SEDIMENTATION IN RESERVOIRS

INVESTIGATING RESERVOIR PRESERVATION OPTIONS AND THE POSSIBILITY OF IMPLEMENTING WATER INJECTION DREDGING IN RESERVOIRS

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Sedimentation in Reservoirs

Investigating reservoir preservation options and the possibility of

implementing Water Injection Dredging in Reservoirs

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Preface

This Master thesis is the final part of my Master of Science program Hydraulic Engineering at the Delft University of Technology. It is the result of 9 months of research done by commission of the University, as well as for the engineering consultant Witteveen + Bos. It analyses the current methods to preserve the capacity in reservoirs and investigates whether or not it is possible to implement Water Injection Dredging in reservoirs, in order to restore the reservoir capacity.

I would like to thank my supervisors, Polite Laboyrie and Cees van Rhee, for giving me the opportunity to work on this thesis. They made it possible to start working on this thesis, even when the final goal of this thesis wasn't sure yet. I would also like to thank Geert Keetels for giving his support and ideas throughout this project. Also Kees Sloff owes my gratitude, for joining the graduation committee on such a short notice. I thank the colleagues of Witteveen + Bos for their comments and feedback during this project and my pleasant stay there. Finally, I would like to thank my family and friends for their support.

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Summary

Sedimentation in reservoirs is a consequence of constructing a barrier in a flowing river, which results in a decrease of the transport capacity of the river. The storage capacity of the reservoir decreases due to the accumulation of sediments and the river downstream starts to erode due to the disturbance of the sediment balance.

A study regarding the sediments in the reservoir has to be carried out before the construction of the dam starts, so that the sedimentation problems during the exploitation of the dam can be reduced to a minimal. However, more than once dam operators are surprised by the sedimentation problems in the reservoir and are counter measurements necessary. These counter measurements are often very expensive and are difficult to implement in an effective way. A proactive attitude towards this sedimentation problem can result in a significant reduction of the problem.

There are methods available however, to counteract the sedimentation problems in an effective way. These methods can roughly be divided into three different strategies: prevent sediments from entering a reservoir, prevent sediments from settling in a reservoir and remove sediments that have already settled.

To determine which method is suitable, the reservoir can be grouped by applying different classifications. Each classification has its own specific favourable reservoir preservation technique, and these classifications can be used to help deciding which method is suitable. However, the final choice is not depending on these classifications but has to be determined after a comprehensive feasibility study, in combination with discussions with all the stakeholders involved.

A dredging method that could be interesting to use in reservoirs is Water Injection Dredging. This method injects water in the bottom of the reservoir, creating hereby density currents which are capable of transporting large amounts of sediment. Because the density current uses gravitation and the natural slope of the reservoir, this method is a relative cheap and quick way to transport sediments. The dredging installation is also simple and basic. Unlike other dredging equipment, Water Injection Dredging pumps water through its pumps. This reduces the wear of the equipment considerably.

Therefore, Water Injection Dredging has the potential to be a quick and efficient way to restore the capacity of reservoirs. Very specific conditions have to be met however. The steepness of a reservoir should be steeper than 10^{-3} and sediment particles must be smaller than 0.2 mm for the method to be effective. A lower deposit site should also be available for the sediments. This means that bottom outlets or a diversion channel should be present, so that the sediments can be sluiced out of the reservoir. It is also possible that the created density current transports the sediments towards the dead storage of a reservoir. The effective storage capacity will be improved in all these three scenarios.

Sediments can be brought back in the river system when Water Injection Dredging is applied in a reservoir. Sediments are sluiced passed the dam, which means that the river can prevent the

erosion of the river downstream of the dam that is a consequence of the sediment blockage. A positive side effect of keeping the sediments in the river is that instead of conventional dredging techniques, the dredged up sediment does not have to be transported towards and eventually removed from a deposit site, which reduces the costs considerably.

It is however necessary to investigate whether or not the river is capable of dealing with the increased sediment load in the river downstream of the dam. The high production rates of Water Injection Dredging results in high sediments peaks, which the river should be able to transport.

Case studies done to test the feasibility of Water Injection Dredging in reservoirs confirm these requirements. In the case of the Mrica reservoir, Water Injection Dredging proved to be a competitive and cost efficient method that can be used to remove significant amounts of sediments out of the reservoir. The bottom outlets of the dam were constructed too high however, which means that the sediments can only be transported within the reservoir itself. Also, a large part of the sediments consist of particles which have a grain size too large for Water Injection Dredging to be effective. If these two specifications were different though, Water Injection Dredging would be able to restore the reservoir capacity for significant lower costs than the conventional techniques. The average yearly amount of sediment that flows in the reservoir will be distributed in a time span of more than 30 weeks. The sediment load is therefore less than twice the average sediment load, which will not be a problem for the river to cope with.

The second case study done for the much smaller Millsite Reservoir shows that the removal rates and the proportional costs of implementing Water Injection Dredging in this reservoir are also promising. However, the sediment peaks created by the density currents are very high. It is not sure if the river downstream of the dam can cope with these sediment peaks. These sediment peaks can be smoothened out, but this will result in higher operational costs.

The case studies do show that the method can be a competitive and feasible method that can be used to counteract sedimentation problems in reservoirs, if some specifications of the reservoirs were different. If these specific requirements for Water Injection Dredging in reservoir are met, the method can restore the reservoir capacity in a cheap and effective way. More research and testing the method in practice will be necessary however.

It is also necessary to do more research on the environmental consequences of the high sediment peaks for the river downstream of the dam. Also, specialised equipment needs to be designed when the reservoir is too deep for a standard Water Injection Dredger.

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1 Orientation on sedimentation in reservoirs

1.1 Introduction

Dams are constructed in rivers for various amounts of reasons. Hydropower can be generated and fresh water can be stored for drinking water or for agricultural purposes. Also, river floods can be controlled in order to increase the river safety. However, the consequences for the environment can be severe, and extensive research is necessary to investigate what the effects of such a structure are. Especially the sediment blockage in the river can be a serious problem. The capacity of the reservoir reduces as a consequence of this blockage and it also has a big influence on the river morphology.

The objective of this thesis is to generate an overview of the currently available methods to preserve the capacity within reservoirs and to investigate whether or not it is possible to implement Water Injection Dredging in reservoirs. As a first step though, a more detailed introduction is given with respect to sedimentation in reservoirs. After that, the objectives and the research approach of this thesis will be discussed.

1.2 Background information

1.2.1 River hydraulics

A river system starts with precipitation that falls down in the mountains. This water is collected by small streams that discharge their water into bigger streamlets. The streamlets will end up discharging their water into a river, which keeps on growing in size. While the volume of the river keeps on growing, the river leaves the mountains and the surface below the river flattens out. The velocity of the river decreases and the river is now in a meandering state, where it curves its way through a flat landscape. Eventually, the river ends up in a delta where it will discharge the water into a lake, sea or ocean (see also Figure 1).

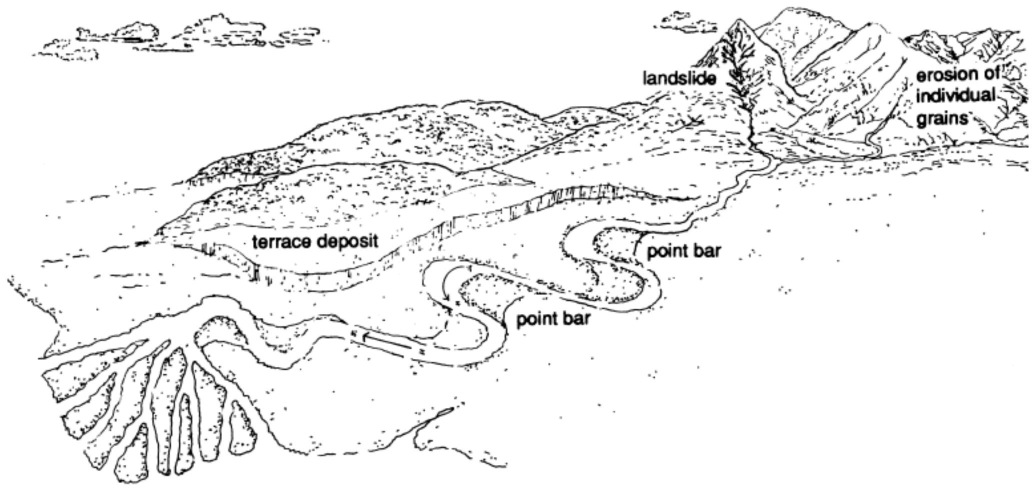

FIGURE 1: THE WATER CYCLE – (KONDOLF, 1997)

The amount of water that is transported by the river grows from a few litres per second in the stream to a substantial amount of cubical meters of water per second or even more, depending on the size of the river. This means that besides a considerable amount of water, the flow is now also carrying a lot of energy. It is this amount of water and the energy potential of the river, especially in the mountainous regions, that interests dam engineers. It can be used to generate hydropower and to store fresh water.

A side effect is that the river collects a lot of sediment throughout this process, due to the friction of the water with the subsurface. Especially in the mountains, where the flow velocities are higher, the water takes a lot of sediments along the way. When the river calms down and starts to meander, the nutrient rich sediment particles start to settle and provide fertile grounds that can be used for agriculture. At the river mouth, the sediment supply contributes to the protection of the coast against wind, waves and currents.

This process of sediments that are picked up in the mountains and deposited in the lower areas and at the river mouth has been going on since the first water drop fell in the mountains. It results in a balance between erosion and accretion in the river morphology. The supply of sediment is approximately equal to the amount of sediment that erodes away, keeping in mind that there are some (seasonal) fluctuations. This process is schematised in Figure 2, where S is the sediment transported by the river. The same process yields for the coastline, where there is a balance between the supply of sediments from the river and the erosion of the coastline.

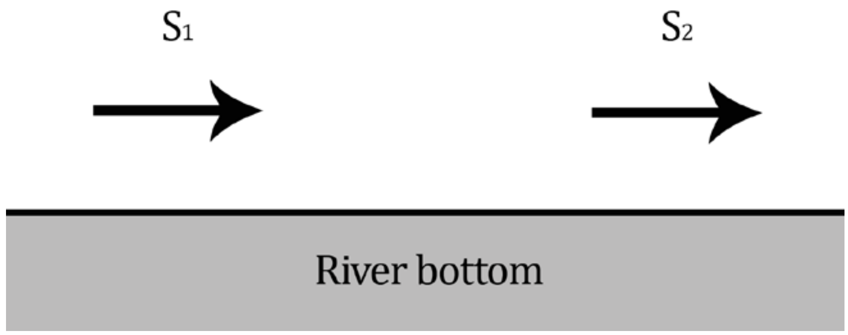

FIGURE 2: DYNAMICS OF THE RIVER MORPHOLOGY

If $S_1 = S_2$, the river bottom is in an equilibrium state

If $S_1 > S_2$, the river bottom is accumulating

If $S_1 < S_2$, the river bottom is eroding

Figure 2 shows that erosion or accretion will get the upper hand if this balance is disturbed. This will influence the river morphology until another equilibrium is found. Constructing a dam in the river will block the sediment flow in the river and will disturb this sediment balance in the river considerably. Upstream of the dam, the sediment inflow S_1 will be higher than the amount of sediment S_2 that is taken away due to the blockage. This results in sediment accumulation close to the dam. Downstream of the dam, the sediment inflow will be lower than the amount of sediment that is taken away. This results in erosion of the river bottom.

1.2.2 DAMS AND RESERVOIRS IN GENERAL

The most common reasons to construct dams are to create storage of fresh water for irrigation and drinking water supply, generate electricity by means of a hydro power installation or to control dangerous river floods. With the ongoing rise of the world's populations, the need for fresh water and electricity has increased. This combined with the general idea that a dam can provide sustainable energy has led to the fact that the number of dams has grown considerably in the last few decades. The International Commission on Large Dams, the ICOLD, has registered about 37.600 dams higher than 15 meter[1], but it is estimated that the actual number is more than 40.000 since not all dams are registered. This increase of the number of dams and their reservoirs has stimulated the need for knowledge about their properties and their design challenges.

[1] http://www.icold-cigb.org – (Website ICOLD International Commission on Large Dams, 2012)

One of the bigger design problems of a dam is the enormous influence it has on the surroundings. Because of the size of the dam and the created reservoir, the life of the inhabitants of the valley changes considerably. The lake is creating a big barrier which cannot easily be crossed and takes up a lot of space. This barrier influences ship navigation in the river, as well as fish migrating through the river. Counter measurements, such as fish stairs and ship locks, are expensive. Another side effect is the moving of a considerable number of people and other inhabitants away from the lake to higher grounds. Valuable cultural heritage has to be moved as well or gets drowned. This results in a lot of friction with the local communities.

Another side effect is the fact that hydraulic conditions in the river change. Instead of the original turbidity circumstances of the fast flowing river, the water in the reservoir is very calm and this has an influence on the water quality. The stirring of the river causes movement in the water and makes the water rich with oxygen. But the water quality is declining, now that the stirring of the water has stopped in the reservoir. This has a negative influence on the fish population, which will decrease considerably. Also due to the dam structure, there is a blockage of the sediment transport in the river. Sediment particles settle in the reservoir due to the calm conditions and this eventually results in a decrease of the storage capacity.

Besides these negative side effects of a dam construction and the friction it creates with the local communities, dams are still constructed all over the world. It is clear that there are conflict interests. The power to control a substantial amount of water is very attractive, especially since the fresh water storage and the hydropower generation accommodates the ongoing growth of the world's population. Unfortunately, side effects are often underestimated during the feasibility studies. This results in dams and reservoirs that create a lot of unforeseen problems to the environment and the local communities, which could have been reduced or even prevented if proper research was carried out.

1.2.3 Reservoir sedimentation

Reservoir sedimentation is a process that has been going on since the first dams were build and is a consequence of creating a calm reservoir lake where there used to be a fast flowing river. It eventually starts to influence the reservoir capacity and the river morphology. The siltation of the reservoir could hinder the usage of the dam and interfere with the functionality of the reservoir. With the sediments taking up space in the reservoir, the storage capacity of the reservoir is decreasing. If the sediments settle all the way towards the dam structure, the hydropower installation can be influenced by the sedimentation process as well. Also, the navigability of the river can be negatively influenced due to the fact that the river morphology is changing. It has an effect on the ecology too, since the continuous river flow is interrupted and fragile ecological equilibriums will be disturbed.

These undesirable developments result in expensive measurements to counteract or prevent these sedimentation processes. To give an impression of the process, a schematisation of the reservoir sedimentation at the Three Gorges Project is presented in Figure 3.

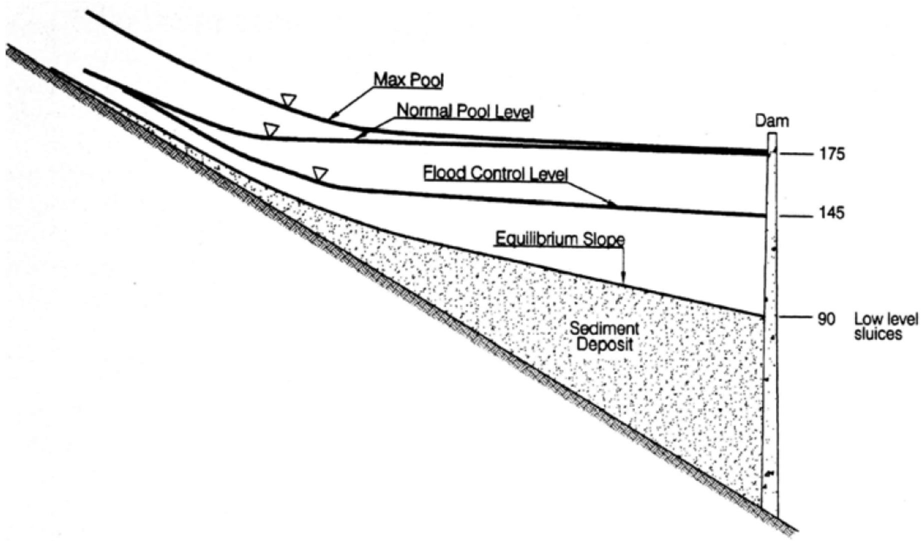

FIGURE 3: SCHEMATISATION OF THE RESERVOIR SEDIMENTATION AT THE THREE GORGES PROJECT ON THE YANGTZE RIVER IN CHINA - (MORRIS, L. AND FAN, J., 2010)

A global approach done by Mahmood in 1987 has resulted in the estimation that the annual loss of storage within reservoirs is roughly 1%, corresponding to about 50 km³ each year[2]. This corresponds to a yearly average loss of $6 billion due to sedimentation problems.

The sedimentation problems strongly depend on the local circumstances of the reservoir. Some reservoirs won't have any troubles with siltation and other reservoirs can lose up to 5% of their storage capacity each year, like the Welbedacht Reservoir in South Africa. In the case of the Welbedacht reservoir, sedimentation problems have resulted in a total capacity loss of almost 90%[3] (see also Figure 4). Primary functions of the Welbedacht dam are seriously harmed and expensive counter measurements have to be executed to keep the dam operational.

[2] Reservoir Sedimentation – (Mahmood, 1987)
[3] Modelling of long-term sedimentation at Welbedacht Reservoir, South Africa - (De Villiers, J.W.L. and Basson, G.R., 2007)

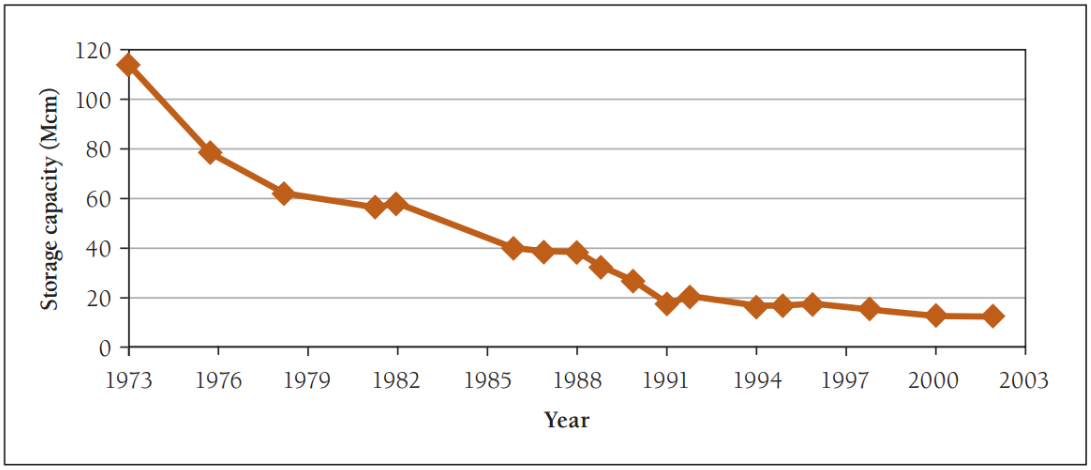

FIGURE 4: THE OBSERVED LOSS IN STORAGE DUE TO SEDIMENTATION IN THE WELBEDACHT RESERVOIR - (DE VILLIERS, J.W.L. AND BASSON, G.R., 2007)

Sedimentation in reservoirs is also of big influence downstream of the dam. A river system consists of a continuous balance between erosion and accretion, where sand is picked up due to the river flow and deposited elsewhere in the river. If the inflow of sediment is blocked due to a dam structure, the equilibrium of the river morphology is disturbed and the river channel downstream of the dam starts to erode to compensate for the lack in sand particles. An example of these river dynamics is given below in Figure 5.

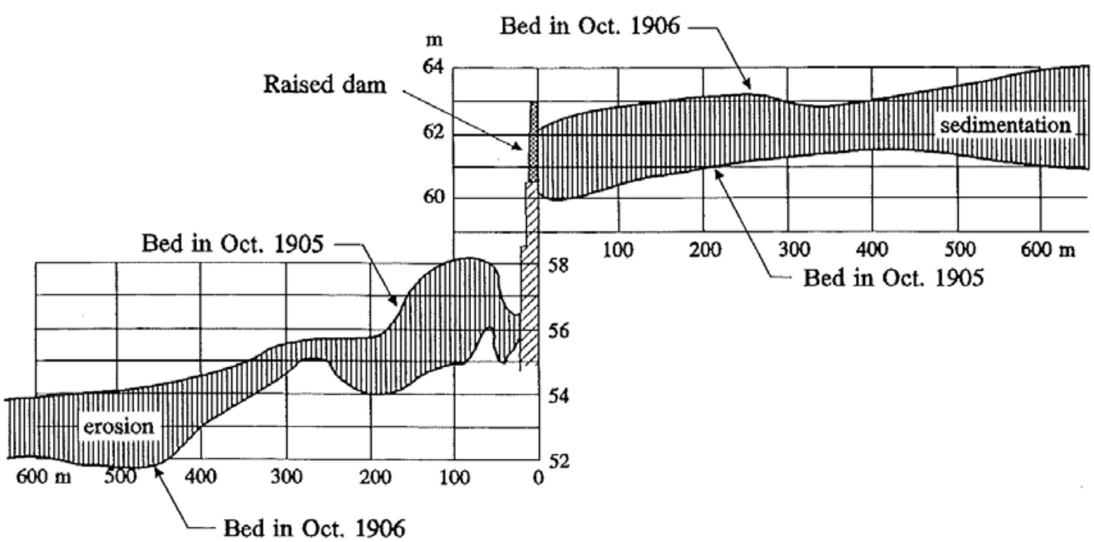

FIGURE 5: MEASURED BED VARIATIONS DUE TO HEIGHTENING OF A DAM IN THE YUBA RIVER –ADAPTED FROM (SLOFF, C.J., 1991)

The nutrient rich particles are now stored behind the dam, whereas in the original situation the river floods would deposit these particles on the river beds downstream. This would result in fertile land which would accommodate agriculture. With these enrichments now gone, the agricultural sector is suffering from a decrease in crop production.

The decrease in the flow of sediment particles due to the siltation in the reservoir continues all the way till the river mouth, where the river feeds the coastline with sand particles to protect the beaches from eroding due to waves and currents. If the supply of sand particles reduces because of the sediment blockage upstream of the river, the balance between the erosion and accretion of the coastline is disturbed as well. The drop of the sediment supply results in a change in the morphology of the coast and eventually a retreat of the coastline. The decrease of the inflow of sediment particles due to dam structures in the Nile River for example, has led to the retreat of the coastline (see Figure 6). Since coastlines are generally densely populated or have other important values, this process of a retreating coastline cannot be neglected.

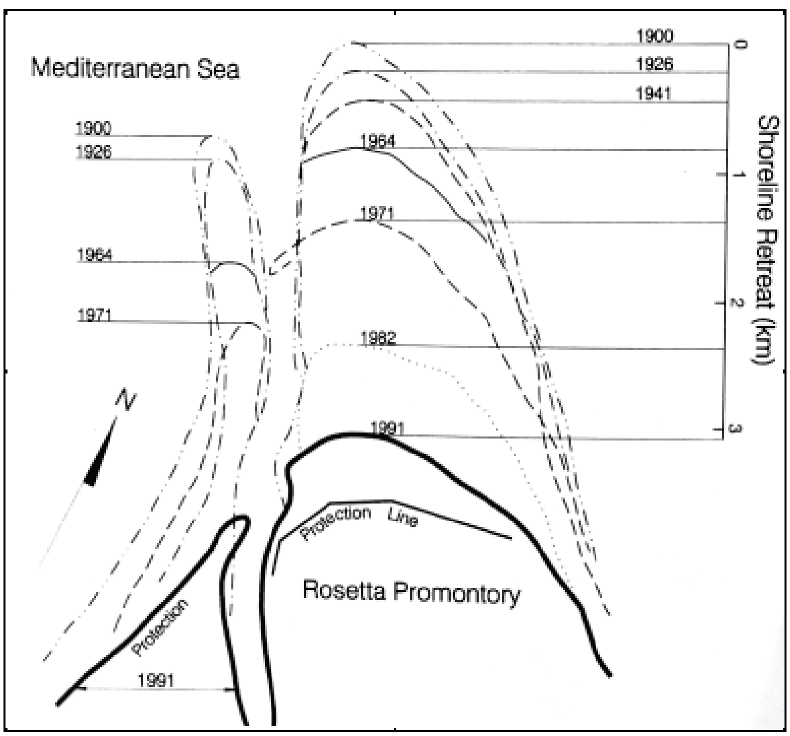

FIGURE 6: HISTORY OF EROSION OF THE NILE DELTA - (MORRIS, L. AND FAN, J., 2010)

This coastline retreat of more than 3 kilometres (see Figure 6) is a very extreme example of what can happen to a river system when misguided interventions in that system are implemented. Unfortunately, this example doesn't stand by itself. Coastline retreats of hundreds of meters have been reported in many cases. Like the São Francisco River Mouth, where the coastline has retreated nearly 700 metres due to reservoir sedimentation[4].

It depends on the local circumstances if the construction of a dam will influence the shape of the coastline. If the dam is situated far inland, the stream length of the river is sufficiently long, so that the river can regenerate the quantity of sediments that was lost by the river because of the intervention of the dam. This does mean however that the river has to take these sediments from the river beds and this will result in the scouring of the river channels.

These river and coastal morphology changes are usually underestimated or not even considered at all when a dam is structured. This unless the fact that the consequences for the environment can be enormous and in many cases irreversible.

More than once dams are shut down long before their expected lifespan due to siltation problems. It is therefore essential to understand these processes and try to control them, not only to benefit the owners of the dam but for all the stakeholders that are involved.

1.3 Objectives

Sedimentation in reservoirs is a considerable and severe problem which results in undesirable side effects for the environment and costly counter measurements. A literature survey has to be carried out to investigate what the currently existing counter measurements are that can be used to avoid or counteract problems with reservoir sedimentation.

The main question that has to be answered is: Is it possible to give an estimation of the expected sedimentation problems in a reservoir and is it possible to quantify these problems? And which methods are preferred to preserve the reservoir capacity and is it possible to introduce a new method?

An attempt has to be made to find out if it is possible to use knowledge from the dredging industry within the perspective of this thesis to find out if this knowledge can contribute to counteract reservoir sedimentation. Developments from the dredging industry can possibly be used to create new insights and new methods.

Estimating the amount of sand that settles behind a dam is difficult due to many factors that influence the sedimentation process. The sedimentation processes within a reservoir need more research and more information is needed to quantify the sedimentation problem.

An overview of the available reservoir preservation methods is necessary with all the specific information and properties provided. A cost efficient analysis is needed to evaluate these different

[4] Morphological response of São Francisco River Mouth, due to sediment retention in dams – (Bandeira et al., 2012)

methods. This will eventually lead to an overview of different classifications of reservoirs with the proportional reservoir preservation methods.

Formulas and parameters from the dredging industry can be implemented for reservoir sedimentation models. The sedimentation processes within the basin of a dredger are roughly similar to sedimentation processes in a reservoir, where especially the settling velocity of the sediments and the scatter of the sediments are important variables.

1.4 RESEARCH APPROACH

For a proper approach of the reservoir sedimentation problem, an extensive literature survey is needed to gather the necessary information. In order to make a distinction between reservoirs, research will have to be carried out to find strategies that are able to categorize reservoirs. This is necessary in order to group reservoirs and link reservoirs to methods that can counteract reservoir sedimentation. Parameters that can distinguish reservoirs into useful groups have to be investigated and eventually used to make these differences.

To get an overview of which reservoir preservation technique is useful in which situation, a connection has to be made between the preservation techniques and the reservoir classifications. This connection will eventually be helpful to make a decision when a choice has to be made between reservoir preservation techniques.

Research has to be done in order to find a new strategy that can be used to preserve the capacity within a reservoir. Knowledge from the dredging industry can in this case be used to create new insights and to find a competitive and economical feasible method.

When these analyses are finished, a model has to be constructed to calculate the cost efficiency of the possible methods. It can be used as a guideline to choose between reservoir preservation techniques, when reservoir sedimentation is a problem.

The practicability of a possible new method can be examined by applying the method in various case studies. Cost efficiency calculations of all the possible reservoir preservation methods can then be used to determine the feasibility of the method in various circumstances.

The results of the research and the case studies can then be used to draw conclusions regarding the problems with reservoir sedimentation and the possibility of implementing a new method. Finally, recommendations have to be made for future steps.

2 Reservoir classification and sediment quantification methods

2.1 Introduction

For individual reservoirs, numerical models are used nowadays to model the behaviour of sediments in a reservoir. This is a very time consuming process, and for an overall approach of the reservoir sedimentation problem, use is made of empirical models to set up reservoir classifications and to quantify the sedimentation problem.

To come towards a general approach of the reservoir sedimentation problem, an overview of the different types of reservoirs has to be generated. With the use of characteristic parameters, the reservoirs can be divided into different classifications. After the classification, different techniques are discussed to quantify the sedimentation in reservoirs.

2.2 Classification of reservoirs

In order to make a general approach of sedimentation in reservoirs, a classification of the different types of reservoirs has to be made. Because of the enormous variety within the reservoirs, it is not possible to generate one overall parameter that can represent the complexity of a reservoir and make a distinction between reservoirs. Therefore, the classification is split up with the help of multiple parameters. These parameters represent the sediment distribution within the reservoir, the hydraulic conditions in a reservoir and take into account administrative aspects of the reservoir sedimentation problem.

2.2.1 Empirical Area-Reduction method

The first method discussed to classify reservoirs is the Empirical Area-Reduction method, developed by Borland and Miller in 1958[5]. The basis of this method is the shape of the reservoir, which is determined by using the reservoir depth and the reservoir capacity. The method divides

5 Distribution of sediment in large reservoirs -(Borland W.M. and Miller C.R., 1958)

the reservoirs in 4 standard types. Within these standard reservoir types, the parameter "M" divides the types in different classes and it represents the reciprocal of the slope of the line obtained by plotting the reservoir depth at the vertical axis against reservoir capacity at the horizontal axis on log-log paper. This result in the classification presented in Table 1 and Figure 7.

TABLE 1: TYPES OF RESERVOIRS

Reservoir type	"M"	Standard classification
Gorge	1.0-1.5	IV
Hill	1.5-2.5	III
Flood plain-foothill	2.5-3.5	II
Lake	3.5-4.5	I

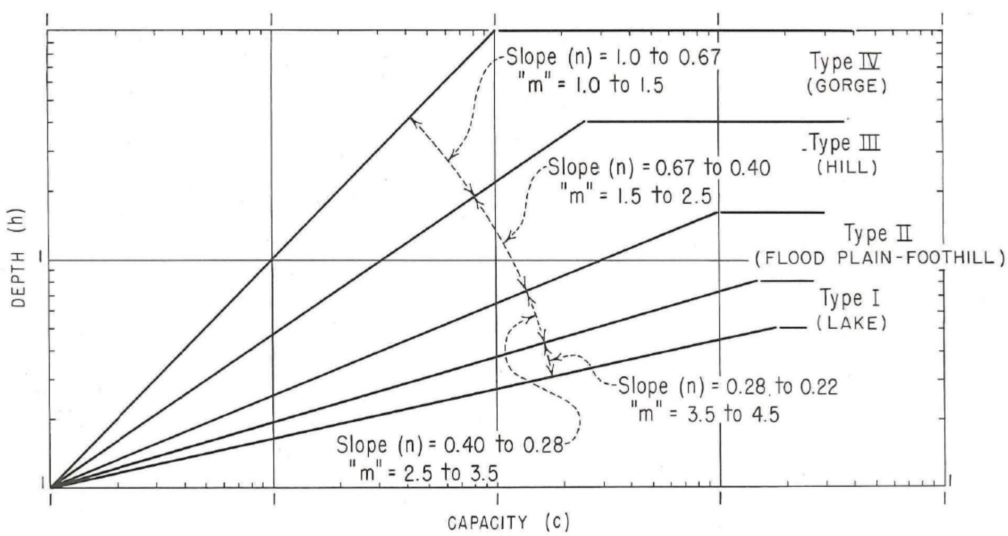

FIGURE 7: DETERMINATION OF THE DIFFERENT TYPES OF RESERVOIRS - (BORLAND W.M. AND MILLER C.R., 1958)

These types of reservoirs can then be linked to the sediment distribution within these reservoirs. It is important to know where sediment settles if a decision has to be made between the different reservoir preservation techniques. In Figure 8 is the reservoir depth plotted against the sediment deposition. A reservoir depth percentage of 100 means that the reservoir is at its full depth, so that is the depth just before the dam.

From Figure 8 follows that in the situation of a type I reservoir, the sediment already starts to settle at shallower depths, close to the point where the river enters the reservoir. This makes sense since a type I reservoir is described as a “Lake” reservoir and has a relatively flat bottom slope. It reduces the flow velocity and therefore facilitates the settling of sediments. For type IV reservoirs, sediment starts to settle at the deeper parts of the reservoir, much closer to the dam. This is due to the steeper bottom slope of the reservoir, which results in a faster flow in the reservoir. Sediments will be kept longer in suspension and will settle further away from the point where the river enters the reservoir.

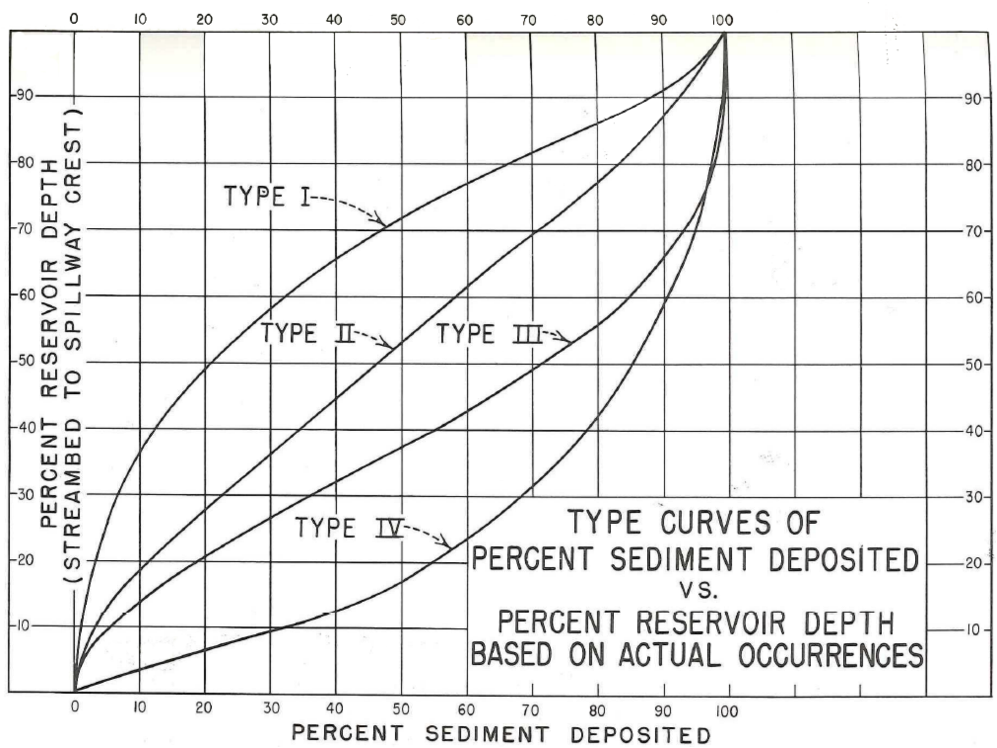

FIGURE 8: SEDIMENT DISTRIBUTION WITHIN A RESERVOIR - (BORLAND W.M. AND MILLER C.R., 1958)

The majority of the sediments also settles close to the dam with type III reservoirs, but not as extreme as with type IV. A type II reservoir has a more or less constant dispersion of sediment throughout the reservoir.

2.2.2 *PERMITTED RESERVOIR OPERATIONS*

Whether or not it is permitted to (partially) draw down the water level in the reservoir determines which preservation method can be used and which one cannot. Also, some methods can be used during full operational water level as well as during total draw down, but that has an influence on the effectiveness of that method.

Permission to draw down the water level in a reservoir depends on the function of the dam and the time that is necessary to restore the water level after a draw down. If the dam is built to act as fresh water storage for instance, drawing down the water level for a long period of time will not be an option since its primary function cannot be fulfilled then. Geo-technical instability and keeping the navigation of the river intact can also be reasons to maintain the water level of the reservoir.

Also, if the time that is necessary to restore the water level to the operational level is too long, the functionality of the dam will be lost for a long period and that makes the draw down very costly. This aspect is also discussed in the next paragraph.

The possibility of a (partial) draw down is therefore depending on the functionality of the dam and the economic consequences of the draw down. The decision finally has to be made by the owner of the dam, who will have to decide if drawing down the water level is allowed.

The classification based on the drawing down options is divided into three different groups:

- It is permitted to completely draw down the water level in the reservoir
- It is only permitted to partially draw down the water level in the reservoir
- It is not permitted to draw down the water level at all

2.2.3 *CAPACITY-INFLOW RATIO*

The last classification of reservoirs is based on the relationship between the yearly inflow of water from the river and the capacity of the reservoir.

If the river has relative high discharges compared with the volume of the reservoir, it is easier to draw down the water level in a reservoir. The reservoir fills up relatively fast and the functionality of the reservoir can be restored more easily. Economic losses due to the water level drop are therefore in general much lower than the scenario where the discharge of the river is relatively low.

If, on the other hand, the ratio between the river discharge and the reservoir capacity is big and the reservoir is relative large compared with the river discharge, it takes much longer before the operational water level of the reservoir is restored again. Drawing down the water level can be very uneconomic in this case.

The ratio between the reservoir capacity (C) in [m^3] and the inflow of water (I) in [m^3/y] has a significant influence on the amount of sediment that is caught in the reservoir. If the water retention time in the reservoir is large, and therefore the C/I ratio is relatively high, the water remains within the reservoir for a long time and sediments will settle much more easily in the reservoir. When the C/I ratio is small and the retention time of the water in the reservoir is small as well, the amount of sediments that settle in the reservoir will be lower as well. More about this will be elaborated in Paragraph 2.3, where the quantification of sedimentation in reservoir is discussed.

The definition of the capacity is depending on the local circumstances of the dam. The operational capacity is usually used, but it is also an option to use the original capacity (the capacity of the dam when the dam was starting to operate), the current capacity of the reservoir or the maximum capacity of the reservoir (the capacity when the highest possible water level in the reservoir is reached). The same yields for the definition of the reservoir depth.

A distinction can be made between reservoirs that are fully refreshed with water during a year and reservoirs that aren't. With this approach, seasonal effects can be taken into account. A third distinction is made for reservoirs which have an average retention time that is less than half a year. These reservoir types have a relatively fast flowing water volume through their reservoirs.

Therefore, this classification can be divided into 3 types of reservoirs:

- $C/I > 1$ year. The capacity of the reservoir is larger than the mean annual runoff from the watershed
- $0.5 < C/I < 1$ year. It takes half a year to a year to completely refresh the reservoir volume. This is without taking into account the seasonal floods.
- $C/I < 0.5$ year. The average water retention time in the reservoir is less than half a year.

2.3 Quantity estimation - Trap Efficiency

An important aspect of managing the sedimentation problems in a reservoir is to determine the quantity of sediments that will settle in a reservoir. A quick way to make an estimation of the amount of sediments that settles in a reservoir is to calculate the Trap Efficiency. This is the rate of the amount of sediment that is caught by the reservoir.

The Trap Efficiency is formulated as follows:

$$TE = \frac{S_{inflow} - S_{outflow}}{S_{inflow}} = \frac{S_{settled}}{S_{inflow}}$$

Where:

S_{inflow} = The sediment mass entering the reservoir [kg/s]

$S_{outflow}$= The sediment mass that flows out of the reservoir [kg/s]

$S_{settled}$ = The sediment mass that settles in the reservoir [kg/s]

Given the many parameters that influence the sedimentation process, it is very difficult to predict the Trap Efficiency in a simple manner. To make an accurate prediction, an extensive and complex model has to be developed which is based on theoretical relations and incorporates all the influencing factors. This is a very time-consuming process. For a more general approach, empirical data and formulas are used.

When using empirical methods, one should always be aware of the fact that the parameters are very dynamic and change during the sedimentation process. The storage capacity (C) for instance, changes during the sedimentation process and therefore influences the C/I ratio during time.

2.3.1 BRUNE CURVES

The first method explained is developed by Brune[6]. It is the most widely used method to empirically determine the Trap Efficiency. The curves of this method are based on data from 44 reservoirs and are used worldwide to determine the Trap Efficiency. The curves are based on the capacity-inflow ratio of reservoirs and are presented in Figure 9. These are the curves developed by Brune, and modified by (Verstraeten, G. and Poesen, J., 2000).

It must be emphasised that these curves should only be used for normally situated reservoirs (reservoirs which are completely filled by water and have their outlet at the top of the embankment). These curves are not suitable for floodwater-retarding structures, desilting ponds or semi-dry reservoirs. Misusing these simplified curves may lead to large errors in the calculation of the Trap Efficiency.

[6]Trap Efficiency of Reservoirs - (Brune, 1953)

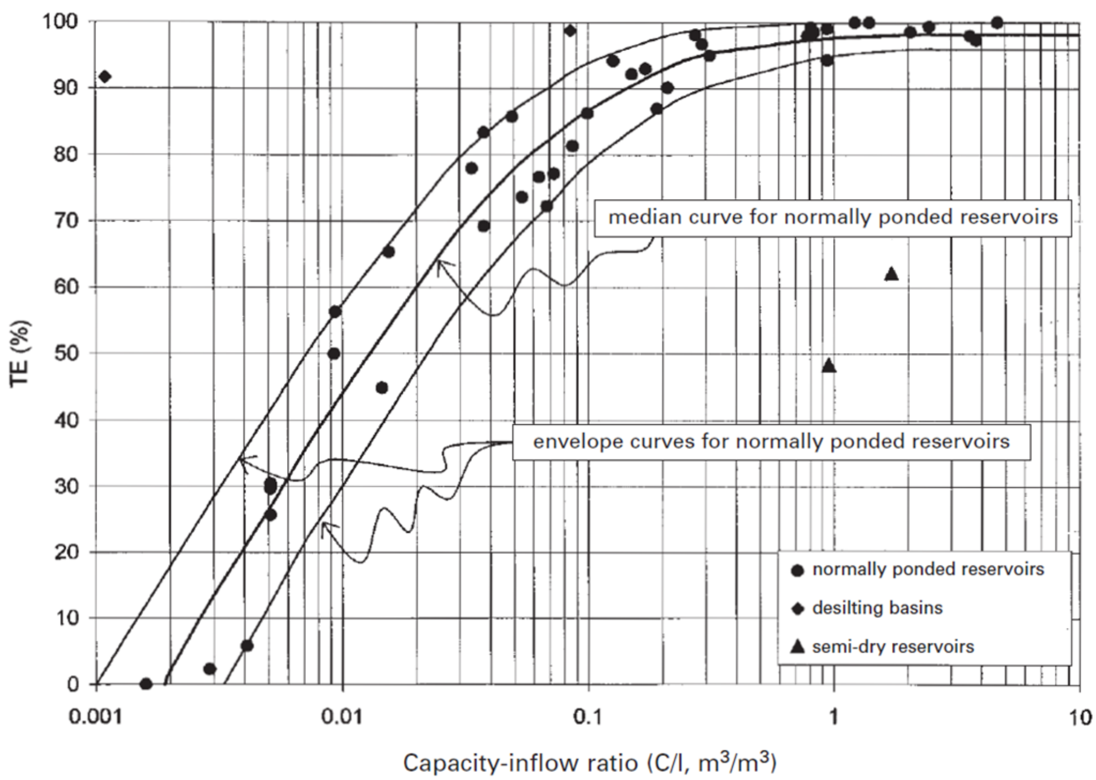

FIGURE 9: MODIFIED BRUNE CURVES RELATING THE TRAP EFFICIENCY TO THE CAPACITY/ANNUAL INFLOW RATIO - (VERSTRAETEN, G. AND POESEN, J., 2000)

On the horizontal axis is the same C/I ratio as was used in Paragraph 2.2.3, where C represents the capacity of the reservoir and I the average annual water inflow. Because the unity of C is [m^3] and I is [m^3/y], the C/I ratio is expressed in years (which is incorrectly presented in Figure 9). When the C/I ratio is smaller than 1 year, it means that the amount of water in the reservoir is replaced totally during one year. If the C/I ratio is bigger than 1 year, it means that the amount of water in a reservoir is bigger than the total amount of water that yearly flows into the reservoir. The C/I ratio therefore describes the average retention time of the water in a reservoir. The upper curve yields for predominantly coarse-grained sediments, the median curve yields for mixtures of grain sizes and the lower curve yields for primarily fine sediments.

2.3.2 *CHURCHILL CURVES*

Another widely used method is the method developed by Churchill in 1948[7]. Churchill suggested that there is a relationship between the amount of sediments that passes a reservoir (100-TE(%)) and the sedimentation index. The sedimentation index of a reservoir is defined as:

$$Sedimentation\ Index = \frac{Period\ of\ retention}{Mean\ velocity}$$

With the Sedimentation Index, a ratio is added of two reservoir characteristics which both have a significant influence on the reservoir sedimentation. The bigger the retention time of the pool and the lower the mean velocity, the higher will be the sedimentation rate of the reservoir and with that the Sedimentation Index (see also Figure 10).

Borland (1971) added data from desilting basins and semi-dry reservoirs to Churchill's curves, as can be seen from the data points in Figure 10. In contrary to the Brune curves, these curves can be used for desilting basins and semi-dry reservoirs. This is a result of the fact that with the Sedimentation Index, more aspects of the hydraulic conditions within the reservoir can be taken into account.

With this graph, also a distinction is made between sediments that have passed a previous reservoir and sediments that haven't. Sediments that have passed through a reservoir before in most cases are finer and are more likely to pass a next reservoir. These sediments are indicated in the upper curve in Figure 10.

The Churchill curves may give a better prediction of Trap Efficiency than the Brune curves, the big disadvantage of this method is that it is very difficult to determine the Sedimentation Index. The data necessary to calculate the Sedimentation Index is often not available, which makes the method in that case useless. This is the main reason why the Brune curves are more widely used to determine the Trap Efficiency.

[7] Discussion of *Analysis and use of reservoir sedimentation data* - (Churchill, 1948)

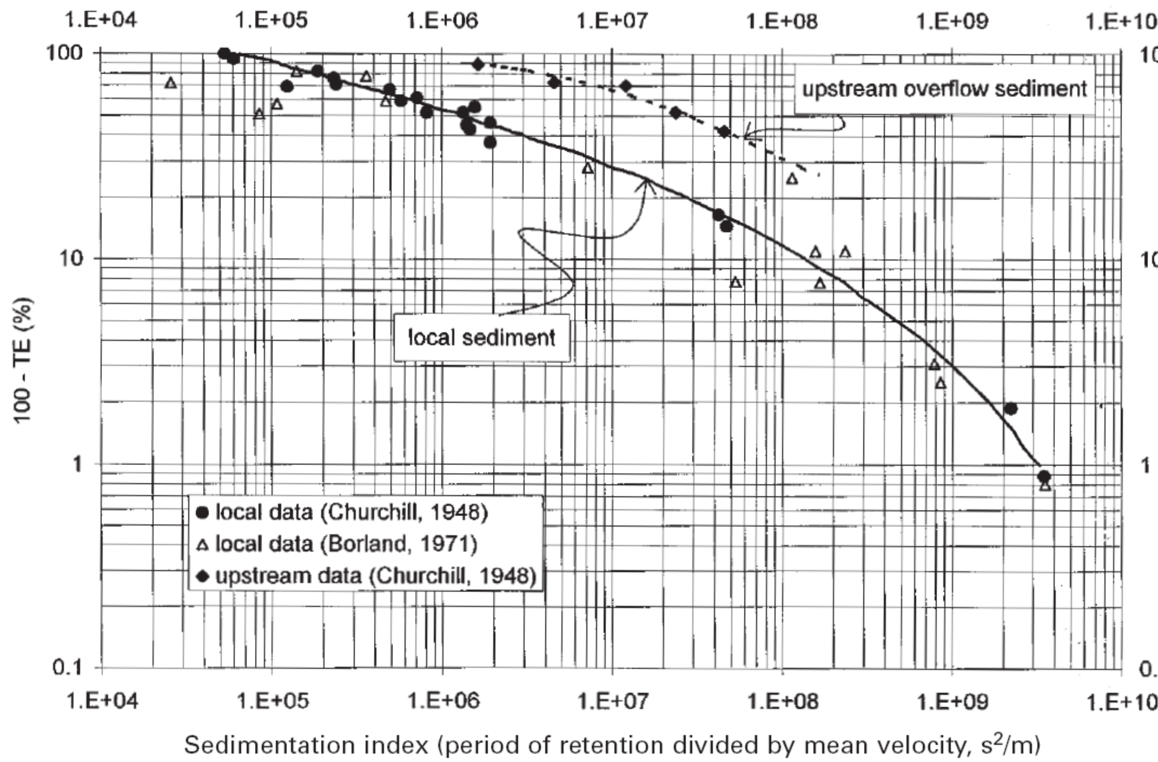

FIGURE 10: CHURCHILL'S CURVES FOR LOCAL AND UPSTREAM SEDIMENT, RELATING TRAP EFFICIENCY TO THE SEDIMENTATION INDEX, INCLUDING DATA FROM (BORLAND, 1971) – AFTER (VERSTRAETEN, G. AND POESEN, J., 2000)

2.3.3 BROWN CURVES

A third method to determine the Trap Efficiency is by using the ratio between the capacity of a reservoir versus the watershed. This capacity/watershed ratio is then connected to the Trap Efficiency (see Figure 11). The Trap Efficiency is in this figure described as C_T and the capacity/watershed ratio is expressed in the capacity of the reservoir S_R per square mile of drainage area.

The use of the capacity/watershed ratio (the C/W ratio), has the disadvantage that this parameter is not very reliable. The run-off production of the watershed (W) is highly depending on the soil characteristics, which differs heavily per watershed. This is the reason why for low C/W ratios (and therefore a relatively high W) the span of the Trap Efficiency is large.

This method therefore is not preferred if an estimation of the Trap Efficiency has to be made. However if other methods can't be used, a considerable uncertainty has got to be taken into account if the Brown curves are considered.

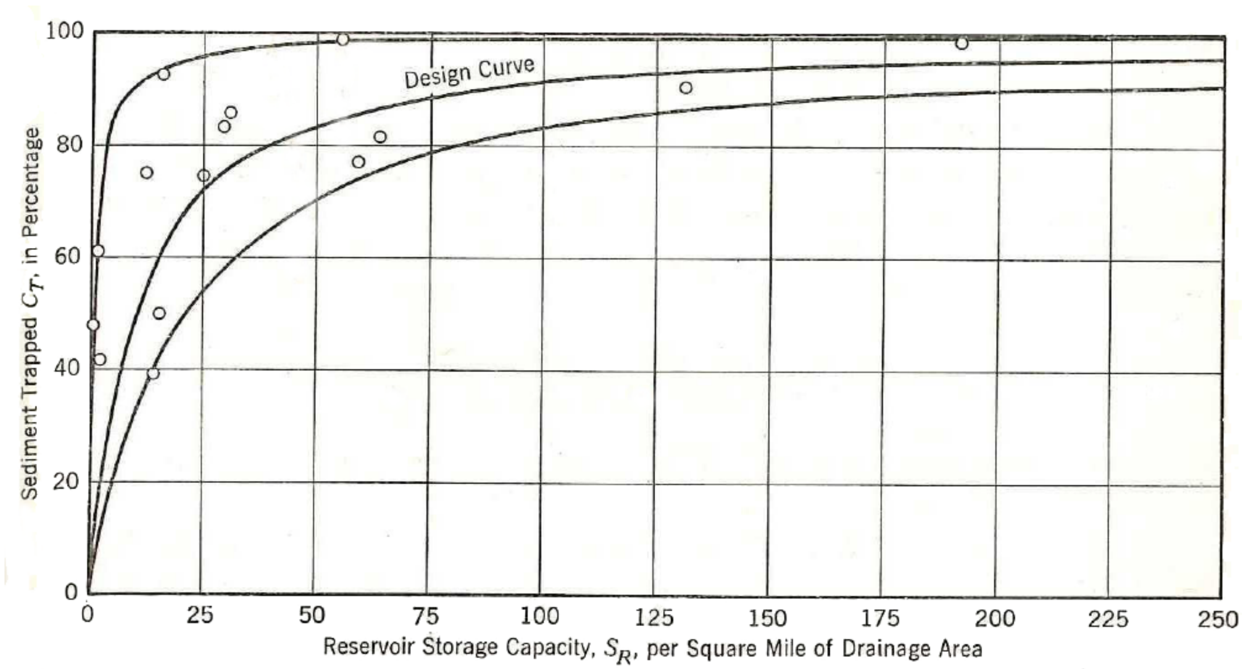

FIGURE 11: BROWN CURVES FOR CALCULATING THE TRAP EFFICIENCY USING THE CAPACITY/WATERSHED RATIO - (BROWN, 1943)

2.4 CONCLUSION RESERVOIR CLASSIFICATION AND SEDIMENT QUANTIFICATION

Multiple attempts have been made to generate a parameter that can be representative for a reservoir and describe its specifications. Due to the complexity en the enormous variation of the reservoirs, no clear method is available that can provide this distinction between reservoirs.

In this case, the parameters that are chosen to make a distinction between reservoirs are the shape of the reservoir, permitted reservoir operations and the capacity/inflow ratio. With these parameters, a classification is made of different types of reservoirs.

Different methods are available to quantify the reservoir sedimentation problem. In spite of recent developments in computer technology, computing a mathematical model to gain insight into the reservoir sedimentation problem still needs a lot of effort. Empirical models can deliver a first estimate of the sedimentation problems within a reservoir in a fast way however. Well known methods are the graphs of Brune, Churchill and Brown.

The basis for these empirical methods is founded by researchers quite some time ago (the 40's and the 50's). Although these methods have proven themselves and it is well known that there are some uncertainties within themselves, a remark regarding this aspect has got to be made. The development of the computer has made is possible to make detailed calculations with respect to reservoir sedimentation. This however will still take a lot of time to compute and that is why the empirical methods are still used. They have been updated and revised by a numerous of researchers, but the essence of these methods is still the same.

Within these models, the Churchill curves are preferred. This is because more aspects of the hydraulic conditions of the reservoir are taken into account, which will lead to a more accurate estimation of the Trap Efficiency. All the variables are not always available to calculate the Sedimentation Index, which is a necessary parameter for the Churchill curves. That is why the Brune curves are more widely used. If it is not possible to use the Churchill curves or the Brune curves, the Brown curves can be used to determine the Trap Efficiency. This will include a high rate of uncertainty of the Trap Efficiency.

Another note that has to be made is that the Trap Efficiency changes during time. The hydraulic conditions change when reservoir sedimentation occurs and this eventually will change the Trap Efficiency as well. This change has to be taken into account when the reservoir sedimentation calculations are carried out.

3 EXISTING RESERVOIR PRESERVATION METHODS

3.1 INTRODUCTION

Now that the reservoirs can be categorized into different classes, the next step is to describe the different techniques that are available to counteract the sedimentation processes in reservoirs.

Sedimentation takes place in every reservoir that has been constructed in a river. It is a process that is the consequence of building a water retaining structure and can generate serious problems in the reservoir, as described above. Various attempts have been made to generate a method that could preserve the reservoir capacity and counteract the sediment blockage in the river. The effectiveness of these methods is influenced by local circumstances and is depending on the specifications of each individual method.

The methods known nowadays can be used separately or combined, depending on the local circumstances. As described before, it is strongly depending on the local conditions to determine whether a certain method is feasible or not. Overall, the reservoir preservation methods can be divided into three different groups:

- Methods that reduce the inflow of sediment into a reservoir
- Methods that minimise the deposition of sediments in reservoirs
- Methods that remove the settled sediment

A further elaboration of these methods is discussed in the next paragraphs. Connections between the earlier discussed classifications and these reservoir preservation methods are then made, in order to generate an overview of which methods are preferred in which situation.

3.2 METHODS THAT REDUCE THE SEDIMENT INFLOW INTO A RESERVOIR

The principle of these methods is to avoid the sediments from entering the reservoir. Precaution measurements make sure that the sediment particles will not reach the reservoir, which results in a reservoir without any siltation problems. To avoid sediments from entering the reservoir, three methods are used.

The first method is to catch the sediment before it reaches the reservoir. With a relatively small dam structure, or any other sediment capture structure for that matter, the sediments upstream of the reservoir in question are captured and stored behind that structure. From there on, the sediments will be transported towards a storage site or brought back to the river downstream of the dam. The river is now mostly sediment free when it reaches the reservoir, which results in a reservoir where very few sediments settle.

This method has the advantage that sand particles won't reach the reservoir and therefore eliminates any siltation problems that could exist in the reservoir. However, the construction of the sediment capture structure is very costly. Also, the construction of such a structure has to fit into the local conditions, such as a suitable valley where the structure can be constructed, which is not always possible. The percentage of the sediments that is captured is very high, so this method can be considered as an effective method. Another advantage is the fact that there is hardly any loss of water volume. A considerable amount of water is needed in other reservoir preservation methods and this water cannot always be missed. Therefore, this could be one of the options if the complete volume of water in the reservoir is needed to make the dam structure feasible.

The second method that avoids sediments from reaching the reservoir consists of the construction of a bypass system to redirect the sediment flow. High river floods which carry lots of particles are diverted via a bypass system, such as a tunnel or a side channel.

As well as in the first method, expensive structures have to be built to avoid the sediments from entering the reservoir. An option to make this solution cheaper is to make use of the diversion channels that were constructed when the dam itself was build. These temporary channels are used to redirect the river flow during the construction of the dam and to make sure that the dam could be constructed under dry circumstances. To use them for sediment diversion, these channels have to fulfil some requirements. They will have to be capable of diverting the sediments without interfering with the useful functioning of the reservoir. Also, in- and outlet structures for the bypass channels are necessary with movable doors.

Not all the sediment within the river can be caught when this method is used. The sediment bypass is only used when there are sediment peaks. This is to make the method more efficient and to reduce the amount of water that is lost during the bypass operations.

The volume of water that is necessary for this method is large. During high water floods, which consist of a large volume of water but also a large volume of sediments, the bypass system can be used and sediments are prevented from entering the reservoir. These operations result in a great amount of water that is lost and this method can therefore only be used if these losses are acceptable and will not harm the functionality of the dam. A loss of a few percentage of the total water flow should be permitted when this method is applied. Another requirement for this method is that the river flow should consist of these high water floods.

The third method that is based on the reduction of the sediment inflow in a reservoir, tries to control the erosion of particles in the watershed upstream of the reservoir. The amount of sediment that ends up in the river can be minimised in this way.

This is done by influencing the amount of sediment that is eroding away from the subsurface, when precipitation falls onto the subsurface and flows away. By reducing the amount of particles that are carried along by the water, the amount of sediments that enter the reservoir can be reduced as well. This is done by managing the soil erosion in the watershed and increasing the amount of vegetation in the watershed area. The roots of plants, grass and trees are capable of keeping the soil together and reduce the amount of particles that are eroding away from the subsurface.

It is a relatively cheap method which is very environmentally friendly. It is however a very comprehensive method which will need a rather extensive rate of cooperation with local communities and stakeholders for it to be effective. And even then, a considerable amount of sediments will still enter the reservoir, since the vegetation is not capable of retaining all the sediment particles. This method has therefore a low effectiveness. Another disadvantage is that this method has to compete against the worldwide deforestation trend which counteracts the means of this method.

3.3 Methods that minimise the deposition of sediments in reservoirs

The basic principle of these methods is to avoid the settling of sediments that have already entered the reservoir. This can be done by using the hydraulics of the flow to avoid settling of the sediments or to induce erosion of the already settled sediments. To be successful, it is essential for these methods that the velocity of the flow stays sufficiently high and it is necessary that the dam has bottom outlets. The location of the bottom outlets is shown in Figure 12.

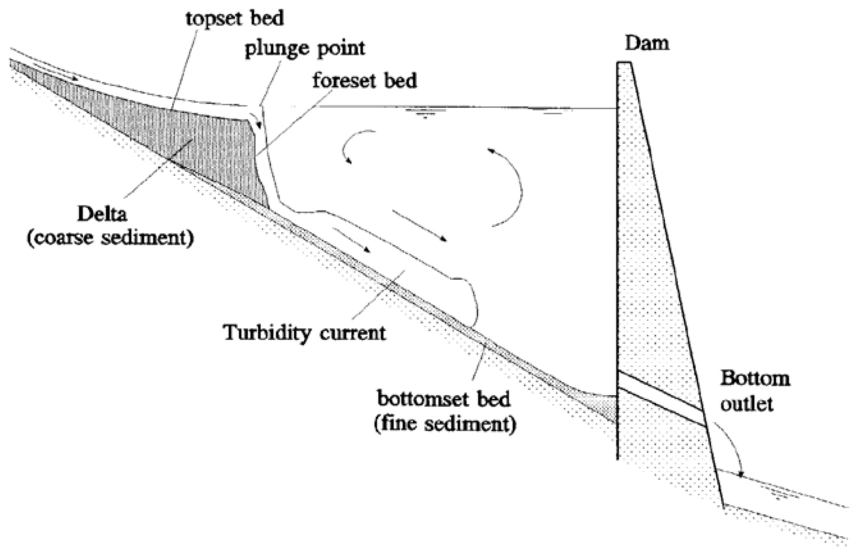

FIGURE 12: LOCATION OF THE BOTTOM OUTLETS OF A DAM AND AN EXAMPLE OF A DENSITY CURRENT (SLOFF, C.J., 1997)

The first method that avoids entered sediments from settling in the reservoir is when density currents are used. Density currents are defined as the movement of a fluid through another fluid with a different density. They occur in reservoirs due to differences in concentration of suspended solids, salt concentration or temperature concentration. It is formed when the turbid river inflow plunges below the clear reservoir water and continues as a density underflow. Other processes can also generate them, such as an underwater slide. The low velocity currents are capable of transporting large quantities of sediments over long distances. An example of a density current is shown in Figure 12, were also the bottom outlets are displayed. When the density current reaches the dam, the bottom outlets are opened so that the current can pass the dam.

The big advantage of this method is that the water level in the reservoir doesn't have to be lowered. Only a fraction of the total water volume will be lost when the density current is transported through the dam. This makes the technique attractive for cases where big losses of water are not acceptable.

However, predicting density currents is difficult. There are lots of uncertainties regarding the conditions on which a density current occurs. This makes the method not very reliable. It also transports only a part of the total sediment load out of the reservoir, which means that a significant part will still settle. And above all, not all dams will be suitable for this method since bottom outlets are required for this method.

The other method that minimises the settling of sediments by using the hydraulics of the flow is "Sluicing". The principle of this method is to let high water floods with proportional high sediment peaks immediately through the dam.

The high water floods, which usually occur during flood seasons, carry a substantial amount of sediments and are immediately let through the dam. Bottom outlets in the dam or flood channels are therefore necessary. It is essential that the sediments are kept in suspension and that means that the water flow cannot calm down. Because coarse sediments settle down more easily, this method is more successful with smaller particles, such as clays and silts, which have a much lower settling velocity.

Because sediments only pass the dam during high water peaks, sediments still are going to settle in the reservoir during normal circumstances. Therefore, this method will not prevent that sediments will still settle in the reservoir and the efficiency of this method is usually low. Under some circumstances however, if the conditions are right, 45% or even more per cent of the incoming sediment load can be sluiced through the dam (like for instance the Iril Emda reservoir in Algeria[8]).

The advantage of this method is that the investment costs are not extremely high. The costs of the installation of bottom outlets in the dam are still considerable, but compared with other methods are these investments relatively low.

A significant amount of water is lost during sluicing operations, which makes this solution only feasible if this loss can be afforded. It is also essential that high water flows occur in the river, so that these peak flows can be used to sluice the flows and their sediments out of the reservoir.

To increase the effectiveness of the sluicing operations, the following properties of the reservoir are preferred (Sloff, C.J., 1991):

- A short reservoir with large incoming discharge
- Reservoirs with high density concentration
- Reservoirs with low large outlets
- Reservoirs with high outflow

3.4 Methods that remove accumulated sediments

The last group of methods is the group were the sediments have already settled in the reservoir and need to be removed. They can be added to the river downstream of the dam or transported to a storage site close by.

The first method that removes accumulated sediments is called "flushing". When flushing is implemented, sediments that have settled on the bottom of the reservoir are washed out from the reservoir. This can be done by lowering the water level of the reservoir and opening the bottom

[8] New methods of sediment control in reservoirs - (Duquennois, 1956)

sluices of the dam. Now that the water level is brought down, the water is carving through the deposits and the turbulent motion starts to stir up the particles again. The sediment loaded water is then transported through the bottom sluices of the dam, where it adds its particles to the river.

The method has its highest efficiency rate when the water level in the reservoir is brought completely down, so that the water can flow fast through the deposits and has its highest erosion rates. This is also the biggest disadvantage of flushing. A lot of water is lost with this operation, because of the water level drop that is necessary to flush out the sediments. White (2001) states that at least 10% of the mean annual run-off is required for effective flushing[9]. Flushing discharges of at least twice the mean annual flow are also required to achieve a sufficient turbulent flow. This method is in general suitable for smaller reservoirs, where the storage capacity is smaller than 30% of the mean annual inflow.

Not all the particles can be transported out of the reservoir when this method is used. There is still a considerable amount that stays in the reservoir. The efficiency rate depends strongly on the shape of the reservoir and the type of sediments. Silt and clay are kept longer in suspension than (coarse) sand for instance, and will therefore be more easily transported out of the reservoir. Another critical point is that not all reservoirs are suitable for flushing operations. Because of the fact that the sediment has to be kept in suspension, this method works better in reservoirs that have a steep bottom profile. A narrow reservoir is also preferred, so that sediments won't consolidate far away from the flushing channel.

Besides flushing, settled sediments can also be removed by using dredging or mechanical means. Equipment that is normally used for sediment removal within rivers or for sediment removal at the coast can be used for the removal of sediment particles out of a reservoir.

If dredging equipment can be transported towards the reservoir, it may be possible to dredge. This is quite an extensive operation, since a dredging unit is usually of a considerable size and the location of the reservoir is most of the time situated in a mountainous and remote environment.

The operational costs for this method are high. Every cubical meter has to be dredged out of the reservoir and this makes the method expensive. The operation results in a peak load of sediment and this cannot be added straight away to the river. A storage site of a considerable size is therefore necessary to store the excavated sediments.

The effectiveness of this method however is high. It is, in contrast to other methods, possible to excavate sediments at an exact location and the amount of sediments that will be removed can be controlled as well. The amount of water that is lost during this operation is very little, since the water level of the reservoir doesn't have to be lowered. The only amount of water that is used is water that is necessary to transport the sediments from the excavation site towards the storage site.

[9] Evacuation of sediments from reservoirs – White (2001)

As mentioned earlier, different types of excavation and dredging equipment can be used. A cutter suction dredger has a high production rate, but has the disadvantage that the unit is very large and cannot be installed easily. This method is especially for small and remote reservoirs not desirable. In this case is mechanical operation equipment, like a backhoe, more suitable. This type of equipment is relatively small and easier to install. The disadvantage is that it has a lower production rate.

A process that could be interesting for removing sediments from reservoirs is the breaching process (see also Figure 14). Breaching is the occurrence of instabilities on a sandy slope causing a density flow running downwards from the slope. The big advantage is that it uses a relatively simple installation, which consists of a pontoon, a suction tube, a dredge pump and a discharge pipeline. The suction tube is lowered to a certain depth in a sand layer, where a hole is created around the suction mouth. The walls of this hole are almost vertical and when time passes, these walls will move away from the suction tube. The sand will flow over a certain slope towards the suction mouth.

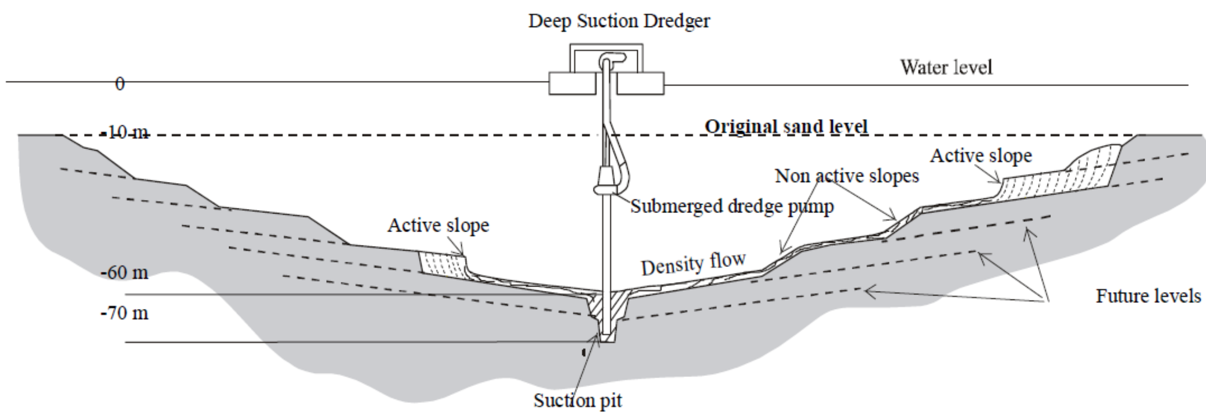

FIGURE 13: THE BREACHING PROCESS - (VAN RHEE, PROF. DR. IR. C., 2003)

The simplicity of the installation makes is possible to use it in places where other suction dredgers, like the cutter suction dredger, are not applicable. The production and the accuracy for this type of dredging is high, which makes the method very effective. It can be used at great depths, which is very convenient for reservoirs with high water levels.

The downside is that the sediments meanly have to consist of sand. This coarser material is usually found in the delta part of the reservoir, where the river enters the reservoir. Another downside effect is that storage sites are necessary, since most of the sediment cannot be delivered directly to the river due to the damage that the enormous amount of sediment will do to the environment downstream of the dam.

This system is therefore only effective in reservoirs with (coarse) sand deposits and with sufficient space for storage sites. If the deposits are not polluted, the dredged up sand can even be sold.

3.5 Combining reservoir classification and reservoir preservation methods

Now that the reservoir preservation methods have been discussed, the connection between the different reservoir preservation methods and the different types of reservoirs can be made. This overall approach makes it possible to describe which method is in general suitable for which type of reservoir. The final decision of which reservoir preservation type to use, can only be made after a thorough research of the local circumstances, discussions with all the stakeholders involved and evaluations made by experienced engineers.

The combination of the reservoir preservation methods and the classifications of the reservoirs are presented in a table, where the methods are valued with respect to the applicability of that method. If a method is valued with a '+', the method is suitable for that particular reservoir type. If the method is valued with a '+/-', the method has no significant advantages or disadvantages for that reservoir type. If the method is not suitable for the reservoir type, the method is valued with a '-'.

3.5.1 Empirical Area-Reduction method

For the classification based on the Empirical Area-Reduction method, the reservoirs are divided into 4 different types (see also paragraph 2.2.1)

- Gorge
- Hill
- Flood plain-foothill
- Lake

These classes are combined with the reservoir techniques and this is presented in Table 2.

TABLE 2: EMPIRICAL AREA-REDUCTION CLASSIFICATION VERSUS RESERVOIR PRESERVATION METHODS

	Methods that reduce sediment inflow			**Methods that minimise sediment deposition**		**Methods that remove accumulated sediment**		
Classification	Sediment catchment structure	Sediment bypass	Watershed management	Density currents	Sluicing	Flushing	Dredging	Mechanical excavation
Type IV: Gorge	+/-	+	+/-	+	+	+	+/-	+/-
Type III: Hill	+/-	+	+/-	+/-	+/-	+/-	+/-	+/-
Type II: Flood plain-foothill	+/-	+/-	+/-	-	-	-	+	+
Type I: Lake	+/-	-	+/-	-	-	-	+	+

A few remarks have to be made with respect to the values within this table.

- The sediment catchment structure can be used in all different types of reservoirs.
- The sediment bypass can in general be more useful for steeper reservoirs. This is due to the fact that for flatter slopes, longer bypass channels are needed and these longer bypass channels are more costly.
- Watershed method can be used for all different types of reservoirs.
- Density currents are more likely to be effective in steeper reservoirs. Therefore, this method is more suitable for a Hill type reservoir and especially a Gorge type reservoir.
- Sluicing is a more effective method in steeper reservoirs, because the sediments will be kept much longer in suspension. The steeper reservoirs are therefore more suitable for this method.
- Flushing is more effective in steeper reservoirs, due to their capability of maintaining turbulent conditions within the flow. The steeper reservoirs are therefore more suitable for this method.
- Dredging can be done in all different types of reservoirs, but the sediments are more scattered in the flatter reservoirs. This result in the fact that particles are well-spread over the bottom of the reservoir, which makes is easier to dredge up a specific type of particles. The flatter reservoirs are therefore rated as more suitable than the steeper reservoirs.
- The reasoning done for Dredging also yields for Mechanical excavation.

3.5.2 PERMITTED RESERVOIR OPERATIONS

As described in the previous paragraphs, some reservoir preservation methods are highly benefited if the water level in the reservoir can be brought down. This is in contrast to some of the other methods, that can't be applied when the water level is lowered. The combination of the permitted reservoir operations and the reservoir preservation methods is therefore necessary.

The permitted reservoir operations are divided into three classes: it is allowed to fully draw down the water level, it is allowed to partially draw down the water level and drawing down the water level is not allowed at all. An overview of the combination between the permitted reservoir operations and the reservoir preservation methods is given in Table 3.

TABLE 3: PERMITTED RESERVOIR OPERATIONS VERSUS RESERVOIR PRESERVATION METHODS

	Methods that reduce sediment inflow			**Methods that minimise sediment deposition**		**Methods that remove accumulated sediment**		
Permitted reservoir operation	Sediment catchment structure	Sediment bypass	Watershed management	Density currents	Sluicing	Flushing	Dredging	Mechanical excavation
Fully draw down	+/-	+	+/-	Not possible	Not possible	+	Not possible	+
Partially draw down	+/-	+/-	+/-	+	+	+/-	+/-	+/-
No draw down	+/-	+/-	+/-	+/-	+/-	-	+	+/-

A few remarks have to be made with respect to the values within this table.

- For sediment catchment structure, it is irrelevant if it is permitted to draw down the water level or not.
- The sediment bypass structure is a bit more suitable if the water level is completely brought down. This is because of the fact that the complete sediment load can be diverted through the channels. Using sediment bypass when the water level is brought down is only functional however if there are no bottom outlets in the dam. This is because of the fact that when bottom outlets are available, it is more efficient to flush the sediment through the outlets. In this way, already settled sediments can be flushed away as well.
- The influence of drawing down the water level or not is not relevant for the watershed management method.
- For sluicing and density currents, drawing down the water level has positive effects on the efficiency and therefore the suitability of the method. This is because the travel distance of the density currents and the sluiced sediments will be shorter. A full draw down makes these methods unrealizable, since the means of these methods are to transport the sediments while they are in suspension in the reservoir. When the water level is fully drawn down, density currents or sluicing is therefore 'not possible'.
- The suitability of flushing is growing significantly if the water level is brought down. Especially when the water level is completely drawn down, it will have positive effects on the amount of sediment that is flushed out.

- Because a dredging unit needs to float on the water, it is essential that the water level in a reservoir is not completely brought down. For a partial draw down of the water level, some parts of the settled sediment are above the water line and can't be dredged up. The positive effect though is that the deeper parts of the reservoir are now better accessible. Since it has a significant positive and negative effect, this combination is valued as'+/-'.
- For mechanical excavation, a fully draw down of the reservoir results in a better accessibility of the settled sediments.

3.5.3 *Capacity-Inflow ratio*

The last classification that has to be linked to the reservoir preservation methods, is the classification based on the capacity-inflow ratio (C/I ratio), where C is the capacity of the reservoir and I the total water inflow in the reservoir per year. The C/I ratio is representing the refreshing time of the reservoir. In other words, the time (in years) that is needed to completely replace the water volume within a reservoir.

Within this classification, a distinction is made based on the C/I ratio that is bigger than 1 year, smaller than 0.5 year or reservoirs that have a C/I ratio between 0.5 and 1years.An overview of the combinations between the capacity-inflow ratio and the reservoir preservation methods is given in Table 4.

TABLE 4: CAPACITY-INFLOW RATIO VERSUS RESERVOIR PRESERVATION METHODS

	Methods that reduce sediment inflow			**Methods that minimise sediment deposition**		**Methods that remove accumulated sediment**		
Classification	Sediment catchment structure	Sediment bypass	Watershed management	Density currents	Sluicing	Flushing	Dredging	Mechanical excavation
C/I > 1	+/-	+/-	+/-	-	-	-	+/-	+/-
0.5 < C/I < 1	+/-	+/-	+/-	+/-	+/-	+	+/-	+/-
C/I < 0.5	+/-	+	+/-	+	+	+	+/-	+/-

A few remarks have to be made with respect to the values within this table.

- The C/I ratio has no influence on the sediment catchment structure.
- For the sediment bypass structure it can be an advantage if the C/I ratio is low. The relative fast refreshment of the reservoir volume could mean that the river contains high water floods, which gives the ideal sediment peaks that can be used to bypass the dam structures. A low C/I ratio is therefore rated as more suitable.

- For the watershed management method, the C/I ratio is irrelevant. This because sediment is caught before it can enter the reservoir, and reservoir specifications (like the C/I ratio) are therefore not relevant.
- Reservoirs that have a relative quick refreshing time are in general more suitable for sluicing operations and density currents. Water is flowing faster through the reservoir and is therefore more suitable to transport suspended sediments through the reservoir.
- Flushing operations are much more economical if the reservoir volume can be brought back to the original level relatively quick. C/I ratios that are relatively high are therefore preferable if the flushing method is implemented.
- For dredging operations and mechanical excavation, the C/I ratio is of no importance.

3.6 Conclusion existing reservoir preservation methods

The overview of the Tables from Paragraph 3.5.1 to Paragraph 3.5.3 can now be used to give a first estimation about which reservoir preservation technique can be used when reservoir sedimentation is becoming a problem.

At any time, a more extensive research is necessary to decide which method has to be implemented. It is possible to use a combination of methods. This is depending on the local circumstances in combination with the preferences of the involved stakeholders.

An example of the fact that local circumstances can be decisive for the reservoir preservation technique that has to be used is given in Figure 14. A long or flat reservoir is considered not to be suitable for a bypass system. But as can be seen in Figure 14, the local circumstances are creating a different scenario. Although this is a very long reservoir where normally the costs of a construction of a bypass would be considerable, in this case it’s not due to the shape of the reservoir.

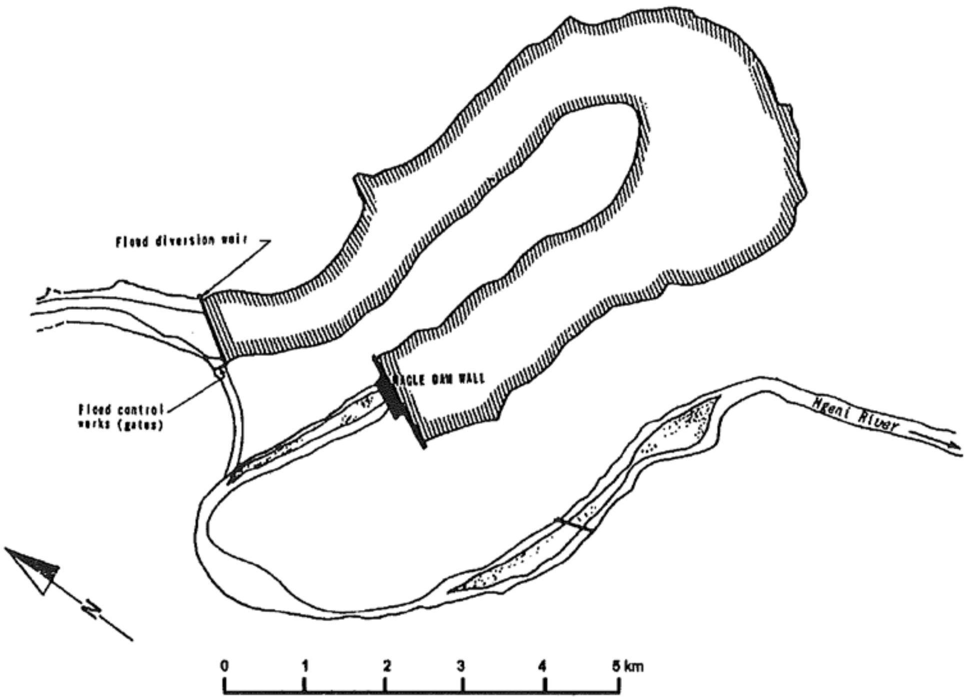

FIGURE 14: THE NAGLE RESERVOIR WITH OPEN CHANNEL SEDIMENT BYPASS FACILITY – FROM (BATUCA, D. AND JORDAAN J., 2000)

An overview of the specifications of each reservoir preservation method is given in Table 5. The table shows that every preservation method has to meet specific requirements for the method to be applicable. It is important to keep in mind that this table only provides a general indication of the properties and effectiveness of the discussed reservoir preservation methods.

An overview of the different steps that have to be made when reservoir sedimentation is going to hinder the functionality of the reservoir is presented in Figure 15. The flow chart divides the problem in two parts: the part where the reservoir has to be classified with the methods discussed in the previous paragraphs and the part where the sedimentation problem is quantified. As can be seen in the flow chart, the quantification should be preferably done with the help of the Sedimentation Index. If that's not possible, the Capacity/Inflow ratio should be used. If this information is also not available, the Capacity/Watershed ratio can be used to quantify the sedimentation problem.

TABLE 5: OVERVIEW OF THE RESERVOIR PRESERVATION METHODS

Method	Advantages	Disadvantages	Requirements	Impact on river morphology and reservoir capacity
Methods that reduce sediment inflow				
• Sediment catchment structure	- high sediment catchment rate - no water losses	- expensive	- storage site - suitable location	- minor loss of reservoir capacity - erosion downstream
• Bypass	- relatively cheap, if diversion tunnels can be used - no water level drop	- expensive, if diversion tunnels can't be used - not all sediments are captured - loss of water volume	- high water floods - bypass channel with movable doors	- some loss of the reservoir capacity - some erosion downstream - high sediment loads downstream
• Watershed management	- cheap - environmentally friendly - no water losses	- effects are noticeable after a considerable amount of time	- cooperative communities	- high loss of reservoir capacity - erosion downstream
Methods that minimise sediment deposition				
• Use density currents	- no water level drop - low water losses	- difficult to predict - very specific conditions required	- bottom outlets	- loss of reservoir capacity - erosion downstream - high sediment loads downstream

		- some water losses		
• Sluicing	- no water level drop	- very specific conditions required - some water losses	- high water floods - bottom outlets	- loss of reservoir capacity - erosion downstream - high sediment loads downstream
Methods that remove accumulated sediment				
• Flushing	- significant sediment removal	- high water losses - lowering water level necessary	- bottom outlets - steep/narrow reservoir for effective flushing	- high sediment loads downstream - some loss of reservoir capacity
• Dredging	- significant sediment removal - no water level drop	- expensive - very high sediment loads	- easy accessible reservoir - storage site	- high sediment loads downstream - some loss of reservoir capacity
• Mechanical excavation	- significant sediment removal - no water level drop	- expensive - high sediment loads	- storage site	- high sediment loads downstream - some loss of reservoir capacity

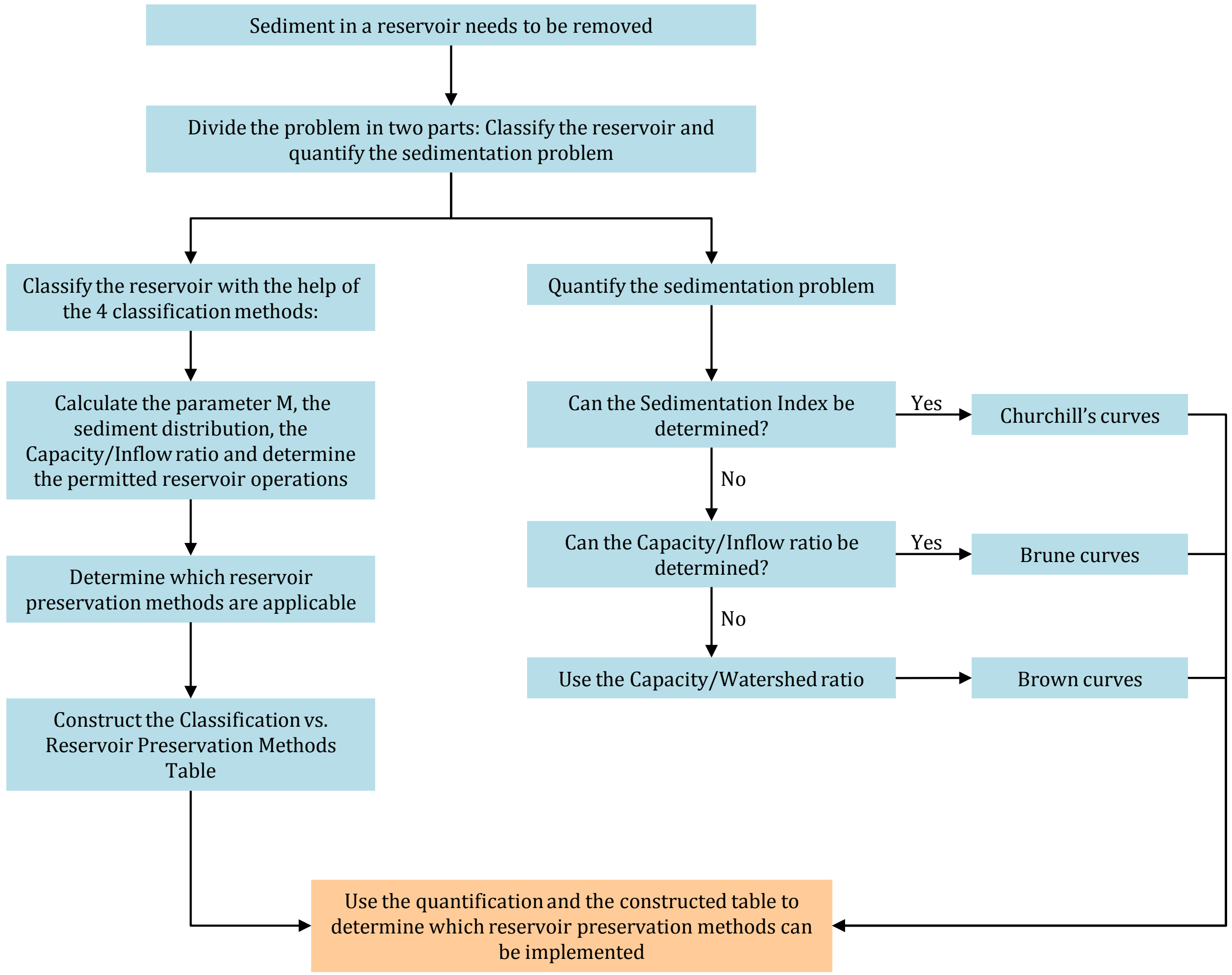

FIGURE 15: RESERVOIR SEDIMENTATION FLOW CHART

4 WATER INJECTION DREDGING AS A NEW RESERVOIR PRESERVATION METHOD

4.1 INTRODUCTION

The orientation and the analysis done in the previous chapters have resulted in an overview of methods to classify reservoirs, methods to estimate the quantity of sediments that settle in a reservoir and an overall overview off the methods that can be used to counteract reservoir sedimentation. The next step is to do more research in order to find a new method that can contribute to the sedimentation problem in reservoirs.

Research is done by using knowledge from the dredging industry and put that in the perspective of this thesis. One of the interesting options in this case is using Water Injection Dredging in reservoirs. In the following paragraphs, more information is given about this dredging technique. The option of Water Injection Dredging in a reservoir is discussed and a model for the production and cost estimation of Water Injection Dredging is constructed. At the end of this chapter, the option of using Water Injection Dredging in reservoirs is evaluated.

4.2 WATER INJECTION DREDGING

The basic principle of Water Injection Dredging is that water is injected in the top layer of the bottom, where the material from the bottom is stirred up and transported away under the influence of gravity. More specifically, the Water Injection Dredger consists of a water jet array which is lowered to the bottom. The water jet nozzles penetrate the bed and inject large amounts of water to stir up the bed material. Because the bottom material is now suspended in the water, the density of the mixture decreases until it becomes a liquid. This liquid will have a higher density than the ambient water and will start flowing under the influence of gravity towards lower situated areas (see also Figure 16).

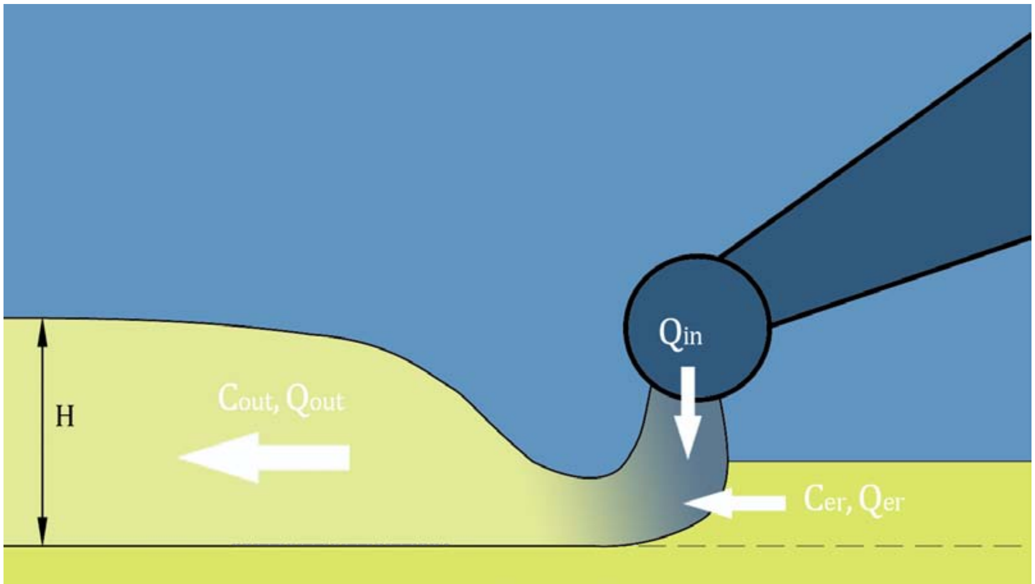

FIGURE 16: A DENSITY CURRENT CREATED BY WATER INJECTION DREDGING

The success of this method depends on the suspension characteristics of the sediment. If particles are small and the suspension time of the particles is large, the transport distance of the density current can be significant. Sand or other coarser material has a relatively high settling velocity, which means that the suspension time is very low. Clay and Silt on the other hand are kept much longer in suspension and will therefore be much more suitable for Water Injection Dredging. If the material gets too cohesive though, the particles will be kept together and can act as a bigger particle. This means that the clustered particles will settle much faster and will not be transported over a very long distance. A more detailed explanation of the requirements for Water Injection Dredging will be discussed in Paragraph 4.3.

The origin of this dredging method lies in the dredging of channels and harbours, where the density currents uses the natural slope of the bottom to transport the material out of the harbour or channel towards lower situated areas. At first a transport gully is dredged with the Water Injection Dredger, to make sure that the density currents can be transported over the needed distance. After that, material that is put in suspension by the Water Injection Dredger is flowing, under the influence of gravity, via the gully towards the deposit site.

The advantage of this method is that the material does not have to be picked up and transported to the deposit site. Other dredger types bring the sediment up towards the water level and pump the mixture towards a storage site, which takes a lot of energy. Water Injection Dredging on the other hand uses the natural slope of the bottom to transport the material and this makes the method much cheaper than other dredging methods.

Another big advantage is the fact that the water level of the reservoir does not have to be lowered. Lowering the water level for sediment removal is a very time consuming and costly process, which may take months. During this time, the reservoir loses his functionality and cannot be used for its design purpose. With Water Injection Dredging, lowering the water level is not necessary for sediment removal. The only water that is spilled is the mixture of sediment and water that is released through the bottom outlets when the density current is let through the dam.

A big disadvantage of Water Injection Dredging is the high sediment peaks it creates. Because Water Injection Dredging can be very productive and delivers high sediment peaks, the river downstream is not always capable of coping with that sediment load. An investigation on the local downstream conditions will be necessary to find out which sediment loads can be delivered back into the river.

The installation necessary for Water Injection Dredging is relatively simple. A small (tug)boat can provide the needed mobility and propulsion, while an installation on board of the ship pumps the water towards the water jet arrays (see Figure 17). It is even possible to design containerized Water Injection Dredging units which can be easily mounted on suitable vessels, where only a few adaptations are necessary[10]. This makes it possible to dismantle a Water Injection Unit quickly and transport it to other locations.

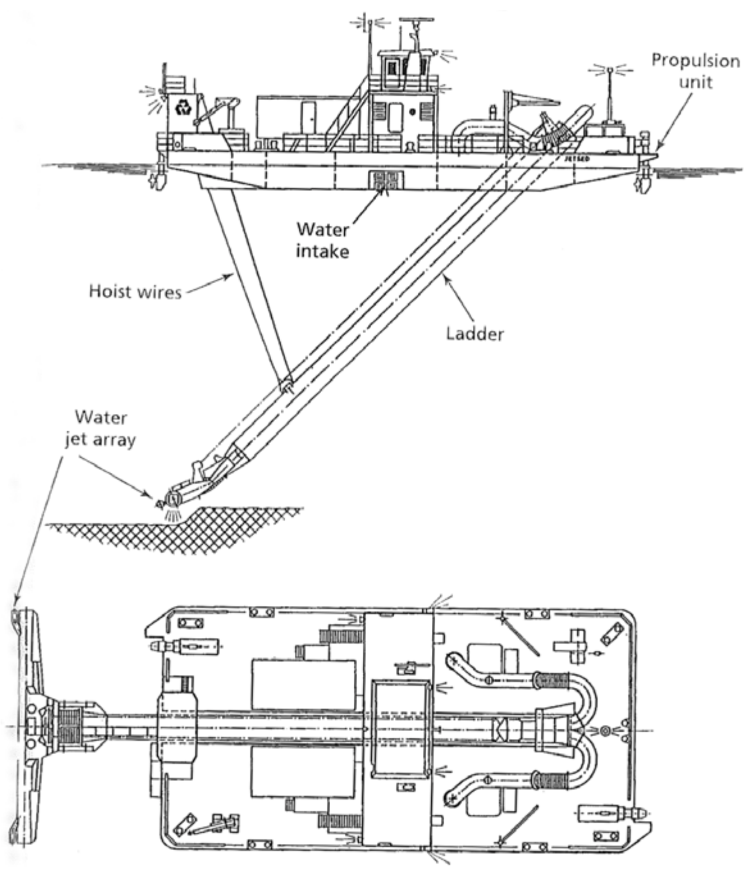

FIGURE 17: SKETCH OF A WATER INJECTION DREDGER – FROM (BRAY, ENVIRONMENTAL ASPECTS OF DREDGING, 2008)

[10] A special unit for water injection dredgers - (De Vries, G. and Beyen, J., 2009)

The production of a Water Injection Dredger can be significant. Production rates of 2804 m^3/hr have been reported[11], with a proportional cost rate of 0.37 \$/m^3. The production rate is highly dependent on the local circumstances. As said, sediment characteristics are an important parameter, but also the bathymetry of the channel plays an important role. This is also the biggest disadvantage of this dredging method. Due to the restricted circumstances where Water Injection Dredging can be effective, it cannot always be implemented.

4.3 Requirements for water injection dredging

Some local requirements have to be met if Water Injection Dredging is going to be applied. A long, straight channel is preferred to provide the ideal circumstances for the density current to travel long distances. It makes it much easier for the operator of the Water Injection Dredger to maintain a constant downward slope, so that the flow mixture can travel far.

For Water Injection Dredging, smaller particles are preferred. The suspension time of clay and silt is much longer than sand or other coarser materials, so these materials can be transported over longer distances. Grain sizes smaller than 0.2 mm are therefore much more suitable for Water Injection Dredging. The highest production rates that where produced in the U.S. waterways where achieved with soil that is classified as Silt[12].

Water Injection Dredging results achieved in the Elbe estuary clearly show that particles smaller than 0.2 mm are much more sensitive for Water Injection Dredging than particles bigger than 0.2 mm (see also Figure 18). The classification map on the right side shows that the finer silt particles, which are marked blue, are mostly gone after Water Injection Dredging has been carried out. This means that the median grain size of the particles must be much smaller than 2 mm, so that all the particles will be affected by the Water Injection Dredger.

If the sediment particles are too small though, they can be subjected to flocculation. This is the process of fine, cohesive particles that aggregate together into bigger particles. This aggregation results in higher settling velocities of the particles, which have a negative influence on the sediment transport rate of density currents. The agglomeration of particles is depending on the cohesive and plasticity properties of the sediment. Since sediment characteristics can be extremely diverse, the flocculation of sediment particles is difficult to predict. A strict boundary of the size of the sediment particles is therefore not possible to provide.

[11] Water injection dredging in U.S. waterways, history and expectations - (Wilson, 2007)
[12] Water injection dredging in U.S. waterways, history and expectations - (Wilson, 2007)

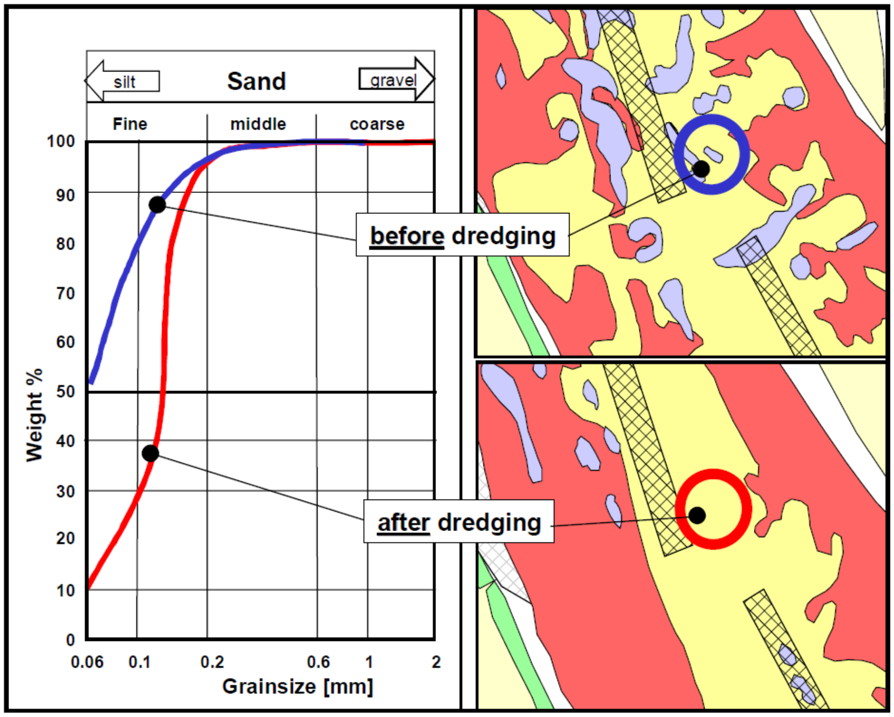

FIGURE 18: CHANGE IN SEABED CHARACTERISTICS, BEFORE AND AFTER DREDGING WITH A WATER INJECTION DREDGER – FROM (MAUSHAKE, C. AND COLLINS, W.T., 2002)

An important note is that Water Injection Dredging does not remove sediments, it only repositions is to lower situated areas. From there on, it can be dredged up with other dredging equipment or be transported away by currents.

The following requirements should be taken in account, if Water Injection Dredging wants to be implemented:

- A lower situated deposit site should be available, where the density current can deposit the sediments
- A channel with a slope of 10^{-3} or steeper, so that the density current can flow under the influence of gravity
- The grain sizes should smaller than 0.2 mm for the method to be effective
- A long straight channel is preferred so that the density current can continue to flow without meeting any obstacles
- The pump capacity of the Water Injection Dredger may range from 3.000 to 12.000 m^3/hr, see also (Bray, Environmental Aspects of Dredging, 2008)

4.4 Applying Water Injection Dredging in Reservoirs

Compared with the normal conditions of a Water Injection Dredger, working conditions in a reservoir are relatively calm. Only small wind waves occur in a reservoir lake, which means that the dredger will have little trouble with the roll motions of the ship.

Besides the fact that the reservoir has to fulfil the requirements for Water Injection Dredging, which are mentioned in the previous paragraph, it also needs to fulfil some extra requirements:

- Bottom outlets are necessary in the dam structure. The created density currents have to be able to transport the sediments out of the reservoir. Sufficiently large and rightly located bottom outlets are therefore necessary. With the term rightly located bottom outlets is meant that the outlets must be located at a sufficiently low point of the dam, so that the density current can pass through the dam. A bypass channel could also fulfil this function, but these structures are usually not as effective as bottom outlets. An exception to this requirement is when the Water Injection Dredger is only used to transport the sediments within the reservoir itself. This can be done when the sediments need to be transported towards a collection point within the reservoir or when the effective storage of the reservoir needs to be increased (see also Paragraph 4.5: Dead storage).
- Because the sediments are brought back into the river system, the sediment mixture may not be polluted. Samples taken from the reservoir should provide the information necessary to determine whether or not it is acceptable to bring the sediments back into the river.
- The river downstream of the dam should be able to cope with the sediment peak that is the result of the Water Injection activities. A dispersion of the sediment load is not possible, so the river has to deal with large volumes of sediments that are added to the river system.

4.5 Dead storage

The dead storage of a reservoir is the volume of the reservoir that is beneath the water intake or the outlets of a dam. This volume can be considered as not usable since this part of the reservoir will always be filled with water. The dead storage volume is situated below any outlets or water intakes (see also Figure 19).

If there are no bottom outlets available, it is possible to transport the sediment towards the dead storage of the reservoir. With this sediment replacement, the effective volume of the reservoir will be restored and the dead storage will be filled with the sediments. This is not a sustainable solution, since the core of the problem is not counteracted. But it can be an option if the reservoir specifications allow these operations.

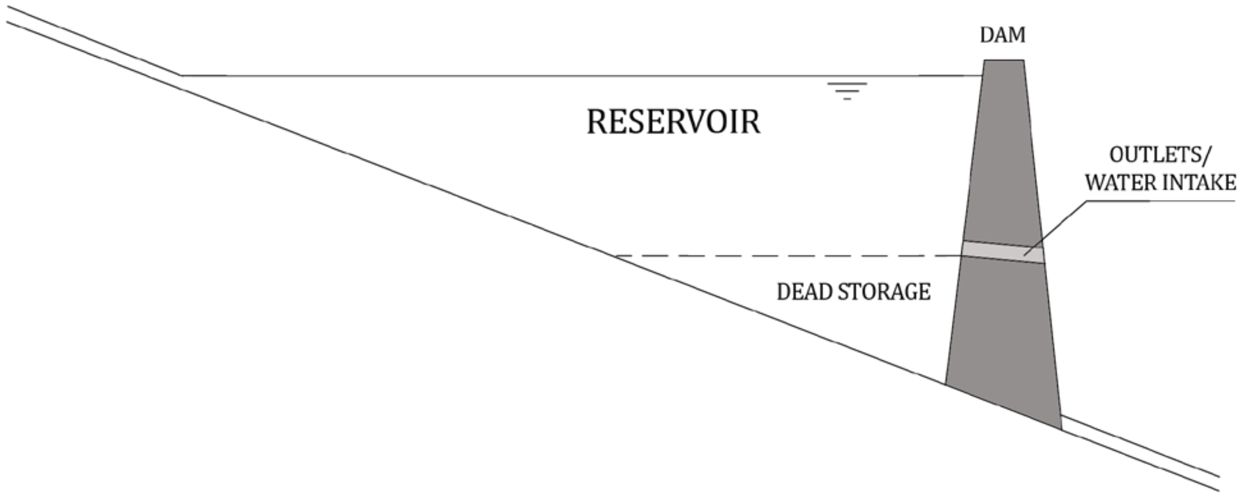

FIGURE 19: DEAD STORAGE WITHIN A RESERVOIR

4.6 Production estimation of Water Injection Dredging

An estimation of the expected sediment removal production is necessary to determine if Water Injection Dredging is effective method to counteract the sedimentation problems in a reservoir. If the expected production of Water Injection Dredging is low, other sediment removal methods are more likely to be suitable for that particular reservoir.

A simple model has been constructed to calculate the production rates of different reservoir preservation methods. Various parameters that describe the reservoir specification techniques are taken into account within this sheet. This has also been done for Water Injection Dredging, so that the production rate of Water Injection Dredging can be compared with conventional reservoir preservation techniques.

Because Water Injection Dredging is a relatively new dredging technique, not much information is available to calculate the production rates. Therefore, the used production estimation is based on three basic processes of Water Injection Dredging. These processes are:

- The process of detaching the sediments from the bottom
- The horizontal movement of the created density current
- The settling process of the sediment particles

These processes combined provide an estimation of the detaching process and the travel distance of the density current. A detailed description of the used calculation methods for the production of Water Injection Dredging is provided in Appendix A.3.1. A short description of the used methodology and an elaboration of the used parameters are discussed here.

When a water jet is placed just above a bed of a certain reservoir, the water will intrude the bottom up to a certain depth. This depth is depending on soil characteristics, the flow velocity of the injected water and the velocity of the Water Injection Dredging vessel. The relationship between the velocity of the vessel and the penetration depth of the injected water needs more research. In this thesis therefore, the water is assumed to reach a certain maximum penetration depth, regardless of the velocity of the vessel.

It is assumed that the sediment layer that is put into suspension has the same thickness as the penetration depth of the injected water. All the sediments are therefore assumed to be put into suspension. The suspension will then dilute towards a mixture with a lower density. This means that the thickness of the mixture layer will increase. The thickness of the mixture layer is therefore depending on the soil characteristics: the deeper the water can penetrate in the bed, the more sediment will be put into suspension and the thicker the sediment-water mixture layer will be.

After the mixture has reached a certain thickness, a gravity current will start flowing. It is assumed that the flow will act as a density current in a supercritical flow state, where the Froude number is estimated to be 1.1 (for more information, see the article of Van Rijn[13]). This can then be used as a starting point for the propagation calculations of the density current. At every step Δx, the change of the velocity and of the thickness of the density current is calculated. This information can then be used to describe the propagation of the density current.

Eventually, the sediment will start settling under the influence of gravity. The formulas that are used to calculate the time it takes for the sediments to settle are discussed in Appendix A.3.1.3. The time span following from these formulas can then be used in combination with the propagation of the density current to determine how far the density current will travel in the reservoir.

Examples of the calculations that now can be made with the production estimation model are shown in Figure 20 and Figure 21. It shows how the velocity of a density current u2(Xn) in a reservoir changes over the distance it travels. In these two figures, one parameter has been changed in order to investigate the influence it has on the velocity of the density current. In Figure 20, the reservoir steepness dhb/dx has been changed, while other parameters stayed at a constant value. These parameters are the particle diameter d_{50}, the thickness of the density current a_2, the undrained cohesion of the soil c_u and the relative density $\Delta\rho$. In Figure 21, the reservoir steepness dhb/dx has been kept at a constant, while the thickness of the density current has been changed.

[13] Water Injection Dredging - (Van Rijn, L.C., 2012)

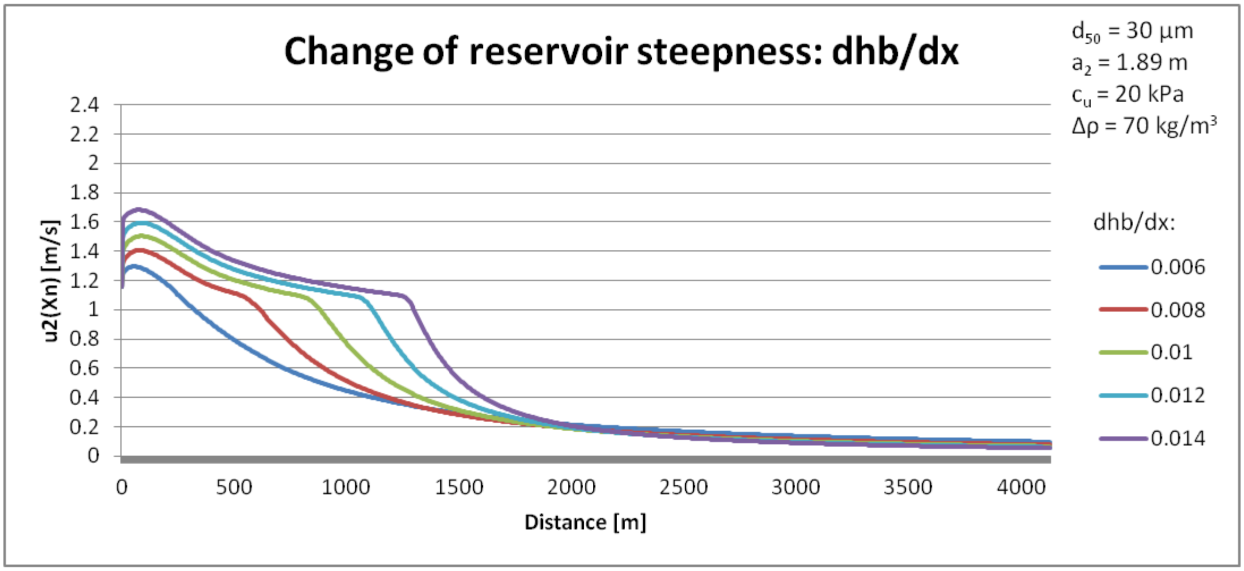

FIGURE 20: VARIATION OF THE STEEPNESS OF THE RESERVOIR USING THE PRODUCTION CALCULATION MODEL

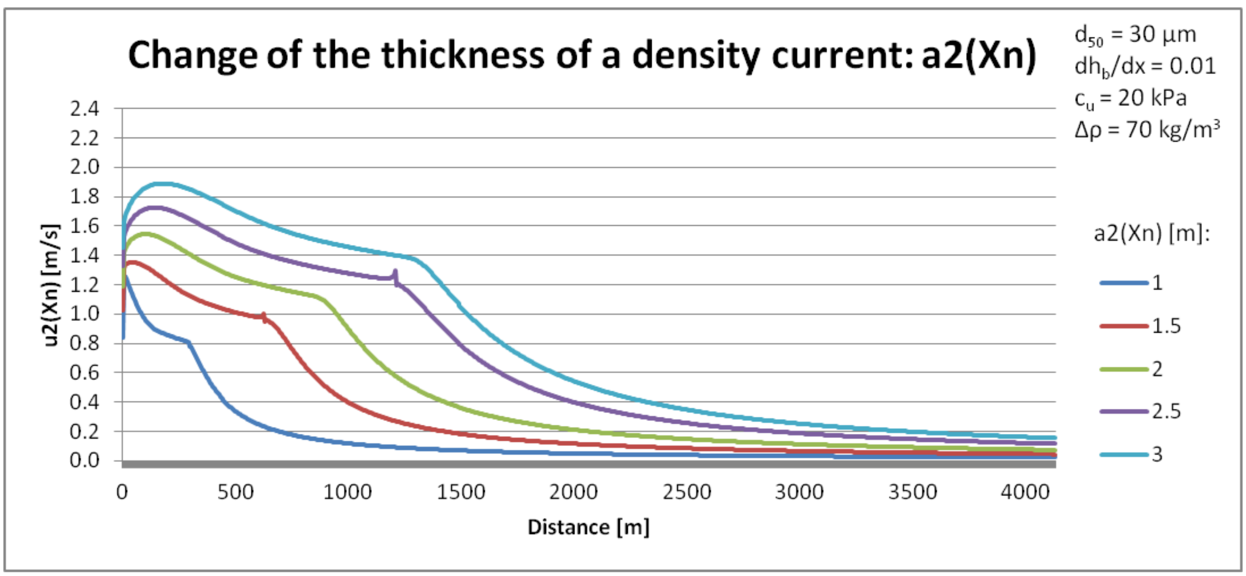

FIGURE 21: VARIATION OF THE THICKNESS OF THE DENSITY CURRENT USING THE PRODUCTION CALCULATION MODEL

Figure 20 clearly shows that a steeper reservoir results in higher velocities of the density current. This means that a density current will travel further in a reservoir, when the reservoir is steeper. The figure also shows for all the different scenarios that a created density current will first accelerate towards its maximum velocity. After that, the velocity will slowly decrease. At the velocity of about 1.1 meter per second, the density current has a breaking point and the velocity starts to decrease more rapidly. This could be because the flow at that point changes from a supercritical flow towards a subcritical flow.

Figure 21 shows that a thicker density current results in higher velocities of the density current. This is due to the fact that a smaller density current will have relatively higher friction forces that slow the current down. A thicker density current will be less influenced by these friction forces and will therefore propagate faster. Also in this figure is a breaking point noticeable, where the velocity suddenly decreases. This is probably because the flow changes from supercritical to subcritical flow as well. In the line of the density current of 1.5 and 2.5 meter thick, there are 2 small errors noticeable. These errors could be the result of the switch between these two types of flow, where the model temporarily switches between super- and subcritical flow.

4.7 Cost estimation of Water Injection Dredging

Besides estimating the production rates of Water Injection Dredging, an estimation of the costs has to be made as well. These two approximations combined can provide the information that is needed to determine if Water Injection Dredging is an effective method to preserve the reservoir capacity.

Within the Excel-sheet that is discussed in the previous paragraph, an estimation of the costs of Water Injection Dredging is added. As was the case for estimating the production rate, the cost estimation has to be constructed from basic knowledge. In this way, local specification of the reservoir can be taken into account, so that a detailed cost approximation can be provided. A more detailed description on the used methodology for the cost calculation can be found in Appendix A.3.

The combination of the calculated production rates and the cost estimation can then be compared with Water Injection Projects done in the past, so that the calculated values can be validated. An article from Wilson[14] on Water Injection Projects done in the United States provides these reference projects (Figure 22).

[14] Water Injection Dredging in U.S. waterways, history and expectations - (Wilson, 2007)

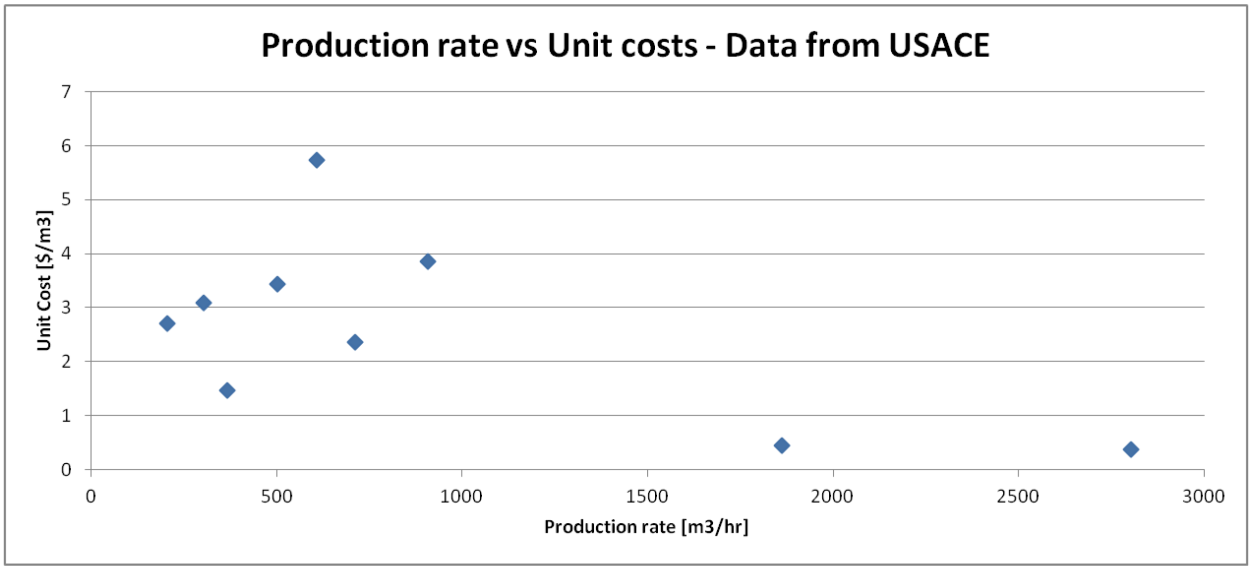

FIGURE 22: DATA FROM THE UNITED STATES ARMY CORPS OF ENGINEERS WITH THE PRODUCTION RATES AND UNIT COSTS OF WATER INJECTION DREDGING PROJECTS

4.8 Conclusion Water Injection Dredging in reservoirs

Water Injection Dredging has the potential to remove significant amounts of sediments from reservoirs, in a very effective way. The relatively simple installation makes it possible to implement this method in a cheap and quick way. The downside is though, that very specific conditions have to be met. The consequences for the river downstream of the dam due to the high sediment peaks are also uncertain.

Water Injection dredging has never been implemented in reservoirs. It can however be a cheap and effective method to remove accumulated sediment from reservoirs, once the specifications for Water Injection Dredging have been met. It can also be used to transport sediment within a reservoir towards a dead storage, or help improving sluicing operations.

An Excel-sheet has been constructed in order to estimate the costs and the production rates of Water Injection Dredging in reservoirs. Within these estimations, parameters that describe the specifications of a reservoir are taken into account in order to calculate production rates and costs. The detailed elaboration of the calculating model is presented in Appendix A.3.

In order to test if Water Injection Dredging can compete with conventional reservoir preservation techniques, case studies have to be done. These case studies are discussed in the next chapter.

5 Case studies on the effectiveness of Water Injection Dredging in reservoirs

To find out if Water Injection Dredging can compete with other reservoir preservation techniques, the method has to be tested in practice. This means that an economic feasibility study has to be carried out to find out if Water Injection Dredging can compete with the conventional methods. All possible reservoir preservation techniques have to be considered and valued.

This will be done with case studies of reservoirs where sedimentation is a problem. More than just one case study is necessary for a proper evaluation of the efficiency of Water Injection Dredging. The considered cases will have to meet the conditions of Water Injection Dredging, as was discussed earlier in Paragraphs 4.3 and 4.4. A detailed analysis can be carried out with the help of the Excel-sheet that was constructed to estimate the production rates and the costs for different reservoir preservation techniques. More information regarding this Excel-sheet can be found in Appendix A.

5.1 Case 1: Mrica Reservoir

The first reservoir where the Water Injection Dredging option is evaluated is the Mrica Reservoir, which is located in Central Java, Indonesia. This multifunctional reservoir is an important water source for the local community. It has a hydropower installation which can generate up to 580.000 MWH year^{-1} and the reservoir provides water for the local irrigation system[15]. The capacity of this reservoir is 140 million m^3 and the reservoir has been suffering from sedimentation since the start of the usage of this reservoir in 1989. The yearly rate of capacity decrease is 2.60%, which eventually will result in a completely filled up reservoir in 2021 (see also Figure 23). Since reservoir sedimentation is starting to hinder the functionality of the reservoir, measurements to counteract this process will have to be considered.

To investigate the sedimentation problem of the reservoir and to find out if Water Injection Dredging can be an effective solution to this problem, all possible reservoir preservation methods have to be evaluated. The evaluation will then show if Water Injection Dredging can compete with the other methods as an effective and cost-efficient reservoir preservation method.

[15] Sedimentation control: Part II. Intensive measures the inside of the Mrica Reservoir, Central Java - (Soewarno and Syariman, 2008)

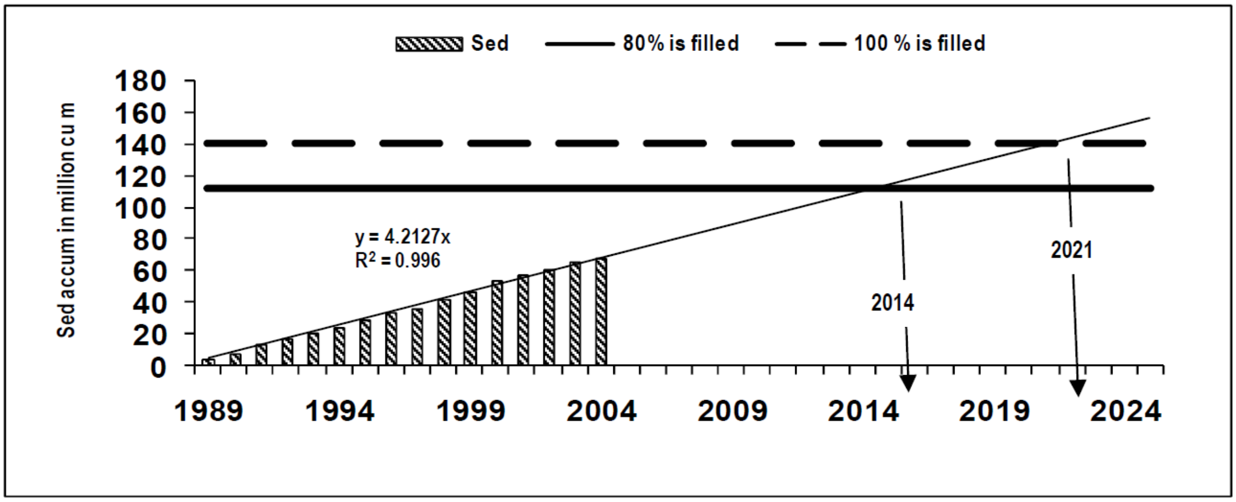

FIGURE 23: PREDICTION OF REMAINING USEFUL LIFE TIME AT MRICA RESERVOIR - (SOEWARNO AND SYARIMAN, 2008)

The evaluation of each method starts with the Reservoir Sedimentation Flow Chart, discussed earlier in Paragraph 2.4. First, the reservoir is classified with the 4 classification methods and the reservoir sedimentation problem is quantified.

5.1.1 Quantify the sedimentation problem in the Mrica Reservoir

Quantifying the sedimentation problem in a reservoir consists of using the empirical curves of Churchill, Brune or Brown. Investigations done by Soewarno and Syariman[16] have resulted however in more detailed measurements of the sedimentation rates within the Mrica reservoir. A hydrometric station has measured the discharge and the sediment transport throughout the years. These measurements show that the yearly transport rate through the river before construction of the dam is estimated to be around 7.06±2.65 million m^3 sediment per year. After construction of the dam, the average rate of the yearly capacity decrease is 2.60%. The process of the sediment accumulation in the reservoir is shown in Figure 23.

The figure shows that in 2012, the total amount of sediment that has accumulated in the reservoir is 105 million m^3. The sediment distribution in the reservoir is presented in Figure 24.

[16] Sedimentation control: Part II. Intensive measures the inside of the Mrica Reservoir, Central Java - (Soewarno and Syariman, 2008)

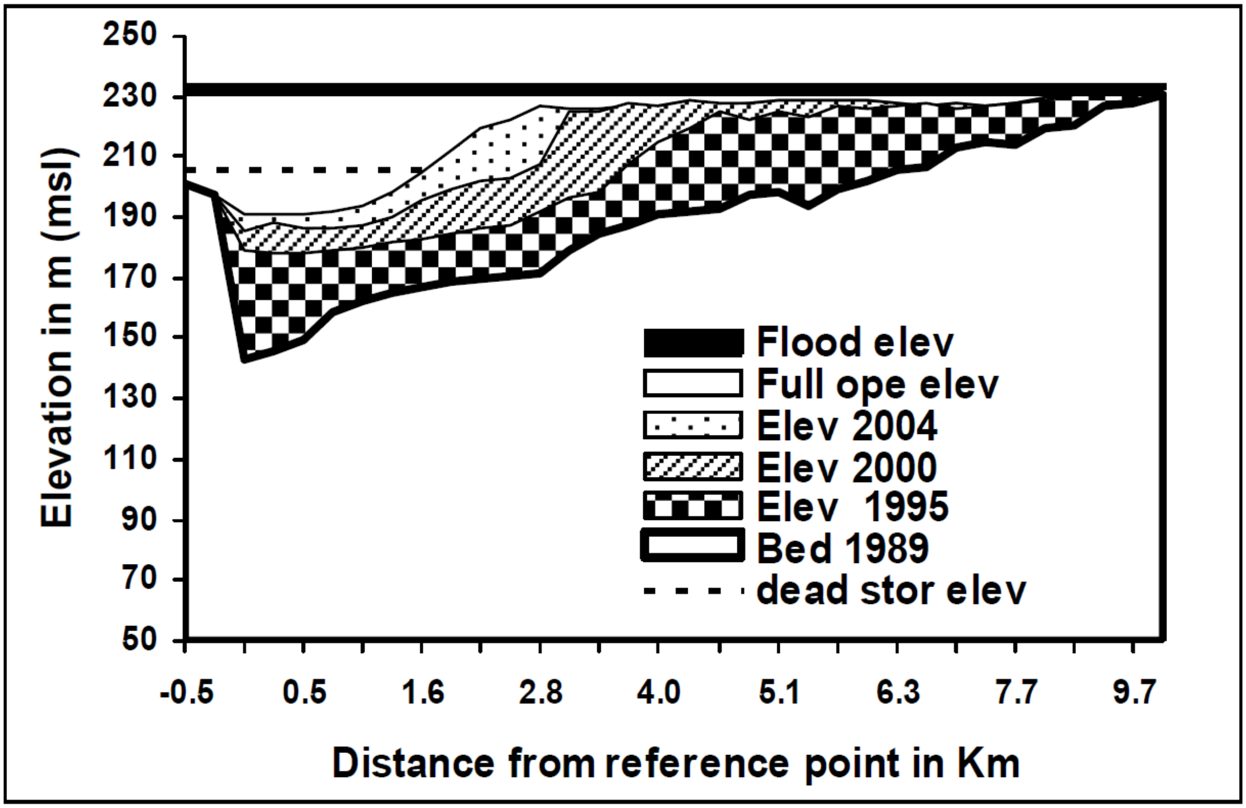

FIGURE 24: SEDIMENT DISTRIBUTION IN THE MRICA RESERVOIR - (SOEWARNO AND SYARIMAN, 2008)

Figure 24 clearly shows that the sedimentation problems in the Mrica reservoir are severe. Already more than 50% of the reservoir has been filled with sediment in 2004. Sediment deposits in front of the Mrica reservoir flushing intake gate reached an elevation of +190.0 meter. With the water intake for the hydropower installation and the irrigation system situated at an elevation level of +205.0 meter, the functionality of the reservoir is endangered.

5.1.2 Qualify the sedimentation problem in the Mrica Reservoir

An important aspect of analyzing the Mrica reservoir is qualifying the sedimentation problem. The distribution and the size of the sediment particles are important parameters. Based on data analysis of bed material[17], the sediment distribution within the Mrica Reservoir can be divided in a few segments. The distribution of sediments and the different segments are presented in Table 6.

[17] Sedimentation control: Part II. Intensive measures in the inside of the Mrica Reservoir, central Java - (Soewarno and Syariman, 2008)

TABLE 6: DISTRIBUTION OF SEDIMENTS IN THE MRICA RESERVOIR

Sediment classification	Grain size [mm]	Distance in reservoir from reference point [km]
Clay	< 0.005	0 – 1.1
Mud/Silt	0.005 – 0.05	1.3 – 2.5
Fine to coarse sand	0.05 – 2.0	2.5 – 9.0
Fine to coarse gravel	2.0 – 60	9.0 – 9.2
Pebbles or coral stone	> 60	> 10

5.1.3 CLASSIFY THE MRICA RESERVOIR

Now that the sediment characteristics are known, the next step is to find out which reservoir preservation methods are suitable for this particular reservoir. This can be done by classifying the reservoir with the classification techniques discussed in Paragraph 2.2. If that classification is done, the link between the reservoir class and the reservoir preservation method will then lead to suitable solutions to counteract the reservoir sedimentation problem in the Mrica Reservoir.

5.1.3.1 CLASSIFY THE MRICA RESERVOIR BASED ON THE EMPIRICAL AREA-REDUCTION METHOD

The first classifying method applied on the Mrica reservoir is the Empirical Area-Reduction method. The basic of this method is the shape of the reservoir and the method divides the reservoir into 4 different shapes. The shape is determined by the parameter "M", which is the reciprocal of the slope of the line obtained by plotting the reservoir depth at the vertical axis against the reservoir capacity at the horizontal axis on log-log paper.

The parameter M can be now be calculated for the Mrica reservoir. The first point that can be plotted on the log-log paper is the point with the Reservoir Capacity 140 * 10^6 m^3 and the proportional Reservoir Depth of 95 meter. The second point that is necessary for the plot has to be calculated and interpolated from the longitudinal profile of the reservoir:

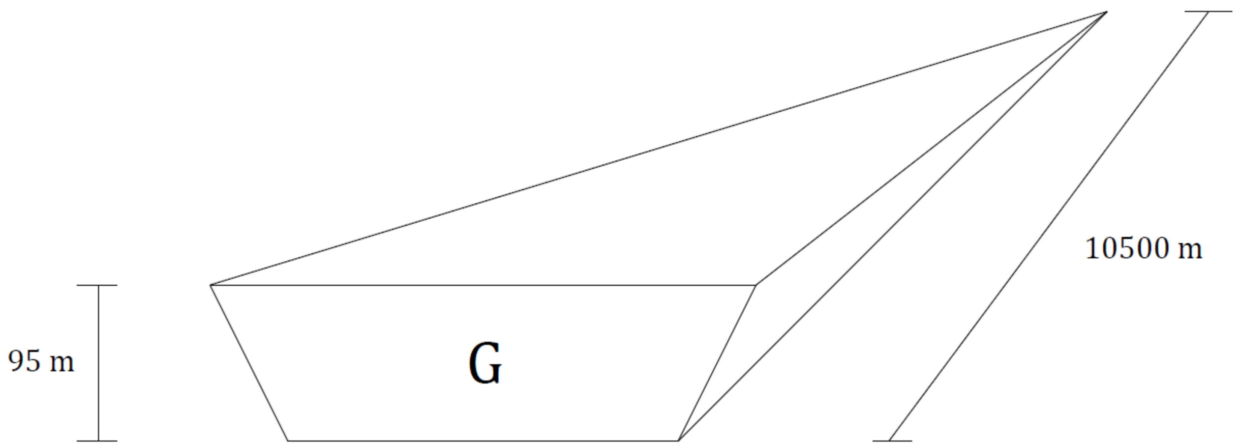

FIGURE 25: SCHEMATISATION OF THE MRICA RESERVOIR

The assumed simplified profile of the Mrica reservoir is presented in Figure 25, where G represents the ground surface of the schematised pyramid. The total volume of the reservoir V is 140 * 10^6 m^3, when the depth of the reservoir is 95 m. The length L of the reservoir is 10.500 meter.

The surface of G is then:

$$V = \frac{1}{3} GL$$

$$140 \cdot 10^6 = \frac{1}{3} \cdot G \cdot 10500$$

$$G = 40 \cdot 10^3 \text{ m}^2$$

To plot the line on the log-log paper, the volume of the reservoir at a certain depth has to be calculated. The depth of 40 meter is chosen, where it is assumed that the profile of the volume has the same shape as the profile on the 95 meters depth. From detailed measurements results that the proportional length of the reservoir at 40 meters depth is 3400 meter.

Because it is assumed that the shape of the reservoir at 40 meters depth is the same as the shape of the reservoir at 95 meters depth, the ratio between the two shapes can be used to determine the surface G of the reservoir at 40 meters depth:

$$G\ (at\ depth\ 40\ m) = \frac{40}{95} \cdot 40 \cdot 10^3 = 16.8 \cdot 10^3 \text{ m}^3$$

The volume of the reservoir V at depth 40 meters is then:

$$V = \frac{1}{3} GL$$

$$V\ (at\ depth\ 40\ m) = \frac{1}{3} \cdot 16.8 \cdot 10^3 \cdot 3400 = 19.1 \cdot 10^6\ \text{m}^3$$

With these volumes of the reservoir at two different depths now known, the line on the log-log paper can be plotted to determine parameter "M".

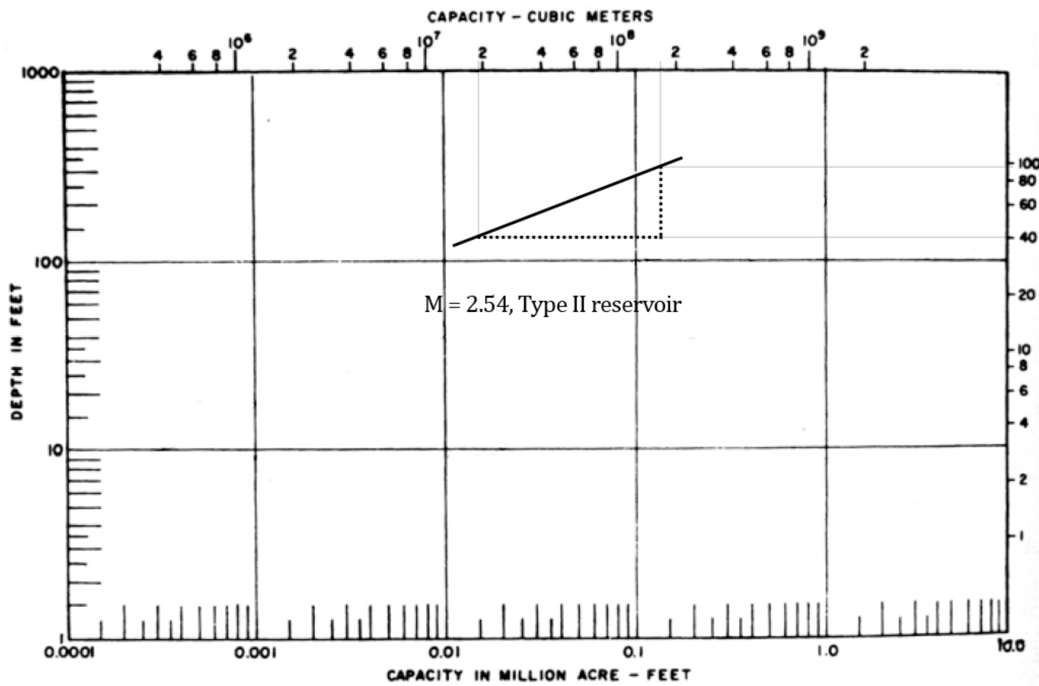

FIGURE 26: DETERMINATION OF PARAMETER M FOR THE MRICA RESERVOIR

TABLE 7: TYPES OF RESERVOIRS

Reservoir type	"M"	Standard classification
Gorge	1.0-1.5	IV
Hill	1.5-2.5	III
Flood plain-foothill	2.5-3.5	II
Lake	3.5-4.5	I

When the parameter M is determined, the reservoir type can be determined with the help of Table 7. As can be seen in Figure 26, the parameter M is assessed on 2.54. This indicates that the reservoir falls under the category of a Floodplain-foothill reservoir type. It also indicates that the reservoir type is very close to the Hill type of reservoir. The boundaries for this type of reservoir are between 1.5 and 2.5, so this is very close.

The next step is to look at Table 2 (presented in Paragraph 3.5.1), where the classification of the Empirical Area-Reduction method is combined with the reservoir preservation techniques. The classification of the Mrica reservoir is a type II: Food plain-foothill, but is also close to a type III: a Hill type reservoir. Consequently, the reservoir preservation methods that are recommended for this reservoir are the following methods:

- A sediment catchment structure
- A sediment bypass structure
- Implementing watershed management
- Sluicing high sediment loaded water peaks through the reservoir
- Flushing the reservoir
- Hydraulic dredging
- Use mechanical excavators to remove the accumulated sediment
- Water Injection Dredging

As was mentioned earlier in this document, local circumstances can influence the final decision for the method that eventually is chosen. That is why common sense in combination with engineering expertise is necessary to evaluate the final result when the classification is combined with the reservoir preservation methods.

This evaluation results in the conclusion that in the case of the Mrica reservoir, the sediment has already settled in large amount and has replaced more than 50% of the initial reservoir volume. This means that certain methods cannot be implemented anymore and are ruled out. Methods that are based on sediment diversion or catch sediment before it can settle in the reservoir are not possible, since the sediment has already entered the reservoir. Therefore, only the methods that remove accumulated sediment can be implemented in this case. This finally results in the following methods that can be implemented:

- A sediment bypass structure
- Flushing the reservoir
- Hydraulic dredging
- Use mechanical excavators to remove the accumulated sediment
- Water Injection Dredging

5.1.3.2 Classify the Mrica Reservoir based on the permitted reservoir operations

Whether or not it is permitted to draw down the water level is essential for some of the reservoir preservation methods. This is depending on the economical and environmental consequences of drawing down the water level and especially on the discussion if these consequences are acceptable. This is strongly depending on the local circumstances of the reservoir and on the choices of the operator and the owner of the dam.

In the case of the Mrica reservoir, no information is available regarding the option of drawing down the water level. There are no analyses available about the consequences of drawing down the water level for the environment, or what the economical consequences would be.

In the past however, some flushing activities are reported in the Mrica reservoir[18]. These flushing activities where limited due to the fact that the electricity production was not to be disturbed. This report also states that there is an uncertainty regarding the water distribution during the wet and dry seasons. Due to the large fluctuations in the river discharge, a full water level draw down is not possible in the reservoir.

These two given facts indicate that only a partial draw down is permitted in the Mrica reservoir. This has no consequences for the reservoir preservation methods that can be implemented in the reservoir, see also Table 3. Therefore, the list of possible reservoir preservation methods remains the same:

- A sediment bypass structure
- Flushing the reservoir
- Hydraulic dredging
- Use mechanical excavators to remove the accumulated sediment
- Water Injection Dredging

5.1.3.3 Classify the Mrica Reservoir based on the Capacity/Inflow ratio

The last classification that can decide which reservoir preservation methods can be implemented for the Mrica reservoir is the classification based on the Capacity/ Inflow ratio. The yearly inflow of water from the river has been measured between the years 1959 and 1981. The result is that the average river flow rate was 2610±500 million m^3 water per year.

[18] Sedimentation control: Part II. Intensive measures the inside of Mrica reservoir, central Java - (Soewarno and Syariman, 2008)

With the initial capacity of the reservoir known, the original Capacity/Inflow ratio can be determined as follows:

$$\frac{C}{I} = \frac{140 \cdot 10^6}{2610 \cdot 10^6} = 0.054$$

This means that the average discharge of the river is capable of filling up the initial volume of the reservoir more than 18 times per year. During the sedimentation process, the volume of the reservoir decreases significantly. This has an influence on the Capacity/Inflow ratio, since the original volume has decreased and it will therefore take less time to refresh the water volume in the reservoir. This means that during the operational years of the reservoir, the Capacity/Inflow ratio becomes even smaller than the initial 0.054. The next step is connecting the Capacity/Inflow ratio to the reservoir preservation methods. This can be done with the help of Table 4 (presented in Paragraph 3.5.3). The low ratio of the Capacity/Inflow ratio of the Mrica reservoir results in the conclusion that every preservation method is suitable in this case, according to Table 4. The consequence is that after all the classification done earlier, the list is unchanged:

- Constructing a sediment bypass structure
- Flushing the reservoir
- Use hydraulic dredging
- Using mechanical excavators to remove the accumulated sediment
- Use Water Injection Dredging

5.1.4 Cost efficiency calculations

Now that the possible methods to preserve the Mrica reservoir capacity are determined, the costs of implementing these methods can be calculated to find out if Water Injection Dredging is a good alternative. It is important to note that in practice a long term dredging strategy has to be chosen, so that the used method to preserve the reservoir capacity can be optimized. In this case though, since no strategy is chosen, the cases are calculated for a reservoir preservation technique that has to be implemented every year. This is done in order to compare the different techniques.

To calculate if a certain method is cost efficient, the production rates and the costs of implementing this method are estimated. For some methods, including the Water Injection Dredging method, it is necessary that bottom outlets are constructed in the dam. Although the construction of these bottom outlets can be very costly, these costs are not considered within these calculations. This is because of the fact that the reservoir preservation methods are implemented after the construction of a dam is already finished. The costs of the possible construction of the bottom outlets are therefore already made and don't have to be taken into account again.

5.1.4.1 *SEDIMENT BYPASS STRUCTURE*

Passing by the sediment is a costly operation in the case of the Mrica reservoir. This is because a bypass structure is not available and therefore has to be constructed. However, a cost efficiency calculation of constructing a sediment bypass needs extensive knowledge of the surroundings and detailed costs calculations. The volume of sediments that are removed by this method is also difficult to determine, since this process is dominated by unpredictable high sediment peaks from the river upstream of the dam. As a result of the uncertainty regarding the costs and the removal rate, this method is not considered in this thesis.

5.1.4.2 *FLUSHING OPERATIONS*

The costs of implementing flushing operations in a reservoir are the costs that are the consequence of lowering the water level in the reservoir. In the case of the Mrica reservoir, lowering the water level can have negative consequences for the hydropower station that is constructed in the dam. Also the water intake, which is constructed for distributing the water to the irrigation system, can become situated below the water level. This means that the irrigation system cannot function, and this will eventually cost money.

Under normal conditions, the reservoir generates 580.000 MWH per year and delivers 7 – 11 m^3/sec to the irrigation system[19]. Assuming that the profit per produced kWh is 10 eurocent, a production stop of 20 days already results in a total profit loss of € 3.132.000. This indicated that the losses for flushing can be considerable.

The sediment removal rate of this method is not certain however. As was the case with the sediment bypass structure, it is not possible to calculate how much sediment is removed with this method. This makes it impossible to compare this method with the other ones and the cost efficiency calculations of this method are therefore not taken into account in this thesis.

5.1.4.3 *HYDRAULIC DREDGING*

The earlier discussed Excel-sheet with the production and cost estimations of different reservoir preservation techniques is used to make the cost efficiency calculations of hydraulic dredging. A detailed explanation of this Excel-sheet can be found in Appendix A.1.

[19] Sediment control: part II. Intensive measures the inside of the Mrica Reservoir, central Java - (Soewarno and Syariman, 2008)

For the Mrica reservoir, hydraulic dredging operations with a Cutter Suction Dredger are considered. The reservoir cannot be accessed through waterways (there are no ship lifts or sluices in the Mrica Dam) and the location can be considered as remote. This makes it necessary to use a dismountable Cutter Suction Dredger.

The maximum water depth of the Mrica reservoir is 90 meter. Given the fact that the costs will increase significantly when the sediments are dredged at a greater depth, a dredger with a lower dredging depth is chosen. A dredger with a dredging depth of 30 meters would be able to reach about half of the bottom of the reservoir (see also Figure 24). Therefore, the dismountable dredger IHC Beaver 9029C is chosen, with a dredging depth of 29 meters, with a discharge pipeline diameter of 0.9 meter. This limited dredging depth would mean that some of the sediments will not be removed from the reservoir. However, after the removal of the sediments that are located inside the 29 meter limit, new sediment will settle at that location. This means that future dredging operations will be able to remove that new accumulated sediment.

The velocity within the pipeline will have to be maintained above 3 meter per second, to avoid sediments from settling in the pipeline. A velocity higher than 4 meter per second is not preferable, due to high energy losses and therefore high extra costs. A velocity of 3.5 meter per second is therefore considered here.

The transport concentration of in situ soil C_{vsi} for the IHC Beaver 9029 C has a maximum of 35 percent[20]. Since the used Cutter Suction Dredger has a limited dredging depth of 29 meters, a combination of Table 6 and Figure 24 shows that the only material that can be dredged up by the Cutter Suction Dredger is fine to coarse sand, with a particle diameter between 0.05 to 2.0 mm. This fine to coarse sand has an in situ density of 1800 to 2000 kg/m^3, see also Table 8.

The representative in situ density that is used in the Excel sheet for the Mrica Reservoir is therefore chosen to be 1900 kg/m^3. Also, the density of the water is set to be 1000 kg/m^3. In order to fulfil the requirement that the volumetric concentration of the in situ solids cannot exceed 35 per cent, the density of the mixture is set to be 1310 kg/m^3. The volumetric concentration is automatically calculated by the sheet, and this can be verified by using the following formula (see also the Reading Guide in Appendix A.1.1):

$$C_{vsi} = \frac{\rho_m - \rho_w}{\rho_{si} - \rho_w}$$

[20] Also see the IHC Beaver 9029 C specifications - (IHC Merwede, 2012)

TABLE 8: TYPICAL VALUES OF DENSITY AND POROSITY OF VARIOUS SOILS

Soil description	Density of solids ρ_s [kg/m³]	Density of soil in situ (wet) ρ_{si} [kg/m³]	Porosity n [%]
Silt	2650	1100 – 1400	80 – 90
Loose clay	2650	1400 – 1600	60 – 80
Packed clay	2650	1800 – 2000	35 – 50
Sand with clay	2650	1800 – 2000	40 – 50
Sand	2650	1900 – 2000	35 – 45
Coarse sand with gravel	2650	2050 – 2200	28 – 36
Clay boulders	2650	2320	20

Operational hours also have to be taken into account in order to calculate the total needed production weeks of a Cutter Suction Dredger. A workweek of 12 hours per day and 7 days per week is chosen. A net work efficiency of 60 per cent takes into account the time in which the Cutter Suction Dredger cannot operate due to moving of the dredger to another location in the reservoir, maintenance, repair or other work troubling issues.

The number of Cutter Suction Dredgers that are used in this particular project is 1. According to the calculation sheet is this amount of dredgers sufficient for the Mrica Reservoir. An overview of the chosen values for the calculation of the production weeks is presented in Table 9.

TABLE 9: VALUES FOR THE CALCULATION OF THE NECESSARY PRODUCTION WEEKS

Parameter	Value	Unit
Type dredger	IHC Beaver 9029C	[-]
Total installed power	13000	[kW]
Diameter pipeline	0.9	[m]
Velocity in pipeline	3.5	[m/s]
Density of in situ soil	1900	[kg/m³]
Density of the water	1000	[kg/m³]

Density of the mixture	1310	[kg/m³]
Operational hours per day	24	[hr/day]
Operational days per week	7	[days/week]
Net work efficiency	60.00	[%]
Number of CSD's used	1	[-]

From the production and cost estimating sheet follows that the amount of time that is necessary to remove the yearly sediment inflow in the Mrica Reservoir is 25 weeks.

The calculation values of Ciria Dredging Cost Standards[21] are used for the calculation of the weekly production costs. The value for the depreciation and interest and the value for maintenance and repair are found within these costs standards.

The total installed power is 13000 kW for the IHC Beaver 9029C. With the price for marine diesel at 1454 $/ton[22] and the Euro/Dollar rate at 0.764[23], the weekly costs for fuel and lubricants can be calculated.

Extra costs that are made for this project are the costs that are made to transport the material towards the deposit site. For a first estimate it is assumed that the dredged up sediments are transported towards the river downstream of the dam and no storage site is needed. This assumption is valid because the total volume of the dredged up sediment equals the yearly inflow of sediment into the reservoir. The sediment load will be a bit above average because of the smaller time frame, but the extra sediment load will be acceptable. Extra costs that have to be made to construct a storage site are therefore not necessary.

As can be seen on the map in Figure 27, the Mrica Reservoir stretches far into inland. The pipeline for the Cutter Suction Dredger therefore needs to be sufficiently long. Maintenance and repair of the pipeline is also taken into account, since the duration of such a project can be significant. The long duration of the project means that pipelines also need to be repaired and maintained. This is taken into account by adding a percentage of 5 percent to the total costs of a pipeline.

[21] Table 201 of the CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)
[22] Marine Diesel Oil Prices - (Bunkerworld Prices BWI, 2012)
[23] ECB: Euro exchange rates USD - (European Central Bank, 2012)

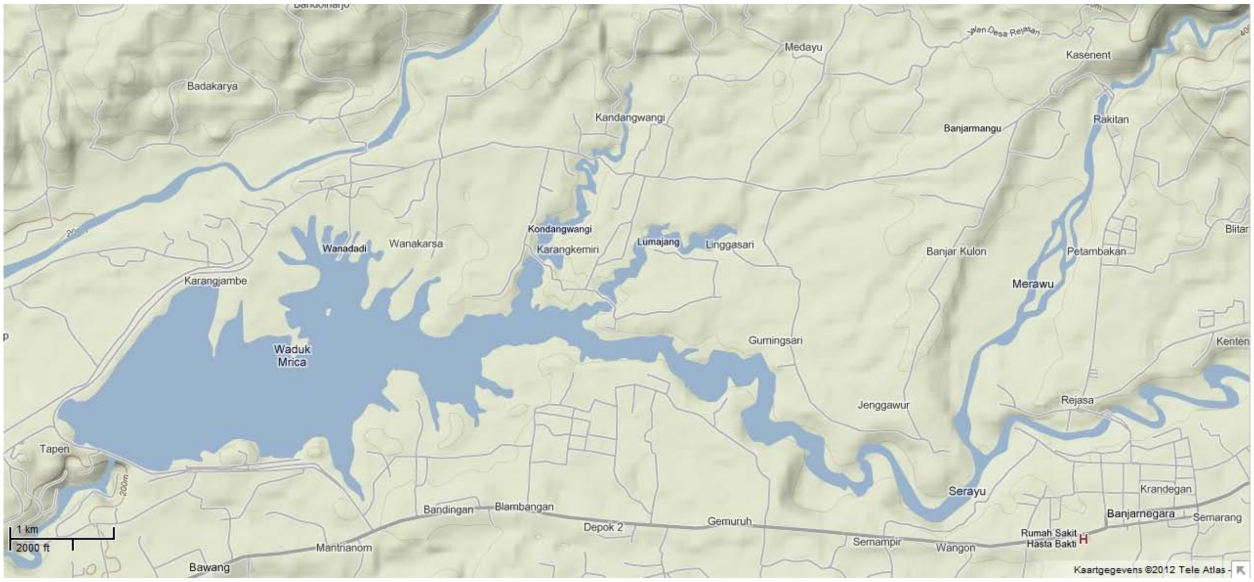

FIGURE 27: MAP OF THE MRICA RESERVOIR - (GOOGLE EARTH, 2012)

The pipeline length on shore is 9000 meter and length of the floating pipeline is chosen to be 1000 meter. The remaining values that are necessary to calculate the costs for a pipeline follow from the CIRIA cost standards. The amount of booster stations that are necessary to transport the material over the 10.000 meter long pipeline is 2. An overview of the used values for the weekly production costs is presented in Table 10.

TABLE 10: VALUES FOR THE WEEKLY COSTS CALCULATION

Parameter	Value	Unit
Depreciation and interest	155078	[€/week]
Maintenance and repair	66923	[€/week]
Total installed power	13000	[kW]
Price marine diesel	1454	[$/ton]
Euro/Dollar rate	0.785	[€/$]
Needed amount of booster stations	2	[-]
Price per booster station	22988	[€]
Storage site	-	[€]

Costs of the pipeline, per week		
• Length pipeline on shore	9000	[m]
• Price per meter	1.34	[€/m]
• Length floating pipeline	1000	[m]
• Price per meter floating pipeline	16.40	[€/m]
• Needed amount of bends	10	[€]
• Price per bend	16.70	[€]
• Maintenance and repair pipeline, percentage of total costs pipeline	5	[%]

Other expenses that have to be taken into account, such as the risk and the insurance, are taken as a percentage of the weekly production costs and are calculated by the Excel-sheet. The one-time costs that are considered are rough estimates of what the costs would be in reality. These one-time costs consist of transporting the dredger and all the material towards the reservoir and the costs that have to be taken into account for the assembly and disassembly. For transport costs 400.000 euro is taken into account, for assembly and disassembly costs 300.000 euro.

This eventually leads to the production of 278.308 m^3 per week, which means that there are 25 production weeks necessary to remove 7.060.000 m^3 of sediment with one Cutter Suction Dredger. The total weekly production costs are 891.352 euro per week and the total one-time costs 500.000 euro. The total costs of using a Suction Cutter Dredger in the Mrica Reservoir are 3.30 euro per removed m^3 sediment.

It is important to note that the sediment in the deeper parts of the reservoir is not removed, because of the limited dredging depth of the chosen Cutter Suction Dredger. Also, as a starting point of the costs efficiency calculations, the amount of sediments that are removed is equal to the yearly inflow. This is done so that the different reservoir preservation techniques can be compared. Another important note is that all the dredged up material is brought back into the river system downwards of the dam. For simplicity reasons, it is assumed that the river has the capacity to transport these sediments. A more detailed study is necessary to investigate whether or not the river has enough capacity, since the sediment load is more than doubled compared with the original river conditions (yearly amount of sediment is distributed in 25 weeks instead of 52 weeks). The capacity of the river has also decreased due to the loss of water for irrigation purposes.

Another remark that has to be made is that it is also possible to permanently install a Cutter Suction Dredger. Especially since the dredger is used for 25 weeks per year, while the assembly and disassembly of the dredger also takes a lot of extra time. It is therefore important that a long term dredging strategy is chosen, so that the used method to preserve the reservoir capacity can be optimized.

5.1.4.4 MECHANICAL EXCAVATORS

The Excel-sheet for production and costs estimations for sediment removal from reservoirs can also be used to make cost efficiency calculations for mechanical excavators in the Mrica Reservoir. Two types of mechanical excavators can be used in this case: an excavator on tracks and a grab dredger.

The first option that is elaborated is the use of an excavator on tracks. Excavators on tracks have the limitation that they can only dredge up to a certain depth. This is also the case for the Mrica Reservoir, where the maximum water depth of the reservoir is 90 meter. The type of dredger that is chosen in this case is the backhoe dredger with 1600 kW installed power. This type of backhoe has a grab capacity of 15 m^3 and a normal dredging depth of 21 meter. Although this isn't the dredging depth that is needed to remove all the sediments from the reservoir, the dredger will still be able to remove most of the settled sediments from the reservoir. This can be verified in the cross section of the Mrica Reservoir in Figure 24.

It is assumed that the operational speed of the backhoe allows the dredger to deliver 1 bucket per minute. This can be transformed towards a discharge of sediments per time unit by the Excel-sheet. Operational hours also have to be taken into account in order to calculate the total needed production weeks of an excavator on tracks. A workweek of 24 hours per day and 7 days per week is chosen. A net work efficiency of 60 per cent takes into account the time in which the backhoe can't operate due to moving of the dredger to another location in the reservoir, maintenance, repair or other work troubling issues.

The number of excavators on tracks that are used in this particular project is 3. This is the sufficient amount of dredgers for the Mrica Reservoir according to the calculation sheet. An overview of the chosen values for the calculation of the production weeks is presented in Table 11.

TABLE 11: VALUES FOR THE CALCULATION OF THE NECESSARY PRODUCTION WEEKS

Parameter	Value	Unit
Type dredger	Backhoe	[-]
Volume excavator bucket	15	[m³]
Amount of bucket delivered per minute	1	[bucket/min]
Operational hours per day	24	[hours]
Operational days per week	7	[days]
Net work efficiency	60.00	[%]
Number of excavators used	3	[-]

The calculation values of Ciria Dredging Cost Standards[24] are used for the calculation of the weekly production costs. The value for the depreciation and interest and the value for maintenance and repair are found within these costs standards. The pontoon that is necessary for the backhoe to work on is included within these values.

Extra costs that are made for this project are the costs that are made to transport the material towards the deposit site. This is because extra pontoons and tugboats are necessary to transport the material from the dredgers towards to shore. Also, a quay wall has to be designed and constructed so that the pontoons can be unloaded. Unloading cranes also are necessary here. Since there are 3 backhoe's operational, 9 pontoons are needed to be able to transport the material towards the shore. This makes sure that there is always an empty pontoon available where the dredger can leave the material. The needed amount of tugboats that is lower than the amount of pontoons and the needed amount of tugboats in this case is 4. Calculating values for this equipment can be found in the CIRIA cost standards[25]. This also yields for the unloading cranes that are necessary at the quay wall[26]. The amount of unloading cranes that are necessary on the shore is set to be 2. This amount is lower than the amount of backhoes, since the unloading process of the pontoons is must faster. The value for constructing and maintaining the quay wall is a rough first estimate of the costs and this is estimated to be 5000 euro per week.

For a first estimate it is assumed that the dredged up sediments are transported towards the river downstream of the dam and no storage site is needed. This assumption is valid because the total volume of the dredged up sediment equals the yearly inflow of sediment into the reservoir. The sediment load will be a bit above average because of the smaller time frame, but the extra sediment

[24] Table 510 of the CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)
[25] Table 810 and 831 of the CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)
[26] Table 510b of the CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)

load will be acceptable. Extra costs that have to be made to construct a storage site therefore are not necessary.

An overview of the used values for the weekly production costs is presented in Table 12.

TABLE 12: VALUES FOR THE WEEKLY COSTS CALCULATION

Parameter	**Value**	**Unit**
Depreciation and interest	105112	[€/week]
Maintenance and repair	45080	[€/week]
Price marine diesel	1454	[$/ton]
Euro/dollar rate	0.785	[€/$]
Needed amount of extra pontoons	9	[-]
Price per pontoon	3837	[€/week]
Needed amount of tugboats	4	[-]
Price per tugboat	4701	[€/week]
Needed amount of unloading cranes at the shore	2	[-]
Price per unloading crane at the shore	32036	[€/week]
Costs constructing and maintaining and maintaining quay wall	5000	[€/week]
Costs storage site	-	[€/week]

Other expenses that have to be taken into account, such as the risk and the insurance, are taken as a percentage of the weekly production costs and are calculated by the Excel-sheet. The one-time costs that are considered are rough estimates of what the costs would be in reality. These one-time costs consist of transporting the dredgers and all the material towards the reservoir and the costs that have to be taken into account for the assembly and disassembly. For transport costs 50.000 euro is taken into account, for assembly and disassembly 50.000 euro. This number has to be multiplied by 3, since that is the amount of dredgers that are used.

This eventually results in the production of 54.432 m^3 per backhoe per week, which means that there are 43 production weeks necessary to remove 7.060.000 m^3 of sediment with 3 backhoes. The total weekly production costs are for the 3 backhoes combined 912.413 euro per week and the total one-time costs 300.000 euro. The total costs of using a backhoe in the Mrica Reservoir are 5.63 euro per removed m^3 sediment.

The other option of using a mechanical excavator in the Mrica Reservoir is using a grab dredger. As was the case with the use of an excavator on tracks, a grab dredger also has a limited dredging depth. The grab dredger is therefore not capable of reaching till the bottom of the reservoir. The production rate is also lower due to the smaller volume of the bucket, but the operational costs are less expensive.

In the case of the Mrica Reservoir, a grab dredger with an installed power of 212 kW is chosen. This type of grab dredger has a grab capacity of 5 m^3 and is capable of dredging up to 24 meter. Although this is not the dredging depth that is needed to remove all the sediments from the reservoir, the dredger will still be able to remove most of the settled sediments from the reservoir. This can be verified in the cross section of the Mrica Reservoir in Figure 24.

It is assumed that the operational speed of the backhoe allows the dredger to deliver 1 bucket per minute. This can be transformed towards a discharge of sediments per time unit by the Excel-sheet. Operational hours also have to be taken into account in order to calculate the total needed production weeks of an excavator on tracks. A workweek of 24 hours per day and 7 days per week is chosen. A net work efficiency of 60 per cent takes into account the time in which the backhoe can not operate due to moving of the dredger to another location in the reservoir, maintenance, repair or other work troubling issues.

In order to remove the set amount of sediment of 7.060.000 m^3, the number of grab dredgers that are used in this particular project is 9. This is the sufficient amount of dredgers for the Mrica Reservoir according to the calculation sheet. An overview of the chosen values for the calculation of the production weeks is presented in Table 13.

TABLE 13: VALUES FOR THE CALCULATION OF THE NECESSARY PRODUCTION WEEKS

Parameter	**Value**	**Unit**
Type dredger	Grab dredger	[-]
Volume excavator bucket	5	[m^3]
Amount of bucket delivered per minute	1	[bucket/min]
Operational hours per day	24	[hours]
Operational days per week	7	[days]
Net work efficiency	60.00	[%]
Number of grab dredgers used	9	[-]

The calculation values of Ciria Dredging Cost Standards[27] are used for the calculation of the weekly production costs. The value for the depreciation and interest and the value for maintenance and repair are found within these costs standards. The pontoon that is necessary for the grab dredger to work on is included within these values.

As was the case with the excavator on tracks, there are also pontoons and tugboats needed to transport the dredged up material towards the deposit site. A quay wall will have to be designed and constructed, and unloading cranes are necessary. Since there are 9 grad dredgers operational, 22 extra pontoons are necessary to transport the material towards the shore, in order to make sure that there is always an empty pontoon available for the grab dredger. To transport these pontoons, 8 tugboats are needed. Because the production rate is about the same as when the backhoe is used, there are also in this case 2 unloading cranes necessary. The calculating values for this equipment can be found in the CIRIA cost standards[28]. The value for constructing and maintaining the quay wall is a rough first estimate of the costs and this is estimated to be 5000 euro per week.

For a first estimate it is assumed that the dredged up sediments is transported towards the river downstream of the dam and no storage site is needed. This assumption is valid because of the fact that the total volume of the dredged up sediment equals the yearly inflow of sediment into the reservoir. The sediment load will be a bit above average because of the smaller time frame, but the extra sediment load will be acceptable. Extra costs that have to be made to construct a storage site are therefore not necessary.

An overview of the used values for the weekly production costs is presented in Table 14.

TABLE 14: VALUES FOR THE WEEKLY COSTS CALCULATION

Parameter	Value	Unit
Depreciation and interest	6741	[€/week]
Maintenance and repair	4250	[€/week]
Price marine diesel	1454	[$/ton]
Euro/dollar rate	0.785	[€/$]
Needed amount of extra pontoons	22	[-]
Price per pontoon	3837	[€/week]
Needed amount of tugboats	8	[-]
Price per tugboat	4701	[€/week]

[27] Table 520 of the CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)
[28] Table 810, 831 and 510b of the CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)

Needed amount of unloading cranes at the shore	2	[-]
Price per unloading crane at the shore	32036	[€/week]
Costs constructing and maintaining and maintaining quay wall	5000	[€/week]
Costs storage site	-	[€/week]

Other expenses that have to be taken into account, such as the risk and the insurance, are taken as a percentage of the weekly production costs and are calculated by the Excel-sheet. The one-time costs that are considered are rough estimates of what the costs would be in reality. These one-time costs consist of transporting the dredgers and all the material towards the reservoir and the costs that have to be taken into account for the assembly and disassembly. For transport costs 50.000 euro is taken into account, for assembly and disassembly 50.000 euro. This number has to be multiplied by 9, since this is the amount of dredgers that will be used.

This eventually results in the production of 18.144 m^3 per grab dredger per week, which means that there are 43 production weeks necessary to remove 7.060.000 m^3 of sediment with 9 backhoes. The total weekly production costs are for the 9 backhoes combined 441.121 euro per week and the total one-time costs 900.000 euro. The total costs of using a backhoe in the Mrica Reservoir are 2.83 euro per removed m^3 sediment.

It is remarkable to see that there is a big difference between the two mechanical excavators. The unit cost for backhoes is 5.63 euro per m^3, while the unit costs for the use of grab dredgers is 2.83 euro per removed m^3. This is due to the fact that the operational costs of using a backhoe are much higher, even though the amount of dredgers that are needed is lower.

It is important to note that the sediment in the deeper parts of the reservoir is not removed, because of the limited dredging depth of the chosen mechanical excavators. Also, as a starting point of the costs efficiency calculations, the amount of sediments that are removed is equal to the yearly inflow. This is done to make it possible to compare the different reservoir preservation techniques. Another important note is that all the dredged up material is brought back into the river system downwards of the dam. For simplicity reasons, it is assumed that the river has the capacity to transport these sediments. A more detailed study is necessary to investigate whether or not the river has enough capacity, since the sediment load has increased compared with the original river conditions (yearly amount of sediment is distributed in 43 weeks instead of 52 weeks). The capacity of the river has also decreased due to the loss of water for irrigation purposes.

Another remark that has to be made is that it is also possible to permanently install mechanical excavators. This will reduce the one-time costs. It is therefore important that a long term dredging strategy is chosen, so that the used method to preserve the reservoir capacity can be optimized.

5.1.4.5 WATER INJECTION DREDGING

With the help of a Water Injection Dredger, density currents can be created to transport large amount of sediments towards the dead storage of the reservoir or transport the density current through the bottom outlets out of the reservoir.

As is described earlier in this thesis, Water Injection Dredging in reservoirs is only possible if very specific requirements are met. An important requirement is the sediment characteristics, where the grain sizes should be smaller than 0.2 mm. The grain size distribution within the Mrica Reservoir is presented in Table 15.

TABLE 15: DISTRIBUTION OF SEDIMENTS IN THE MRICA RESERVOIR

Sediment classification	Grain size [mm]	Distance in reservoir from reference point [km]
Clay	< 0.005	0 – 1.1
Mud/silt	0.005 – 0.05	1.3 – 2.5
Fine to coarse sand	0.05 – 2.0	2.5 – 9.0
Fine to coarse gravel	2.0 – 60	9.0 – 9.2
Pebbles or coral stone	> 60	> 10

In order to calculate the cost efficiency of Water Injection Dredging within the Mrica Reservoir, the reservoir is divided into 3 different parts, the proportional in situ density of the soil can be found in Table 25 in Appendix A):

- The first part is where the soil is classified as clay and the particles have a grain size smaller than 0.005 mm. As a calculating value, a representative grain size of 0.002 mm is chosen. The in situ density of the soil is 1600 kg/m^3, since loose clay is assumed.
- The second part is where the soil is classified as mud/silt and where the grain size has an average value of 0.028 mm. The representative in situ density of the soil is 1400 kg/m^3.

- The third part is where the soil is classified as fine to coarse sand and where the grain size has an average value of 1.0 mm. The representative in situ density of the soil is 1900 kg/m^3.

The other parts of the reservoir where the soil is classified as coarse gravel or as pebbles have grain sizes that are too large for Water Injection Dredging to be effective. These sediments will not be removed in this case.

The remaining parameters for the calculation sheet are the same for all parts and they will be discussed below.

The density of water is set to be 1000 kg/m^3, since the reservoir contains fresh water. The density of the created turbidity current is set to be 1070 kg/m^3, this is a number based on practical experiences with Water Injection Dredging[29].

Reference projects are used[30] for the dimensions of the used Water Injection Dredger. This results in the width of the Water Injection barge of 15 meter, the amount of nozzles of 42, the diameter of a single nozzle of 0.09 meter and a flow velocity when the water leaves the nozzle of 14.1 meter per second.

The values for the cohesion of the sediments in the Mrica Reservoir are not known. From Water Injection Dredging projects done in the past, it is known that the cohesion is usually in the range of 0 to 20 kPa[31]. Since the sediments in the Mrica Reservoir are likely to have settled in the reservoir for a long period of time, the cohesion value is considered to be relatively large in this case. A value of 15 kPa is therefore assumed.

A work efficiency of 60 per cent is chosen to take into account the inefficiency that is the result of manoeuvring the vessel. The considered gravitational constant is 9.81 m/s^2. The steepness of the reservoir can be estimated with the help of the cross section of the reservoir in Figure 24. The reservoir loses 90 meters of elevation in over a stretch of 10.000 meter, so a reservoir steepness of 0.009 is considered.

The kinematic viscosity of water is $1.004 \cdot 10^{6}$ m^2/s and the particle diameter that has to be filled in into the sheet is depending on the location within the reservoir, as was discussed earlier in this paragraph. This also yields for the calculation length of the reservoir, since this is also depending on the location of the particles within the reservoir.

Operational hours also have to be taken into account in order to calculate the total needed production weeks of a Water Injection Dredger. A workweek of 24 hours per day and 7 days per week is chosen. A net work efficiency of 80 per cent takes into account the time in which the Water Injection Dredger can't operate due to maintenance, repair or other work troubling issues.

[29] Waterinjectiebaggeren, modellering van afstroming - (Verweij, 1997)
[30] Specifications Parakeet Water Injection Dredger - (Dredging International, 2012) and Specifications Jetsed Water Injection Dredger - (Van Oord, 2012)
[31] Jetten in slib t.b.v. waterinjectie baggeren - (Schuling, 1998)

In order to remove 7.060.000 m^3 of sediment, the number of Water Injection Dredgers that is used in this particular project is 1. This is the sufficient amount of dredgers for the Mrica Reservoir according to the calculation sheet. An overview of the chosen values for the calculation of the production weeks is presented in Table 16.

TABLE 16: VALUES FOR THE CALCULATION OF THE NECESSARY PRODUCTION WEEKS

Parameter	**Value**	**Unit**
Type dredger	Water Injection Dredger	[-]
Density water	1000	[kg/m³]
Density soil in situ	1400	[kg/m³]
Density mixture	1070	[kg/m³]
Width of the WID barge	15	[m]
Amount of nozzles	42	[-]
Diameter nozzle	0.09	[m]
Flow velocity when leaving the nozzle	14.1	[m/s]
Cohesion	15	[kPa]
Inefficiency due to manoeuvring of the vessel	60.00	[%]
Gravitational constant	9.81	[m/s²]
Thickness density current	1	[m]
Reservoir slope	0.009	[-]
Kinematic viscosity	$1.004 \cdot 10^{-6}$	[m²/sec]
Particle diameter	Depending on location within reservoir	[μm]
Calculation length reservoir	Depending on location within reservoir	[m]
Operational hours per day	24	[hours/day]
Operational days per week	7	[days/week]
Inefficiency due to downtime	80.00	[%]
Number of WID vessels used	1	[-]

For the weekly production costs a multipurpose pontoon is considered with a width of 12.5 meter, so that the injection pipes can be made on the side of the vessel and reach the full width of 15 meter. Costs of this multipurpose pontoon can be found in the CIRIA cost standards[32].

In contrary to the previous discussed methods, Water Injection Dredging can be executed to the maximum depth of 90 meters of the reservoir. To reach this depth, a sufficient long pipe is necessary. The price of an 800 mm diameter pipe is 7175 euro per 12 meter[33]. This equals 431.25 per meter pipeline. Followed from a discussion with a pump specialist from Witteveen+Bos the cost estimation of the pump is 200.000 euro.

As a rough estimate, it is assumed that it takes 5 employees 16 weeks to construct the dredger, working at 45 hours per week. The price per hour per employee is 100 euro. An overview of the values for the cost calculation is presented in Table 17.

TABLE 17: VALUES FOR THE COSTS CALCULATION

Parameter	Value	Unit
Depreciation and interest	27521	[€/week]
Maintenance and repair	21900	[€/week]
Maximum dredging depth	90	[m]
Price of pipe per meter	431.25	[€/m]
Cost of pump	200.000	[€]
Amount of weeks necessary for construction	16	[weeks]
Amount of employees needed	5	[-]
Working hours per week	45	[hours/week]
Price per hour, per employee	100	[€/hour]

The specifications of the three different segments of the Mrica Reservoir can now be used to calculate the costs and the production per segment of the Mrica Reservoir. These segments are discussed earlier in this paragraph and specifications of the sediment can be found in Table 15.

[32] Table 820 of the CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)
[33] Table 910 of the CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)

- The first segment is the part where the soil is classified as clay. The representative in situ density of the soil is 1600 kg/m^3, the representative grain size is 0.002 mm and the calculation length of the reservoir 550 meter. From the production model follows that sediments from this part of the reservoir can be removed for the total costs of 1.14 euro per m^3. The sediment only has to be picked up once.
- The second segment is the part where the soil is classified as mud/silt. The representative in situ density of the soil is 1400 kg/m^3, the representative grain size is 0.028 mm and the calculation length of the reservoir is 1900 meter. From the production model follows that sediments from this part of the reservoir can be removed for the total costs of 0.78 euro per m^3. Also in this case, the sediment only has to be picked up once.
- The third segment is the part where the soil is classified as fine to coarse sand. The representative in situ density of the soil is 1900 kg/m^3, the representative grain size is 1.0 mm and the calculation length of the reservoir is 5750 meter. From the production model follows that sediments from this part of the reservoir can be removed for the total costs of nearly 300 euro per m^3 sediment. This is due to the fact that the particles are too big to be transported with density currents. Therefore, sediments from this segment cannot be removed with Water Injection Dredging, since it is far too costly.

This eventually leads to the conclusion that Water Injection Dredging in the Mrica Reservoir can only be implemented in the part of the reservoir close to the dam, where the particles are small enough to be efficiently removed. This part of the reservoir includes the first 2.5 kilometres of the reservoir (see also Table 15). With the information that the outlet of the dam is located at elevation 205 meter, this results in the fact that it is only efficient to move a small part of the settled sediment in the Mrica Reservoir, as is presented in Figure 28.

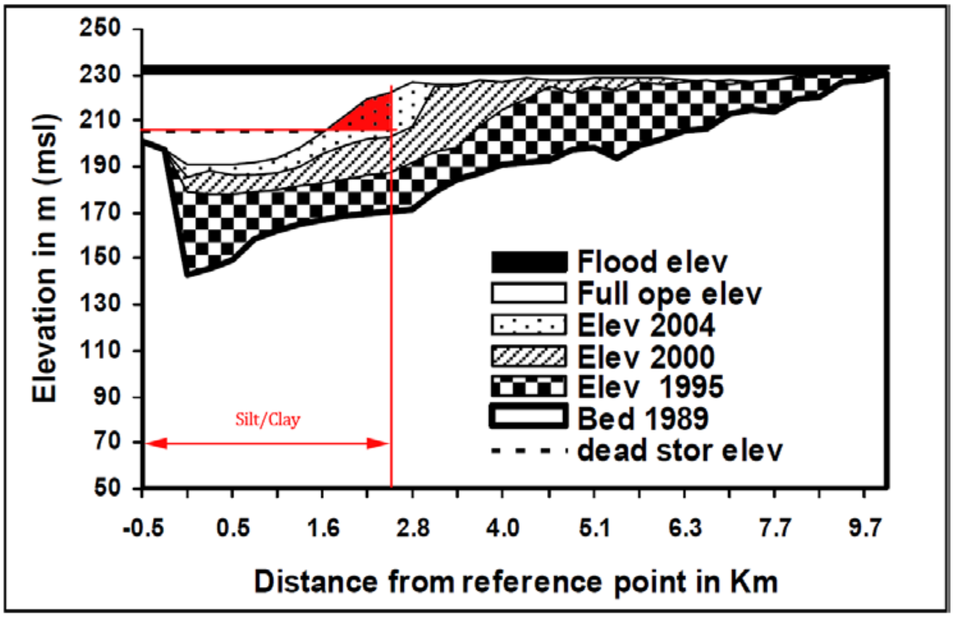

FIGURE 28: PART OF THE SETTLED SEDIMENT THAT IS EFFICIENT TO MOVE WITH WATER INJECTION DREDGING

However, a much bigger amount of sediments could be able to be removed if bottom outlets were constructed. All the sediments that have settled in the first segment of the reservoir (Silt and Clay) could in that case be removed with Water Injection Dredging.

5.1.5 Conclusion case study Mrica Reservoir

The Mrica Reservoir has severe sedimentation problems within the reservoir. If no effective counter measurements are taken, the reservoir will lose primary functions already in 2014.

Hydrodynamic solutions such as flushing and sluicing offer a relative cheap method to remove sediment. However, these methods are not able to cope with the massive yearly sediment load of more than 7 million m^3. These solutions can contribute to the sedimentation problem, but do not provide a sustainable solution for the Mrica Reservoir.

Therefore, the only long term solution therefore is to remove the sediment by using a mechanical excavator (a grab dredger or an excavator on tracks), a Cutter Suction Dredger or by a Water Injection Dredger. Cost calculation of these methods result in the following diagram (see Figure 29).

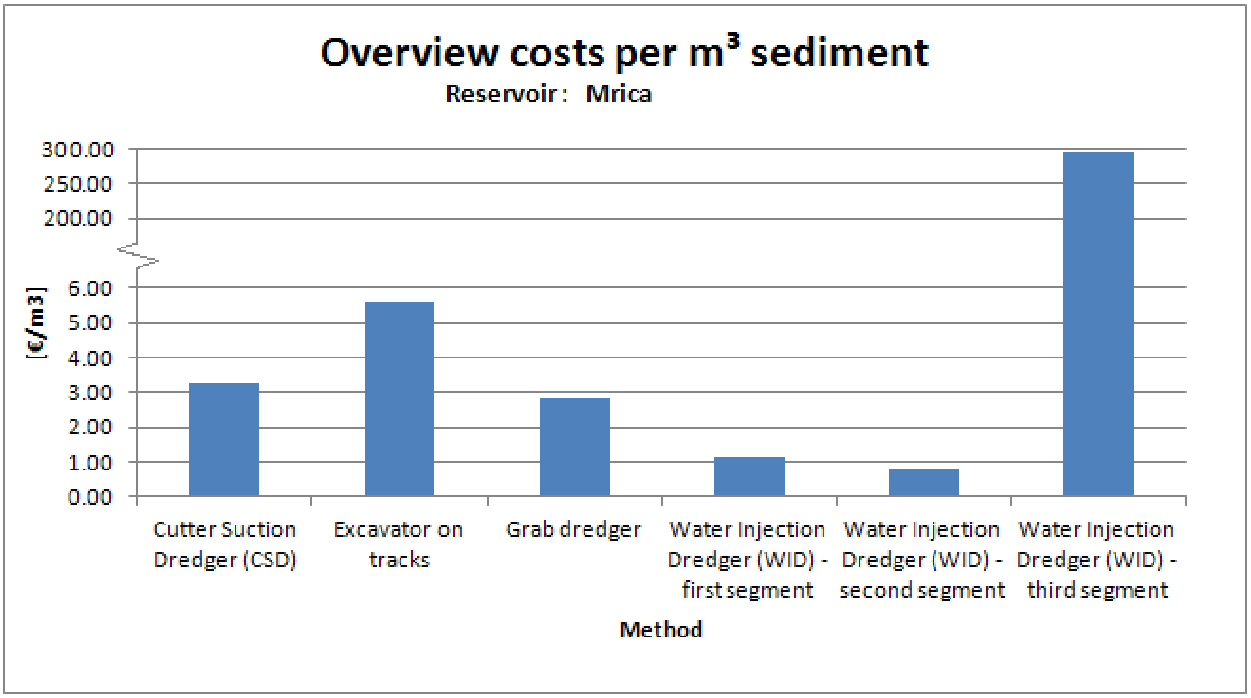

FIGURE 29: OVERVIEW OF THE COSTS PER M3 SEDIMENT WITHIN THE MRICA RESERVOIR

Because of the diversity of the sediment characteristics, the reservoir is divided into three different segments when Water Injection Dredging is considered (see also Table 15). Although this figure shows that it would be cost efficient to use Water Injection Dredging in the first two segments of the reservoir, it is not efficient to use this method in this particular case. This is because the water outlets of the dam are constructed too high. As can be seen in Figure 28, it is only effective to move a small section of the total amount of settled sediment in the Mrica Reservoir with Water Injection Dredging. If the outlets were constructed lower, the total volume of Silt and the Clay particles could be effectively removed with a Water Injection Dredger.

This is not the case in reality, so the use of Grab Dredgers would be the most cost efficient solution. A good alternative would be using a Cutter Suction Dredger, since the costs of implementing this method are not much higher. More detailed investigations are necessary in order to find out what the best strategy is to preserve the capacity of the Mrica Reservoir.

In this case, no deposit sites are considered to store the dredged up sediment. It is assumed that the sediments can be immediately brought back to the river system, in order to restore the river morphology downstream of the dam. This is an acceptable assumption, since the total amount of sediments (which equals the annual yearly amount of sediments that is caught in the reservoir) that is removed, is in all scenarios brought back in the river in more than 30 weeks. This means that the sediment load in the river downstream of the dam is less than twice the normal amount of sediment that flows in the river, which is acceptable. Constructing a deposit site for these amounts of sediment volumes would also be too costly due to the enormous volume of the sediment.

The final conclusion is that if the bottom outlets were constructed much lower than in the current situation, Water Injection Dredging is a cost efficient and compatible method to preserve the capacity of the Mrica Reservoir. Since this is not the case, only a fraction of the total sediment volume can be moved efficiently to increase the storage capacity of the reservoir. Other conventional methods are therefore more cost efficient.

5.2 Case 2: Millsite Reservoir

The second reservoir that has been investigated is the Millsite Reservoir. This reservoir is located in the state Utah, in the United States of America. It is situated close to Ferron City and has been constructed in 1971. The original storage capacity of the reservoir was 22.2 million cubic meters and the purpose of the reservoir was to fulfil irrigation needs of the local community.

Sedimentation in the reservoir has led to a capacity decrease of 3.2 million m^3, which coincides with a capacity decrease of 14%[34]. This means that the yearly capacity decrease of the Millsite Reservoir is 0.44%. The primary function of the reservoir is going to be harmed if this decrease of reservoir capacity continuous. Therefore, measurements to counteract this sedimentation process have to be investigated in order to maintain the current reservoir capacity and possibly restore the original capacity.

As can be seen in Figure 30, the Millsite Reservoir is much shorter and smaller than the Mrica Reservoir. The average steepness of the Millsite Reservoir is 0.014, which is steeper than the Mrica Reservoir. The water level is partly brought down in the satellite picture of Figure 30, which makes the sedimentation at the river mount clearly visible.

FIGURE 30: SATELLITE PICTURE OF THE MILLSITE RESERVOIR – FROM: (GOOGLE EARTH, 2012)

[34] Also see the report of Managing Sediment in Utah's Reservoirs: (Plan, conserve, develop and protect Utah's water resources, 2012)

To investigate which reservoir preservation method is suitable for this particular reservoir, the reservoir needs to be categorized and the sedimentation problem needs to be quantified (see also the flow chart in Figure 15). These steps are discussed in the following paragraphs, where also the Water Injection Dredging option will be evaluated.

5.2.1 Quantify the sedimentation problem in the Millsite Reservoir

The yearly sedimentation rate of the Millsite Reservoir is 0.44 per cent per year. Since the start of the exploitation of the reservoir, 3.3 million m^3 of the original capacity has been replaced by sediments that settled in the reservoir. This is 14 per cent of the total original volume of the reservoir. The reservoir has been operating for 34 years since this inventory was made in 2004, so the yearly amount of sediment that settles in the reservoir is $3.3 \cdot 10^6 / 34 = 97 \cdot 10^3\ m^3$.

The sediment properties can be described as fine sediment. This means that the sediments consist of silt and clayey material. Data of the period of retention, as well as data of the mean velocity in the reservoir is not available. The Churchill curves can therefore not be used to determine the Trap Efficiency.

As a good alternative for the Churchill curves, the Brune curves can be used to determine the trap efficiency. The determinative parameter for these curves is the Capacity/Inflow ratio, which represents the ratio between the capacity of the reservoir and the average annual water inflow.

The capacity of the reservoir is already known. From data of the United States Geological Survey (USGS), the average annual inflow can be determined[35]. A graph of the discharge of the last five years of the Ferron Creek is presented in Figure 31.

The figure shows that the Ferron Creek is a seasonal river, which results in large fluctuations. It also shows that the discharges of the river are quite similar to the median daily statistic of the discharge. This means that the discharge of the Ferron Creek doesn't show very large variation towards the mean value.

[35] The National Water Information System - (United States Geological Survey, 2012)

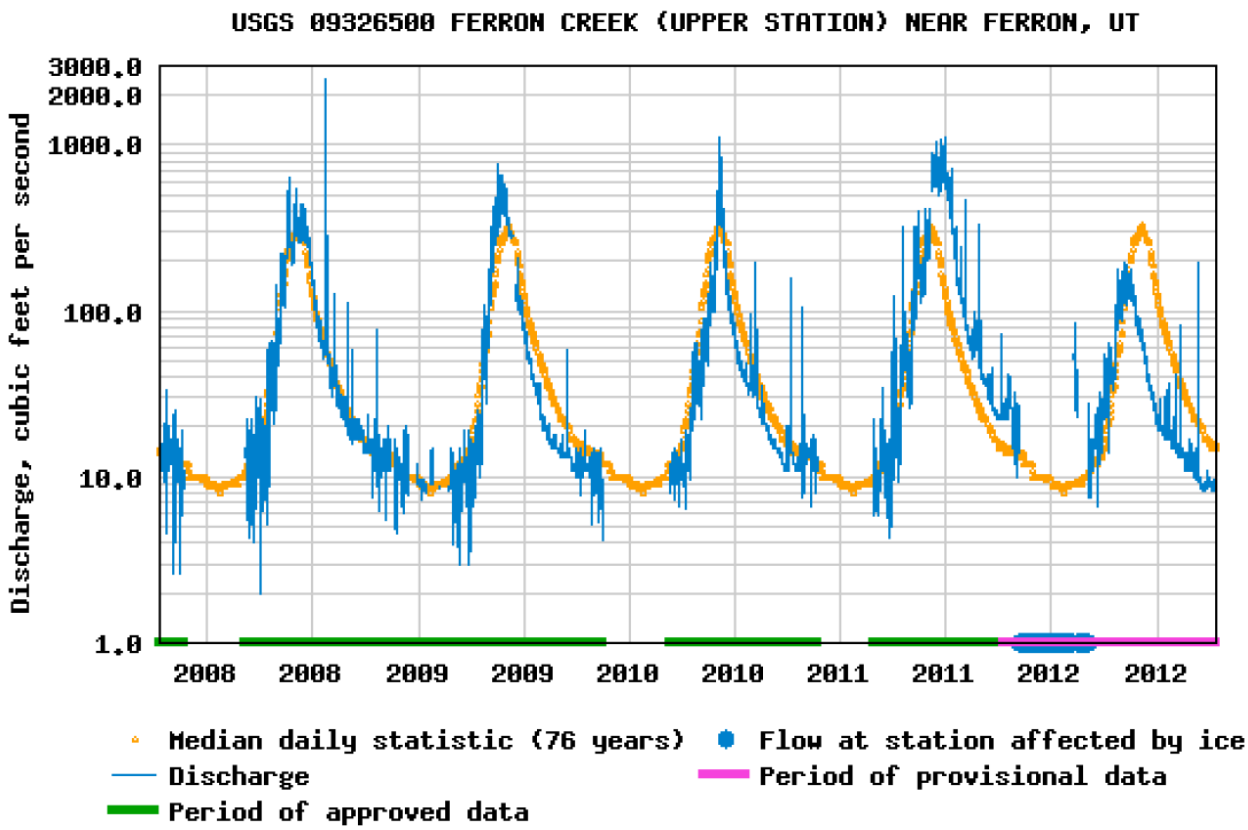

FIGURE 31: WATER DISCHARGE OF THE FERRON CREEK, UTAH – GRAPH FROM: (UNITED STATES GEOLOGICAL SURVEY, 2012)

From the data of 76 years of measurements done by the USGS, follows that the mean discharge value is 20 cubic feet per second. This corresponds with 0.57 m^3 per second and 0.57*3600*24*365 = 17.8 million m^3 per year.

The original capacity of the reservoir was 22.2 million cubic meters. The Capacity/Inflow ratio of the reservoir, when the reservoir had its original capacity, is therefore:

$$\frac{C}{I} = \frac{22.2 \cdot 10^6}{17.8 \cdot 10^6} = 1.25 \text{ [year]}$$

This means that it will take the Ferron Creek more than one year to completely refresh the water volume of the reservoir. The current capacity of the reservoir is 19.0 million m^3, which means that the current Capacity/Inflow ratio is lower, because the yearly water inflow will stay the same. The current ratio is:

$$\frac{C}{I} = \frac{19.0 \cdot 10^6}{17.8 \cdot 10^6} = 1.08 \text{ [year]}$$

Also in the current situation will it take the Ferron Creek more than one year to completely refresh the water volume inside the Millsite Reservoir. Looking at the Brune curves in Figure 9, the Trap Efficiency of the Millsite Reservoir can therefore be determined on 95 to 100%.

5.2.2 Qualify the sedimentation problem in the Millsite Reservoir

The sediments in the Millsite Reservoir are described as 'fines' in the report of Managing Sediment in Utah's Reservoirs[36]. This is a very general description of the particles and it is therefore considered that the particles can be categorized as Silt, which as a particle diameter of 0.002 to 0.06 mm (see also Table 26 in Appendix A). The median grain size is therefore considered to be 0.031 mm.

5.2.3 Classify the Millsite Reservoir

Now that the sedimentation problem within the Millsite Reservoir is quantified and qualified, the Millsite Reservoir can be classified. This is necessary as a tool to find out which reservoir preservation methods are feasible for this specific reservoir.

5.2.3.1 Classify the Millsite Reservoir based on the Empirical Area-Reduction method

The first classification method that is applied to the Millsite Reservoir is the Empirical Area-Reduction method. A more detailed explanation of this method can be found in Paragraph 3.5.1. The basic of this method is the shape of the reservoir and the method divides the reservoir into 4 different shapes. The shape is determined by the parameter "M", which is the reciprocal of the slope of the line obtained by plotting the reservoir depth at the vertical axis against the reservoir capacity at the horizontal axis on log-log paper.

[36] Managing Sediment in Utah's Reservoirs- (Plan, conserve, develop and protect Utah's water resources, 2012)

Data from the Utah Department of Environmental Quality- Division of Water Quality provides specifications that are necessary to classify the Millsite Reservoir[37]. For the initial capacity of 22.2 million cubic meters, the reservoir depth is 31 meters. To obtain the second point on the log-log paper, a calculation has to be done, where the reservoir is schematized in the same way as is done in Figure 25. The reservoir length L is 2220 meters, so the surface G is then:

$$V = \frac{1}{3}GL$$

$$22.2 \cdot 10^6 = \frac{1}{3} \cdot G \cdot 2220$$

$$G = 30 \cdot 10^3 \text{ m}^2$$

The surface G at the maximum depth of 31 meter is then $30 \cdot 10^3$ m^2 and this coincides with the data from the Utah Department of Environmental Quality. They state that the width of the reservoir is 1066 meter, which leads combined with the reservoir depth of 31 meter to a surface G of 1066·31 = 33.046 meter. Since the dam is a little bit smaller than the maximum reservoir width (as can be seen in Figure 30), the surface G of $30 \cdot 10^3$ is correct.

To calculate the second point needed for the plot on the log-log paper, a reservoir capacity proportional to a certain reservoir depth has to be determined. The mean reservoir depth is chosen, which corresponds with a reservoir depth of 14 meter.

Since a similar surface profile of G can be assumed at reservoir depth of 14 meter, G can be calculated as follows:

$$G(at\ depth\ 14\ m) = \frac{14}{31} \cdot 30 \cdot 10^3 = 13.5 \cdot 10^3 \text{ m}^2$$

The proportional length of the reservoir can be calculated with the use of similar shapes. The length of the reservoir when the reservoir is at maximum capacity is 2220 meter. The length L of the reservoir at depth 14 meter is then:

$$\frac{31}{14} = \frac{2220}{L(at\ depth\ 14\ m)}$$

$$L(at\ depth\ 14\ m) = 1003 \text{ m}$$

The volume of the reservoir V at depth 14 meter is then:

$$V = \frac{1}{3}GL$$

$$V(at\ depth\ 14\ m) = \frac{1}{3} \cdot 13.5 \cdot 10^3 \cdot 1003 = 4.51 \cdot 10^3 \text{ m}^3$$

[37] Data from: http://www.waterquality.utah.gov - (Utah Department of Environmental Quality, 2012)

The reservoir depths and the proportional reservoir volumes can now be plotted on log-log paper to calculate the parameter M. This plot is presented in Figure 32.

As can be seen in the plot, the parameter M for the Millsite Reservoir is equal to 2.04. This means that the reservoir can be classified as type III, also known as the Hill type reservoir. The Millsite Reservoir can therefore be described as a steeper reservoir as the Mrica Reservoir, which has been discussed earlier.

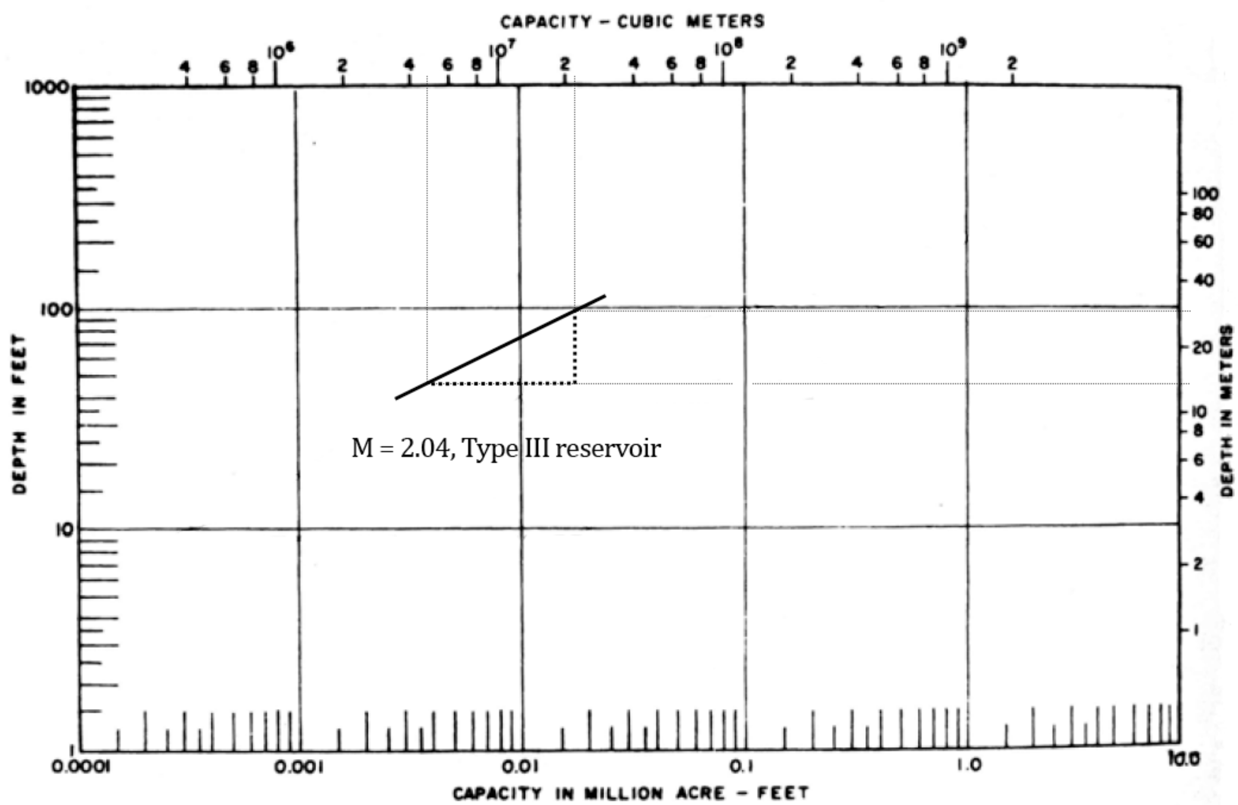

FIGURE 32: DETERMINATION OF PARAMETER M FOR THE MILLSITE RESERVOIR

The next step is to look at Table 2, where the classification of the Empirical Area-Reduction method is combined with the reservoir preservation techniques. From that table, the following methods are recommended to preserve the Millsite Reservoir capacity:

- Sediment catchment structure
- A sediment bypass
- Implement watershed management
- Sluice high sediment loaded water peaks through the reservoir
- Flush the reservoir
- Hydraulic dredging
- Mechanical excavators
- Water Injection Dredging

5.2.3.2 *Classify the Millsite Reservoir based on the permitted reservoir operations*

Whether or not it is permitted to draw down the water level within the reservoir is essential for some of the preservation methods. This decision is depending on the economic and environmental consequences of the draw down and the discussion if these consequences are acceptable.

In the case of the Millsite Reservoir a full draw down is not possible due to the high Capacity/Inflow ratio, which was discussed in Paragraph 5.2.1. It takes the Ferron Creek more than one year to completely refresh the reservoir volume. In the case of a full draw down, it will therefore take more than one year to fill up the reservoir. Since the Millsite Reservoir distributes water to local irrigation systems, shutting down these water distributions for more than one year is unacceptable.

Partial drawing down the water level in the Millsite Reservoir is permitted. Because of the seasonal fluctuations of the Ferron Creek, the water level within the reservoir fluctuates significantly. A partial drawdown is therefore inextricably part of the reservoir operations.

These permitted operations have no consequences on the list which was composed in the previous paragraph, which means that the following reservoir preservation options are still under discussion:

- Sediment catchment structure
- A sediment bypass
- Implement watershed management
- Sluice high sediment loaded water peaks through the reservoir
- Flush the reservoir
- Hydraulic dredging
- Mechanical excavators
- Water Injection Dredging

5.2.3.3 *Classify the Millsite Reservoir based on the Capacity/ Inflow ratio*

The ration between the capacity of the reservoir and the average annual water inflow discussed in Paragraph 5.2.3.1 can now be used to classify the reservoir. The original Capacity/Inflow ratio of the reservoir when the reservoir was just constructed was:

$$\frac{C}{I} = \frac{22.2 \cdot 10^6}{17.8 \cdot 10^6} = 1.25 \text{ year}$$

The current Capacity/Inflow ratio of the Millsite Reservoir is:

$$\frac{C}{I} = \frac{19.0 \cdot 10^6}{17.8 \cdot 10^6} = 1.08 \text{ year}$$

Both of the equations have a ratio higher than 1, which means that the Millsite Reservoir can be classified in the category C/I > 1. This is regardless of the initial capacity or the capacity of the reservoir after the sedimentation.

This classification has consequences for the suitability of the reservoir preservation methods. Because it will take a lot of time to refill the reservoir and this process suggests that there are calm conditions in the reservoir, the methods that require a complete draw down or turbulent flow will be eliminated. The following methods remain:

- Sediment catchment structure
- A sediment bypass
- Implement watershed management
- Hydraulic dredging
- Mechanical excavators

5.2.4 COST EFFICIENCY CALCULATIONS

The eliminated methods are: Water Injection Dredging, sluice high sediment loaded water peaks through the reservoir and flush the reservoir. This is also presented in the overview in Table 18.

TABLE 18: OVERVIEW OF THE POSSIBLE PRESERVATION METHODS IN THE MILLSITE RESERVOIR

Preservation method	Sediment catchment structure	Sediment bypass	Watershed management	Density currents (WID)	Sluicing	Flushing	Hydraulic dredging	Mechanical excavation
Classification method								
• Empirical Area-Reduction method	√	√	√	√	√	√	√	√
• Permitted reservoir operations	√	√	√	√	√	√	√	√
• Capacity/Inflow ratio	√	√	√	X	X	X	√	√

As is mentioned earlier in this thesis, using these classifications always has to be combined with engineering expertise. In this particular case, the options of sluicing high sediment loaded water peaks through the reservoir and create density currents current should be considered instead of eliminated. Normally these methods would be withdrawn from the list because the reservoir capacity is relatively large compared with the annual average water inflow. Due to the high fluctuations of the Ferron Creek (see also Figure 31), these methods should be considered.

Another consideration that has to be made is that implementing watershed management is a very comprehensive and time-consuming process. Since the reservoir is already in operation and the sedimentation problem has to be handled in a quick and efficient way, watershed management is not an option.

The list of possible reservoir preservations is therefore:

- Sediment catchment structure
- A sediment bypass
- Sluice high sediment loaded water peaks through the reservoir
- Hydraulic dredging
- Mechanical excavators
- Water Injection Dredging

Now that the possible reservoir preservation options are determined for the Millsite Reservoir, a cost efficiency calculation can be carried out to compare the costs of the different methods with Water Injection Dredging. To calculate if a certain method is cost efficient, the production rates and the costs of implementing this method are estimated. For some methods, including for Water Injection Dredging, is it necessary that bottom outlets are constructed in the dam. Although the construction of these bottom outlets can be very costly, these costs are not considered within these calculations. This is because of the fact that the reservoir preservation methods are implemented after the construction of a dam is already finished. The costs of the possible construction of the bottom outlets are therefore already made and don't have to be taken into account again.

A feasibility study done in 2008 by Rollin H. Hotchkiss has resulted in a cost calculation of some of the reservoir preservation options[38]. These calculations can be used to compare the results of the costs efficiency calculations made in this thesis.

No data is available whether or not the Millsite Reservoir has bottom outlets or not. Therefore, in the line of this thesis, it is assumed that there are bottom outlets. This makes it possible to test if Water Injection Dredging can be implemented or not.

[38] Managing Sediment in Utah's Reservoirs - (Plan, conserve, develop and protect Utah's water resources, 2012)

5.2.4.1 SEDIMENT CATCHMENT STRUCTURE

The first option that is discussed is the use of a sediment catchment structure. A sediment catchment structure is constructed to catch the sediments before it can enter the reservoir. The caught sediment is then periodically removed from the catchment structure. The sediments can then be brought back into the river downstream of the dam or be permanently removed. The yearly amount of sediment that is caught by the river is $97 \cdot 10^3$ m^3.

The feasibility study done by Rollin H. Hotchkiss has resulted in an estimation of the cost for a sediment catchment structure of $650.950 per year, and an investment cost of $805.000. This can be converted in euro by using the same euro/dollar rate as was used by the previous case study: 0.785 €/$. This means that the annual costs are €510.996 and the capital costs are €631.925. Divide the annual costs by the yearly sediment inflow of 97 million m^3 and the unit cost are 5.27 euro per removed m^3.

5.2.4.2 SEDIMENT BYPASS STRUCTURE

Passing by the sediment is usually a costly operation. A sediment bypass structure is not available, so this will have to be constructed. A cost estimating of constructing a sediment bypass structure is a comprehensive and time-consuming task, where a lot of aspects of the local circumstances have to be taken into account. The cost estimation done by Hotchkiss in 2008[39] is therefore considered.

The annual cost of the sediment bypass would be $650.950, and the investment costs $805.000. This can be converted with the same euro/dollar rate as was used in the previous paragraph: 0.785 €/$. This means that the annual costs for a sediment bypass structure are €510.996 and the capital costs are €631.925.

However, a sediment bypass structure does not guarantee that the yearly amount of sediment that flows into the reservoir is also floating through the sediment bypass out of the reservoir. Only a part of the sediments will be bypassed through this system. This makes it impossible to grade this method by using the unit costs, which are expressed in euro per removed m^3 sediment. Since the method is therefore impossible to compare with, this option is not considered in this thesis.

[39] Managing Sediment in Utah's Reservoirs - (Plan, conserve, develop and protect Utah's water resources, 2012)

5.2.4.3 HYDRAULIC DREDGING

The earlier discussed Excel-sheet with the production and cost estimations of different reservoir preservation techniques can be used to make the cost efficiency calculations of hydraulic dredging in the Millsite Reservoir. For more details on these calculations, see Appendix A.1.

For the Millsite Reservoir, hydraulic dredging operations with a Cutter Suction Dredger are considered. The reservoir cannot be accessed through waterways (there are no ship lifts or sluices in the Millsite Dam) and the river Ferron Creek is very small. This makes it necessary to use a dismountable Cutter Suction Dredger.

The maximum water depth of the Millsite Reservoir is 31 meter. Given the fact that the costs of a Cutter Suction Dredger will increase significantly with the depth, a dredger with a lower depth is considered. What also has to be taken into account, is that so far 14 per cent of the reservoir is filled up with sediments. These sediments are likely to have settled in the shallow parts of the reservoir, close to the river mouth. A Cutter Suction Dredger with a dredging depth lower than the maximum depth of the reservoir is therefore valid to choose.

The dismountable dredger IHC Beaver 6518C is chosen in this case[40]. This dredger can dredge up to 18 meter and is able to reach most parts of the reservoir. The total installed power is 2700 kW and the internal diameter of the discharge pipes of this dredger is 0.65 meter. The velocity within the discharge pipes is considered to be 3.5 meter per second.

The transport concentration of in situ soil C_{vsi} for the IHC Beaver 6518 C has a maximum of 30 per cent. The soil in the Millsite Reservoir is classified as Silt (see also the soil classification in Paragraph 5.2.2). The in situ density of the soil in the Millsite Reservoir is therefore 1400 kg/m^3, this follows from Table 8. In order to fulfil the requirement that the volumetric concentration of the in situ soil must not exceed 30 per cent, the density of the mixture is determined to be 1120 kg/m^3 (see also the Appendix A.1.1).

Operational hours also have to be taken into account in order to calculate the total needed production weeks of a Cutter Suction Dredger. A workweek of 24 hours per day and 7 days per week is chosen. A net work efficiency of 60 per cent takes into account the time in which the Cutter Suction Dredger can’t operate due to moving of the dredger to another location in the reservoir, maintenance, repair of other work troubling issues.

The number of Cutter Suction Dredgers that is used in this operation is 1. More dredgers are not necessary, since the Millsite Reservoir is relatively small. An overview of all the used values for the calculation sheet is presented in Table 18.

[40] Also see the specifications IHC Beaver 6518 C - (IHC Merwede, 2012)

TABLE 19: VALUES FOR THE CALCULATION OF THE NECESSARY PRODUCTION WEEKS

Parameter	Value	Unit
Type dredger	IHC Beaver 6518C	[-]
Total installed power	2700	[kW]
Diameter pipeline	0.65	[m]
Velocity in pipeline	3.5	[m/s]
Density of in situ soil	1400	[kg/m^3]
Density of the water	1000	[kg/m^3]
Density of the mixture	1120	[kg/m^3]
Operational hours per day	24	[hr/day]
Operational days per week	7	[days/week]
Net work efficiency	60.00	[%]
Number of CSD's used	1	[-]

From the production en cost estimating sheet follows that the amount of time that is necessary to remove the yearly sediment inflow in the Millsite Reservoir is 1 week.

The calculation values of Ciria Dredging Cost Standards[41] are used for the calculation of the weekly production costs. Interpolation of these calculating values from is necessary in order to find the exact value for the depreciation and interest and for the value of maintenance and repair. The power of the cutters motors is 585 kW for a 6518C Cutter Suction Dredger, which results in 44.091 euro per week for depreciation and interest and 31.920 euro per week for maintenance and repair.

The total installed power is 2700 kW for the IHC Beaver 8518C. The price for marine diesel is set to 1454 $/ton[42] and the Euro/Dollar rate at 0.764[43]. The calculation sheet then calculates the total weekly costs for fuel and lubricants.

Extra costs that have to be taken into account for this project are the costs that are made to transport the material towards the deposit site. The pump and pipeline characteristics of the Cutter,

[41] Table 201 of the CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)
[42] Marine Diesel Oil Prices - (Bunkerworld Prices BWI, 2012)
[43] ECB: Euro exchange rates USD - (European Central Bank, 2012)

which are provided with the dredger specifications[44], state that the pipeline connected with the dredger can be more than 6000 meter for this mixture. The length of the Millsite Reservoir is 2220 meter[45], so an extra booster station will not be necessary for this particular case.

The storage site, which is discussed at the one-time costs section, is located close to the reservoir. The bank at the south-west point of the reservoir provides a cove where the reservoir can be constructed. Since this is close to the reservoir, the pipeline length has a maximum length of 2000 meter, from which 1700 meter is floating and 300 meter is on shore. The remainder costs of the pipeline with a diameter of 0.65 meter can be found in the CIRIA cost standards. No percentage for maintenance and repair has to be taken into account, since this duration length of this method is small. An overview of the calculating values for the weekly production costs is presented in Table 19.

TABLE 20: VALUES FOR THE WEEKLY COSTS CALCULATION

Parameter	Value	Unit
Depreciation and interest	44091	[€/week]
Maintenance and repair	31920	[€/week]
Price marine diesel	1454	[$/ton]
Euro/Dollar rate	0.785	[€/$]
Needed amount of booster stations	0	[-]
Price per booster station	-	[€]
Costs of the pipeline, per week		
• Length pipeline on shore	300	[m]
• Price per meter	0.90	[€/m]
• Length floating pipeline	1700	[m]
• Price per meter floating pipeline	9.35	[€/m]
• Needed amount of bends	5	[€]
• Price per bend	16.70	[€]
• Maintenance and repair pipeline, percentage of total costs pipeline	0	[%]

[44] IHC Beaver 6518C specifications - (IHC Merwede, 2012)
[45] http://www.waterquality.utah.gov - (Utah Department of Environmental Quality, 2012)

One-time costs that have to be considered in this case are costs to construct a storage site, costs to transport the dredger to the reservoir and costs to assemble and disassemble the dredger. A storage site is necessary, since it is not possible to return the dredged up sediment back into the river downstream of the dam due to high sediment peaks. The storage site has to be able to store 97.000 m^3 of sediment, which means that the dimensions of the storage site must be in the order of 180 x 180 x 3 meter. A cove just south-west of the reservoir can be used to construct a relatively cheap storage site, where a levee of 400 meter long and 3 meters high is necessary. Assuming that the cubical meter sand necessary per meter levee is in the order of 25 m^3, the total volume of sand is than 10.000 m^3. Taken into account a rough estimate that the transport and the treatment of the construction material costs 10 euro per m^3, results is the estimate that the construction of the deposit site is in the order of 100.000 euro. For transport costs and costs to assemble and disassemble the dredger is 200.000 euro, respectively 150.000 euro taken into account.

The total costs for using a Cutter Suction Dredger in the Millsite Reservoir are 521.364 euro, which is equal to 6.41 euro per removed m^3 sediment. This is relatively high because of the high one-time costs. These costs represent more than half of the total costs. A permanent Cutter Suction Dredger would avoid these one-time costs, but a similar dredger such as the dredger that is considered here costs more than 10 million euro.

An important remark that has to be made here is that the dredged up sediment also has to be removed from the deposit site. This is a very costly operation since these removal rates are usually in the order of more than 5 euro per m^3 sediment. This means that the total costs of the operation would double to more than 10 euro per removed m^3 sediment.

5.2.4.4 Mechanical excavators

It is also possible to use mechanical excavators in the Millsite Reservoir. The Excel-sheet for production and costs estimations for sediment removal from reservoirs can also be used to make cost efficiency calculations for mechanical excavators. Two types of mechanical excavators can be used in this case: an excavator on tracks and a grab dredger.

The first option that is discussed is the use of an excavator on tracks. Excavators on tracks have the limitations that they can only dredge up to a certain depth. The maximum depth in the Millsite Reservoir is 31 meters and the selected dredger in this case has a maximum dredging depth of 21 meters in order to limit the costs of this method. This results in a backhoe dredger with a bucket of 15 m^3 and a total installed power of 1600 kW.

The estimated production rate of the backhoe is 1 bucket per minute and it is assumed that the dredger is operating 24 hours a day, 7 days a week. To compensate the inefficiency of the dredger due to maintenance, repair and re-positioning, a net work efficiency of 60 per cent is taken into account. The number of excavators that are used in this project is 1. An overview of the used calculating values for the calculation of the production weeks is presented in

TABLE 21: VALUES FOR THE CALCULATION OF THE NECESSARY PRODUCTION WEEKS FOR AN EXCAVATOR ON TRACKS

Parameter	**Value**	**Unit**
Type dredger	Backhoe	[-]
Total installed power	1600	[kW]
Volume excavator bucket	15	[m^3]
Amount of bucket delivered per minute	1	[bucket/min]
Operational hours per day	24	[hours]
Operational days per week	7	[days]
Net work efficiency	60.00	[%]
Number of excavators used	1	[-]

The amount of production weeks that are necessary when an excavator on tracks is used in the Millsite Reservoir is 2.

The CIRIA costs standards are used for the calculation of the weekly production costs. The value for the depreciation and interest and the value for maintenance and repair are found within these costs standards. The pontoon that is necessary for the backhoe to work on is included within these values. The price for marine diesel is assumed to 1454 $/ton, and the Euro/Dollar rate is 0.785. These are the same values as the values that were taken for hydraulic dredging in the previous paragraph.

Extra costs that are made for this project are the costs to transport the material towards the deposit site. This is done by using pontoons and a tugboat. In this case 3 pontoons and 1 tugboat are sufficient to deal with the sediment load. This is due to the limited size of the reservoir. One crane on shore is capable of dealing with the sediment load. The costs per unit for this equipment are equal to the costs that were considered for this equipment in the previous paragraph. An overview of the used values is presented in Table 21.

TABLE 22: VALUES FOR THE WEEKLY COSTS CALCULATION OF AN EXCAVATOR ON TRACKS

Parameter	Value	Unit
Depreciation and interest	105112	[€/week]
Maintenance and repair	45080	[€/week]
Price marine diesel	1454	[$/ton]
Euro/Dollar rate	0.785	[€/$]
Needed amount of extra pontoons	3	[-]
Price per pontoon	3837	[€/week]
Needed amount of tugboats	1	[-]
Price per tugboat	4701	[€/week]
Needed amount of unloading cranes at the shore	1	[-]
Price per unloading crane at the shore	32036	[€/week]
Costs constructing and maintaining and maintaining quay wall	5000	[€/week]

Other expenses that have to be taken into account are taken as a percentage of the weekly production costs and are calculated automatically by the Excel-sheet. Rough estimates are made for the one-time costs that are considered. The costs for the construction of a storage site are similar to the costs of the storage site treated in the previous paragraph: 100.000 euro. For transport costs 50.000 euro is taken into account, for assembly and disassembly costs 50.000 euro.

This results in the total costs of 769.929 euro for using an excavator on tracks in the Millsite reservoir in order to remove the yearly inflow of sediment, which is equal to 7.94 euro per removed m^3 sediment. This is quite high since the size of the mechanical excavator is considerable in order to reach the required depth of the reservoir.

An important remark that has to be made here is that the dredged up sediment also has to be removed from the deposit site. This is a very costly operation since these removal rates are usually in the order of more than 5 euro per m^3 sediment. This means that the total costs of the operation would increase significantly.

The second option when using mechanical excavators in the Millsite Reservoir is using a grab dredger. As was the case with the excavator on tracks, a grab dredger also has a limited dredging depth. The grab dredger that is selected in this case is the grab dredger with an installed power of 212 kW and a limited dredging depth of 24 meter. Although this isn't the needed dredging depth to reach every part of the reservoir, this depth is still selected in order to minimise the costs. The volume of the bucket is 5 m^3 and the grab dredger is able to produce 1 bucket per minute.

A workweek of 24 hours per day and 7 days per week is chosen. A net work efficiency of 60 percent takes into account the downtime of the grab dredger due to the moving of the dredger, maintenance, repair or other work troubling issues. The number of dredgers that are used in this case is one. According to the sheet, it results in the fact that 5 weeks are necessary to remove the yearly amount of sediment that flows in the reservoir. An overview of the chosen values is presented in Table 22.

TABLE 23: VALUES FOR THE CALCULATION OF THE NECESSARY PRODUCTION WEEKS FOR A GRAB DREDGER

Parameter	**Value**	**Unit**
Type dredger	Grab dredger	[-]
Total installed power	212	[kW]
Volume excavator bucket	5	[m^3]
Amount of bucket delivered per minute	1	[bucket/min]
Operational hours per day	24	[hours]
Operational days per week	7	[days]
Net work efficiency	60.00	[%]
Number of excavators used	1	[-]

The yearly amount of sediment that flows in the reservoir can be removed with a grab dredger in 5 weeks.

The CIRIA cost standards are also used in this case for the calculation of the weekly production costs. The value for the depreciation and interest and the value for the maintenance and repair are achieved in this way. Similar to the use of an excavator on tracks, 3 pontoons and 1 tugboat are necessary in the Millsite Reservoir to transport the dredger up material to the shore. Also 1 unloading crane at the shore is considered in this case. An overview of these input values is presented in Table 23.

TABLE 24: VALUES FOR THE WEEKLY COSTS CALCULATION OF A GRAB DREDGER

Parameter	**Value**	**Unit**
Depreciation and interest	6741	[€/week]
Maintenance and repair	4250	[€/week]
Price marine diesel	1454	[$/ton]
Euro/Dollar rate	0.785	[€/$]
Needed amount of extra pontoons	3	[-]
Price per pontoon	3837	[€/week]
Needed amount of tugboats	1	[-]
Price per tugboat	4701	[€/week]
Needed amount of unloading cranes at the shore	1	[-]
Price per unloading crane at the shore	32036	[€/week]
Costs constructing and maintaining and maintaining quay wall	5000	[€/week]

The construction of a storage site is estimated to be 100.000 euro, as was considered with the case of an excavator on tracks. The transport and assembly/disassembly costs are lower however, since the used equipment is much smaller. This is estimated to be 25.000 euro each.

This results in the total costs of using a grab dredger in the Millsite Reservoir of 627.691 euro. Divide this by the amount of sediment that is going to be removed, than the unit costs of this method are 6.47 euro per m^3 sediment removed.

Also in this case has to be remarked that the sediment still has to be removed from the deposit site. This will increase the costs of using a grab dredger considerably.

5.2.4.5 *Water Injection Dredging*

The production and cost estimation Excel-sheet can be used to estimate the cost efficiency of Water Injection Dredging in the Millsite Reservoir. The Water Injection dredger will be smaller than the one used in the Mrica Reservoir case study, since the Millsite Reservoir is also significantly smaller.

As was discussed earlier in Paragraph 5.2.2, the sediment in the Millsite reservoir can be described as Silt. The median grain size is 0.031 mm and the in situ soil density is 1400 kg/m^3.

The used Water Injection dredger is smaller than the one is in the Mrica Reservoir. The width is 10 meter and the amount of nozzles 22. The total installer power on the vessel is smaller than the one used in the Mrica Reservoir case study. A total installer power of 650 kW is considered in this case, which is about half of the total installed power of the Water Injection Dredger used in the Mrica Reservoir.

The values for the cohesion of the sediments in the Millsite Reservoir are not known. From Water Injection Dredging projects done in the past, it is known that the cohesion is usually in the range of 0 to 20 kPa[46]. Since the sediments in the Millsite Reservoir are likely to have settled in the reservoir for a long period of time, the cohesion value is considered to be relatively large in this case. A value of 15 kPa is therefore assumed.

A work efficiency of 60 per cent is chosen to take into account the inefficiency due to manoeuvring of the vessel during dredging operations. The length of the Millsite Reservoir is 2220 meter[47] and as a calculation length 1110 meter is taken. The steepness of the reservoir is the maximum depth in front of the dam divided by the length of the reservoir: 31/2220 = 0.014. The multipurpose pontoon is 10 meters wide and has a value for depreciation and interest of 16.632 euro, and a value for maintenance and repair of 13.020 euro[48]. The costs of the pump are 100.000 euro. This is about half of the costs of the pump used in the Mrica case study.

The remaining parameters are considered to be the same as the parameters that were used in the Mrica Reservoir case study. An overview of all the used parameters in the Excel sheet for Water Injection Dredging in the Millsite Reservoir is given in Table 24.

[46] Jetten in slib t.b.v. waterinjectie baggeren - (Schuling, 1998)
[47] Millsite report of the Division of Water Quality - (Utah Department of Environmental Quality, 2012)
[48] Table 820 of the CIRIA costs standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)

Table 25: Overview of the used parameters for Water Injection Dredging in the Millsite Reservoir

Parameter	Value	Unit
Density water	1000	[kg/m³]
Density in situ soil	1400	[kg/m³]
Density mixture	1070	[kg/m³]
Width of the WID barge	10	[m]
Amount of nozzles	22	[-]
Diameter nozzle	0.09	[m]
Flow velocity when leaving the nozzle	14.1	[m/s]
Cohesion	15	[kPa]
Inefficiency due to manoeuvring of the vessel	60.00	[%]
Kinematic viscosity	$1.004 \cdot 10^{-6}$	[m²/sec]
Particle diameter	31	[µm]
Gravitational constant	9.81	[m/s²]
Steepness reservoir	0.014	[-]
Calculation length of the reservoir	1110	[m]
Operational hours per day	24	[hours/day]
Operational days per week	7	[days/week]
Inefficiency due to downtime	80.00	[%]
Number of WID vessels used	1	[-]
Depreciation and interest	16.362	[€]
Maintenance and repair	13.020	[€]
Total installed power	650	[kW]
Price marine diesel	1454	[$/ton]
Euro/Dollar rate	0.785	[€/$]

Maximum dredging depth	31	[m]
Price of pipe per meter	431.25	[€/m]
Cost of pump	100.000	[€]
Amount of weeks necessary for construction	16	[weeks]
Amount of employees needed	5	[-]
Working hours per week	45	[hours/week]
Price per hour, per employee	100	[€/hour]

The production costs per week are in this case 99.097 euro and the total production weeks 0.8. If the Water Injection Dredger is permanently installed, the total construction costs also have to be taken into account. These costs are 938.831 euro in total.

Since in all the cases dismountable equipment is considered, this will also be done in this case. For transport costs and assembly/disassembly will both be considered the costs of 100.000 euro. In that case, the total costs would be $0.8 \cdot 99097 + 2 \cdot 100.000 = 279278$ euro. Divide this number with the removed amount of sediment of 97.000 m^3 and the unit costs are: 2.88 euro per m^3 sediment removed.

If Water Injection Dredging is going to be implemented in the Millsite Reservoir, the sediment peak has to be smoothened out. The 0.8 weeks that are now needed to remove the yearly amount of sediment gives a sediment peak that is too high for the river downstream of the dam to cope with.

5.2.5 Conclusion case study Millsite Reservoir

To investigate whether or not Water Injection Dredging is a cost efficient method to preserve the capacity in reservoirs, a smaller reservoir than the earlier discussed Mrica Reservoir is investigated. This way, a sensitivity analyses can be made to investigate the influence of the size of the sedimentation problem to the Water Injection Dredging method.

Some of the possible methods require a permanent installation. To make these methods comparable with the other ones, these installation are considered to operate for 30 years and a 1/30 part of the capital costs is added to the yearly costs. It results in the following overview (Figure 33).

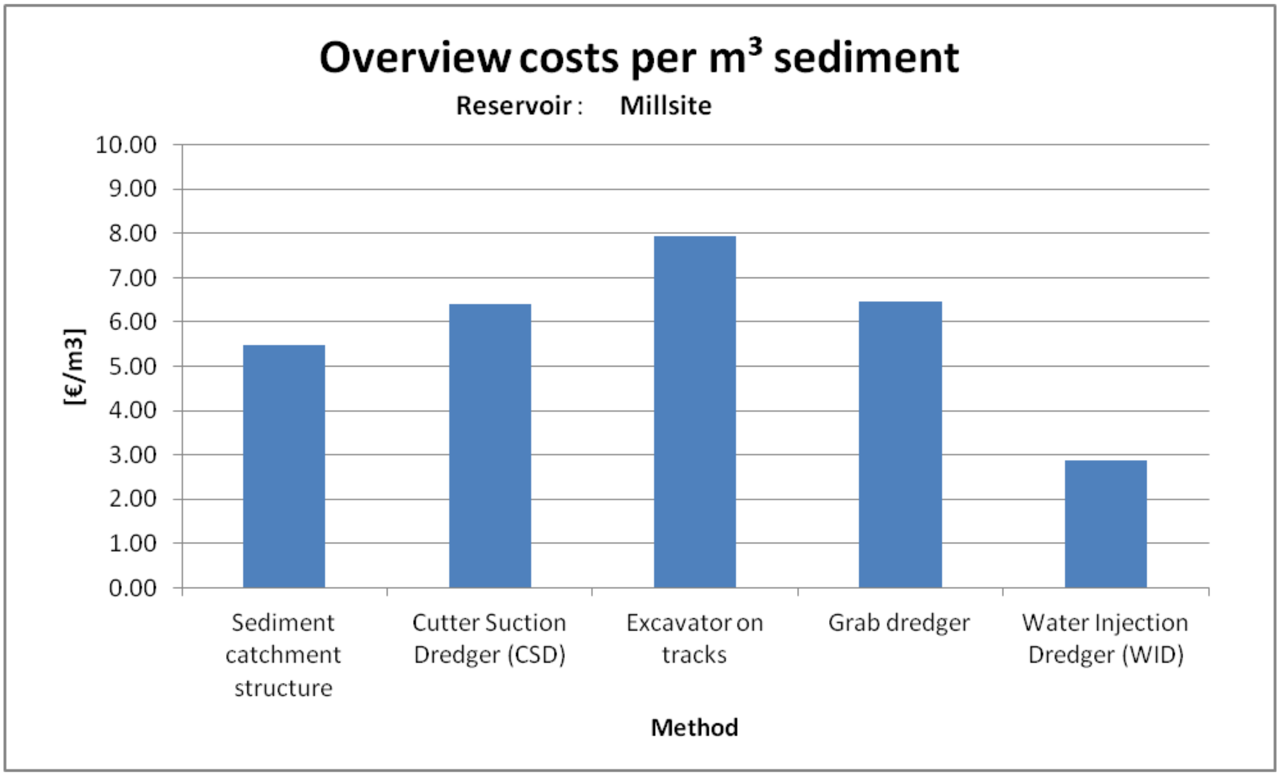

FIGURE 33: OVERVIEW COSTS PER M³ SEDIMENT WITHIN THE MILLSITE RESERVOIR

Figure 33 shows that also in this case, Water Injection Dredging is a good alternative from a cost perspective. The installation of a sediment catchment structure, where sediment is caught before it can enter the reservoir, is a good alternative.

For all methods besides the Water Injection Dredging method, costs will have to be taken into account for the removal of the dredged up sediments from the deposit site. This is usually in the order of 5 to 10 euro per m³ sediment.

Although Water Injection Dredging is the cheapest option for the Millsite Reservoir, a critical note has to be made. The consequences of a high sediment peak for the river downstream of the dam are not known. Sluicing the yearly volume of sediment from the reservoir back into the river in 0.8 weeks creates a very high sediment peak and it is not sure if the river can cope with this peak. A too high sediment peak would result in muddy water, which can have negative influences on the environment. Since the transport capacity of the river is limited, large volumes of sediments can accumulate after the sediments have been brought back into the river system. This can result in an change of the river flow pattern.

An option would be to smoothen out the sediment distribution over a longer period of time. This means however that the costs will rise as well, which will make the option of applying Water

Injection Dredging less attractive. Therefore, further research has to be done in order to determine the limit of the maximum allowable concentration.

6 CONCLUSIONS AND RECOMMENDATIONS

The final part of this thesis includes the conclusions and recommendations regarding reservoir sedimentation problems and the possibility of implementing water Injection Dredging in reservoirs. Also, the results of the case studies will be discussed.

The conclusions of this thesis will be discussed in the first paragraph of this chapter. In the second paragraph, recommendations towards future steps are discussed.

6.1 CONCLUSIONS

Sedimentation in reservoirs is a consequence of the blockage of the sediment flow in the river. The capacity of the reservoir decreases due to the accumulation of sediments and the river downstream starts to erode due to the disturbance of the sediment balance.

An extensive research study with respect to the sediments in the reservoir has to be carried out before the construction of the dam begins, so that the sedimentation problems during the exploitation of the dam can be reduced to a minimal. However, more than once are dam operators surprised by the sedimentation problems in the reservoir and are counter measurements necessary. These counter measurements are often very expensive and are difficult to implement in an effective way.

A proactive attitude towards the sedimentation problem is far more effective than trying to solve the reservoir sedimentation problems when the problems are already there. Therefore, when a dam structure is considered, should sedimentation in the reservoir already in the design phase emphasised and taken into account. This will result in fewer problems with reservoir sedimentation and thereby lower costs to counteract these problems.

In order to give a first impression of the sedimentation rate in a reservoir, empirical formulas such as the formulas of Brune, Brown and Churchill can be used. An overview of the possible reservoir preservation methods can be generated by dividing the reservoir into different classes and linking these classes to different reservoir preservation techniques. The final decision of which technique to use should in any case be done in consultation with all the stakeholders involved and with experienced engineers. It is also possible to use a combination of the different techniques, in order to improve the overall effectiveness.

Although detailed cost calculations are difficult, the case studies show that Water Injection Dredging is a good alternative to the conventional methods to counteract sedimentation problems in reservoirs. It has the potential to remove significant amounts of sediments from reservoirs, in a very effective way. The relatively simple installation makes this technique cheap and fast.

The downside of this method is though, that very specific conditions have to be met in the reservoir. Bottom outlets are necessary to sluice out the created density currents and only certain particles with the correct sediment characteristics can be removed in an effective way. The created high sediment peaks can also be too high for the river downstream of the dam and can exceed the maximum sediment suspension capacity of the river. This can result in a muddy river flow, which can have negative influences on the inhabitants of the river. Also, large volumes of sediment can accumulate close to the dam, since the river can not distribute all the sediments. A study is necessary in order to find out what the maximum sediment transport capacity of the river downstream of the dam is and how high the sediment peak capacity could be.

Detailed calculations to determine the exact production rates and the costs of Water Injection Dredging are not possible, because the method is relatively new and not much information about this technique has been published. However, rough estimations made for the case studies of the Mrica and the smaller Millsite Reservoir provide information about the feasibility of implementing Water Injection Dredging in reservoirs.

There are only a few methods capable with counteracting the immense yearly sediment load of more than 7 million m^3 in the case of the Mrica Reservoir. Water Injection Dredging proved to be the most cost efficient way of removing sediments. The outlets of the dam were constructed too high however, and most of the sediments in the reservoir have too large particle diameters to be effectively removed by a Water Injection Dredger. The case study demonstrated though that Water Injection Dredging is an effective sediment removal technique, if some aspects of the reservoir were different.

The case study for the Millsite Reservoir showed that the production rates of a Water Injection Dredger are very high for such a small reservoir. The yearly sediment inflow can be removed out of the reservoir in just 0.8 weeks, which creates high sediment peaks in the river downstream of the dam. The effects of this high sediment peak are not certain in this case. The costs of Water Injection Dredging were again low though. The sediment peak can be lowered by lowering the production rate of the Water Injection Dredger. However, the costs would increase much in that case and this could endanger the attractive position of Water Injection Dredging as a reservoir preservation method.

A long term dredging strategy has to be developed per reservoir so that Water Injection Dredging can be implemented in an effective way. The high water discharges during raining seasons can for instance be used to transport the created density currents out of the reservoir. The amount of water that is lost can in that case be minimised. Also, a combination can be made between different types of reservoir preservation methods. Water Injection Dredging can for instance be used to move sediment to a part in the reservoir where a Mechanical Excavator or a Cutter Suction Dredger can dredge up the material.

In the case of a larger reservoir, a good alternative is that the dam operator constructs its own Water Injection Dredger, so that the transport, assembly and disassembly costs of the Water Injection Dredger are eliminated. A Water Injection Dredger is a relative simple installation, so the construction costs for the dam operator are relatively low. The dam operator is then free to determine when he wants to use the Water Injection Dredger, and is not depending on the planning of a dredging company. In this way, he can adapt his dredging strategy to high water floods for instance.

6.2 RECOMMENDATIONS

More research is necessary in order to establish under which exact circumstances Water Injection Dredging can be a cost efficient method to counteract sedimentation problems in reservoirs. The details of the limits of Water Injection Dredging in reservoir are still vague, so a more detailed investigation is necessary. Sediment characteristics like the penetration of water in the soil during Water Injection Dredging and the cohesion of the sediment are important factors to take into account, but these parameters are not extensively discussed in this thesis. More research about this topic is needed.

A search has to be carried out in order to find reservoirs that fulfil the specification of Water Injection Dredging. A dialogue with the operator can be started to find out if there are possibilities to implement Water Injection Dredger in reality. Also, companies that own Water Injection Dredgers can be contacted to find out if they are interested.

Also, more research is necessary to investigate what the consequences are downstream of the dam, when the high sediment peaks of the created density currents are let through the dam. A further investigation is necessary to find out under which circumstances the capacity of the river downstream of the dam can cope with the large amounts of sediment. It is also interesting to investigate if these operations can contribute to the erosion problems of the river.

More studies are necessary in order to find out how much water is lost during the process of letting the density currents through the dam. This research can for instance be combined with an investigation about the combination of Water Injection Dredging and high water peaks in seasonal rivers.

The high sediment peaks can harm sensitive environmental balances in a river downstream of a dam. The influences of these peaks have to be investigated as well, in order to find out if these disturbances are acceptable.

More investigation is needed with respect to the specialised Water Injection Dredging equipment that is necessary in deeper reservoirs. Extendable water injection pipes could for instance be a far more attractive method than the traditional design of a Water Injection Dredger. More information about the feasibility and the costs of these options is needed.

For the case studies, the yearly sediment inflow was considered as the calculating value for the reservoir. It would probably be more useful for some preservation methods to remove more sediment at once, especially when sediments are transported towards a deposit site and not brought back into the river system. The yearly sediment inflow value however is chosen in order to make a comparison between different reservoir preservation methods. If the methods are really going to be implemented, more investigation should be done on long term dredging strategies in order to make the specific method more effective. More sediment than just the yearly sediment inflow could be dredged up for instance.

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APPENDICES

A. Reading guide Excel-sheet production and cost calculation

An Excel-sheet is constructed in order to calculate the production rates and the costs of the different reservoir preservation techniques. The production calculation sheet is divided in a few different worksheets. The first worksheet gives an overview of the costs of the reservoir preservation techniques that are discussed in this Excel-sheet. These reservoir preservation techniques are:

- Using a Cutter Suction Dredger to remove sediment
- Using a Mechanical Excavation to remove sediment, which can be done by using two types of dredgers:
    - A Grab dredger
    - An Excavator on tracks
- Using a Water Injection Dredger

Within this overview sheet, the amount of sediment that has to be removed has to be filled in. This value will be used in the other worksheets, in order to calculate the production rates. General values of the density and porosity of various soils are presented in Table 25. The classifications of different soil types are presented in Table 26. The information from these tables is also needed in the worksheets.

TABLE 26: TYPICAL VALUES OF DENSITY AND POROSITY OF VARIOUS SOILS

Type of soil	Density of solids ρ_s [kg/m³]	Density of soil in situ (wet) ρ_{si} [kg/m³]	Porosity n [%]
Silt	2650	1100 – 1400	80 – 90
Loose clay	2650	1400 – 1600	60 – 80
Packed clay	2650	1800 – 2000	35 – 50
Sand with clay	2650	1800 – 2000	40 – 50
Sand	2650	1900 – 2000	35 – 45
Coarse sand with gravel	2650	2050 – 2200	28 – 36
Clay boulders	2650	2320	20

TABLE 27: CLASSIFICATION OF SOIL

Type of soil	**Particle size**	
	Identification	Size in [mm]
Gravel	Coarse	60 – 20
	Medium	20 – 6
	Fine	6 – 2
Sand	Coarse	2 – 0.6
	Medium	0.6 – 0.2
	Fine	0.2 – 0.06
Silt	Coarse	0.06 – 0.02
	Medium	0.02 – 0.006
	Fine	0.006 – 0.002
Clay	-	< 0.002

After the first worksheet, which includes an overview of all the different techniques, the more detailed costs of the reservoir preservation techniques are calculated. Within these worksheets, the cost calculations are divided into the following sections:

- Calculation of the production weeks that are necessary
- Calculation of the weekly production costs
- Calculation of the costs that only have to be made once
- The total costs of the method
- The total costs of the method per m^3 removed sediment

The detailed elaboration of the different worksheets is discussed in the chapters below. A list of the used symbols is given at the end of this reading guide.

A.1 WORKSHEET CUTTER SUCTION DREDGER

The start of a production and cost estimate of a Cutter Suction Dredger is to choose the type of dredger that is suitable for the job. This will depend on local circumstances, such as the amount of sediment that will have to be removed and the depth of the reservoir. The pipeline diameter is linked to the type of dredger that is chosen. So when the type of Cutter Suction Dredger is known, the pipeline diameter is given as well. The velocity of the mixture within the pipeline cannot be lower than 3 meter per second, because otherwise the sediments will start to settle. A velocity higher than 4 meter per second will results in high energy losses with that an inefficient dredging strategy. Therefore, the velocity U_m within the pipeline has to be chosen somewhere between 3 and 4 meters per second.

A.1.1 Calculation of the production weeks

The amount of production weeks that are necessary to remove the settled sediment with a Cutter Suction Dredger will depend on a combination of the amount of sediments and the production of the dredger per week. The amount of sediments that will have to be removed is a fixed number, but the calculation of the weekly production rate needs a more detailed calculation. The discharge of the total mixture Q_m can be calculated with the given velocity of the mixture flow U_m and the pipeline diameter D_p using the following formula:

$$Q_m = U_m \cdot A_p = U_m \cdot 0.25\pi {D_p}^2$$

To determine what the production rate of the sediments is going to be, the transport concentration C_{vsi} of the in situ mixture has to be calculated. This can be done with the following formula[49]:

$$C_{vsi} = \frac{\rho_m - \rho_w}{\rho_{si} - \rho_w}$$

When the transport concentration is multiplied with the discharge of the mixture, the discharge of the sediments is obtained. This is the discharge of sediments if continuous dredging is executed. This is not the case, since a dredger will not operate for 100 per cent of the time. The operating hours will be restricted due to break down, maintenance and a possible restriction of the operating hours. To include these limitations on the availability of the Cutter Suction Dredger, the operational hours per day, the operational days per week and the work efficiency have to be taken into account. This will eventually lead to the weekly production rate of a Cutter Suction Dredger. This value has to be multiplied by the number of Cutter Suction Dredgers that are used, in order to obtain the total

[49] Lecture notes Dredge Pumps and Slurry Transport -(Matousek, 2004)

production per week. If the amount of sediments that has to be removed is divided by the total production per week, the necessary production weeks can be calculated.

A.1.2 Calculation of the weekly production costs

The costs of using a Cutter Suction Dredger to remove the settled sediments in a reservoir consists of costs that only have to be made once, and costs that will have to be made every week that the Cutter Suction Dredger is operating. The calculation of the weekly production costs is discussed in this paragraph.

The basic weekly production costs are:

- Costs for depreciation and interest
- Costs for maintenance and repair
- Costs for fuel and lubricants

The value for the Depreciation and Interest, and the value for the Maintenance and Repair of the Cutter Suction Dredger can be determined with the CIRIA costs standards[50]. The costs of the fuel and lubricants will have to be determined with a more detailed calculation, since these costs are depending on the installed power of the used Cutter Suction Dredger and the price for marine diesel at that moment. Within the cost calculation of the consumption of fuel and lubricants, a distinction has to be made between the consumption during operation hours and during down time.

As a general rule of thumb, the fuel consumption of a modern diesel engine is approximately 0.2 litres per horse power, per hour[51]. The installed power is usually given in Watt, so this has to be converted to Horsepower with the following formula:

$$[HP] = 1.341 \cdot [kW]$$

With the fuel consumption at full operation now known, the fuel consumption during down time can be calculated as well. This is about 10 per cent of the fuel consumption during full operation. The weekly fuel consumption combined with the price of marine diesel then leads to the weekly costs of the fuel consumption.

Since the price of marine diesel is presented in tons, and the consumption of diesel in litres, a conversion of tons to litres has to be carried out. The density of diesel is 0.87 kg/l, which means that the volume of 1 ton (1000 kg) marine diesel is 1000/0.87 = 1150 litres.

[50] CIRIA cost standards - (Bray, A guide to cost standards for dredging equipment 2009, 2009)
[51] Lecture notes Dredging Technology - (Van der Schrieck, 2011)

The weekly consumption of lubricants is generally 10 percent of the weekly fuel consumption. The fuel consumption and the lubricant consumption combined finally leads to the total consumption of fuel and lubricants.

The extra costs that have to be taken into account for the use of a Cutter Suction Dredger are the costs that are necessary to transport the dredged up material towards the deposition site. These costs consist of costs for the use of one or more booster stations, costs for the construction and maintenance of a storage site (if necessary) and the costs of a pipeline. The costs of the use of a booster station can be found in the CIRIA costs standards. A detailed costs calculation of the construction and maintenance of a storage site is depending on the local circumstances and has to be calculation per individual situation.

A detailed cost calculation of the use of a pipeline can be standardized however, and this calculation is divided in the use of pipeline on shore, the use of floating pipelines, the needed amount of valves and needed amount of bends. This combined with the diameter of the pipeline and the price per meter or per used piece, can then be expressed in the total costs of the pipeline with the use of the CIRIA costs standards. Since it is possible that the pipeline will be in place for a long period of time, a value for the maintenance and repair of the pipeline should also be considered. In general, this percentage is in the order of 5 per cent of the total costs of the pipeline and these costs have to be added to the total costs of the pipeline.

The other weekly expenses that have to be considered are the following:

- Staff on site (6%)
- Insurance (8%)
- Risk (5%)
- Profit (4%)
- General (3%)

The proportional percentages that have to be taken into account are also given. These percentages are the values that are normally used within the company Witteveen+Bos[52].

All these values combined eventually leads to the total weekly costs that are made when a Cutter Suction Dredger is used.

A.1.3 Calculation of the one-time costs

One-time costs that have to be considered when a Cutter Suction Dredger is used consist of two general costs. The first part is the costs that are made when the cutter suction dredger has to be

[52] Result of a discussion with dredging engineer H. Timmer – Witteveen + Bos

transported towards the location of the reservoir. These transportation costs are depending on the local circumstances and cannot be standardized into an Excel-worksheet.

This also yields for the second part of the one-time costs: the costs that are made to assemble and disassemble the used equipment. Also in this case is it not possible to standardize these costs, since these values are strongly depending on the local circumstances.

The one-time costs have to be considered per dredging operation. In the case when the Cutter Suction Dredger is installed permanently, the one-time costs only have to be considered once in total.

A.1.4 Total costs

Now that the amount of production weeks, the weekly production costs and the one-time costs are known, the total costs when using a Cutter Suction Dredger can be calculated. Combined with the amount of sediments that have to be removed, the total costs can be expressed in the costs per removed m^3 sediment.

A.2 WORKSHEET MECHANICAL EXCAVATOR

The worksheet for mechanical excavation is divided in two parts: mechanical excavation with an excavator on tracks (backhoe type) and mechanical excavation with a grab dredger. The strategy to calculate the production rates and the total costs is for both methods the same. Only one method is therefore explained here.

First, the type of dredger has to be chosen in order to calculate the production rates and the total costs. This choice is depending on the local circumstances, such as the reservoir depth, the type of sediment and the possibility of pollution of the sediment. When the type of dredger is chosen, the amount of production weeks and the total costs can be calculated.

A.2.1 Calculation of the production weeks

The production per mechanical excavator is depending on the volume of the bucket, which can be determined after the type of dredger is chosen. The amount of buckets that can be delivered per minute is depending on the depth of the reservoir and the sediment characteristics. The delivery rate combined with the volume of the bucket results in production rate, expressed as the discharge of the sediments in [m^3/hr].

This is the delivery rate when continuous dredging is executed. This is not the case, since some downtime and work inefficiency has to be taken into account. After these limitations are taken into account, the result is the net production per week. The amount of mechanical excavators that are used also has to be taken into account.

Combined with the amount of sediments that has to be removed, this then leads to the net production weeks necessary.

A.2.2 Calculation of the weekly production costs

As was the case with the weekly production costs of a Cutter Suction Dredger, the weekly costs of a mechanical excavator are also based on the value for the depreciation and interest, and on the value for maintenance and repair. These values can be found in the CIRIA costs standards handbook.

Fuel and lubricants also have to be taken into account for mechanical excavators. The same calculation method is used here as was done with the fuel and lubricant calculation for a Cutter Suction Dredger, where the costs are based on the total installed power.

The extra costs that have to be considered in the case of mechanical excavation are the costs that are necessary to transport the dredged up material towards the deposition site. This means that pontoons and tugboats are necessary to transport the material to the shore. The values for the pontoons and the tugboats can be found in the CIRIA handbook.

The amount of tugboats and pontoons that has to be used is depending on the amount of mechanical excavators that is used and the dimensions of the reservoir. The mechanical excavator has to be able to continuously dredge, so a constant supply of empty pontoons must be secured. This logistic circle has to be defined per individual reservoir.

The remove the sediment from the pontoons on the shore, a key wall has to be designed. Cranes on the quay will remove the sediment from the pontoons. The sediments will then be transported towards the deposit site. The size of the quay wall is depending on the amount of mechanical excavators that are working in the reservoir. The production of the cranes on the quay walls is generally higher than the production of the excavators that remove sediment from the reservoir, so the amount of cranes on the shore is lower than the amount of mechanical excavators.

Costs for maintaining and constructing the quay wall also have to be considered. This is depending on the size of the quay wall, since a longer quay wall will lead to higher construction and maintenance costs.

If the removed sediment is going to be transported towards a storage site, costs for constructing and maintaining this storage site also have to be considered.

The other weekly expenses that have to be taken into account are the same as the expenses that have to be taken into account when using a Cutter Suction Dredger, and these costs are:

- Staff on site (6%)
- Insurance (8%)
- Risk (5%)
- Profit (4%)
- General (3%)

A.2.3 Calculation of the one-time costs

Also for mechanical excavators, the one-time costs that have to be considered consist of two general costs. The first part is the costs that are made to transport the mechanical excavators towards the location of the reservoir. These transportation costs are depending on the location of the reservoir and cannot be standardized into an Excel-sheet.

This also yields for the second part of the one-time costs; the costs that are made to assemble and disassemble the used equipment. Also here it is not possible to standardize these costs since they are strongly depending on the local circumstances.

The one-time costs have to be multiplied by the number of mechanical excavators that are used. Also, the one-time costs have to be considered per dredging operation. When the mechanical excavators are installed permanently, the one-time costs only have to be considered once in total.

A.2.4 Total costs

The necessary production weeks, the weekly production costs and the one-time costs can now be used to determine the total costs. If the total costs are divided by the amount of sediment that is removed, the costs can be expressed in costs per removed m^3.

A.3 WORKSHEET WATER INJECTION DREDGER

No standard cost or production standards are available for Water Injection Dredging, since this technique is relatively new and companies keep this information to themselves. The cost and production estimations therefore have to be constructed from basic principles.

A.3.1 Calculation of the production weeks

The production calculation of Water Injection Dredging is divided into three processes:

- the process of detaching the sediments from the bottom
- the horizontal movement of the created density current
- the vertical movement of the sediment particles

These three processes will be discussed in the paragraphs below. The horizontal and vertical movement of the sediment particles combined will then determine the travelling distance of the created density current. With the dimensions of the reservoir, it is then possible to calculate the amount of times that the sediment will need to be picked up and also the net production rate of the Water Injection Dredger.

A.3.1.1 Detaching the sediments from the bottom

The basis of the detaching process of Water Injection Dredging is the assumption of the density of the turbidity current that is created. From Water Injection Dredging projects done in the past[53], it can be assumed that the created turbidity currents have a density of around 1070 kg/m^3. With this density given, it is now possible to calculate the volume of water V_w what is necessary to transform the density of 1 cubical meter of sediment V_{si} towards the mixture density.

The density of a mixture can be calculated with the following formula:

$$\rho_m = \frac{V_w \cdot \rho_w + V_{si} \cdot \rho_{si}}{V_w + V_{si}}$$

It is assumed that V_{si} = 1 m^3, since this is the amount of sediment that is brought into suspension. The equation can then be rewritten as:

[53] Waterinjectiebaggeren, modellering van afstroming - (Verweij, 1997)

$$\rho_m \cdot (V_w + 1) = V_w \cdot \rho_w + 1 \cdot \rho_{si}$$

$$\rho_m \cdot V_w + \rho_m = V_w \cdot \rho_w + \rho_{si}$$

$$V_w \cdot (\rho_m - \rho_w) = \rho_{si} - \rho_w$$

$$V_w = \frac{\rho_{si} - \rho_w}{\rho_m - \rho_w}$$

This is the volume of water V_w that is necessary to put 1 cubical meter of sediment into suspension, which is expressed in [m³/m³]. Multiply this value with the total volume of sediments that has to be removed and the total amount of water that is necessary to put the sediments into suspension is known.

An important aspect of Water Injection Dredging to take into consideration is the penetration of the injected water into the soil. The cohesion of the soil and the velocity of the vessel will limit the penetration depth of the water. The deeper the water can be injected into the soil, the higher the production rate of the vessel.

There is a relationship between the velocity of the vessel and the penetration depth of the injected water. If the vessel has a high velocity, the penetration depth of the injected water will be lower. This is logical, since the jet stream of the Water Injection Dredger has less time to penetrate into the sediments. The relationship between the velocity of the vessel and the penetration depth of the injected water is still subject of many research programs and can not be described in detail. The velocity of the vessel is therefore left out of this production estimation and it is assumed that the injected water reaches a limited depth. That limited depth is then used to calculate the production rate.

The start of the injection process is that the pressure of the penetrated water into the sediment has to be bigger than the soil tension of the sediment. It can be assumed that the distribution of the pressure when the water leaves the nozzle can be described as a 3D cone penetration[54], where the following condition yields:

$$p(s) \geq 9 \cdot c_u$$

$p(s)$ can be described as the effective jet pressure in the hart of the jet stream and c_u is the undrained cohesion of the soil material.

[54] Modellering van het jetten van slappen menggronden t.b.v. het waterinjectiebaggeren - (Schuurman, 1997)

Since there is not much known about water penetration in sediment, the formulas for jetting in water will be used in this case. The following formula is therefore used[55]:

$$u(s) = U_0 \cdot \sqrt{k/2} \cdot \frac{D_N}{s}$$

With:

$u(s)$ = flow velocity in the centre of the jet stream [m/s]

U_0 = flow velocity when leaving the nozzle [m/s]

k = entrainment coefficient [-]

D_N = diameter nozzle [m]

s = distance along the jet stream [m]

It is assumed that the value of k is about 77. The critical flow velocity is the point in the sediment at which no large sediment erosion occurs. This point is reached when the flow velocity at the edge of the jet stream equals the max flow velocity U_{max}. This is the point where the maximum penetration depth is reached. Rewriting the formulas gives the following equation:

$$U_{max} = U_0 \cdot 6 \cdot \frac{D_N}{s}$$

The earlier discussed jet pressure $p(s)$ can now be used to relate soil properties to the critical velocity, using the following formula:

$$p(s) = 0.5 \cdot \rho \cdot [u(s)]^2$$

This formula then finally can be used to write down the relationship between the cohesion of the soil and the penetration depth:

$$9 \cdot c_u = 0.5 \cdot \rho \cdot \left(U_0 \cdot 6 \cdot \frac{D_N}{s}\right)^2$$

This can be rewritten as:

$$s = \frac{U_0 \cdot 6 \cdot D_N}{\sqrt{\frac{9 \cdot c_u}{0.5 \cdot \rho}}}$$

This is the formula that can be implemented in the model. It is assumed that the density of the injected water does not change during the process. This is not the case in reality, since the density

[55] Modellering van het jetten van slappen menggronden t.b.v. het waterinjectiebaggeren - (Schuurman, 1997)

of the injected water increases because soil particles are added to the flow during the erosion process.

The water injection capacity per individual Water Injection Dredger can be calculated with the diameter D_N of the used nozzles, the amount of nozzles per dredger m and the flow velocity through the nozzles U_N. The total discharge through the nozzles Q_N can be calculated with the help of the following formula:

$$Q_N = m \cdot \frac{1}{4} \pi {D_N}^2 \cdot U_N$$

As a reference, most Water Injection Dredgers have a discharge of water in the order of 3.5 m^3 per second[56]. If the total necessary volume of water to detach the sediment is divided by this calculated discharge, the amount of time necessary to detach the sediments is known. Divide the amount of time necessary to loosen up the sediments by the amount of sediments and the production rate of the detaching process is known, expressed in m^3 per hour. This number has to be corrected by the fact that a Water Injection Dredger cannot always work 100 percent of the time. Manoeuvring the vessel, such as sailing back to the start position, takes time and a correction factor has got to be taken into account. This eventually leads to the net production rate of the detaching process.

The next step is to calculate how far the created cloud of sediments will travel within the reservoir. This can be done by splitting the transport process up into two pieces: the horizontal travel velocity and the vertical settling velocity.

A.3.1.2 Horizontal transportation

The horizontal travel velocity of the created density current is depending on the hydraulic conditions within a reservoir. Density currents are very dynamic currents with complex flow patterns. To estimate the flow rate of a density current, a simplification of the situation is necessary. The dynamics of the density current can be schematized as a two layer system with a high concentrated mud layer and a relatively clear upper layer. The Froude number can then be used describe the state of the mud layer.

From experiences with density current created by Water Injection Dredging is known that the Froude number of these currents is larger than 1 when they start to flow. This means that the density current will start as a supercritical flow. Depending on the circumstances in the reservoir, the flow can stay supercritical or can transform to subcritical.

[56] Specifications Parakeet Water Injection Dredger - (Dredging International, 2012) and Specifications Jetsed Water Injection Dredger - (Van Oord, 2012)

When the density current reaches a point where the Froude number is smaller than 1, the flow can be described as subcritical (see also Figure 34). Due to the relatively large friction forces, the thickness of the layer will increase until an internal hydraulic jump occurs. The thickness of the density current will then slowly decrease.

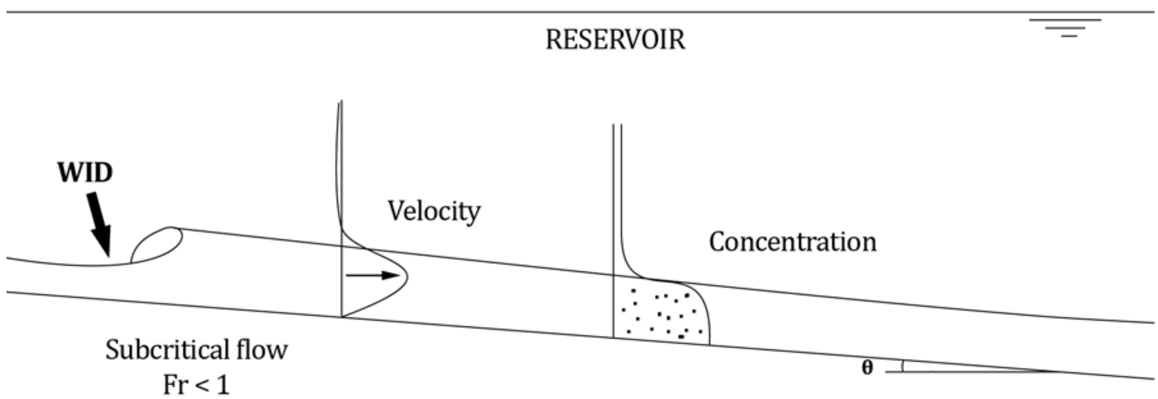

FIGURE 34: SUBCRITICAL FLOW CONDITIONS IN A RESERVOIR

If the slope of the bed is sufficiently large, the flow of the density current will stay supercritical and the flow velocities will be higher than with subcritical flow. The thickness of the density current will slowly increase and the material can be transported over a large distance (see also Figure 35).

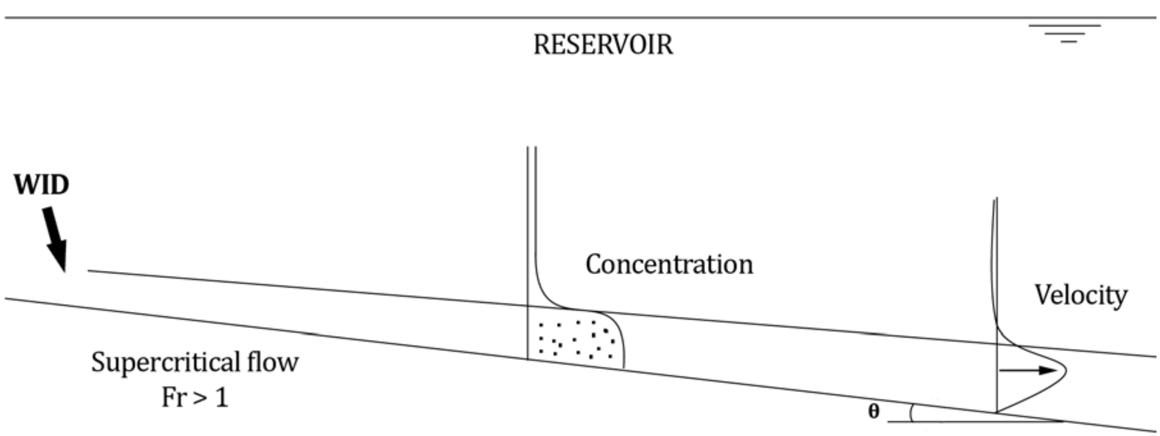

FIGURE 35: SUPERCRITICAL FLOW CONDITIONS IN A RESERVOIR

It is assumed that after the Water Injection Dredger has injected the water into the sediment, the density current has a Froude number of 1.1. This number is based on experiences with Water

Injection Dredging done in the past[57]. After that, the development of the flow can be described with the two layer model on density currents, described by Kranenburg[58] (see also Figure 36).

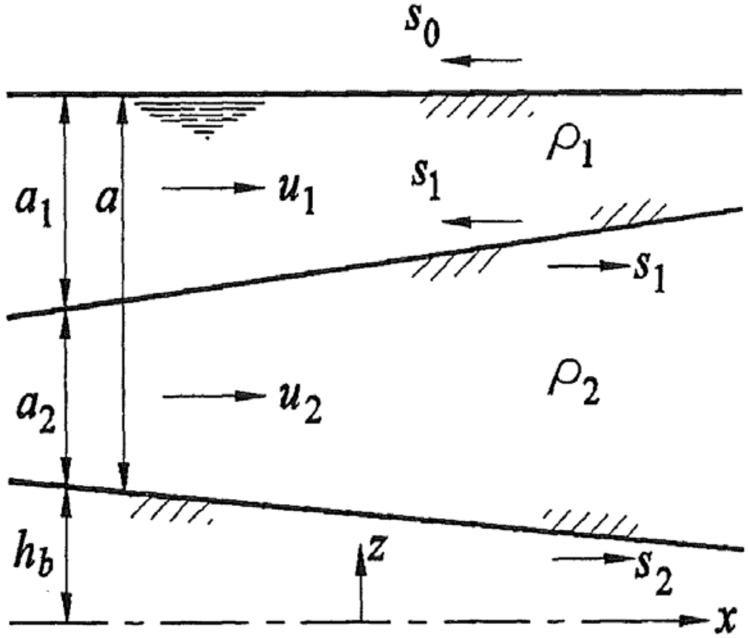

FIGURE 36: TWO LAYER SYSTEM – FROM (KRANENBURG, 1998)

The lower layer is the density current created by a Water Injection Dredger with a flow velocity u_2 and the upper layer is the clear water in the reservoir. Since this water is not moving (conditions in a reservoir) the flow velocity of u_1 = 0. The situation in Figure 36 can be described by the following formula:

$$\left(1 - \frac{q_2^2}{\frac{\Delta\rho}{\rho_2} g a_2^3}\right) \frac{\mathrm{d}a_2}{\mathrm{d}x} + \frac{\mathrm{d}h_b}{\mathrm{d}x} = 0$$

Where $\Delta\rho = \rho_2 - \rho_1$ and $q_2 = u_2 \cdot a_2$, which is the discharge of the density current per meter width.

In order to take the friction of the density current with the bottom of the reservoir into account, a friction term has to be added to the equation. Instead of equalizing the used formula with zero, it is now equalized with the following friction term:

$$-\frac{s_1 - s_2}{\rho_2 a_2}$$

[57] Water Injection Dredging - (Van Rijn, L.C., 2012)
[58] Lecture notes 'Dichtheidsstromingen' - (Kranenburg, 1998)

Where:

$$s_1 = -k_1 \rho_1 |u_1 - u_2|(u_1 - u_2)$$

$$s_2 = -k_2 \rho_2 |u_2| u_2$$

And:

$$k_1 \approx 15 \cdot 10^{-4}$$

$$k_2 = \frac{g}{C^2} \approx 35 \cdot 10^{-4}$$

To estimate how the density current propagates, the density current is transformed with the help of the Euler Forward method. The horizontal distance is divided in parts with the size Δx and the change of the height of the density current $\frac{\mathrm{d}a_2}{\mathrm{d}x}$ is calculated at every step X_n:

$$a_2(X_{n+1}) = a_2(X_n) + \Delta x \cdot \frac{\mathrm{d}a_2}{\mathrm{d}x}(X_n)$$

The discharge q_2 will stay constant, the velocity u_2 will increase or decrease with the change in the height of the density current a_2. This can now be used to calculate how much time it will take for the density current to travel the distance of each step Δx. The Euler Forward method can also be used in this case:

$$t(X_{n+1}) = t(X_n) + \frac{u_2}{\Delta x}(X_n)$$

The complete movement of the density current can now be calculated in the Excel-sheet. When the information about the settling processes of the sediment is known, the estimated travelling distance of the density currents can be calculated.

A.3.1.3 Settling process

Now that the movement of the density current is known, it can be used to estimate how far the density current will travel. With the help of formulas for settling of sediment, it can be estimated how long it will take before the sediments of the density current start to settle.

In general, the settling velocity U_v of a single particle can be determined with the following equation[59]:

[59] Lecture notes Dredge pumps and slurry transport - (Matousek, 2004)

$$U_v = \frac{\rho_s - \rho_w}{18 \cdot \rho_w} \cdot \frac{gd^2}{\nu_f}$$

This is the vertical velocity of a single particle in the density current. This equation yields for particles with a diameter of approximately 0.05 mm or smaller (Stokes regime). This can be assumed here, since Water Injection Dredging can only be effectively executed when the particle diameter is smaller than 1 mm, as was stated earlier in Paragraph 4.3.

The particle moves down and the same volume of water moves upwards. This means that in a mixture flow, an upward flow is created due to the settling of the multiple particles. The settling velocity will therefore decrease, which is also known as hindered settling. However, at very low concentrations, the settling velocity will increase because the particles will settle in each other's shadow.

In general, the following equation yields to calculate the influence of multiple particles to the settling velocity:

$$\frac{U_{v,c}}{U_v} = (1 - C_{\mathrm{v}})^{\beta}$$

Where $U_{v,c}$ is the hindered settling velocity, C_{v} the volumetric concentration and β the power for hindered settling depending on the Reynolds number.

The following values for β should be used:

$Re < 0.2$	➔	$\beta = 4.65$
$Re > 0.2$ and $Re < 1.0$	➔	$\beta = 4.35 \cdot Re^{-0.03}$
$Re > 1.0$ and $Re < 200$	➔	$\beta = 4.45 \cdot Re^{-0.1}$
$Re > 200$	➔	$\beta = 2.39$

The Reynolds number Re can be calculated with the following formula:

$$Re = \frac{U_v \cdot d}{\nu_f}$$

And the volumetric concentration can be calculated with the equation:

$$C_v = \frac{\rho_m - \rho_w}{\rho_s - \rho_w}$$

The hindered settling velocity is now known, so the time is will take for the particles of the density current to settle can now be calculated. In order to take the average amount of time for the particles to settle, half of the thickness of the density current a_2 is taken (see also Figure 37). The thickness of a density current created by Water Injection Dredging is in the order of 1 to 3 meters[60].

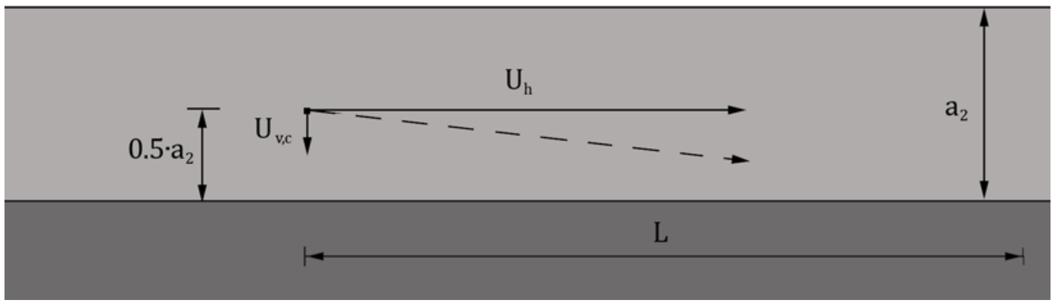

FIGURE 37: CALCULATION OF THE HORIZONTAL TRAVEL DISTANCE

The average time it takes for the particles to settle is therefore:

$$T = \frac{0.5 \cdot H}{U_{v,c}}$$

Because the movement of the density current is already known from calculation made in the previous paragraph, it is now possible to determine the travelling distance of the density current. This can then be used to calculate how many times the sediment needs to be picked up and with that the estimated net production of the Water Injection Dredger.

With this approach, the settling of the sediments is not coupled to the propagation of the density current. In reality, these two processes influence each other when a density current is moving through a reservoir. However, for simplicity reasons, this approach has been chosen.

A.3.1.4 Net sediment production per Water Injection Dredger

The last part that has to be taken into account is the amount of operational hours and the percentage of downtime of the Water Injection Dredger. This results in the net production hours per week.

From the model follows the production that is transported over a certain distance, and the representative length of the reservoir is then used to determine how many times the sediments need to be picked up. Now that the production rate of the detaching process is known, the amount of times that the sediment needs to be picked up is calculated and the net production hours are

[60] Water Injection Dredging - (Verhagen, 2000)

filled in, the net production can be calculated. This is the net production of sediments that are picked up and transported towards the bottom outlets of the dam.

The necessary production weeks can now be calculated by taking the net sediment production per week per Water Injection dredger and multiply that number with the amount of vessels that are used. Divide this number with the total amount of sediment that need to be removed and the production weeks that are necessary can be calculated.

A.3.2 Calculation of the weekly production costs

For the calculation of the weekly production costs of a Water Injection Dredger, a multipurpose pontoon is considered. The dimensions of this pontoon must be about the same as the dimensions of the used Water Injection Dredger. The CIRIA costs standards can then be used to determine the value for the depreciation and interest and the value for maintenance and repair.

Fuel and lubricants also have to be taken into account for Water Injection Dredger. The same calculation method is used here as was done with the fuel and lubricant calculation for a Cutter Suction Dredger, where the costs are based on the total installed power.

Other weekly expenses that have to be taken into account are:

- Staff on site (6%)
- Insurance (8%)
- Risk (10%)
- Profit (4%)
- General (3%)

These values are percentages of the weekly costs of a multipurpose pontoon. These other expenses are also used for the reservoir preservation methods used earlier, but the Risk is in this case raised from 5 to 10 percent. This is done because of the higher uncertainty of the production rates of Water Injection Dredging.

A.3.3 Calculation of the construction costs

Since there is not much data available on the costs of Water Injection Dredging, the cost estimation has to be done by determining what the costs would be to construct a dredger. This can then be taken into account when the total costs of Water Injection Dredging are determined.

The costs for the pontoon are already taken into account at the weekly production costs, so this doesn't have to be considered here. The next costs that are considered are the costs of the pipes that are used. These pipes transport the water from the pumps towards the bottom of the reservoir, where the water is injected through nozzles into the soil. The costs of the pipes depend on the pipe length needed and the prices of the pipe per meter.

The price per meter depends on the diameter of the pipe and can be found in the CIRIA cost standards. The total length can be determined with the help of designs of other Water Injection Dredgers (see also Figure 38). The total needed pipe length consists of:

- Length of the injection arm. This is the necessary length of the pipes from the front of the vessel to the bottom of the reservoir. It is a function of the depth of the reservoir, where the angle of the arm with the vessel is considered as a 45 degree angle.
- Length of the pipes on board. This is about three times the width of the vessel.
- Length of the pipes at the point where water is injected (left part of Figure 38). This is about two times the width of the vessel.
- A percentage for bends and construction failures (10%)

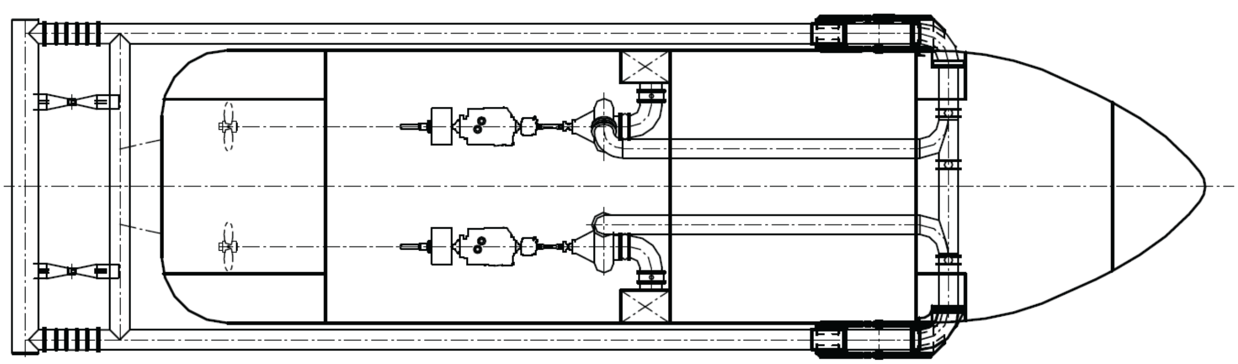

FIGURE 38: WATER INJECTION DREDGER WITH WATER INJECTION PIPES – FROM DE VRIES AND BEYEN[61]

These parts combined determine the total needed pipe length. Together with the price per meter, the total costs of the pipes can be determined.

Other costs that have to be taken into account are the costs for A-frames, winches, rubber bends, nozzles and other equipment. These costs are considered to be around 40 percent of the costs of

[61] A special unit for water injection dredgers - (De Vries, G. and Beyen, J., 2009)

pipes. Other expenses that have to be taken into account are the costs for smaller equipment that is necessary to construct a Water Injection Dredger. This is considered to be around 50 percent of the total material costs.

The Water Injection Dredger is going to be constructed by construction workers. These costs consist of the necessary amount of working hours to construct the dredger times the price per hour. A 10 percent uncertainty is added in order to cope with any construction setbacks.

This eventually leads to the total employee costs. Combined with the material costs, this gives the total construction costs per Water Injection Dredger Installation.

A.3.4 Calculation of the one-time costs

Normally the one-time costs consist of the assembly and the disassembly of the used reservoir preservation technique. However, the costs for constructing a Water Injection dredger are already taken into account, so the only one-time costs that have to be considered here are the costs that are made to disassemble the dredger. These costs are the same as the costs for the working hours that were taken into account for the assembly of the Water Injection Dredger.

Together with the number of Water Injection Dredgers that are used, this leads to the total one-time costs for Water Injection Dredgers.

A.3.5 Total costs

The needed production weeks multiplied with the weekly costs provides the production costs. Add these costs with the construction costs of a Water Injection Dredger and the total one-time costs and the total costs for Water Injection Dredging is known. Divide these costs with the amount of sediments that are going to be removed, and the total costs per m^3 sediment are known.

A.4 USED SYMBOLS

a_2 = thickness of the density current [m]

A_p = surface of the pipeline [m^2]

$b(s)$ = half of the width of the jet stream [m]

C_d = drag coefficient [-]

c_u = cohesion [kPa]

C_{vsi} = volumetric concentration of in situ soil [-]

d = diameter particle [m]

D_N = diameter nozzle of the Water Injection Dredger [m]

D_p = diameter pipeline [m]

Fr = Froude number [-]

g = gravitational constant [m/s^2]

k = entrainment coefficient [-]

L = travel distance of the density current [m]

m = amount of nozzles of the Water Injection Dredger [-]

n = porosity [-]

$p(s)$ = effective jet pressure [kPa]

q_2 = discharge of the density current [m^2/s]

Q_N = total discharge through the nozzles [m^3/s]

Re = Reynolds number [-]

s = distance along the jet stream [m]

T = time it takes for the particles to settle [sec]

$U_{critical}$ = critical flow velocity [m/s]

U_h = horizontal flow velocity of the density current [m/s]

U_m = the velocity of the mixture in the pipeline [m/s]

U_N = flow velocity through the nozzles of the Water Injection Dredger [m/s]

$u(s)$ = flow velocity in the centre of the jet stream [m/s]

U_v = settling velocity [m/s]

$U_{v,c}$ = hindered settling velocity [m/s]

U_0 = flow velocity when leaving the nozzle [m/s]

ν_f = kinematic viscosity [m^2/sec]

V_{si} = volume of in situ sediment [m^3]

V_w = volume of the water necessary to put 1 m^3 sediment in suspension [m^3/m^3]

β = power for hindered settling [-]

θ = steepness of the reservoir [degrees]

ρ_m = density of the mixture [kg/m^3]

ρ_w = density of the water [kg/m^3]

ρ_{si} = density of the solids in situ [kg/m^3]

$\Delta\rho$ = relative density [kg/m^3]