The result is that sedimentation problems for a flood retention reservoir are perceived to be less urgent at a short timescale. This will most likely lead to a delay for the decision of investing in mitigating the effect. If a flood occurs that can not be retained, damage is usually significant.

These are a few examples of different functions that a reservoir can perform and different issues associated with each reservoir. The function of the reservoir and how vital this function is for people influences the investment decision. The more significant the sedimentation problems are for nature and people, the more the willingness to solve or prevent these problems. The function of the reservoir is crucial for determining if dredging of a reservoir is a financially feasible option.

After discussion with experts in the field and the survey it became clear that the willingness for investing in sediment related issues is highest for hydro power and water supply reservoirs.

The reservoirs for which in the survey it is reported that sedimentation problems are mitigated fulfill at least one of these functions. Hydro power is the main function for the three out of five reservoirs. The importance of the reservoir function thus has a large influence on the investment decision, concerning reservoir sedimentation.

## 4.3. Reservoir size

The overall conclusion of the survey and of interviews with reservoir owners that did not fill in the survey is that in North America there are enormous reservoirs which are so immense that sedimentation is not affecting the active storage in a way that the reservoir function is negatively influenced.

The volumes of these reservoirs are large enough and the sedimentation rate is low enough, that sediment issues do not lead to problems. A good example of such a case is the W.A.C. Bennett dam in British Columbia, Canada. This reservoir has a volume of $74 * 10^9 m^3$. Sedimentation is the reservoir is low, since it is located in a mountainous area and the reservoir is enormous, therefore sedimentation problems do not occur. Large reservoirs are most likely not affected by sedimentation problems now or in the near future. They are therefore not taken into account for a solution to these problems.

The resulting question however is, how the separation can be made between a big reservoir, that acts as a 'black hole' absorbing all incoming sediment without issues and a smaller reservoir where sedimentation does indeed lead to problems. According to Fruchard & Camenen a black hole reservoir has a volume of billions of cubic meters. These dams capture both floods and sediment. If the limit where black holes start is set to $1 * 10^9 m^3$ there are 1,268 dams with a larger reservoir volume found in the world register of dams (ICOLD (International Commission on Large Dams), 1998). While for 1,955 dams and reservoirs no data is found. However there are still over 55,000 dams that are smaller and thus potentially have to deal with reservoir sedimentation.

Smaller dams, in the order of millions of cubic meters act as sorting dams. Most of the coarse sediment is retained in the reservoir and finer particles are carried through the dam (Fruchard & Camenen, 2012). This leads to the previous mentioned 'hungry water' effect.

Each dam and reservoir will have to deal with site specific issues, but all reservoirs deal with a sediment imbalance. It is crucial that the sediment imbalance is restored to retain both usable space in the reservoir and to protect the upstream and downstream reach of the river from negative consequences.

## 4.4. Reservoir depth

An important parameter for dredging is the maximum depth of the reservoir. This is one of the important parameters to determine what equipment is suitable for specific projects. To establish the potential for different dredging methods, the different depths that possibly have to be dredged, have to be determined.

The ICOLD database (ICOLD (International Commission on Large Dams), 1998) contains the height of each dam. Since the height of dams can easily be obtained, it would be beneficial if this height could be used as an indicator for the maximum reservoir depth.This maximum reservoir depth is important for the selection of the dredging equipment later on.

The original depths of the reservoirs are not registered, therefore a relation is established between the dam height and the maximum reservoir depth. This relationship is determined by collecting data on specific dams. The data for the dam height in the WRD is compared to data found on the maximum reservoir volume. In appendix C it is shown that the dam height is an over estimator for the maximum depth of the reservoir. This is in accordance with expectation since there is always free-board needed on top of a dam, to keep waves contained in the reservoir for instance.The relationship found for dam height ($h_{dam}$) and maximum depth ($d_{max}$) is:

$$d_{max} = 0.87 * h_{dam} \tag{4.1}$$

This relation can be used to determine in an early stage what dredging methods will be suitable and what dredging methods are not.

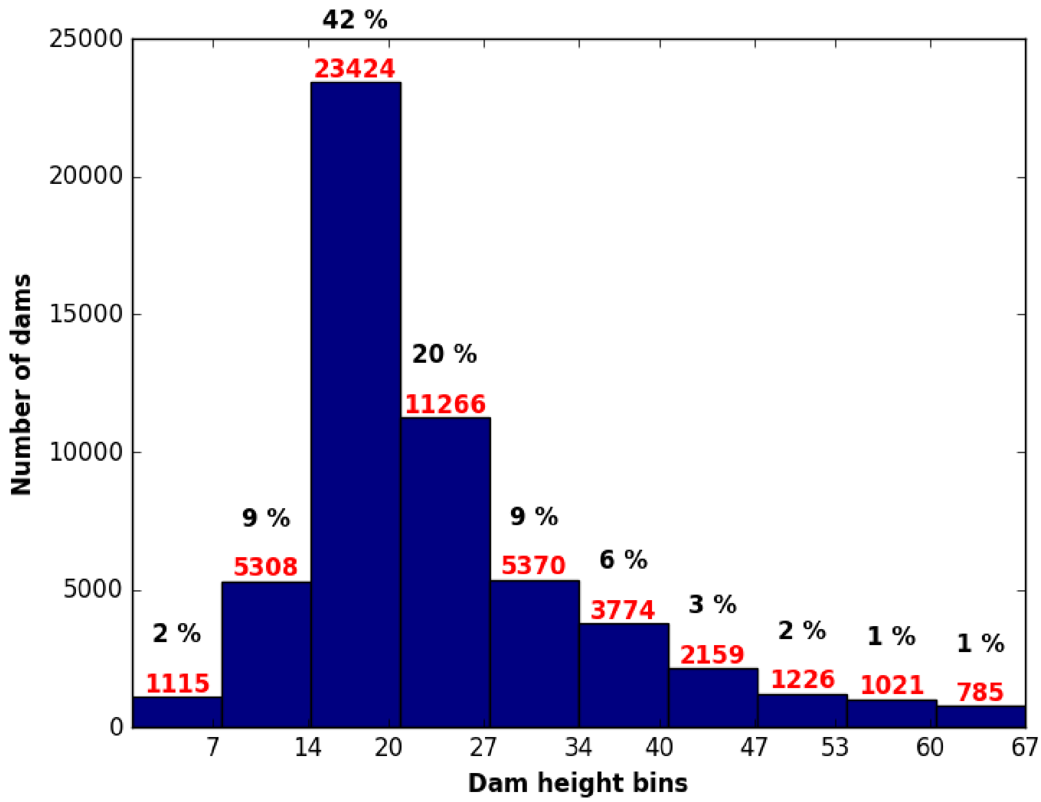



Figure 4.8: Dams in the WRD with a height up to and including 67 m, sorted by height, given as a percentage of the total amount of dams.

The maximum depth of the reservoir will not be the only factor important for dredging. The 'delta-effect' also has to be kept in mind. As shown in Figure 2.3 the sediment at the beginning of the delta is coarse and close to the surface. The fine sediment is located at the greatest depth near the dam itself. This distribution of the sediment is different for each reservoir, as has follows from Figure 2.4.

For the type I reservoirs 70% of the sediment will be deposited in the top 50% of the reservoir. If however the gorge type reservoir (type IV) is considered, roughly 60% of the sediment will be deposited in the bottom 20% of the reservoir. This is favourable if there is enough dead storage at the bottom of the reservoir to capture this sediment, however if the active storage is influenced, this will make dredging extra challenging.

The sediment excavating depth will differ greatly depending on the type of reservoir and thus the build up of the delta. The maximum depth is however located near the dam and can be estimated using Equation 4.1.

## 4.5. Location of sediment in the reservoir

In order to determine in what way the reservoir should be dredged, it is necessary to determine where the sediment entering the reservoir is deposited. Furthermore it has to be determined which factors influence the deposition of the sediment in the reservoir. Lastly it has to be determined if the types of sediment influences the deposition location in the reservoir. In Chapter 2 the model of Borland & Miller is presented, linking four types of reservoirs to different curves for the distribution of sediment over the depth of the reservoir.

### 4.5.1. Modelling approach

In order to verify these sediment to depth curves, different reservoirs are simulated in Delft3D, each reservoir symbolizing a different type of reservoir. The starting point for these different reservoirs is a river of 100 $km$, an original bed slope of $10^{-4}$ and a width of 1,000 $m$. A grid of 100 $m$ by 100 $m$ cells is used, leading to a grid size of 1,002 by 12 cells. The created reservoir is shown in Figure 4.9. The full model setup boundary conditions are described in Appendix E.

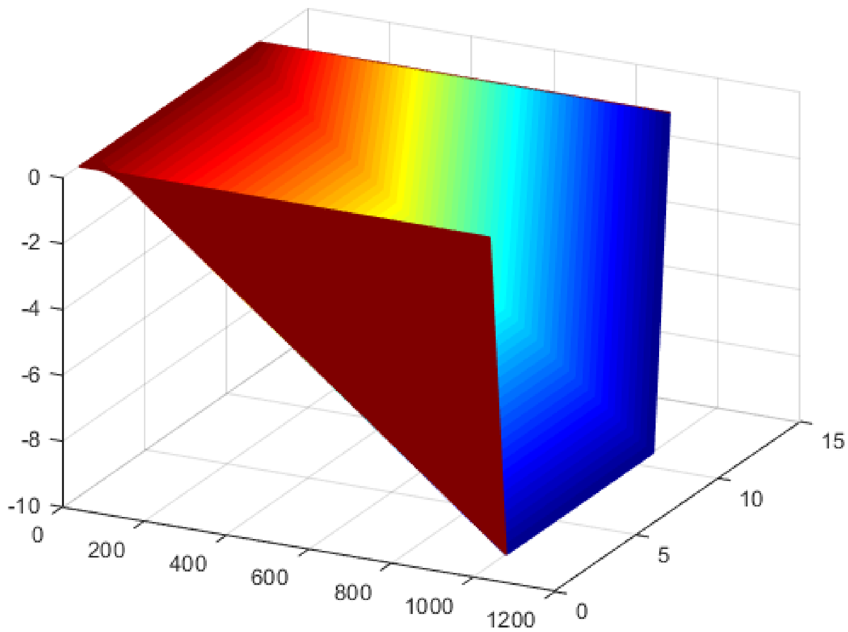



Figure 4.9: The bathymetry for the initial reservoir used for simulations in Delft3D.

The dam is assumed to be on the right side of the reservoir. The outflow through the dam is assumed to keep the water level constant, therefore the dam is schematized by a constant water level on the right side of the reservoir. In all calculations the maximum reservoir depth ($y_m$) is assumed to be 7.5 $m$. The inflow at the top boundary, upstream of the reservoir is taken to be a total discharge of 1000 $\frac{m^3}{s}$. The hydraulic situation in the reservoir, after equilibrium is reached, a longitudinal cross section of the reservoir will be a close match to the the situation depicted in Figure 4.10.

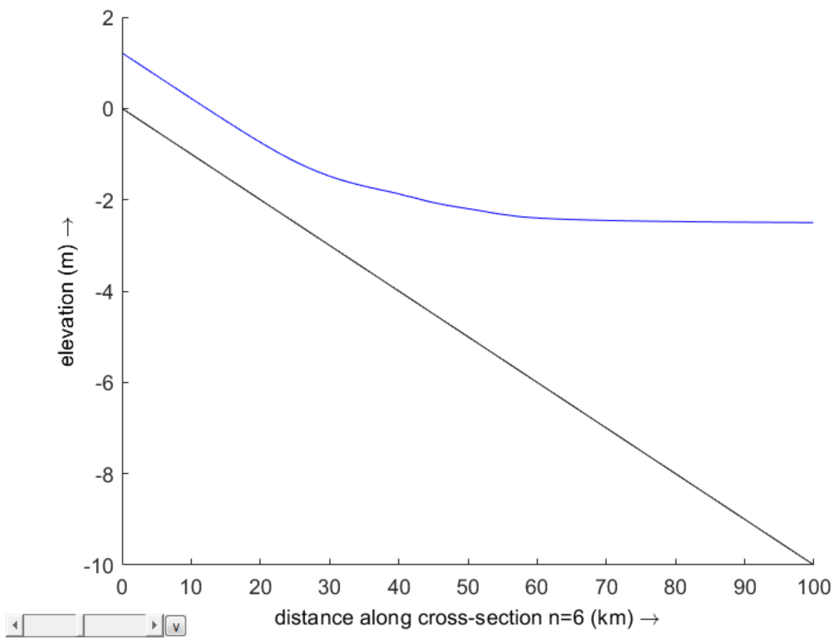



Figure 4.10: Water level in the reservoir, in a longitudinal cross section, after equilibrium is reached.

For the given reservoir the M-value according to the method of Kaveh et al. is used. Combining Equation 2.3 & 2.4 this results in:

$$M = \frac{2}{\frac{2 * V_m}{y_m * A_m}} \tag{4.2}$$

Filling in Equation 4.2 for the initial results in a M-value of the reservoir of 2, as shown in Appendix E. This value makes that the reservoir can be identified as a reservoir of type III, the hill type reservoir. By changing the cross sections in stream wise direction, the M-value is manipulated to represent other types of reservoirs as well. The computations to create these different M-values can be found in the appendix as well.

It is not possible to create a reservoir with an M-value in the range of a gorge type reservoir. In order to create a reservoir that has a M-value low enough, the shape of the cross-section would have to become wider as the depth increases, like a triangle. That is not possible to simulate in Delft3D. It is however no big loss that this type can not be simulated, since most of the sediment ends up in the dead storage for this reservoir type. The dead storage is not the part where dredging is assumed to be the most useful solution. For that reason the Gorge type reservoir is not further investigated.

The reservoir shape that is found representing a M-value of 3 has the shape of an upside down triangular pyramid. The reservoir is presented in Figure 4.11.

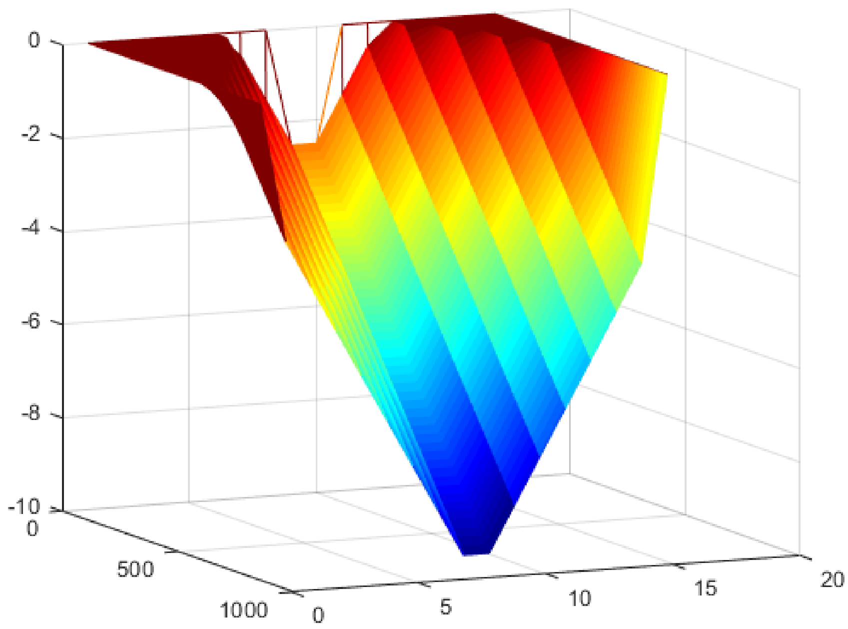



Figure 4.11: The reservoir shaped to obtain a M-value of 3 (Equation 4.2).

If the M-value is evaluated by integrating the volume of the reservoir under the water surface, due to rounding differences if differs from the analytically calculated M-value, the value for M that is found is 2.8. This is however still within the range of a type II reservoir, therefore it classifies as a floodplain-foothill reservoir.

The reservoir with a M-value of 4 is found to have a shape of two square root functions going in opposite directions. This reservoir is presented in Figure 4.12.

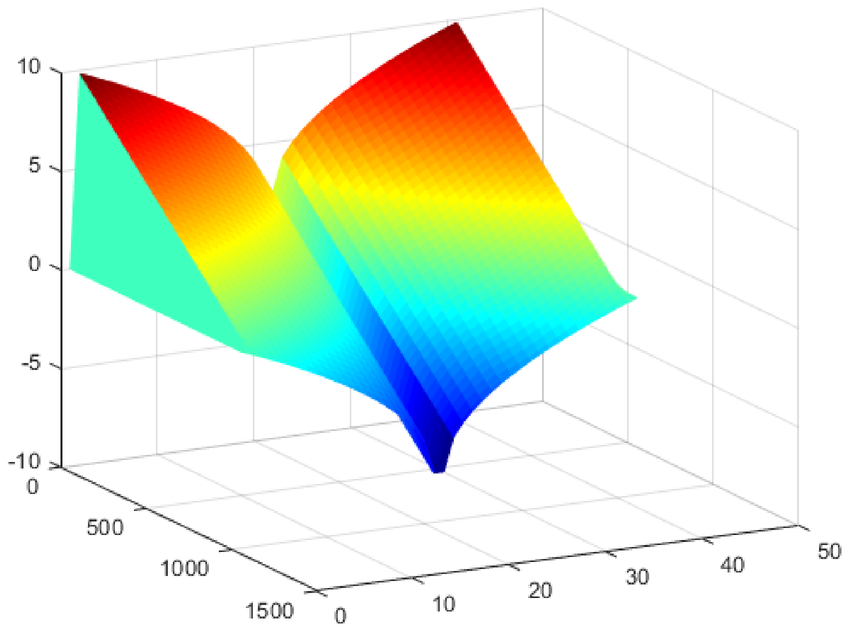



Figure 4.12: The reservoir shaped to obtain a M-value of 4 (Equation 4.2).

The M-value of the created reservoir is also evaluated using the integrating method. The resulting value for M is 4.36. This is most likely related to the linear interpolation of the depth in the reservoir. This results in an overestimate of the M-value. The resulting value is however still within the range of a lake type reservoir and therefore it can be used.

### 4.5.2. Modelling results

In order to determine if sediment does really settle in the reservoir as is depicted by Borland & Miller in Figure 2.4, simulations are performed for the different types of reservoirs. The simulations are performed for one month for each reservoir. The boundary conditions are specified in Appendix E. The hydrodynamic boundaries are kept constant, while runs are performed using three scenarios.

- Only the clay fraction
- Only the sand fraction
- Both sand and clay simultaneously

These combinations of morphologic boundary conditions are used for modelling the three different reservoir types.

The difference in height between the original bed and the bed at the end of the simulation is calculated (Appendix E).For different heights in the reservoir the volume of deposited sediment determined, using a depth increment of 0.1 $m$ each run. These different calculated volumes are divided by the total volume of sediment deposited. Using this method the percentage of sediment that is deposited is known for each depth. Then each depth is divided by the maximum depth of 7.5 $m$. An overview like the one in Figure 2.4 can be plotted. This shows the percentage of sediment deposited at a percentage of the maximum depth. In Figure 4.13 the curve is shown for each reservoir with different M-value, for the deposit of both clay and sand.

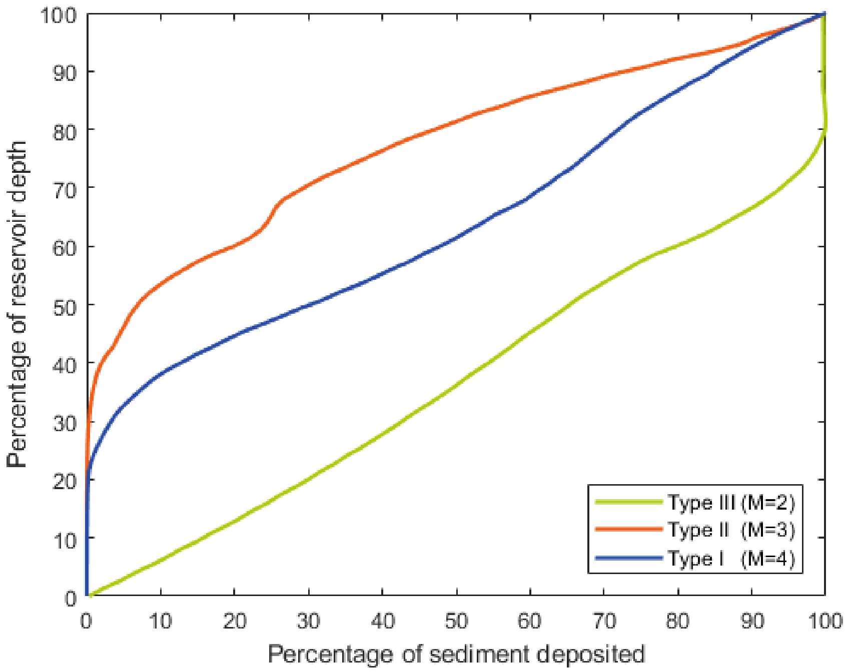



Figure 4.13: Sediment percentage deposition curves obtained by modelling each reservoir in Delft3D.

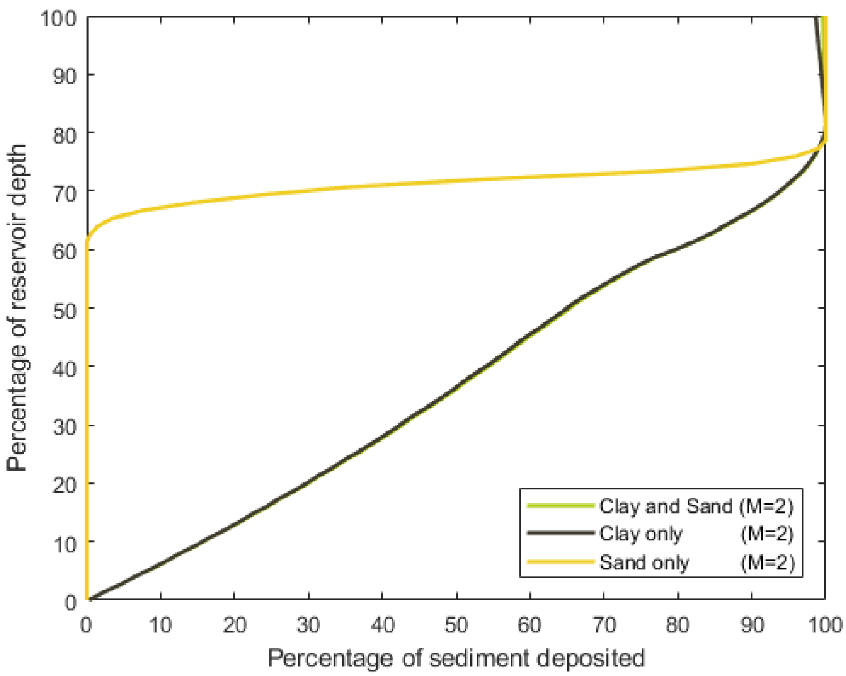



Figure 4.14: Sediment percentage deposited, for clay, for sand and a combination of both, modelled using Delft3D for a reservoir with M=2 (Equation 4.2).

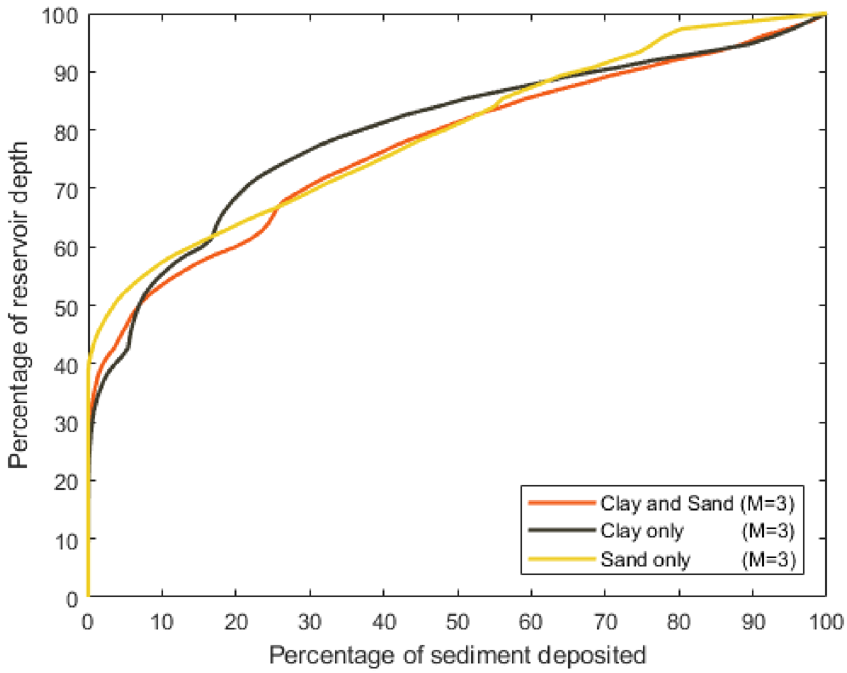



Figure 4.15: Sediment percentage deposited, for clay, for sand and a combination of both, modelled using Delft3D for a reservoir with M=3 (Equation 4.2).

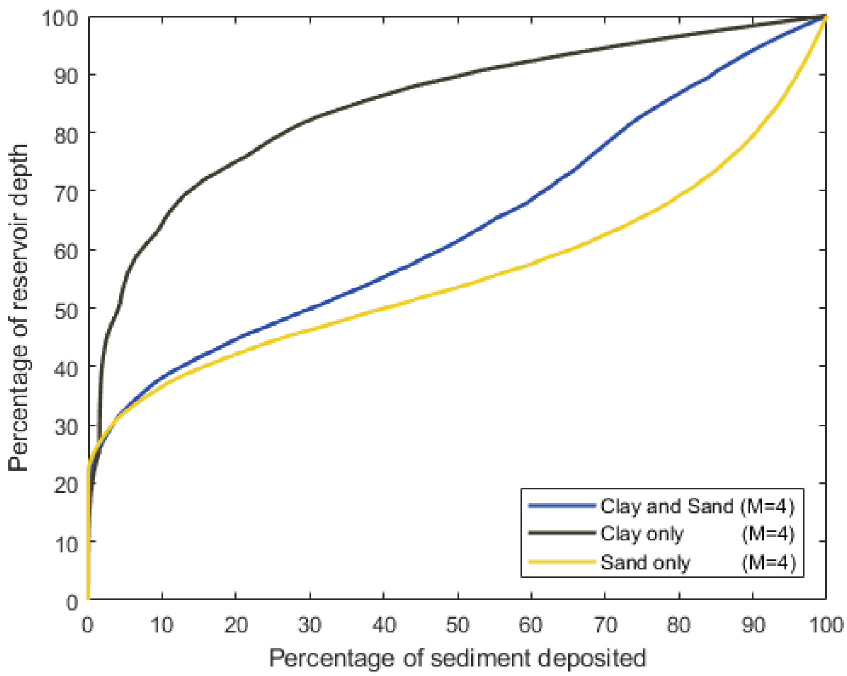



Figure 4.16: Sediment percentage deposited, for clay, for sand and a combination of both, modelled using Delft3D for a reservoir with M=4 (Equation 4.2).

The type III curve in Figure 4.13 shows reasonable similarities to the type III curve in Figure 2.4. The type II and type I curves seem to be opposite to curves given in that figure. When only clay is entering the reservoir with a M-value of 4 (Figure 4.16), the curve for clay looks reasonably like the curve given for the type I reservoir.

For the reservoir with a M-value of 2 (Figure 4.14 it is striking that sand is only deposited at the top of the reservoir. This results in an almost horizontal line between 60 and 80% of the maximum reservoir depth.

The reservoir with a M-value of 3 has no clear distinction between the distributions for the clay, sand and combined curves (Figure 4.15). A possible explanation for this is the shorter length of the reservoir. Hereby the water flows into the reservoir directly, leading to deposits further in the reservoir.

In the reservoir with a M-value of 4, sediment is as expected deposited in the upper part of the reservoir. Clay however appears to be deposited much higher in the reservoir than the sand.

The depth of the sediment can be of great value for the setup of a dredging plan. The dredging of sand is different from the dredging of clay. It follows from the model results that for an M-value of the reservoir of 2, only be sand will be deposited above 60% of the maximum reservoir depth. No additional boundary to the curve found by Borland & Miller can be found for a M-value of 3. For a M-value of 4 it is assumed that sand will deposit not lower than 40% of the maximum reservoir depth.

### 4.5.3. Conclusion

Taking the model results into account it is clear that the curves depicted by Borland & Miller can not be directly recreated by modelling different reservoirs and only one inflow of water and sediment. It is clear that the M-value of the reservoir is not the only factor that has an influence on the deposition of sediment in the reservoir.

The sediment type is of importance, hence the difference in lines between clay and sand in Figures 4.14, 4.15 & 4.16. The assumed concentration of sediment will have an influence on the sediment deposition curve as well. If the concentration of one of the sediment fractions is different, this will inevitably have an effect on the combined deposition curve. In a following investigation it could be further investigated if it is possible to create different shapes with the same value for M, besides the shapes presented in this research. In that manner it can be further determined what influence this parameter has on the deposition of sediment.

Possible explanations for the dis-congruence between the found sediment deposition curves and Figure 2.4 are that only lakes and reservoirs in the United States are evaluated by Borland & Miller. Furthermore the bandwidth for the curves given by Borland & Miller is not taken into account. The time factor can also be an important factor since the modelled period is merely one month, multiplied by a morphological factor of 100. Therefor it does not represent more than 8.5 years. A longer modelling period could have a large influence on the found deposition curves.

Further research into shape of the reservoir and the deposition curves is thus necessary. It is clear that more factors than only the reservoir type influence the location of the sediment deposits in the reservoir.

## 4.6. RESCON model

In 2003 the RESCON model was developed for the World Bank (Palmieri et al., 2003; Kawashima et al., 2003). The RESCON model stands for REServoir CONservation. The goal of this model is combining engineering and economics. The RESCON model is meant to indicate whether or not sediment management techniques can be used to extend the functional life of a dam and reservoir longer. It is used to find a sustainable solution or to determine that abandoning the reservoir is a better solution. For the evaluated dam and reservoir it results in an indication of the economical feasibility of the extension of the dam life. The model uses an economic optimization algorithm in combination with engineering relationships. This optimization leads to an advise on whether or not to use sediment management techniques for a certain reservoir and which technique would economically be advised based on having the larges net present value (Palmieri et al., 2003).

The RESCON model works as follows: the sediment management options evaluated in the RESCON model are Flushing, Hydrosuction, Dredging, Trucking and finally the option of No sediment removal. These options are all evaluated based on the technical feasibility in each reservoir. The amount of sediment that has to be removed from the reservoir is calculated using the Brune curve and the input parameters for the investigated reservoir. The RESCON model determines how much sediment has to be removed from the reservoir. The model evaluates the management options that are given.

For flushing and hydro-suction technical feasibility is determined using given formulae and the input for the reservoir parameters. Dredging and trucking are assumed to be always feasible, the only required input from the user is the mixture density and the price in \$ per $m^3$ of dredging or trucking. This can lead to enormous amounts of sediment which have to be removed from the reservoir. The outcome of the model is a financially most attractive sediment management option (Kawashima et al., 2003).

In 2017 an updated version of the model is supposed to be released. In the new version the graphical user interface is updated, climate change is taken into account, two more models for the development of the reservoir storage are taken into account. The location of the sediment is taken into account as well. This way the difference between active and dead storage in the reservoir can be made. More sediment removal and rerouting options are taken into account, the dredging options have however not been updated (Efthymiou et al., 2017).

Since the updated model has not been released yet, it is impossible to evaluate the full model. However, the RESCON model gives an indication for whether or not sediment can be removed from the reservoir. It could be very useful to have a further idea of the costs associated with different dredging techniques and their feasibility. A model that can be used to estimate dredging costs based on reservoir parameters could prove to be very useful. A model like that could be used to get an accurate comparison between dredging and other sediment management options evaluated in the RESCON model.

# 5

# Dredging of reservoir sediment

The conclusion of Chapter 2 & 3 is that sedimentation in reservoirs can indeed lead to problems. In Chapter 4 the focus is placed on reservoir parameters that influence the feasibility of dredging. In this chapter the focus will be on solutions to sedimentation problems. Specifically dredging of reservoirs is investigated. Suitable dredging techniques are evaluated. Furthermore the influence of sediment size and other factors on the applicability of certain methods is included. The experience of dredging companies on the subject of reservoir dredging is taken into account as well.

## 5.1. Sediment management in general

The accumulation of sediment in a reservoir can lead to different problems. These problems vary from not having enough drinking water available, to not enough water to produce power all year, blocked water intakes and thus to reservoirs which are out of service, to a large sediment load against the dam. In order to prevent these problems from occurring the amount of sediment in the reservoir has to be kept in control. This can be done using different techniques. Each technique has different strong and weak points. The techniques for controlling sediment can be classified in four different classes (Morris, 2015):

1. Reduction of sediment coming into the reservoir from upstream
2. Routing the sediment around or through the reservoir
3. Adapt the reservoir to the sediment
4. Removal of already deposited sediment

The techniques included here are sluicing, flushing, bypassing and excavating or dredging. These different sediment management techniques are briefly explained and discussed. The focus is then placed on dredging solutions.

### 5.1.1. Reduction of sediment from upstream

The goal of this method is to stop the problem at the source. By preventing large amounts of sediment from entering the reservoir. Sediment can be retained if the soil is retained during periods of erosion.

In the catchment area of a river, all precipitation flows into one river. Vegetation is usually responsible for keeping soil together. If vegetation is absent as the result of forest fires or wood cutting, the soil is no longer retained by vegetation. This makes the soil vulnerable to erosion. Especially during heavy rains, large amounts of water flow over the bare soil, leading to erosion. Due to climate change heavier rains occur, therefore the amount of sediment entering the river due to erosion of surrounding terrain increases.

The erosion of soil can be prevented if enough vegetation is present in the catchment area to retain soil. Therefore possible measures that can be taken to ensure the presence of vegetation are prevention of the woodcutting season from coinciding with the flood season (Annandale et al., 2016) and planting new vegetation on bare land.

The big advantage of the reduction approach is that the amount of sediment entering the river flowing into the reservoir is reduced at the source. However this is also the reason for the three biggest disadvantages. First of all, the river basin is enormous and therefore it is hard to show the direct relation between vegetation and reservoir sedimentation to the inhabitants of the catchment area. Secondly the enforcement of policies that increase the amount of vegetation in the catchment area is difficult. Due to the scale of the catchment area. Lastly the funding of a project can also lead to difficulties, since it show who profits the most of such a measure and should therefore fund this form of sediment reduction.

### 5.1.2. Routing of sediment

The routing of sediment is controlling the flow of sediment laden water. There are different options and methods that can be used, a few will be mentioned briefly and some discussed in more detail.

#### Sediment bypass

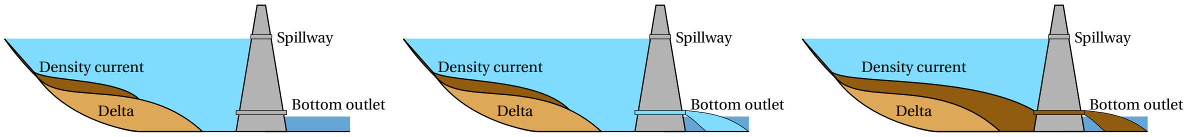
Sediment can be passed around the reservoir in different ways, this mainly depends on the local geography. The sediment laden water can be bypassed using a channel or in mountainous regions, a bypass tunnel is often used. The water containing the most sediment will be led around the dam & reservoir and re-enter the river downstream.

The same idea is applied when a reservoir is located off stream. In this case water is only allowed to enter the reservoir, when the stream contains low sediment concentrations. The reduction of sediment entering the reservoir is high, however not all sediment can be held back, therefore at one point in time, the reservoir most likely has to be cleaned out (Morris, 2015).

#### Sediment through the dam

The first technique that allows sediment to flow through the dam is sluicing. Sluicing is the technique where first the reservoir level is drawn down in anticipation of a flood. When the flood has reached the lower gates of the reservoir are opened and the flood is allowed to flow through the reservoir, the retention time of the water is thus reduced. In this way sediment entrained in the water is directly transported through the reservoir. Some excess scour of already deposited sediment does occur as well (Morris, 2015).

Venting is the process based on opening the gates in time, to let the density currents (mentioned in Chapter 2.2) exit the reservoir before there is time for them to settle into a muddy pool. The sediment laden density currents are thus prevented from settling in the reservoir. This reduceds the amount of sediment in the reservoir (ICOLD Sedimentation Committee, 2009). The venting process is presented in Figure 5.1.




(a) Entry of density current. (b) Bottom gates are opened. (c) Density current leaves reservoir

Figure 5.1: The venting of a density current through a reservoir.

The third option is trapping the sediment before it flows into the reservoir. One method to do this is by sending the water coming into the reservoir via a sandtrap first. In a sand trap the water is slowed down, so the heavier sediment will settle. The settled sediment can be mechanically excavated or flushed using a sediment bypass tunnel into the downstream reach of the reservoir. The result is that only a small percentage of the sediment in the river will pass the sandtrap and end up in the reservoir. Reducing the amount of sediment that s reduced.

Advantages of sediment bypassing are that sediment is delivered to the downstream river in peak flows, when it would also be delivered in an undisturbed state. The downstream erosion of the river can thus be reduced using this method. Also the draw down of the reservoir is not required, thus the operation of the reservoir is not significantly impacted (Kondolf et al., 2014).

The disadvantages of sediment bypassing are that not all sediment exits the reservoir by venting. Sediment will therefore continue to be build up. Also the reservoir bottom has to be smooth enough in order to not break up the density current before it reaches the dam. The sand traps have to be positioned at the right location, if this is not the case, it is possible that barely any sand is trapped resulting in filling of the reservoir by sediment.

### 5.1.3. Adapting to reservoir sedimentation

In this case not the sediment is influenced, but the reservoir is changed. For instance if sedimentation of the dam has lead to a reduced volume of the reservoir, the dam height can be raised to regain storage capacity.

Also the dam structures can be modified to cope the higher sediment load. The turbines of a hydro power dam can for instance be coated in order to be more resilient against abrasion. The operating rules of a dam can be changed in order to change the way in which sediment deposits. If for instance the lower operating limit is raised, sediment build up will not occur on the face of the delta mentioned in Chapter 2.2, but on top of that delta. Finally a dam can be decommissioned when it is not longer economically viable (Morris, 2015).

The decommissioning of dams leads to a depleted storage capacity in the world, which will need to be replaced by another dam somewhere in order to maintain the benefits of the current water storage capacity. Furthermore the building of a new dam becomes increasingly controversial due to the impact on the environment and possible allocation of people living in the area to be inundated by the reservoir.

All of this pleads for management of the current dams, in a way that they can be operated in a sustainable manner. That is also the result of most analysis of dams using the RESCON model (Section 4.6).

### 5.1.4. Removal of accumulated sediment

This gets to the core of this thesis. There are different options to remove the accumulated sediment. The options discussed here are:

- Flushing
- Trucking
- Dredging

Flushing of the reservoir can be done using two methods. Method 1 is done when the water in the reservoir is high, the bottom gates in the dam are opened and the water is forced out of the reservoir by the water pressure. Method 2 is applied by drawing down the water and create a river state in the reservoir. The river flows freely into and out of the reservoir. The water due to the higher velocity scours the sediment from the bottom, when it is accelerating towards the bottom gate. The sediment flows through the dam and enters the river system downstream.

Both methods result in large amounts of sediment being carried into the river downstream of the reservoir in one large peak.

The advantage of flushing is that it is relatively cheap when bottom gates are available. The only resource requirement is that enough water flows into the reservoir through the river to ensure that no shortage in water will occur.

The disadvantages are however that operational time for the reservoir is lost, since it will take time to fill the reservoir with water again. The ratio of mean annual flow (*MAF*) to reservoir volume should not exceed 4% (Kondolf et al., 2014). Water is also lost during flushing, making flushing an impossible solution in arid regions.

Flushing will help manage the sediment problems, however coarse sediments will keep entering the reservoir and can not be flushed out due to their higher weight, making flushing not a permanent solution (Morris & Fan, 1998).

Another big disadvantage of flushing is the large environmental the flushed sediment can have downstream. The sediment can lead to filling of downstream pools and cover the river bed, this affects and can even kill the biodiversity (Fruchard & Camenen, 2012).

Sediment can also be removed using mechanical equipment. If this is done using land based equipment and by draining the reservoir, this is called 'trucking'. In that case the sediment is excavated using excavators, wheel loaders and bulldozers. The excavated sediment is than removed by truck to the desired location.

The largest advantage of this method is that this type of equipment is locally available. It is however a costly operation since the reservoir is out of order for a longer period of time. Many pieces of equipment are necessary to reach a high hourly production.

The other option for mechanical removal is dredging of the deposited sediment. Dredging is the removal of material, while under water. Dredging can thus be performed while the water level is maintained in the reservoir. Different methods for dredging exist, the focus in this thesis is on different techniques for the dredging of reservoirs.

## 5.2. Dredging equipment

There are many different pieces of dredging equipment available which are suitable for the dredging of reservoirs. In this section the most important types of dredging equipment are summarized, including the associated advantages and disadvantages for each type of equipment. The discussed pieces of dredging equipment are:

- Suction Dredge
- Cutter Suction Dredge
- Grab Dredge
- Backhoe Dredge
- Submersible Dredge Pump
- Water Injection Dredge
- Siphon Dredge

One of the largest pieces of dredging equipment used in today's dredging industry is the Trailing Suction Hopper Dredge (*TSHD*). This is a ship, which is capable of dredging sediment off the bottom, collecting the sediment in the hopper and the ship sails to it's destination, transporting the sediment to the desired location. The location of most reservoirs is however not directly accessible by ship. If reservoirs are located in a river close to the sea, the dam itself forms a mayor obstacle and dams including ship-lifts, like the Three Gorges Dam in China are scarce. Transport of such a vessel would be impossible by road. For these reasons the *TSHD* is not further considered as suitable equipment for the dredging of reservoirs.

In the considerations below, bucket-ladder dredges are excluded as well. They have been replaced by higher capacity dredging methods like the *CSD* and the backhoe dredge. The same goes for dragline dredgers, the dragline is used seldom and is not common anymore. That is the reason it is not included as a potential dredging solution.

Both hydraulic and mechanical dredging options are considered. The hydraulic dredgers use water to transport the dredged material and work continuously, an example is the *CSD*. Mechanical dredging equipment works discontinuously, every part of soil has to be excavated individually. Examples are the backhoe and grab dredge.

All equipment that is discussed here is available in different sizes. The required size depends on the amount of sediment that has to be removed. The transportation can however be done by road. For some dredging methods the use of local available equipment is possible as well.

### 5.2.1. Suction Dredge

A suction dredge is basically a pontoon with a large pump and a long suction pipe. An example of a suction dredge is given in Figure 5.2. The suction pipe is brought down to the bottom and the pump is switched on. The water is pumped up and the sediment close to the intake of the suction pipe is entrained if it consists of loose material. Examples of material that can be dredged are sand or silt. To speed up this process often water jets are mounted on the end of the suction pipe, to loosen the sediment even further.

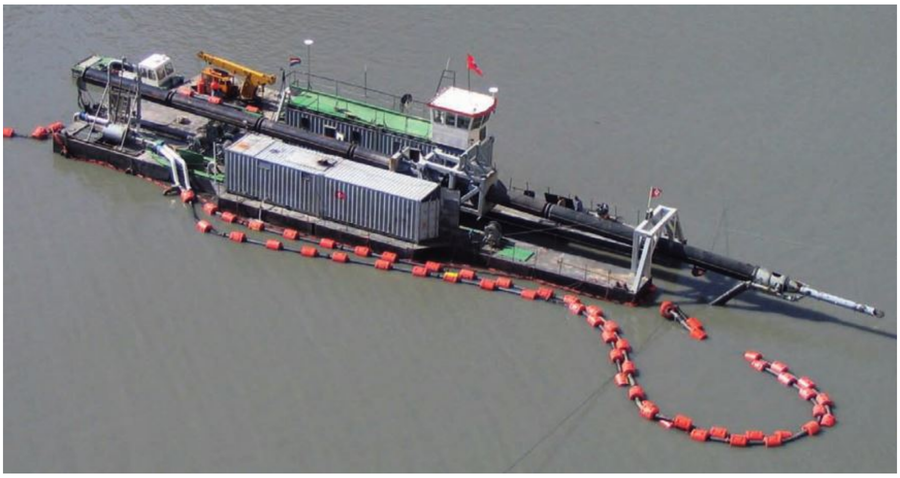


Figure 5.2: Example of a suction dredge (Baggerbedrijf de Boer B.V., 2014). Note the very long suction pipe used for reaching great depths.

The suction dredge can be used to generate large productions in loose soils. The highest production can be reached using the so called 'breaching process'. The 'breaching process' is the process where sand is pumped up from the bottom creating a suction pit. Due to gravity, the flow of water and the steep slope on the side of the suction pit, additional sand or silt flows towards the suction pipe in the form of a density current. This process is called 'breaching'. Breaching leads to high productions in materials like sand. The bigger the flow of the density current towards the suction pipe, the higher the production of the suction dredge (van der Schrieck, 2016).

By placing the pump not on the pontoon, but underwater, close to the suction mouth, high mixture densities can be dredged. Great depths can also be reached. Dredging depths in excess of 60 $m$ (Marine Development Holland BV, 2017) have been reported.

The suction dredge is dependant on the flow of silt and sand towards the suction pipe. In areas where debris is present, the flow of sediment towards the suction mouth of the dredge can become obstructed. For this reason the suction dredge is far less suitable for sediment mixed with tree stumps, plastics or boulders.

### 5.2.2. Cutter Suction Dredge

The Cutter Suction Dredge (*CSD*) is a piece of dredging equipment that is used for the cutting and sucking up of material and then the pumped up material is discharged a designated location.

The *CSD* is thus derived from an ordinary suction dredger. The ordinary suction dredger is able to move loose material only, but by applying a cutter head, a *CSD* is able to fragment hard or compacted soils, which can than be sucked up and moved by pumping it. In Figure 5.3 an example of a *CSD* is shown.

The large beam at the front of the *CSD* is called the 'cutter ladder'. This ladder has the 'cutting head' attached to the front of it. The ladder is lowered to the bottom using a winch. At the bottom the cutter is switched on, and it cuts the material that has to be dredged. The material is than sucked up via the suction tube, which is integrated in the ladder. The dredged material is pumped to the back of the dredge, which can be connected to a floating pipe line, to pump the so-called 'slurry' to the designated location. Depending on the distance the material has to travel, 'boosters' (extra pump stations in the line) can be used to increase the distance that the slurry can be transported.

Figure 5.3: Example of a Cutter Suction Dredge (IHC, 2017).

The biggest *CSD's* in the world are self propelled, however the *CSD's* that most likely can be used for the dredging of reservoirs have to be small enough that they can be transported to the designated reservoirs by truck or train. These smaller *CSD's* are not self propelled.

The cutting process using a *CSD* contains different steps. First the *CSD* starts at a point at the side of the centre line through the *CSD*. The cutter ladder is lowered to the soil and the cutter head is switched on. Using two side anchors attached to the cutter ladder the cutter head is pulled from left to right or from right to left. This is called a 'swing' of the *CSD*. The spuds (the two poles at the back of the *CSD*) are used for forward motion at the end of a 'swing' and are used to absorb the forces that occur during the cutting of soil. One pole is placed on a 'spud carrier', which can be used to slowly push the dredger forward, when a 'swing' has been completed. When the dredger has been pushed forward the right to left motion is initiated again. This is repeated till the one spud is at the end of the carriage. The second spud, called the 'auxiliary spud pole', is than lowered to maintain the position of the *CSD* while the other spud is moved forward again. This process is repeated till a full lane has been completed. That process is repeated until the entire area that has to be dredged has been covered and brought to the right depth.

Depending on the type of the soil to be dredged different cutter heads can be used. For excavating big volumes of dense soils a bucket wheel can be mounted on the cutter. For other purposes cone-like cutter heads exist. These cutter heads can also be fitted with teeth, the teeth can be replaced when they have been damaged by wear and tear. For sand broad teeth are used, while for rock cutting very pointy and strong teeth are used. Loose soil will lead to a higher production per hour than the cutting of very dense soil (van der Schrieck, 2016).

The *CSD* is a very versatile dredger and can be used for dredging a wide variety of soils, however the presence of rocks and tree stumps at the bottom of a reservoir could lead to blocking of the suction pipe or damage to the cutting head. It is therefore impracticable to use a *CSD* for removing sediment in an environment contaminated by these materials.

During a discussion at dredge constructor Royal IHC it became clear that depths up to 35 *m* can be reached using their biggest small dredge, an IHC4035. This dredge is demountable, making it transportable by road (IHC, 2017). This is important, since one of the key aspects of the dredging of reservoirs is that the dredging equipment has to be able to reach the reservoir site. It became clear that the research and developments are ongoing, a design for a *CSD* that can reach depths up to 40

$m$ have been made as well (*L. op de Beek, personal communication, 18-9-2017*).

### 5.2.3. Grab Dredge

The grab dredger is commonly used all over the world, this is mostly due to it's simplicity. A grab dredge is a stationary floating crane with a grab attached to it. The grab can be as small as 1 $m^3$ up to 200 $m^3$. The bigger the grab, the bigger the crane needs to be, to lift the full grab. Dredging using a grab dredge is a discontinuous process. The cycle of a 'grab' is as follows: the grab is lowered to the bottom, than closed, the closed grab is hoisted up, the content of the grab is deposited in a 'transport barge' or 'hopper barge'. This cycle is repeated till all the required material has been dredged. An example of a grab dredge can be found in Figure 5.4.

For an efficient operation it is necessary to have more than one barge, for the crane to continue dredging while another barge is full and being emptied. This is off course not needed when the crane is used for emptying the barges as well, however in that manner the full dredging potential of the crane would not be used, since the traveling results in downtime. Also the fact that the dredged material is easy accessible when in a barge, makes an excavator for unloading or a hopper barge more suitable for such a job.

Figure 5.4: Example of a grab dredge, used to dredge the Luzzone reservoir (Liebherr, 2017)

The grab dredge is especially useful in areas which are difficult to access, where the depth to be dredged varies a lot and for the dredging of areas containing boulders or old trees. The grab or clamshell can be fitted according to site specific conditions. For muddy material the edges of the clamshell are flat, while for sand and clay the clamshell is fitted with teeth. The weight of the bucket is also adapted to the local conditions. For a heavy and dense soils a small in volume but heavy grab is used. While for a soil containing silt a lighter, but greater in volume type of grab is used (van Duivendijk, 2007).

To reduce the environmental impact of dredging and a possible dust plume, special clamshells exist that close completely, to seal the dredged material from the surrounding water, this prevents water from leaking away. Grab dredgers can be used for great depths as well. The only limiting factor will be the cable available. Depths up to 200 $m$ can easily be reached, this was for instance the case in the Luzzone reservoir (Figure 5.4), excavating deeper would however also be possible, but this would have a large impact on the production of the grab dredge.

### 5.2.4. Backhoe Dredge

A backhoe dredge consist of an excavator mounted on a pontoon. The excavator can be directly installed on the pontoon or a normal excavator on tracks can be mounted on the pontoon.

Examples of a excavator mounted on a barge and a fixed backhoe dredge can be found in Figures 5.5 & 5.6. The combination of different attachments and the possibility of dredging from land or from water makes backhoes very versatile machines.

The dredging cycle of backhoes is discontinuous and similar to the grab dredge cycle. It starts by lowering the bucket to the bottom, then retracting the bucket, thus scooping it full of dredged material, lifting it to the surface and than emptying the bucket in a barge. This is repeated till the barge is full and then a new barge is moored alongside the excavator.

Figure 5.5: An excavator mounted on a pontoon with spuds (Baggerbedrijf de Boer B.V., 2014).

Figure 5.6: An example of a backhoe dredge, mounted on a barge (Van Loon Maritime Services B.V., 2017).

In dredging operations backhoes can be equipped with different buckets or grabs. In reservoir dredging operations the backhoe dredge type shown in Figure 5.6 can be hard to use, since reservoirs are usually hard to excess from open water. However, excavators are usually available worldwide which is also the case for pontoons. This could lead to efficient local solutions using excavators.

Excavators are suitable for dredging a wide range of soil types. Soils that include rocks, boulders, clay and sand. Depending on the size of the excavator used and on the presence of currents and the cutting force that has to be resisted, the pontoon for a water based solution will need spuds for stabilization. Backhoe dredges as shown in Figure 5.5 are suitable for dredging in semi deep reservoirs. Depths of 10 $m$ can easily be reached, deeper than 15 $m$, small backhoe dredges become unsuitable, according to experts.

The removed sediment can be put into towed or self-propelled barges and then sailed to the desired location, at that location another backhoe can be used to unload these barges. A big advantage of using backhoes for dredging is the high precision of the positioning of bucket, making it easier to know where the material is exactly dredged. Another advantage is the absence of anchor wires, the lack of auxiliary equipment needed and the faster cycle time of excavators in comparison to a grab dredge of the equivalent size (International Association of Dredging Companies (IADC), 2014).

### 5.2.5. Submersible Dredge Pump

The submersible dredge pump is a compact version of a suction dredger. By making the dredge pump submersible it can be lowered to the desired depth and operated from there. In this way the pump does not have to be stationed on the floating platform itself, the suction pipe of the pump can is thus reduced. By lowering the pump close to the material to be dredged, a higher concentration of solids can be pumped leading to an increased efficiency of the dredging operation (Vlasblom, 2004).


Figure 5.7: Example of a pump dredge, used to dredge a reservoir in Peru (Damen, 2016)

The dredge pumps can be mounted on an excavator boom or *CSD*boom or the pump can be suspended from a wire. This makes the dredging pump very versatile, since the height can be easily adjusted. The pump can also be equipped with different heads. A cutter head can be used to loosen compressed sand and water jets can fluidize loose sand. The cutter head is only possible while mounted on an excavator. The jet version can be mounted on a wire and let down from a pontoon.

A possible combination of a floating pontoon with a submersible dredge pump is shown in Figure 5.7. The removed material can be transported to the desired location, directly by the submersible pump, or if the distance becomes to large, by using booster stations.

The big advantages of using submersible pumps are the continuous dredging process, the great depths that can be reached and the difficult to access locations that can be reached. For the cutting of dense sand, the reach is limited to the excavator or *CSD* reach. Suspended pumps are limited by the maximum available total head. A version of suspended pumps is the DOP Submersible Dredge pump. The maximum available head in these series is 5.3 bar, which is equal to a water depth of 54 $m$ (Damen Dredging Equipment, 2015). The material has to be loose enough to be pumped and the pump can not be obstructed by garbage or debris in order to obtain the maximum production of 600 and 4,000 $\frac{m^3}{hour}$, depending on the size of the chosen pump.

### 5.2.6. Water Injection Dredge

The method of water injection dredging is a way of moving the material to be excavated, without physical contact. Water is injected in large volumes at low pressure in the sediment, leading to the loss of contact between the grains. The sediment and water creates a fluid mixture, similar to the density current described in Chapter 2.2. This mixture will then flow to a lower located part of the bottom. Depending on the sediment settling velocity, the density current will travel a short or a long distance. Sand for instance will settle faster than silt, thus to move sand the same distance as silt, the sand will have to be injected with water more often to re-fluidize it. An example of a water injection dredge can be found in Figure 5.8.

Figure 5.8: Example of a water injection dredge, the injection part will be lowered to the bottom (Dredging Today, 2014).

The water injection dredger can work at low costs, if the sediment that has to be moved meets the requirements of a water injection dredge. The material is moved by nature, so only the pumping of water requires energy, which is cheaper than pumping of a sediment mixture.

The biggest advantages of the water injection dredge are that high production rates can be obtained under ideal conditions, the dredges are very compact which makes them easy to transport to and from reservoirs and because water jets are used contact between dam infrastructure and dredger is less likely to lead to damage (US Army Corps of Engineers, 2015).

Furthermore the sediment is injected with water, gravity transports the sediment further. Because only water is pumped and not a sediment mixture wear and tear of the pump is reduced, thus reducing maintenance. Since gravity is used for transportation, the costs of the *WID* are usually low.

The main disadvantages are the sediment can only be displaced downward, so through the dam or in available dead storage. If this storage is unavailable, the use of a *WID* is not possible.

The resulting density current can have negative environmental impacts comparable to the venting of density currents. Another consideration is that the movement of sediment in this manner has to be accepted under local regulations.

Another disadvantage is that the water injection method is best applicable for silts and clay. For material like sand in the order of 50 $\mu m$ to 0.2 $mm$ the slope of original bottom has to relatively steep for the *WID* method to work, due to the high fall velocity of these particles(US Army Corps of Engineers, 2015; van Rijn, 2012). It is however possible to travel a larger distance by re-injecting water into sand that has already traveled a certain distance and settled again. This does decrease the efficiency of the *WID* however. Water injection dredgers can work in depths up to 26 $m$ (International Association of Dredging Companies (IADC), 2013).

### 5.2.7. Siphon Dredge

The siphon dredge works based on the difference in hydraulic head between the reservoir and the downstream river.No dredge pump is thus used to process the dredged mixture, but the available head, is used to move the dredged mixture. The siphon dredge is thus especially suitable for the dredging of reservoirs, since the height difference is present around the dam. This process is illustrated in Figure 5.9.

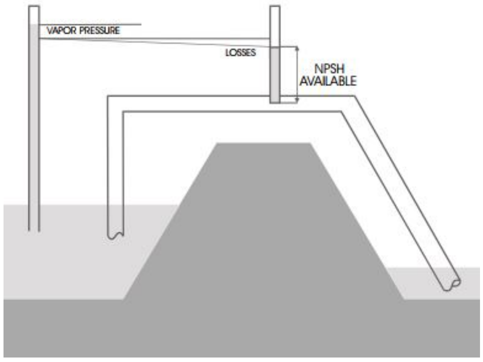



Figure 5.9: Example of the working principle of a siphon dredge (Vlasblom, 2004).

A big advantage of the siphon is that not having to operate a dredge pump reduces the costs of dredging. Big disadvantage of the siphon dredge is that it is most suitable for the area close to the dam. Here the head difference is the greatest and the necessary amount of pipes is shortest. The further away from the dam, the more pipe is needed, leading to a higher pipe resistance, which results in a smaller remaining head for transporting the excavated material. Also when part of the pipe is above the maximum water level, the system has to be primed. This is the process of filling the the pipe with water to create the necessary vacuum in the pipe to start the flow of the sediment mixture.

This problem can be prevented by using s pipe which is connected to the bottom outlet of the dam of the reservoir to be cleaned up. This way the entire pipe can be under water. This way priming is avoided and low pressures points are avoided as well (Basson & Rooseboom, 1999). The depth that can be dredged using a siphon is unlimited due to the available head, that is always present. However the limiting factors for the successful use of a siphon dredging system are that the available head difference has to be large enough to be able to transport the flow of sediment over a sufficient distance. The length of the pipeline has an inverse squared negative effect on the volumetric transport rate (Hotchkiss & Huang, 1995).

Also at least the yearly amount of sediment coming into the reservoir has to be transported by the system to offer a sustainable solution. Furthermore the sediment size has to be small enough that it can be easily transported, sand for instance is possible, but for gravels the amount of head needed will increase dramatically. Furthermore the sediment can not be too dense, if that is the case, a separately driven cutter is needed to loosen sediment before it can be transported (Hotchkiss & Huang, 1995).

A determination of the feasibility of a siphon dredge is given in the RESCON model (presented in Section 4.6), based on given parameters. For that reason the siphon dredge is not further considered in the rest of this thesis. For detailed information on siphon dredging the paper of Hotchkiss & Huang or the manual of the RESCON model (Kawashima et al., 2003) can be used.

## 5.3. Advantages and disadvantages of dredging

Different dredging methods have been described above. The main advantages of dredging compared to flushing, trucking and routing are described. Furthermore possible disadvantages are investigated.

### 5.3.1. Advantages of dredging reservoirs

The different advantages of dredging reservoirs are summarized as follows:

1. Continued reservoir operation
2. Specific removal location
3. Small water loss
4. Measurable sediment volume removed
5. Combinations with other sediment techniques

The first advantage of dredging is that sediment can be removed while the reservoir can continue operating. Continued reservoir operation is especially an advantage in the hydro power industry, since a short period of production loss results in large financial losses. It could be useful to reduce the water level in the reservoir to reduce the dredging depth, however that is not necessary. The reservoir definitely does not have to be completely drained for dredging, contrary to the water loss due to trucking or flushing. Therefore dredging is a more attractive solution than trucking or flushing.

The second advantage of dredging contrary to flushing is that sediment can be removed at specific locations. If for instance the intakes are silted up, sediment around the intakes can be removed using a CSD or grab dredge. The removal of sediment using dredging is more site specific than removal of sediment using flushing. Another positive aspect of dredging is that the volume of sediment re-entering the downstream river can be controlled. This contrary to flushing or sluicing, where the downstream river is faced with a large sediment load concentrated in one peak.

The third advantage of dredging is, that compared to flushing less water per $m^3$ of removed material is used to create reservoir space. This advantage is especially useful in arid countries where water loss can not be tolerated.

The fourth advantage of dredging is that effects of dredging are measurable. It can therefore be proven what sediment volume is removed from the reservoir. This is contrary to the effects of flushing and sediment routing, for which the effect are difficult to quantify in numbers.

The fifth and final advantage of dredging is that dredging is possible under a great variety of conditions. It can for instance be used to empty sand traps if necessary and therefore it is complementary to sediment routing. By dredging a reservoir which is already build, investments into extra infrastructure like bypassing tunnels can be avoided.

### 5.3.2. Disadvantages of dredging reservoirs

A possible disadvantage of dredging can be that it is not possible year round. This could be for instance be an issue if the water is let out of the reservoir via the overflow. It is dangerous to be near the overflow with dredging equipment while the overflow is operating since there is a risk that the dredger is thrown over the dam or at least suffers serious damage to the equipment and dam structure. This risk however has to be taken into account in a risk assessment for individual projects.

The two main concerns associated with the dredging of reservoir sediment are the costs of dredging and the disposal of the dredged material. These main disadvantages are further investigated, including potential measures to mitigate these disadvantages.

### The costs of dredging

Dredging is often assumed to be costly. For example the costs of a dredging operation in the 'Ruzizi 2' reservoir in Congo are estimated to be between \$30 and \$50 per $m^3$, but no clear break down of these costs has been given (Bonviller et al., 2017). The idea of dredging as an expensive solution for the issues of reservoir sedimentation has to be changed. This can only be done by showing the actual costs using case studies or by actual performing a dredging project in a reservoir.

The current state of the dredging industry is such that large volumes of sediment can be displaced, using different dredging methods which all result in different costs. Consultation of different experts at Witteveen+Bos and dredging companies indicate that projects starting at rates below \$3 per $m^3$ have been achieved, but that this is very site specific.

The costs of dredging always have to be put in the perspective of the benefits of dredging the reservoir. If dredging is compared to flushing, the amount of water that is saved, can be used for performing the reservoir function. This means tat it can be sold as drinking or irrigation water or for the production of hydro power. If a hydro power reservoir is dredged it could be beneficial to use an electric dredger, in this manner power generated by the hydro dam can be directly used for dredging. It is also possible that dredged material can lead to added value if it can be sold as an aggregate for concrete or other construction material.

Indirect added value can also be created if the downstream erosion mentioned in Chapter 2.3.5 can be mitigated using the dredged sediment. Dredging of reservoirs does not only lead to costs, but also to benefits. It is necessary to always make a feasibility study to determine if a dredging project is financially feasible.

### Disposal of dredged material

One of the main problems of the dredging reservoirs is the disposal of the dredged material. If the removed sediment is deemed contaminated, the sediment has to be disposed at special disposal sites for contaminated materials. This makes removal of contaminated sediments costly. It should always be investigated if sediment is contaminated, since this is an important factor in making a financial business case. For the removal of non-contaminated sediment there are a few different options. The following sediment disposal options are possible:

- Relocation inside the reservoir
- Deposit outside of reservoir
- Return sediment into the downstream river

The first option is removing the sediment from the place where the reservoir operation is affected, to another place inside the reservoir, preferably the dead storage. The advantage of this method is that the storage area is already available and no temporary storage or facility to dewater the sediment is needed. A big disadvantage of this method is that the underwater deposited sediment must be deposited at a location where it will not be washed back into the locations where it was affecting the reservoir function. Also if no dead storage is available for deposit, the active storage capacity of the reservoir will be affected, thus leading to volume loss. This method was applied for a hydro power plant in Austria (Royal Smals, 2017).

The second option is dredging the material and deposit it in an area close to the reservoir. In this case the material has to be de-watered. This can be realized by using settling ponds for instance.

There are different options for these settling ponds. Building dikes and fill up the area inside these dikes with dredge slurry. The sediment will settle and the surplus of water can be returned to the reservoir. The complete drying of the extracted sediments will take years. If enough land is available, this can however be a good solution. This solution has for instance been used in the John Redmond reservoir project in Kansas, USA (Hill, 2015) and (*M. Unruh, personal communication, 21-6-2017*).

The mixture of water and sediments can also be pumped into large geotubes. Geotubes are big tubes made of geotextile, a fabric that is permeable for water but not for soil. Using a flocculant silt particles are combined which makes it easier for these particles to settle. The excess water flows out of the geotubes, while the sediment is contained in the tubes. For these tubes less space is needed than for regular dikes and de-watering goes faster, however the adding of flocculant and a permanent inflow of the mixture of water and sediments is required to make this solution successful (*K. van de Graaf, personal communication, 26-6-2017*). Also a combination with the second option of building a settling pond can be created. In this case the dike is formed using geotubes. This was proposed as an option for the removal of sediment from the John Compton Dam in St. Lucia (DB Sediments, 2013b).

The above options can be combined with stockpiling of sediment for future use or the direct use of material. For example, currently investigations are ongoing into the use of sediment to create bricks. Another example is Japan, where it is common practice to use gravel taken from reservoir as construction material (Batuca & M.Jordaan, 2000). The material can also be used to raise land or to develop new land. If the removed sediment is fertile, it can be used to revitalize agricultural land. To use land for this purpose however suitable locations have to be in the vicinity of the reservoir, otherwise the transportation of the material becomes expensive, making the solution financially unattractive.

The last option is disposal of the dredged material downstream of the dam. This way the natural flow of sediment of before the dam construction can be imitated. However, it has to be determined if this is a feasible solution. Points of added value are the disposal of sediment downstream saves on finding a disposal location, dredged material transport and can solve possible downstream bed erosion. However, it needs to be investigated if the downstream river can handle the extra amount of sediment, or if the river will get clogged. Also the best times for disposal have to be investigated, since this is very site specific.

## 5.4. Experience of dredging companies

For more insight into the reason for dredging certain reservoirs, dredging contractors are contacted to learn from their experience. It is quite interesting to see that only smaller contractors have reservoir dredging reference projects.

The first contacted company is Royal Smals, a Dutch dredging company. They have gained experience in a few projects that had to do with reservoirs. Royal Smals advertises also deep-dredging solutions near hydro dams for dredging up to 85m (Smals, 2017), this gives hydraulic possibilities for the dredging of reservoirs. Three reference projects are examined closer.

The first project is the dredging of a reservoir near the city of Siegen in Germany. Here a total volume of 4,000 $m^3$ silt had to be removed for environmental reasons. For this project two different cutter-suction dredgers have been used for the shallow and deep sections of the reservoir. The sediment mixture was pumped into large geo textile containers, where it was drained, to decrease the volume of sediment that had to be transported. The main achievements of this project are that the nature is preserved and the fish were removed on forehand.

Figure 5.10: Example project, reservoir in Solingen (*screenshot from: (Smals, 2016)*).

The second project is a drinking water reservoir, near the city of Solingen (Figure 5.10), also in Germany. Blue algae was an issue in this reservoir. The a total volume of 26000 $m^3$ sediment was removed. The reservoir was located in a difficult location, making it hard to reach the reservoir with the equipment. The sediment was removed using a cutter-suction dredger and pumped over 3 km downstream. The value of this project is the preservation of 2.8 million $m^3$ drinking water.

The third project was for the Tiroler Wasserkraft AG, in Lake Langental, located in Austria. Sediment was removed from the intakes of the hydro power plant, and relocated to the middle of the lake. The depth of this lake was 35 m. For the dredging of the sediment a suction rotary wheel trencher dredger was used. The total volume of sediment moved is 70,000 $m^3$. The value gained by this project is damage control to the turbines, so less maintenance, keeping electricity costs at a lower level.

From the experience so of dredging companies so far it is clear the vital functions as drinking water and hydro power are valued high enough to be able to invest in dredging. The volumes for ponds are very small, but for larger reservoirs volumes can thus become tens of thousands of cubic meters.

## 5.5. Factors influencing dredging production

### 5.5.1. Sediment characteristics

In reservoir different dredging parameters are important. For the different dredging methods these parameters and their influence on the dredging production is investigated.

| Soil type | Minimum diameter | Maximum diameter |
|---|---|---|
| *clay* | | 0.002 $mm$ |
| *silt* | 0.002 $mm$ | 0.063 $mm$ |
| *sand* | 0.063 $mm$ | 2 $mm$ |
| *gravel* | 2 $mm$ | 63 $mm$ |

Table 5.1: Soil classification based on grain sizes, according to (Verruijt, 2012).

An important parameter for dredging itself is the size of the sediment that is dredged and the material that is dredged. For an optimal decision on what tools to use good information on the material that needs to be dredged is needed. Materials that can be encountered in reservoirs can reach from sand, to silt, to clay all the way to the presence of boulders. Any combination of these soils is possible as well.

The classification of the soil as clay, silt, sand or gravel is based on the grain size of a single grain. The diameters of the minimum and maximum grain size for each soil type are given in Table 5.1.

Most soils and sediments are however not homogeneous, thus containing just one soil type. More often different mixtures occur, due to combination of different grain sizes. Different possible combinations of soil types are shown in Figure 5.11.

Not every dredging method is suitable for each soil. In Table 5.2 the dredging methods and the different types of sediment to be dredged are summarized. The '++' indicates that the dredging method is very well suitable for the soil type. The '∼∼' indicates that under the right circumstances

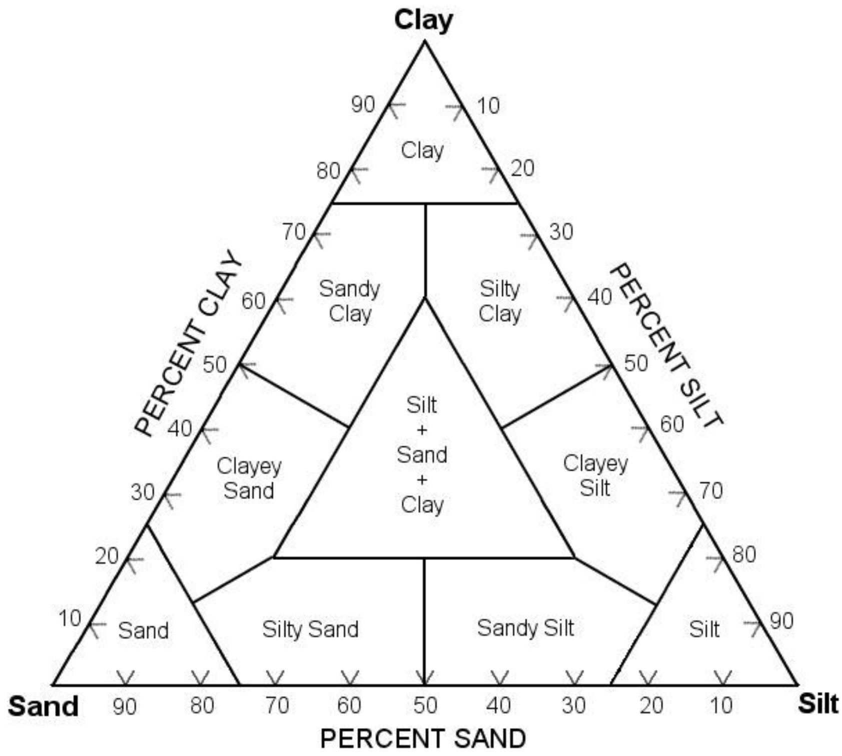



Figure 5.11: Possible soil combinations and their names. (*author unknown*)

the dredging method can be suitable to dredge the indicated soil type. An empty box means that the dredging method is not suitable for the indicated type of soil.

| Method | Silt | Sand | Soft Clay | Dense Clay | Gravel | Boulders / Debris |
|---|---|---|---|---|---|---|
| Suction Dredge | ++ | ++ | | | | |
| *Cutter Suction Dredge* | ++ | ++ | ++ | ++ | ++ | |
| *Grab Dredge* | | ++ | ++ | ∼∼ | ++ | ++ |
| *Backhoe Dredge* | | ++ | ++ | ++ | ++ | ++ |
| *Submersible Pump* | ++ | ++ | ++ | | | |
| *Water Injection Dredge* | ++ | ∼∼ | ++ | | | |

Table 5.2: Indication of the suitability of dredging equipment for different types of soil.

The soil types that are combinations of the soil types, as shown in Figure 5.11, it depends on the composition on the soil. A water injection dredge will for instance be able to dredge sandy silt, but more difficulty will arise for silty sand. The same goes for a grab dredge, silty clay is possible, but clayey silt is a challenge.

The soil type is also important for the production for each dredging method.The production is important because it determines the size of the required dredger or the number of dredgers, if one dredger does not suffice. In reservoirs only wind waves will be present, these are not comparable to offshore conditions. For that reason it is assumed that waves will not have a negative influence on the dredging production, for the dredging of reservoirs.

### 5.5.2. Reservoir depth

The maximum depth of the reservoir is also a factor influencing the feasibility of using a certain type of dredging equipment. The maximum depth that can be reached by each type of equipment is summarized in Table 5.3.

| Dredging equipment | Maximum dredging depth (m) |
|---|---|
| Suction Dredge | 60 |
| Cutter Suction Dredge | 35 |
| Grab Dredge | At least 200 |
| Backhoe Dredge | 15 |
| Submersible Dredge Pump | 54 |
| Water Injection Dredge | 26 |

Table 5.3: Maximum depth for each type of dredging equipment.

If the goal of the dredging operation is to increase the active volume, the dredging can take place in different parts of the reservoir. It can include the easier to access sediment in the delta the beginning of the reservoir. When the goal of the dredging operation is however the clearing of the outlets, dredging has to be performed close to the dam. The depth is in this case equal to the maximum dredging depth. Using a smart approach in the setup of a dredging plan it is possible to reduce this depth by decreasing the operating volume of the reservoir. Therefore equipment is not only selected based on the maximum dredging depth, it is however an important factor to determine the amount of sediment that can be dredged.

### 5.5.3. Dredging productions

For each type of equipment discussed in Section 5.2 the different factors influencing the production are described in here.

#### Cutter Suction Dredge

The production of hydraulic equipment can be estimated by taking the discharge pipe diameter of the *CSD* into account. Using the diameter ($D$ in $m$) of the discharge pipe the area ($A$ in $m^2$) for the flow can be calculated ($A = \frac{1}{4} * \pi * D^2$). By using a flow velocity ($v$ in $\frac{m}{s}$) in the pipe that is higher than the critical flow velocity, the sediment in the mixture is prevented from settling, a flow through the pipe can be determined ($Q = A * v$ in $\frac{m^3}{s}$).

A flow velocity of 4 $\frac{m}{s}$ is usually high enough (Herbich, 2000). Using the obtained flow through the pipe and the known fraction of sediment in the mixture, the volume of actual soil moved can be calculated. The fraction is usually in the order of 0.30.

The flow per second can be converted into the production per hour. The production per hour can be converted to the production per week, using the time that the *CSD* is actually active and thus dredging sediment, which is the net operational hours (NOH). The net operational hours are determined from the hours in a week that are used for working (gross operational hours = GOH) and is thus maximally 168. These hours are compensated for delays, the skills of the operator and time needed for re-positioning of the *CSD*. These factors are summarized in a operational efficiency factor ($\eta$). The weekly production ($P_{week}$ in $\frac{m^3}{week}$) can thus be estimated according to Equation 5.1.

$$P_{week} = \frac{1}{4} * \pi * D^2 * v * 3600 * GOH * \eta \tag{5.1}$$

#### Suction Dredge

For the production of a suction dredge the breach process is important. The initiation of this process takes time, but once the breaching has started high productions can be achieved, as long as the slope does not collapse and clog the suction tube. In practice it is assumed that not the availability of material is the determining factor for the production of the suction dredge, but that this is the discharge through the pump.

The production for the suction can therefore be estimated using the same method that is used for all hydraulic equipment. This method is described in Section 5.5.3. The Equation 5.5.3 can thus be used to estimate the production.

#### Grab Dredge

For a grab dredge the production depends on the dredging depth and on the type of soil. The longer the distance between the water surface and the material to be excavated, the more time is taken for traveling of the grab. The grab dredging cycle is described in Section 5.2.3. The travel time for the grab increases linearly with the depth, as shown in Figure 5.12, for a lifting speed of 100 $\frac{m}{minute}$. Assuming that the time for closing the grab at the bottom and the turning and deposit of the dredged material takes a total of 40 seconds, a production can be estimated for different grab sizes.

In Figure 5.12 this is done for the grab size of 5, 10 and 20 $m^3$. It is clear that the production reduces exponentially with the dredging depth. To mitigate this effect , the grab would need to become larger with increasing dredging depth. This is often not possible since the grab size will be limited by the maximum weight of the grab and the excavated soil in total, that can be lifted by the crane.

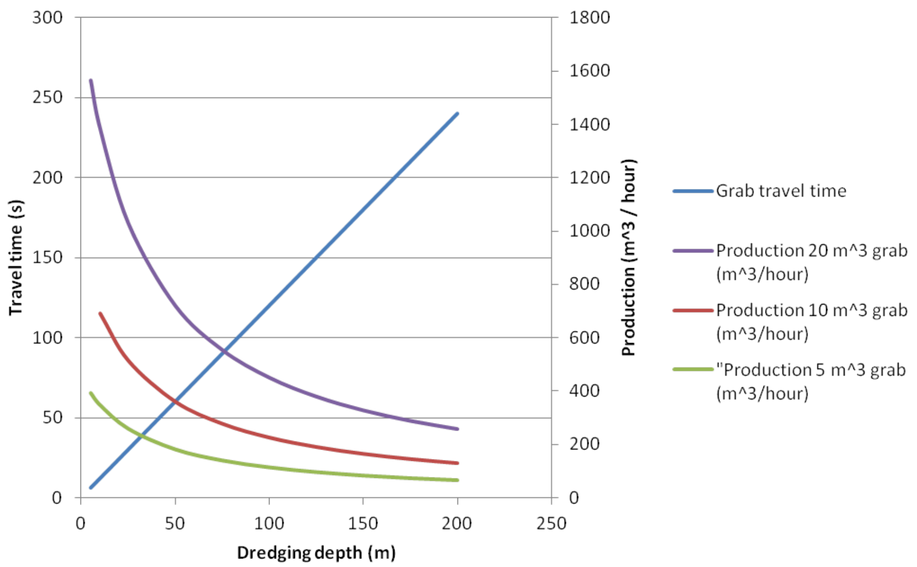



Figure 5.12: Relation between the dredging depth and grab size for a grab dredge.

Especially in the case of reservoir dredging the crane will be the limiting factor. The largest grab dredge in the world has a grab with a volume of 200 $m^3$ (Guinness World Records, 2017). This is however a seagoing barge which will not be able to sail to a reservoir. A solution that is more locally applicable is obtaining a pontoon and a crane locally, which can be combined with a clamshell grab. Based on the local soil, the grab can be outfitted with teeth for the dredging of sand, gravel or clay.

An example of a 10 $m^3$ clamshell grab, used in this manner is shown in Figure 5.4.

Grab dredges are especially useful in situations were the dredging depth is large or where debris is present. The soil type has barely any influence on the closing time of the grab, thus on the production.

#### Backhoe Dredge

The dredging production of a backhoe dredge is influenced by the type of soil that is excavated. First of all, the cutting forces must not be too large, to avoid dragging the excavator off the pontoon. This is a risk when a loose excavator on tracks on top of a pontoon is used contrary to an excavator mounted directly on a pontoon.

Second of all the production depends on the speed of moving the boom, the speed of rotating the excavator and the size of the bucket. For the dredging of reservoirs it is most likely that locally available excavators will be used. Normal bucket sizes range between 1 and 2.5 $m^3$ (International Association of Dredging Companies (IADC), 2014).

The third factor influencing the production is the percentage of the bucket that is filled, this differs per soil type. In Table 5.4 the percentage of the bucket that is filled can be found.

| **Material** | **Fill Factor (%)** |
|---|---|
| Moist loam / Sandy clay | 100 - 110 |
| Sand & Gravel | 95 - 110 |
| Hard, tough clay | 80 - 90 |
| Rock (well blasted) | 60 - 75 |
| Rock (poorly blasted) | 40 - 50 |

Table 5.4: The bucket fill factor of an excavator for different soils, as found in (US Army, 2000).

Under normal conditions the cycle time ($t_{cycle}$) in $s$ of an excavator on tracks, operating at 60% of the maximum digging depth is 15 $s$ (US Army, 2000). For dredging application it will be assumed that the cycle time will be slightly higher, in the order of 20 $s$. The production ($P$) in $\frac{m^3}{hour}$ can than be calculated using Equation 5.2, according to (US Army, 2000).

$$P = \frac{3600}{t_{cycle}} * V_{bucket} * f_{fill} * \eta \tag{5.2}$$

In Equation 5.2 the $V_{bucket}$ is the bucket volume in $m^3$, $f_{fill}$ is the fill factor according to Table 5.4 and $\eta$ represents the efficiency of the excavator. The efficiency is included because the excavator will not operate continuously every hour, breaks for fueling and changes of the barges that are filled will be needed. If the excavator operates 50 $minutes$ out of the hour, the efficiency becomes 83 %.

As an example, the production for a long boom excavator, having a bucket of 2 $m^3$ and dredging hard clay is determined: ($\frac{3,600}{20} * 2 * 0.85(averaged\ fill\ factor) * 0.83 =$) 254 $\frac{m^3}{hour}$. This in much lower than the production of a suction dredger or a *CSD*. The advantage of excavators is that they are cheaper to operate than these machines, so multiple excavators can work simultaneously, to achieve a higher production rate.

#### Submersible Pump

The submersible pump is comparable to the suction dredge and cutter suction dredge for production. It is a piece of hydraulic equipment and the production can thus be estimated according to

Equation 5.1. Due to the freely hanging pump, the submersible pump can only be used for loose material, since the cutting forces can not be resisted by the cable from which the pump is suspended.

#### Water Injection Dredge

Using water injection dredging production rates between 15 and 150 $\frac{\frac{m^3}{m}}{hour}$ have been reported (van Rijn, 2012). This means that if the beam containing the water injection is wide enough, large volumes of mud can be displaced. If for example a width of 9 $m$ is used, the theoretical volume that can be displaced is between 135 and 1350 $m^3$. The exact production will depend largely on the local parameters and sediment type. It can be estimated by estimating the velocity of the dredge vessel ($v_{dr} f$), the depth till where the water is injected ($h_{cm}$) and the width of the boom ($w$) of the WID vessel. The production ($P$) is than: $P = v_{dr} * h_{cm} * w$.

The injected water in combination with the sediment at the bottom of the reservoir will form a fluid mixture. This mixture will travel downward in the reservoir due to gravity. This process will only be stopped due to the settling of the sediment particles. Sand particles will settle fast, while mud particles will be able to stay in suspension much longer. An estimate for the settling length of a mud layer of 1 $m$ is 1000 $m$, while for the settling of fine sand, the length is only 50 $m$ for a layer of 1 $m$ thick (van Rijn, 2012).

## 5.6. Powering the dredging equipment

For a financial optimization of a dredging solution, the type of power supply to the equipment can be important as well. If for instance the reservoir that is dredged supplies a hydro dam, it could be possible to use electric dredge pumps, on for instance a Cutter Suction Dredge. This saves on both the trucking of diesel, but also on the environmental impact of the dredging operation. This can also be a consideration when a reservoir for drinking or irrigation water is dredged. During a dredging operation there is always the possibility of an oil spill. This can be a possible reason to come up with a solution using electricity as a power supply.

## 5.7. Environmental considerations

Another consideration for the viability of dredging for a reservoir is the environmental impact. This can influence the feasibility of dredging in two ways.

In a negative way, if there are constraints for the turbidity in the reservoir or the river downstream. If the downstream deposit of dredged material is allowed, but the turbidity has to be kept between certain levels, the production is possibly limited. In the reservoir itself most turbidity can be kept in check, by using the appropriate equipment, like fully closing clamshell grabs, visor buckets or silt screens.

However, it can also be a positive aspect. If the disposal of dredged material can be combined with restoration of the effected downstream river. This is a positive impact, especially since the dredged material can be placed very precisely in the river. This is contrary to flushing the reservoir or any other sediment removal technique.

## 5.8. Sediment transfer over the dam

The above mentioned issues of finding a location for the dredged sediment. The high costs of mobilizing and demobilizing equipment and the fact that siltation is a continuous reservoir process, indicate that a permanent dredging process could possibly be a good solution. Especially when the downstream issues related to the absent sediment in the river downstream (Chapter 2.3.5) are taken into account.

This leads to the possibility of implementing a solution that would deliver sediment downstream of the dam. A permanent dredging solution, where sediment is returned to the river downstream of the dam, results in the transfer of sediment past the dam, the dam is thus opened for sediment. That is the reason that this concept is further referred to as a '*sediment open dam*'. The original sediment balance that existed in the river before the construction of the dam is imitated. This option could be beneficial and is therefore further investigated in this section.

### 5.8.1. Case study: Neosho river

In order to investigate the possibility of the 'sediment open dam' concept, a case study is performed. The goal of this investigation is to determine the feasibility of disposal of dredged sediment downstream in the river downstream. It has to be determined if the transfer of dredged sediment, does not result in immediate clogging of the downstream river for instance.

The river chosen for this case study is the Neosho river, located in Kansas in the United States of America, which flows through the John Redmond reservoir. The river is shown in Figure 5.13.

Figure 5.13: Downstream view of the John Redmond dam, releasing 283 $\frac{m^3}{s}$ (King, 2015).

To investigate if the concept of depositing sediment downstream of the dam does not lead to immediate clogging of the river downstream, a case study is performed. The first approach in determining the downstream disposal of sediment is setting up a 1D model using Sobek (*version 3.4.1*).

To set up such a model, extensive information on a local river is needed. For that reason a river that flows through a reservoir, with enough available data is chosen. The Neosho river, found in the United States of America meets these criteria. This case study is therefore focused on this river, which flows through the John Redmond reservoir. The river is shown in Figure 5.13. The river is chosen because data is available for both the John Redmond dam and on the Neosho river.

The topographic location of the Neosho river is shown in Figure 5.14. The river starts downstream of the John Redmond dam (*JRD*), flows past Burlington and continues to Iola. The distance between the John Redmond dam and Iola is 108 $km$. The height difference between these points is found using Google Earth to be 21 $m$. The slope of the river is consequently $1.9 * 10^{-4}$, making this a relatively steep river.

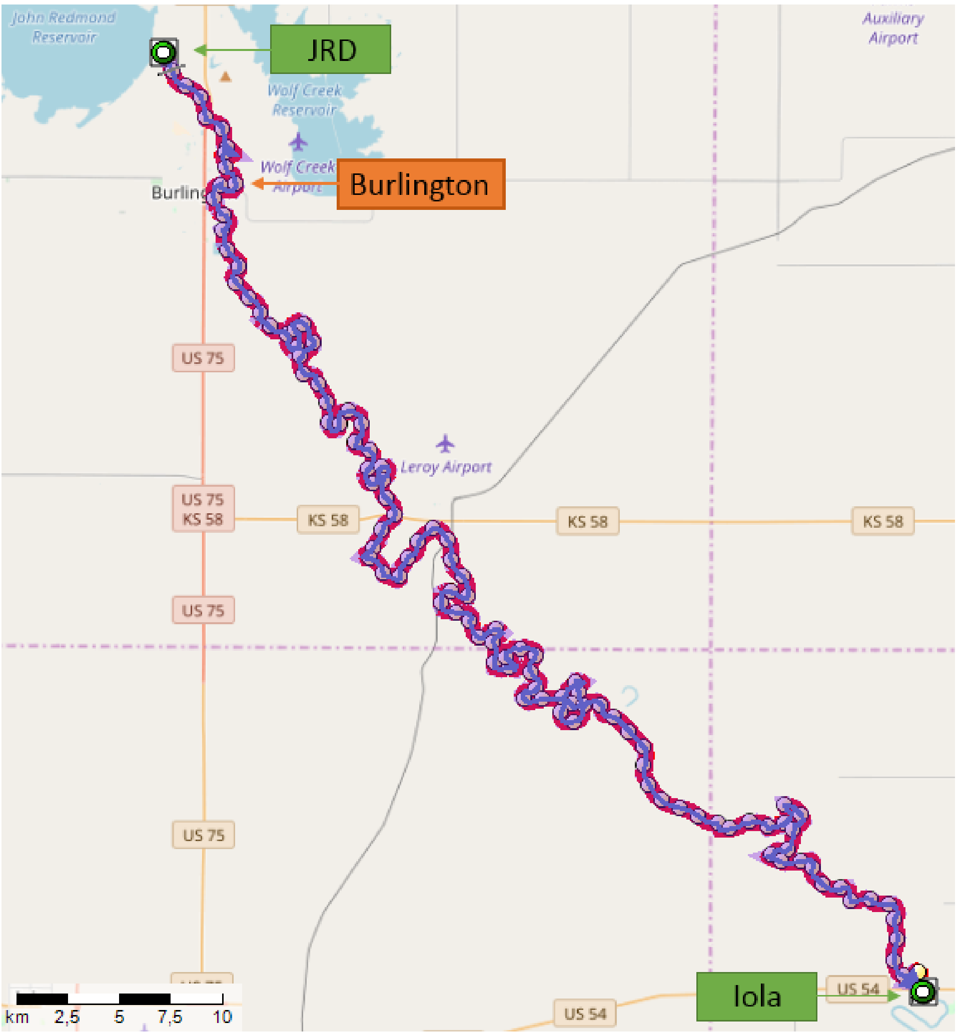



Figure 5.14: Topographic location of the Neosho river, including important locations.

The discharge data of the John Redmond dam is taken from the website of the US army corps of engineers in Kansas. The discharge through the John Redmond dam for the year 2016 is given in Figure 5.15. From the figure it is clear that the river has large fluctuations in the daily discharge. The discharge can be close to zero $\frac{m^3}{s}$ and a peak discharge larger than 500 $\frac{m^3}{s}$ occurs.

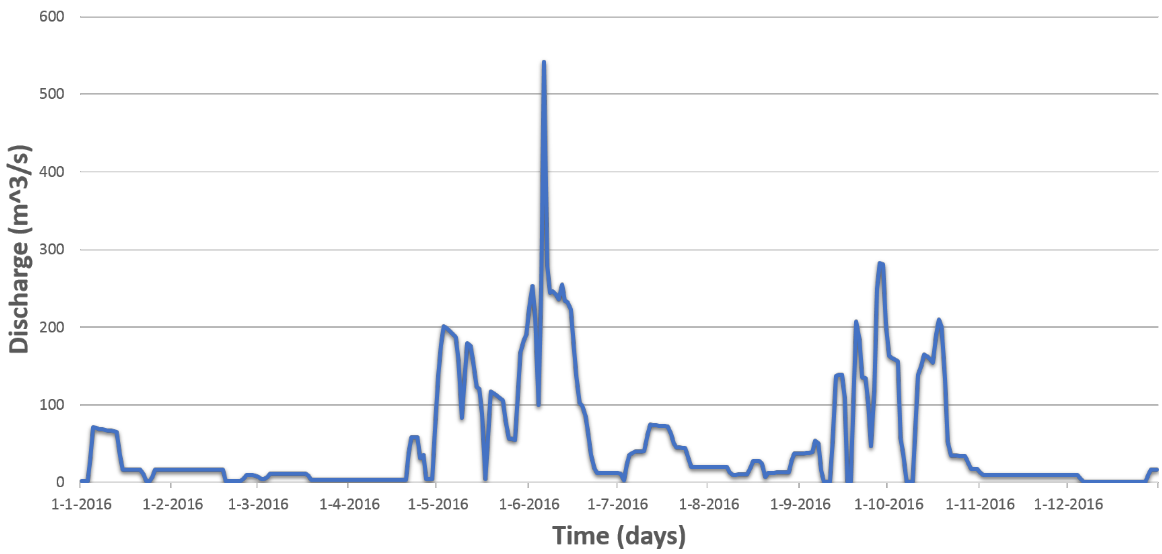



Figure 5.15: The average daily discharge through the John Redmond dam for 2016.

### 5.8.2. Model set-up

In order to model the morphologic development of the Neosho river, a representative 1D hydrodynamic model is created in Sobek. For the set up of this model the following information on the river is needed:

- Bathymetry
- Discharges
- Water levels
- Sediment characteristics

The complete set up, data collection, calibration and modelling for the Sobek model is described in Appendix D.

### 5.8.3. Model results

Transport of sand is modelled, by specifying the transport rate at the beginning of the model, thus near the JRD boundary. If a sediment transport of 0.00126 $\frac{m^3}{\frac{s}{m}}$, excluding pores is specified the model crashes. In this case sand is pumped into the river during low flow conditions, therefore it can not be transported further downstream. The result is blockage of the river, which leads to a model crash. Using this transport rate, the modelled Neosho river development after 75 days, shortly before the model crash is presented in Figure 5.16.

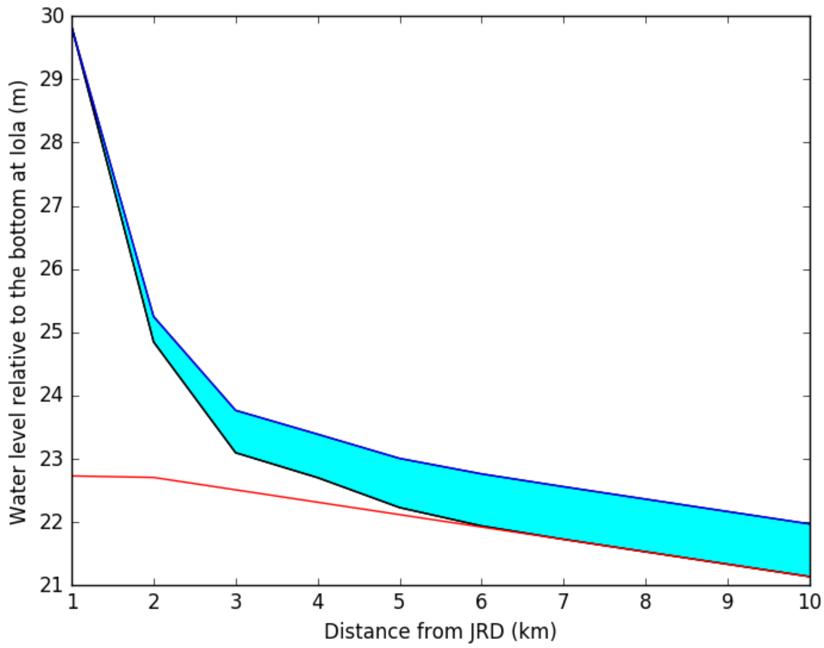



Figure 5.16: Longitudinal cross section of the Neosho river: initial bed (red), bed after 75 days of simulation (black) and water level at end of simulation (blue).

It is clear that a sediment hill forms downstream of the dam, leading to a crash of the model. The total transport can also be theoretically estimated for each day, using the Engelund-Hansen formula (Equation D.1) and the average velocity of every 12 hours, found using a run of the Sobek model without using the morphology module. The determined velocity is used to determine the transport capacity, which is than specified as the morphologic boundary condition.

If the sediment transport boundary is specified using this method, the result is indeed that no accretion or erosion occurs downstream of the JRD (Figure 5.17). It is therefore concluded that the sediment out of the reservoir that is returned into the river, has to correspond to the available transport capacity of that river.

If the inflow of sediment at the boundary is increased by multiplying the calculated transport by a factor, it becomes clear that the transport capacity of the Neosho river becomes insufficient. The result is accretion at the beginning of the reservoir. The results for modelling these increasing sediment inflows at the JRD boundary is presented in the Figures 5.19, 5.18 & 5.20.

From the data in the Figures 5.17 through 5.20 it becomes clear that dredged sand can indeed be transported by the river downstream . If the maximum calculated transport capacity of the river is exceeded by the in-flowing sediment, this will lead to accretion. It has to be decided upon if this accretion is acceptable or not. It could for instance be possible to create a ridge of sediment near one side of the river, which can be transported during high discharges of the dam. This can be calculated using a two- or three-dimensional model, where the positioning of the sediment in the cross section can be taken into account as well. This is not possible in a one-dimensional model like Sobek.

The total mass of sand that is transported during a simulation can be extracted from the Sobek model as well. The total mass of sediment that is transported is equal to 48,642 metric tons per year

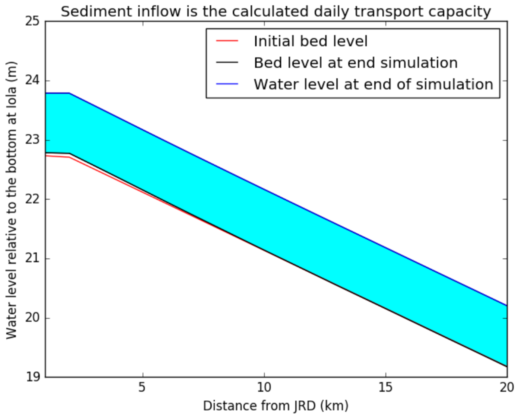



Figure 5.17: Development of the Neosho river in one year, using the calculated transport capacity on a daily basis.

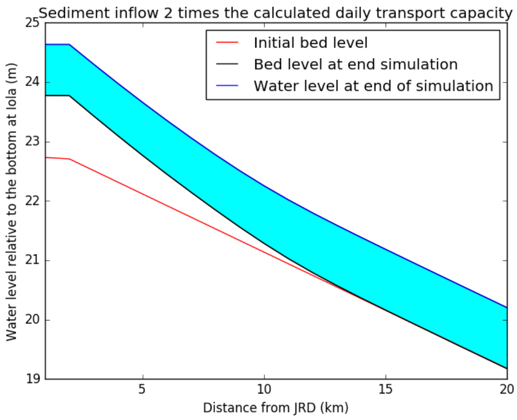



Figure 5.18: Development of the Neosho river in one year, using 1.5 times the calculated transport capacity on a daily basis.

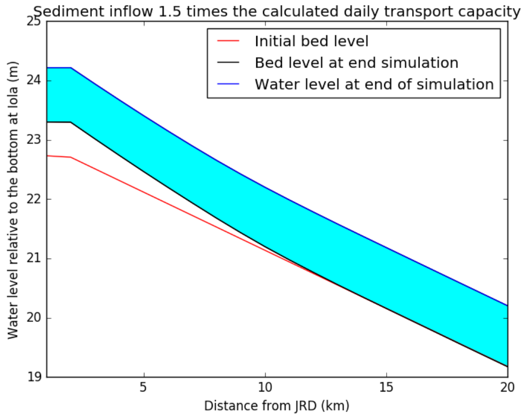



Figure 5.19: Development of the Neosho river in one year, using 2 times the calculated transport capacity on a daily basis.

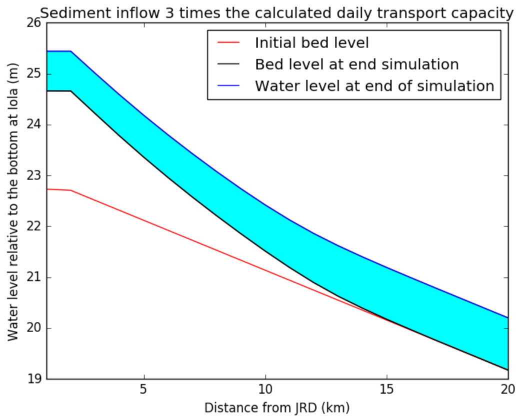



Figure 5.20: Development of the Neosho river in one year, using 3 times the calculated transport capacity on a daily basis.

if the theoretical sediment transport (Figure 5.17) is assumed.

For a sediment inflow of 1.5 times the theoretical yearly maximum transport becomes 62,142 metric tons of sand. According to the survey the yearly inflow of sediment into the John Redmond reservoir is equal to $2.19 * 10^6$ US tons per year. Using the conversion factor between of $907.185 \frac{kg}{US\,Ton}$ this in converted to 1,986,735 $\frac{metric\,ton}{year}$. In the Sobek model, the net transport rate in $\frac{kg}{s}$ is given. By multiplying this rate and the time between different time steps (12 hours * 60 minutes * 60 seconds) the total mass of transported sediment is found. If the total sediment load into the John Redmond reservoir would consist of only sand, in the scenario where 1.5 times the maximum calculated load is allowed only 3% of the yearly inflow of sediment is transported by the river downstream of the John Redmond dam. This means that 97% of the in-flowing sediment would still deposit in the reservoir.

In Sobek 3, currently the modelling of clay is not yet supported. It is however possible to conclude that the transport capacity for clay would be higher than the transport capacity for sand. As a result of the weight of the sand particles, the settle faster. If part of the in-flowing sediment into the John Redmond reservoir thus would be clay, sediment transport could be higher and thus the total remaining part of the sediment in the reservoir would be lower.

One of the reasons for the lack of transport capacity of the river downstream is the leveling of the flood peaks. These flood peaks carry the most sediment into the reservoir. Since one of the functions of the reservoir is storing flood peaks large volumes of sediment enter the reservoir and settle. The discharge through the dam is therefore much lower, than river discharges in the pre-dam situation. The flood wave is spread in time, resulting in lower flow velocities. Since the transport capacity of the river is related to this flow velocity to the power 5, the transport capacity of the river downstream of the dam is much lower than transport capacity of the river entering the reservoir.

### 5.8.4. Feasibility of sediment transfer into the downstream river

The case study confirms that part of the in-flowing sediment can be re-entered in the river downstream of the dam. Only part of the in-flowing sediment can returned, nonetheless this option should be further explored. The downstream deposits could have a positive effect, preventing erosion in the river downstream. Further modelling using a two- or three-dimensional model could be useful to determine if it is possible to deposit material downstream, purposely collecting it. In this manner the material can be carried further downstream during periods of large discharges through the dam. If that is possible, dredging at higher densities than the maximum theoretical transport capacity becomes possible. Therefore a smaller range of mixture densities is required of the dredger, making more dredging equipment suitable..

## 5.9. Conclusion

The overall conclusion that can be drawn for the dredging of reservoirs is that it is a viable option for mitigating the sedimentation of reservoirs. Numerous dredging methods are available that could be used for the dredging of reservoirs. Potential gains are the precise removal of sediment and the restoration of the river downstream of the dam. The possible obstacles that have to be overcome are the perception that dredging is expensive and finding a location for the dredged sediment, not used for river restoration.

That dredging is indeed feasible has been shown by dredging projects in the past in Austria (Royal Smals, 2017) and America (*M. Unruh, Personal communication, 26-6-2017*). Furthermore it can also be concluded from the survey, since 9 of the 14 individual respondents indicate that they are willing to invest in the dredging of their reservoir if this leads to a sustainable solution or if the benefits exceed the costs. Therefore considering these arguments, further investigation into the dredging of reservoirs is warranted.

# 6
# Feasibility of reservoir dredging

In order to determine the financial feasibility of the dredging reservoir, it is necessary to make a business case for the reservoir. In the business case the costs of dredging the reservoir are weighed against the benefits of dredging the reservoir. In this chapter the decision steps for investigating dredging of a reservoir are shown. Furthermore the costs related to reservoir sedimentation are investigated. Finally the costs of dredging are estimated. These factors are used to discuss the feasibility of the dredging of reservoirs.

## 6.1. Decision steps

The first step to determine if investigations into the removal of sediment from a reservoir by dredging is beneficial, is determining if the reservoir volume is large enough to store the required volume of water. The water volume ($S$) in a reservoir can be found at any time using the Equation 6.1 (Savenije, 2014):

$$S_{new} = S_{previous} + Inflow * \Delta t - (Outflow + Evaporation + Leakage) * \Delta t - Overflow * \Delta t \quad (6.1)$$

The volume of water change in the reservoir is thus a direct result of the inflow and outflow of water in the reservoir for a certain time period ($\Delta t$). The inflow is related to the local hydro-graph, which is the amount of rain and melt-water entering the reservoir. The reservoir has a certain capacity and once this capacity has been filled, the surplus of water that enters the reservoir will leave the reservoir via the overflow. This water can thus not be used for performing the reservoir function. By increasing the reservoir capacity, the amount water that is stored can be increased and the amount of water that is lost due to overflow is reduced.

In Figure 6.1 the water balance is determined using Equation 6.1. A fictitious hydro-graph is assumed, creating the given inflow in the reservoir per month for four years. At the start the reservoir is assumed to be empty and the water demand is assumed to be constant year round, at 25 million cubic meters (*Mcbm*).

Three reservoir sizes are used to calculate shortages, 50 Mcbm, 75 Mcbm and 100 Mcbm. All excess water that flows into the reservoir once it is full is spilled. From the graph in Figure 6.1 it follows that for the smaller reservoirs there is a water shortage in both August and October in the

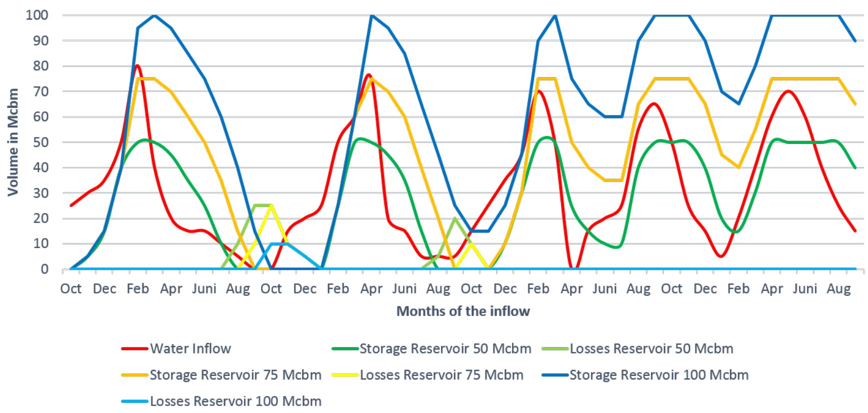



Figure 6.1: Water volume balance in a fictitious reservoir, based on three different reservoir volumes and a hydrograph of 4 years.

first two years. While for the bigger reservoir the shortage only occurs in October of the first year, this is mostly due to the fact that the reservoir has not completely filled up yet.

The presented figure illustrates that an optimum balance has to be found between the volume of the reservoir, the allowance of a supply shortage and the costs of maintaining the optimal reservoir volume. The bigger the reservoir is, the more water can be stored. The more room there is available to store water for periods with a low inflow. As presented in Figure 6.1 the shortages are reduced for the larger reservoir. In this case an increase in the water volume of the reservoir of 5 Mcbm leads to a reduction in water shortage of 10 Mcbm. If the same hydrograph is used, an investment in the removal of sediment would thus return twice. This is different for each reservoir, since each reservoir has an individual hydrograph and thus a specific water balance.

The decision to start investigating the possibility of dredging a reservoir starts by following the scheme presented in Figure 6.2. The first question that has to be answered is whether or not the there is a risk of blockage of the water intake. If this intake becomes fully or partially blocked the reservoir will lose all functionality. Therefore no more income is generated. In most cases this warrants direct action.

If not the direct blockage of the water intakes is a problem, but the volume balance of the reservoir, this is usually a problem for the long run. In this case the costs of the water shortage have to be weighed against the possibility of dredging sediment from the reservoir.

If no direct shortage is foreseen, but extra revenue can be generated, when extra water is available, this could warrant an investigation into dredging of the reservoir as well.

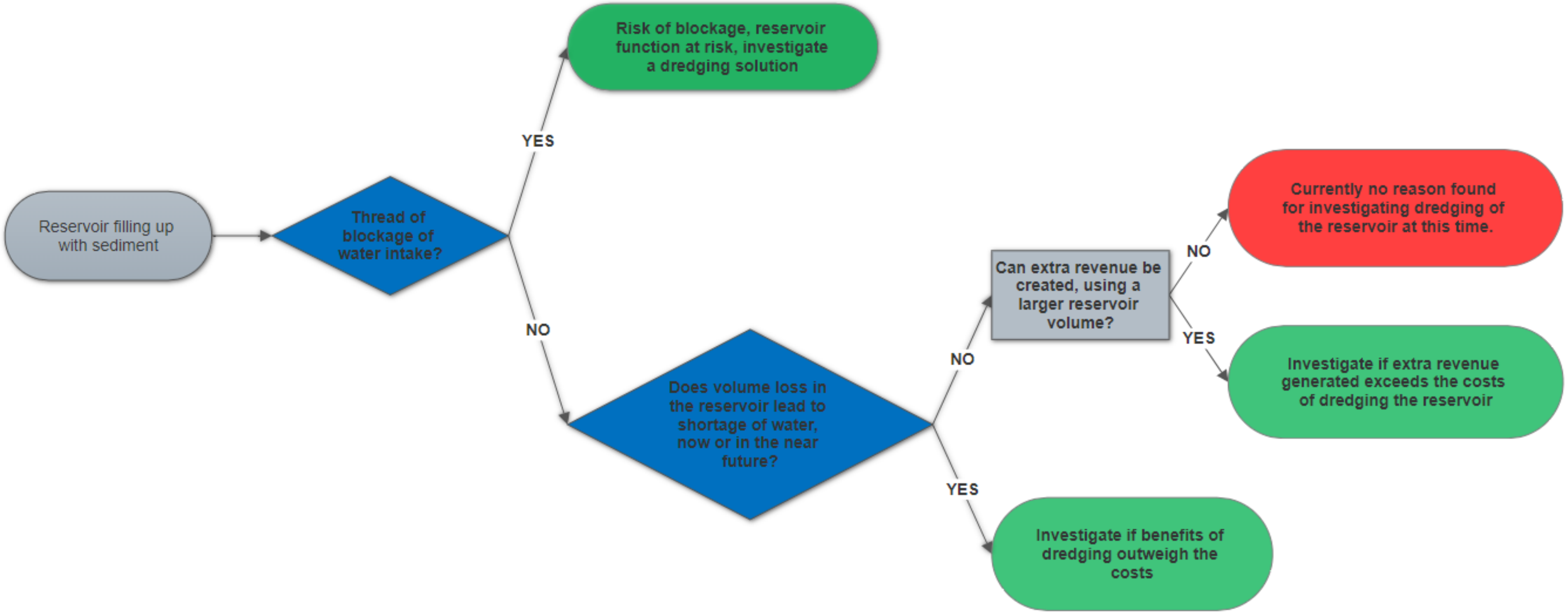



Figure 6.2: Decision model to determine if an investigation into the dredging of a reservoir should be initiated.

To define a positive business case, it is necessary to determine what the costs are of sedimentation in the reservoir. Furthermore the costs of dredging have to be determined and the possible extra revenue that can be generated by dredging a reservoir.

## 6.2. Approach to determine feasibility

In order to establish if the dredging of reservoirs is beneficial, after the decision scheme presented in Figure 6.2 has been followed, the problem can be approached in four different ways. The four approaches are:

- Business case
- The damage approach
- Lowest cost approach
- Social cost-benefit analysis

Using a business case approach, the feasibility of dredging a reservoir is determined based purely on the added benefits. The extra reservoir space that becomes available as a result of dredging can be used to generate revenue. It is however impossible to generate generic prices for power, raw water used to produce drinking water and irrigation water. This is a result of the fact that these prices are dependant on the local demand and availability at each reservoir site.

The second approach that can be used is the damage approach. In this case the costs of reservoir sedimentation have to be estimated. This can be done by estimating the damage that occurs if a measure is not taken. For instance the costs if the dam and reservoir would not perform the assigned function anymore. To determine the full extend of this damage, all different functions that a reservoir performs have to be taken into account. These functions can be: irrigation, hydro power production, water supply, flood control, recreation, navigation, fishing or other.

If the damage that can be prevented by dredging a reservoir is larger than the costs of such a dredging operation the solution is beneficial and should therefore be carried out.

The third approach is the lowest cost approach. Here all sedimentation in the reservoir is not accepted. This means that the status quo of the reservoir has to be maintained. The volume of sediment trapped in the reservoir, has to be removed. Since no volume loss is accepted, the cheapest method to remove the deposited sediment can be selected in this case. The dredging method therefore has to be cheaper than the other sediment removal methods mentioned in Section 5.1.4. If that is the case dredging is a feasible solution.

The fourth and final approach to determining the feasibility of dredging is performing a social cost=-benefit analysis. Here the measures in the reservoir are evaluated not only based on the monetary value, but also based on the social impact in the catchment area of the reservoir. The added value of creating extra reservoir storage for the local farmers is for instance taken into account. Furthermore the costs that are a result of downstream river erosion that can be mitigated are evaluated as well.

These approaches can be used to determine the feasibility of the dredging of reservoirs. In the following sections the costs of reservoir sedimentation are further investigated. Also the possbile added value of reservoir sediment is evaluated.

## 6.3. Costs of reservoir sedimentation

In Chapter 2 the negative impact of reservoir sediment on the performance of the reservoir has been described. In order to come up with a positive business case it has to be determined what costs are associated with this sedimentation. The possible costs are investigated based on the benefits per extra $m^3$ of reservoir volume available. It is assumed that 1 $m^3$ of reservoir sediment, directly replaces 1 $m^3$ of reservoir volume.

### 6.3.1. Power production

There are two main types of hydro power reservoirs. The large storage reservoirs, having a large active volume, used to capture floods, store water to generate electricity when the power demand peaks. Using these reservoirs seasonal water peaks are evened out.

The second type of hydro power reservoir is the run-of-river reservoir. This reservoir is used to regulate the power production on a smaller scale. Run-of-river reservoirs have a smaller active reservoir space, which can be used to mitigate peaks in power demand in the order hours or days. The fundamental difference between the two types is the difference in the active storage reservoir.

A study of regulating and storage reservoirs in Japan found that the sedimentation in the active storage area leads to a decrease in water use efficiency. Especially for storage reservoirs with a low annual turnover, the sedimentation in the active reservoir can have a negative effect on the water use (Okumura & Sumi, 2012). The production of hydro power reservoirs can be influenced in two ways by sedimentation. The first problem that can occur is the blockage of the intakes by sediment, leading to less water passing through the turbines, thus to a production loss.

The second problem that can occur it that not enough water is available in the reservoir to produce the required electricity. If this is the case, power outages can occur in a season with low water inflow.

The potential power ($P$) that can be harvested from a water reservoir is based both on the flow through the turbine ($Q$) and the available head ($H$):

$$P = \rho * g * Q * H \tag{6.2}$$

The density of the water ($\rho$) is in the order of 1,000 $\frac{kg}{m^3}$ and the acceleration of gravity is 9.81 $\frac{m}{s^2}$. Using a head in meters and a flow in $\frac{m^3}{s}$ this leads to a power in Watt. However this does not directly result in the power produced by a hydro power facility, since the losses in the transport pipes, turbines and generators have to be taken into account as well. Estimating the different losses, the power production (in kW) can be estimated using based on head and flow only (van Duivendijk, 2007):

$$P_{generated} = 8 * Q * H \tag{6.3}$$

The generated power is thus directly influenced by the flow that can enter the turbine and the available head. It becomes clear that if the inlets to the power outlet become (partially) blocked, the flow will reduced and thus the energy production will decrease. This results in loss of income.

For lake type reservoirs, the available head will be lower than for the gorge type reservoirs. This means that for production of the same amount of energy, more water will need to flow through the turbine, so a higher flow ($Q$) is realized in a lake type dam than in a gorge type dam.

The different sedimentation problems, both require different solutions. In case of risk of blocked water intakes, the reservoir can lose complete functionality. Generally, the volumes of sediment that need to be removed are smaller than the volumes required to increase the reservoir volume. The impact of no production of the reservoir is large, warranting high investment costs in the local removal of sediment. Dependant on the size of the reservoir and the general production, the financial losses could be in the order of millions.

If the volume of water that is available is too low, the solution has to be optimized.The equation shows that the amount of dredging that has to be done in order to create enough volume is dependant on the required power. A prediction of the extra power that can be generated and sold, versus the investment in sediment removal have to be considered. Both aspects have to be weighed, to determine the most feasible solution.

The benefits for the production of 1 $kWh$ of hydropower are hard to determine. However the levelised cost of operation can be used as an indication for these benefits. The values reported range from \$0.02 to \$0.27 (International Renewable Energy Agency (IRENA), 2012).

### 6.3.2. Irrigation

For irrigation reservoirs, the extra reservoir space that is created will lead to the extra storage of water that can be used to fulfill the demand. If the demand is met, water stored can be used to create extra agricultural opportunities.

The price for irrigation water varies all over the world. The local prices for irrigation water have to be taken into account for a site specific business case. An indication for the price of 1 $m^3$ is given by Dinar to range between a minimum of \$0.01 in Portugal and a maximum of \$1.96 in Switzerland (Dinar, 2000). It has to be kept in mind that these values are leveled for the dollar in the year 1996. It shows however the wide variety associated with the costs.

### 6.3.3. Drinking water

Drinking water is critical to sustain people. That is the reason that supply and demand have to match. If this is not the case drastic measures like water rationing have to be taken. Every extra $m^3$ of storage created in a water supply reservoir can be used to store raw water. The existing water shortage or the chance thereof, has to be reduced by creating extra space in the reservoir. The reduced water shortage is the extra water that can can be used. This extra water is sold and this is the benefit of removing sediment.

The value of this lower chance of water shortage will have to be reviewed locally, since it depends on the level of organization of the local government. The accepted chance of drinking water shortage will be higher in Africa than in for instance America. An example of the influence of the location on the price of a $m^3$ of water for domestic use is presented bu Dinar. The prices presented in 1996 dollars are as low as \$0.01 in India up to a maximum of \$3.79 in Yemen (Dinar, 2000).

### 6.3.4. Recreation

The recreation aspect of reservoirs is important as well. It is however hard to pinpoint a value per $m^3$ of reservoir volume. The aspects for recreation in reservoirs are more dependant on the area of the water that is available and the quality of the water. Volume addition is only beneficial if this has a positive effect on the water quality or if a dry period is reduced by adding reservoir volume. The price per $m^3$ is however impossible to determine, due to the difference in the rating of the recreational value of reservoirs worldwide.

### 6.3.5. Flood control

The value for the flood control function of a reservoir is based on the damage that would occur due to a flood that is retained by the dam. Since such a flood occurs with large irregular intervals the effects are difficult to establish. Furthermore the volume reduction due to sedimentation occurs slowly and as long the design flood wave does not enter the reservoir, no damage occurs downstream of the dam. It is however important to maintain reservoir volume at such a level that this design flood can be retained in the reservoir, both now and in the future. The damage that occurs due to flooding of a reservoir is in the order of millions of euros. The resulting damage should therefore be prevented and dredging is a suitable solution if reservoir volume can be maintained at a low price.

### 6.3.6. Other added benefits

The removal of sediment can have other positive aspects on making a business case as well. First of all the sediment that is removed from the reservoir can, if the quality is good enough, be used as an aggregate for concrete or construction of roads. If the sediment is of poor quality it can be used as sand to raise land near the reservoir. This is a specific point of added value of a dredging scheme, since the dredging equipment can be used to harvest the sediment as a resource. The value of 1 $m^3$ of sand differs worldwide.

The second aspect that could prove to be beneficial, is the aspect of downstream erosion. Downstream river erosion has negative consequences both for the aquatic life and for residents downstream. If (part of) the dredged sediment can be returned to the downstream side of the dam, these effects can be mitigated. This is positive for the dredging operation as well, since a difficult aspect of sediment removal is the location of the dredged material. Therefore two issues are mitigated simultaneously.

The third added benefit could be sponsoring of a dredging project by local authorities. This is naturally a less preferred option. However it can be a motivator to initiate a dredging project and this can lead to developments in the local economy. Leading to added social value of a dredging project.

### 6.3.7. Conclusion on the Benefit side

For each reservoir project the benefits of sediment removal using dredging have to be evaluated. For multi functional reservoirs multiple goals could be served by each $m^3$ of sediment removed. To make a business case, all the value gained due to the removal of 1 $m^3$ of sediment have to be added. The effect of dredging on the reservoir volume has to be determined. The return period of the dredged material has to be found, in order to determine for what time period the added value of a dredging operation is created.

If the costs of dredging the reservoir are below the extra value generated in the time period thereafter, the business case becomes positive. The benefits of reservoir dredging have been reviewed, the next section focuses on the cost of dredging a reservoir.

## 6.4. Dredging cost model

To determine the feasibility of dredging a reservoir it is necessary to estimate the costs of dredging a reservoir. Using the information of Chapters 4 & 5 a model is set up that can be used for estimating the costs of dredging a reservoirs based on different parameters.

### 6.4.1. Model input

The first input required is the volume of material that has to be dredged. This can be determined by the model user using either a survey or the yearly volume of sediment flowing into the reservoir. If the volume is known, the sediment fractions have to be specified. The material will not be homogeneous in most cases, therefore the percentage of each fraction can be specified. These fractions can be split up according to the classes defined in Chapter 4. The sum of the soil fractions has to be equal to 100. If this is achieved the check cell background becomes green.

By entering the maximum reservoir volume, reservoir area and dam height the reservoir type is determined by calculating the M-value according to Equation 4.2. The maximum depth of the reservoir is estimated by applying Equation 4.1. Using the resulting M-value the type of reservoir is determined. For each reservoir type the percentage of sediment deposited at each depth is obtained applying Figure 2.4 as specified by Borland & Miller. The graph of Figure 2.4 is translated into Table 6.1 containing both the depth percentage and the percentage of sediment deposited for each reservoir type.

| Percentage of depth | Type I | Type II | Type III | Type IV |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 10 | 1 | 3 | 5 | 30 |
| 20 | 4 | 10 | 18 | 54 |
| 30 | 8 | 22 | 35 | 66 |
| 40 | 12 | 32 | 55 | 80 |
| 50 | 20 | 45 | 70 | 85 |
| 60 | 32 | 60 | 85 | 90 |
| 70 | 48 | 70 | 92 | 92 |
| 80 | 68 | 82 | 95 | 95 |
| 90 | 88 | 92 | 98 | 98 |
| 100 | 100 | 100 | 100 | 100 |

Table 6.1: Table containing the percentage of sediment deposited at each percentage of the depth, for different types of reservoirs according to (Borland & Miller, 1960).

The maximum depth that can be reached by each piece of dredging equipment evaluated is presented in Table 5.3. Combining these depth with the calculated maximum reservoir depth, the percentage of sediment that can be reached and thus dredge is determined for each type of equipment.

The time available for the dredging operation has to be entered as well. The available time influences the amount of dredging equipment needed to remove the specified volume in time. If large volumes of sediment have to be dredged in a short period, the number of dredging machines has to be increased to achieve high production rates.

If a continuous solution has to be found, this can be done on a yearly basis. In this case the sediment volume to be removed is equal to the yearly inflow of sediment and the time available is in that case equal to 1 year.

The weekly production is determined for each piece of dredging equipment as shown in Appendix F. Hereby the downtime due to re-positioning and maintenance is factored in, resulting in a net weekly production. This production can be used to determine the number of weeks required to perform the dredging operation in the reservoir.

Before this calculation of the number of weeks necessary, it is reviewed whether or not a dredging method is plausible or not. This is done by checking the input parameters. The parameters are described in detail in Appendix F. The most important ones are whether or not sediment can returned into the river downstream of the dam. Another option is deposit of sediment in the dead storage of the dam. These factors determine if water injection dredging is an option.

The total amount of weeks that one piece of dredging equipment is needed is calculated by adding the required time to dredge each fraction. Furthermore it is determined whether or not the machine is able to dredge each sediment fraction. If not all fractions of sediment can be dredged, a warning is given in the 'Output' sheet. It not all sediment can be dredged by one type of equipment, this is indicated by a ´yes´ for the column: "extra machines necessary?".

Other input factors that can be specified by the user are the discharge distance of the dredged material. The discharge distance is used for each type of equipment. The maximum discharge distance has to be specified here. The distance from the dredging location to the deposit location using a WID has to be specified specifically. This distance is the average distance between the dredging location and either the dam in case of sediment return to the downstream river or the dead storage in case sediment is transported there. If at forehand it is known that the WID is not a suitable option, the value can be set to 0. In this case the WID is not further considered.

The amount of machines is determined by dividing the number of dredging weeks required by the time available as specified by the user. Furthermore for the hydraulic dredging equipment the amount of booster is determined based on the defined pumping distance. Any distance below 2,000 $m$ no booster is added, above 2,000 $m$ and below 4,000 $m$, one booster is added. Between 4,000 $m$ and 6,000$m$ a second booster is added. The second booster is last booster that can be added. Adding more boosters is not possible according to experts. The dredging costs can now be determined for each method.

Other parameters that can be changed locally are the price of fuel, the number of hours in a working week and the price of one week of labour. For these parameters default values are given, these values can however be adapted by the user.

### 6.4.2. Dredging costs estimation

In order to estimate the costs that come with the dredging of reservoirs for each type of equipment the following costs are determined:

- Costs of equipment
- Auxiliary equipment needed
- Crew costs
- Fuel costs

These costs of equipment a determined by applying the book 'A guide to cost standards for dredging equipment 2009' (Ciria, 2009). To obtain values for the current year, the Cost standards indexation 2017 (Ciria, 2017) is used as a percentage of the costs of 2009. Forward this book will be referred to as 'the Ciria'. Since the goal of this model is comparison of the different dredging method costs, all prices are expressed in the same currency; the euro.

### Costs of equipment

For the costs of equipment the different tables in the Ciria are used in combination with some assumptions. Discussion with experts at Witteveen+Bos lead to the conclusion that the Ciria values tend to overestimate the costs of dredging equipment, however in this phase of cost calculation this overestimation can very well represent the uncertainty related to overhead costs, margin of error and profit. The Ciria cost standards are therefore applied.

The evaluated equipment in the dredging cost model is:

- Suction Dredge
- CSD1, smaller discharge pipe, depths up to 40 $m$
- CSD2, larger discharge pipe, depths up to 25 $m$
- Grab Dredge
- Backhoe Dredge
- Submersible Pump
- Water Injection Dredge

For each type of equipment different properties are assumed, based on real life examples. The costs for these pieces of equipment are determined using the Ciria. The full description of this process is presented in Appendix F. The costs found for each type of equipment are presented in the sheet "Financial computation".

To start off the costs for hiring a contractor to do the job are estimated. The costs for the contractor are the depreciation & interest (D+i) and the Maintenance & Repair (M+R) in the Ciria. For each hydraulic method a discharge is assumed through the discharge pipe. The transport distance is input from the user and therefore specified on the "Input" sheet. The obtained transport distance is divided by the length of one pipe. The pipe diameter is taken the same as the discharge pipe. All pipes are assumed floating. If boosters are required, these are assumed to be floating as well and of the same order of magnitude as the pump on the hydraulic dredger. For the suction dredge and the submersible pump boosters of the smallest type are assumed.

For non-hydraulic dredgers the transport is performed using barges. The longer the transport distance is, the more barges will be needed to make the production as continuous as possible. A waiting piece of dredging equipment would only lead to financial losses. Therefore the number of tugs and hopper barges is based on the filling time of the grab or excavator dredge of one barge and the distance that the tug has to sail to the discharge location.

For both the cutter suction dredges and the suction dredge a multi purpose pontoon is added for support during the dredging operation. For all dredging works a survey vessel is needed to monitor the work. This vessel will however not be utilized full time during dredging operations and is therefore assumed at 20% of the weekly costs.

The crew costs are estimated by deciding the amount of people working in each dredging operation. Each piece of dredging equipment is operated by at least one person. The cutter suction dredger, suction dredger and submerged pump will all be operated by two people. Each tug will have it's own captain and each multi purpose pontoon will have 2 crew members. Th number of people required at all times can therefore be determined for each dredging operation. Assuming that a work week consists of 42 hours, the number of people working full time can be determined. This number is based on the service hours for each dredging operation.

By multiplying the number of people needed by the number of workweeks needed, the number of weekly salaries can be determined. The price per workweek is specified on the ´Input´ sheet and can be changed to the represent the local value of labour..

The fuel consumption can be estimated using the formula according to VOUB as indicated by an expert of Witteveen+Bos (*personal communication, M. Huijsmans, 3-11-2017*). The fuel consumption of a diesel engine at full speed is equal to 0.25 $\frac{kg}{\frac{kW}{hour}}$. For each dredging piece of equipment the engine size can be estimated. Assumed is that full power is only used 50% of the time for a work week of 84 hours and 75% of the time for a workweek of 168 hours. This assumption is made due to the fact that the engines do not run full time all the time. When the equipment is on hold, large parts of the equipment will not run. The price of the fuel is taken from Bunkerworld.com and is $770 per tonne of fuel. The exchange rate of 1.176 $ per euro, which is the exchange rate of *27-9-2017*. The price per tonne is thus €655.

### 6.4.3. Implementation of limitations

The obtained limitations for each dredging method have to be implemented in the model as well. If not every fraction of sediment that is given in the input can be dredged using one method, a warning is given in the 'Output' sheet. This warning is based on the fact that sediment is present for fractions that can not be removed using the given dredging method. However, for the other fractions a price per $m^3$ is given.

If the reservoir is to deep to remove all sediment, the percentage of sediment that can be removed is presented. These methods are however not taken into account for the advice for the recommended dredging equipment. The recommended equipment removes all given sediment fractions at the lowest price. The owner can however choose another type of equipment, not able to remove all sediment. In this manner a cheaper solution can be implemented.

Other factors are taking into account as well. If downstream discharge of the sediment or deposit in the dead storage is possible the WID dredge is considered, otherwise an error message is given on the 'Output' page for the WID. If downstream regulations for the turbidity are enforced, this results in a warning for the WID as well. Further research into return of the sediment in the downstream river has to be performed.

If hydro power can be used for powering the dredges and boosters, the fuel costs will reduce to zero. However for the survey launches and tug boats fuel is still required. The price reduction is achieved by setting the power of all dredges and boosters to zero, if on the 'Input' sheet the option of hydro power is set to 'Yes'.

If contaminated sediment is present a warning is produced in the "Output" sheet. Contaminated sediment has to be disposed in a special manner. This leads to an increase in costs for the disposal of dredged material. Further research is required and additional costs on top of the presented dredging costs will most likely occur. The exact height of these costs is base on the local conditions and the type of contamination and is therefore outside the scope of the dredging cost model.

## 6.5. Model results

The full model is now set-up. The price per $m^3$ of dredged material can now be calculated for each dredging method. All costs are added and divided by the volume of sediment dredged. The result of the model is given in the sheet 'Output'. Here the duration of the dredging operation is presented in weeks for each method. The total price in euro of the complete operation is given. The number of machines used is given as well and the price per $m^3$ of moved sediment is presented as well. Warnings if not all sediment is removed are shown here as well. The result is an advice on the type of equipment to use. This type of equipment results in the lowest price per $m^3$ for the removal of all sediment.

### 6.5.1. Parameters influencing dredging costs

Now it has to be determined what factors influence the costs of reservoir dredging the most. The applied method is that one parameter is varied across a range, while the other parameters are maintained constant.

The default parameters used are 1 year available to dredge the reservoir, the volume to be dredged is $1 * 10^6 m^3$ of sediment, containing fractions of 50% silt, 25% sand and 25% soft clay. The discharge distance is by default set to 1,500 m. The default weekly salary is set to €4,200 per week, which is equal to €100 per hour, for a workweek of 42 hours. The default price of fuel is taken to be €655 per tonne. The dam height is assumed to be 10 $m$. The default transport distance for the WID is set to 250 $m$.

First of all the weekly salary is evaluated. The value for the weekly salary is varied between €0 and €10,000 per week. The obtained results can be represented by the graph in Figure 6.3. It is clear that the increase of the price is linear. The WID is most influenced due to the number dredges and number of weeks and the total amount of weeks that this dredge is deployed. The steeper slope for some types of equipment is related to the higher amount of people necessary operate this type of equipment.

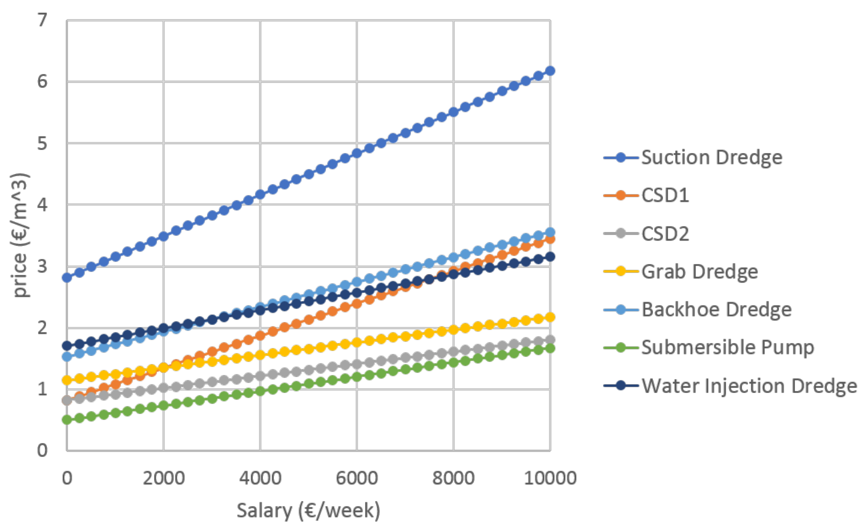



Figure 6.3: The development of the price per $m^3$ of dredged material, related to an increase of weekly salary.

From Figure 6.4 it can be concluded that the discharge distance has a large influence on the dredging price as well. The transport distances is especially important for the WID. This is related to the fact that if sand is present, it has to be re-injected each 50 $m$ of displacement.For mud fractions of the soil, this is only for each 1,000 $m$. The result is that WID is an expensive method if large transporting distances have to be achieved. If the transport discharge to either the dam or dead storage is short, the costs for using a WID are unrivalled.

The steps in the price for the suction dredge, CSD1, submersible pump and CSD2 are related to the fact that after each 2,000 $m$ an extra booster is needed. Therefore the costs become higher after 2,000 and 4,000 $m$. The further increase is related to the extra length of pipe required. The smaller steps for the grab dredge are extra tugs and hopper barges required. Due to the slower loading cycle of the backhoe dredge, fewer tugs are required and therefore the costs are relatively level up till 3,000 $m$.

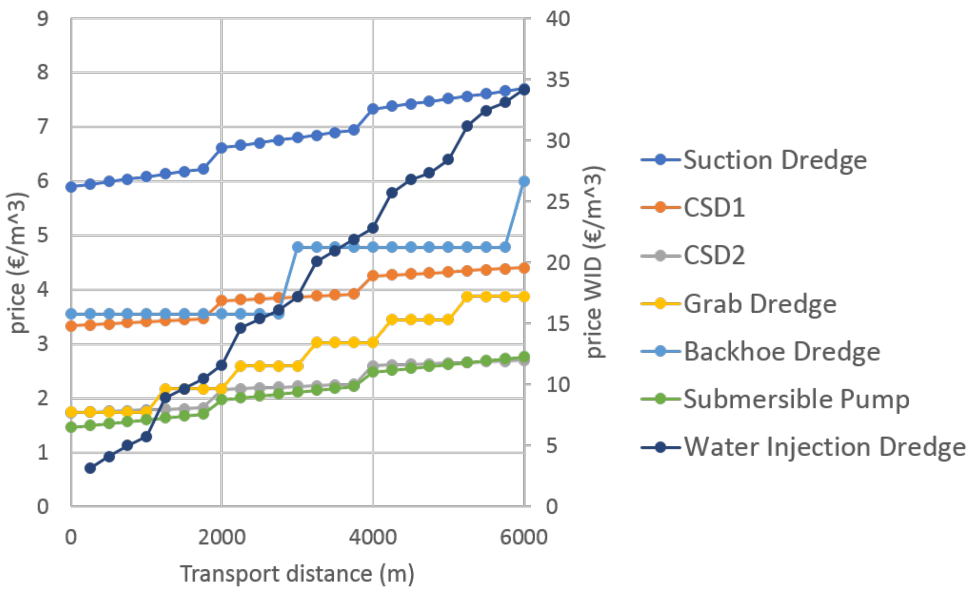



Figure 6.4: The development of the price per $m^3$ of dredged material for an increasing transport distance.

The influence of the volume of sediment on the dredging costs is shown in Figure 6.5. The increase in dredging volume leads to an exponential decrease in dredging costs. The price of a dredged $m^3$ of sediment stabilizes for volumes larger than 50,000 $m^3$. The price per $m^3$ is levelling because the dredging of small volumes does not result in the use of all available capacity. For smaller volumes of sediment only the submersible pump and backhoe dredge are suitable for dredging at low costs. For larger sediment volumes the hydraulic equipment becomes more suitable than the mechanical equipment.

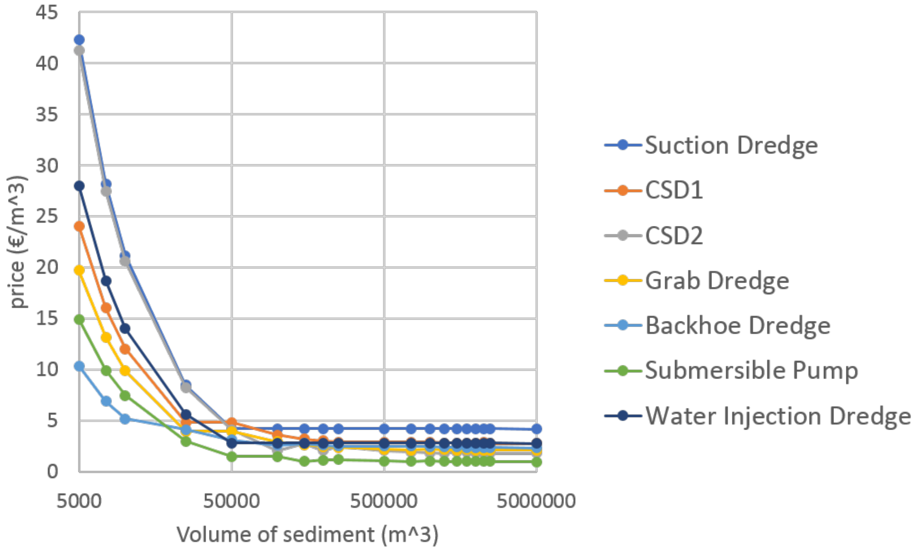



Figure 6.5: The development of the price per $m^3$ of dredged material for an increasing volume of material to be dredged.

Another potential factor that can reduce the price of dredging, is the use of hydro power to power the dredging equipment. If hydro power is used the costs for fuel can be neglected. The total dredging cost thus become lower. This effect is presented in Figure 6.6. The effect of reduced fuel costs increases if amount of dredging equipment required rises. Only dredging equipment is assumed to be electric, the auxiliary equipment requires fuel in both cases.

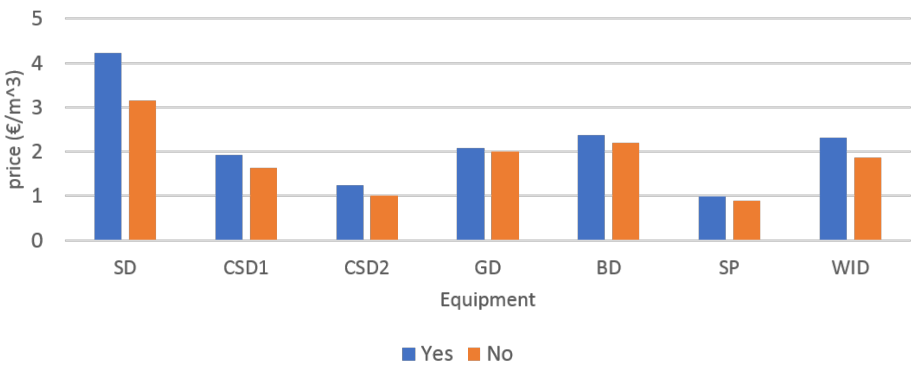



Figure 6.6: Price (€) of dredging in relation to the use of hydro power ('Yes') or regular fuel ('No').

### 6.5.2. Influence of soil fractions

The different fractions of soil whereof the sediment consists have a large influence on the dredging costs as well. To show this the dredging costs are calculated for different sediment fractions scenarios. The different scenarios are presented in Table 6.2. The dam height and thus the maximum reservoir depth is varied as well. The reservoir type is maintained constant to type III, which is the hill type.

The assumed parameters are 1,500 $m$ discharge length for each dredging method, only for the WID downstream discharge at no more than 1,000 $m$ is assumed. It is assumed that no electricity is available for powering equipment and a sediment volume of 1,000,000 $m^3$ has to be dredged.

| Scenario # | Silt (%) | Sand (%) | Soft Clay (%) | Dense Clay (%) | Gravel (%) | Boulders / Debris (%) |
|---|---|---|---|---|---|---|
| 1 | 100 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 100 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 100 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 100 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 100 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 100 |
| 7 | 20 | 20 | 20 | 20 | 20 | 0 |
| 8 | 25 | 50 | 25 | 0 | 0 | 0 |
| 9 | 50 | 0 | 50 | 0 | 0 | 0 |
| 10 | 0 | 50 | 0 | 0 | 50 | 0 |

Table 6.2: Different sediment fraction scenario's for a reservoir.

For each scenario the recommended type of dredging equipment and corresponding price in euro per $m^3$ is determined. The recommended equipment is able to remove all sediment at the lowest cost. The recommended type of equipment for each scenario and the corresponding dredging costs are shown in Table 6.3.

| # | **dam height 10 m** | | **dam height 30 m** | | **dam height 40m** | | **dam height 60 m** | |
|---|---|---|---|---|---|---|---|---|
| | *Equipment* | $\frac{euro}{m^3}$ | *Equipment* | $\frac{euro}{m^3}$ | *Equipment* | $\frac{euro}{m^3}$ | *Equipment* | $\frac{euro}{m^3}$ |
| *1* | SP | 1.01 | SP | 1.01 | SP | 1.01 | SP | 1.01 |
| *2* | SP | 1.01 | SP | 1.01 | SP | 1.01 | SP | 1.01 |
| *3* | CSD2 | 1.24 | CSD2 | 1.24 | CSD1 | 1.92 | GD | 4.04 |
| *4* | CSD2 | 1.65 | CSD2 | 1.65 | CSD1 | 2.53 | GD | 5.74 |
| *5* | BD | 2.43 | CSD2 | 2.47 | CSD1 | 3.73 | GD | 5.74 |
| *6* | GD | 2.84 | GD | 4.01 | GD | 4.59 | GD | 5.74 |
| *7* | CSD2 | 1.65 | CSD2 | 1.65 | CSD1 | 2.41 | GD | 5.13 |
| *8* | CSD2 | 1.24 | CSD2 | 1.24 | CSD1 | 1.92 | GD | 4.04 |
| *9* | CSD2 | 1.24 | CSD2 | 1.24 | CSD1 | 1.92 | GD | 4.04 |
| *10* | CSD2 | 1.86 | CSD2 | 1.86 | CSD1 | 2.89 | GD | 5.44 |

Table 6.3: Recommended equipment for different scenario's of sediment fractions.

The abbreviations used in the table are SP for the Submersible Pump, BD for a Backhoe Dredge and GD for a Grab Dredge.

From the combinations it is clear that as long as there is no cutting of soil is required the hydraulic submerged pump can be used for high productions at low costs. If cutting is required a larger cutter is cheaper than a smaller cutter. The tipping point where the smaller cutter becomes more beneficial is where the reservoir becomes to deep for the large cutter.

The backhoe dredge is most suitable for the removal of gravel in shallow reservoirs. The grab dredge becomes the best option for deep reservoirs, although it is clear that for deeper reservoir the costs of dredging increase. Silt and sand (scenario 1 & 2) are the most promising materials to be removed using dredging at low costs, while gravel and debris lead to high costs per $m^3$ removed.

### 6.5.3. Mobilization & Demobilization costs

It has to be noted however that mobilization and demobilization costs of the dredging equipment are not taken into account in the above discussed scenarios. It is possible to add these costs on the "Input" sheet of the dredging cost model. Due to the very localized conditions these costs depend on, by default they are not included in the calculation and therefore their value is set to zero. The costs are one time investment costs and are therefore directly added to the total costs of the dredging operation. The result is that these costs become relatively large if only small amounts of sediment have to be dredged.

The costs for mobilization and demobilization can be divided into a part related to the fact that the dredging equipment can not be used during the transportation and assembly period. he second part of these costs is the actual transport of the dredging equipment. The transport of for instance a CSD by road to a reservoir in the mountains requires multiple trucks and trailers and a mobile crane for assembly once the CSD is delivered to the reservoir. An example of the transport of dredging equipment by road is depicted in Figure 6.7.

Figure 6.7: Transport of a dredge towards a reservoir (*screenshot* (J.Lammers, 2012)).

The mobilization and demobilization costs can be mitigated by either using local available equipment like excavators, wire cranes, tug boats, barges and pontoons. If continuous dredging of the reservoir is required a possibility that arises is the purchase of dredging equipment by the responsible reservoir authorities. By purchasing equipment the mobilization and demobilization costs of a dredging contractor are avoided. Furthermore it is possible to combine the dredging of multiple reservoirs located near each other, thereby reducing the dredging costs.

### 6.5.4. Depot costs

If the dredged sediment can not be returned into the river downstream a depot has to be setup where the sediment is stored. The set up of a dredging depot results in additional costs. The assumptions used to determine these costs are presented in Section F.4 of Appendix F.

It can be chosen to take depot costs into account in the dredging model. If this is done, for each method, except for the WID additional costs for the set up of the depot are added to the dredging costs. This is tested for the standard case and shown in Figure 6.8. It is clear that depot costs raise the costs of dredging by over €1 per $m^3$.

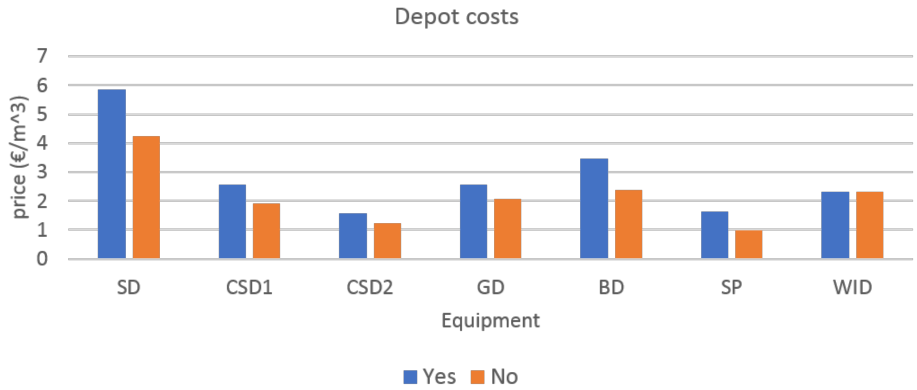



Figure 6.8: Price (€) of dredging if material deposit in a depot is taken into account ('Yes') or not ('No').

## 6.6. Comparison RESCON model

The RESCON model (Palmieri et al., 2003; Kawashima et al., 2003) (described in Section 4.6) is used to determine if a sustainable solution for continued reservoir operation can be found. By applying the low dredging costs per $m^3$ found in a fictitious reservoir and the other applied reservoir parameters of the dredging model, a possible outcome is that dredging the reservoir is the sustainable solution having the highest net present value. It is proved that prices below the default value of 5 $\frac{\$}{m^3}$ are definitely possible therefore the RESCON model shows that dredging can also be a financially attractive solution for sustainable reservoir development.

## 6.7. Conclusion

Based on the dredging model it is clear that each different reservoir and sediment parameter influences the dredging costs in a different way. It is clear that low dredging costs are possible and therefore dredging of reservoirs could result in a financially attractive solution.

The transport distance has to be kept small to maintain low dredging costs. The model is limited by a maximum transport distance of 6 $km$. Labour costs should be maintained at a reasonable level. Since an increase in labour costs leads to a linear increase in dredging costs.

If the sediment to be dredged contains silt, sand or soft clay, dredging prices can be as low as €1.01. For dams up to 60 $m$ without debris present, dredging costs well below €3 per $m^3$ can be obtained.

If the dam height is below 40 $m$ this is an extra indicator that dredging of the reservoir is possible at reasonable cost. If the dam height is further increased, the grab dredge has to be applied. The dredging costs for deeper reservoirs increases since the production rate decreases.

If the low costs found by applying the low dredging costs in the RESCON model it is possible that dredging becomes the sustainable solution with the largest net present value.

If additional benefits of dredging are included in the feasibility evaluation as well, on top of the dredging costs, the feasibility of dredging is further increased.

# 7 Conclusions

The main research question addressed in this research is determining when the dredging of reservoirs is feasible. By approaching the subject from different perspectives an overview of the problem of reservoir sedimentation is created. Furthermore the possibilities of dredging a reservoir are investigated, including the added values and possible obstacles to a dredging solution.

## 7.1. Reservoir sediment

The main issues associated with the sedimentation of reservoirs are the loss of reservoir volume, which is vitally important for irrigation reservoirs, drinking water reservoirs, flood retaining reservoirs and storage hydro power reservoirs.

Furthermore the sediment retained by the dam leads to sediment shortages downstream of the dam, possible blockage of water intakes near the dam and upstream of the dam to flooding and navigation issues occur due to the associated backwater curves. These sedimentation issues occur mostly in sediment laden rivers. Rivers close to the origin, for instance in mountainous terrain do usually not suffer from severe sedimentation issues.

## 7.2. Survey

From a survey among people responsible for different reservoirs it became clear that not every reservoir suffers sedimentation issues. Therefore sedimentation in the reservoir is only an issue for a part of the worldwide reservoirs.

The most important conclusion is that sedimentation issues are currently only dealt with if the reservoir function is already affected or is threatened in the near future. The matter has to be urgent enough that owners are willing to spend funds on mitigating sedimentation issues. Owners are willing to invest in dredging of the reservoir if a business case can be made. Added value can be gained using the sediment removed from the reservoir. Through the survey it is shown that people are willing to invest in the dredging of reservoirs if this benefits the dam owner.

## 7.3. Classification of reservoirs

The different reservoir functions are important because they help determine the feasibility of dredging. The reservoir function indicates the importance of a reservoir. Over 70% of all reservoirs has a storage function like irrigation, water supply or flood control. Part of the hydro power reservoirs have a storage function and part operate run-of-river. The storage function is specifically endangered by sedimentation in the active part of the reservoir.

If 'black holes' which are large enough to capture both water and sediment without negative consequences, are excluded, still over 55,000 dams and reservoirs remain.

Furthermore it is found by modelling that different types of reservoirs as found by Borland & Miller indeed lead to different sedimentation patterns in the reservoir. It can however be concluded that not only the M-value and thus reservoir type is important for determining this deposition pattern, but other parameters like sediment concentration and sediment type are important as well. The maximum reservoir depth can be linked to the dam height by the formula: $d_{max} = 0.87 * d_{dam}$

## 7.4. Dredging reservoirs

Dredging is presented as a serious option for mitigating the sedimentation issues of reservoirs. Numerous dredging methods are available that can be used for the dredging of reservoirs. Potential gains of dredging are:the precise removal of sediment; the possible restoration of the river downstream of the dam and the prevention of big sediment laden flood waves entering the downstream river compared to flushing. The possible obstacles that have to be overcome are the perception of dredging as expensive and finding a proper location for dredged sediment that can not be used for river restoration.

For the restoration of the river downstream it is shown that further research is needed into the allocation of the sediment. Using the 1-dimensional Sobek model it became clear that for the test case only part of the yearly sediment load could be transferred into the downstream river.

Using a two- or three-dimensional model it would be possible to investigate for instance the deposit of sediment on the side of the river, making transport possible during high flow conditions. In this way, the low discharges are not dominant anymore.

## 7.5. Cost of dredging

If all of the above is taken into account, it can be concluded that the necessity of dredging has to be shown to the owners of a certain reservoirs. For this matter the decision model in figure 6.2 can be used. It has to be clear that the reservoir function or intake is threatened to be affected by sediment.

Based on the function of the reservoir a business case can be made. On the benefit side the benefits of extra reservoir volume have to be estimated. Added values such as: the possible sale of dredged material or possible downstream river restoration has to be taken into account.

Using a dredging model the costs of the dredging of a reservoir are estimated. This is done for different sediment compositions, different dam heights, different reservoir types and different distances that the dredged material has to be transported.

Based on different scenarios it is shown that dredging prices start as low as €1.01 per $m^3$ under favourble conditions and not taking into account additional costs. If the sediment is made up of soft and loose material this reduces the price of dredging. Furthermore the transport distance of the dredged material to shore has a large influence on the dredging costs. Thus the labour must not be to expensive, the transport distance for the dredged material must be kept small and under 6 $km$. The volume of material to be dredged must be over 25,000 $m^3$ to find a stable price.

## 7.6. Feasibility of dredging reservoirs

The main question when the dredging of reservoirs is feasible can now be answered. It has been shown using the dredging model that prices of dredging can start as low as €1.01 per $m^3$ under favourable conditions. Dredging would be financially feasible if the costs of dredging the reservoir are exceeded by the benefits for the dam & reservoir. Furthermore dredging is feasible if the costs of dredging are the lowest compared to other sediment management measures when sediment has to be removed at all costs.

Added benefits of dredging are:

- Precise removal of sediment
- Small volumes of water lost

On a larger scale, applying an economic approach dredging feasibility increases if extra benefits are generated:

- Downstream river restoration using the dredged material
- Market value or re-use of dredged sediment
- Revitalizing arid land using fertile sediment

These added values are hard to express directly in a monetary value.

In short, dredging of reservoirs is feasible, possibly at a lower price than other mitigation methods. In practice this has to be shown as well, proving that dredging is not necessarily expensive. The dredging has added benefits: downstream river restoration, possible sale of dredged sediment and increasing downstream soil fertility. Dredging of reservoirs is most likely beneficial for mitigating reservoir sedimentation and should therefore be considered for each individual reservoir sediment management project. Furthermore, reference projects have to be implemented to validate that this is indeed the case.

# 8 Recommendations

During the research different insights were gained, which can possibly be used current and future design of reservoirs.

## 8.1. Existing reservoirs

The current filling of the reservoirs with sediment is related to the fact that most reservoirs are designed with a design life approach. This approach means that the reservoirs are build to last a certain period of time, for instance 50 to 100 years. The period thereafter is often not considered. For a lot of reservoirs build in the last century this period is full filled, the reservoir function is however still required. Especially if climate change is taken into account, reservoirs importance increases for distribution of heavier rainfall over the year. Storage capacity is therefore still needed.

The reservoir function is thus required now and in the future. Therefore it is better to change the reservoir design-life to a life-cycle approach. The sediment balance has to be taken into account and therefore permanent solutions to sedimentation in the reservoir have to be investigated to make sure that the function of the reservoir is preserved. Dredging is one of possible solutions, but as shown in Chapter 7 it could also be the financially attractive one.

The best approach for a sustainable solution would be a dredging solution in combination with catchment management. The amount of sediment flowing into the reservoir can be reduced by planting vegetation in the catchment area of the reservoir. The remaining sediment flowing in the reservoir can than be removed using dredging.

Where possible sediment should be returned to the downstream river. The amount of sediment that has to be stored in a depot after dredging is reduced. This reduces the costs of dredging while downstream erosion is mitigated. In order to make these measures successful cooperation with local governments is most likely required. The rules for allowed sediment concentrations in the river downstream of a dam should be reviewed in light of this solution.

For the dredging of reservoirs goes the same as for a lot of other challenges: prevention is better than curing. Therefore it is important that reservoir owners are made aware of possible consequences of reservoir sedimentation. If reservoir owners awareness of the consequences of reservoir sedimentation is raised, it becomes easier to deal with the challenge of reservoir sedimentation. Raising awareness to the possible impact of reservoir sedimentation could be an important role of engineers around the globe.

Dredging could is a valuable tool in extending the life of reservoirs, this has to be realized by the owners and authorities responsible for the management of reservoirs as well. During discussions it became clear that there is a knowledge gap between the reservoir authorities and the dredging industry. It is therefore recommended to show dredging possibilities and to ensure that results of successful dredging projects are shared with reservoir owners.

Furthermore it is recommended to determine the optimal reservoir volume balance. Thus to determine the current water balance and take into account current and future demand for energy, irrigation, drinking water and flood control. By applying this approach an optimum reservoir volume can be found. If this optimum is higher than the current reservoir volume, it is clear by what volume the active reservoir has to be enlarged.

This is important, as during the course of this research it was found that in some dredging volumes are specified purely based on the original sedimentation rate prognosis. It is important to update these prognoses with respect to climate change and the local demand.

## 8.2. Design changes for new reservoir

In the design of new reservoirs the incoming sediment should be included in the design at an early stage. By modelling the sediment deposition patterns it is possible to act pro-active. Reducing sediment inflow in the reservoir is recommended if possible. If that it is not possible construction of check dams is a good possibility. Check dams retain sediment at the beginning of the reservoir, where the sediment can be easier accessed for removal. In this way the sediment does not spread out over the entire reservoir and a dredging operation can be focused in one location.

If building check dams is not possible, another possibility is installing a permanent piece of dredging equipment. Sediment from the reservoir can be removed at the same rate as that it flows in.

For new reservoirs it is also recommended to clear the full area of the reservoir of scrubs and trees before the first filling of the reservoir. If dredging is required in a later stage the debris in the reservoir is decreased as a result. During the operation of the reservoir the reservoir should be kept free of garbage. Garbage can also result in possible hindrance during a dredging operation.

## 8.3. Recommendations for future research

First of all for further research it is recommended to further investigate the deposition of sediment in the downstream river. It was found that only part of the incoming sediment can be transported downstream of the dam if all the delivered sediment has to be transported by the river directly. It should therefore be investigated what possibilities are for deposition of sediment at the side of the river downstream. Applying that method it becomes possible to wait for a moment of higher discharge through the dam to carry the deposited sediment further downstream. Furthermore the effects of depositing muddy type sediment should be included in future research.

Second of all scientific verification of the costs of dredging in reservoirs should be obtained. There are example projects where reservoirs are being dredged, but the associated costs can not be verified or are not shared. In order to show the feasibility of dredging it is important to show that low costs per $m^3$ of dredged material can be obtained. Part of this research could be verification of the described dredging model case studies.

The third subject that could be further investigated is the ideal volume of a reservoir. The factors influencing this ideal volume of a reservoir should be determined. The optimal balance between the costs of maintaining the reservoir volume and the decrease of water availability can be investigated as well.

The fourth and final subject that could be further investigated is the influence of sediment concentration and composition on the deposit of sediment in the reservoir. If this is further investigated, it could be more accurately predicted what type of sediment is located at which location. Especially if reservoir type can be coupled to this. If the location of each sediment fraction is known this could be used for dredging specific locations. Besides it would become possible to determine where sediment fractions suitable for retail can be found.

# Epilogue

During the course of my thesis it became clear that the dredging of reservoirs is gaining more and more attention worldwide. Especially with relation to climate change the importance of being able to store water is becoming vitally important. During my thesis I have participated with Witteveen+Bos in a group of dutch companies looking for different ways to promote dredging as a way to make reservoirs sustainable and future proof. It is my hope that my research can be part in showing that dredging of reservoir is not only a possible financial attractive solution, but that it comes other benefits which can be benefical not only to the reservoir itself, but also to the surrounding areas. Meanwhile Witteveen+Bos has started a collaboration with Imotec to investigate the possibilities of an autonomous dredging robot, which can be used to continuously dredge a reservoir and complete the sediment cycle by returning dredged sediment to the river downstream of the dam. This could prove to be a sustainable solution. It was encouraging to see that the subject of reservoir sedimentation is gaining more attention and that possible dredging solution are being promoted. I hope that my thesis is part of a movement toward sustainable development of dams and reservoirs worldwide.

*L. Elzinga*
*Delft, November 2017*

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# A

# Survey for reservoir authorities

The survey that is conducted is presented below. The survey could be filled in using an online Google form, automatically switching to the appropriate question, based on response or by filling in the PDF version and returning it by email. A full printed version of the survey is presented below.

# Survey Reservoir Sedimentation

This survey is about sedimentation in reservoirs, with reservoir defined as: "a place where water is stored for future use". The results of this survey will be used for my MSc thesis at the Delft University of Technology, in cooperation with the Dutch engineering and consultancy firm Witteveen+Bos. All responses will be anonymized, before using them in my thesis. I would be more then happy to share the results of this survey with the respondents.

Louwrens Elzinga
louwrens.elzinga@witteveenbos.com

*Required

1. **Email address** *

## Basic respondent information

2. **What is your name?** *

3. **What is your function for the concerning reservoir?** *
   *Mark only one oval.*
   - Owner
   - Operator
   - Researcher
   - Manager
   - Other: ______

## General Questions on the Reservoir

4. **What is the name of the reservoir?** *

5. **In what year was the construction of the reservoir finished?** *

6. **What is the function of the reservoir?** *
   *Tick all fucntions that apply.*
   - [ ] Hydro Power
   - [ ] Irrigation
   - [ ] Flood control
   - [ ] Recreation
   - [ ] Other: ____________________

7. **How much water flows into the reservoir (in 10^6 m^3/year)?** *
   Please keep in mind that the requested unit for the inflow of water here is m^3/year. If you have a different unit,you're kindly requested to convert the number to 10^6 m^3/year, using for instance this link: [https://goo.gl/z9DrbQ](https://goo.gl/z9DrbQ).

   ____________________

8. **How much sediment flows into the reservoir (in 10^6 ton/year)?** *
   Please keep in mind that the requested unit for the inflow of sediment here is 10^6 ton/year. If you have a different unit, you're kindly requested to convert that number to 10^6 ton/year.

   ____________________

9. **What was the initial reservoir capacity (in 10^6 m^3)?** *
   Please keep in mind that the requested unit for the volume is 10^6 m^3. If you have a different unit, you're kindly requested to convert the number to 10^6 m^3, keeping in mind that for instance 10^6 m^3 = 810.7 acre-foot.

   ____________________

10. **In what year was the last bathymetric survey of the reservoir carried out?** *

    *Mark only one oval.*

    ( ) No survey has been performed since the building of the reservoir. *Go to question 14*

    ( ) I don't know. *Go to question 14.*

    ( ) The last survey was performed in: ____________________

## Bathymetric survey

11. **Is the reservoir being surveyed at a regular interval? If so, please mention the interval**

    ____________________

12. **How many surveys have been performed since filling of the reservoir?**

13. **What is the current capacity of the reservoir (in 10^6 m^3)?**
Please keep in mind that the requested unit for the volume is 10^6 m^3. Please enter the volume corresponding to the last bathymetric survey test here.

## Trapment Efficiency

14. **Do you know what the trapment efficiency of the reservoir is?** *
The Trapment Efficiency (TE) of a reservoir is defined as the percentage of sediment that is flowing out of the reservoir. The TE is defined as a percentage and can be calculated using the following formula: TE = Sediment flowing out of reservoir / Sediment flowing into reservoir * 100%
*Mark only one oval.*

- Yes
- No *Go to question 17.*

## Trapment Efficiency

15. **Has the trapment efficiency of the reservoir changed over time?**
*Mark only one oval.*

- Yes, the TE is increased.
- Yes, the TE is decreased.
- No, the TE has not changed over time.

16. **What is the current trapment efficiency of the reservoir (in %)?**

## Sedimentation

17. **Has sedimentation in the reservoir caused problems?**
Examples of problems are: less power production for hydro power reservoirs, blockage of spillways, volume loss.
*Mark only one oval.*

- Yes
- No *Go to question 19.*

## Sedimentation

18. **Can you please describe some of these problems?**

*Go to question 20.*

## Sedimentation

19. **Please elaborate why sedimentation does not cause problems in your reservoir**

## Downstream effects

20. **Are you aware of downstream effects related to the reservoir?**
*Mark only one oval.*

- Yes
- No *Go to question 24.*

21. **Can you elaborate on those effects?**

22. **Are you willing to mitigate those effects if possible?**
*Mark only one oval.*

- Yes
- No *Go to question 24.*

23. **How much are you willing to spend on mitigating these effects?**
Please elaborate what would be your consideration; would you be open to a cost-benefit analysis, are there sustainable management goals that can be achieved?

## Removal of reservoir sediment

24. **Are you mitigating reservoir volume loss, due to sedimentation?** *
*Mark only one oval.*

- Yes
- No *Go to question 26.*

## Removal of reservoir sediment

25. **Can you elaborate on how you are mitigating sedimentation in your reservoir?**

## Dredging of reservoir sediment

26. **Are you willing to invest in the dredging of sediment from the reservoir?** *
*Mark only one oval.*

- Yes *Go to question 28.*
- Yes, only if the gain exceeds the costs *Go to question 28.*
- Yes, if it leads to a sustainable solution for my reservoir. *Go to question 28.*
- No

## Dredging of reservoir sediment

27. **Please explain why sediment removal is not considered.**

## Dredging of reservoir sediment

28. **How much are you willing to spend on the dredging of sediment (in $/m^3)?**

    Please give an order of magnitude estimation, if you prefer a fixed amount, this is also a viable answer.

29. **What would be points of added value if implemented in a dredging plan?**

    Please explain here what could really motivate you to invest in sediment removal from the reservoir. A few examples are: restoration of the river downstream, extra volume in the reservoir available, continued operation of the reservoir, etc.

## Environment

30. **Is your reservoir required to produce environmental flows?**

    Environmental flows are certain amounts of water that have to be flushed through the dam, out of the reservoir, for environmental purposes.
    *Mark only one oval.*

    - Yes
    - No
    - I don't know
    - Other:

## Final questions

31. **Are you interested in the results of this survey or the final thesis?** *
    *Mark only one oval.*

    - Yes, please inform me with the results of this survey.
    - Yes, please let me know when your thesis is complete.
    - No, thank you.

32. **Do you have any final comments or remarks on the subject of reservoir sedimentation?**

# B
# Survey results

In order to determine what the response rate says over the response of the total population, the relevance of the survey results has to be determined. This is done using statistical analysis.

## B.1. Sample size

The sample size needs to be determined and the non response bias has to be considered as well. The relevance of the survey can be given using a few different parameters. By using these parameters the confidence interval for survey results can be determined and also the influence of the sample size on the results can be explained. The method followed comes from the book 'A Modern Introduction to Probability and Statistics' (Meester et al., 2005). To determine the sample size, the following formula is given:

$$Sample \quad Size = \frac{(Z - score)^2 * P * (1 - P)}{(margin \quad of \quad error)^2} \tag{B.1}$$

The first parameter is the Z-score. The Z-score is determined using the confidence level. The confidence level is a measure for the certainty of the fact that a given response will be between the given limits. The usual confidence interval used in scientific research is 95%. This means that there would be a 5% chance that the given level of confidence is wrong, so that the given value will not be in the given confidence range. For a confidence level of 95% the value for $\alpha = 5\% = 0.05$. Now the Z-value can be determined: $Z_{\frac{\alpha}{2}} = Z_{0.025} = 1.960$, this is a standard value.

The second parameter used is chance ($P$) that a certain answer will be given in the survey. For determining the confidence interval, for a specific question the received response can be used as an estimator. If for example 5 out of 9 responses are that sedimentation is an issue in the reservoir, this results in: $P_{sample} = \frac{5}{9} = 0.556$. However, for determining the initial relevance the value for $P$ is chosen in such a way that it leads to the biggest uncertainty. This results in an initial value $P = 0.5$. If during the survey a lot of the same answers are given, this leads to a smaller confidence interval, thus to a bigger certainty that the given answers are a correct representation of the entire population of dams and reservoirs.

The next parameter is the population that is used. This is the overall population. In the case of this survey, the population would be all people that could fill in the survey, or all dams and reservoir owners that are represented by the survey. A choice has to be made here. On the one hand there are all the dams and reservoirs registered in the ICOLD World register of dams database (*WRD*), which are in total more than 58,000 dams. The other option for the population is the 6,862 dams and reservoirs represented in the GRanD database. The last option would be only the owners of reservoirs, so each owner individually. The last option makes it very hard to determine the population size, since an accurate overview of the owners of all dams is not centrally maintained, the WRD database contains at least 10,716 different owners, but does not have an owner registered for 28566 dams. Since the GRanD database is used primarily to select the reservoirs and the WRD database contains all dams and reservoirs registered in the world, for now the WRD database is taken as the population size.

If a response of more than 5% is reached or if the margin of error is selected to be very small, the sampling size has to be corrected, since there is a finite population in both cases. However, it is unlikely that more than 2900 surveys will be completed (5% of a population of 58000). The population size does not matter in this case, both populations would be big enough, since the correction factor would only have a large influence if the population or the margin of error becomes very small. However for completeness the correction factor for a small finite population is given:

$$Corrected \quad sample \quad size = \frac{Sample \quad size}{1 + \left(\frac{Sample \quad size - 1}{Population}\right)} \tag{B.2}$$

The final parameter is the margin of error. The margin of error can be used to determine the bandwidth around the chance of a certain response. The upper and lower bound of the chance for this response can be determined and this gives the confidence interval. The uncertainty is given as a percentage (3% uncertainty = 0.03). The sample size can now be determined for different values of the uncertainty. An example is given for an uncertainty of 5%. Filling in Equation B.1 results in:

$$Sample \quad Size = \frac{Z_{0.025} * 0.5 * (1 - 0.5)}{0.05^2} = 384.16$$

So the Sample Size has to be 385. However, if the sample size is corrected for a population of 58,000 dams, filling in Equation B.2 results in:

$$Corrected \quad sample \quad size = \frac{384.16}{1 + \left(\frac{384.16 - 1}{6{,}862}\right)} = 363.84$$

The corrected sample size is thus 364 samples. Those are needed to obtain a confidence interval with margins of 5% at each side and a certainty of 95% that a random sample taken from the population will be in the given interval. In Table B.1 a few scenario's are given for different margins of errors and both population sizes. Table B.1 shows that for a large margin of error (up to 10 %), the population size has barely any influence on the sample size.

Depending on the results of the survey the confidence interval of these results can thus be given. Ideally there would be 25 responses, that would lead to a 20% confidence on each side.

## B.2. Relevance of the survey

Following Table B.1 a margin of error is obtained for 14 responses that is just below 25% in both directions for the different answers.

The exact margin can be determined for each question, using Equation B.3/ As an example this is done for the question 'Has sedimentation in the reservoir caused problems?' The band width of

| Margin of Error (%) | Sample size using GRanD database | Sample size using ICOLD database |
|---|---|---|
| 50 | 4 | 4 |
| 40 | 6 | 7 |
| 30 | 11 | 11 |
| 25 | 16 | 16 |
| 20 | 24 | 25 |
| 15 | 43 | 43 |
| 10 | 95 | 96 |
| 8 | 147 | 150 |
| 5 | 364 | 382 |
| 4 | 553 | 595 |
| 2 | 1,779 | 2,306 |
| 1 | 4,003 | 8,240 |

Table B.1: Sample sizes required for different margins of error and different databases.

the error, that gives a 95% certainty that the error is within this bandwidth, for a positive answer to this question, can be calculated:

$$Margin \quad of \quad error = \sqrt{\frac{Z-score^2 * P * (1-P)}{Sample \quad Size}} \tag{B.3}$$

The chance $p$ for a positive answer is $\frac{7}{18} = 0.389$. The $Z-score = 1.960$ and the $SampleSize = 18$. This results in a margin of error of: 23%. So with a 95% certainty it can be said that a positive answer to the question if sedimentation has caused problems for the total population will be between 16% & 61%. This gives a band width which is indeed large. However, if the total amount of reservoirs that indeed suffers problems associated with reservoir sedimentation is only 16%, that would still be (16% of $58,000 =$) $9,280$ reservoirs with problems, which is more than enough reservoir with possible sedimentation problems to further investigate dredging as a possible solution to these problems.

# C

# Depth of reservoirs

For reservoir dredging it is important to know at which depth there has to be dredged. In order to investigate what the dredging potential for reservoirs is, an indication for the reservoir depth is the dam height. This is recorded in the ICOLD database (ICOLD (International Commission on Large Dams), 1998) for most dams. The dam height is more than the original reservoir depth. The dams have a crest which is higher than the maximum water level, since there usually is an overflow located below the crest. Also the foundation level is assumed to be below the reservoir bottom level. The original level is important here, since that would be the maximum level that has to be dredged, assuming that the reservoir is restored to initial volume. Taking all reported dam heights of the database (58060) into account, a histogram can be plotted. The dam heights are divided into bins, for each bin the number of dams having a height that falls in a bin is plotted. This is can be seen in figure C.1.

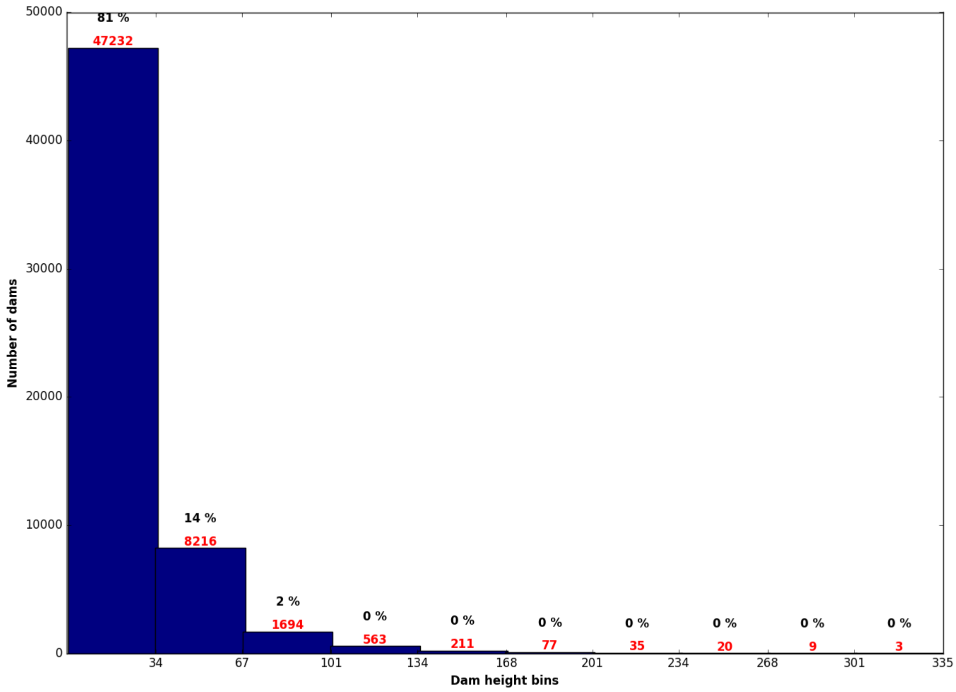


Figure C.1: Dams sorted by height

From figure C.1 it follows that 95% of all dams for which the height is reported, are 67 $m$ or lower. It is clear that the largest percentage (81%) is 34 $m$ or lower. The 95% can be plot in a histogram again, this results in figure C.2.

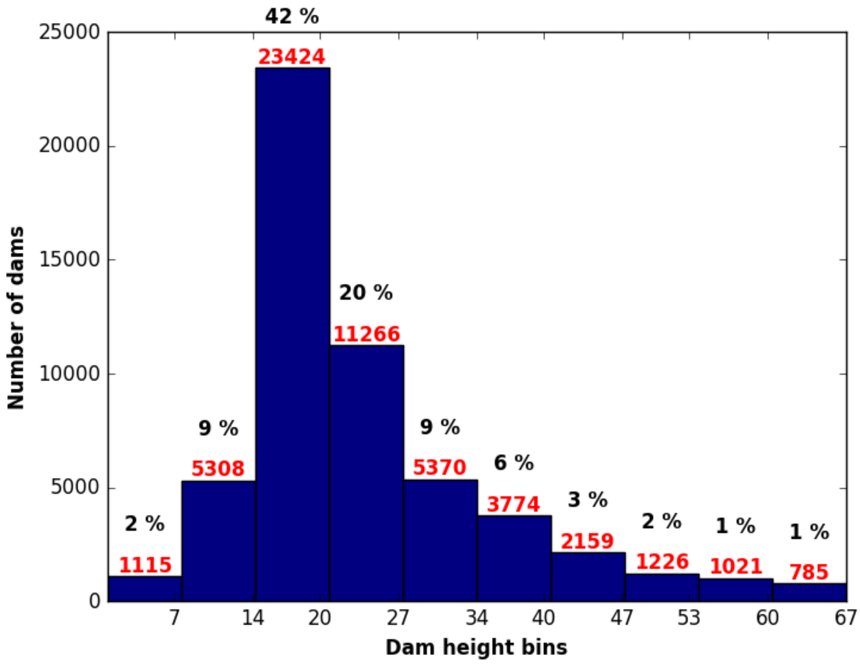


Figure C.2: Dams registered in the WRD, up to and including 67 m, sorted by height

Almost three quarters of all dams (73%) are below 27 $m$ and half (53%) is below 20 $m$. It is important to keep in mind that these are still dam heights, not the original depths of reservoirs. To verify if the assumption is correct that the reservoir depths are indeed smaller than the dam heights, a samples from the database are checked using other data.

## C.1. Verification of reservoir depth

### John Redmond reservoir

According to both the GRanD database and the ICOLD database the height of the John Redmond dam is 27 $m$. This matches the data given by the United States Army Corps of Engineers, Tulsa district. The height of the dam is 1081.5 $ft$ and the elevation of the original bed level is 995 $ft$, this results in a dam height of 86.5 $ft$, which is equal to 26.4 $m$ (USACE Tulsa district, 2017). If this is compared to a 2014 survey of the John Redmond reservoir, the maximum depth based on a pool elevation of 1038.4 $ft$, is 10 $ft$ (Kansas Biological Survey, 2014). Taking this depth of 10 $ft$, adding the difference with the 2007 survey of 5.5 $ft$ and adding the difference of the 2007 survey with the original depth of the basin, excluding the original river bed of 12 $ft$ (Kansas Biological Survey, 2010), the total depth becomes 27.5 $ft$ which is equal to 8.4 $m$. This is the maximum dredging depth when restoring the pool to the original bed level at a normal reservoir water level. It is indeed much less than the given height of 26 $m$ for the dam. If the full supply level is taken into account, another 1068 $ft$ − 1038.4 $ft$ = 29.6 $ft$ has to be added, resulting in a total height of 17.4 $m$.

### Luzzone reservoir

According to both the GRanD database and the ICOLD database the Luzzone dam in Switzerland is 225 $m$ high. This matches the data of the Swiss Committee on Dams (Andrea Baumer (Ofima SA), 2017). However in figure C.3 schematic of the Luzzone dam is given. From the schematic it is clear that the dam height is indeed 225 $m$ from the top till the foundation. However with a free board at 1606 $m$ and the original bottom of the reservoir is estimated at 1410 $m$, the total depth of the reservoir, when the reservoir is full would be $1606 - 1410 = 196$ $m$. This is indeed much smaller than the reported dam height. It also matches with the maximum reported dredging depth of 200 $m$ (Liebherr, 2016)

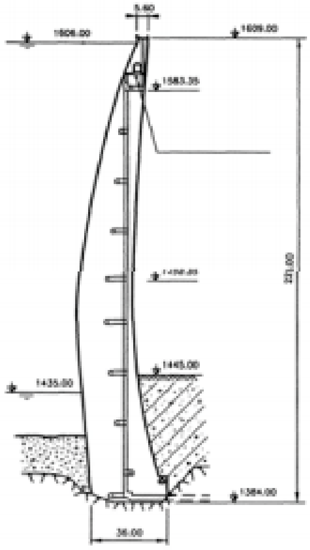


Figure C.3: Height of Luzzone dam and adjacent bed levels (Andrea Baumer (Ofima SA), 2017).

### Welbedacht Dam reservoir

The reported height in the GRanD and ICOLD databases is 32 $m$. Using a recent survey of the Welbedacht Dam reservoir (Jacobs, 2017) the original depth can be determined. Full supply level is given to be at 1402.9 $m$. The original bed has a height of 1380 $m$ and the height of the bed in 2017 is roughly equal to 1398 $m$. The original reservoir depth is thus $1402.9 - 1380 = 22.9$ $m$. The maximum depth for 2017 is only $1402.9 - 1398 = 4.9$ $m$. It is very clear that a large part of the storage of the Welbedacht Dam reservoir has been lost.

### Vindsachtske lake

The Vindsachtske lake dam, in Slovenia is 17 $m$ high according to the ICOLD database. In a survey comparing the recent bathymetry to a bathymetry of 1887, the original depth of the reservoir is found to be 14.1 $m$, compared to a depth of 12.7 $m$ in 2014 (Fuska et al., 2015). Again the dam height is higher than the maximum depth to be dredged.

## C.1.1. Dredging depth related to dam height

The height of the dam is not necessarily the height that has to be dredged in case of reservoir volume restoration, or for dredging the bottom outlets. This maximum depth to be dredged will always be less than the dam height, considering that the dam has a partial foundation that will be in the original bottom. To determine what the relation is between the dam height and the difference between maximum water level behind the dam and the original reservoir bottom level, a few dams of the ICOLD database are compared with bathymetric surveys found in different sources. Using Microsoft Excel the dam height is plotted against the maximum depth that has to be reached to restore the dam to original volume. This results in the maximum depth that dredging equipment has to overcome when dredging to the original reservoir bottom, when the water level is maximum. The values for eight different dams can be found in table C.1.

Plotting the heights of table C.1, results in figure C.4. It follows from this figure that the relation is most likely linear. Using Microsoft Excel a linear trend line is added. This trend line has the equation $d_{max} = 0.87 * h_{dam} - 4$. The estimation is quite rough, only eight different dams are taken into account, since bathymetric data is hard to find for each dam. The mean root squared error of the trend line with respect to the results is 0.99, meaning that the outliers are explained quite well

Table C.1: Dam heights and the maximum depths to be dredged across the globe.

| Reservoir name | Height of dam (m) | Max dredging depth (m) | Source |
|---|---|---|---|
| John Redmond | 27 | 17.4 | (Kansas Biological Survey, 2014, 2010) |
| Luzzone | 225 | 196 | (Andrea Baumer (Ofima SA), 2017) |
| Welbedacht | 32 | 22.9 | (Jacobs, 2017) |
| Vindsachta Lake | 17 | 14.1 | (Fuska et al., 2015) |
| McKay Dam | 50 | 48 | (US Bureau of Reclamation, 2017) |
| John Compton | 40 | 28.5 | (DB Sediments, 2013b,a) |
| Englebright Lake | 85 | 70.6 | (Childs et al., 2003) |
| Dokan Reservoir | 116 | 85 | (Hassan et al., 2017) |

by the estimation.

In order not to under estimate the maximum reservoir depth for small dams, the slope only is used, the formula thus becomes:

$$d_{max} = 0.87 * h_{dam} \tag{C.1}$$

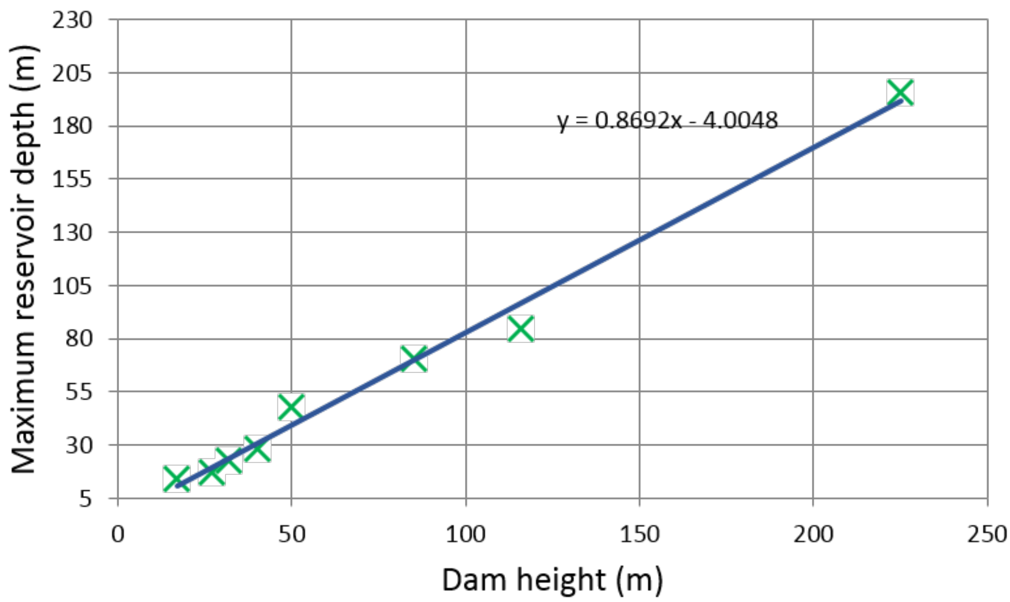


Figure C.4: Dam height plotted against the maximum depth to be dredged, including a trend-line.

## C.2. Conclusion

From the above examples and resulting equation it can be concluded that the dam height by itself leads to an over-estimate of the maximum reservoir depth. This result is to be expected since the foundation of the dam is taken into account in the dam height, however the dam foundation is usually located below the level of the reservoir bottom. The obtained formula gives an indicator for the maximum depth based on the height of the dam. Taking into account that it can also be avoided to dredge the reservoir during full supply levels and the fact that dredging the dead storage does not lead to gain, the dredging depth could be further reduced. This means that the dredging depth will be well below the value of maximum reservoir depth, making the estimate valid.

# D

# Sobek model

To determine the feasibility of a dredging method with continuous deposition dredged sediment in the river downstream of a dam, a case study is performed for the Neosho river. This river is located downstream of the John Redmond Dam. The modelling is done using Sobek (*version 3.4.1*). This appendix contains:

- Data collection
- Model set-up
- Calibration and validation
- Model results

## D.1. Data collection

In order to create a model representing the river Neosho river, first data has to be collected. The data that has to be obtained is:

- Bathymetry
- Discharges
- Water levels
- Sediment characteristics

Here it is described where the different data-sets are obtained.

### Bathymetry

The bathymetry of the river defines the flow of the water through the river. In a 1-dimensional Sobek model the cross section of the modelled river has to specified at different locations.

The cross section of the river is not constant along the river, but for simplicity and due to scarcity of available data, one cross section is assumed to be representative for the entire river model. In order for the morphological module in Sobek to work, the cross section has to be symmetrical. Thus a depth-width profile is specified.

Data on the cross section is obtained from the USGS (United States Geological Survey) (*personal communication, 11-8-2017*). The width of the river is specified at different depths. Using the measured depths along the river at different distances from the bank at different discharges, a shape of the river cross-sectional profile can be created. This shape is shown in Figure D.1. The measured profile is transformed to a width-depth profile, shown in Figure D.2.

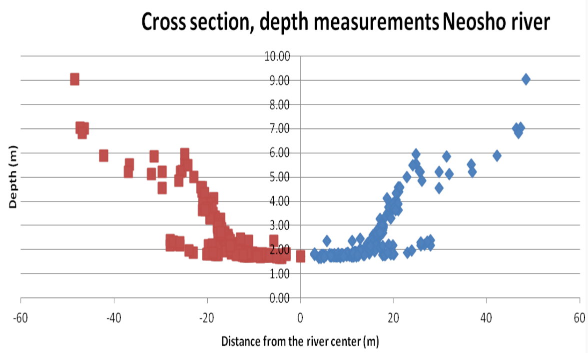


Figure D.1: Depth measurements at different days, in the Neosho river (*source: USGS*).

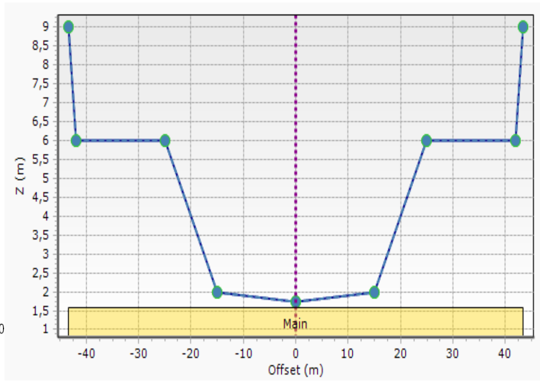


Figure D.2: Schematized cross section of the Neosho river.

The data points used to create the schematized cross section of the Neosho river in the model are given in Table D.1.

| Depth (m) | Width (m) |
|---|---|
| 9 | 87 |
| 6 | 84 |
| 6 | 50 |
| 2 | 30 |
| 1.73 | 0 |

Table D.1: Depth-width values of the schematized cross section.

Using Google Earth the vertical elevation difference of the Neosho river between the river just downstream of the John Redmond dam and the river near Iola is measured to be 21 $m$. The distance between these points was also measured using Google Earth to be 108 $km$. The resulting slope of the Neosho river is consequently $1.9 * 10^{-4}$.

### Discharges

In order to model the river, the discharge through the river at a given time is required. This discharge is given by the release of the John Redmond dam. Daily average release data for the John Redmond dam is collected from the website of the US army corps of engineers (*http://www.swt-wc.usace.army.mil/JOHNcharts.html*). This website contains links to the data for each month since November 1994. The average daily release data is downloaded for the year 2016. The average flow given in *CFS* (Cubic Feet per Second) is converted to $\frac{m^3}{s}$ by multiplying by a factor 0.028317. The data for the year 2016 is used because this is the most recent complete year. The obtained daily averaged discharges are shown in Figure D.3.

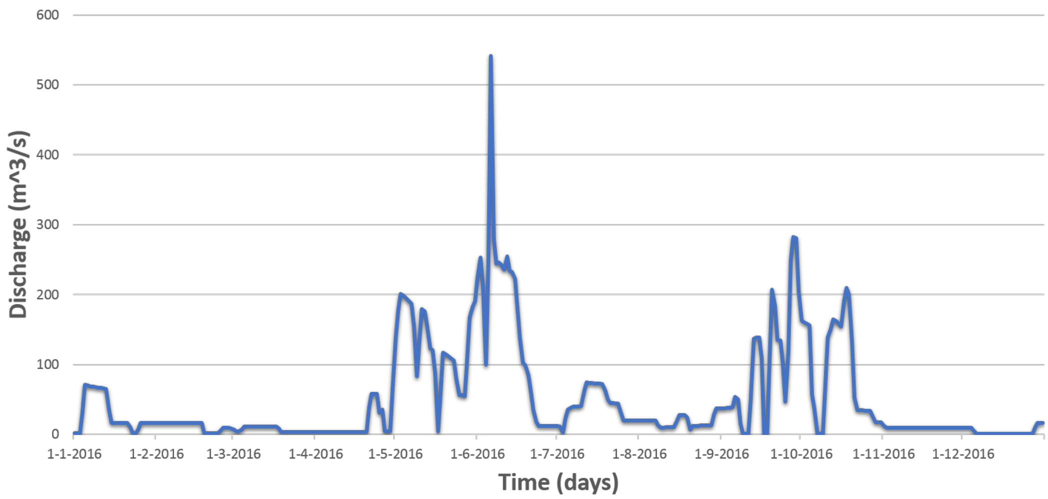


Figure D.3: The daily averaged discharge through the John Redmond dam in the year 2016.

### Water levels

The downstream boundary of the model is represented by a water level. Measuring stations are operated along the Neosho River by the USGS. The water level is recorded near Burlington and Iola (shown in Figure D.5). The water level data is downloaded from the website of the USGS. For calibration of the hydraulic model measured water levels are needed between the dam and Iola. This information can be obtained from the Burlington measuring station.

Both for Iola (station number 07183000) and for Burlington (station number 07182510) the data is downloaded for the year 2016. The water level data is available on a daily basis. For the year 2016 no data gaps are present. The water level given in feet ($ft$) is converted into meters ($m$) by multiplying by a factor 0.3048. The obtained daily water levels for the year 2016 near Iola are presented in Figure D.4.

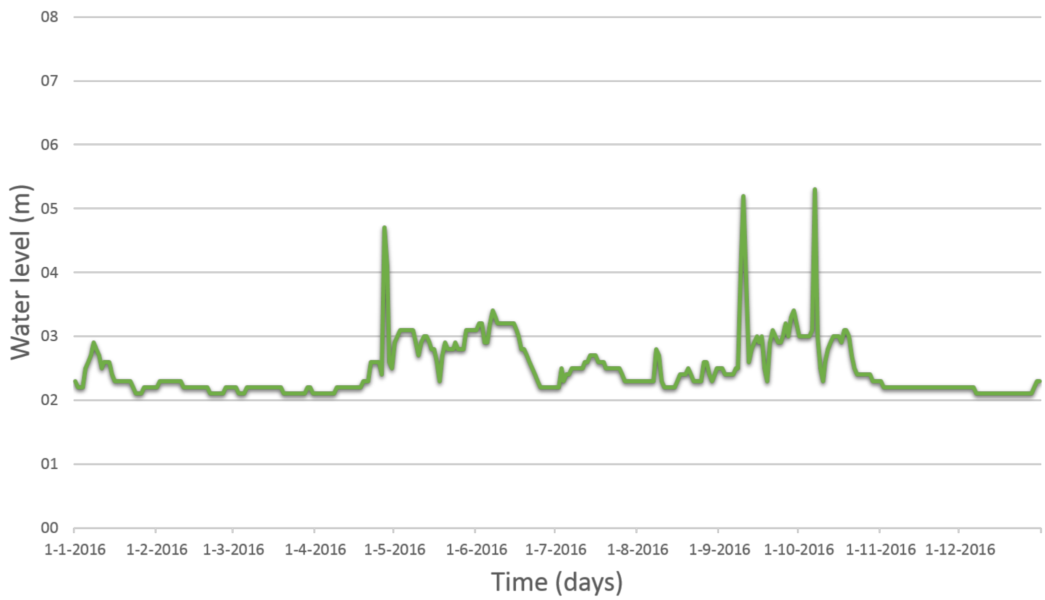


Figure D.4: The average daily water level near Iola in the year 2016.

### Sediment characteristics

Information on the sediment characteristics of the Neosho river are unavailable. The used version of Sobek can only be used to model the transport of sand. Therefore in this case study the sediment in the river will be assumed to be sand. The median diameter of the sediment is set to 200 $\mu m$.

## D.2. Model setup

In order to set up the model of the Neosho river, the following components of the model have to be specified:

- Grid
- Bathymetry
- Boundary conditions
- Model settings

### Grid

The course of the Neosho river is manually entered by adding geometric points on top of the river on the map in the graphical user interface of Sobek 3. After the location of the river is indicated, a computational grid is generated by Sobek. The computational grid points is distanced roughly 1 $km$. The total length of the Neosho river in the model is 108 $km$. An overview of the computational grid, on top of a map of the area is presented in Figure D.5.

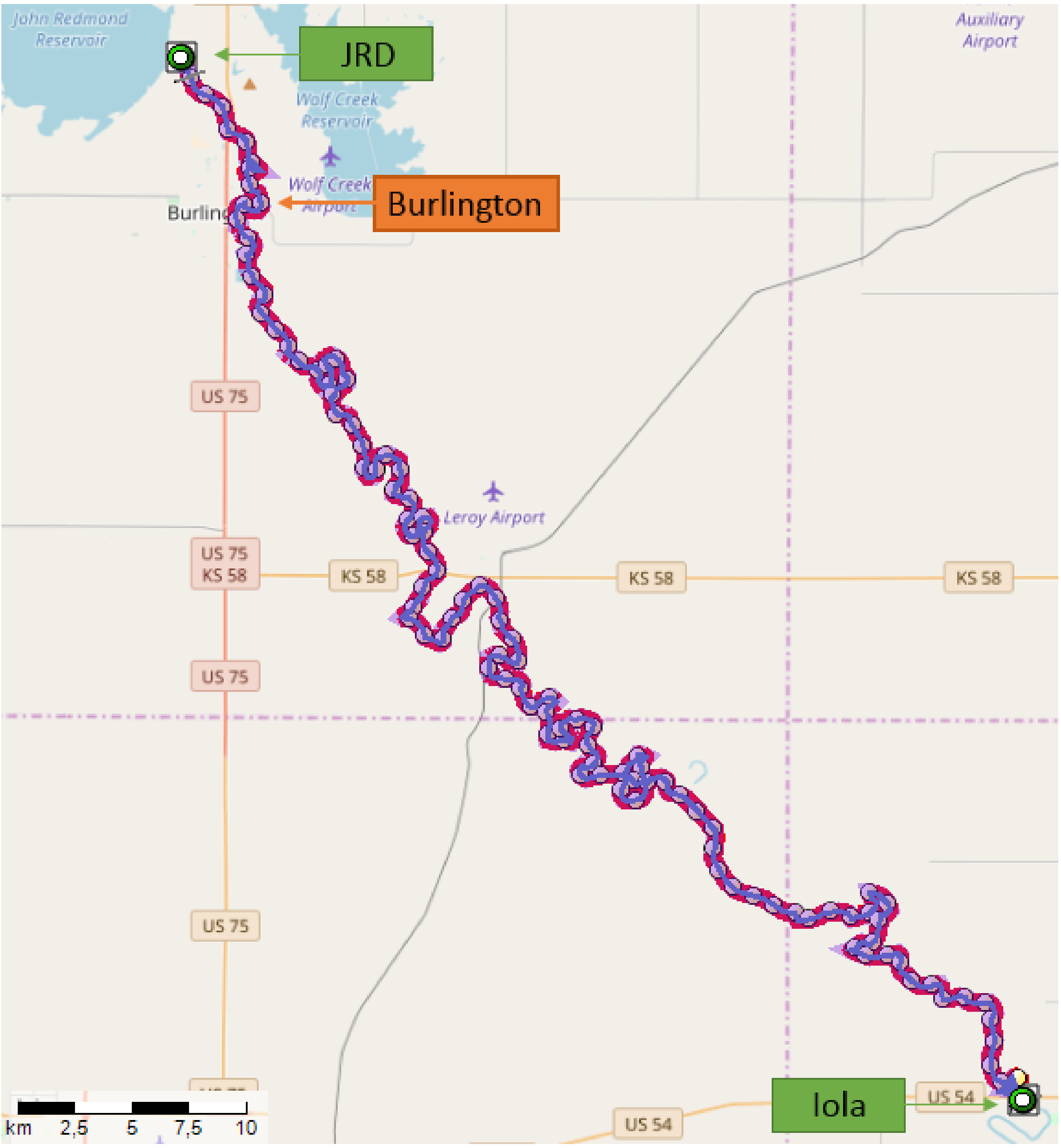


Figure D.5: Computational grid of the Neosho river, used in the Sobek model.

```
[SedimentFileInformation]
FileCreatedBy = Delft3D-FLOW-GUI
FileCreationDate = Thu Jul 13 2017, 15:42:30
FileVersion = 02.00

[SedimentOverall]
IopSus = 0 Suspended sediment size is Y/N calculated dependent on d50
Cref = 1.60e+03 [kg/m3] CSoil Reference density for hindered settling

[Sediment]
  Name            = #Sediment_sand#               Name of sediment fraction
  SedTyp          = sand                          Must be "sand", "mud" or "bedload"
  RhoSol          =  2.6500000e+003     [kg/m3]   Specific density
  SedDia          =  2.0000000e-004     [m]       Median sediment diameter (D50)
  CDryB           =  1.6000000e+003     [kg/m3]   Dry bed density
  IniSedThick     =  0.0000000e+000     [m]       Initial sediment layer thickness at bed
  FacDSS          =  1.0000000e+000     [-]       FacDss * Se
  TraFrm = #Engelund_Hansen.tra#
```

Listing D.1: Sediment file used for the Sobek simulation near the John Redmond Dam.

## Bathymetry

The cross section shown in Figure D.2 is set as a Shared Cross Section in Sobek. This cross section is specified near the beginning of the river (*JRD*) and near the end (*Iola*). The river slope is taken into account by introducing a level shift for the cross section. Near the dam this level shift is set to 21 $m$ to recreate the measured height difference of the Neosho river in the model.

## Boundary conditions

In order to enable modelling the boundary conditions at the start and end of the modelled river have to be specified. In Figure D.5 the boundaries are indicated as JRD (John Redmond Dam) and Iola.

At the JRD boundary the daily averaged discharge is set as a Flow Time Series boundary. The opposite boundary is set at Iola. Here the water level data is used as a Water Level Time Series boundary.

## Model settings

The Sobek model is used to simulate one year between 1-1-2016 and 1-1-2017, using a simulation time step of 1 minute.

Sediment entering the reservoir is specified in a .sed file and presented in Listing D.1). No initial sediment layer is assumed and the $D_{50} = 200\mu m$.

The Engelund-Hansen total load transport formula (Engelund-Hansen (1963), as cited in (Deltares, 2017)) is used (*TraFrm*).

The transport ($S$) can be calculated as follows:

$$S = \frac{0.05 * \alpha * q^5}{\sqrt{g} * C^3 * \Delta^2 * D_{50}} \tag{D.1}$$

The factor $\alpha$ is assumed to be 1, the $q$ is the magnitude of the flow velocity, $g$ is the gravitational

```
[MorphologyFileInformation]
FileCreatedBy = Delft3D-FLOW-GUI
FileCreationDate = Thu Jul 13 2017, 14:47:50
FileVersion = 02.00

[Morphology]
MorFac = 1.00000000e+000 [-] Morphological scale factor
MorStt = 720.000e+00 [min] Spin-up interval from TStart till start of morph changes
MorUpd = true Update bathymetry during flow run
BcFil = #boundary_JRD_dredging.bcm# Name of morphological boundary condition file

[Boundary]
Name = #JRD# Boundary node ID
IBedCond = 5  0: free none - -
    1: fixed none - -
    2: time series depth m
    3: depth change prescribed depth change m/s
    4: transport incl pores prescribed transport incl pores m3/s
    5: transport excl pores prescribed transport excl pores m3/s

[Boundary]
Name = #Iola# Boundary node ID
IBedCond = 0
```

Listing D.2: Morphologic file used for the Sobek simulation near the John Redmond dam.

acceleration of 9.81 $\frac{m}{s^2}$, $C$ is the Chézy value, which follows from the model (unit: $\frac{\sqrt{m}}{s}$), $\Delta$ is the value $\frac{\rho_{soil}-\rho_{water}}{\rho_{water}} = \frac{2{,}650-1{,}000}{1{,}000} = 1.65$ and the $D_50$ is equal to 0.0002 $m$.

The total transport capacity is related to the variation in flow velocity to the power 5. This means that during high flows there will be high sediment transport rates and during low discharges of the John Redmond Dam, sediment transport will be low. The important variable for sediment transport in the model is thus the flow velocity.

The morphology is specified in a .mor file, of which an example is presented in Listing D.2. The spin-up time of the hydraulic model is less than 720 minutes. To prevent hydraulic spin-up from negatively influencing the morphological results, the morphological changes are delayed by 720 minutes.

The boundary type at the dam is given by varying time series of transport excluding pores ('5'), while the morphological boundary near Iola is taken to be free ('0'). The different assumed transport values near the JRD are specified in a .bcm files.

## D.3. Calibration and validation

Before the model is used with the morphological module turned on, validation and calibration is needed. The hydrodynamic model is validated using the obtained data near Burlington (see Figure D.5). The calibration is performed by varying the Chézy friction coefficient. The values used range between 35 and 60 $\frac{\sqrt{m}}{/}s$. The measured and modelled water levels are shown in figure D.6.

From the data in Figure D.6 it is apparent that there is a good match in form between the modelled water level data for different Chézy values and the measured water level values near Burlington. However, there is a difference of about 1 $m$ when the measured depth is below 2 $m$. This is most likely the result of assuming a simplified form for the cross section adapted for the entire system.

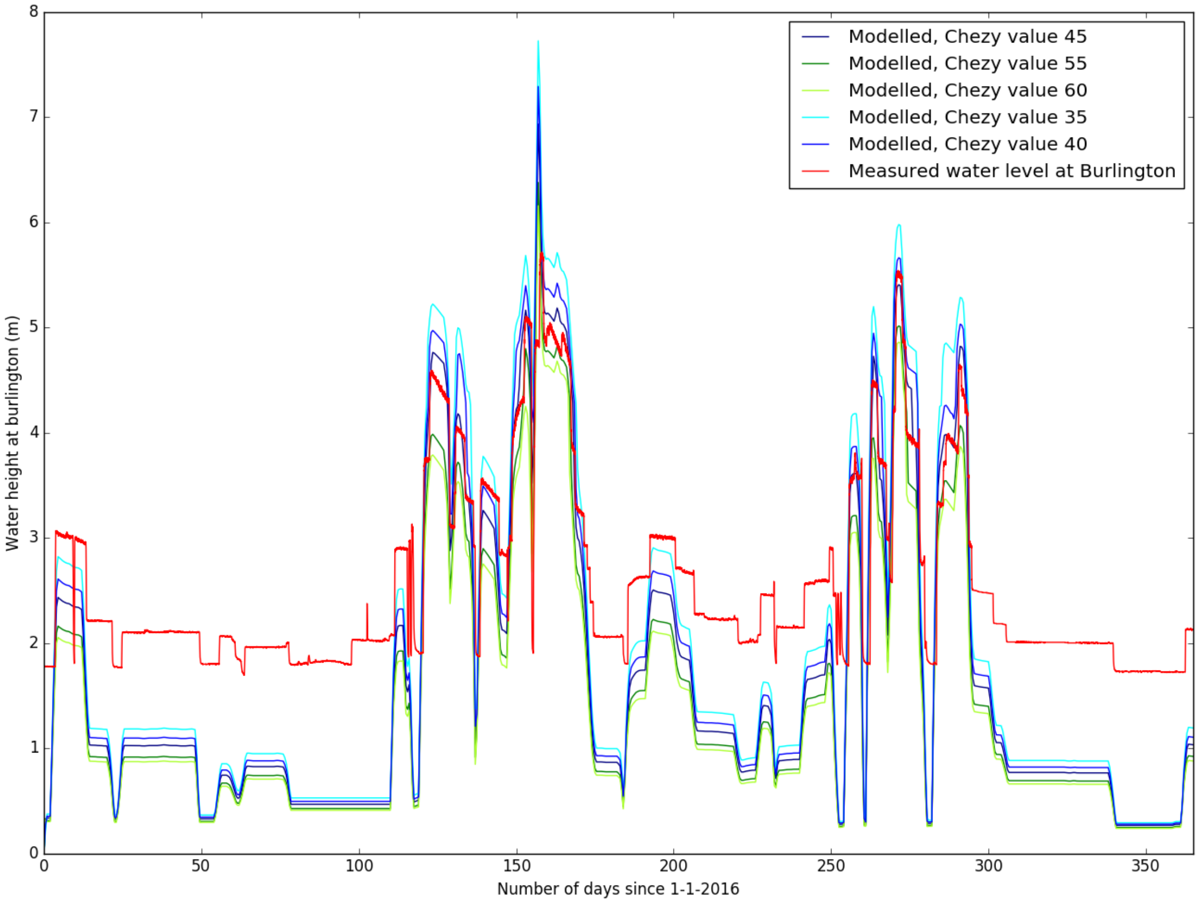


Figure D.6: The measured and calculated water levels near Burlington for the year 2016.

The underestimation of the low water levels leads to an overestimation of the transport capacity, since the calculated velocity will be higher than the actual velocity of the river. Vice versa an overestimation of the water level will lead to an underestimate of the sediment transport capacity. Most sediment will be transported in periods of high discharge in the river (leading to high values of $q$ in Equation D.1). The Chézy value chosen is therefore the one representing the peak water heights best. As Figure D.6 shows, the line associated with a Chézy value of 45 $\frac{\sqrt{m}}{/}s$ is the best fit. This value is therefore assumed to be representative for the entire system.

# E

# Modelling of sediment deposition

In this chapter the approach to modelling of sediment inflow and sediment deposition in different reservoir types is explained.

## E.1. Model setup

The modelling approach chosen for modelling different types of reservoirs is described in this appendix. For each reservoir of a different type, runs were performed using Delft3D. The model set-up is done using the Delft3D GUI (Graphical User Interface). Delft3D is a model that solves the shallow water equations or Saint-Vernant equations in a 2DH way. By solving these equations the flow of water can be calculated. Using this flow of water the transport abilities can be determined, thus the morphologic development of the modelled section of water can be predicted. The following items are discussed in the model setup:

- Assumptions
- Boundary conditions
- Reservoir shapes

### Assumptions

In the modelling approach it is assumed that each reservoir type is based on the starting river. The slope of the original river ($10^{-4}$) is assumed constant in each reservoir. The cross sectional shape of the reservoir is changed in order to model different types of reservoirs. The reservoir type is hereby assumed to be dependant on the M-value of the reservoir, which can be calculated according to Equation 4.2. The is assumed that only the reservoir shape is changed in order to model the different types of reservoirs. The other parameters are kept constant.

### Boundary conditions

In order to solve the shallow water equations, the boundary conditions have to be specified by the user. For each different reservoir type, the starting point is a constant inflow of water at 1,000 $\frac{m^3}{s}$ at the upstream side of the reservoir. The upstream hydrodynamic boundary is a total discharge boundary, in this case not changing over time. It is therefore entered as a time series where the start and end time for the simulation are set to be the given discharge.

The downstream hydrodynamic boundary is chosen to be a water level specified for the simulation time. The water level is defined constant in such a way that at the virtual 'dam' creates a reservoir where the maximum depth is 7.5 $m$. The dam is thus simulated by a constant water level.

In order to do add the morphology to the simulation as well, a transport formula has to be specified. The used formula for sediment in the total transport formula of Meyer-Peter-Muller (as cited in (Deltares, 2014)). This formula is given in equation E.1.

$$S = 8 * \alpha * D_{50} * \sqrt{\Delta * g * D_{50}} * (\mu\theta - \xi\theta_{cr})^{\frac{3}{2}} \tag{E.1}$$

In formula E.1 the value of alpha is set to 1. The $\Delta$ is the relative density of a grain compared to the water. The acceleration of gravity is represented by $g$ and the critical mobility parameter is $\theta_{cr}$ (=0.047). The factor $\theta$ represents the Shields mobility parameter. Based on the flow of water, the Chézy value, the $\Delta$ and the $D_{50}$. If the shields parameter becomes large enough, the sediment grains at the bottom will start to move, if however the Shields mobility parameter is smaller than the critical mobility parameter, the already suspended grains will settle.

For the morphologic simulation boundary conditions have to be specified as well. In this case the sediment concentration is specified. At the upstream boundary, representing the river flowing into the reservoir a sediment concentration of 0.01 $\frac{kg}{m^3}$ sand and 0.01 $\frac{kg}{m^3}$ clay is assumed.

At the downstream boundary, so at the virtual dam, it is assumed that no sediment can leave the reservoir. This is represented by implementing a boundary condition where the concentration of both sand and clay is set to 0 $\frac{kg}{m^3}$.

Since morphologic developments take a very long time in practice and the time available for modelling is limited, the morphologic factor is used. The morphologic factor is a multiplier for the sediment flux. The multiplied sediment flux creates the effect of a longer simulation period. The morphological factor used in all simulations is 100.

The simulated period is 1 month, the month of January, this results in a simulation of 31 days. The time step used is 0.1 minute. This small time step resulted a more stable bottom profile, due to smaller numerical errors, than for a larger time step.

The morphological process are added once the hydrodynamic spin-up effects have faded. The delay of implementing the morphology is therefore set to 12 hours.

The used sand and clay are given as input in the Delft3D in a .sed file. The used clay and sand are the same in each simulation and an example of a .sed file containing the properties of the used sand and clay is given in listing E.1.

## E.2. Reservoir shapes

The modelling is performed for different reservoir types. These reservoirs are based on the M-value (as defined in Equation 4.2 and Equation E.2). The reservoirs are classified according to the system by Borland & Miller as described in Section 2.2. The different shapes for the reservoirs are described below.

```
[SedimentFileInformation]
FileCreatedBy = Flow GUI
FileCreationDate = Fri 8 september 2017, 14:47:46
FileVersion = 02.00

[SedimentOverall]
IopSus = 0 Suspended sediment size is Y/N calculated dependent on d50
Cref = 1.60e+03 [kg/m3] CSoil Reference density for hindered settling

[Sediment]
   Name              = #Sediment_clay#                  Name of sediment fraction
   SedTyp            = mud                              Must be "sand", "mud" or "bedload"
   RhoSol            =  2.6500000e+003      [kg/m3]   Specific density
   SalMax            =  0.0000000e+000      [ppt]     Salinity for saline settling velocity
   WS0               =  2.5000000e-004      [m/s]     Settling velocity fresh water
   WSM               =  2.5000000e-004      [m/s]     Settling velocity saline water
   TcrSed            =  1.0000000e+003      [N/m2]    Critical bed shear stress for sedimentation
   TcrEro            =  5.0000000e-001      [N/m2]    Critical bed shear stress for erosion
   EroPar            =  1.0000000e-004      [kg/m2/s] Erosion parameter
   CDryB             =  5.0000000e+002      [kg/m3]   Dry bed density
   IniSedThick       =  0.0000000e+000      [m]       Initial sediment layer thickness at bed
   FacDSS            =  1.0000000e+000      [-]       FacDss * SedDia = Initial suspended sediment diameter.
[Sediment]
   Name              = #Sediment_sand#                  Name of sediment fraction
   SedTyp            = sand                             Must be "sand", "mud" or "bedload"
   RhoSol            =  2.6500000e+003      [kg/m3]   Specific density
   SedDia            =  2.0000000e-004      [m]       Median sediment diameter (D50)
   CDryB             =  1.6000000e+003      [kg/m3]   Dry bed density
   IniSedThick       =  0.0000000e+000      [m]       Initial sediment layer thickness at bed
   FacDSS            =  1.0000000e+000      [-]       FacDss * SedDia = Initial suspended sediment diameter.
   TraFrm = #Meyer-Peter-Muller.tra#
```

Listing E.1: Sediment file used for the simulation of different sediment inflows in different reservoirs.

### Reservoir with a M-value of 2

For the initial triangular reservoir the maximum depth of 7.5 $m$ at the dam has to be set. Since the maximum depth of the bathymetry is 10 m, the water level boundary is set to -2.5 $m$. This is shown in Figure E.1.

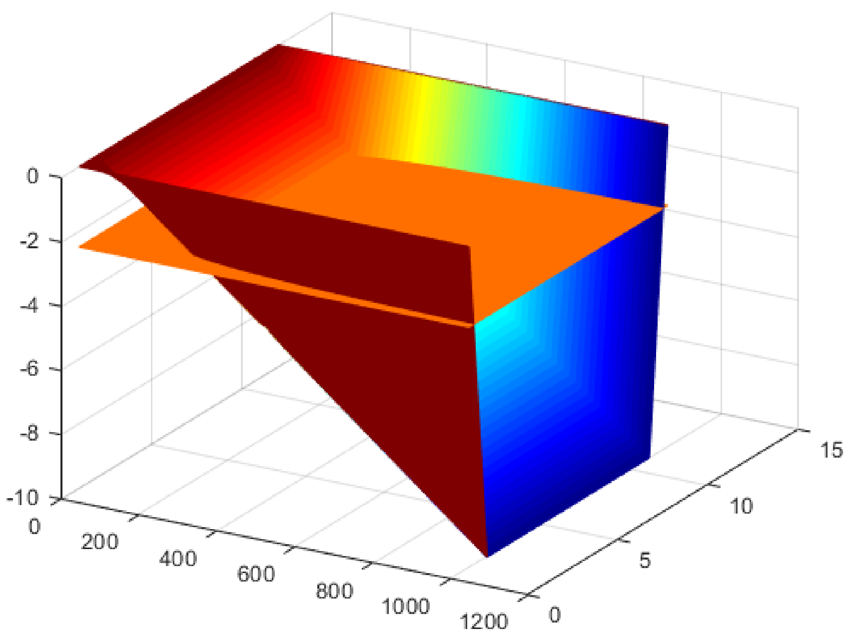


Figure E.1: Maximum water level indicated at -2.5 $m$ in a 3-dimensional reservoir.

The depth-volume plot for the reservoir on a log-log scale is shown in Figure E.2. By filling in Equation 4.2 with a $V_m$ of 375,000,000 $m^3$, $y_m$ of 7.5 $m$ and $A_m$ of $(100,000m * 1,000m =)\ 100,000,000m^2$ a M-value of 2 is found.

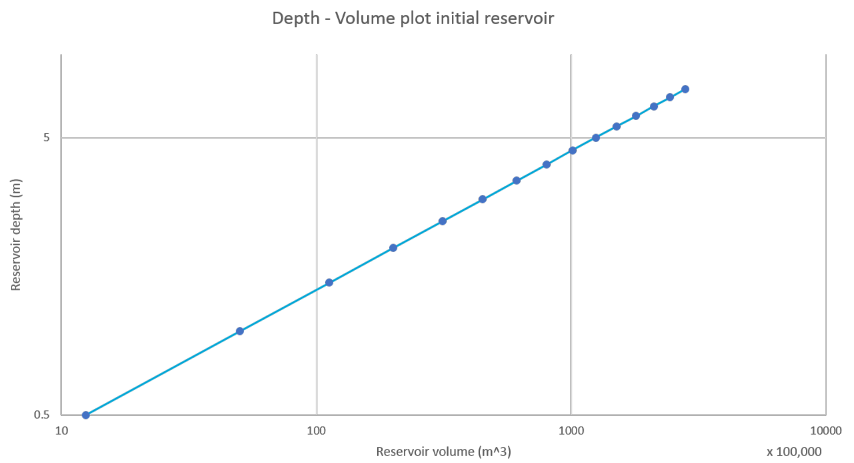


Figure E.2: Depth volume plot for the reservoir with a M-value of 2, plotted on a log-log scale.

The M-value according to Kaveh et al. (2013) is equal to 2. To show that this is correct the M-value is also calculated using the slope of the graph in Figure E.2. This can be done using the following formula:

$$M = \frac{log(\frac{V_{new}}{V_{old}})}{log(\frac{D_{new}}{D_{old}})} \tag{E.2}$$

Filling in equation E.2 for the maximum depth ($D_{new}$) of 7.5 $m$ and another depth ($D_{old}$) of 0.5 $m$ and the maximum volume ($V_{new}$) of 281,250,000 $m^3$ and another volume ($V_{old}$) of 1,250,000 $m^3$, results in a M-value of 2.

The M-value of the basin for a depth of 7.5 $m$ is evaluated numerically as well. The volume of the reservoir is found by multiplying each depth value below the maximum depth of 7.5 $m$ by the area of 1 grid cell (100 $m$ by 100 $m$), this is the area round one grid point. The surface area is found by counting the number of points in the reservoir which are below or equal to the maximum water level of -2.5 m. The number of grid points found is than multiplied by the area of one grid cell as well. Using this method a M-value of 1.997 is found. It can thus be said with confidence that the M-value of the reservoir is 2, thus that the reservoir is of the hill type.

### Reservoir with a M-value of 3

The initial reservoir has a M-value of 2. For the other reservoirs, a M-value has to be assumed, to create a reservoir that falls within the boundaries of the M-value for a certain type of reservoir. The approach chosen is to create reservoirs in the middle of each class. The reservoir of type III, is thus represented by a M-value of 2, for the reservoir of type II, a M-value of 3 is chosen.

The M-value is based on the rate that the reservoir volume increases with respect to the increase of water depth. The parameters are kept constant, only the cross section of the reservoir, parallel to the fictitious dam is changed. Therefore the same maximum dam height and maximum volume as for the initial reservoir with a M-value of 2 are assumed ($V_m = 281,250,000m^3$ and $y_m = 7.5m$).

$$V_y = V_m * \frac{y}{y_m}^{\frac{2}{N}} \tag{E.3}$$

Using Equation E.3 by (Kaveh et al., 2013), the volume ($V_y$) can be calculated for each depth ($y$). Using the maximum depth ($y_m$), the maximum volume ($V_m$) and the known value for N. Using the M-value of 3, $N = \frac{2}{3}$. The values for $V_y$ can now be computed and plotted on a log-log scale. This is shown in figure E.3.

The slope of Figure E.3 matches with the value found using Equation E.2. It is found that if the cross section, in the direction of the dam is taken to be an upside down triangle, of which the side slope is related to the depth of the reservoir, a triangular pyramid is created. For a triangular pyramid the M-value is equal to 3. The maximum cross section is found near the dam and has a height of 7.5 $m$, the begin triangle area of the reservoir has no influence on the M-value of the reservoir. For this case a triangle with a base width ($W_{base}$) of 1,500 $m$ and a height of 7.5 $m$ is chosen as the maximum cross section (Figure E.4).

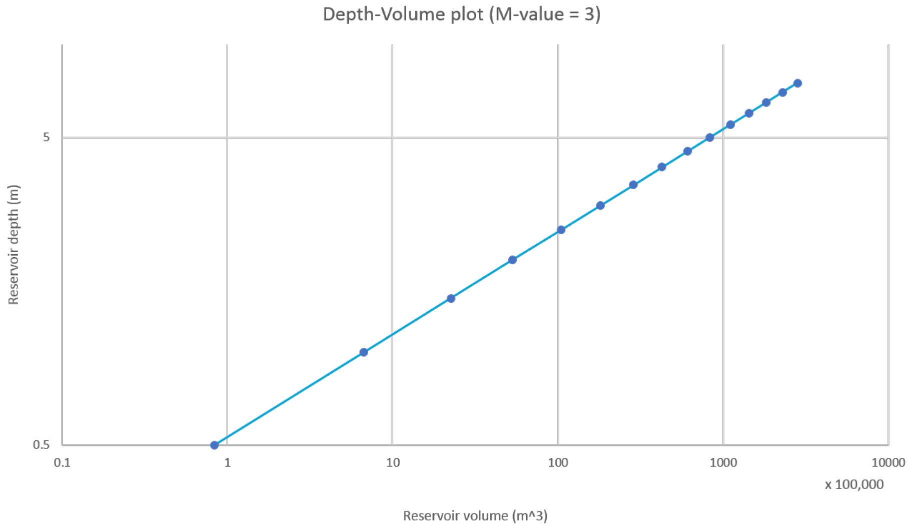


Figure E.3: Depth volume plot for the reservoir with a M-value of 3, both plotted on a log-scale.

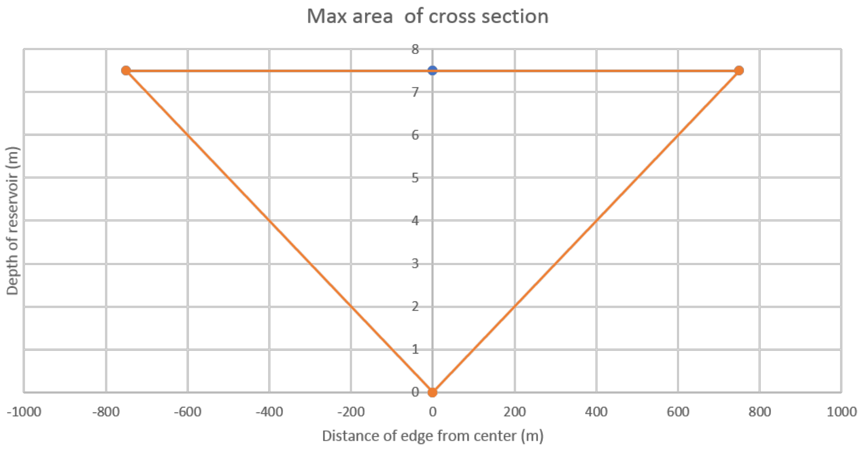


Figure E.4: Assumed maximum cross section of the reservoir with a M-value of 3.

The M-value for this reservoir can be calculated, using Equation 4.2. The maximum volume ($V_m$) is the volume of a triangular pyramid, which can be calculated using: $V = \frac{1}{3} * W_{base} * y_m = \frac{1}{3} * 1,500m * 7.5m$. The maximum area of the reservoir ($A_m$) can be calculated using the area of a triangle. Thus $A_m = \frac{1}{2} * W_{base} * l$. In this case $l$ is the length of the reservoir, which is equal to 75,000 $m$. Filling in these values in Equation 4.2 results in a M-value of 3.

The grid cell size is taken as 100 $m$ by 100 $m$, the grid itself is therefore 752 by 17 cells, including dummy cells. The triangular pyramid is specified for each corner of each cell using Excel and then pasted into a .dep file, which can be read by Delft3D. The depth at the bottom in the center is made 10 m. The 3 dimensional view of the reservoir with a M-value of 3 is given in Figure 4.11 in Section 4.5.

### Reservoir with a M-value of 4

For the reservoir with a M-value of 4, the capacity curve can be calculated in the same manner as before. The obtained curve is presented in Figure E.5.

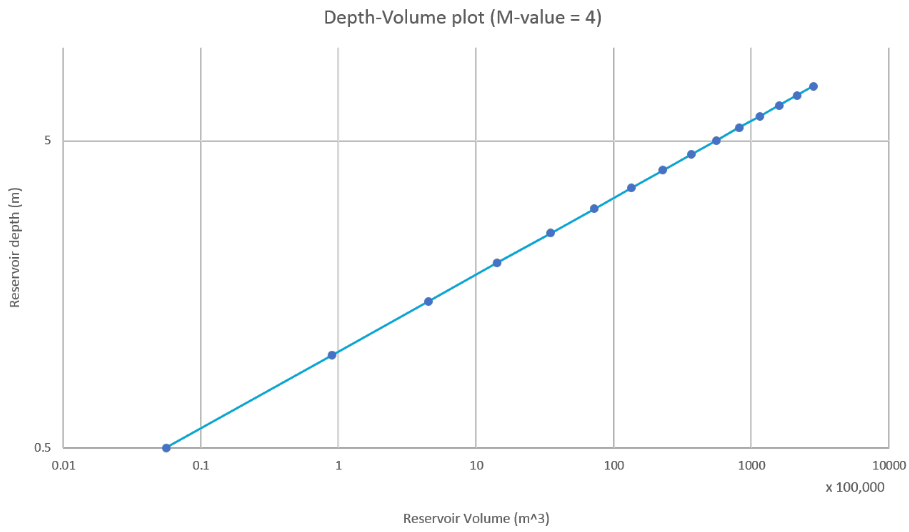


Figure E.5: The depth-volume plot for a reservoir with a M-value of 4.

The area can be calculated for each depth, according to Equation E.4 (Kaveh et al., 2013):

$$A_y = \frac{2 * V_m}{N * y} * (\frac{y}{y_m})^{\frac{2}{N}} \tag{E.4}$$

In formula E.4 the following values can be filled in: $V_m = 281,250,000 m^3$ , $N = \frac{2}{4} = 0.5$ en $y_m = 7.5m$. Using this formula the depth ($y$) can be related to the width of the reservoir ($w$, where width is defined as: $w = \frac{A_y}{L_{res}}$. The length of the reservoir ($L_{res}$) is a function of the depth: $L_{res} = \frac{y}{i}$). The formula for the width than becomes:

$$w = \frac{A_y * i}{y} \tag{E.5}$$

The maximum width can than be calculated combining Equation E.4 & E.5 at the maximum depth ($y_m$), slope ($i$) and a maximum area ($A_y$) of $150,000,000 m^2$ to be 2000 $m$. In order to create a bathymetric profile of this reservoir, the depth is related to the width, using this relation the depth in each grid cell corner can be calculated. The rewritten formula is given in equation E.6.

$$y = (\frac{N * width}{2 * i_{originalriver} * V_m * y_m^{\frac{-2}{N}}})^{\frac{1}{\frac{2}{N}-2}} \tag{E.6}$$

By entering the values the equation can be simplified to $y = 0.167705 * w^{0.5}$. The grid size is chosen smaller in the N-direction, since linear interpolation of the grid is used, for an exponential decrease in depth. An appropriate grid size is taken to be 1002 in the M direction and 42 in the N direction. The width needs to be a maximum of 2000 $m$, so the grid cells are made 100 $m$ by 50 $m$. The increase due to the original river slope is calculated by adding the value of the center line to the calculated depth values. The width is known in each grid cell point, thus the depth is calculated and used to create a .dep file, which is used in the Delft3D simulation. The created reservoir is given in Figure 4.12. The maximum depth of the reservoir is -7.5 $m$. To create a reservoir with a depth of 7.5 $m$, the water level boundary is set to 0 $m$ for this reservoir.

### Reservoir with a M-value 1.25

To create a reservoir with a M-value of 1.25 using the given conditions, a reservoir cross section becoming smaller to the top is needed, thus a triangular shape. This shape can not be applied using Delft3D, therefore the shape is not included here. The gorge-type reservoirs is however less important than the other reservoir types, due to the fact that most sediment will be deposited in the dead zone of the reservoir. The dead storage is not crucial to the reservoir function and therefore dredging the dead storage is an unlikely scenario.

## E.3. Results of the simulation

In each of the different reservoirs the sand and clay locations are compared after a run of 1 month using a morphological factor of 100. Following Figure E.6 and E.7 it is clear that the sand is only located near the top of the reservoir and hence the fraction of clay (red) is located at the bottom, near the virtual dam. However, in the blue part clay and sand are mixed.

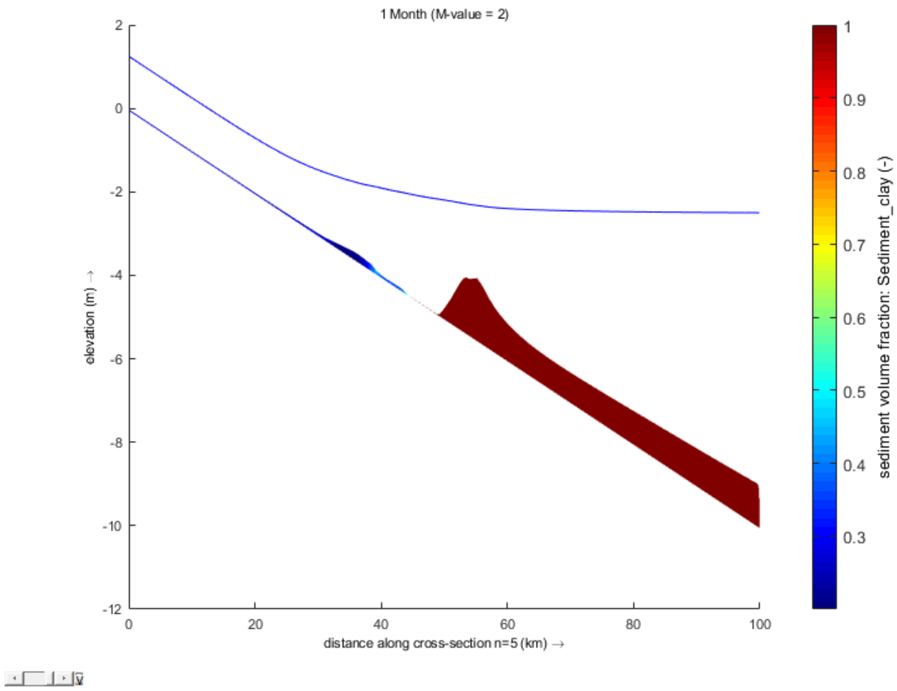


Figure E.6: Delft3D output for a longitudinal cross section of the volume fraction, indicating the fraction of clay for a reservoir with M=2.

The sand settles first, which is related to the heavier grains of the sand, compared to clay. This follows from the individual simulations of sand and clay for a reservoir of type III (M-value of 2) as well. The result of this Delft3D simulation are presented in Figure E.8. It is clear that Figure E.6 is the cumulative version of Figure E.8.

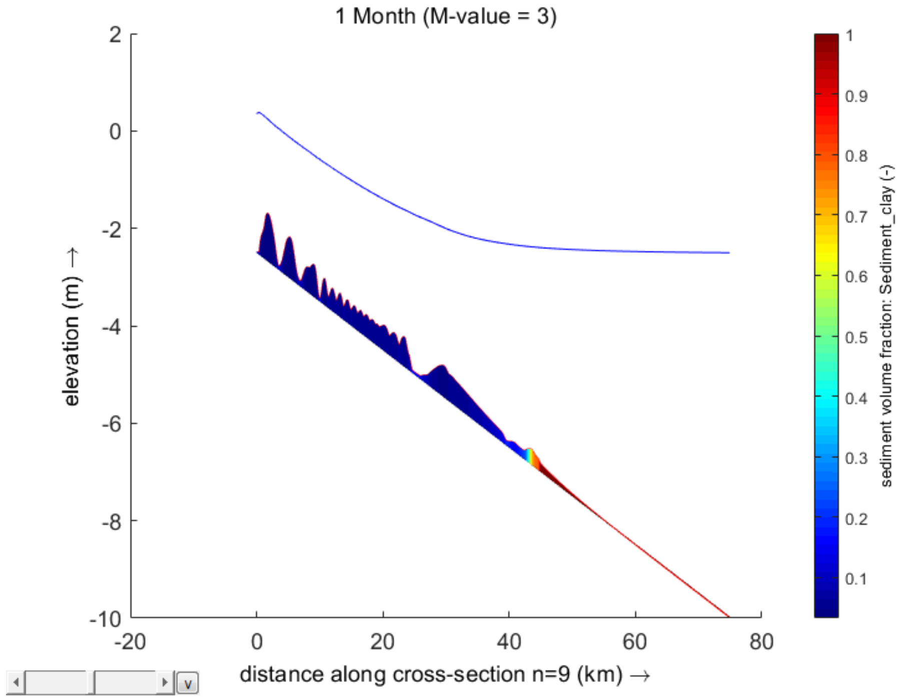


Figure E.7: Delft3d output for a longitudinal cross section of the volume fraction, indicating the fraction of clay for a reservoir with M=3.

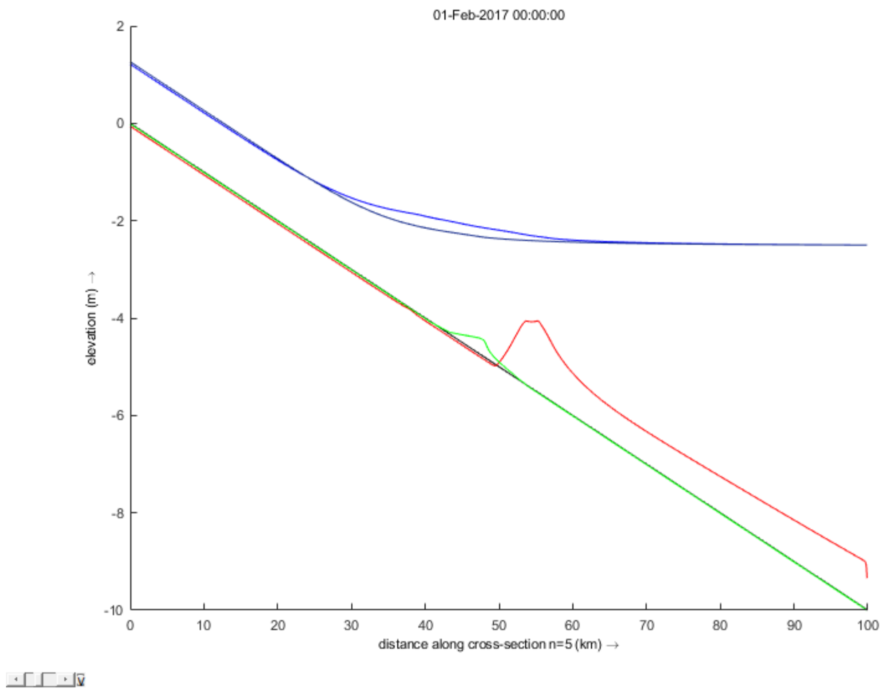


Figure E.8: Result of Delft3D simulation for only clay (red & blue) and only sand (green & navy), for a reservoir type with M=2.

In Figure E.9 some spin-up problems are shown, causing the green ripples.

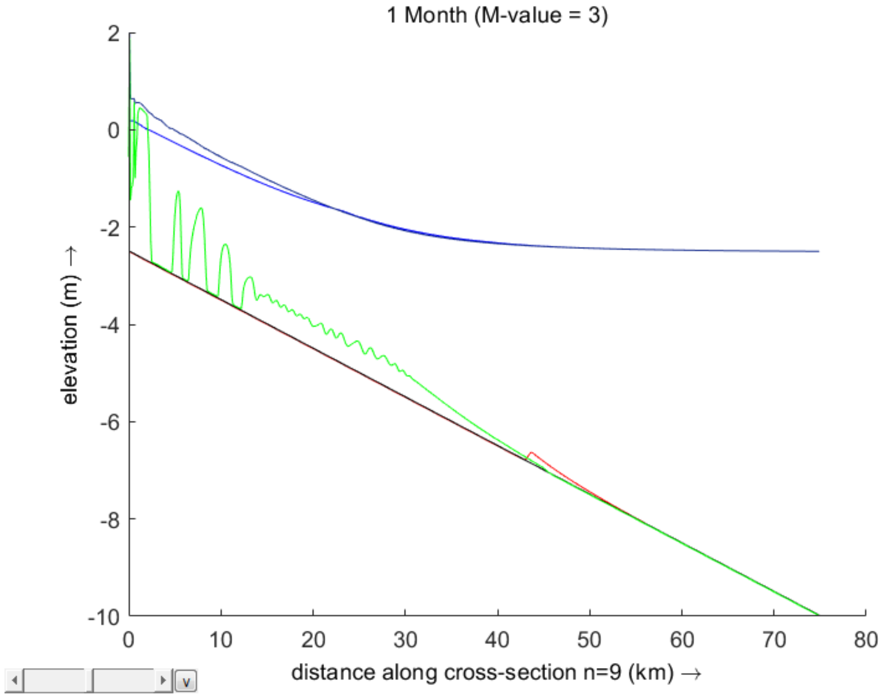


Figure E.9: Result of Delft3D simulation for only clay (red & blue) and only sand (green & navy), for a reservoir type with M=3.

## E.4. Scripts used

Using Quickplot the different fractions of sediment and their location in a cross-section are identified. The volume of sediment is calculated for each depth, including the original reservoir volume at each depth. Using these values a the sediment distribution over the reservoir depth is calculated. These values are indicated as a percentage of the total volume of the deposited sediment after one month.

The Matlab script used to perform these calculations is given in Listing E.2, for each run, the type of reservoir (*M2, M3 or M4*) has to be indicated, separate from the specified file, in order to smooth out differences in grid size, grid cell dimensions and the water level, water depth values.

```matlab
file_name = 'Specified location of the trim-file generated by Delft3D';

%The reservoir value of M has to be indicated to set parameters correct
reservoir_type = input('Please enter the type of reservoir (M2/M3/M4)', 's');
while reservoir_type ~= 'M2'|reservoir_type ~= 'M3'|reservoir_type ~= 'M4'
    reservoir_type = input('Please try again; enter the type of reservoir (M2/M3/M4)', 's');
end
%For each reservoir the neccessary parameters that change are given
if reservoir_type == 'M2'
    N_max = 12;
    M_max = 1002;
    N_width = 100;
    M_width = 100;
    max_depth = 7.5; %[m]
    bottom_level = 10;
end
if reservoir_type == 'M3'
    N_max = 17;
    M_max = 752;
    N_width = 100;
    M_width = 100;
    max_depth = 7.5; %[m]
    bottom_level = 10;
end
if reservoir_type == 'M4'
    N_max = 42;
    M_max = 1002;
    N_width = 50;
    M_width = 100;
    max_depth = 7.5; %[m]
    bottom_level = 7.5;
end

data_simulation = vs_use(file_name_6);
start_bottom = vs_get(data_simulation,'map-sed-series',{1},'DPS',{1:N_max 1:M_max});
end_bottom = vs_get(data_simulation,'map-sed-series',{373},'DPS',{1:N_max 1:M_max});
%373 default value for 1 full month of output every 120 minutes
[N, M] = size(start_bottom);
[X, Y] = meshgrid(1:1:M,1:1:N);

%Create series, where values can be stored
depths = linspace(bottom_level-max_depth,bottom_level,((bottom_level-(bottom_level-max_depth))/0.1)+1);
depth_plot = linspace(bottom_level-max_depth,bottom_level,((bottom_level-(bottom_level-max_depth))/0.1)+1);
%Reverse the values of the depth, so depth is specified from top down
for b = 1:length(depths)
    depth_plot(b) = bottom_level - depths(b);
end
%Create series, where values can be stored
volumes = linspace(bottom_level-max_depth,bottom_level,((bottom_level-(bottom_level-max_depth))/0.1)+1);
sediment_volumes = linspace(bottom_level-max_depth,bottom_level,((bottom_level-(bottom_level-max_depth))/0.1)+1);

%Here accretion or erosion is shown at different locations
difference = start_bottom - end_bottom;

%Plot figure of the initial reservoir
figure()
mesh(-start_bottom);
colormap('jet')
%Plot figure of the reservoir after sedimentation, at end of simulation
figure()
mesh(-end_bottom)
colormap('jet')
```

Listing E.2: Matlab script used for creating the depth-sediment percent curves.

```
%Plot only the accretion in the reservoir
figure()
mesh(difference)
xlabel('M')
ylabel('N')
zlabel('Deposited sediment (m)')
colormap('jet')

%Calculating for each grid cell the reservoir volume and sediment volume
for a = 1:length(depths)
    reservoir_volume = 0;
    sediment_volume = 0;
    Z = X.^0 * - depths(a);
    for q = 1:N
        for c = 1:M
            if -1*start_bottom(q,c) <= Z(q,c)
            reservoir_volume = reservoir_volume +  (start_bottom(q,c)+Z(q,c));
            sediment_volume = sediment_volume + start_bottom(q,c) - end_bottom(q,c);
            end
        end
    end
    %Multiplying the found height difference by area of grid cell
    Correct_for_gridcell = reservoir_volume*N_width*M_width;
    Correct_sed_for_grid = sediment_volume*N_width*M_width;
    volumes(a) = Correct_for_gridcell;
    sediment_volumes(a) = Correct_sed_for_grid;
end
%All sediment trapped found by integrating the difference curve
tot_sed_trap = -trapz(trapz(difference))*N_width*M_width;

%Create series, where values can be stored
percentage_depth = linspace(bottom_level-max_depth,bottom_level,((bottom_level-(bottom_level-
    max_depth))/0.1)+1);
percentage_sediment = linspace(bottom_level-max_depth,bottom_level,((bottom_level-(
    bottom_level-max_depth))/0.1)+1);
for i = 1:length(percentage_depth)
    percentage_depth(i) = depth_plot(i) / max_depth;
    percentage_sediment(i) = sediment_volumes(i) / max(sediment_volumes);
end
%Plotting the % of sediment deposited related to the depth %
figure()
plot(percentage_sediment*100,percentage_depth*100)
xlabel('Percentage of sediment deposited')
ylabel('Percentage of reservoir depth')
%Maximum reservoir volume, is the largest volume in the series of volume
max_reservoir_volume = max(volumes);

%Water level defined in for each grid cell
water_level = X.^0 * - (bottom_level - max_depth);
%Determine area by counting each cell that is 'under the water level'
counter = 0;
    for q = 1:N
        for c = 1:M
            if -1*start_bottom(q,c) <=  water_level(q,c)
            counter =  counter + 1;
            end
        end
    end
%Plot the waterlevel in the reservoir after simulation
figure()
mesh(-end_bottom)
hold on
mesh(water_level)
colormap('jet')
%Each cell 'under water' multiplied by grid cell dimensions to obtain area
max_reservoir_area = counter * N_width * M_width;
%M-value calculated based on Equation 4.2
M_value_Kaveh = 2/((2*max_reservoir_volume)/(max_depth*max_reservoir_area))
```

Listing E.3: Matlab script used for creating the depth-sediment percent curves (*continued*).

# F

# Set-up of the dredging cost model

In this appendix the set-up of the dredging model is explained.

## F.1. Input for the model

The volume of sediment that has to be dredged and the duration of these dredging works is required input. The volume to be dredged has to be entered in $m^3$ and the duration of the works in years, which is transformed to the number of weeks available, by multiplying the years by a factor 52.

The fractions of each type of soil have to be specified and add up to 100. Furthermore the maximum volume of the reservoir, the maximum area of the reservoir and the maximum depth of the reservoir have to be specified in order to determine the M-value ($M = \frac{2}{\frac{2*V_m}{y_m*A_m}}$. This value is used to determine the reservoir type and therefore the percentage of sediment at each depth. The input sheet in Excel where these values can be entered is presented in Figure F.1. The maximum reservoir depth is calculated based on Equation 4.1. The reservoir type is determined based on the calculated M-value.

| | | | | |
|---|---|---|---|---|
| **Input** | | | | *Reservoir parameters* | | |
| Dredging duration | 1 | years | Dam height | 30 | m |
| Volume to be dredged | 100000 | m^3 | Max reservoir depth | 26.1 | m |
| | | | Max reservoir area | 5000000 | m^2 |
| **Fractions of soil** | | | Max reservoir volume | 130500000 | m^3 |
| Silt | 50 | | | | |
| Sand | 25 | | M-value | 1 | |
| Soft Clay | 25 | | Reservoir type | Type IV | |
| Dense Clay | 0 | | | | |
| Gravel | 0 | | | | |
| Boulders / Debris | 0 | | | | |
| *Check if fractions total 100* | TRUE | | | | |

Figure F.1: Input parameters for the dredging cost model.

## F.2. Production per type of equipment

The production is determined for each type of dredging equipment. The assumptions used for calculating the production presented in the sheet 'Default calculation values' of the Dredging model.

For hydraulic equipment the production can be estimated using the diameter of the discharge pipeline of the hydraulic equipment, an assumed velocity for the mixture in this pipe and a percentage of solids entrained in the mixture. The result is a more accurate production rate than the one obtained using maximum mixture pumping capacities as presented by the producers of the dredging equipment (*M. Huijsmans, personal communication, 31-10-2017*).

The deep suction dredge can dredge up to 60 m. The dredge is suitable for both silt and sand.The volume of in situ sediment removed is estimated using the above mentioned method.

In this case the discharge pipe diameter is assumed to be 250 $mm$. The area of the pipeline can be calculated using:

$$A = \frac{\pi * D^2}{4} = \frac{3.14 * 0.250}{4} = 0.05m^2$$

The velocity in the pipeline has to be high enough, to prevent the dredged material from settling in the pipeline, a good value according to experts is 4 $\frac{m}{s}$. The mixture flow is than equal to

$$4\frac{m}{s} * 0.05m^2 = 0.2\frac{m^3}{s} = 707\frac{m^3}{hour}$$

Assuming that 30% of the mixture is sediment, the in situ sediment that is removed is 212 $\frac{m^3}{hour}$.

As a default parameter the service hours are taken to be 84 $\frac{hours}{week}$, as mentioned in table 310 (Ciria, 2009). These are the gross operational hours (*GOH*) of the dredging vessel, part of these hours are however needed for the manoeuvring and maintenance to the dredging vessel. For ships with a operational hours of 84 $\frac{hours}{week}$ the percentage of this time that the dredging vessel is actually dredging is set to 83%. The nett operational hours (*NOH*) are thus 70 hours. This value can be adjusted for local parameters if necessary. The net weekly production thus becomes:

$$136\frac{m^3}{hour} * 70\frac{hours}{week} = 9520\frac{m^3}{week}$$

of in situ soil.

For the CSD two types are considered, both are modular and can be transported by road. The one can reach depths up to 40 $m$ and reach productions up to 850 $m^3$ in situ soil (IHC, 2017). The sand is assumed to be governed by a decisive diameter, equal to the $D_{50}$ of 200 $\mu m$. According to an expert at Witteveen+Bos the maximum discharge length that can be reached by a CSD can be estimated at 2 $km$. The given corresponding in situ production for this type of CSD is 510 $\frac{m^3}{hour}$. This matches roughly with the calculation using the diameter of the discharge pipe. The default service hours of table 202 (Ciria, 2009) are used and thus 168 $\frac{hours}{week}$. To convert the *GOH* to *NOH* for 168 $\frac{hours}{week}$ the difference is assumed to be 71%. The difference is related to the implicit assumption that important maintenance can be performed outside the service hours of a 84 hour work week, while for a full week of 168 hours this is not possible. The net weekly production thus becomes:

$$510\frac{m^3}{hour} * 168\frac{hours}{week} * \frac{71\%}{100} = 6.08 * 10^4\frac{m^3}{week}$$

of in situ soil. The second CSD is larger than the first one, but can only reach depths up to 25 m. The maximum production of this dredger is given to be 7000 $\frac{m^3}{s}$ by the manufacturer (Damen Dredging Equipment, 2017). If however the same calculation as before is performed for a given diameter of the discharge pipe of 650 $mm$, the maximum mixture that can be pumped is equal to 6000 $\frac{m^3}{s}$. Assuming the same sediment as before, the in situ removed sediment is than equal to 1433 $\frac{m^3}{hour}$. The same amount of service hours as for the first cutter is set as a default, so 168 $\frac{hours}{week}$ (*GOH*). The net weekly production then becomes:

$$1433\frac{m^3}{hour} * 168\frac{hours}{week} * \frac{71\%}{100} = 1.71 * 10^5\frac{m^3}{week}$$

of in situ soil. For gravel the production values are halved. This is in accordance with the production standard and pump curve, which show that gravel give roughly half the production of fine sand. For dense clay it is assumed that the production value is 75% of the maximum production value.

The distance that the material has to be pumped has a negative effect on the mixture that can be pumped through the pipes. As described before, the maximum discharge length that can be reached is equal to 2 km. The longer the pipe, the smaller the total production. For distances longer than 2 km, the transport length can be elongated, by using booster stations. Each booster station is equal to roughly 2 km extra discharge length. It is however not possible to connect more than two boosters in the same discharge pipeline, due to practical limitations (*personal communication, M. Huijsmans, 31-10-2017*).

The production of a grab dredge is described in chapter 5.5.3. The winch speed ($V_{winch}$) of the grab is assumed to be 100 $\frac{m}{s}$. Considering that local cranes are used, the grab size ($V_{grab}$) is assumed to be relatively small. The assumed sizes are 10 $m^3$ for sand, silt and soft clay and 6 $m^3$ for dense clay, gravel, boulders and debris. The default value for the swing time is assumed to be 40 s. The production is calculated per hour, using:

$$Production_{grabdredge} = \left(\frac{60minutes * 60seconds}{\frac{Dredgingdepth}{V_{winch}} * 60 * 2 + 40}\right) * V_{grab}$$

The grab is assumed to be a cable crane on tracks positioned on a pontoon. Thus table 521 (Ciria, 2009) applies. The service hours are 84 hours per week. The percentage of hours for net production is again taken at 83%. The production is calculated based on the given maximum dredging depth.

The production for local backhoe's used on a pontoon is calculated using the production described in section 5.5.3. The values for the bucket fill factor are taken from table 5.4. The default value for the swing time is set to 20 $s$, the default bucket volume is 2 $m^3$ and the default efficiency of the excavator is assumed to be 83%. Table 511 (Ciria, 2009) is used to determine the service hours at 84 $\frac{hours}{week}$.

The maximum depth of the submersible pump is 54 $m$ and the maximum mixture density that can be pumped is 4000 $\frac{m^3}{s}$. The pump can only be used for loose material, otherwise a cutter head will have to be applied, which will result in torque forces, which can not be transferred by the winch cable. Here also the length of the discharge pipe will have a negative influence on the amount of sediment that can be moved using the pump. Performing the same calculation as for the CSD's, using a pipe diameter of 450 $mm$, a value for the in situ production of 487 $\frac{m^3}{hour}$.

The water injection dredge production is based on the assumed production per m of boom. For silt this value is assumed to be $125 \frac{\frac{m^3}{m}}{hour}$ and for sand this value is assumed to be $30 \frac{\frac{m^3}{m}}{hour}$. The default value for the boom width is set to 9 $m$. For a water injection dredge also a week with 84 *GOH* is assumed.

Using the given production per week, for each sediment fraction the number of weeks needed to remove the sediment can be calculated. This is done in the sheet 'Calculation sheet'.

Furthermore it has to be determined if a dredging method is unsuitable due to other reasons. In the 'Input' sheet some questions are asked, to determine the feasibility of different methods. For instance the question if downstream discharge or deposit in the dead storage of the sediment is possible, determines if water injection dredging is an option.

Another factor that needs to be taken into account is the maximum depth of the sediment and the depth that can be dredged by each type of equipment. For each dredging method the maximum volume of sediment that can be removed is calculated by dividing the maximum reservoir depth by the depth that can be reached by the dredging equipment. If the resulting factor is higher than 1, the full reservoir can be dredged. If the percentage is smaller than 100, this percentage is subtracted from 100, to compensate for the fact that dredging operations are performed from the top of the reservoir. The depth is than matched for the appropriate type of reservoir of table 6.1. The resulting percentage of sediment that is deposited is than also subtracted from 100, leading to the percentage of sediment in the reservoir that can be reached by the dredging equipment.

## F.3. Dredging costs per type of equipment

The different assumptions for determining the costs of each type of equipment are given here. The values can also be found on the sheet 'Economic computation' of the dredging model in Excel. All given values are in euro.

### F.3.1. Suction dredger

The suction dredger width a discharge pipe of 250 $mm$ is not a real dredger. However an example is found in the Grossglockner (Dutch Dredging, 1995). This deep suction dredge has a smaller pipe diameter and a lower power in the pump than the lowest value in table 310. Therefor the closest dredge is used, having a power of 1300 kW. This leads to a value for €22,355 D+i and €9,678 M+R, the index for 2017 is 110. For the transport of the sediment mixture the smallest floating pipelines of table 940 are used. The D+i of the pipe is given at 62,30 per 12 $m$, using an indexation of 90, the D+i for 2017 per week becomes 56.07. The fuel consumption is related to the engine size, which is equal to 1300 kW.

### F.3.2. Cutter suction dredge

For the cutter suction dredge reaching 40 $m$ table 202 is used, since it is a small and dis-mountable dredge. According to the specification sheet it has a cutter power of 110 kW, a total pump power of 500 kW, the weight is assumed to be 100 t and an underwater pump is present, leading to 15% value increase. This leads to a value of:

$$V = 3,000 * 110 + 1,100 * 500 + 4,800 * 100 + 230,000 * 100^{0.20} = 2,231,000$$

. The D+i per week is 0.371% and the M+R per week is 0.428%, the index value for 2017 is 110. Thus M+R per week for 2017 is 10,504 and D+i per week for 2017 is 9105. The floating pipe lines have a diameter of 400 $mm$, leading to the same costs as for the suction dredge of D+i per week of 56.07. The total installed power is equal to 868 kW.

If a booster is needed the lightest version is used. The booster is floating so table 400 is used, the index value for 2017 is 111. This leads to a weekly D+i of 5,558 and M+R of 3,036. For support a multi-purpose pontoon is assumed, the smallest available in table 822. The index value for 2017 is 110. The weekly cost for D+i become than 1.659 and for M+R they become 1,320. For the second cutter suction dredge with a maximum dredging depth of 25 $m$ the cutter power is 700 kW, the pump power 1,725 kW and the weight is 645 t. Here also table 202 is used, since it is specifically specified in the dredger specifications that the dredge is dis-mountable and can be transported by road.

The value becomes 9,131,000. The value of M+R per week for 2017 is than 42,989 and the weekly value of D+i becomes 37,264. The pipes for 650 $mm$ are between 600 and 700 $mm$, linear interpolation leads to 111 D+i per week, compensating for the year 2017 leads to 99.9 per week. The booster that will be used for this cutter has a pump power of 1500 kW. This leads to a 2017 value for D+i of 15,738 and a value of M+R of 8,595. For this CSD the total installed power is equal to 1,825 kW. The same multi purpose pontoon is assumed to be used.

### F.3.3. Grab dredge

For the grab a local solution is assumed, so a crane on tracks, on top of a pontoon. The example of the Luzzone dredging crane is used, thus the weight of the pontoon is 400 t, and the weight of the crane is 125 t. The installed power is 505 kW. The value is calculated using the Ciria: $V = 4000*400+1260*125+2960*505 = 3,253,000$. The index value for 2017 is 106. The M+R per week for 2017 is 19,999 and the D+i per week for 2017 is 30,758.

For the transport of the dug up sediment dumping barges are used in combination with tug boats. The barges are assumed to have a capacity of a 100 cubic meters. A tug is used for propulsion, so they don't have to be self-propelled. The 100 $m^3$ barge can be found in table 633. The index number for 2017 for this table is 106. This leads to a weekly value for D+i of 1,027 and a value of 387 of M+R. The tug is taken to be smallest in table 831, but has to be used 84 hours per week. The index value for tugs is 110. Leading to a value of 1,702 for D+i and a value of 1,580 for M+R. The maximum power for the tug is 283 kW.

The assumed maximum speed of the tug is 10 knots, which is equal to roughly 5 $\frac{m}{s}$. The time it takes to sail the transport distance back and forth can be calculated for the tug and barge. The longer this distance becomes, the more barges and tugs are needed. The time it takes to fill one barge can be calculated by dividing the 100 cubic meter capacity of the barge by the hourly grab production. The time it takes to sail the distance back and forth must not be larger than this filling time. For good production at least 3 barges are needed, one that is filled up, one that can be filled up once the first barge is full and one that can be unloaded. If the barge filling time is greater than the sailing time back and forth, one tug will suffice, if the barge filling time is the same or larger than the time to sail one way, 2 tugs will suffice. For each extra tug also an extra dumping barge is needed.

### F.3.4. Backhoe dredge

For the backhoe dredge a pontoon with an excavator on tracks is assumed. This option can be locally constructed, making it applicable for the dredging of reservoirs. Keeping in mind what is available in the field (for instance the 'Obelix' of the company Dutch Dredging) a pontoon size of 500 t and a excavator weight of 120 t is chosen. From table 511 the values can be obtained. The index value for 2017 is 106. This leads to a value of 30,758 for D+i and a value of 19,999 for M+R. The dumping barges are orchestrated in the same way as for the grab dredge. The same values can therefore be used.

### F.3.5. Submersible pump

For the submersible pump goes the same as goes for cutter suction dredges. The diameter of the discharge pipe is $450mm$, this gives a pipe D+i for 2017 of 62.96. The power of the pump is 400 kW and for the barge 200 kW, making a total of 600 kW. To manoeuvre the pump around in the reservoir it is assumed that a multi-purpose pontoon is used. The medium example of table 822 is used. The index number for 2017 is 110. For the pontoon the D+i per week for 2017 thus becomes 2,999 and the M+R for 2017 per week becomes 2,386. The submersible pump is valued at 1 million euro's and D+i is set to 3,858 and M+R to 4,683 just like a small cutter suction dredge valued at 1 million euro.

### F.3.6. Water injection dredge

For the water injection dredge the example ship 'Jetsed' is used (Van Oord, 2015). No data is available in the Ciria, however it is assumed that the water injection dredge can be seen as comparable to a Multi Purpose pontoon, with pumps instead of cranes. The dredge is taken to have unrestricted navigation area, thus table 820 is used. The second pontoon has the appropriate dimensions. The index value for 2017 is equal to 110. The values per week become 20,403 for D+i and 16,235 for M+R. The total power on board is given to be 1,971 kW.

### F.3.7. Survey launch

For the monitoring of the dredging operation a survey launch will be used. The lightest version is assumed to be enough for a reservoir, since the water here is usually calm. The maximum power is 350 kw, the index value for 2017 is 110, making the weekly values 2,232 for D+i and 2,426 for M+R.

## F.4. Depot costs

If sediment has to be stored in depot after it has been dredged, this results in extra costs. These costs are estimated based on discussion with an expert at Witteveen+Bos (*M. Huijsmans, personal communication, 21-11-2017*).

A depot is considered small if less then 100,000 $\frac{m^3}{week}$ is deposited. In a small depot the necessary equipment is an bulldozer, wheel loader and an excavator. The costs piece of equipment is estimated at €60 per hour. Additional materials, a foreman and a construction shed result in roughly €170 per hour. The costs for a small depot are therefore €340 per hour.

A larger depot is used to handle sediment loads between 100,000 and 250,000 $m^3$ weekly. For a larger depot an additional bulldozer is required. The used equipment is assumed to be larger and is therefore more expensive. It is estimated to cost €70 per hour. The total hourly costs in this case become €450.

The depot costs can be switched on and off in the "Input" sheet. If depot costs are set to "yes", for each equipment type the load on the depot is calculated, except for the WID. Using the load the depot size is determined. This load is used to determine the weekly cost by multiplying the hourly costs by the NOH. These costs are then added to the total weekly costs.