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Revaluation of dredging costs in reservoirs and its impact on reservoir financial performance

Revaluation of dredging costs in reservoirs and its impact on reservoir financial performance

By

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Preface

This Master of Science thesis deals with operational and environmental challenges of sedimentation in reservoirs. Different active sediment management techniques are evaluated based on the operational performance of a reservoir. Basis of the subject is a decrease in average worldwide yields and other different challenges concerning sustainable operations of reservoirs.

Many thanks go out to all people that supported me in completing the thesis. Feedback, constructive criticism and encouragement made this result possible in the end.

I am especially grateful for all input from my supervisors; Prof. Dr. Ir. C. van Rhee (Delft University of Technology), Dr. Ir. C. J. Sloff (Deltares/Delft University of Technology) and Dr. Ir. G. H. Keetels (Delft University of Technology). Attending discussions, offering me with ideas and thinking along about solution directions has led to a more comprehensive study.

I look forward to upcoming decades with all developments in reservoir engineering.

R. Poppe
Delft, March 2020

3D	Three Dimensional
BD	Backhoe Dredger
CFD	Computational Fluid Dynamics
CSD	Cutter Suction Dredger
DOP	Submersible Dredge Pump
GD	Grab Dredger
GRAND	Global Reservoir and Dam database
ICOLD	International Commission on Large Dams
NPV	Net Present Value
CBA	Cost Benefit Analysis
SD	Suction Dredger

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Abstract

Reservoir sedimentation is a wide spread issue around the globe and forecasting this is a complex task. Sedimentation rates can be based either on comparable situations or sediment transport rates in the river prior to construction of a reservoir. Deforestation and road construction loosen top soil, fertile soil becomes mobile and gets transported toward the reservoir. A river basin can lose its agricultural value and long-term effects can go as far as completely vanishing of valuable ecosystems downstream.

Sedimentation in reservoirs is mainly affected by the shape, length and discharge of a reservoir. There is no such thing as a standard shape. Artificial reservoirs usually have simple shapes. Naturally formed lakes however can be very complex to predict, especially the strength of prevailing currents and long-term morphological changes. Particle shape and diameter, concentrations and flow velocities are some of the most important parameters that affect settling in a reservoir.

A three-dimensional computational fluid dynamics model has been developed to predict sediment aggregations in a reservoir. This model is based on the pressure correction method as described by Hirsch (2007). The reservoir is modelled as a large cubical tank with one inlet (upstream) and outlet (dam, downstream). Density enhancing flow is simulated by application of a Boussinesq approach. The aggregation of sediment at the bottom is finally evaluated by tracking sediment that leaves the reservoir through the bottom. Time series extension is used to evaluate the long-term effects of sedimentation and considers mechanical requirements, essential to gain physical realistic results.

Results from the CFD and timeseries extension are finally used to evaluate dredging costs and present value of the reservoir that is examined. A number of different feasible dredging methods is compared; a cutter suction dredger, grab dredge, backhoe dredge, submersible dredge pump and water injection dredge. These methods are initially identified based on transportability and ,later on, evaluated based on costs and technical applicability for a given type of reservoir depth and soil type. The models are applied to an identified case, which is the multifunctional Ke Go reservoir in Vietnam. Its gross capacity is 425 million m^3 with an estimated annual discharge of 900 million m3. The case is identified based on the simple reservoir shape and variety of functions (hydropower generation and water supply for agriculture and consumption). A net present value analysis concludes the study and puts the proportion of dredging costs in context to the life span yields of a reservoir.

Aggregation of sediment concentrates near the river mouth, even when the total annual discharge of a reservoir is relatively large (up to 1000 percent of the gross reservoir capacity). Settling near the dam (Ke Go) is not expected, unless the examined reservoir lifespan is extended to a period of more than 60 years. By then, a significant part of the original storage capacity will be lost, resulting in a decline in functional yields. The quality of water and supply capacity will gradually decline, whereas the hydropower generation decline is much more rapid once sediment reaches the dam.

The results of the simulation are partially comparable to the real Ke Go now. Ke Go currently shows siltation upstream, especially near river mouth(s). The reservoir has an age of 47 years and clearly shows significant effects of long-term sedimentation, comparable to an initially assumed sedimentation rate of 1 percent. The model only shows sedimentation forming from upstream, whereas Ke Go has multiple smaller inlets with one larger inlet upstream.

Limited depth in Ke Go reservoir leaves a number of dredging methods technically feasible. The production costs for the submersible dredge pump are the least, starting from approximately €1.50 per m3 in-situ material (fine sand). This means that at least €63.75 million per year is needed to dredge. Still, dredge costs are relatively low compared to the large initial sunk cost for construction (< 1 percent) and primary function yields during the life span. Dredge costs are largely affected by the usability of sediment. Dredged sediment will be disposed, flushed or put to use for agriculture or industry. Flushing can be a partial alternative in Ke Go to get rid of dredged sediment, but is limited due to a relatively low annual discharge. After a period of 50 years, the difference between NPV with and without sediment management approximates €2 Billion and this number grows with time. Dredging is considered recommendable, given the promised improved service life and benefits of the reservoir.

1. Introduction

1.1. Background

Water is one of the primary resources for any lifeform. Without water, any ecological system would collapse. Animals, plants and not least humans need water on a daily basis. And we as humans don't always seem to understand this concept deeply. For most people it is simply water from the tap. However, it really is water from the source and we need to take care of the sources. Watersources or significant water storage is not only used for consumption, the applications of water are numerous. To mention some; water is used for agricultural purposes (both irrigation and stock-breeding), life habitat, hydro power generation and industrial purposes (manufacturing and processing). This explanation of the essence of water is the start for investigating one of the primary source types, namely the reservoir.

People have created reservoirs for thousands of years. The oldest known reservoir is located in Jordan, the Java Dam. It was built approximately 5000 years ago for irrigation purposes. Since then, a lot of reservoirs have been built. More recently, reservoirs were built for electricity generation (hydropower), though a combination of irrigation, hydropower and storage is also possible.

The number of reservoirs has grown by about 1 percent per year since the 1960s (D. Wisser, 2013). With the significant long-term growth and dam decommissioning after about an average lifespan of 40 years (Wieland, 2010) it is becoming increasingly important to investigate sediment transport and settling near reservoirs. This is not in the least because building new reservoirs often uses natural habitat and returning to its old balance is certainly not always possible. Secondly, it becomes harder and harder to find suitable locations for new reservoirs.

1.2. Reservoir maintenance

Sedimentation and its environmental impact are for contractors and operators of new reservoirs not always an important consideration. For contractors, the most important objective is to execute profitable projects and sometimes to show achievements to the public. These objectives usually do not improve the lifespan of a reservoir or the environment that is in direct relation with a reservoir. Research has been done on the life expectancy and maintainability of reservoirs, most of it concentrates on maintainability of mechanical parts. Less is known about the impact of bottom development due to sediment transport from upstream rivers and trapping in the reservoir. This thesis will emphatically look deeper into the matter of soil and sediment development in reservoirs and give little attention to maintainability of mechanical parts. Sediment transport from upstream river towards reservoirs lead in general to an increased sediment deposition in reservoirs. Both sediment and reservoir properties influence the sedimentation process. Some important parameters are the particle size diameter of sediment and properties of prevailing currents. These in combination with reservoir shape and dimensions have probably significant impact on the spatial distribution of sediment in reservoirs. In addition to maintenance of mechanical parts, reservoir life is often depending on the mode of transport (bottom or suspended transport) and speed of sedimentation. Reservoir

capacity can decline, it is even possible that functioning becomes obsolete due to sedimentation. Available head declines and toxicity can increase alarmingly.
The fact that a reservoir is an artificial barrier for sediment (trapping) is in some cases the cause for decrease of natural habitat or biodiversity downstream. The problem downstream of a dam is possibly the result of a lack of design considerations and knowledge, but it may be a challenging opportunity to improve sediment management for existing reservoirs. Examples of possible solutions are dredging, flushing or the use of tunnels and applicability depends largely on the spatial distribution of sediment in a reservoir and the particle size distribution (Duivendijk, 1997).

Core of this thesis is improving economic and environmental value of reservoirs by sediment management and thereby extending life expectancy of reservoirs. This will also include the effects on downstream natural habitat and environment and upstream hinterland. Bad maintenance and significant sediment aggregation could result in loss of natural delta or ecological systems downstream and therefor belongs to the subject of this thesis.

1.3. Problem formulation

Central problem in this thesis is that reservoirs form a barrier between upstream and downstream rivers for not only water supply, but also sediment. This in turn jeopardizes the often-essential functions of a reservoir for the region and it may lead to major damage to habitat, delta and/or ecological system downstream from dams.

The purpose of this research is to get to know more about the spatial distribution of sediment in a reservoir, how this can be managed by dredging or flushing and what this would mean for the life expectancy of reservoirs and the regional environment.

To solve the prescribed problem in a structured way, the following main question and research questions are identified:

To what extent are active sediment management alternatives worthwhile for the functional value of reservoirs, while environmental consequences are accounted for?

- What are technically feasible active sediment management alternatives for reservoirs?
- What are the most common environmental-technical problems upstream and downstream of reservoirs and how do these relate to sediment transport and aggregations in reservoirs?
- Where in a reservoir can sedimentation be expected?
- What are the opportunities of sediment management relative to the economic value of a reservoir?

1.4. Thesis outline

The thesis starts with a system analysis in which the demarcated system of technology, environment and actors is illustrated. This aims to structure the current situation of policy and technological solutions. The system analysis also includes a literature or cases study to identify current possible solutions and shows knowledge gaps before further research. The technical systems will be divided into three parts, the upstream river system, the reservoir and downstream river system. For these three parts, a classification will be drawn up that will be the base for later models to predict sediment transport and settling. Three-dimensional Computational Fluid Dynamics will be the core method in predicting sediment flows and will be used to design a quantitative estimate of spatial distribution of sedimentation in reservoirs. This in turn will lead to the needed decisive support to choose among different dredging and flushing alternatives to reduce sedimentation. Important criteria are economic feasibility and environmental conservation. Results will finally be presented in a financial analysis (CBA/NPV analysis) and forms a framework for decision making. The thesis ends with a conclusion and recommendations on challenges and opportunities regarding sediment management in and near reservoirs now and in the future. The model results will be presented on the basis of a case, with the aim of being able to use the modelling ideas for other reservoirs in the future.

2. Problem analysis – sedimentation in reservoirs

A problem analysis is performed to gain in-depth understanding about the core problem concerning reservoir performance. Reservoir performance and related problems are typically multi-actor based and complex in terms of conflicting criteria.

2.1. System analysis

A system analysis is typically performed to specify a problem for a client. In this situation however, no specific client is given. Therefore, the actor analysis is the point of departure. Traditionally, a system analysis presumes that a policy problem is resolved by reviewing the perspective, interests and policy instreams or means of the client. This presumption is not valid considering the case of a reservoir and local environment. The network of actors involved is complex, with vastly different perceptions of the problem. A simple example is the objective of an energy supplier to produce hydropower at low cost, while local inhabitants have interests in preserving natural values and improving quality of life. The next section discusses the actor network, in which governmental bodies play leading roles. The system analysis therefore is focussed on perspectives, interests and policy instruments of governmental bodies. Reservoirs are rarely privately owned and governments still have large control over privatized ownership structures. It is stressed that multiple developments and ownership structures are reviewed (A.1 and A.2) and the analysis is based on the generic information from there.

The decision to perform the system analysis with a government as problem owner is cause for the analysis to be more general or can be seen as a helicopter view. While fishermen are engaged in the problem about migratory fish barriers, they have far less interest in production of hydropower or irrigation rates. The government in contrast has extensive responsibilities (both economic and environmental) and should have the complex task to design and implement a balanced set of measures to meet all involved actors.

The system analysis is completely included in appendix A, the most important results are discussed below.

For this thesis, it is given that building a reservoir and dam once was a solution to an undesirable situation. This can vary from undesirable flood events to energy shortages or water deficits. It can be concluded from the analysis of the cases in section A.2.1 that many dam projects are causing serious problems regarding nature, certain business sectors and living environment for residents.
A dam project can cause conflicts with the following criteria in the objectives tree, figure A.1.

- Improving water quality;
- Preserve river delta downstream (natural flow of sediment);
- Increase hydropower storage/generator capacity;
- Extend functional lifespan reservoir;
- Supply of nutrients;
- Prevent obligatory moving;
- Preserve and protect archaeological and cultural sites.

Combining these objectives, they clearly show conflicts. Increasing hydropower/water storage may lead to loss of arable or inhabited land at first and can have large impact on downstream delta in the long run. Economy related criteria suffer from inefficiency while living quality and environmental criteria suffer from overusing and/or heavy burdening raw or natural materials.

At first sight, it seems that objectives contradict from multiple aspects. A transparent example is available in the Alqueva Reservoir case (A. A. Radomes, 2013). Efficiency is a cost for the environment, while preservation of nature could reduce productivity. When considering the longer-term effects of sedimentation (Venkateswara, 2014) and reduced quality of water, the economic value of a reservoir also reduces and the effect on both environment and economy is negatively influenced. The expected functional lifespan might reduce and more importantly, absence of sedimentation management can change morphology in a reservoir drastically and puts power generation and water storage at risk. Additionally, external effects impact performance. Climate change – change in precipitation patterns and seasonal thawing – and political agendas in terms of energy transition may impact economic performance heavily.

2.2. Stakeholders

The water footprint usually changes dramatically after a dam is built and taken into operation. The direct effect of a reservoir is a boost in economic growth opportunities, due to the better connectivity of industry and residents to watermain and electricity. Agriculture production can grow with irrigation, improving the quality of life for residents too. Not only agricultural industry gains, but other industries too. Transport infrastructures (roads, railway and waterways, pipelines) networks grow and change. Growth initially is a direct effect of the construction and operation of the dam, but works through as a chain reaction in the regional economy. Thus far, effects are positive. In the long term and without proper consideration of change in flow patterns compared to the original river system, much more complicated set of effects occur. This set include shrinking of ecological systems downstream due to a lack of seasonal or natural (peak)flows and supply of sediment. Trapping of sediment can also endanger the quality of water in a reservoir, not to mention the threat that the primary functions of a reservoir could become obsolete (K. Takeuchi, 1998).

The next list discusses common stakeholders in the actor network that is affected by construction and operation of a reservoir.

- Country Government;
  In most cases, a central role is reserved for the government of a country. Reservoirs are often publicly or state owned. There are examples of privatized ownerships, but a government almost always remain a majority shareholder. Associated responsibilities are high, governments are often the only capable of imposing measures and with that impacting all kinds of involved stakeholders.
- Multilateral organizations with political influence;
  Some continents have far-reaching multilateral cooperation with political influence. The yield of the reservoir (hydropower/water storage/etc.) as well as external effects are often not limited at national borders.

- Investors, either private or public;
  Financing can be private or public.
- Power (distribution) companies;
  Operational responsibility of hydropower generation and water supply is often in hands of power companies. Primary objectives for these companies include efficient and maximized power generation. Increased reservoir life span is favourable in the end, but not directly prioritized. Operation responsibilities are commonly held for a predetermined period.
- Residents;
  Inhabitants/residents are often severely affected by a reservoir and dam. Economic growth and stable power/water supply is beneficial. Mandatory moving, health issues and loss of nature clearly is disadvantageous. It is conceivable that advantages reach a larger public than disadvantages and a better insight is only observed after a dam has already taken into operation. Primary functions – advantages – are easily grasped in general and ultimate external effects are often much harder to thoroughly understand (L. Berga, 2006).
- Visitors and tourists;
  The effects can be perceived positive or negative. The dam itself is often an impressive structure, while loss of nature can result in decrease of tourism. Water sports/recreation may be limited depending on water quality and safety regulations.
- Farmers and organized agriculture;
  One of the primary functions of reservoirs is to supply agriculture with freshwater for irrigation. Flood control can also be a strong advantage at first. Flood however can result in natural fertilization of land. The primary objective for farmers could be to irrigate arable land. Sedimentation or siltation can be an issue in the long term for water supply.
- Fishery;
  In most cases fishery is negatively affected by a reservoir. Migratory fish species stock declines due to barriers. Dams are most important, change in seasonal flow can also affect fish habitat quality (Miranda, 2017).
- Nongovernmental organisations;
  NGO’s try to put environmental or quality of life questions on the political agenda. A wide range of negative external effects may occur (highly case specific). Often encountered problems are the increase in levels of toxic substances in reservoir water (Morais Calado, 2017) and loss of valuable biodiversity in ecosystems. NGO’s try to represent residents in the local region. Other (sometimes important) subjects represented by NGO’s are obligatory buy out of land to make space for the reservoir or preserving cultural or religious artefacts.

- Construction companies;
  Involved with construction of the dam/reservoir and eventually in maintenance works. The lobby starting from construction can be strong. Problems around reservoir sedimentation or external effects downstream are perceived differently here. Companies are not interested in extending the lifespan of current reservoirs if completely new projects can be considered. Important implicit knowledge about construction and morphodynamical response to artificial changes in river is in the hands of these stakeholders. So is the understanding of and providing with useful advice about construction, maintenance and/or the future of local ecosystems.

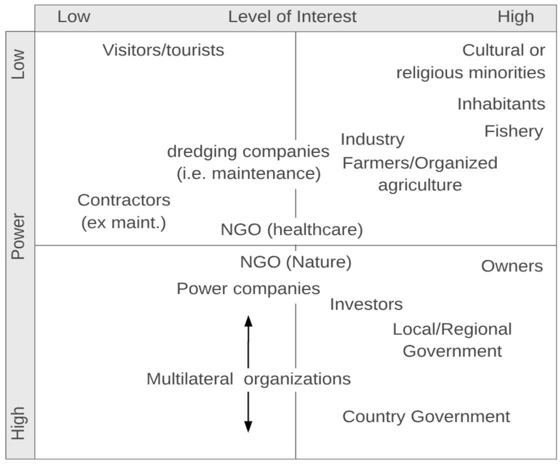


Figure 2-1: P/I grid stakeholders

Figure 2-1 shows the identified actors and their interest and power in the case. The grid is prepared from the point of view of extending reservoir lifespan and view on sedimentation problems in and near a reservoir. While every actor typically has specific and unique perceptions toward sedimentation, only governments (possible in the role of owner) can impose change in the technical system of a reservoir.

Despite the central role of governments in typical issues, it is of great importance to follow up or at least consider perception of other actors. At this point, governments are both responsible for the advance of a region (country) and for its residents. As a result, far reaching measures are considered optional, but application of alternatives should be based on perception of the wide range of actors involved.

2.3. Knowledge gaps

The objective is to find and combine a considered set of alternatives to make the operation of reservoirs both economically viable and sustainable.

Literature availability on the subject typically is about a specific case and about sedimentation in a reservoir *or* about environmental effects near reservoirs. Much research is ex post facto and less focused on quantitative predicting in general. The knowledge gap is found in combining quantitative methods to predict and support decision making for reservoir operation management.

Based on the system analysis, quantitative information about sedimentation (management) in a reservoir is essential. Extending the life of reservoirs was researched extensively in 2016 (Annandale, 2016). Annandale and his team developed the study to facilitate implementation of a programmatic approach for screening water, hydropower and dam investment projects. This thesis will aim to link computational modelling with a limited number of sediment management alternatives to elaborate on the work of Annandale.

Coupling sedimentation (management) to economic performance of the reservoir lead to a forecasting and optimizing model for reservoir operations.

Quantitative sedimentation evaluation will be based on computational fluid dynamics modelling. The latter part, evaluation of reservoir performance, is based on a cost benefit analysis. When the links are developed, it provides a framework for quantitative evaluation of reservoirs. It is essentially not focused on one reservoir in particular at first, but aims to give handles for different reservoirs in general. De model will ultimately be applied to a case, namely Ke Go Reservoir in Vietnam (Vncold, N/A).

3. Research methodology

This chapter deals with the theoretical methodology used in the research. The first section discusses the relation of sedimentation evaluation with reservoir system performance. After this, the substantive theory behind the methodologies is explained and discussed. Simplifications are highlighted, but are necessary to keep the research executable. Large parts of the execution of the project involves programming and matrix operations. All programming has been carried out in Matlab R2019A.

3.1. Combination of research methods

Computational fluid dynamics (CFD) modelling is proposed to evaluate sedimentation in reservoirs and will be the input to evaluate dredging/sediment management methods. Different scenarios will be reviewed to evaluate impact of uncertainty.

CFD modelling will be used to simulate sedimentation processes and to estimate spatial spread of sediment in a reservoir. Information about spread and aggregation of sediment in the reservoir is input for the dredging model. Evaluation of the feasibility of dredging methods or other sediment management processes is the next step.

Annandale (2016) describes a variety of sediment management alternatives. This thesis considers in basis only two alternatives, namely dredging or flushing. Annandale also discusses adaptive sediment management strategies; i.e. strategies that aim to mitigate sedimentation, but without handling sediment. This will not be included in this research.

The two alternatives in this research are defined as follows:

- Dredging of sediment, i.e. a dredging method to stop or slow down sedimentation in a reservoir. Dredging feasibility depends on the type of equipment used, important limiting parameters are dredging depth and type of sediment (grain size, d_{50});
- In case of flushing, sediment aggregation must be near the dam and its flushing sluice gates. On top of that, the sluice gates must be suitable for flushing activities. It means that flushing cannot be executed through hydropower generation sluice-gates (Brandt, 1999). When aggregations develop in upstream places in the reservoir, dredging becomes the only considered alternative. If dredging is feasible only, flushing will be reviewed as alternative to process dredge material/waste.

After dredging, again three options are possible. 1.) Dredged material can be dumped at an alternative remote location in the reservoir. 2.) Dredged material can be transported (either pipelines or barges) to shore and processed for further use of disposal. 3.) Dredged material is dumped at a downstream location in the reservoir suitable for flushing.

The basic alternatives are then compared to the status quo:

- Reservoir operations without sediment management, reservoir functioning continue until a sedimentation threshold is exceeded and the reservoir can no longer function properly. In the long term, sediment aggregation can lead to siltation and a reservoir can become completely obsolete.

The final step in establishing performance of a reservoir system is worked out with a cost benefit analysis. The input is based on the results of sediment management opportunities and the characteristics of sedimentation processes. Such analysis is ultimately always incomplete, but does result in a substantiated alternative with outlooks regarding all kinds of criteria in monetized value.

Separately from above three steps, scenarios are proposed to examine dependencies. Figure 3-1 shows the complete model of prior steps. The next sections discuss the methods used in performing each model step.

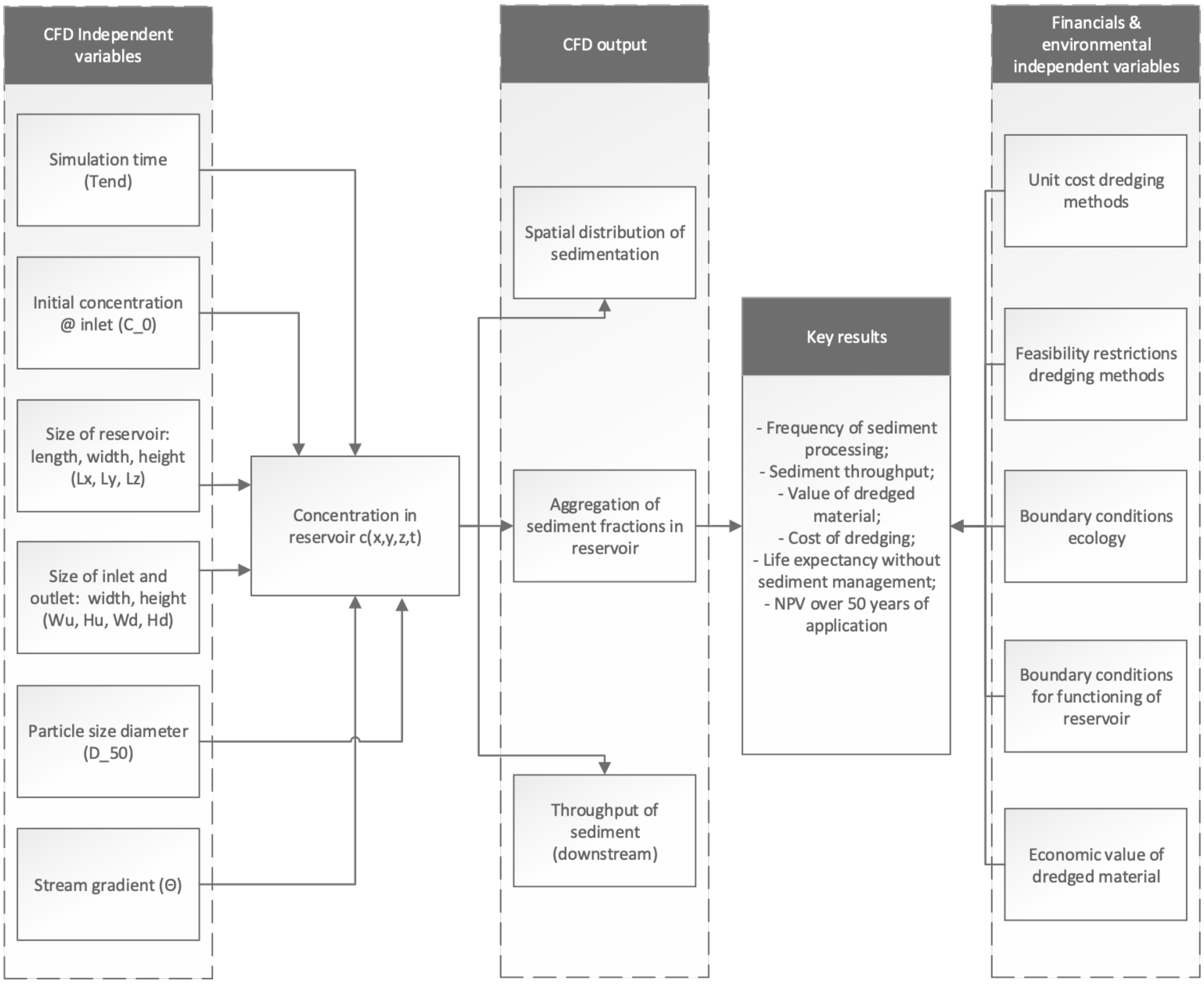


Figure 3-1: Schematic application and combination of methods

3.2. *Sediment transport*

This section deals with sedimentation processes, causes and eventual consequences for reservoir systems. The first section reviews common causes and consequences of sedimentation in and near reservoirs. After this, the computational model will be discussed in depth, this involves details such as application of grid, numerical considerations and important simplifications relative to for example physical modelling.

3.2.1. Origin of sediment

The origin of sediment in reservoirs start in river basins upstream. It is a complex task to predict sediment supply from upstream rivers. It is common that the average sediment transport rate in a river changes significantly after and due to construction of a dam. Understanding of the composition and sources of deposited sediments in watersheds has great significance on exploring the processes of sediment erosion and deposition. A diverse set of factors influences sediment transport, some examples are river depth, vegetation, current velocity (precipitation patterns) and river profile.

The decision to develop a reservoir often has large impact on the local environment. Deforestation of reservoir basins (Paiva, 1988) and infrastructure and urban development is a regular occurrence after or during the construction of a reservoir. Trees anchor otherwise loose topsoil (Butler, 2012) and large civil works also destabilize soil. An example of the consequences of deforestation is found in the Rhine hinterland in Germany after it had become widely deforested. This increased hillslope erosion, which led to more sediment transport by the Rhine to its delta, eventually increased variability in discharge in the Netherlands (University of Utrecht, 2018).

Therefore, erosion increases and a number of consequences take place:

1. Fertile soil from the upstream basin washes away and agriculture/forestry may be affected severely.
2. Deforestation also increases and intensifies peak flows.
3. A morphodynamical reaction occurs in upstream rivers due to change of current and sediment transport and eventually a new long term equilibrium is found. This means that a more intense peak flow may lead to an increase in sediment transport upstream.
4. Change in sediment supply reaches the reservoir and affects the sedimentation rate. The sedimentation rate of a reservoir is defined here as the volumetric percentage of reservoir capacity per year that a reservoir is filled with sediment (Bogner, 1983). The definition of sedimentation rate in research about erosion of river basins or river delta is different, it is in such subjects used as a measure of erosion.

As a result, uncertainty is found in change of erosion processes upstream, leading to consequences for sediment transport rates toward the reservoir. Another performance indicator in a reservoir system is the negative impact on arable land in the river basin. The negative impact on arable land clearly is not easily specified, but needs to be included in the CBA if more accurate and detailed information is necessary.

3.2.2. Reservoir sedimentation

The location of a reservoir, prior to the development of a reservoir, is usually in a natural balance (normal flow conditions) and part of the river system. Development of a dam changes the system completely. A large body of water is formed and average depth and width increase, which is a common cause for residents in the area to move. Average velocities in the reservoir decline compared to the original river profile. Especially near inlets and sluice gates (outlet/dam) large velocity gradients appear, possibly affected by seasonal precipitation and thaw cycle.

Reservoirs can have massive storage capacities, up to several hundred billion m^3 (Li, 2017). An example is the three gorges reservoir with an extraordinary maximum length of more than 600 km. In such large reservoirs, even thermal currents can be a significant cause of circulation and thereby changing sedimentation patterns, see Figure 3-2. Other secondary causes for current in a reservoir are turbulent mixing and stratification.

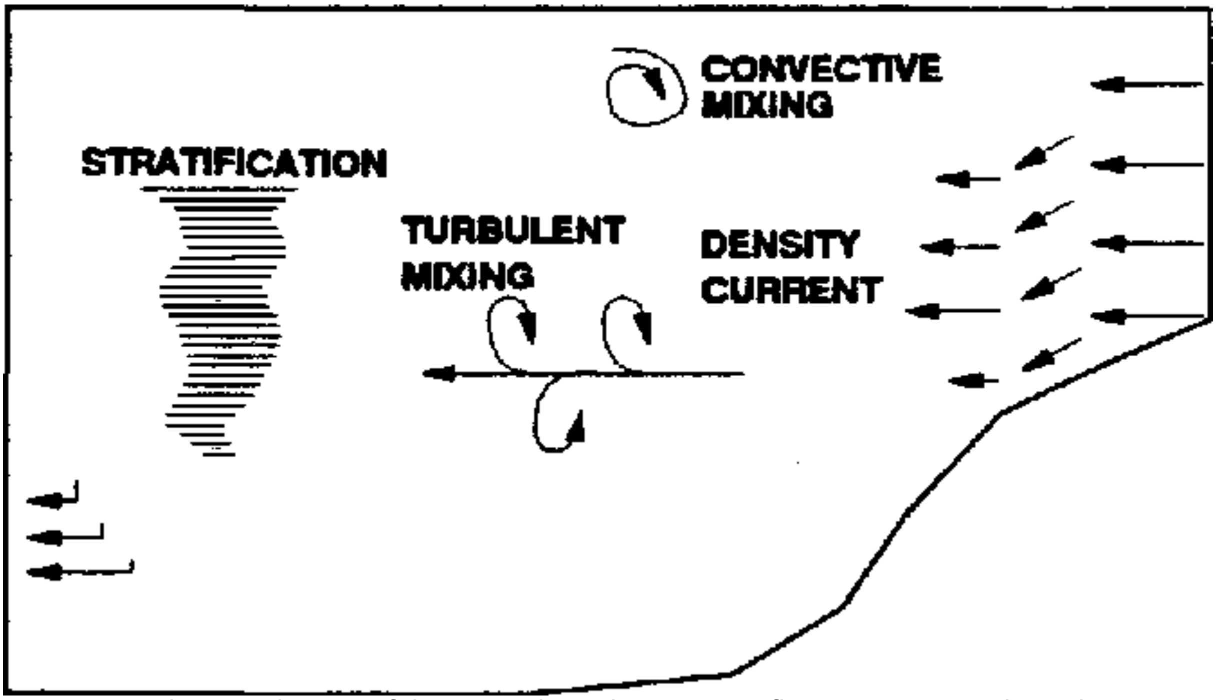


Figure 3-2: Schematic diagram of the major physical processes influencing reservoir thermal structure (Benton, 1993)

A number of simplifications have been made to enable a quantitative model for predicting sedimentation distribution. Computational fluid dynamics in a 3D cartesian coordinate system is used and is based on the pressure correction as described by Hirsch (Hirsch, 2007). The current in a reservoir is assumed to be low enough to ignore turbulent mixing, convective mixing and thermal currents. The velocity patterns in the modelled reservoir will be based on imposed preconditions at the in- and outlet and on an approach for density driven flow (Boussinesq). This will be discussed thoroughly in the next chapter.

Sedimentation rates are measured and researched for various reservoirs and averages are around 1% per year globally (Schleiss, 2016). The total capacity of reservoirs is decreasing currently, mainly due to sedimentation and eventually decommissioning. A clear example is the current reservoir capacity in Kansas. As of 2016, the average age of the reservoirs in Kansas was 51 years and had lost approximately 17% of their original capacity (Rahmani, 2017). Average sedimentation rates in Asia are higher and can easily reach 3% per year or higher (Naisen, 1997).

Assumption 3-A

- Turbulent and convective mixing are neglected. Velocities will not exceed the pickup threshold;
- Morphodynamical reaction to change in the river system will be neglected;
- Only one outlet (dam – sluice gates) and one inlet (upstream river) is considered in modelling sedimentation processes;
- The construct of sedimentation rates will be used to estimate long-term (lifespan) sediment aggradation.

3.2.3. Sediment shortages downstream

The supply and variability in supply of both water and sediment is heavily affected by dams. In addition to hydropower generation and water storage for urban and industrial/agricultural application, an important function of reservoirs can be flood control. An example for this is the High Aswan Dam. The dam consists of 180 sluice gates to regulate the flow of water to achieve flood control (Water-technology.net , 2019). Disadvantages of flood control are declines in the variability of water and nutrients supply and in the long-term poor soil on former floodplains (Schmutz, 2018), possibly very undesirable for agriculture. Seasonal or peak flow events cause natural fertilization of adjacent land, which is minimized after the commissioning of a dam. The combined effect for agriculture can be ambiguous. After commissioning, irrigation maybe a large and major economic driver behind a project, but total earnings can decline when weakening of soils are considered (Kondolf, 2014). This negative effect especially becomes in evidence after decades of operation. As much as upstream, weakening of soil is an important negative side effect of operating a reservoir. These effects will be reviewed in the cost benefit analysis, but excluded in the assessment of dredging costs. This approach aims to render a transparent but separate view on direct costs (dredging) and indirect effects on operating a reservoir.

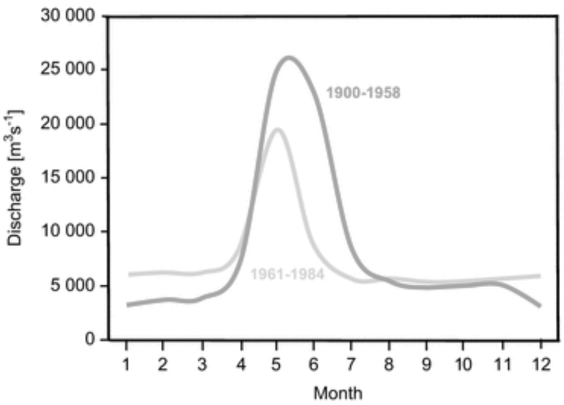


Figure 3-4: Variation in discharge [seasons] (Schmutz, 2018)

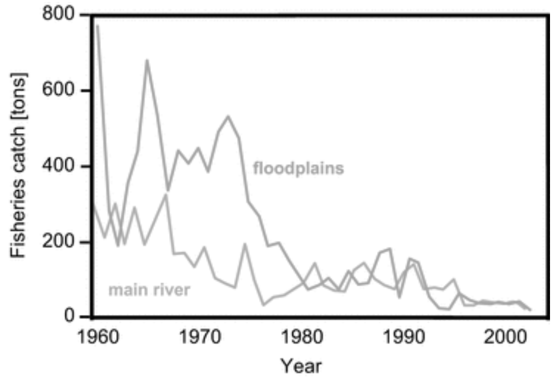


Figure 3-3: Post dam decline in fishery activities (Schmutz, 2018)

Next to agriculture, fishery and large ecological systems can suffer from large reservoir projects. (Schmutz, 2018). Migratory fish species cannot reach breeding grounds and loss in seasonal variation in discharge weakens soil characteristics in ecosystems. Flood events are diminished, while it is of essence for the proper functioning of an ecological and biodiverse system.

The results downstream are somewhat comparable to upstream effects. The quality of topsoil is reduced. Mitigation is the only option, since restoration to pre-damming conditions is impossible. The area affected by erosion or staling of soil is considered in the net cost and benefits, but is not considered in the assessment of dredging.

4. Computational Fluid Dynamics model

To really grasp the concept of sedimentation, a three-dimensional (3D) computational fluid dynamics model (CFD) is proposed. The purpose of this is to obtain quantitative insight into sedimentation patterns and its intensity distribution in a reservoir. The first section deals with the simplification of the reservoir shape and preparation for CFD modelling. Subsequently, the numerical model is discussed and finishes with boundary conditions.

4.1. Reservoir Shape

Each reservoir has a unique set of parameters that translates into the shape of a reservoir. The final objective is to design a model that has predictive power in terms of reservoir life expectancy, which is ultimately connected to the speed and location of sedimentation. The cases in appendix A already show a large variation of possible shapes. It would be unfeasible within this study to implement a wide range of shapes in the CFD modelling. And so, the shape of the reservoir needs to support the basic characteristics of a reservoir, while it remains basic in most details.

A reservoir in essence is a contained body of water. The storage of water is usually used for various functions, but a significant part of the storage leaves almost always through sluice-gates in the dam. Sluice-gates can be designed for multiple functions such as spilling, hydropower generation, flushing or combination of functions. Combining flushing and hydropower generation is not considered possible. The location of these gates usually does not match and it is undesirable to increase wear in a hydropower gate due to concentrated sediment flows. A basic longitudinal cross section of a reservoir in operation is shown in Figure **4-1**. The bottom profile changes continuously and the figure shows a single point in time. A dead storage usually fills gradually and continues depending on sediment transport and management considerations. The total water storage is the active storage (above the outlet in Figure **4-1**) and dead storage together. Hydropower generation takes place in the outlet and can continue at full capacity until settled sediment reaches heights beyond the outlet level.

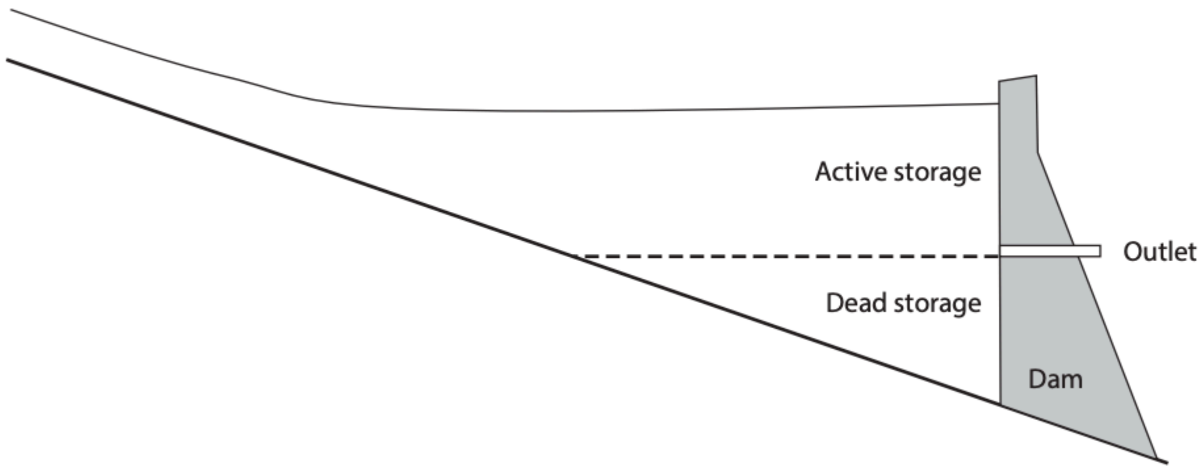


Figure 4-1: Longitudinal cross section of a reservoir

The cross section of a reservoir normally forms with time, depending on the prevailing current and transversal sediment aggregation. Passive sediment management measures can change the cross section. A common measure is excavating a channel in the reservoir to improve density currents. Passive sediment management or other concentrated earthmoving will not be included in the reservoir, but could be a valuable addition in later phase. Figure 4-2 shows in light grey the presumed cross section of a reservoir. The rectangular shape shows the cross section that will be used in the simulation. The figure clearly shows a discrepancy between real and simulated reservoir depth and width. The proportions of a real reservoir case will always need to be adjusted to fit the simulated rectangular shape as well as reasonably possible. The simulated shape must be a reasonable imitation of the real case and adaption depends on the available parameters. Further on in this report it will appear that reservoir depth is especially important in the feasibility of dredging alternatives. The simulated reservoir depth will therefore not be changed and only the simulated reservoir width and if needed the length will be adapted to keep the simulated roughly equal to the real case capacity. An example of adaption of real values to simulated values follows in the case specification, chapter 7. The next step is to translate the rectangular approximation into a three-dimensional grid.

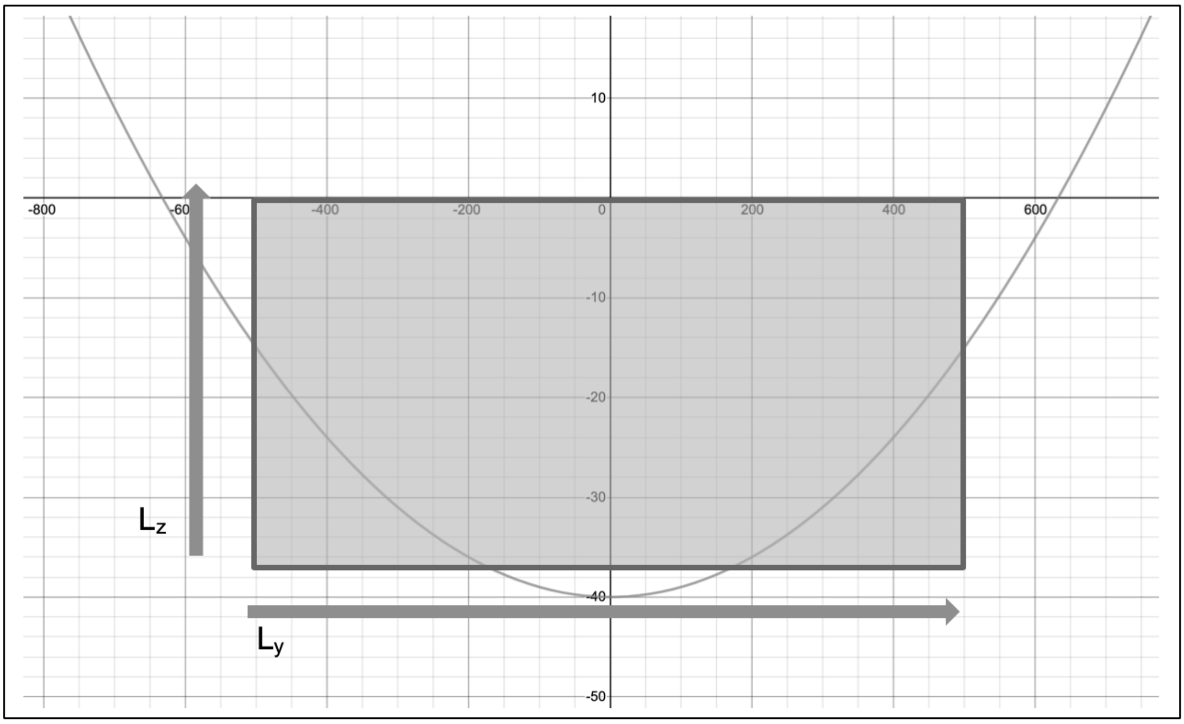


Figure 4-2: Coupling assumed real life cross section and simulated cross section

Figure 4-3 shows the simplified reservoir shape that will be used to simulate sediment transport and settling. Only one inlet and one outlet are included. This means that water supply from a river basin must be translated into a velocity profile at the inlet. On the other hand, the one outlet is a means to model the total water discharge, no matter whether it is for flushing, hydropower or other function. The grid consists of the cubic shaped reservoir, including the boundaries at the inlet and outlet. The rivers (upstream and downstream) are included as entrance and exit only. The following parameters specify the location and dimensions of grid elements:

1. L_x Reservoir length [m]
2. L_y Reservoir width [m]
3. L_z Reservoir height/depth [m]
4. H_u Inlet height [m]
5. W_u Inlet width [m]
6. H_D Outlet height [m]
7. W_D Outlet width [m]
8. H_o/H_{db} Sluice gate base height above reservoir bed [m]

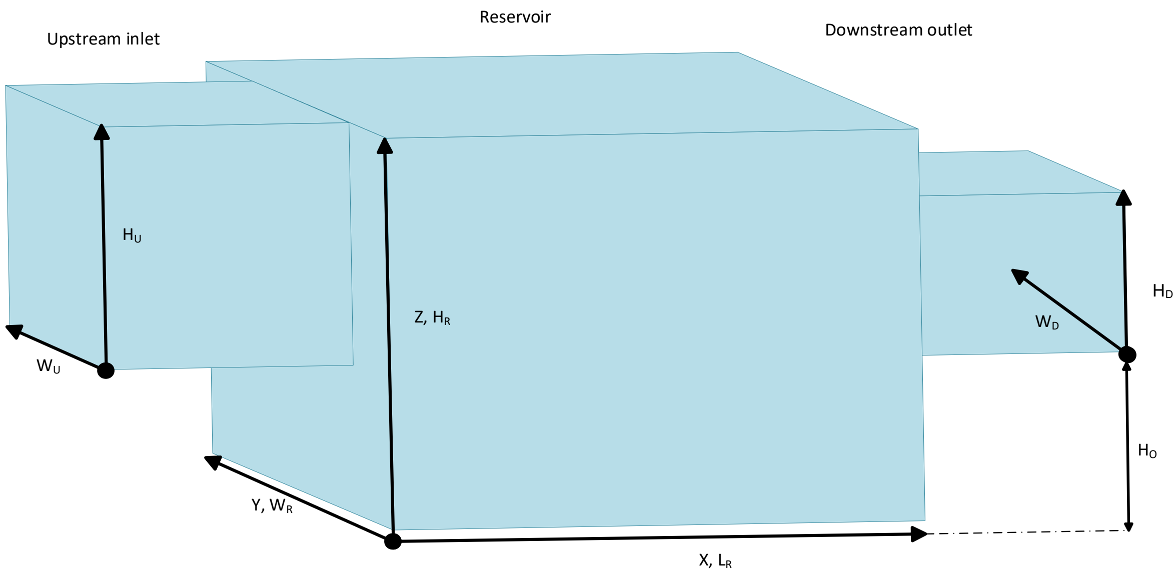


Figure 4-3: Coordinate system for CFD grid. The reservoir upstream and downstream river is not included, only as in- and outlets only.

The cubic shaped grid is constant in size and the grid cells are the same size everywhere. The blocks are rectangular, but not necessarily square. Both the inlet and outlet are transversally centred. The bottom of the reservoir is level at first and develops over time. The number of cells for the different reservoir elements are as follows:

Reservoir

1. m Number of cells in *X* direction (length) $\frac{L_x}{dx}$
2. n Number of cells in *Y* direction (width) $\frac{L_y}{dy}$
3. r Number of cells in *Z* direction (height) $\frac{L_z}{dz}$

Inlet

1. n_u Number of cells in *Y* direction (width) $floor(n * \frac{W_u}{L_y})$
2. r_u Number of cells in *Z* direction (height) $floor(r * \frac{H_u}{L_z})$
3. in_{startk} Cell number start inlet in *Z* direction $r - r_u + 1$
4. in_{startj} Cell number start inlet in *Y* direction $n - n_u + 1$
5. in_{stopj} Cell number stop inlet in *Y* direction $in_{startj} + n_u$

Outlet

1. n_d Number of cells in *Y* direction (width) $floor(n * \frac{W_d}{L_y})$
2. r_d Number of cells in *Z* direction (height) $floor(r * \frac{H_d}{L_z})$
3. r_o Cell number start outlet in *Z* direction $floor(r * \frac{H_O}{L_z})$
4. out_{stopk} Cell number stop outlet in *Z* direction $r_o + r_d$
5. out_{startj} Cell number start outlet in *Y* direction $n - n_d + 1$
6. out_{stopj} Cell number stop outlet in *Y* direction $out_{startj} + n_d$

Figure 4-4 shows the grid for the 3 planes with coordinate system.

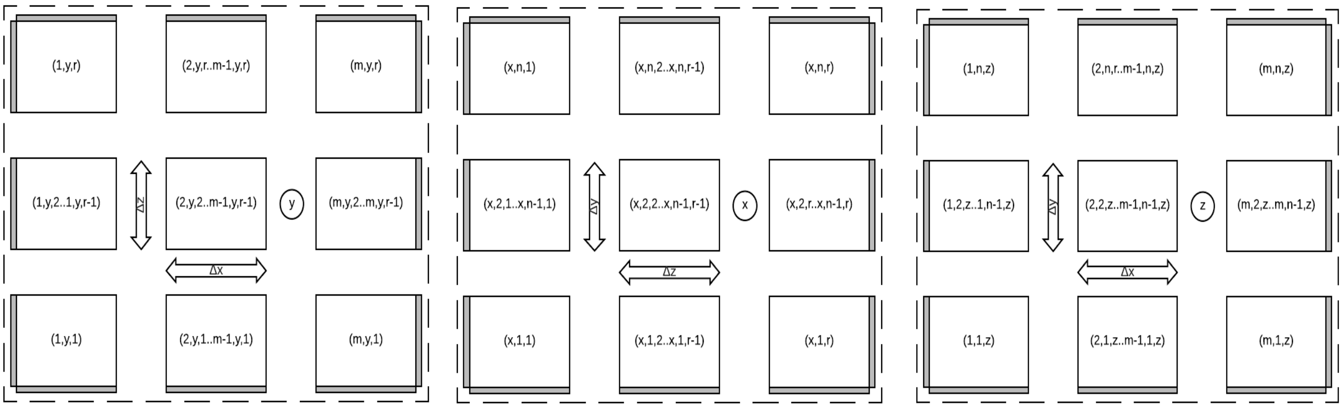


Figure 4-4: Schematized reservoir grid

Assumption 4-A summarizes the initial conditions of the reservoir shape.

Assumption 4-A

- Walls are vertical everywhere;
- The bottom is horizontal and is a significant simplification relative to a normal bed slope in rivers or reservoirs. A slope may also develop after a long period of sedimentation;
- One inlet (upstream river), adjustable in height, width, reference velocity and with a rectangular shape. Top of the inlet is at the free surface;
- The construct of sedimentation rates is used to estimate long-term (life-span) sediment aggradation and development of reservoir shape;
- *The velocity at the inlet is not constant over the inlet cross section @ x=0. The velocity increases nonlinearly from 0 at the bottom to the reference velocity at the free surface. The reference velocity is either given or it is based on the bed slope of the upstream river and total discharge. The nonlinear distribution of discharge at the inlet depends on the bed slope (ϑ) and viscous shear (η). This approach is based on theories of (Fowler, 2012) and (Ames, 2018).*

$$v(z) = \frac{\rho g \theta}{2\eta} * z(2h - z)$$

This is still a rough estimate because of a number of reasons. Most importantly, the velocity only depends on the value of z, not y. The volume flow pushing the velocity and the channel shape (possible meandering) also affects the inflow velocity (Gaballa, 2006).
- *Like the inlet, the outlet (downstream river/dam) is adjustable in height and width (rectangular). The base height of the outlet is defined with parameter H_o, which is the height relative to the bottom of the reservoir. The total discharge at the inlet is set equal to the discharge at the outlet (Volume conservation);*

4.2. CFD basics

Now that the shape and grid is known, the CFD modelling technique is to be discussed. The CFD approach and elementary equations will be discussed first, after which it is converted to a discretized scheme. The inlet and outlet, including concentrations and simulation of density currents is introduced at the end.

4.2.1. CFD model setup

The CFD model is based on the pressure correction method (Hirsch, 2007). The model is built up from separate parts as shown in Figure 4-5. The pressure correction method is typical for updating velocities from the momentum equations. Pressures, on the other hand, are updated by solving the Poisson equation each time step. Aggregation and throughput of sediment is especially important in this case and will be a measure of sedimentation distribution in a reservoir. The following output is important to make such assessments:

1. Amount of sediment passing the output to downstream rivers, only the sediment leaving by normal outflow of water. Trap rates are often well over 90 percent;
2. Aggregation of sediment in the reservoir;
3. Spatial distribution of sedimentation in order to assess feasible dredging and/or sediment management processing.

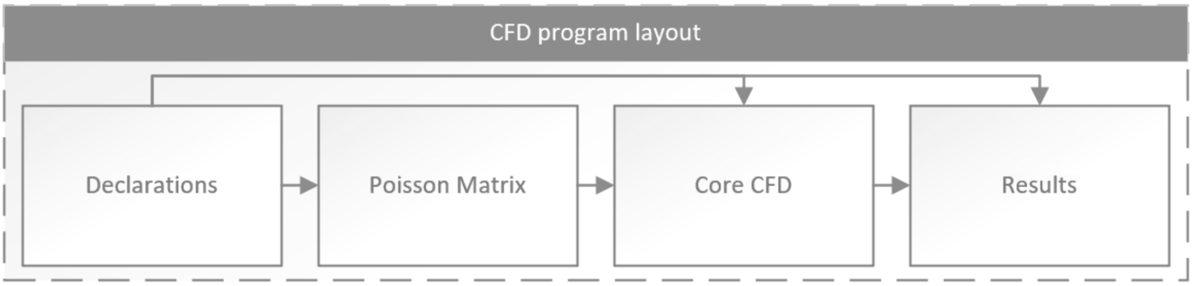


Figure 4-5: CFD general steps

Figure 4-5 shows the general CFD code layout. All control (input) variables are declared in the *declarations* block, except for the Poisson matrix. Initialisation of the *Poisson matrix* is kept outside the core CFD file, it involves many matrix calculations and manipulations. The initialisation only needs to be performed once, and remains constant during the whole CFD simulation. The Poisson matrix is useful to make the solving of the pressure field each time step more transparent. The next CFD steps are performed in the *Core CFD* code, which is shown in Figure 4-6: Schematic steps in CFD modelling sedimentation. The results block further operates data to an appropriate format for further analysis and is important data for the financial analysis later on. The next sections discuss the different steps within the CFD program, based on Figure 4-6.

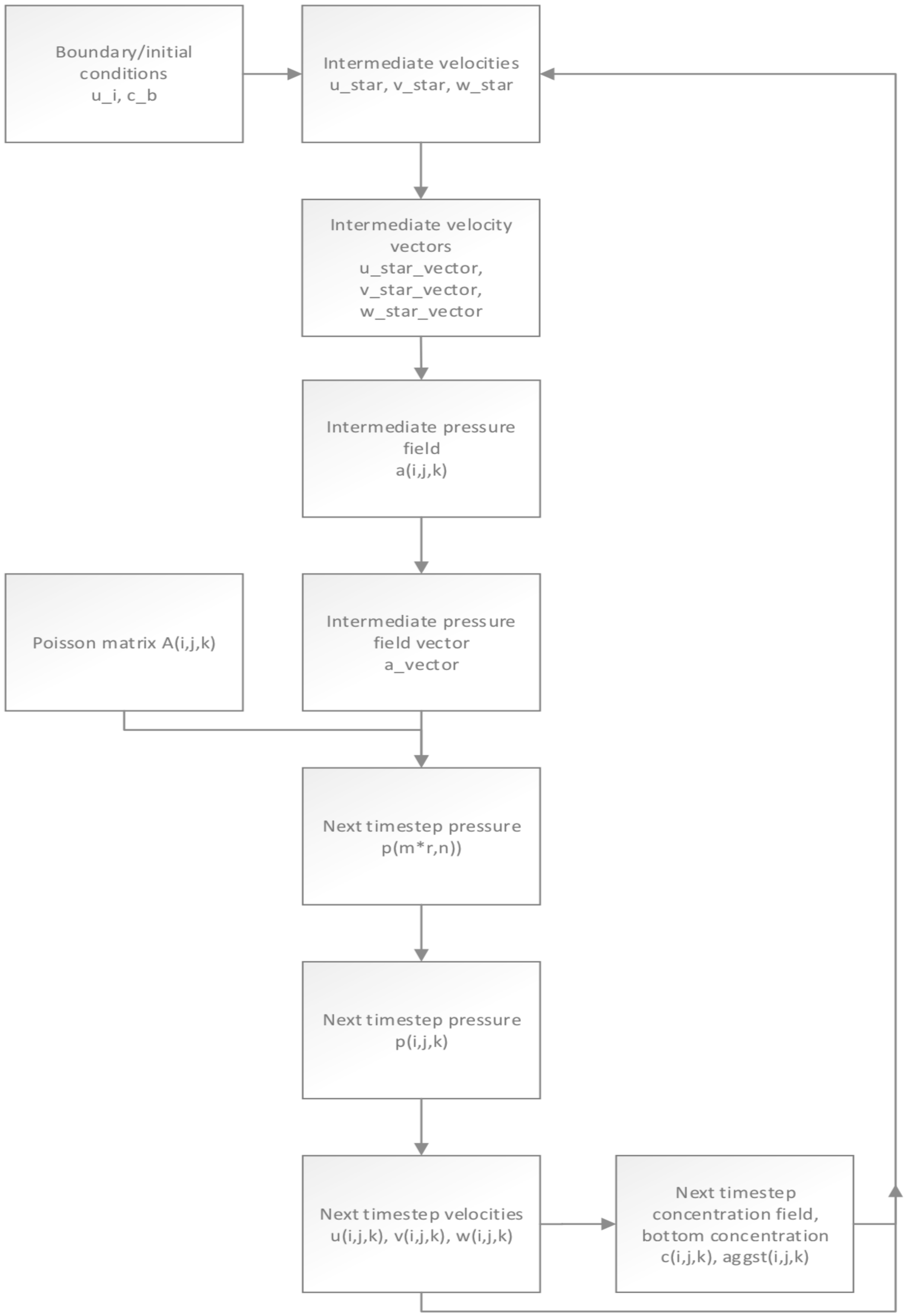


Figure 4-6: Schematic steps in CFD modelling sedimentation

4.2.2. Pressure correction method

The basic approach of the pressure correction method here is strictly for incompressible isothermal flows. The theory starts with alteration of the Navier-Stokes equations for laminar flow and without external forces, Eq. 4-1.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0 \qquad \text{Eq. 4-1}$$

The Navier - Stokes equation in Eq. 4-1, altered for a three-dimensional grid can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \qquad \text{Eq. 4-2}$$

Mass conservation mass conservation reduces for incompressible flows:

$$\vec{\nabla} \cdot \vec{v} = 0 \qquad \text{Eq. 4-3}$$

Eq. 4-3 appears as a constraint to the equation of motion (Eq. 4-4) and the only unknowns in time remain velocity and pressure. A pressure equation (Eq. 4-5) for a velocity field can finally be obtained by taking the divergence of Eq. 4-4.

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} = -\frac{1}{\rho}\vec{\nabla}\, p + \upsilon \Delta \vec{v} \qquad \text{Eq. 4-4}$$

$$\frac{1}{\rho}\Delta p = -\vec{\nabla} \cdot (\vec{v} \cdot \vec{\nabla})\vec{v} \qquad \text{Eq. 4-5}$$

The pressure equation in Eq. 4-5 can be considered a Poisson equation now. The essential approach of pressure correction is decoupling of the pressure field from the velocity field. This can be done by solving the momentum equation (Eq. 4-4) with a known pressure field (current/last timestep). A variety of decoupling approaches has been developed, this study follows the so-called fractional step approach. When applying the fractional step approach, the pressure term in the intermediate pressure is omitted, leading to a complete decoupled velocity field (Hirsch, 2007), chapter 12.4.1, Eq. 4-6.

$$\frac{\vec{v}^* - \vec{v}^n}{\Delta t} = -\vec{\nabla} \cdot (\vec{v} \otimes \vec{v})^n + \upsilon \Delta \vec{v}^n \qquad \text{Eq. 4-6}$$

The Poisson equation for pressure correction finally is:

$$\Delta p^{n+1} = \frac{\rho}{\Delta t}\vec{\nabla} \cdot \vec{v}^* \qquad \text{Eq. 4-7}$$

Intermediate parameters, such as intermediate velocity, is shown with superscript (v)*. Intermediate parameters such as $u^*, v^*\ and\ w^*$ represent an intermediate result before updating the pressure field in the grid.

Taking density currents into account is essential to model sediment flows. As mentioned earlier, thermal gradients will not be considered and density currents will be evaluated by application of a Boussinesq approach (Eq. 4-8). This approach takes into account density differences only. Particle size and shape are kept outside this part of the simulation and the method is usable only if density differences in the reservoir are low.

$$\frac{\partial w}{\partial t} + \cdots = -\frac{1}{\rho_0}\frac{\partial p}{\partial z} - (c \cdot \rho_s - c \cdot \rho_w) \qquad \text{Eq. 4-8}$$

Evaluation of the concentration field starts as follows:

$$\frac{\partial c}{\partial t} + \vec{\nabla}(c\vec{v}) = \vec{\nabla}^2(\kappa c) \qquad \text{Eq. 4-9}$$

This essentially is the convection diffusion equation and becomes for a three-dimensional grid:

$$\frac{\partial c}{\partial t} + \frac{\partial \mathrm{uc}}{\partial \mathrm{x}} + \frac{\partial \mathrm{vc}}{\partial \mathrm{y}} + \frac{\partial \mathrm{wc}}{\partial \mathrm{z}} = \frac{\partial}{\partial \mathrm{x}} k \frac{\partial c}{\partial x} + \frac{\partial}{\partial \mathrm{y}} k \frac{\partial c}{\partial y} + \frac{\partial}{\partial \mathrm{z}} k \frac{\partial c}{\partial z} \qquad \text{Eq. 4-10}$$

4.2.3. Numerical discretization

The numerical scheme follows a relatively simple space discretization. Instead of using a staggered grid, a central collocated grid (Figure **4-7**) will be used. This means that the different variables are defined at the same positions in the grid. All variables will be centrally stored in the grid, except for the concentration. An upwind method will be used to prevent potential checkerboarding or unrealistic alternating of concentrations and pressures.

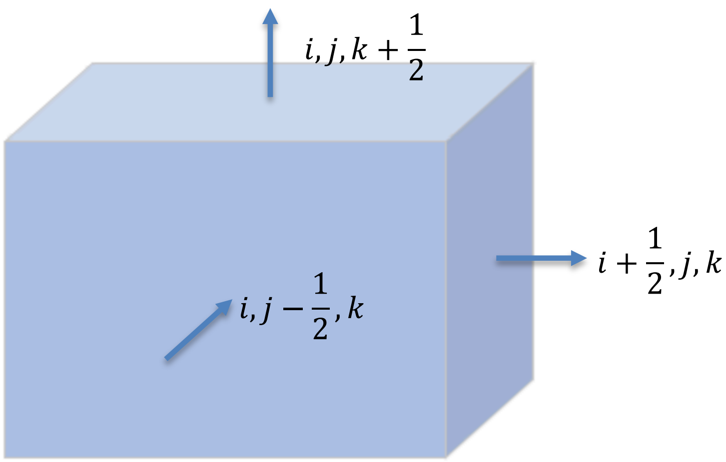


Figure 4-7: Central grid

Intermediate velocities
In the pressure correction method, the velocity field is updated from the momentum equation. The pressure field is updated by discretizing and solving the Poisson equation each time step. Applying the fractional step method (Eq. 4-6/4-7) now gives the intermediate velocity in three directions:

$$u^* = u(i,j,k) - \Delta t * \frac{u^2\left(i+\frac{1}{2},j,k\right)-u^2\left(i-\frac{1}{2},j,k\right)}{\Delta x} - \Delta t * \frac{u\left(i,j+\frac{1}{2},k\right)*v\left(i,j+\frac{1}{2},k\right)-u\left(i,j-\frac{1}{2},k\right)*v\left(i,j-\frac{1}{2},k\right)}{\Delta y} - \Delta t * \frac{u\left(i,j,k+\frac{1}{2}\right)*w\left(i,j,k+\frac{1}{2}\right)-u\left(i,j,k-\frac{1}{2}\right)*w\left(i,j,k-\frac{1}{2}\right)}{\Delta z} + \frac{\Delta t}{\rho} * \frac{\tau_{xx_{i+\frac{1}{2},j,k}} - \tau_{xx_{i-\frac{1}{2},j,k}}}{\Delta x} + \frac{\Delta t}{\rho} * \frac{\tau_{xy_{i,j+\frac{1}{2},k}} - \tau_{xy_{i,j-\frac{1}{2},k}}}{\Delta y} + \frac{\Delta t}{\rho} * \frac{\tau_{xz_{i,j,k+\frac{1}{2}}} - \tau_{xz_{i,j,k-\frac{1}{2}}}}{\Delta z} \qquad \text{Eq. 4-11}$$

$$v^* = v(i,j,k) - \Delta t * \frac{v^2\left(i,j+\frac{1}{2},k\right)-v^2\left(i,j-\frac{1}{2},k\right)}{\Delta y} - \Delta t * \frac{u\left(i+\frac{1}{2},j,k\right)*v\left(i+\frac{1}{2},j,k\right)-u\left(i-\frac{1}{2},j,k\right)*v\left(i-\frac{1}{2},j,k\right)}{\Delta x} - \Delta t * \frac{v\left(i,j,k+\frac{1}{2}\right)*w\left(i,j,k+\frac{1}{2}\right)-v\left(i,j,k-\frac{1}{2}\right)*w\left(i,j,k-\frac{1}{2}\right)}{\Delta z} + \frac{\Delta t}{\rho} * \frac{\tau_{yy_{i,j+\frac{1}{2},k}} - \tau_{yy_{i,j-\frac{1}{2},k}}}{\Delta y} + \frac{\Delta t}{\rho} * \frac{\tau_{xy_{i+\frac{1}{2},j,k}} - \tau_{xy_{i-\frac{1}{2},j,k}}}{\Delta x} + \frac{\Delta t}{\rho} * \frac{\tau_{yz_{i,j,k+\frac{1}{2}}} - \tau_{yz_{i,j,k-\frac{1}{2}}}}{\Delta z} \qquad \text{Eq. 4-12}$$

$$w^* = w(i,j,k) - \Delta t * \frac{w^2\left(i,j,k+\frac{1}{2}\right)-w^2\left(i,j,k-\frac{1}{2}\right)}{\Delta z} - \Delta t * \frac{u\left(i+\frac{1}{2},j,k\right)*w\left(i+\frac{1}{2},j,k\right)-u\left(i-\frac{1}{2},j,k\right)*w\left(i-\frac{1}{2},j,k\right)}{\Delta x} - \Delta t * \frac{v\left(i,j+\frac{1}{2},k\right)*w\left(i,j+\frac{1}{2},k\right)-v\left(i,j-\frac{1}{2},k\right)*w\left(i,j-\frac{1}{2},k\right)}{\Delta y} + \frac{\Delta t}{\rho} * \frac{\tau_{zz_{i,j,k+\frac{1}{2}}} - \tau_{zz_{i,j,k-\frac{1}{2}}}}{\Delta z} + \frac{\Delta t}{\rho} * \frac{\tau_{xz_{i+\frac{1}{2},j,k}} - \tau_{xy_{i-\frac{1}{2},j,k}}}{\Delta x} + \frac{\Delta t}{\rho} * \frac{\tau_{yz_{i,j+\frac{1}{2},k}} - \tau_{yz_{i,j-\frac{1}{2},k}}}{\Delta y} - \mathbf{\Delta t * g * \left(\rho_c(\boldsymbol{i,j,k}) - \rho_o\right)} \qquad \text{Eq. 4-13}$$

The intermediate velocity in *w (vertical)* direction is adjusted for density differences in the grid, as shown in Eq. 4-8. All intermediate velocities are evaluated at the cell centres. The boundary conditions at the inlet, outlet and walls will be discussed later on. The different terms in equations 4-11 to 4-13 are formulated in appendix C.1.

Poisson solver
The next step is to obtain the next time step pressure for all grid locations. Elementary part in decoupling the velocity and pressure is the Poisson equation and will now be used to obtain the pressure. The Poisson equation for the studied case (Eq. 4-14) needs to be solved and needs to be altered according to the equations on the following page:

$$\frac{1}{\Delta x}\left[\frac{p^{n+1}{}_{i+1,j,k}-p^{n+1}{}_{i,j,k}}{\Delta x}-\frac{p^{n+1}{}_{i,j,k}-p^{n+1}{}_{i-1,j,k}}{\Delta x}\right]+\frac{1}{\Delta y}\left[\frac{p^{n+1}{}_{i,j+1,k}-p^{n+1}{}_{i,j,k}}{\Delta y}-\frac{p^{n+1}{}_{i,j,k}-p^{n+1}{}_{i,j-1,k}}{\Delta y}\right]+$$
$$\frac{1}{\Delta z}\left[\frac{p^{n+1}{}_{i,j,k+1}-p^{n+1}{}_{i,j,k}}{\Delta z}-\frac{p^{n+1}{}_{i,j,k}-p^{n+1}{}_{i,j,k-1}}{\Delta z}\right]=\frac{\rho}{\Delta t}\left[\frac{u^*_{i+\frac{1}{2},j,k}-u^*_{i-\frac{1}{2},j,k}}{\Delta x}+\frac{v^*_{i,j+\frac{1}{2},k}-v^*_{i,j-\frac{1}{2},k}}{\Delta y}+\right.$$
$$\left.\frac{w^*_{i,j,k+\frac{1}{2}}-w^*_{i,j,k-\frac{1}{2}}}{\Delta z}\right]$$
Eq. 4-14*

*super script *n* / *n+1* denotes the current respectively next timestep.
The applied Poisson solver in the program will be derived in the following formulas. This starts with a basic form of the Poisson solver in which *Q* is the right-hand-side of Eq. 4-14.

$$\Delta p = \frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2} = Q$$
Eq. 4-15

Integration of the basic Poisson solver:

$$\int\int\int \Delta p dxdydz = \int\int\int\left(\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2}\right)dxdydz = \int\int\int Q dxdydz$$
Eq. 4-16

$$\int\int\int \Delta p\, dxdydz = \int\int\frac{\partial^2 p}{\partial x^2}dxdydz+\int\int\frac{\partial^2 p}{\partial y^2}dxdydz+\int\int\frac{\partial^2 p}{\partial z^2}dxdydz = \int\int\int Q dxdydz$$
Eq. 4-17

Working out the different terms of Eq. 4-17:

$$\int\int\frac{\partial^2 p}{\partial x^2}dxdydz = \left(\left(\frac{\partial p}{\partial x}\right)_{i+\frac{1}{2},j,k}-\left(\frac{\partial p}{\partial x}\right)_{i-\frac{1}{2},j,k}\right)dydz = \left(\frac{p_{i+1,j,k}-p_{i,j,k}}{\Delta x}-\frac{p_{i,j,k}-p_{i-1,j,k}}{\Delta x}\right)dydz$$
$$\int\int\frac{\partial^2 p}{\partial y^2}dxdydz = \left(\left(\frac{\partial p}{\partial y}\right)_{i,j+\frac{1}{2},k}-\left(\frac{\partial p}{\partial y}\right)_{i,j-\frac{1}{2},k}\right)dxdz = \left(\frac{p_{i,j+1,k}-p_{i,j,k}}{\Delta y}-\frac{p_{i,j,k}-p_{i,j-1,k}}{\Delta y}\right)dxdz$$
$$\int\int\frac{\partial^2 p}{\partial z^2}dxdydz = \left(\left(\frac{\partial p}{\partial z}\right)_{i,j,k+\frac{1}{2}}-\left(\frac{\partial p}{\partial z}\right)_{i,j,k-\frac{1}{2}}\right)dxdy = \left(\frac{p_{i,j,k+1}-p_{i,j,k}}{\Delta z}-\frac{p_{i,j,k}-p_{i,j,k-1}}{\Delta z}\right)dxdy$$

Substitution back into equation 4-17 and dividing by *dxdydz*:

$$Q=\frac{p^{n+1}_{i+1,j,k}-p^{n+1}_{i,j,k}}{(\Delta x)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i-1,j,k}}{(\Delta x)^2}+\frac{p^{n+1}_{i,j+1,k}-p^{n+1}_{i,j,k}}{(\Delta y)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i,j-1,k}}{(\Delta y)^2}+\frac{p^{n+1}_{i,j,k+1}-p^{n+1}_{i,j,k}}{(\Delta z)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i,j,k-1}}{(\Delta z)^2}$$
Eq. 4-18

Q can be calculated as the intermediate velocities are known. The last step before solving the Poisson solver for the next timestep pressures is re-evaluating the right-hand-side of Eq. 4-18 into the *Poisson matrix* (Figure 4-5). Derivation of the Poisson matrix (*A*) is included in Appendix C.3.

The next time step pressures can finally be obtained by solving the system of linear equations:

$$p^{n+1} = Q/A$$
Eq. 4-19

Next time step velocities
The last step before re-evaluating the complete cycle in Figure 4-6 is calculating the next time step velocities. The new velocities are calculated from the intermediate velocities and updated pressure field, which now satisfies the continuity equation.

$$u_{i,j,k}^{n+1} = \frac{\Delta t}{\rho}(p_{i+\frac{1}{2},j,k}^{n+1} - p_{i-\frac{1}{2},j,k}^{n+1}) \quad \text{Eq. 4-20}$$
$$v_{i,j,k}^{n+1} = \frac{\Delta t}{\rho}(p_{i,j+\frac{1}{2},k}^{n+1} - p_{i,j-\frac{1}{2},k}^{n+1}) \quad \text{Eq. 4-21}$$
$$w_{i,j,k}^{n+1} = \frac{\Delta t}{\rho}(p_{i,j,k+\frac{1}{2}}^{n+1} - p_{i,j,k-\frac{1}{2}}^{n+1}) \quad \text{Eq. 4-22}$$

The evaluation of (intermediate) velocities and pressures can start again now.

Application of the convection - diffusion equation
The computational model is now able to simulate a pressure and velocity field in a hypothetical reservoir. The convection – diffusion equation is already mentioned shortly in Eq. 4-9/4-10. Numerical discretization and application of this approach to evaluate concentration distribution in the reservoir setup will follow next.

The convection – diffusion equation will be added to the already discussed CFD model, indicated by *next timestep concentration field* (Figure 4-6). The approach makes it possible to evaluate the concentration each timestep for the entire grid. Numerical discretization of the continuous convection – diffusion equation (Eq. 4-23) is as follows:

$$\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} + \frac{\partial wc}{\partial z} = \frac{\partial}{\partial x}\kappa\frac{\partial c}{\partial x} + \frac{\partial}{\partial y}\kappa\frac{\partial c}{\partial y} + \frac{\partial}{\partial z}\kappa\frac{\partial c}{\partial z} \quad \text{Eq. 4-23}$$

Discretization of the individual parts of the formula:

$$\int\int\int \frac{\partial c}{\partial t}dxdydz = \frac{c^{n+1} - c^{n}}{\Delta t} \Delta x \Delta y \Delta z$$

$$\int\int\int \frac{\partial uc}{\partial x}dxdydz = ((uc)_{i+\frac{1}{2},j,k} - (uc)_{i-\frac{1}{2},j,k}) \Delta y \Delta z$$

$$(uc)_{i+\frac{1}{2},j,k} = \frac{(uc)_{i,j,k} + (uc)_{i+1,j,k}}{2}, (uc)_{i-\frac{1}{2},j,k} = \frac{(uc)_{i,j,k} + (uc)_{i-1,j,k}}{2}$$

$$\int\int\int \frac{\partial vc}{\partial y}dxdydz = ((vc)_{i,j+\frac{1}{2},k} - (vc)_{i,j-\frac{1}{2},k}) \Delta x \Delta z$$

$$(vc)_{i,j+\frac{1}{2},k} = \frac{(vc)_{i,j,k} + (vc)_{i,j+1,k}}{2}, (vc)_{i,j-\frac{1}{2},k} = \frac{(vc)_{i,j,k} + (vc)_{i,j-1,k}}{2}$$

$$\int\int\int \frac{\partial wc}{\partial z}dxdydz = ((wc)_{i,j,k+\frac{1}{2}} - (wc)_{i,j,k-\frac{1}{2}}) \Delta x \Delta y$$

$$(wc)_{i,j,k+\frac{1}{2}} = \frac{(wc)_{i,j,k} + (wc)_{i,j,k+1}}{2}, (wc)_{i,j,k-\frac{1}{2}} = \frac{(wc)_{i,j,k} + (wc)_{i,j,k-1}}{2}$$

$$\int\int\int \frac{\partial}{\partial x}\kappa\frac{\partial c}{\partial x}dxdydz = k \Delta y \Delta z \left(\left(\frac{\partial c}{\partial x}\right)_{i+\frac{1}{2},j,k} - \left(\frac{\partial c}{\partial x}\right)_{i-\frac{1}{2},j,k}\right)$$

$$\left(\frac{\partial c}{\partial x}\right)_{i+\frac{1}{2},j,k} = \frac{c_{i+1,j,k}-c_{i,j,k}}{\Delta x}, \left(\frac{\partial c}{\partial x}\right)_{i-\frac{1}{2},j,k} = \frac{c_{i,j,k}-c_{i-1,j,k}}{\Delta x}$$

$$\int\int\int \frac{\partial}{\partial y}\kappa\frac{\partial c}{\partial y}dxdydz = k \ \Delta x \Delta z \left(\left(\frac{\partial c}{\partial y}\right)_{i,j+\frac{1}{2},k} - \left(\frac{\partial c}{\partial y}\right)_{i,j-\frac{1}{2},k}\right)$$

$$\left(\frac{\partial c}{\partial y}\right)_{i,j+\frac{1}{2},k} = \frac{c_{i,j+1,k}-c_{i,j,k}}{\Delta y}, \left(\frac{\partial c}{\partial y}\right)_{i,j-\frac{1}{2},k} = \frac{c_{i,j,k}-c_{i,j-1,k}}{\Delta y}$$

$$\int\int\int \frac{\partial}{\partial z}\kappa\frac{\partial c}{\partial z}dxdydz = k \ \Delta x \Delta y \left(\left(\frac{\partial c}{\partial z}\right)_{i,j,k+\frac{1}{2}} - \left(\frac{\partial c}{\partial z}\right)_{i,j,k-\frac{1}{2}}\right)$$

$$\left(\frac{\partial c}{\partial z}\right)_{i,j,k+\frac{1}{2}} = \frac{c_{i,j,k+1}-c_{i,j,k}}{\Delta z}, \left(\frac{\partial c}{\partial z}\right)_{i,j,k-\frac{1}{2}} = \frac{c_{i,j,k}-c_{i,j,k-1}}{\Delta z}$$

After substitution of the individual parts back into Eq. 4-23 and further rewriting, the total discretized convection – diffusion equation is adjusted to the following:

$$c_{i,j,k}^{n+1} = c_{i,j,k}^{n} - \frac{\Delta t}{2\Delta x}\left((uc)_{i+1,j,k} - (uc)_{i-1,j,k}\right) - \frac{\Delta t}{2\Delta y}\left((vc)_{i,j+1,k} - (vc)_{i,j-1,k}\right)\big) - \frac{\Delta t}{2\Delta z}\left((wc)_{i,j,k+1} - (wc)_{i,j,k-1}\right) + \frac{k\,\Delta t}{(\Delta x)^2}\left(c_{i+1,j,k} - 2c_{i,j,k} + c_{i-1,j,k}\right) + \frac{k\,\Delta t}{(\Delta y)^2}\left(c_{i,j+1,k} - 2c_{i,j,k} + c_{i,j-1,k}\right) + \frac{k\,\Delta t}{(\Delta z)^2}\left(c_{i,j,k+1} - 2c_{i,j,k} + c_{i,j,k-1}\right) \qquad \text{Eq. 4-24}$$

The discretization scheme belongs to a collocated grid, as discussed earlier. Results appeared to be unstable after a first series of tests due to undesirable oscillations. Oscillating around a value or checkerboarding is a common cause for unrealistic pressure and concentration fields.

A number of alternatives are available to prevent oscillations and negative concentrations and an upwind scheme is ultimately chosen and implemented. The approach involves evaluation of convective cell face fluxes depending on the direction of the prevailing velocity field (current). The upwind scheme takes the cell boundary flux equal to the flux generated in the cell upstream.

Discretization of the upwind scheme is as follows:

Case $u_{i,j,k} \geq 0$

$(uc)_{i+\frac{1}{2},j,k} \approx (uc)_{i,j,k}$ $\qquad$ $(uc)_{i-\frac{1}{2},j,k} \approx (uc)_{i-1,j,k}$

Case $u_{i,j,k} < 0$

$(uc)_{i+\frac{1}{2},j,k} \approx (uc)_{i+1,j,k}$ $\qquad$ $(uc)_{i-\frac{1}{2},j,k} \approx (uc)_{i,j,k}$

Case $u_{i,j,k} \geq 0$

$(vc)_{i,j+\frac{1}{2},k} \approx (vc)_{i,j,k}$ $\qquad$ $(vc)_{i,j-\frac{1}{2},k} \approx (vc)_{i,j-1,k}$

Case $u_{i,j,k} < 0$

$(vc)_{i,j+\frac{1}{2},k} \approx (vc)_{i,j+1,k}$ $\qquad$ $(vc)_{i,j-\frac{1}{2},k} \approx (vc)_{i,j,k}$

Case $u_{i,j,k} \geq 0$

$(wc)_{i,j,k+\frac{1}{2}} \approx (wc)_{ij,k}$ $\qquad$ $(wc)_{i,j,k-\frac{1}{2}} \approx (wc)_{i,j,k-1}$

Case $u_{i,j,k} < 0$

$(wc)_{i,j,k+\frac{1}{2}} \approx (wc)_{i,j,k+1} \qquad (wc)_{i,j,k-\frac{1}{2}} \approx (wc)_{i,j,k}$ Eq. 4-25

Application of the upwind scheme is a relatively facile approach to prevent oscillating/checkerboard effects occurring in flow parameters and negative values for the concentration. The method is implemented to be able to better check consistency in results.

Stability of an upwind system requires the Courant Friedrichs–Lewy (CFL) to be lower or equal to one (Eq. 4-26).

$\sigma = a\frac{\Delta t}{\Delta x} \leq 1$ Eq. 4-26

a	Velocity magnitude
Δt	Time step
Δx	Space step (vertical space step Δz will define the limit, as it is the smallest)

A rough first estimation based on a depth of 50 metres, 20 cells in vertical direction and maximum velocity of 5 m/s yields a maximum timestep of approximately 0.5 sec.

The current approach already uses a Rhie – Chow interpolation alternative to prevent alternation. Rhie–Chow interpolation is a commonly used method in CFD calculations on a collocated grid and aims to suppress non-physical pressure oscillations arising from checkerboard effects (Zhang, 2013). Non-physical values for the concentration are checked every time step and corrections are processed through the grid. This is done by redistributing concentration based on relative weight of surrounding grid cells.

Sedimentation with an open bottom

The model now supports sediment flows in a reservoir. The concentration of sediment blurs through convection and diffusion. Gravity effects are considered with the Boussinesq approach for low concentrations. The Boussinesq approach is not valid for higher concentrations, which is one of the reasons why the model is not suitable to simulate morphodynamical changes in a reservoir.

Still, the model now offers insight in the sedimentation process. Concentrations develop throughout the reservoir and results show the distribution of sediment, both tabulated and visually in plots. Since higher concentrations are not desirable and actual sedimentation (soil growth) is not supported, a solution needs to be found for aggregating particles at the bottom. The simplest alternative (with lowest validity) is to check the bottom of the reservoir for sediment each timestep. If sediment then has reached the bottom, it is immediately removed from the reservoir and added to a separate two-dimensional (m*n) matrix [Agg]. After the simulation, all the sediment is stored in that particular matrix and the concentration at the bottom in the simulated reservoir remains zero. Disadvantage of this method is that the density in the bottom cells always remain low ($\rho_w \cong 1000$), which affects the Boussinesq results. Concentration differences may be higher and particles reach the bottom faster.

The second alternative to track sedimentation is to consider the reservoir bottom open and sediment leaves the reservoir through the bottom, as it were. This method still keeps track of sedimentation rates; after sediment leaves the bottom, it is stored in the aforementioned matrix [Agg]. Sediment at the bottom falls through the bottom at settling velocity (details of settling velocity available section 4.2.4). The boundary condition and equation at the bottom are provided below:

The concentration at the bottom of the reservoir is set equal to the concentration in the centre of that particular cell:

$$c_{i,j,k-\frac{1}{2}} = c_{i,j,1} \qquad \text{Eq. 4-27}$$

$$(wc)_{i,j,k-\frac{1}{2}} = c_{i,j,1} * w_0\left(1 - c_{i,j,1}\right)^n \qquad \text{Eq. 4-28}$$

Once sediment has passed the bottom, it can no longer re-enter the reservoir. Morphological modelling is explicitly not included, but the matrix [Agg] can be an important step in future research to evaluate the bottom development during simulation.

4.2.4. River mouth and sluice gate

The river mouth and sluice gate are the only simulated in- and outlet respectively. This section deals with imposed preconditions and shows the discretization used in the program.

Considerations at the river mouth

Different modes of sediment transport are possible in river systems. The two most common types of sediment transport are bed-load transport and suspended transport. A third type is wash load sediment transport.

- The bed load regime is characterized by transport through the current in a river but in which moving sediment particles have on and off contact with the riverbed. The particles are in fact making small jumps from the bed.
- Suspended sediment transport is in general the most important type of sediment transport. Suspended particles are transported by the current and at the same time affected by its settling velocity. It refers to the particles that are continuously entrained in the middle zone of the water column (Texas Commission on Environmental Health, N/A).
- Wash load sediment transport is a specific part of sediment transport, containing smaller size particles. It is in near-permanent suspension and, therefore, is transported through the stream without deposition (Van Rijn L. , 1986).

A complex combination of parameters and processes influence the development of a streambed. This includes concentration, type/mixture (size/shape) of particles in the fluid, sedimentation, and pick up. A short description of these factors follows below.

2. Concentration of sediment particles: the settling velocity of a particle is directly influenced by the concentration and follows a negative function (Richardson, 1954).

$w_s = w_0(1-c)^n, n = \frac{4.7+0.41Re_p^{0.75}}{1+0.175\ Re_p^{0.75}}$ Eq. 4-29

The effect of hindrance is smaller for coarser particles due to a higher Reynolds number. The hindrance velocity is shown in Eq. 4-29.

3. The composition of a mixture with different particle sizes has impact on the settling velocity. Finer materials tend to settle slower or can even show negative settling velocities (particles moving upward). This is caused by return flow due to settling of coarser particles. The return flow is under certain circumstances (for example a relatively high concentration of coarser material and lower concentration with fine material) enough to push up finer material.

4. Sedimentation velocity: sedimentation can change the depth of a river or reservoir in the long term and therefore changes the bathymetry and flow parameters.

5. Pick-up can affect the morphology in a reservoir. Particles are entrained from the bed into a flow when the bed shear stress exceeds a certain threshold, also known to happen at a certain critical velocity. Pick up is also a function of bed vegetation and can result in the forming of channels or aggregation elsewhere.

A resulting sediment transport mode is complex to predict and a quantitative pick-up function will not be included in the model. On the other hand, a representation of the vertical concentration distribution at the river mouth will be included and the specification of sediment discharge in the reservoir is as follows.

Seasonal discharge

The discharge of sediment in the river is held constant during the simulation. This can be assumed as the simulation time is short compared to a seasonal peak period. A seasonal peak period (active period) typically takes a few months, volumetric discharge during the remaining months is significantly less. The length of this period usually depends on freezing and thawing cycle, precipitation patterns and soil characteristics of the river basin.

The approach to include seasonal discharge patterns is as follows.

- The total annual discharge Q_{ann} is an imposed condition and constant during a reservoir life. The upstream river will transport sediment during the active period only.
- A discharge rate ratio (R_d) between active P_a and passive period P_d is set; Specification of R_d is reviewed below.
- The active period P_a with higher discharge rates allows sediment transport, the passive period P_p on the other hand is without sediment transport.

The discharge rate during the active period can be determined now.

$$q_a = \frac{Q_{ann}}{P_a + \frac{12 - P_a}{R_d}} \quad \text{Eq. 4-30}$$

Eq. 4-30 defines the discharge rate during the active period, q_a. Specification of the seasonal parameters is discussed next.

The total amount and variation in discharge is a unique property for reservoirs, differences between continents alone are very large (Figure 4-10).

For example, the Volgograd reservoir capacity is 31.5 km^3. Long term discharge of this reservoir is shown in Figure 4-9. It is clear that peak flow periods influence flow velocities significantly, the total annual discharge in Volgograd is approximately 330 km^3 (based on mean monthly discharge, Table 4-1). This means that discharge is approximately 10 times the total reservoir capacity for the Volgograd example. Discharge in relation to reservoir capacity strongly depends on climate and reservoir basin. This example of Volgograd reservoir is probably relatively high. Areas with lower precipitation or smaller basins can have an annual discharge approximately equal to the reservoir gross capacity. Based on the example and seasonal discharge characteristics globally, a mean total annual discharge is set at 5 times the reservoir capacity. Again, development of hinterland and erosion are external effects and can change the estimated values significantly.

Assumption 4-B

- Seasonal flow often entails that a bimodal flow pattern can be identified; an active period with higher discharge and sediment supply and a passive period without sediment supply and lower discharge.
- The active period is especially important for establishing sedimentation and aggregation in a reservoir. The total annual sediment supply is defined earlier (appr. 1%). Distribution of supply is defined as follows (based on a rough estimation with Figure 4-8 Figure 4-10):
  - Sediment supply only in active period, in 4 months total annual sediment supply;
  - Discharge in active period approximately 2 times higher than in the passive period.
  - Final evaluation of inlet velocity during active period is based on the presumed relation between discharge and reservoir storage capacity.

Table 4-1: Monthly discharge of Volgograd

Month	Discharge $[m^3.s^{-1}]$
Jan	6
Feb	5
Mar	4
Apr	5
May	10
Jun	25
Jul	25
Aug	15
Sep	8
Oct	7
Nov	8
Dec	8
Mean	10.5

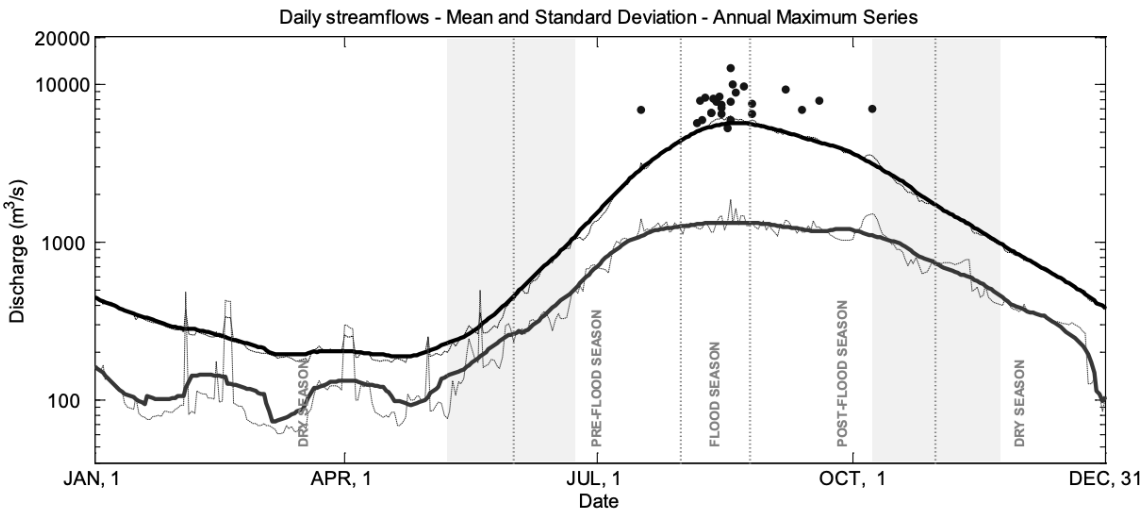


Figure 4-8: Example of Seasonal flow in Volgograd (Baratti, 2012)

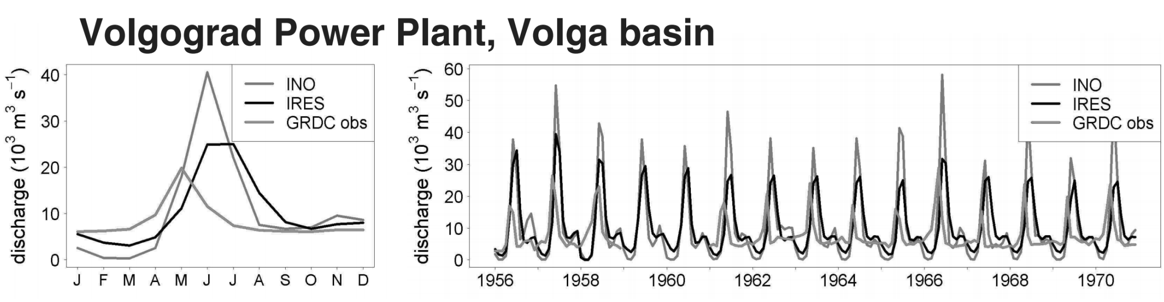


Figure 4-9: Long term discharge variability for a number of reservoirs (Biemans, 2011), Volgograd reservoir shown

A possible improvement for future research could be to introduce a seasonal gradual variation in concentration at the inlet (Peak discharges). While the variables are now dichotomous, it is much more likely that a discharge grows and declines step by step or at least a finer approximation of a gradual change. The discharge properties of the active period (instead of passive period) are used since this has been the only period with sediment supply. The standard seasonal settings indicate that the total discharge during the active period is approximately equal to the total discharge during the passive period.

The discharge rate, q_a, is known now and gives a rough estimation about the sedimentation in a reservoir. The next step is to implement a realistic concentration distribution over the vertical water column at the river mouth.

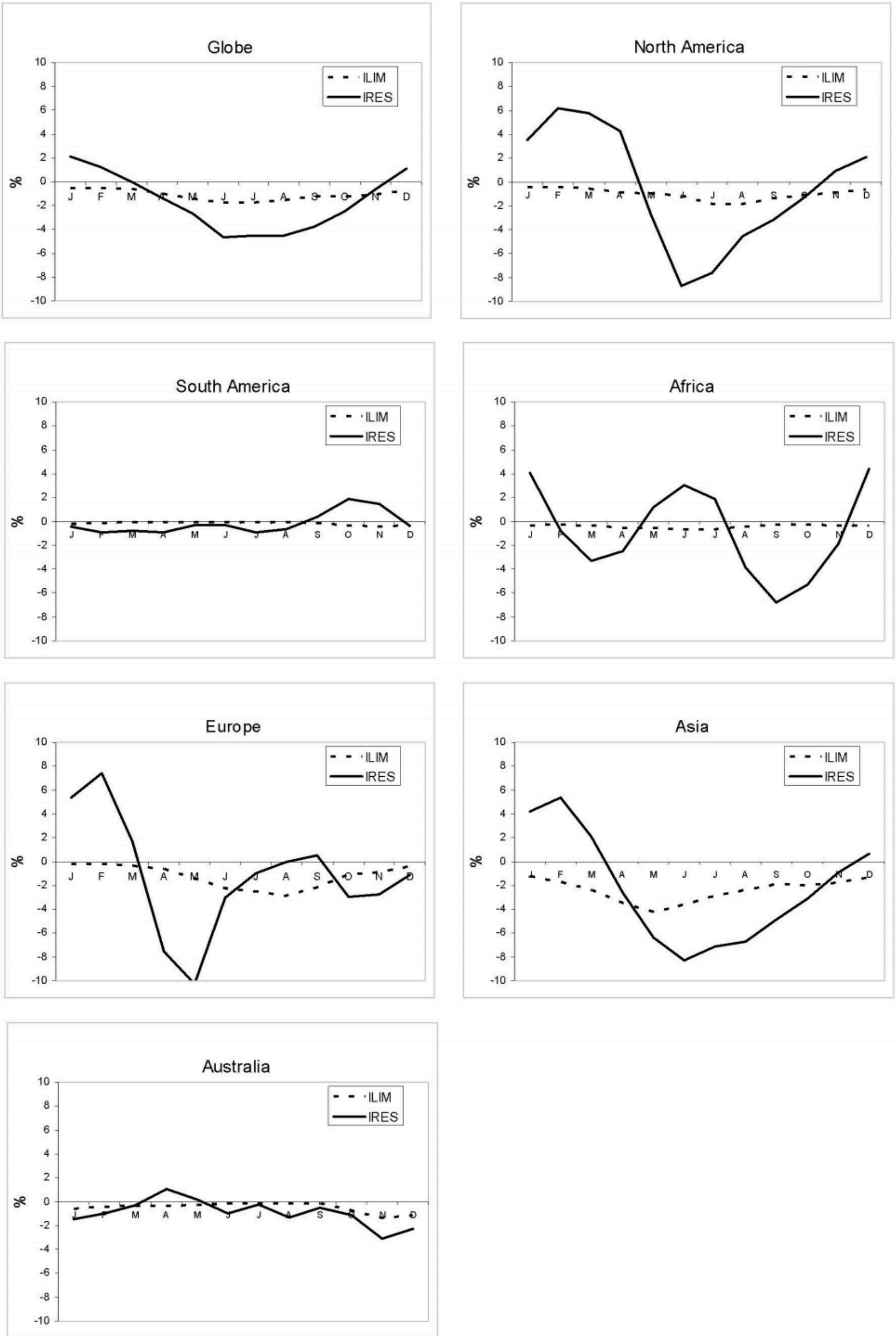


Figure 4-10: Seasonal river discharge across continents. (Biemans, 2011)

Vertical concentration distribution

The particle size distribution is assumed constant and narrow during a simulation. The vertical concentration profile at the inlet is modelled with a Rouse profile and can be seen as a balance between sediment settling and upward sediment diffusion from turbulence (Eq. 4-32). Table 4-2 and Figure 4-11 show the effect of the use of different values for Rouse number *P*. In the CFD simulation, the rouse distribution is only used as an artificial distribution at the inlet. It can be changed manually, but does not automatically correct for changes in velocity, particle size or other influential parameters.

Table 4-2: Modes of transport and values for Rouse number

Mode of Transport	Rouse Number, P
Bed load	>2.5
Suspended load: 50% Suspended	>1.2, <2.5
Suspended load: 100% Suspended	>0.8, <1.2
Wash load	<0.8

The Rouse number is determined as the ratio between the settling velocity and the production of the *von Karmann* (κ) constant and the shear velocity (u_*), see Eq. 4-31.

$$P = \frac{w_s \cdot \sigma}{\kappa \cdot u_*} \qquad \text{Eq. 4-31}$$

$$w_s * c = -K_s \frac{dc}{dz}, with\ K_s\ the\ diffusivity \qquad \text{Eq. 4-32}$$

The diffusivity is parabolic for the Rouse concentration profile where the concentration ultimately follows the following relationship (Memorandum, 1988), (Environmental Hydraulics, N/A):

$$\frac{c}{c_a} = \left(\frac{H-z}{z} * \frac{z_a}{H-z_a}\right)^{\frac{w_s\sigma}{ku_*}} \qquad \text{Eq. 4-33}$$

$$w_s = w_0(1-c)^n, w_0 = \frac{\Delta g d^2}{18*\upsilon+\sqrt{0.75*\Delta g d^3}} \qquad \text{Eq. 4-34}$$

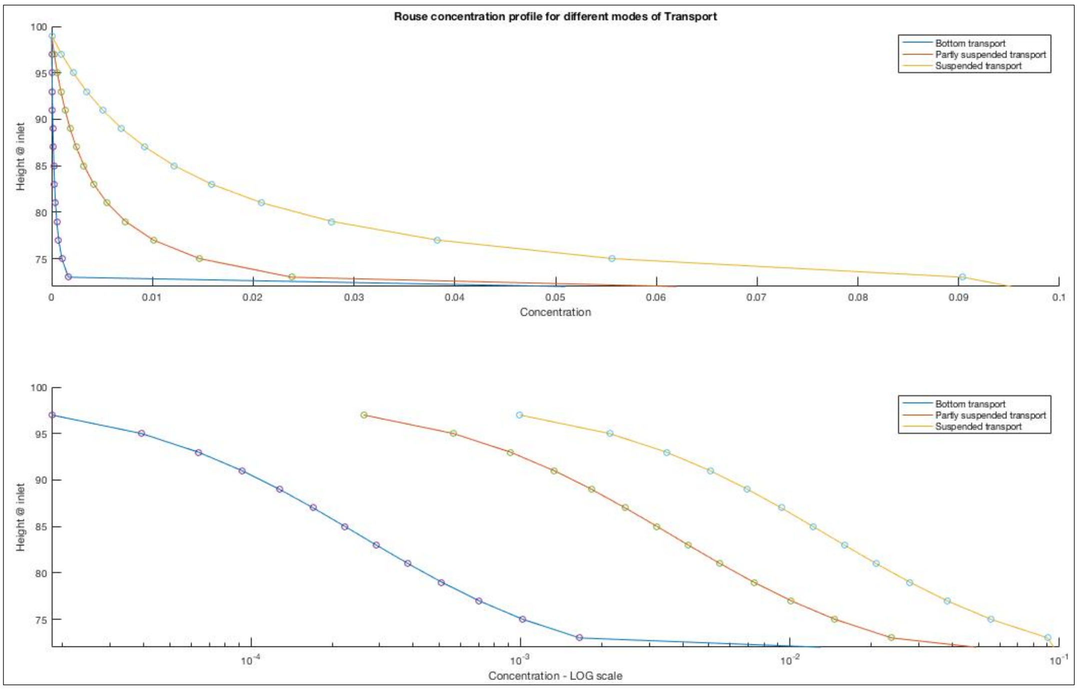
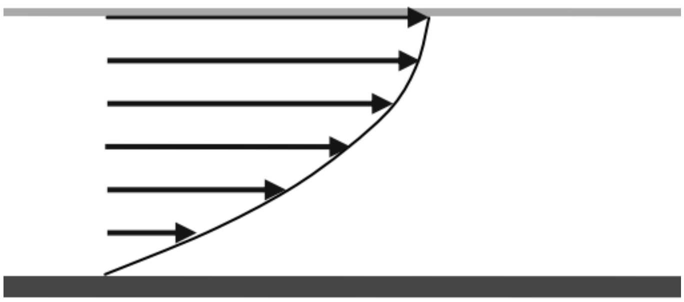


Figure 4-11: Rouse profile

The velocity at the river mouth is set non-zero positive in *x*-direction and zero in *y*- and *z*-direction. As discussed earlier, the velocity in *x*-direction is held constant during the simulation and based on the discharge rate in the active period, q_a. Similar to the vertical concentration distribution, the horizontal velocity at the inlet (u_i & $i=1$) profile in Z direction is also not uniform and implemented as follows (Fowler, 2012):

$$u_i\left(\frac{1}{2}, j, k\right) = \frac{\rho g \theta}{2}\left((k - in_{startk} + 1) * \frac{H_u}{r_u}\right)\left(2H_u - \frac{H_u}{r}(k - in_{startk} + 1)\right) \qquad \text{Eq. 4-35}$$

$$\theta = \frac{2q_a}{H_u W_u}\left(\frac{1}{\rho_w g H_u r_u}\right) \qquad \text{Eq. 4-36}$$



- Bottom slope $[\theta]$, in order of magnitude 10^{-5} near the reservoir.
- Density $[\rho]$, in order of magnitude 10^3, including variation due to Rouse distribution.

Considerations at sluice gates
The one outlet simulates the sluice gates. The horizontal velocity at the outlet *(i = m)* is set as follows:

$$u\left(i+\frac{1}{2},j,k\right)=u(i,j,k) \quad \text{Eq. 4-36}$$

The pressure at the outlet is equal to the ambient/atmospheric pressure.

4.3. Long term sedimentation

The CFD model generates initial results about velocity and concentration profiles in the reservoir. These results are now used to make an assessment about sedimentation over a reservoir life span. Application of sediment management will follow in chapter 5. The CFD simulation time is short, since it is still limited due to potential explosions in results and computing power. The resulting XY concentration distribution at the bottom is now input in a simple time series to acquire the total sediment aggregation over a longer period or essentially a reservoir life span.

Sediment aggregation or morphodynamical response to sediment trapping in the reservoir is not a uniform process. On the contrary, it depends on a large number of variables and often with wide ranges around the mean. It is important to note that the CFD model is not able to recognize morphodynamical response and only very rough morphodynamical changes will be included in the next timeseries. In reality, aggregation of sediment in the reservoir can lead to bed patterns, for example dunes and humps. This and other effects change turbulence and flow patterns in the reservoir. Therefore, it is of great importance to note that the CFD is an important and useful tool in assessing sediment aggregation, but observations can differ significantly from results based on the theoretical framework in this research. Additionally, the period in which sediment management is possibly performed, changes the bottom development noticeable.

The resulting total aggregation, after adjusting the time horizon from CFD simulation to reservoir lifespan is determined as follows:

Net sedimentation flux:

$$\Delta S = S - E \quad \text{Eq. 4-37}$$

S	sedimentation flux	$\left[\frac{kg}{m^2s}\right]$
E	erosion flux	$\left[\frac{kg}{m^2s}\right]$

The erosion is assumed negligibly small, the sedimentation flux is therefore the only normative parameter. The CFD model results in a matrix [*agg*] with *m X n* cells with the concentration in *XY* direction at the bottom. The sedimentation flux at the bottom is determined in Eq. 4-38.

$S(i,j) = \frac{\rho_s \cdot agg(i,j)}{t_{CFD}}$ Eq. 4-38

t_{CFD}	simulation time	$[s]$

The sedimentation height can now be determined.

$H_{sed}(i,j) = \frac{S(i,j)}{\rho_s \cdot (1-n_o-c)} \cdot 365 \cdot 24 \cdot 3600 \cdot T_{lifespan}$ $[m]$ Eq. 4-39

n_o	porosity of soil in situ ≈ 0.4	$[-]$
c	concentration, assumed ign. small	$[-]$
T_{end}	reservoir lifetime	$[Years]$

By subtracting the dead storage level from the sedimentation height, it gives immediately insight how much and in what locations sediment can be deposited without later issues regarding aggregation at those specific locations. The above makes it possible to evaluate the sedimentation velocity in the reservoir.

$v_{sed}(i,j) = \frac{S(i,j)}{\rho_s \cdot (1-n_o-c)}$ Eq. 4-40

The extension from the CFD simulation time to a reservoir life span involves some issues. The CFD model checks each timestep if sediment reaches the bottom part of the reservoir. Sediment at the bottom then *seeps* through at settling velocity and is stored in the matrix that keeps track of the aggregation at the bottom of the reservoir. This approach in combination with the overall CFD approach can lead to an unrealistic small area with noticeable sedimentation effects. Extending this to the reservoir lifespan also leads to unrealistic sedimentation heights and locally extreme bottom slopes. A number of alterations are introduced to obtain plausible sedimentation results:

- The bottom must comply with the critical angle of repose for the soil in-situ;
- Dredging activities are evaluated per grid cell (m X n) and carried out by a maximum of one dredger at the time per grid location. This is enough for most reservoirs, it offers enough capacity up to large reservoirs (>10,000,000 m^3) with normal sedimentation rates.
- Sediment heights cannot exceed the bottom of the upstream river mouth, unless the reservoir is filled in every location up to this level.

Table 4-3: angle of repose for different types of soil

Type of soil	**Angle of repose**
Clay	15
Silt	20
Sand	25
Gravel	30
Boulders	45

Flushing as passive sediment management
The applicability of flushing in reservoirs depends primarily on the average grain diameter of the sediment and annual discharge. Flushing is usually performed through special bottom gates, as shown in Figure 4-12.

The major issue with flushing at high concentrations is the negative impact on the downstream ecology. Acceptable low concentrations must be guaranteed to prevent external effects. Flushing at higher concentrations (for example approx. 15 gr. l^{-1}) cannot carried out longer than 30 minutes at the time. On the other hand, flushing at low concentrations (up to approx. 5 gr. l^{-1}) can be maintained for extended periods (Compagnie centrale du Rhone, 2008). If such rates can really be maintained for longer period is still questionable. It requires a balanced flushing process and it still depends on the capacity of a case specific downstream river or ecological system.

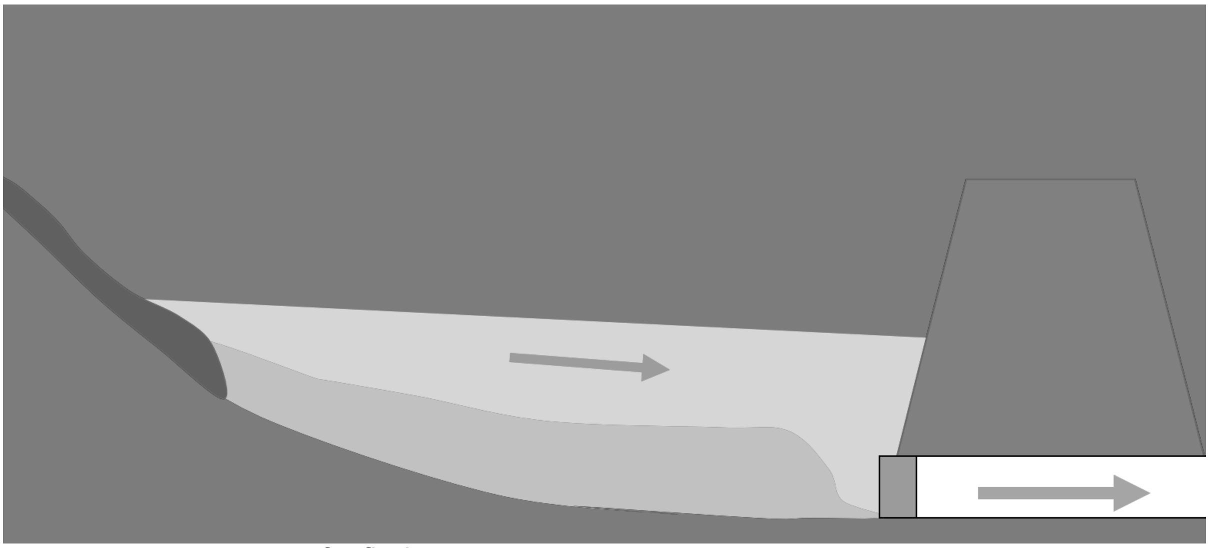


Figure 4-12: Bottom gates for flushing

Assumption 4-D

- It is assumed that an annual discharge of at least equal to the gross reservoir storage is available for flushing;
- Building on the annual available discharge and a maximum average concentration of 5 gr. l^{-1} (SEE Hydropower, 2000) in the flushing discharge, the sediment rate is brought down by 0.2 percent. This is the case for a total annual discharge of 10 times the gross reservoir capacity;
- The combination of an average sedimentation rate of approximately 1 percent per year, means a residual sedimentation rate of 0.8 % per year after flushing;
- The discharge available for flushing is evaluated in the NPV model, along with other purposes of discharge (irrigation/industrial, drinking water, hydropower generation);
- Flushing is not considered feasible for rock or gravel.

The results of previous modelling approaches now enable to analyse whether or not sediment management is favourable for environment and economic functioning of a reservoir. The next chapter deals with assessing the feasibility of various dredging and flushing methods. The final step in assessing the overall performance of a reservoir and the expediency of dredging methods is to implement all results in a net present value analysis or cost benefit model.

5. Dredging process and cost model

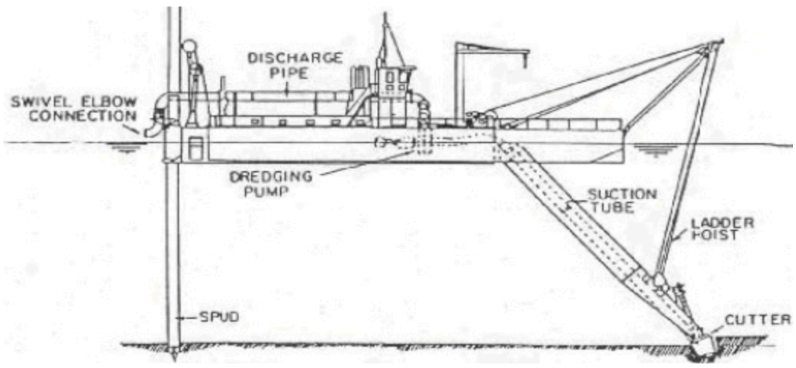
The technical feasibility of dredging methods under comparable circumstances are essential. Identification of dredging methods will partly elaborate on the findings of (Elzinga, 2017). Elzinga defines a number of feasible methods and analyses production costs. The different dredging methods will be introduced next, Table 5-1 shows general technical specification of the dredging alternatives. The approach to evaluate sediment management (dredging) will be discussed subsequently and finishes with a cost and benefit analysis.

5.1. Dredging methods

The considered technical feasible methods are shown in the list below. Feasibility mainly depends on the dredging depth and transportation options. Reservoirs are often located in remote areas and alternatives below are either limited in size or can be divided into transportable modules.

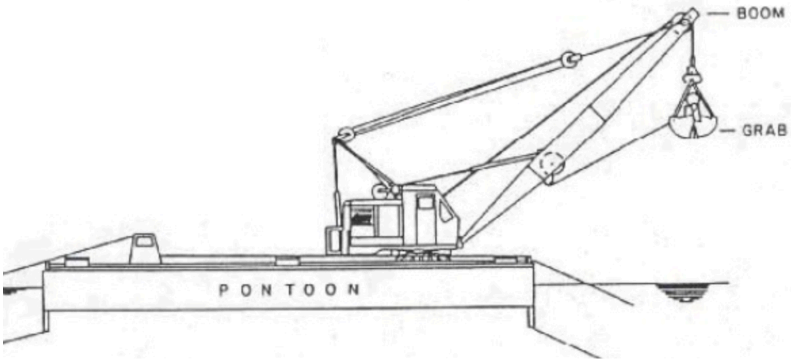
1. (Plain) Suction dredger (SD)
   Based on suction under water only, no rotating cutter heads applied. At first sight in particular interesting for settled sediment such as gravel, sand, clay, silt and other minerals (Vlasblom, 2003). Rock and other hard materials are less easily dredged by the plain suction dredger.

2. Cutter suction dredger 1 (CSD 1) (510 m^3/hr, 868 kW);
   Cutter suction dredgers have the ability to dredge nearly all kinds of soils. Cutter heads are applied for cutting of harder and larger soils and rock (IADC Dredging, N/A).

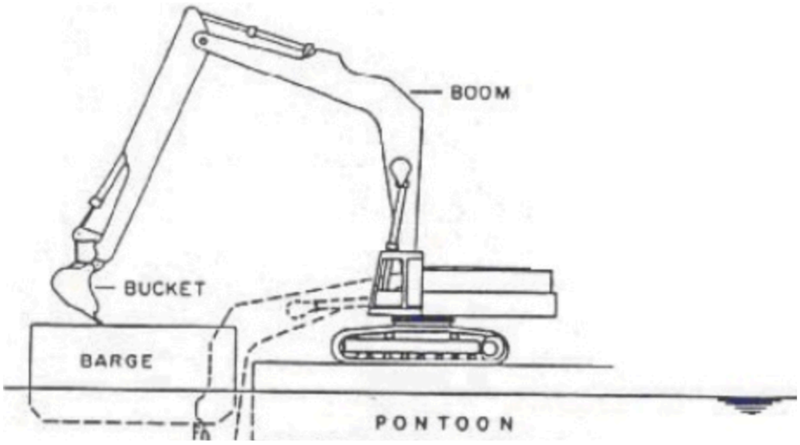


3. Cutter suction dredger 2 (CSD 2)
   (1433 m^3/hr, 1825 kW) Same method, larger production capacity to a limited depth. Cutter suction dredgers are available in different sizes and can be produced in a standardized way. An example for this is the IHC Beaver.

4. Grab/clamshell dredger (GD)
   A Clamshell Dredge picks up seabed material with a clamshell bucket. This type of dredging always includes a barge or comparable structure. The barge functions as base for the crane and has a cargo hold for dredged material (IHC, 2017).



Backhoe dredger (BD)
   The backhoe dredge is a stationary floating type of dredging, anchored by three spuds. A backhoe crane is positioned on a barge and removes sediment from the bottom. This type of dredging is limited to about 18 metres depth, based on crane characteristics from (Dredging.org, N/A), (FAO, N/A).



5. Submersible Pump DOP (SP)
   DOP pumps are compact submersible pumps dedicated to slurry transport (often hanging from an excavator boom). Flexible method in terms of size of equipment and maximum dredging depth (Damen, 2019). A system can be equipped with water injection or a cutter head, depending on soil characterics.

6. Water injection dredge (WID) This type of dredging is based on a series of nozzles on a horizontal jet bar injecting large volumes of water at low pressure to fluidize the sediment (Van Oord, 2019).

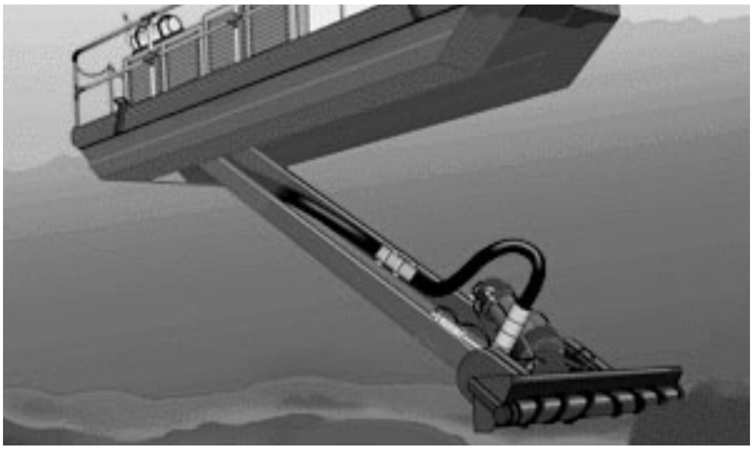


Table 5-1: Production properties dredging methods

Method	**Max. depth [m]**	**Transport mode**	**Capacity [m^3/hour]**	**Power [kW]**
SD	60	Pipe	212	1300
CSD1	40	Pipe	510	868
CSD2	25	Pipe	1433	1825
GD	150	Barge	$\frac{3600}{\frac{2 \cdot \text{dredge depth}}{\text{winch speed}} + 40} \cdot \text{clamshell capacity}$	505
BD	18	Barge	$\frac{3600}{\frac{2 \cdot \text{dredge depth}}{\text{winch speed}} + 40} \cdot \text{buckethoe capacity}$	750
SP (DOP)	54	Pipe	487	500
WID	40	Pipe	$125 \cdot \text{boomlength}$	1500

Production efficiency of the grab and backhoe dredge highly depend on the particle size diameter and bucket fill factor. The backhoe is filled by a certain percentage, depending on particle size, see Table 5-2. Table 5-3 shows applicability of a method for different types of soil and associated efficiencies.

Table 5-2: Backhoe fill factor (CAT, N.A.)

Grain Diameter	**Min. [mm]**	**Max. [mm]**	**Backhoe fill factor**
Clay	0	0.002	0.95
Silt	0.002	0.06	0.95
Sand	0.06	2	0.9
Gravel	2	60	0.85
Boulders	60	-	0.8

Sediment is either transported to shore or transported to a deposit site in the reservoir. The decision if a deposit site in the reservoir is favourable largely depends on the sedimentation rate and the economic value of sediment. Moving sediment within a reservoir is in the long run not a viable alternative, since the objective is to extend the lifespan and reduce sedimentation.

Table 5-3: Dredging efficiency for different types of soil (particle size diameter)

	silt	sand	clay	gravel	boulder
SD	1	1	1	0	0
CSD1	1	1	1	0	0
CSD2	1	1	1	0	0
GD	0.8	1	1	0.6	0.6
BD	0.8	1	1	0.6	0.6
SP	1	1	1	0	0
WID	0.24	1	0.24	0	0

5.2. Sediment management

The model discussed so far gives insight in sedimentation development without dredging and the dredging methods under consideration are known from the last section. This section then follows with a description when and under what conditions sediment management (dredging) should be performed. The approach to determine dredging costs and ultimately indirect costs and benefits will be addressed in section 5.3.

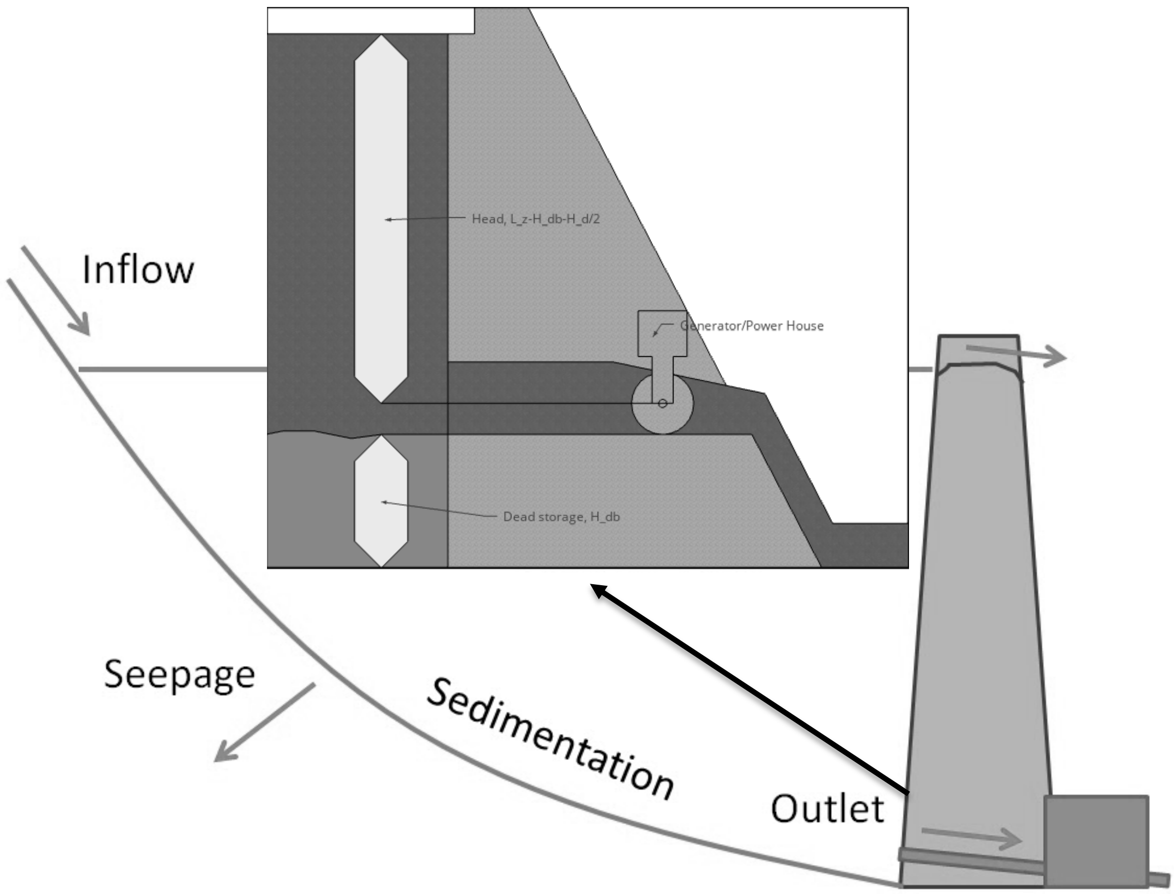


Figure 5-1: Schematic reservoir with dead storage and head

Figure 5-1 shows a schematic cross section of a typical reservoir (near the dam). The dead or inactive storage is defined as the part of the gross capacity that cannot be drained by gravity through the sluice gates in a dam. Hydropower generation is therefore not immediately affected by sedimentation and it takes a considerable amount of time to fill the dead storage. After some time and when sedimentation and the bottom height increase, the impact becomes observable in terms of a decline in hydropower generation (and other functions) output. Necessity of sediment management operations depends largely on the economic functions of a dam (DFID, 2009). Especially hydropower generation is primarily subject to sedimentation since the head becomes reduced over time (ICOLD, NA). Therefore, a threshold is defined which imposes a boundary condition on when to perform dredging or flushing activities.
The threshold is defined as the height of the bottom of the hydropower generation sluice gate, see Figure 5-1. When the sedimentation height reaches this threshold, sediment management will be carried out with the purpose to retain generation and other function efficiencies. The reservoir parameters and dredge method constraints lead to a number of technologically feasible dredging methods. This means that each of the seven predefined dredging methods is checked upon maximum dredging depth and applicable sediment grain size/type.

The minimum dredging depth that a method should be able to reach is defined as the height of the reservoir minus a predefined percentage of the dead storage level (standard 50 percent). The CFD output, combined with technical boundary conditions and feasibility restrictions will lead to possible alternatives to perform sediment management. The identified alternatives must then be analysed financially to determine the economic value of each. Sediment management implementation is determined according to the requirements above.

The selection of dredging methods is evaluated in the following stepwise manner.

1. Check all (7) dredging methods at minimum required depth.

$$D_m = L_z - (1 - eta_{min}) \cdot H_{db} \qquad \text{Eq. 5-2}$$

eta_{min}	minimum percentage of dead storage	[-]
D_m	minimum dredging depth	[m]
H_{db}	Dead storage level/base height sluice gate	[m]

2. Check applicability of remaining dredging methods at particle size in-situ, based on Table 5-3.

The remaining methods are considered feasible for the particular reservoir and are applied as such in the model. The next step is to review the development of sedimentation during the simulated lifetime when dredgers are deployed.

3. Check sediment height each week. Dredging takes place at all locations where sedimentation exceeds the dead storage height.
   Eq. 4-39 already showed the expected sedimentation height after a reservoir life span. The sedimentation height is now again determined, however with interim application of dredging activities. This then starts with Eq. 4-40 and a number of new variables are introduced:

   - Three-dimensional (size *[m,n,#feasible methods]* matrix representing the sedimentation height.

   $$H_{sedd}(i,j,method) = v_{sed}(i,j) * time \qquad \text{Eq. 5-3}$$

   H_{sedd} is evaluated each week and every time corrected for dredging activities. The dredge depth is equal to the smallest attainable dredging depth, with a maximum predefined percentage of the dredging depth. This will be set at 50 percent standard and stretched to 100 percent to review sensitivity.

   - Three-dimensional array representing dredging equipment.
   $dredge_{equipment}(week\ of\ purchase, last\ project\ start\ [week],$
   $last\ project\ duration\ [weeks], method)$

   Every time a new project needs to start the matrix $dredge_{equipment}$ is checked for available dredgers or a new dredger is added to the matrix. A dredger is available if not already engaged in a project and not older than the specified depreciation period (20-25 years, depending on the method).

   - Three-dimensional array representing support equipment.
   $dredge_{support}(week\ of\ purchase,\ method)$

   Every time a new dredger is added in $dredge_{equipment}$, $dredge_{support}$ is checked for the availability of sufficient support equipment. Not each dredger needs own workboats and tugs when sharing is possible. Support equipment is equipment (tugs, workboats, etc.) which is not constantly needed to produce, but necessary from time to time. It is assumed that four dredgers share one support unit.

   - Three-dimensional matrix representing the dredging activities.

   $dredge_{activities}(starttime, projectduration, location_i, location_j, dredgingmethod$
   $, dredgerID)$

   The matrix is filled every time when a location will be dredged. The matrix indicates whether a dredger is already underway and will be input for the CBA. The project duration is determined with the available estimated production capacity and efficiency/fill factor.

   Next to a prediction about sedimentation without dredging, a prediction is now available about the extent of sedimentation with dredging/sediment management. Moreover, it is now clear how much will be dredged to keep sedimentation between the desirable limits and it is clear over which period these operations are distributed.

The next section will discuss the resulting dredging costs, based on the introduced matrices above.

5.3. Dredging costs

The cost for dredging is divided into two types, namely capital expenses (CAPEX) and operational expenses (OPEX). The capital expenses CAPEX consists of dredging and support equipment. The OPEX consist of fuel, labour, transport and storage cost.

Table 5-4: Estimation of CAPEX cost per method

Method	Dredging eq. [M€]	Barge [M€]	Tug [M€]	Pipe/metre [€]	Workboat [M€]	Pontoon [M€]
SD	1	-	-	250	1	-
CSD1	1.5	-	-	250	1	-
CSD2	2	-	-	250	1	-
GD	4	2	2	-	-	1
BD	4.5	2	2	-	-	1
SP(DOP)	1.5	-	-	250	1	-
WID	4.5	-	-	250	1	-

The purchase cost of equipment, shown in Table 5-4, is based on a review of available dredging equipment online (dredgepoint, hollanddredgedesign) and findings of Elzinga (2017).
The first distinction regarding the purchase cost of dredging equipment is based on the mode of transport from dredging location to deposit location (shore). The grab dredge and backhoe dredge depend on transportation by barge, the other methods use a pipeline possibly with required boosters.

The number of tugs and barges or metres of pipeline for the two different modes of transport respectively depend on the distance between the dredging location and shore/deposit location. The average length from the dredge location to shore is evaluated as half of the total reservoir width. The distance may be longer in exceptional situations, resulting in temporary pipeline shortages. A shortage in pipelines at one dredger can be resolved by using temporary spares from other dredgers in the reservoir operating at a distance shorter from shore. The maximum distance that can be bridged by a pipeline is approximately two kilometres. Boosters make it possible to increase the distance. Each booster increases the maximum distance by two kilometres and no more than two boosters can be used for one pipeline. This is more than sufficient for most situations, assuming that discharge locations can be positioned flexibly along the side of a reservoir.

The number of barges needed is evaluated as follows:

$$required\ barges = \frac{2 \cdot \frac{offloading\ distance}{speed_{tug}} + offloading\ time}{\frac{barge\ capacity}{productionrate}} \quad \text{Eq. 5-4}$$

The depreciation time is estimated at 25 years for the backhoe dredge and grab dredge and 20 years for the other methods. Support equipment depreciates in 25 years. Equipment can potentially have a longer lifespan, but this number defines annual deprecation without ambiguity.

Table 5-5: Units of labour and fuel consumption per method. Other operational expenses are equal.

Method	Dredging [labour un.]	Support [labour un.]	Fuel l/hour
SD	2	2	348
CSD1	2	2	232
CSD2	2	2	489
GD	2	1	135
BD	2	1	201
SP(DOP)	2	2	134
WID	2	2	402

The first two terms on the right-hand side of Eq. 5-5 above come directly from Table 5-5. The *average workweek* is set at 70 hours per week, while *income* is the estimated normal fulltime (40 hours/week) salary per month. Assumed is that sediment is transported to shore through pipelines or by barges or transported to a deposit site in the reservoir. The decision whether a deposit site in the reservoir is more favourable than transporting sediment to shore depends on the sedimentation velocity and economic value of sediment. Sediment dredging and dumping at another location within a reservoir is in the long run only moving the problem. The option would be viable only if the reservoir has a large unused area which does not affect the productivity of the reservoir.

The operational expenses are simplified to two cost items, labour and fuel. The amount of labour is estimated based on the type of dredging and type of transport (pipeline or barge). Fuel consumption is based on the power of the equipment (Table 5-5)

Labour cost per dredger is evaluated as follows:

$$cost_{dredge,labour} = \left(labour_{dredge} + \frac{labour_{support}}{\#dredges/supportunit}\right) \cdot \frac{avg\ workweek}{40} \cdot income \quad \text{Eq. 5-5}$$

The fuel cost is calculated as the average price per litre fuel multiplied by the fuel consumption (Table 7-9). Remaining operational expenses are the storage/transfer cost and sediment transport cost on shore. Both cost items are independent on type of dredge method and effectively depend on the supply of sediment from dredging activities and the surface area size of the reservoir (causing transport to be longer or shorter than averaged).

The cost expectation of dredging will be presented separately from indirect effects and reservoir yields. The next chapter will discuss the cost-benefit analysis approach. This includes reservoir construction and maintenance costs, functional yields, direct and indirect sediment management effects and external effects.

6. Monetized performance of reservoirs - CBA

A considerable number of variables influence the real value of sediment management alternatives. Each alternative has (dis)advantages considering both environmental and financial performance. A financial analysis is developed to analyse all feasible alternatives with combination of reservoir input variables. The cost-benefit analysis (CBA) is based on the interim results from the sedimentation predictions. The main goal of the CBA is to determine which alternatives are economically and environmentally altogether most valuable.

Various alternatives are compared within the analysis:

- Dredging and transport to shore.
  This alternative has a great potential to mitigate external effects. The alternative is characterized by high dredging and transportation costs compared to flushing or depositing sediment elsewhere in the reservoir. Benefits include available sediment that can be used for different purposes, depending on the soil characteristics. If soil is valuable, dredged material can partially compensate for the direct cost of sediment management/dredging.
- Dredging and dumping elsewhere in the reservoir.
  Sediment would not have to be transported to shore and therefore could not be used for any purpose. Extending the life of a reservoir is only possible if dredged material can be dumped in parts of the reservoir that are not in use. The current model is not able to recognize vacant parts in the reservoir, hence does not provide an extension of the reservoir life span.
- (Dredging and) Flushing.
  In the past, flushing was a favourable solution for the removal of trapped sediment. Negative external effect on ecological systems downstream were not always reviewed. Regular consequences of flushing are too high sediment concentrations downstream and abrupt changes in suspended sediment transport. This can lead to high mortality rates in (migratory) fish populations and in a strong decline in biodiversity. Flushing in the end leads to a decline in sediment aggregation in the reservoir. Sediment cannot be used for any purpose after flushing and may endanger the downstream ecology.

Determination of future policy for a reservoir depends on some important indirect effects coupled to sediment management:

- Usability of sediment.
  Sediment can be valuable for construction, agriculture and ecological purposes. This depends largely on the soil characteristics. Specification of the usability and value of sediment is discussed in section 6.4.
- Negative external effects.
  External effects are largely due to lack or excess of sediment supply and change in seasonal supply to downstream ecological systems. As a consequence, the ecological status downstream is often classified as poorly or bad. (Schmutz, S.). Land degradation can occur both upstream and downstream. Quantification into the financial analysis follows in the next sections.

Then there are the main drivers of a reservoir of course. Yields and costs of general reservoirs operations will be included too and will be discussed next.

6.1. General approach

The ultimate objective of this research is to get to know more about the long-term value of reservoirs and the economic effects of sediment management. In the past, damages done to the environment and especially done to ecological systems downstream were not always considered important. Awareness creation about negative external effects and sedimentation issues comes step by step. Research starts to focus more toward external effects on ecological systems and change of the local biodiversity. The net result of operations and external effects together are complex to accommodate in one model. In many cases, external effects are not standard market priced products and must be monetized to be able to compare on a financial basis.

Cost-benefit modelling (CBA) is a methodology for evaluating large investment projects. CBA is concerned with tactical decision-making and offers a meaningful monetized framework for policymakers. Surveying and integrating a set of significant impacts on society is an important objective. As a result, heterogeneous effects are compared in a uniform manner and deliver powerful insights for decision making by considering multiple perceptions. The two most important fundamentals of CBA are monetizing and discounting. Monetizing involves the conversion of qualitative factors into financial terms, making it comparable with economic or financial constructs. Discounting is the underlying process to determine the present value of the different factors, it basically is correcting for inflation. The net present value is calculated as follows:

$$NPV = \sum_{f=1}^{f\_end} \sum_{t=1}^{t_{end}} \frac{C(B)}{(1+r)^t} \qquad \text{Eq. 6-1}$$

Variable $C(B)$ represents the nominal cost or benefit of a factor in a year. The present value of this factor is then calculated by correcting $C(B)$ for inflation, $(1+r)^t$. The sum over the years of lifespan and the number of factors finally yield the net present value. The next section discusses the number and types of factors included.

A complete cost benefit analysis typically tries to include all significant economic, societal and environmental effects. This means that large macro-economic effects are included, such as rate of employment and quality of life indicators.

Reservoirs also tend to have effect on macroeconomics (Gao, 2003) & (Ortiz Partida, 2016). An example is change in economic growth, due to better connectivity to freshwater and electricity. Development and in later phase maintenance works lead to improved employment rates. On the other hand, compulsory relocation and external effects on the local environment decline overall performance. The variety of included factors in this research attempt to reflect a realistic and complete set that satisfy both economic and societal/environmental effects. The limited number of factors that is considered reflects the limited amount of time and resources available to finish this study.

The following variables will be discussed in this chapter as to clarify details in the CBA approach:

- Value of sediment, industrial purposes [€/ton]
- Value of sediment, fertilization purposes [€/ton]
- Freshwater yields (consumer drinking water) [€/ton]
- Freshwater yields (irrigation) [€/ton]
- Hydropower yields [%]
- Plant/Head (hydropower) losses [%]
- Transport distance on shore [km]
- Expropriated land area [km^2]
- Value of arable land [€/ha.]

The costs and benefits are subdivided, according to the following list.

- (Direct) reservoir costs
- Sediment management costs (discussed 5)
- Direct economic effects
- Indirect economic effects
- Societal and environmental effects

Important to underline is the level of detail. Direct or semi-direct effects are included as far as possible. A wide range of plausible effects is not included, since there is either too much ambivalence between reservoirs or previous researches or it will broaden and fade results. Some excluded, but notable effects:

- Average economic growth and employment rate.
  Too much ambivalence with (in)direct included economic effects. It would lead to poorly substantiated reasoning.
- Fish stock;
  Change in fish stock and its quality can be a direct effect of the implementation of a reservoir. The change in current profiles, toxic levels in a reservoir or barriers (in case of migrant fish species such as salmon) may lead to a decline in fish stock. Including this effect would not coincide with the level of detail of other included effects and reservoir morphology predictions.
- Recreation;
  Fish stock can coincide with the assigned value of recreation. Change in recreation activities is typically of the same level of detail of fishery and therefore excluded.

The effect of change in fish stock and partially recreation could be accommodated within environmental effects, but remains excluded in this research. The core objective remains to analyse the monetized effect of sediment management on reservoir performance, including a wide spread of (smaller) effects fade the results.

6.2. *Direct costs and benefits*

The cost-estimation to develop a reservoir can be a complex task, since total costs of the development depend on a great number of variables. Some quick examples that impact the total costs are the required strength of the dam and its foundation type due to soil characteristics and water level in the reservoir. Other important aspects are the reservoir and dam functions (irrigation, drinking water, hydropower generation, etc.) and the mass flow rate through sluice gates.

Performing an in-depth cost-estimation based is in this research not feasible. Estimation of the costs is therefore based on a simple regression analysis of existing reservoirs, see Figure 6-1. The construction costs are present in the financial analysis as sunk costs that lead to significant negative results in the first phase of a typical project. An analysis of construction costs has been performed recently (Petheram, 2019). This research eminently involves construction costs for smaller dams and only in Australia. Petheram (Petheram, 2019) concludes that final costs (2016) are between 48 and 2040 / ML. Comparing this to the regression in Figure 6-1 would lead to a final price of between €750 Million and €31.6 Billion (at a capacity of 25 km^3). The results of Petheram overlap with the regression. The trendline from the regression will be used to estimate the final construction costs.

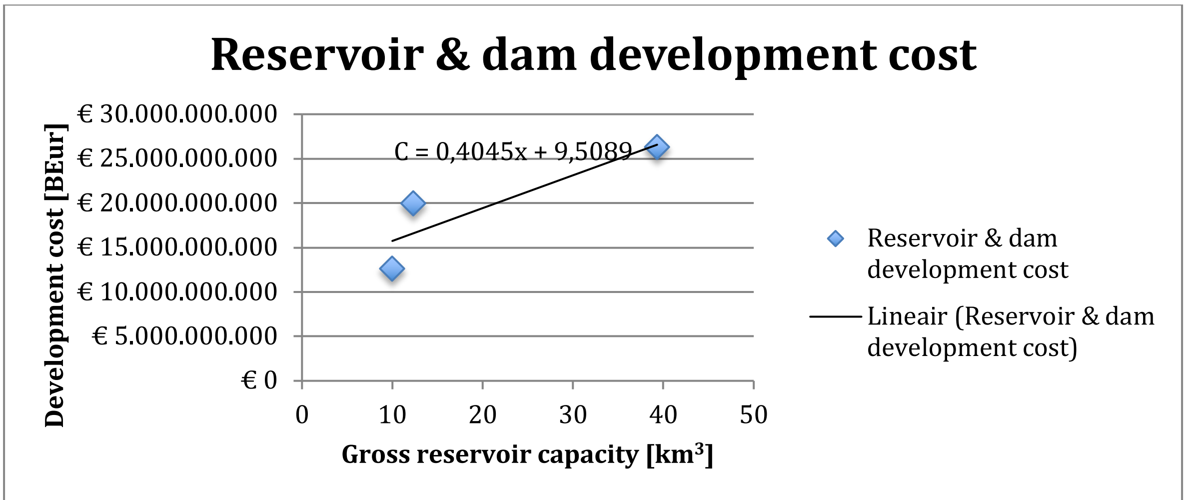


Figure 6-1: Reservoir development cost, based on Diamer Basha site, Itaip reservoir, Three gorges dam

A budget for maintenance cost is taken in to account. This cost item is to keep the dam and other auxiliary systems in operational condition. A yearly budget is set at €10 million, not including sediment management. Sediment management costs (i.e. dredging or flushing) is discussed in the next section.

A reservoir is typically developed for one or more primary economic functions. Examples are hydropower generation and water supply. A variety of secondary functions are often considered, such as flood control and recreational opportunities. The most common functions are included mathematically:

- Hydropower generation
  Yields from hydropower generation primarily depend on the available discharge and hydraulic head of a dam. Head losses (approx. 5-10%) and hydropower plant efficiency (between 85 – 95%) lower the theoretical yields

by 15 – 35% (Renewables first, NA). Furthermore, research shows that efficiency improvement opportunities are large. Improvements of 23% are reported in Iran (Yassi, 2010). Currently, Ke Go reservoir (see section 7.3) has an installed hydropower generation plant of 2.3 MW. The base height of associated sluice gates (H_{db}) is set at 10 metres. The available head declines linearly from 100 percent to 0 for a sediment height at the dam between H_{db} and $H_{db} + H_d$ (See 4.2.1). Market prices of electricity are available everywhere, the current rate is around 0.20 €.kWh^{-1}.

- Water supply
  Water storage in reservoirs can be used for irrigation, industrial use and consumption. A combination of functions is possible and depends on regional demand, discharge and water quality (Heydari, 2016). Heydari and colleagues propose a quantified model to optimize the distribution of various functions. It underlines the importance of reservoir and regional characteristics. In this research, the total discharge can be used for one or multiple functions and is specified by input parameters (percentages of the total storage for described functions, specified in 7.3).
  For CBA application, monetizing is required. The value of water depends on the quality of the water and whether it is applicable for tap (drinking) water or irrigation. The value of drinking water ranges between 0.5 USD and 5 USD per m^3 (OECD, 2013). Prices of water for irrigation purposes have a wide range between 160 USD in Spain and 1330 USD per ML in the Netherland (FAO, NA). Prices are especially subject to the origin of water. In the Netherlands, water for irrigation comes mainly from municipal supply network. Lower prices in Spain are possible since it is directly taken from groundwater. The willingness to pay (WTP) and the case location in Vietnam compares better to the situation in Spain. The assigned monetized value is therefore set equal to the data from the situation in Spain.

6.3. *Indirect economic effects*

Included indirect effects are all associated with sedimentation. Two types of possible sediment applications will be included; construction and fertilization purposes. Numerous studies report about the applicability of dredged material and the percentages of total sediment that can be used for economic valuable purposes. Sediment from Japanese reservoirs is above average useful (up to approx. 90%). On the contrary, reservoirs with sedimentation or siltation problems can also face issues with potentially toxic sediment waste. The lower limit is therefore set at 10 percent useful dredged material and checked upon sensitivity in the end results. After sediment is dredged and transported to shore, further processing is needed.

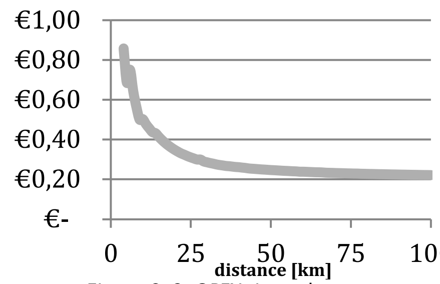


Figure 6-2: OPEX tipper lorry transport

Dumping or processing sediment in agriculture or industry is always preceded by temporary storage on land (€1 per ton, Elzinga (2017)) and transport to final location (€1 per ton.km, (European Commission DG Tren, 2006)). Transport prices depend primarily on distance (Figure 6-2), but are kept constant in the net present value analysis (TWUWA, 2007).

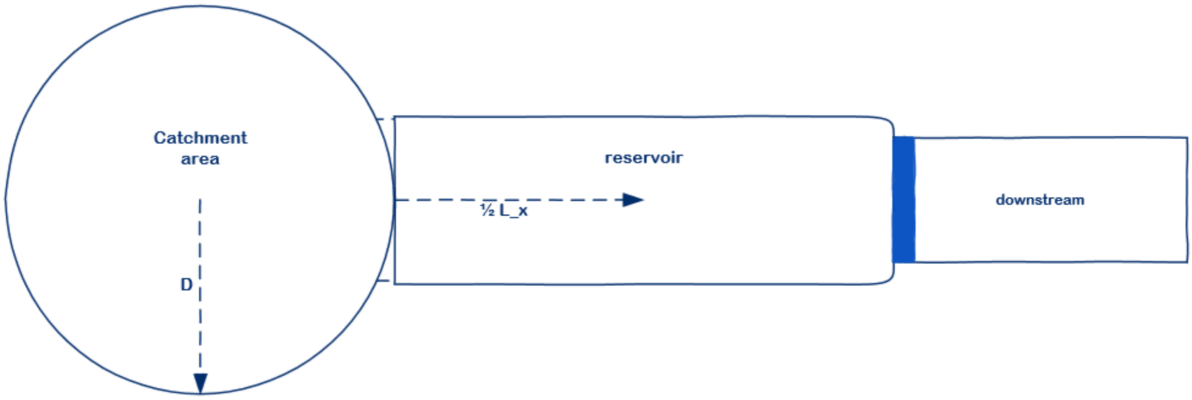


Figure 6-3: Estimation of transport distance for fertilization and local industrial purposes of sediment.

The transport distance on land is based on potential effects in the reservoir basin/catchment area and downstream river system (see Figure 6-3). Deforestation and civil works can have a significant effect on erosion of fertile soils in the upstream catchment area. The transport distance on land in upstream direction is therefore estimated as follows:

$$D_{tu} = \frac{1}{2} L_x + D \qquad \text{Eq. 6-2}$$

D_t	Transport distance on shore	$[km]$
L_x	Reservoir length	$[km]$
$A_{catchment}$	Catchment area, circle shape assumed (see Figure 6-3)	$[km^2]$
D	Catchment diameter, $D = \sqrt{\frac{4\, A_{catchment}}{\pi}}$	$[km]$

The transport distance on land in downstream direction is even more complex to estimate. The possible presence of endangered nature reserves and the length over which sediment deficiencies prevail, are seriously uncertain. The average transport distance downstream will therefore be largely rough, but build up from a distance along the reservoir plus a distance along the downstream river:

$$D_{td} = \frac{1}{2} L_x + D_d \qquad \text{Eq. 6-3}$$

D_d Uncertain average distance downstream of the dam, assumed equal to D.

This distance will be used to estimate the total transport cost for both usable and waste material. In practice, the transport distance will range between one to two times the total reservoir length.

After rail or road transport, the following effects will be reviewed in the CBA

- Construction purposes
  Sediment can be an important basis for a variety of construction related products. Examples are concrete (Junakova, 2017) and geopolymer binders (Ferone, 2012).
  The monetized value of sediment for construction purposes is based on the average value of sand and gravel in the United States. Average prices in 2019 are between 5 – 20 dollar per ton for usable (construction) sediment. The value is subject to the region and of its composition. The value is set relatively low, €8.00 per ton (Wang, 2019).
- Fertilization purposes
  A second common use of dredged material is in agriculture. Sediment is often a valuable product for fertilization of crop. More generally, dredged material can be applied to fertilize arable land and in the extension of this, ecological systems downstream too. Monetized value of sediment, applicable for fertilization, is based on fertilizer cost in agriculture (Schnitkey, 2017). Monetized value is approximately $60 per ha. Approximately 2 mm can be spread as top layer (fertilizer) over arable land and ecological systems or nature reserves. This means that around 50 tons of material can be spread per hectare. Taking these values in to account, the value of sediment applicable for fertilization (or top layer) is around €1 per ton.
- Sediment waste
  Still, a significant percentage of total dredged material is usually considered waste and must be disposed. The cost of disposal depends on the volume and characteristics of the material. The largest proportion of waste is in no way hazardous and differs only marginally from naturally occurring minerals (Salomons, 1988). Still, trace levels of toxics can appear in exceptional cases and accumulation can result in degrading of ground- and surface water in the surrounding environment. Toxic concentrations are typically higher in mining situations, but the large volumes of material in reservoirs make significant accumulations possible. Besides material that originates from river basins, human induced toxicity is also a cause to keep in mind. An example for this is 300,000 cubic meters of polluted water in the Aulencia reservoir, Spain (Sanchez, 2013). Since toxic levels in reservoirs are usually low/ignorable, the monetized cost of sediment waste is here based on transport- and storage cost. Storage cost is set at €1 per ton, as discussed earlier (Elzinga, 2017). The estimation cost for dumping is set equally high; €1 per ton.

Other impacts of sedimentation and management include (qualitative, not modelled):

- Fishery;
- Recreation/tourism;
- Quality of life for local residents;

6.4. Environmental effects

- Ecology
  Ecological impairment downstream of a reservoir is primarily caused by changes in water discharge and sediment depositions. Seasonal water

storage, sediment trapping and significant change of water discharge downstream of a reservoir lead to weakening of ecological systems (Power, 1996). The status quo in the analysis is the situation in which sediment is not dredged and cannot be used for the mitigation of ecological impairment. The idea is to supply the ecological system with fertile soil and maintaining the top layer. The monetized effect is then set equal to the monetized value of sediment for fertilization purposes (€1 per ton). The effect of mitigation and thus preventing loss of valuable ecological systems is included too. The monetized value of mitigation is approximated at €600 per hectare. This rough estimation is based on (Farmland LP, 2017).

- Forced moving
  One of the largest relocations of people due to reservoir development was during the construction of the Three Gorges Dam (Wee, 2012). More than a million people had to move. Next to forced moving, it is common that land is bought out and becomes part of the reservoir. Market prices of inhabited and arable land differ a lot worldwide. In Europe, prices range between approximately $5,000 and $100,000 per hectare for arable land (Thakore, 2019). However, prices can be much lower, depending on population density and whether or not the land is arable. Within the research a base nominal (2019) value of $5,000 per hectare is used. The amount of land bought out for reservoir development is specified as a percentage of the face surface of the reservoir. The base value is set at 20% of the face surface (Figure 6-4).

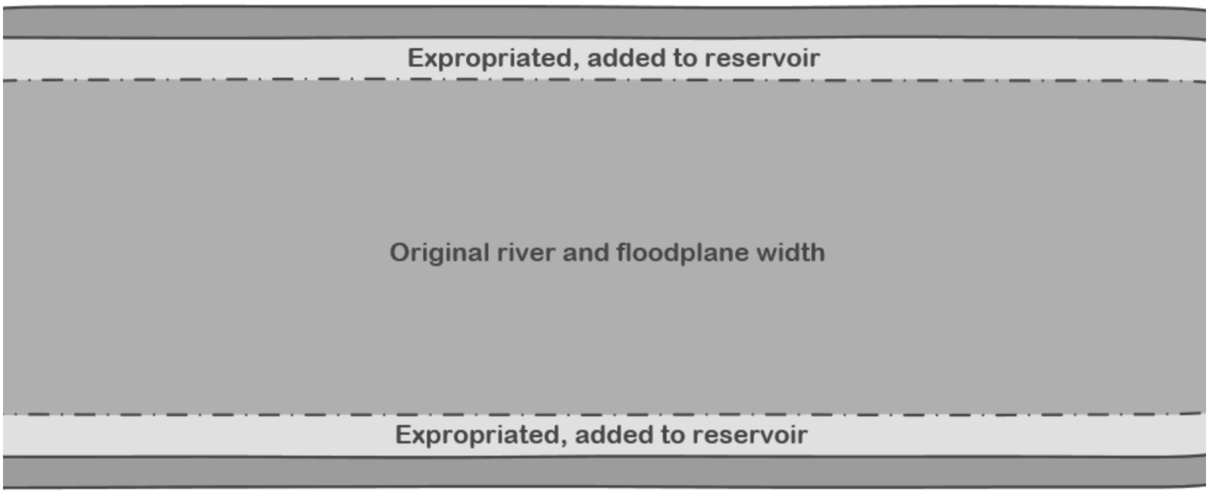


Figure 6-4: Top view possible expansion of original river width

7. Case specification

The general approach is discussed in chapter 3-6, this chapter deals with specification of input variables to work out the sequence of models. A case will be introduced to give practical meaning to common reservoirs. Specification of reservoir parameters is first discussed. After which, the case is identified and the approach developed is applied to it. The last section summarizes parameters with potential scenarios to verify sensitivity.

The next sections deal with model input parameters that primarily involve the reservoir:

- reservoir simulation time;
- dimensions
- inlet/outlet dimensions;

7.1. Simulation time

The average life expectancy of a dam is 40 - 50 years. The global reservoir capacity was increasing rapidly between 1940 -1980 (MIT, 2012). Since then, dam construction slowed down and average age of reservoirs increased slightly. 85% of dams in Army Corps of Engineers National Inventory of Dams is now over 50 years old (NID, 2019), replacement or major maintenance will be needed in the upcoming decade(s).

The predefined model life span is set equal to the average life expectancy for dams, 50 years. It is expected that sedimentation management will not be necessary at first, but becomes of interest after the dead storage is filled. When sedimentation height exceeds the dead storage level, sediment management/dredging activities will start and gradually increase until a certain moment that sediment management activities equal the inflow of sediment. The model will show when and how fast the need for sediment management develops. The analysis will then be extended to 75 – 100 years to be able to evaluate economic effects of extended life spans.

7.2. Dimensions

The shape of a reservoir is a very unique property and, in most cases, determined by how it was formed in the first place (Table 7-1: Reservoir sizes [km]). A reservoir can either be artificial or formed by nature. Even when a reservoir is artificial, it still is a complex matter to influence the dimensions. It depends largely on existing bathymetry, height differences, soil characteristics, etc. Some reservoirs are actual lakes with a natural maximum depth at the centre, while other reservoirs are longer and slender like a longitudinal river profile. Table 7-1 shows some possible values for the length, width and depth of a reservoir. This is based on the case analysis in appendix A.2. The length over width ratio should always be at least 1 (i.e. L>W).

Table 7-1: Reservoir sizes [km]

Reservoir	Length [km]	Width [km]	Depth [m]	Capacity [Bm^3]
Alqueva	100	5	100	4
Kariba	220	30	97	180
Bratsk	636	50	100	169
Daniel Johnson	450	450 [40]	90	142
Guri	290	50	100	135
Aswan High (Nile)	500	5	100	132
Three Gorges	600	1.12 km	110	39.3

The examples above were suitable to investigate ownership and organizational structure previously, but are characterized by above average high capacities. The examples in Table 7-1 do show the deviation between the actual capacity (column 4) and the capacity that would be used if the dimensions were 1:1 adopted in the model. Because both the capacity and the ratio between dimensions and actual capacity deviates, somewhat more precise reservoir parameters must be found. Adjusting these parameters has been discussed in section 4.1 and will be applied to the case to be identified.

The average reservoir size is evaluated based on the GranD/FAO aquastat database. All reservoirs in the database up to fifty years old (1969) are included, the total average turns out to be approximately 450 million m^3. The total number of reservoirs and averages per included region is shown in Table 7-2. Figure 7-1 shows the distributions of reservoirs by capacity and the relative importance when considering the size of reservoirs. The largest reservoirs deliver a great amount of the total capacity, despite the fact that only a very small number of reservoirs are larger than 25 billion m^3. On the other hand, a vast majority of the reservoirs is smaller than 500 million m^3, and the median is just smaller than 500 m^3 too. The research focuses now on the total average capacity, since the final objective is to supply with long-term advice how to deal with sedimentation in reservoirs in general. Analysis around the average will be representable for far more reservoirs than applying it to the largest reservoirs (>25 billion m^3). The next step is to identify a suitable case to look into.

Table 7-2: Average capacities of reservoirs

Region	Average capacity [Mm^3]	Number of reservoirs
Northern America	1067	514
Europe	792	515
Asia	209	2730
Africa	835	488
Average/Total	**456**	**4247**

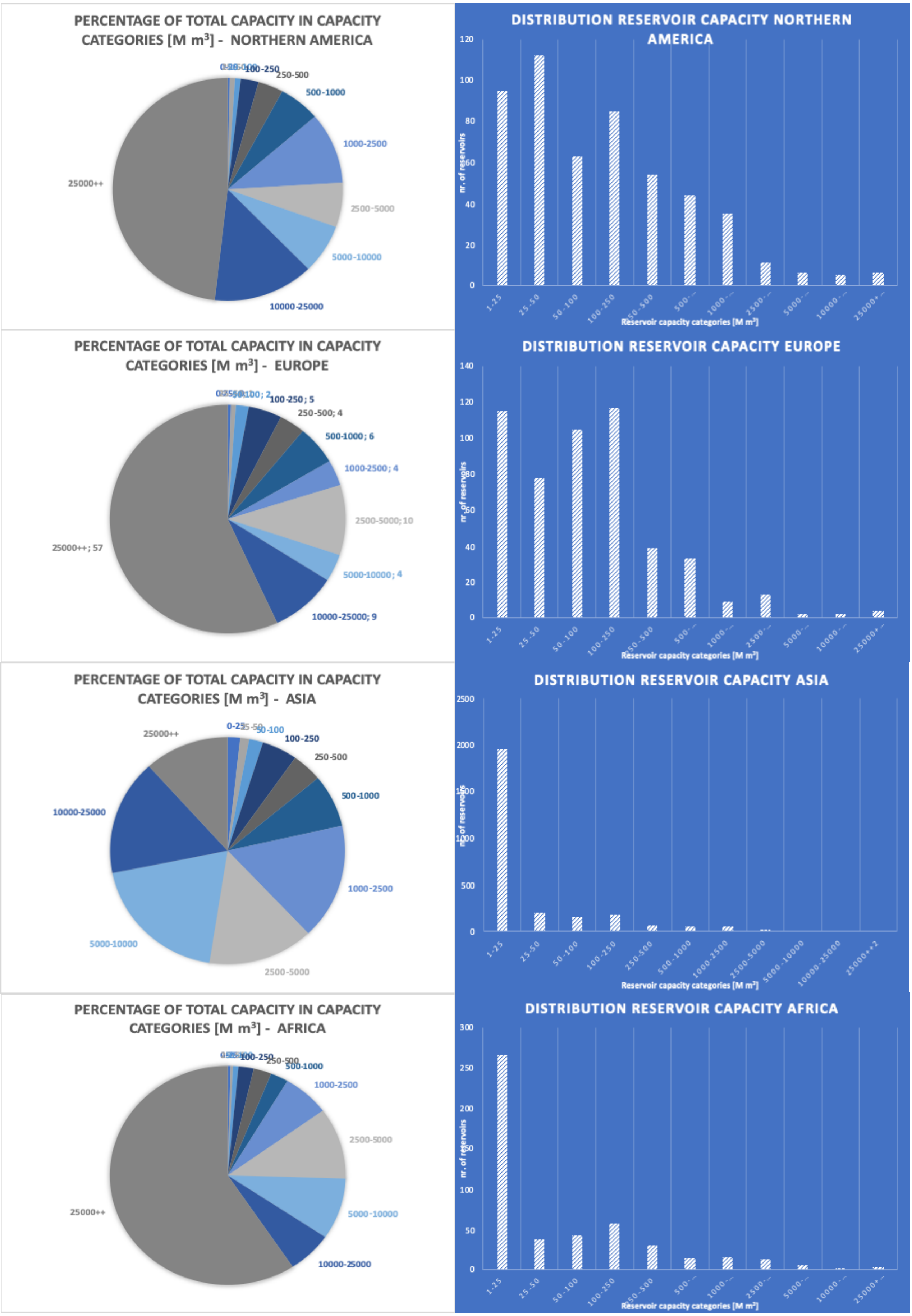


Figure 7-1: Reservoir characteristics in 4 regions

7.3. Case identification

Table 7-6 shows all reservoirs from the GranD database with a capacity between 425 and 475 million m^3. Selection of the case is based on the next properties:

- Application of multiple functions (hydropower generation, irrigation, consumption);
  Information about the distribution of discharge over the various functions is key. A multifunctional reservoir provides a better understanding about costs and benefits in reservoir operations.
- Shape of the reservoir
  The model is based on a hypothetical rectangular reservoir with a single in- and outlet. It is beneficial if the case has a fairly similar shape, for example in contrast to Manicouagan reservoir which was formed following the impact of an asteroid.

There are two multifunctional reservoirs available in the database within the specified capacity range:

- **Serebrianka 2 reservoir/dam**
  Very limited in useful information. The shape of the reservoir is moderately comparable. Unfortunately, there are multiple incoming rivers which cannot be modelled as such (IndustryAbout, 2018).
  Type: Dam, Hydro Power Plant
  Area: Murmansk
  River: Voroniya
  Main purpose: Hydroelectric
  Power Capacity: 150 MW
  Water Capacity: 428 million m^3

  Activity since: 1972

Figure 7-2: Serebrianka 2

- **Ke Go reservoir**
  Most required information is available (Vncold, N/A). The shape is reasonably comparable with sedimentation mostly near the main upstream river mouth.
  Type: Earth fill dam, Hydro Power Plant
  Area: Cam My commune, Cam Xuyen district, Ha Tinh province,
  River: Ke Go
  Main purpose: Hydroelectric
  Power Capacity: 2.3 MW
  Water Capacity: 425 million m^3
  Activity since: 1988

Figure 7-3: Ke Go reservoir/dam

Based on the information above, The Ke Go reservoir is choses as case, both the availability of information and the shape of the reservoir are better than Serebrianka II. The Ke Go Reservoir is in Cam My commune, Ha Tinh province, 70 km from Vinh city in the south. The dam is located near 18°13'19.3"N 105°54'07.3"E

The Ke Go is a biodiverse artificial lake, surrounded by hills and mountains in Cam Xuyen District. Ke Go Nature Reserve is now a very attractive destination for locals and tourists. Forests with precious species of flora and rare species are found around the lake. It took four years to build the 30km long lake, the main dam and the ten auxiliary dams. The reservoir became an attractive recreation area where people go swimming, fishing and hiking. Although not included as primary function, the Ke Go is also an abundant source of food for the local residents. Fish and shrimps are caught and a small fishing industry thrives in the artificial lake.

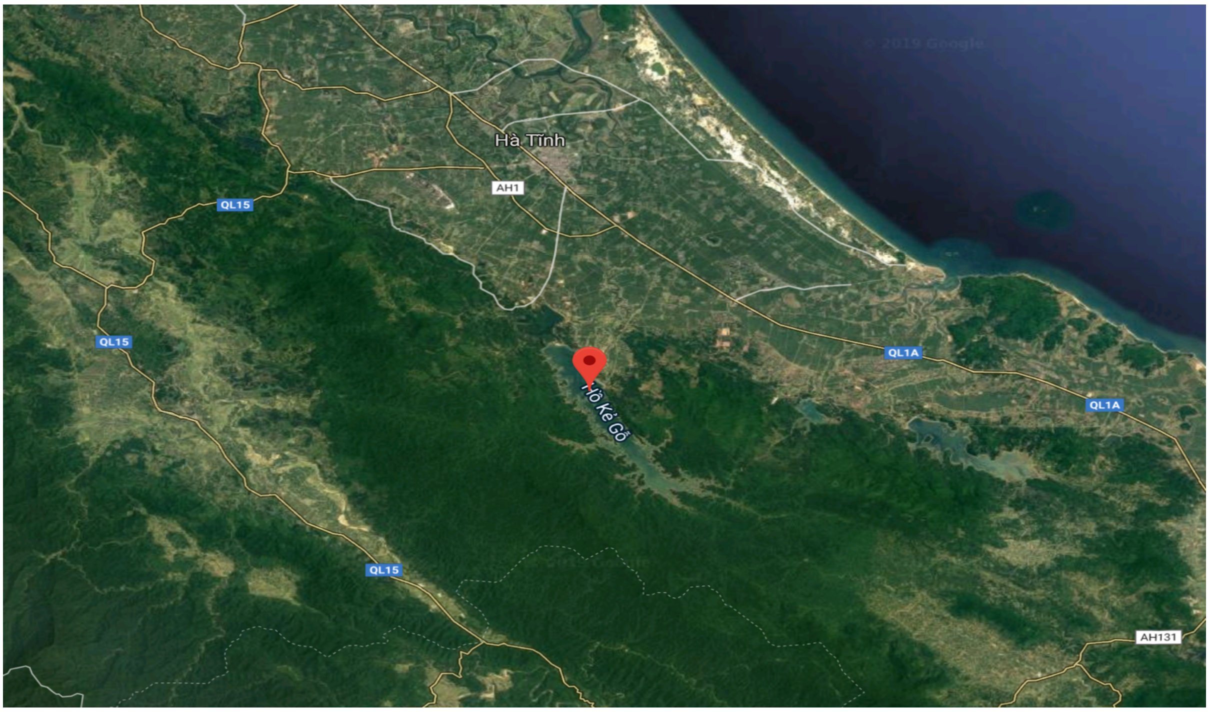


Figure 7-4: Area around the reservoir. Ha Tinh city nearby, natural habitat for endangered species with forest.

Salient parameters

Initial reservoir length:	29km (currently effective 12-15 km)
Reservoir area:	over 30 km^2
Effective storage capacity:	345 x 10^6 m^3
Total storage capacity:	425 x 10^6 m^3
Catchment area:	223 km^2
Homogeneous earth fill dam:	37.4m high, 970m long together with 3 other auxiliary dams and 3 spillways (including Doc Mieu spillway, intake spillway and emergency spillway).
Main canal:	over 10m wide, 17.2 km long, discharge of 28.2 m^3/s; branch canal system is 110 km long.
Annual precipitation:	2300 mm

Reservoir functions

- To irrigate 21,136 ha of cultivated land of Cam Xuyen, Thach Ha districts and Ha Tinh town.
  Daily irrigation per hectare is estimated at 10 m^3 (1 mm).
  The discharge needed for irrigation therefore averages $\frac{21136 \cdot 10}{3600 \cdot 24} = 2.44 \frac{m^3}{s}$
- To protect the downstream area against flash flood and erosion (not included in the modelling).
- To supply water for industry and living with discharge of 1.6m^3/s.
- To generate electricity with installed capacity of 2.3 MW.
  The average discharge rate needed to generate 2.3 MW is estimated as follows:

$$P = q \cdot g \cdot (L_z - H_{db} - \frac{H_d}{2}) \cdot (1 - \eta_{head}) \cdot \eta_{plant} \qquad \text{Eq. 7-1}$$

$$q_{hp} = \frac{2.3 \cdot 10^6}{g \cdot \left(L_z - H_{db} - \frac{H_d}{2}\right) \cdot (1 - \eta_{head}) \cdot \eta_{plant}} \qquad \text{Eq. 7-2}$$

$$q_{hp} = \frac{2.3 \cdot 10^6}{9.81 \cdot \left(37 - 10 - \frac{10}{2}\right) \cdot (1 - 0.1) \cdot 0.95} = 12.4 \frac{m^3}{s} \qquad \text{Eq. 7-3}$$

η_{plant}	estimated efficiency hydropower plant
η_{head}	estimated head efficiency
H_d	sluice gate height
H_{db}	base height sluice gate above initial reservoir bed

The total discharge of the various functions average 16.44 m^3/s, annually equivalent to a discharge of approximately 120 percent of the total reservoir capacity. The total annual discharge in the reservoir from upstream rivers is based on the discharge of the main canal. Normal values for annual discharge range between 1 and 10 times the total reservoir capacity.

In this case, the sedimentation develops clearly near the entrance of the reservoir (main canal), shown in Figure 7-5. Fast sedimentation and a relative low total discharge of the main functions suggest a relative low total discharge from upstream rivers too. The total catchment area is 223 km^2 with an average annual precipitation of 2300 mm. This means that the annual discharge, based on remaining river basin run off (UN Environment program, 2005) and catchment area is between 100 – 200 percent of the gross reservoir capacity. The total annual discharge is set finally set at 200 percent of the total reservoir capacity, following the expected low total annual discharge and the available data from the main canal. Table 7-3 shows the distribution of water discharge over the various functions, including flushing.

Table 7-3: Discharge approximation

Function	Av. discharge [$m^3.s^{-1}$]	[%]
Irrigation	2.44	9%
Consumption	1.6	6%
Hydropower	12.4	46%
Flushing	10.54	39%
Total	27	100%

At present, the World Bank supports the Project: the objective of “Vietnam Water Resources Assistance Project” is to strengthen, upgrade and modernize several irrigation systems including Ke Go.

The use of dredged material from the Ke Go is described earlier. A significant part of the dredged material is considered waste and the amount depends on the technical properties of the material and on local willingness to adapt dredged material in current industrial processes. Normal values range between 10 and 90%. This value is unknown for the Ke Go and therefore a presumed amount of 50 percent of the dredged material is considered waste. The rest is considered useful and equally divided over fertilization and industrial purposes.

Figure 7-5: Discharge from main canal and side canals (Dam at red pointer)

Figure 7-7 shows the measured current (2019) length, other sources report lengths between 20 – 30 kilometres (Vietnamtourism.gov.vn, 2010). This seems to indicate long term effects of sedimentation. Construction of the Ke Go began in 1976, which brings the current age of the reservoir to 44 years. More frequently used sedimentation rates of 1 percent per year seems consistent with the change in length over the years. On the contrary, a relative low discharge rate (approx. 28 m^3/s) and a normal sedimentation rate (1 percent) suggest a rather high average sediment supply at the river mouth of 7.5 grams per litre (Table 7-4). This also emphasizes the importance of precise estimation of the various parameters for practical applications. The current estimated values will be used for now though. The particle size diameter and distribution are important to estimate the prevailing sediment transport modes at the river mouth. Based on pictures and general information about Ke Go, a particle size of 0.15 mm has been assumed. This size is typical for silt, just a little smaller than sand.

Table 7-4: Sediment concentration at the river mouth

Gross reservoir capacity	425,000,000	m^3
Average discharge	28000	$l.s^{-1}$
Annual sedimentation rate	0.01	-
Sedimentation	4,250,000	m^3
Total sediment/year	6,630,000	$ton.year^{-1}$
Sediment supply/sec	210	$kg.sec^{-1}$
Average sediment supply	7.5	$Gram.l^{-1}$

The case still has to be adjusted to fit the hypothetical reservoir (tank) setup. As mentioned earlier, multiplication of the surface area times the depth is larger than the actual gross capacity. Therefore, the reservoir dimensions will have to be adjusted to fit the gross capacity of 425 million m^3. Figure 7-7 shows the estimated width and length of the real reservoir. Important to note is the discrepancy between the simulation setup and the actual situation in the figures above. Figure 7-6 shows the hypothetical cross section for a reservoir, as discussed earlier in chapter 3. Ke Go lake is approximately 37 meters in depth (given). The depth in combination with a total face width of 1500 meters give the equation below.

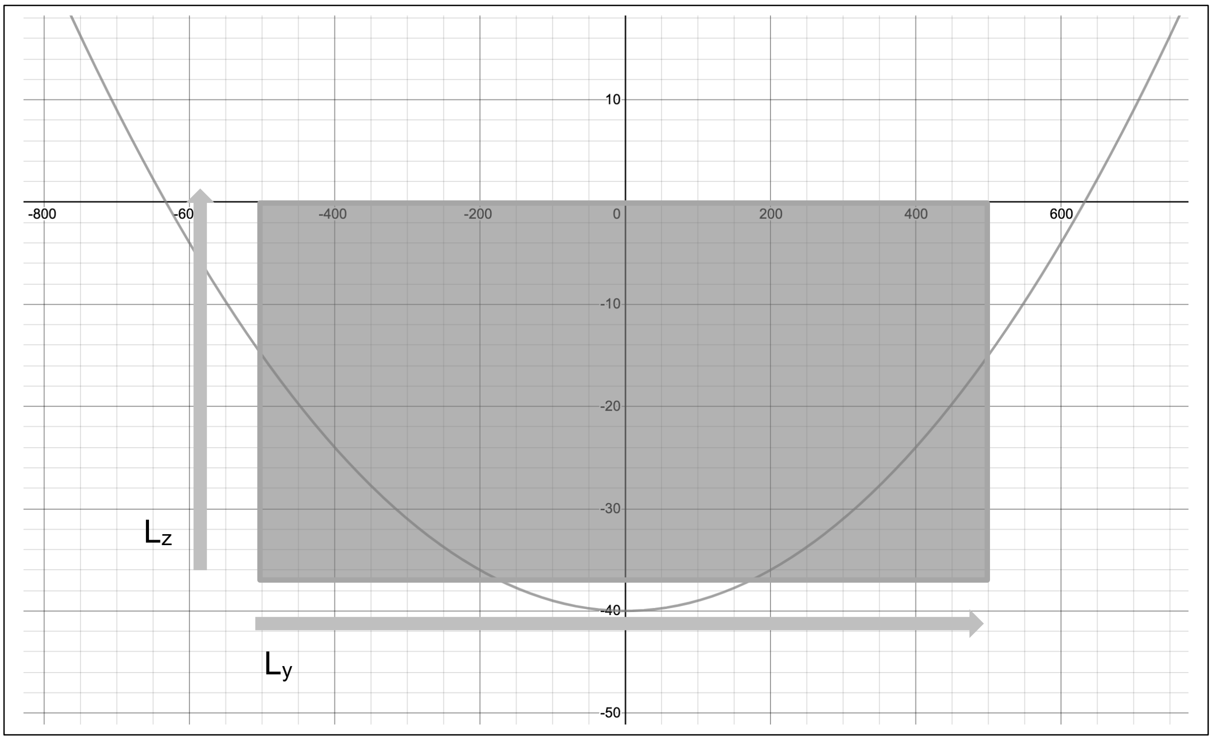


Figure 7-6: Cross section of tank and reservoir

$$a_y = 0.0001 * y^2 + 2 * 10^{-17} - 45$$
$$= \int_{-750}^{750} 0.0001y^2 + 2 * 10^{-17}y - 45\, dy$$
$$= [-0.000033333y^3 - 1 * 10^{-17}y^2 + 45y]_{-750}^{750}$$
$$= 40000\, m^2$$

Since the reservoir shape in the simulation is based on a tank, both the width and length must be adjusted. The adjusted width of the reservoir is based on the approximation of the reservoir cross section (40000 m^2) and real depth (37 metres). The width for the simulation is set at 1000 meters. The corresponding reservoir length is approximately 11.5 kilometres. The river mouth and downstream dam width are estimated based on Figure 7-7 (map). Table 7-5 shows the input parameters for the simulation.

Table 7-5: Reservoir case/model parameters

Parameters	**Case**	**Model**
Reservoir length [m]	12000	11500
Reservoir width [m]	1500	1000
Reservoir height [m]	37	37
Reservoir capacity Mm^3]	425	425.5
River mouth width[m]	200	200
River mouth height[m]	10	10
HP Sluice gate width [m]	400	400
HP Sluice gate height [m]	10	10
HP Sluice gate base level [m]	10	10

Figure 7-7: Measured reservoir dimensions.

Table 7-6: Identified reservoirs with a capacity between 425 - 475 m^3

Country	Name of dam	River	Completed /operational since	Dam height (m)	Reservoir capacity (million m3)	Reservoir area (km2)	Irrigation	Water supply	Hydroelectricity (MW)	Recreation
Bulgaria	Dosspat	Dosspatzka	1969	61	449.3	0.91	x			
Sweden	Parki	Lilla Lulealven	1970	28	460	1.2	x			
Spain	El Atazar	Lozoya	1972	134	426	52		x	x	x
Russian Federation	Serebrianka 2	Voroniya	1972	64	428	300	x	x	x	
United States of America	Sooner	Greasy Creek	1972	30	431.7	21.4				
United States of America	Melvern Dam	Marais des Cygnes	1972	37	447.8	23.9				x
United States of America	Chatfield Dam	South Platte River	1973	45	437.9	5.2				x
China	Qingshan (Chongyang)	Lushui	1973	59	429	9.4			x	
United States of America	Brookville Lake Dam	East Fork of Whitewater River	1974	55	443.6	19.8		x		x
United States of America	Nicatous Stream Dam	Nictous Stream	1974	2	458.2	21.1				x

United States of America	Indian Valley	North Fork of Cache Creek	1975	69	442.8	14		x	x	x
Mexico	Chicayán	Río Chicayan	1976	34	468		x			
United States of America	Clinton Dam	Wakarusa River	1977	35	454.8	28.3		x		x
United States of America	Dequeen	Rolling Fork	1977	49	457.1	7				x
China	Zhuzhuang	Ziyahe	1978	95	436	5.6	x			
Nigeria	Bakolori	Sokoto	1978	48	450	0.005	x			
Norway	Sysenvatnet	Leiro	1979	81	427	1.083	x	x		
Portugal	Aguieira	Mondego	1981	89	450				x	
Thailand	Pranburi	Mae Nam Pran	1982	42	445	3.62	x	x		x
United States of America	Aquilla Lake	Aquilla Creek	1983	32	443.9	9.7		x		x
India	Donkarai	Sileru	1983	71	470	26.66	x			
Russian Federation	Verkhne-Teriberskaya	Teriberka	1984	43	451			x		
Albania	Komani Dam	Drin	1986	133	450		x	x		
Indonesia	Wadas Lintang	Bedegolan	1987	122	443	12.1	x		x	
India	Majalgaon	Sindphana	1987	31.19	453.64	78.13	x		x	
Viet Nam	**Ke Go**	**Ha Vang**	**1988**	**40.4**	**425**		**x**	**x**	**x**	
Algeria	Gargar	Rhiou	1988	70	450				x	
Spain	Chanza	Chanza	1989	85	452	0.343	x	x		

Mexico	Constitución de Apatzingán	Río Grande	1989	105	450		x			
United States of America	Bor Jordanelle	Provo	1993	91	458.9	10.6		x		
United States of America	John T. Montford Dam	Double Mountain Fork Brazos River	1994	43	437.3	4.9				x
Spain	Giribaile	Guadalimar	1996	89	475	0.36		x		
China	Chaishitan	Nanpanjiang	1999	102	440	4	x		x	

7.4. Specification summary

Table 7-7 toTable 7-9 show a summary of the applied parameter values.

Table 7-7: CFD & reservoir variables

CFD & reservoir variables	Base value	Units	Scenario (-)	Scenario (+)
Dynamic viscosity of water	$8.9*10^{-4}$	Pa s		
Density water	1000	kg/m^3		
Density sediment	2600	kg/m^3		
Grain diameter	0.01	mm		
CFD simulation time	3600	s		
Reservoir lifespan	50	years		100
Trap efficiency	0.95	%		
Annual discharge	1000	%/res. cap.		
CFD timestep	0.1	s		
Sedimentation rate	1	%/year		
Rouse number [bottom, suspended average]	1.2	[-]		
Settled sediment concentration	0.6	[-]		
Diffusivity	1.43 × 10−7	m^2/s		
Gravitational acceleration	9.81	m/s^2		
Number of domains i direction	20	[-]		
Number of domains j direction	20	[-]		
Number of domains k direction	20	[-]		
Upstream inlet (river) height	10	m	5	
Upstream inlet (river) width	200	m		400
Downstream outlet (sluice) height	10	m		
Downstream outlet (sluice) width	500	m		
Dead storage height	10	m	1	20
Length reservoir	11500	m		
Width reservoir	1000	m		
Depth reservoir	37	m		

Table 7-8: Dredging process variables

Dredging process variables	**Base value**	**Units**	**Scenario (-)**	**Scenario (+)**
Average tug speed	3	m/s		
Minimum reachable dredging depth	50	% of dead-storage level		
Maximum dredging depth	50	% of dead-storage level		100
Capacity barges	100	m^3/barge		
Offloading time barge	0.5	hours		
Purchase lead time dredging equipment	1	years		
Winch speed grab dredge	1	m/s		
Backhoe fill factor	see Table 5-2	-		
Capacity grab/backhoe dredge	10	m^3		
Turn time grab/backhoe dredge	40	sec		
Max boosters/pipeline	2	-		
Pipeline distance reachable without booster and per booster	2	km		
Workweek	70	hours/week		
Water injection dredge boom	4	m		
Depreciation time dredging equipment	15	years		
Depreciation time support equipment	25	years		
Nr. of dredgers/support units	4	-		
Nr. of employees for support	2	-		

Table 7-9: Financial variables

General financial variables	**Base value**	**Units**	**Scenario (-)**	**Scenario (+)**
EURUSD rate	1.2	[-]		
Base year	2020	[-]		
Construction cost reservoir	€ ±9.5B	EUR		
Maintenance cost reservoir	-	EUR		
Transportation cost	1	EUR/ tonkm		
Storage cost	1	EUR/ton		
Fertilization value sediments	70	EUR/ha		
Construction value sediments	15	USD/ton		
Average tug speed	3	m/s		
Fresh water use (consumers)	13	% of annual inflow		
Fresh water value (consumers)	1	EUR/m^3		
Fresh water value (irrigation)	0,3	EUR/m^3		
Fresh water use (irrigation)	9	% of annual inflow		
Fresh water use (drinking water)	6	% of annual inflow		
Water use hydropower	46	% of annual inflow		
Water use flushing	39	% of annual inflow		
Loss of land due to reservoir development	100	% of surface area		
Value of arable and/or former inhabited land	5000	EUR/ha/year		
Area of ecosystems downstream	100	% of surface area		
Discount rate	3	%		
Wage growth	2.5	% per year		
Base wage	6000	USD/ month (2020)		
fuel price [MDO]	0.577	EUR/l		
fuel consumption	0.2682	EUR/kw/ hr		

cost of suction dredger equipment	1000000	EUR		
cost of cutter suction dredger 1 equipment	1500000	EUR		
cost of cutter suction dredger 2 equipment	2000000	EUR		
cost of grab dredger equipment	4000000	EUR		
cost of backhoe dredger equipment	4500000	EUR		
cost of submersible pump dredger	1500000	EUR		
cost of water injection dredge equipment	4500000	EUR		
Purchase cost support vessel	1500000	EUR		
Purchase cost tug	2500000	EUR		
Purchase cost pipeline	250	EUR/m		
Purchase cost support pontoon	1000000	EUR		
Purchase cost barge	2000000	EUR		
Construction time reservoir	15	years		

8. Results – sedimentation management

This chapter discusses the results from the research approach and application to Ke Go reservoir in Vietnam. The first 2 sections discuss the results of the CFD model and the extension to a reservoir life time. Section 8.3 involves the evaluation of earlier specified sediment management techniques and the work to mitigate sedimentation in the reservoir. Section 8.4 ultimately discusses the dredge costs for as far as the dredge methods are feasible in Ke Go reservoir.
To give meaning to the data that is developed in the models, a case study was introduced in chapter 7. The case study defines a basis to investigate sensitivity to variables, whether this is about sedimentation or about the financial impact of managing sedimentation.

The basic design of the case study is discussed in section 7.3. Since the case study needs to comply with the assumptions made in models earlier, the following initial design was assumed:

- Vertical walls and a horizontal bottom.
- Supply comes from one river, only the main canal is considered with an average discharge of 27 m^3/s.
- The dead storage level is defined as the bottom height of the sluice-gate above the initial bottom of the reservoir.
- Sediment management (dredging) starts at dead storage level and reaches a maximum depth defined as the minimum of the maximum predefined dredging depths of the feasible method.
- Sediment will be transported from the dredger to shore through pipelines (grab dredge, backhoe dredge) or by barge (suction dredger, submersible pump, cutter suction dredging, water injection dredging)
- Sediment offloading is not at one location. The average distance to shore is simplified and approximated as half the width of the reservoir.
- Multiyear sunk costs (construction of reservoir and dam) are distributed uniformly over the number of years lead time.
- Maintenance costs start from the first year of production.

These considerations are in line with the presented approach earlier in this report.

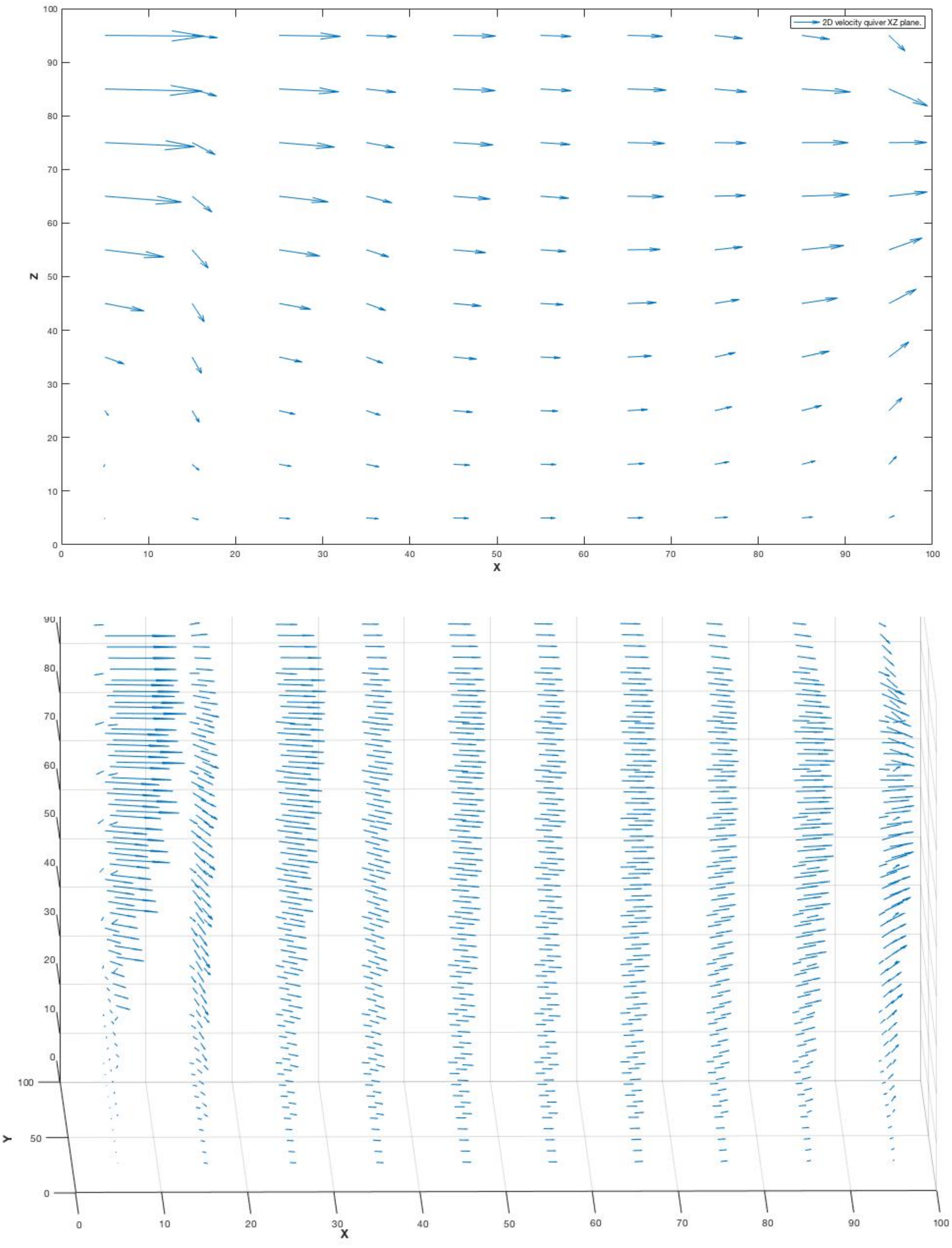
8.1. CFD model results

A graphical representation of the pressure correction method [CFD] starts with the evaluation of flow development in the simulated reservoir. The reservoir basically is modelled as a tank with the one inflow and outflow. Validation of the model is developed in a series of small steps, a quick review of this is discussed next.

Figure 8-1 to Figure 8-3 show velocity quivers for three hypothetical setups that are evaluated in the validation process:

1. Throughput flow in hypothetical tank set up.
   Initial verification of the model was performed without inlet and outlet. After the basic tank set up, this was checked in three direction with imposed initial velocities, the inlet and outlet were introduced and checked (over complete height).
2. Tank setup with theoretical simulation of upstream river and downstream dam sluice gate.
   Extension of the first model with appropriate values for the height and location of inlet and outlet. Both the inlet and outlet are positioned in the centre of the width of the reservoir. The inlet is positioned at the top, while the outlet is positioned approximately at a third of the reservoir height.
3. Velocity quiver (2D & 3D) with CFD simulation for a hypothetical reservoir with in- and output.
   Final values for reservoir parameters directly after starting simulation, but with large values for in & outlet.
4. 3D quiver of reservoir setup.
   Final values for reservoir with in- & outlet.

Initial tank set up

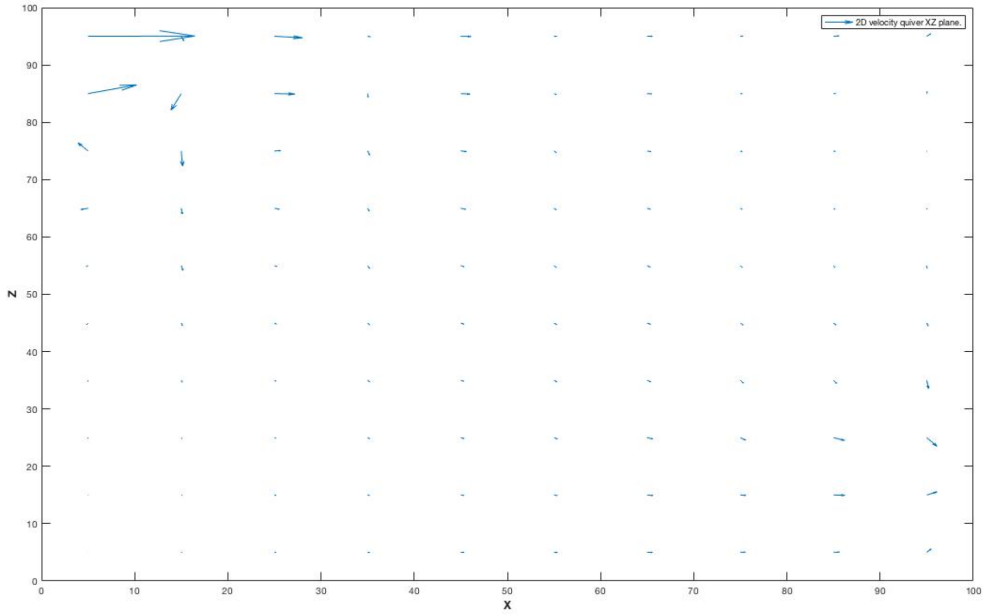


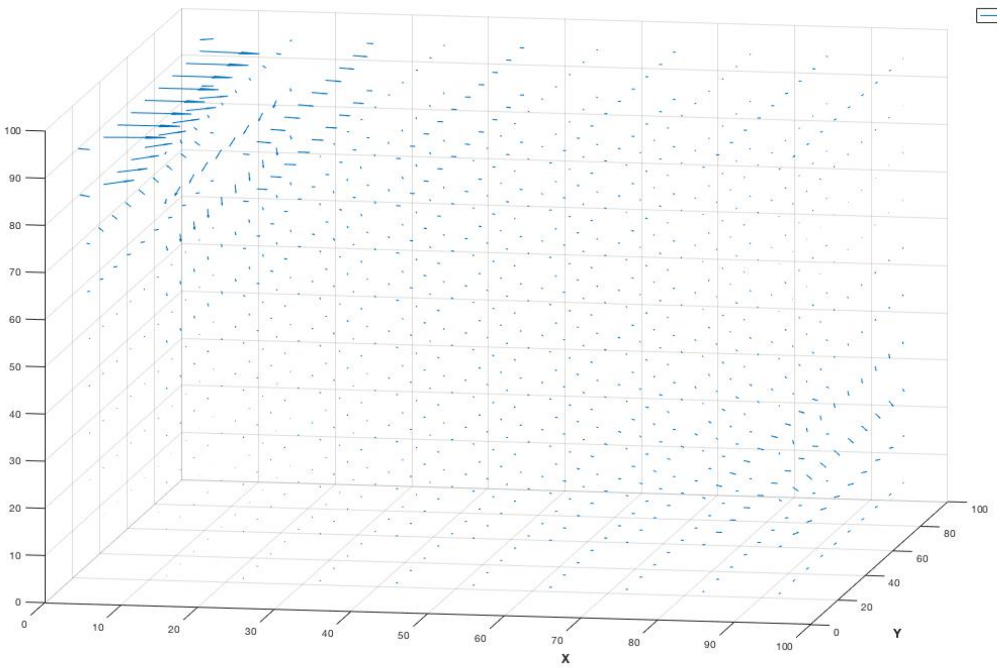
This setup is modelled to verify the pressures and velocities in three directions. Multiple smaller steps were performed: initially without in- & outlet and sediment (concentration). Application of the inlet, outlet and concentration was gradually applied. The intermediate result includes the following properties:

- Concentration implemented;
- Rouse distribution;
- Proposed inlet velocity profile;

Figure 8-1: Throughput flow in hypothetical tank set up

Tank setup with appropriate values for in- & outlet

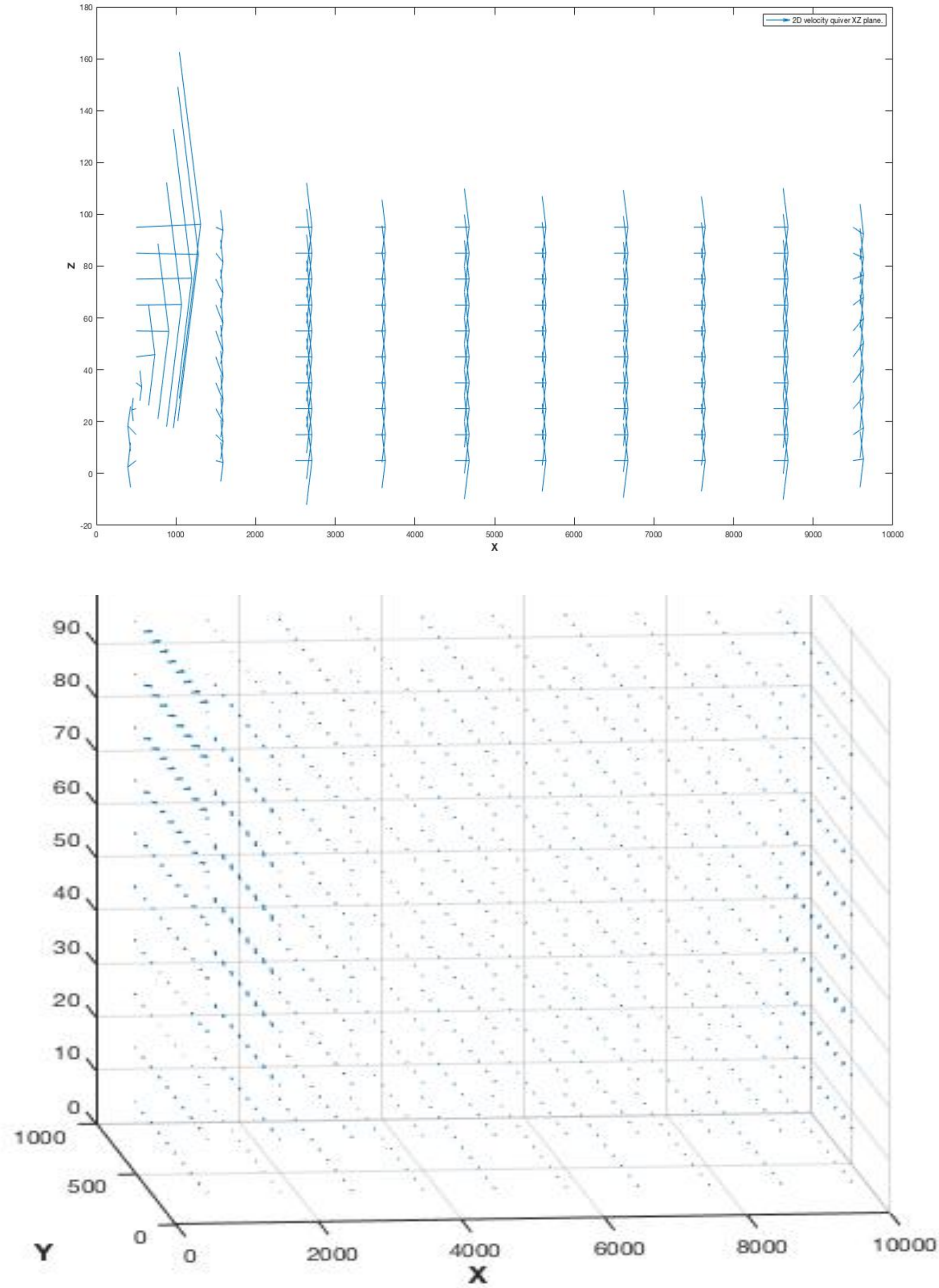




This setup involves verification of modelled in - & outlet height and position in Y and Z direction.

Figure 8-2: Tank setup with theoretical simulation of upstream river and downstream dam sluice gate

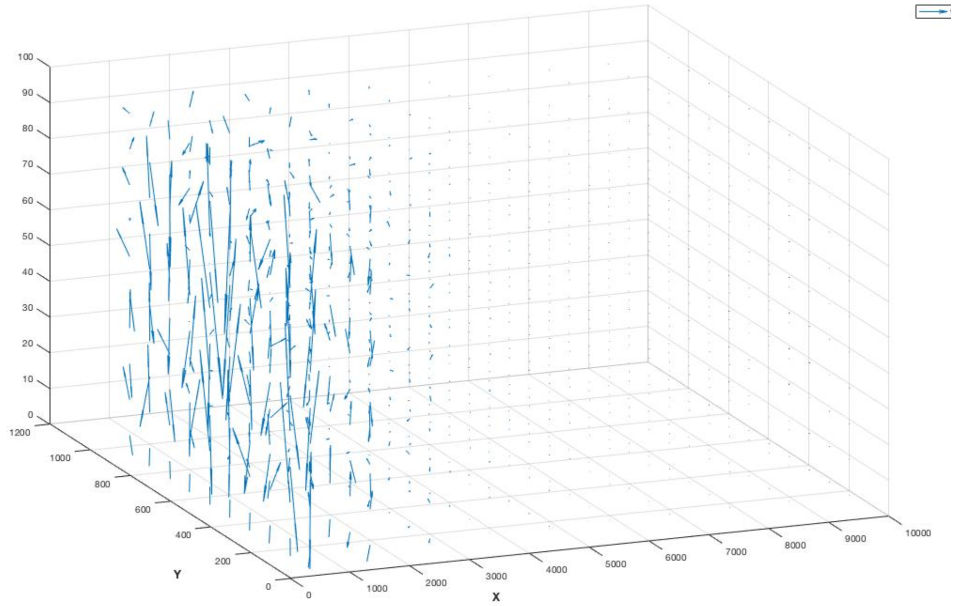
Hypothetical reservoir setup with all open in- & outlet



Validation check with application of specified reservoir dimensions in chapter 4. The quiver graph shows increased values near in- and outlet, the representation of current in the reservoir is slightly faded due to large X (length) range compared to Y (width) and especially Z (height).

Figure 8-3: Velocity quiver (2D & 3D) with CFD simulation for a hypothetical reservoir with in- and output.

Hypothetical reservoir setup with standard values for in- & outlet



Indication of flow in the reservoir after CFD simulation time of 3600 seconds (1 hour).

Figure 8-4: 3D quiver of reservoir setup.

As discussed in chapter 4, the CFD pressure correction model does not support modelling for extended periods of time. Therefore, the CFD model simulation time is specified to be as large as 3600 seconds (1 hour).
The figure above shows increased velocities near the inlet/upstream in the reservoir. Velocities near the inlet develop largely due to the Boussinesq approach (simulation of density current) and continuous inflow of sediment during the active period in a year. The gradient in concentration strengthens the flow until a balance is achieved.

The model is useful and a good basis to obtain general knowledge about settling behaviour in reservoirs, but still has a number of important limitations and issues.

The computing power that is required to model for longer simulation is at least not practical. More importantly, it is not feasible to gain a steady state or balance in the reservoir when it comes to sedimentation and settling. It requires between one month up to one year of simulation time to flush the gross capacity of the reservoir completely, let alone develop a steady state solution. It has already been discussed, but the vertical wall at the inlet in combination with a horizontal bottom profile probably overdraws sedimentation at the entrance to the reservoir. It would be a valuable addition to be able to specify a reservoir depth at the inlet and outlet, resulting in a gradual reservoir slope from the beginning.
Finally, there remains an issue with stability in the solution and the occurrence of unrealistic values occurs over time. The initial solution after the first timesteps are symmetrical and if this model is to be improved in the future, it will be probably be due to boundary conditions or approach of the pressure correction at the inlet.

8.2. CFD sediment aggregation

The first sedimentation results are based on the CFD model. Figure 8-5 toFigure 8-6 show results of the distribution of concentrations in XY - and XZ - plane near the bottom (k = 1) and at the centre of the width of the reservoir.

X →, Z ↑

0.0017	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1828	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0014	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 8-5: Concentration in XZ plane at j = 5 [$*10^{-6}$]

Y →, X ↓

0,0000	0,0314	0,0881	0,2076	0,2899	0,2899	0,2076	0,0881	0,0314	0,0000
0,0000	0,0000	0,0002	0,0633	0,1139	0,1139	0,0633	0,0002	0,0000	0,0000
0,0000	0,0000	0,0000	0,0314	0,0570	0,0570	0,0314	0,0000	0,0000	0,0000
0,0000	0,0000	0,0000	0,0000	0,0002	0,0002	0,0000	0,0000	0,0000	0,0000
0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000

Figure 8-6: Concentrations near bottom after CFD simulation [$*10^{-31}$]

It is clear from above figure that almost all aggregation occurs directly beneath from the upstream river mouth. There are a few probable causes for this result.

- The Boussinesq approach is an important cause to set vertical flows in motion. The concentration near the inlet is high compared to the concentration elsewhere in the reservoir (especially since there is no steady state yet). Despite the still very low concentrations at the inlet, it has large effects on the flow pattern in the reservoir. It overcomes the purely horizontal velocity at the inlet and settling appears to go quickly. Hindrance probably plays almost no role, since concentrations are very low everywhere.
- The simplified shape of the reservoir is a probable cause for such a big influence of the Boussinesq approximation on the development of the flow. Perfect vertical walls directly after the inlet to the bottom of the reservoir and no inclination in the reservoir ($i_{bed,reservoir} = 0$) make settling a more important process than the original river discharge flow pattern.
- Morphological changes are not considered.

Results of the initial sediment distribution in section 8.1 and 8.2 show the first effects after the CFD simulation. From here on, the results of sedimentation after a reservoir lifespan of 50 - 100 years will be discussed.

While the enhanced effect of settling is not a real problem initially, it does become problematic when the sedimentation is extended to a reservoir lifespan. The sediment rate is established at one percent per year. This, in combination with the CFD concentration distribution result in an unrealistic high sedimentation velocity right beneath from the river mouth. Moreover, the sedimentation velocity is assumed constant over time, no matter how the morphology in the reservoir changes. Corrections for unrealistic high sedimentation velocities are discussed in 4.3 and basically involves averaging locations with high sedimentation velocities with neighbouring locations with lower sedimentation velocities (simultaneously meeting the maximum angle of repose).

<u>Sediment height</u>

The hypothetical sediment height after a reservoir lifespan of about 50 years is shown in Figure 8-7. A lot of aggregation appears almost immediately after the upstream river mouth. The CFD approach does not support morphological changes in the bed and even if it would, it would still not result in any meaningful results after such a short simulation time. A more precise and possible improvement of modelling would be to develop a sequence of CFD and morphological models following up one another, eventually bridging a longer period or the complete reservoir lifespan.

Figure 8-7 shows the expected morphological development for the Ke Go reservoir. The base year is 2019 with approximately 425 million m^3 of capacity. The bottom height develops and about half of the original capacity (2019) is left in 2070. After 50 years of operation, the bottom height will still be unchanged at the dam. About 2 – 3 kilometres will still be left from the dam, which is provisionally sufficient for hydropower generation. Without dredging, new generation alternatives will have to be identified quite swiftly. Hydropower generation will drastically decrease shortly after the 50-year period.

While hydropower generation is still in full operation, other functions of the reservoir will likely be reduced already. A large part of the reservoir will have a remaining depth of about 10 meters, which will probably have far-reaching consequences for commercial fishery activities, biodiversity and supply of quality water. The results from the CFD in combination with the extension to 50 (up to 100) years is consistent with the findings of average lifespan of reservoir from Wieland (2013). A reservoir becomes partially obsolete after 4-6 decades. The expected decline in hydropower generation is finally the last substantial loss, which will be faced in the 2 decades after the first period of 50 years.

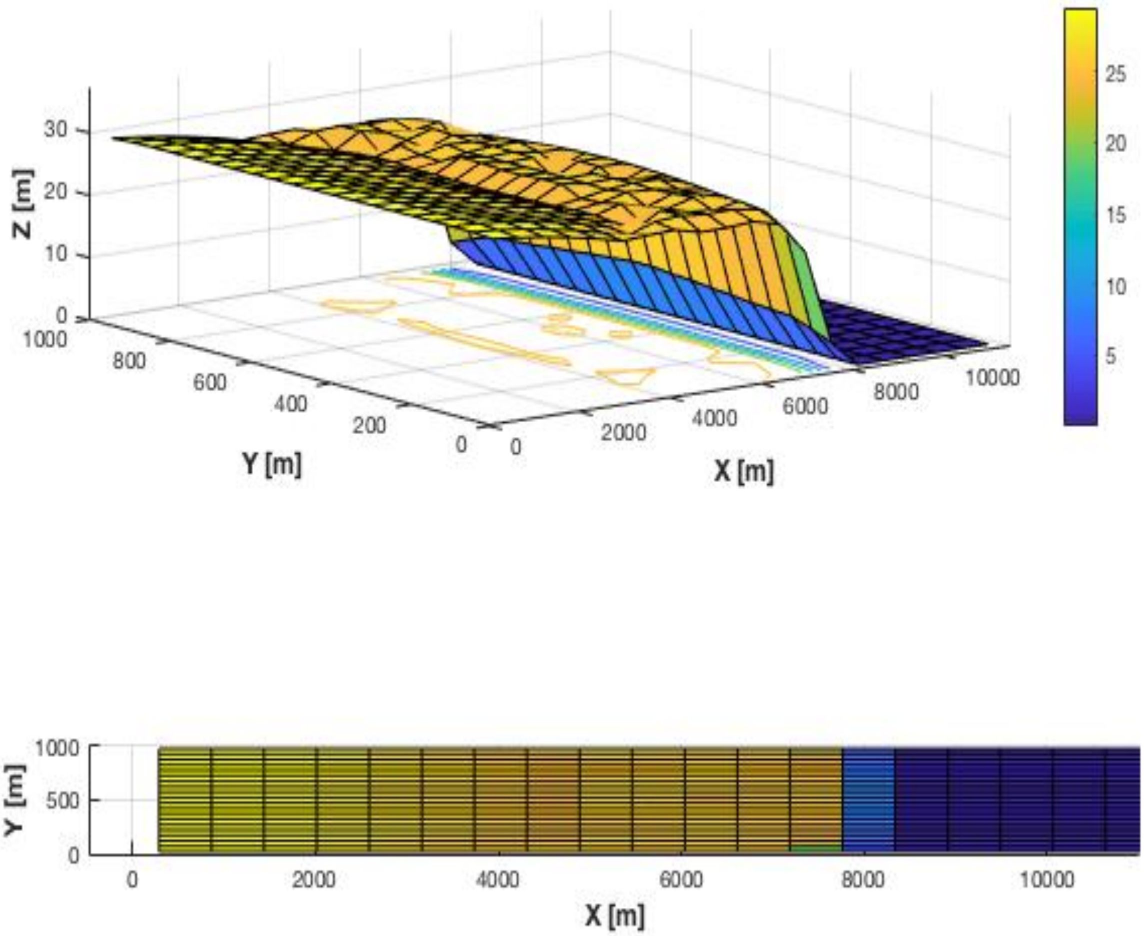


Figure 8-7: Sedimentation after reservoir lifespan without any form of management [dredging or flushing].

8.3. Sediment management

Based on the prognosis of sedimentation, the proposed dredging alternatives are reviewed. This and upcoming sections deal with sediment management (dredging) and identify a best solution given the technical requirements of the case and incurred costs of dredging.

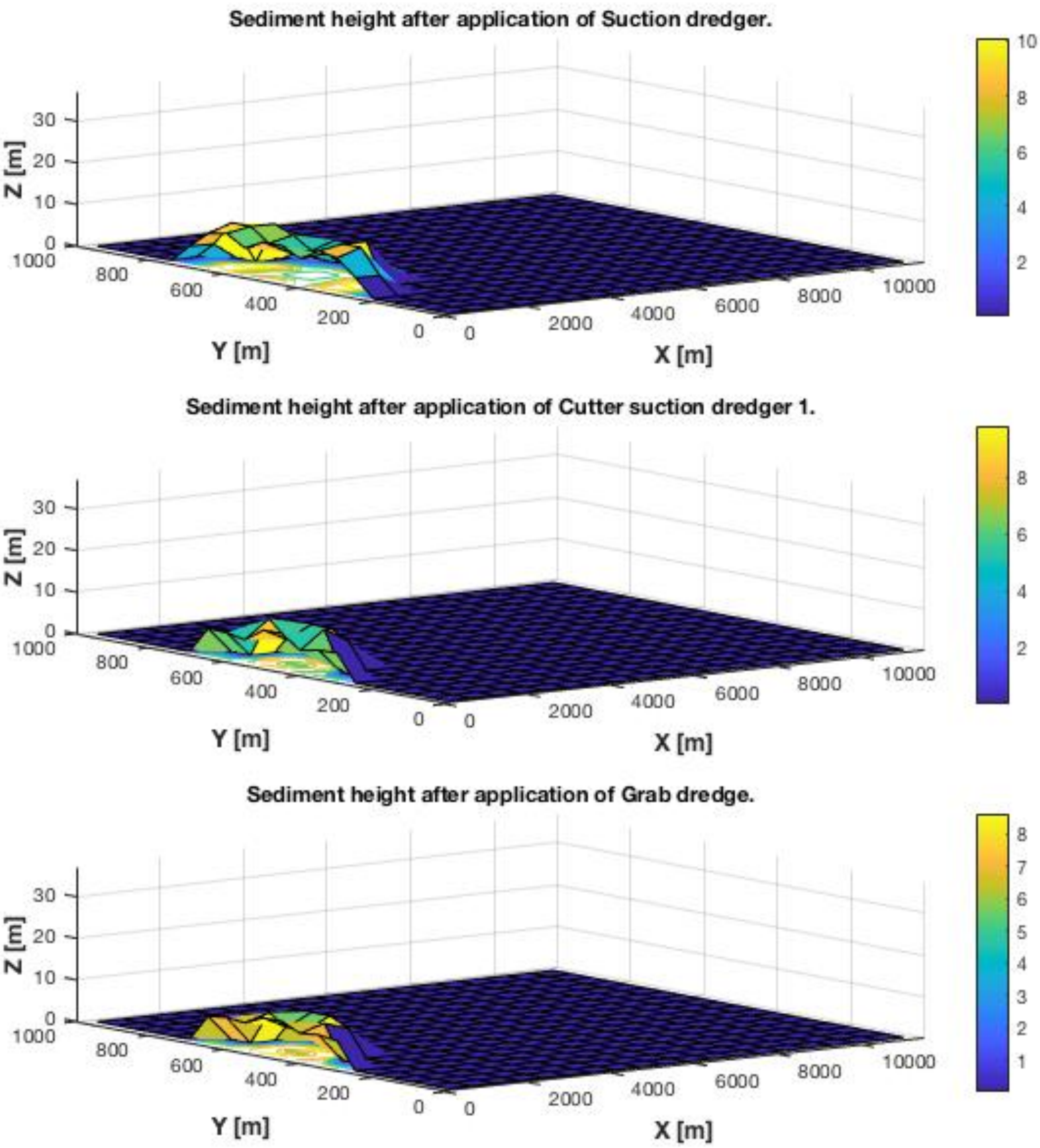


Figure 8-8: Sedimentation after reservoir lifespan with application of feasible dredging equipment [1-3].

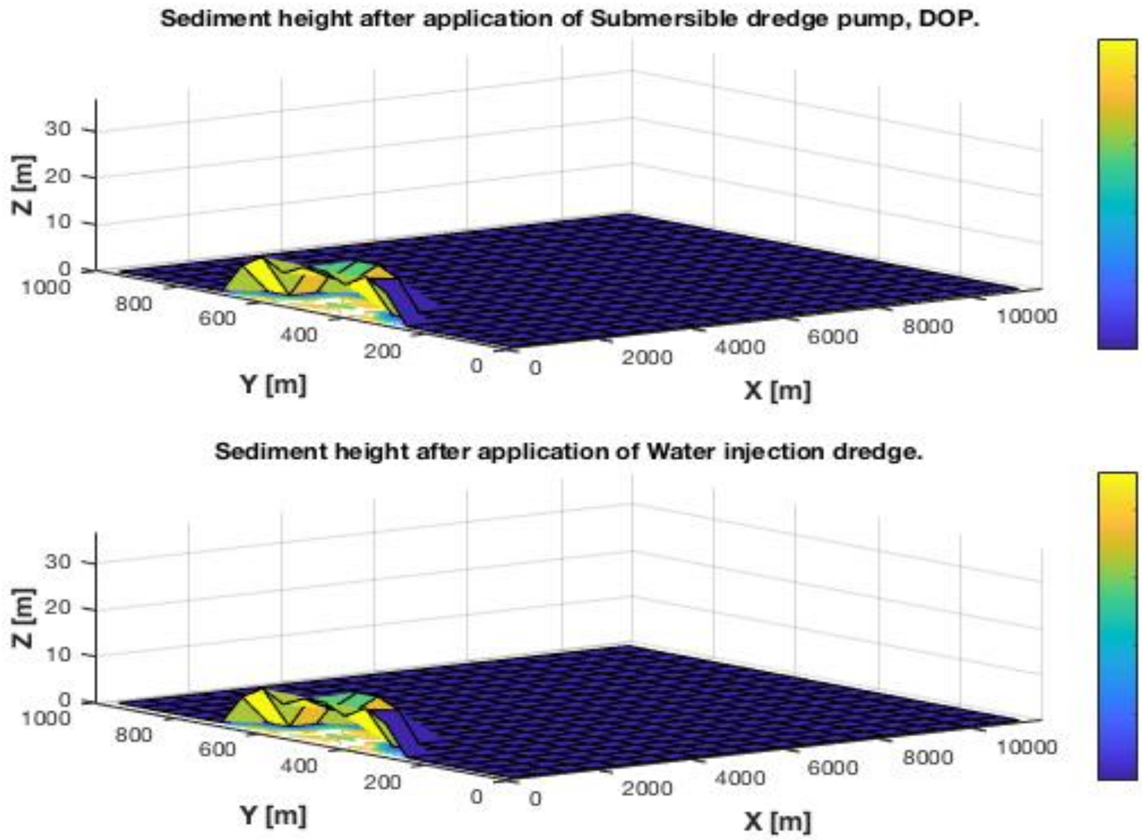


Figure 8-9: Sedimentation after reservoir lifespan with application of feasible dredging equipment [4-5].

Figure 8-8 Figure 8-9 show that 5 dredging alternatives are feasible for the Ke Go reservoir. This is mainly based on particle size diameter and required dredging depth. Every method has enough capacity to prevent sedimentation. Complete prevention of sedimentation is impossible, since dredging activities only commence after a minimum height of sediment in the reservoir. The productivity of the grab (and backhoe) dredge highly depend on the dredging depth at the location. Since most of the sediment settle near the river mouth, it is not necessary to dredge 100% of the original reservoir depth. This would be completely different if sediment would settle near the sluice-gates at the end of the reservoir. Dredging activities are required if the sedimentation height is beyond the base height of the hydropower generation sluice-gates (defined dead storage height) and will then continue to a depth of 50% of the dead storage.

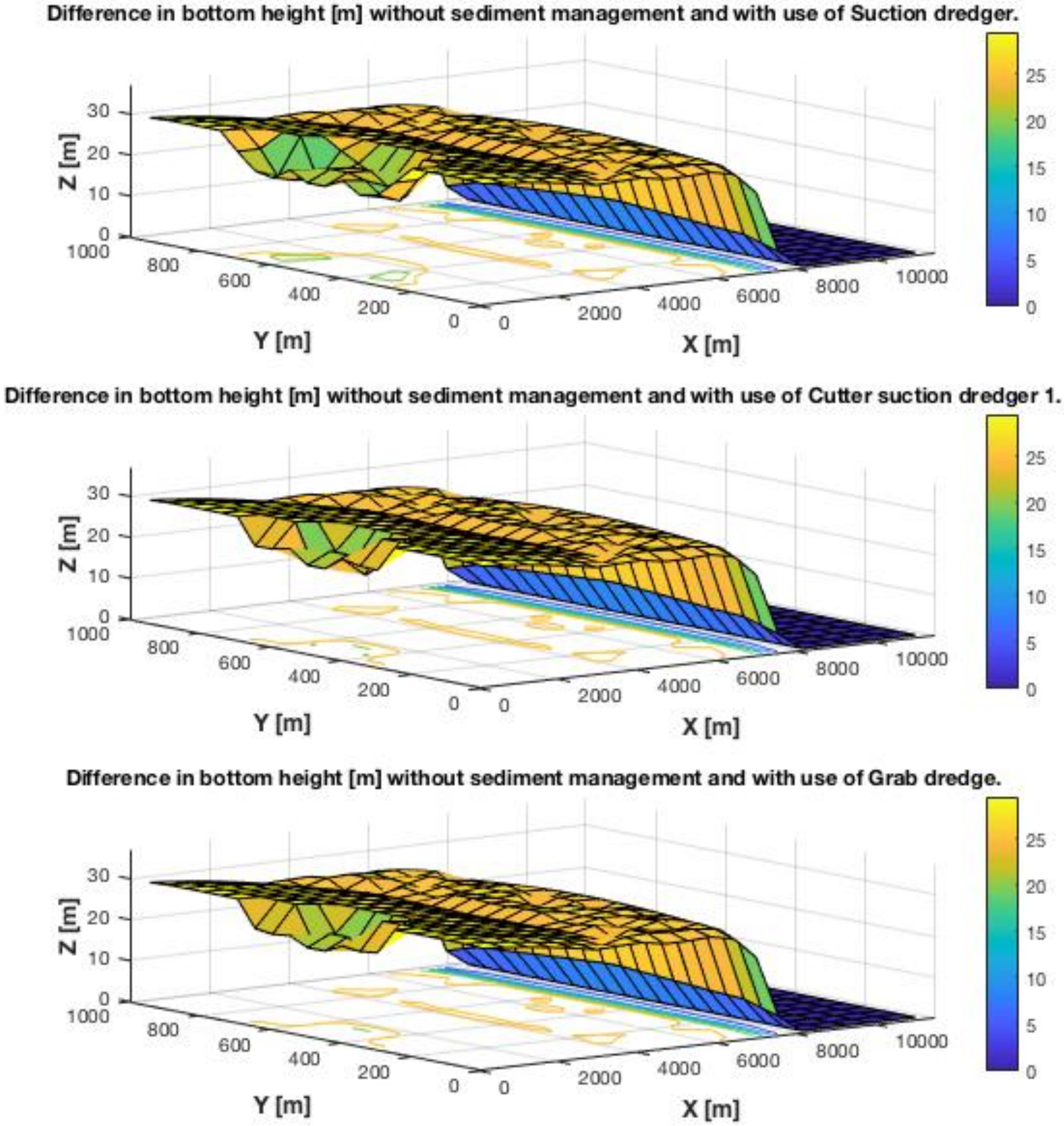


Figure 8-10: Difference in height of sedimentation between sedimentation management and without sedimentation management [1-3]

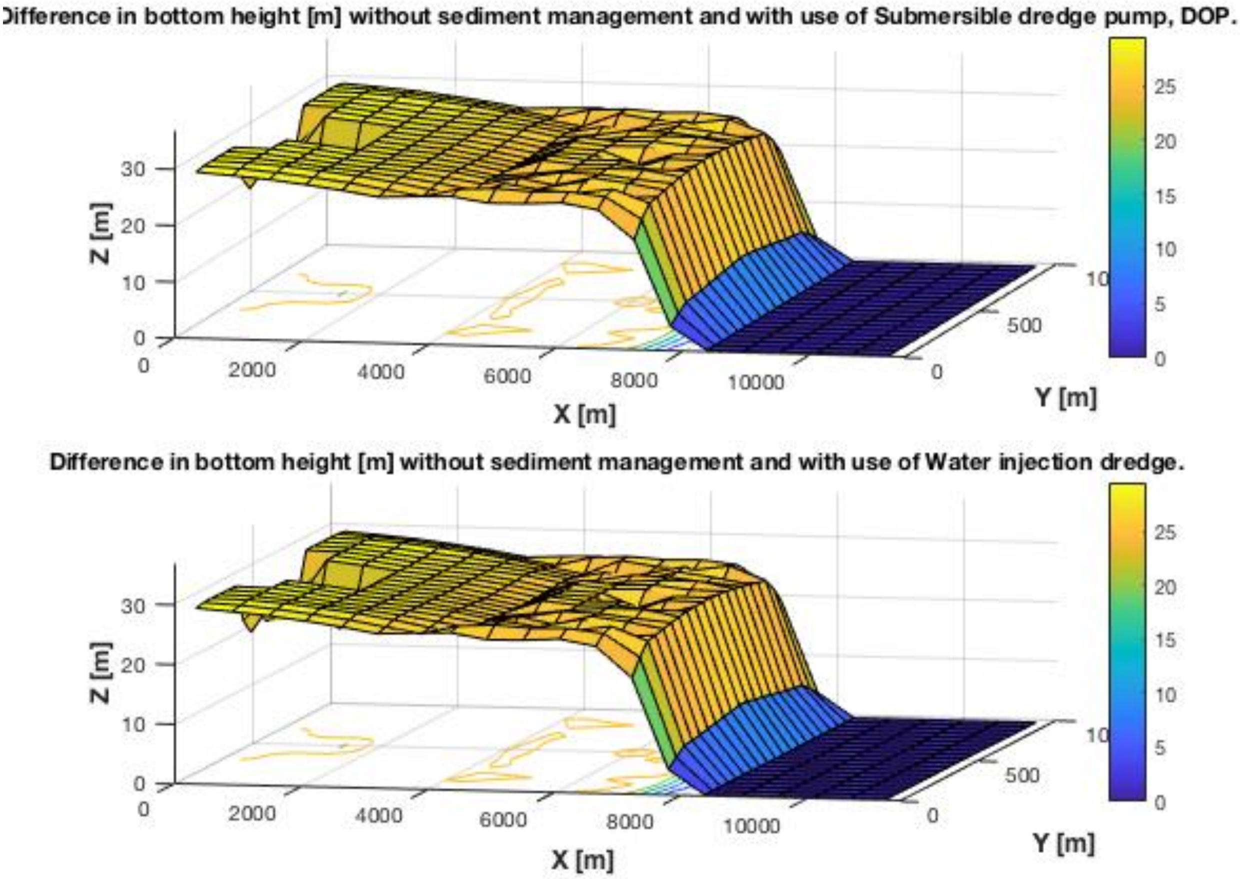


Figure 8-11: Difference in height of sedimentation between sedimentation management and without sedimentation management [4-5]

The difference in bottom height for the 5 feasible methods shows the amount dredged in total. Almost all dredging activities will be executed very close to the river mouth. The figures are therefore not a reflection of dredging locations. It merely gives a clear comparative between sediment height with and without dredging operations during the operational lifespan of the reservoir. Appendix D.2 provides with an overview when and where dredging operation will probably be needed (submersible dredge pump only, as it is the most cost-effective compared to the other 4 methods).

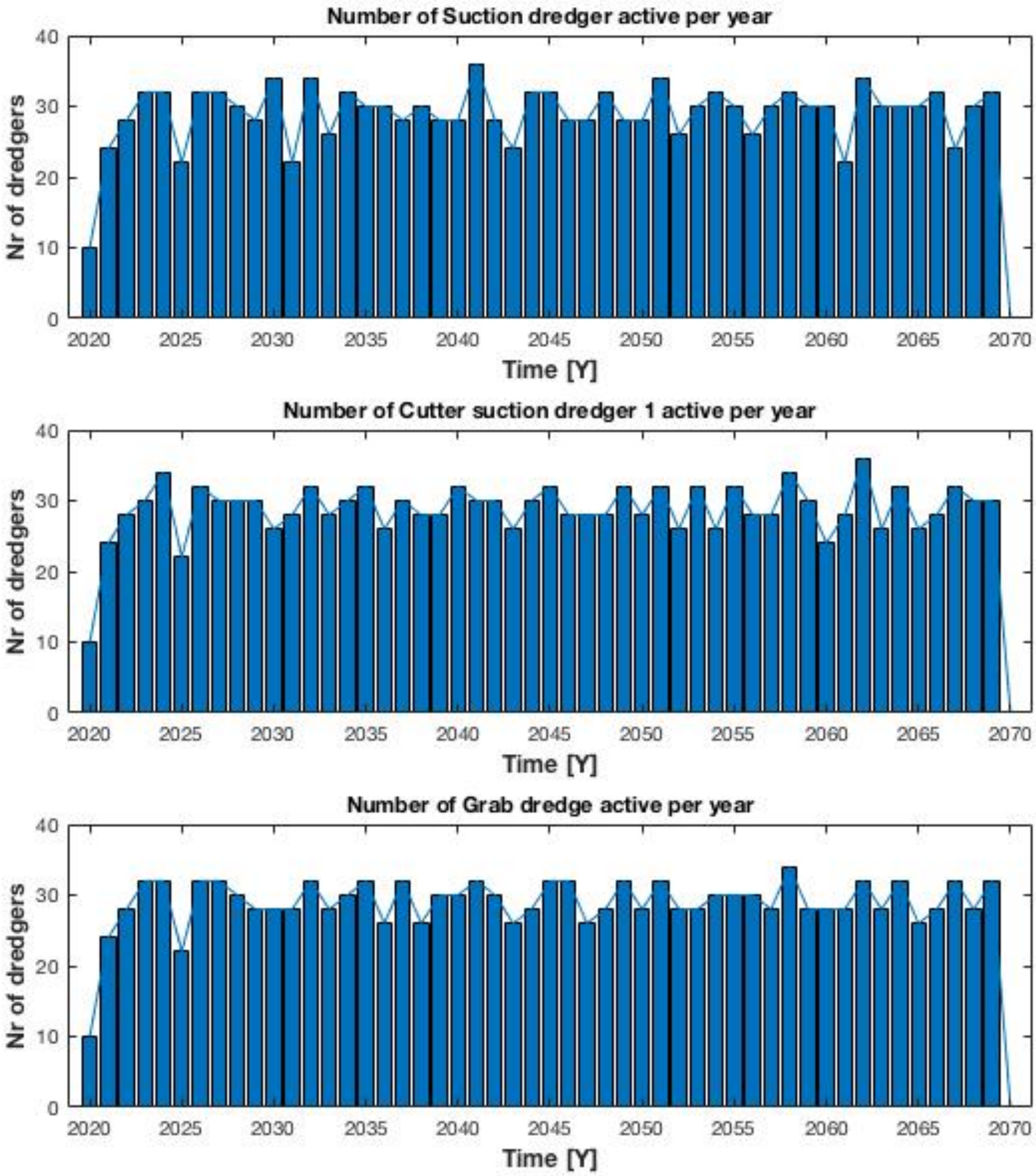


Figure 8-12: Dredging activities per year [1-3]

The duration of a dredging project for the Ke Go case varies from 2.5 to 6 weeks. With this project duration, a dredger can execute between 8 to 20 projects per year. The projects as designed now are relatively short. Decreasing the number of projects is possible. Dredging could be postponed longer too and the maximum dredging depth could be increased to the complete dead storage. There will be a trade of between organizational complexity and dredging/reservoir productivity. Table 8-1Table 8-2 show durations and maximum annual and total number of projects. The course of project intensity is stable and only the first 2 years of reservoir operations are characterized by substantially fewer dredging activities. The uniform progress of dredging activities over the years are an indication that sedimentation is not significantly larger than the installed dredging capacity.

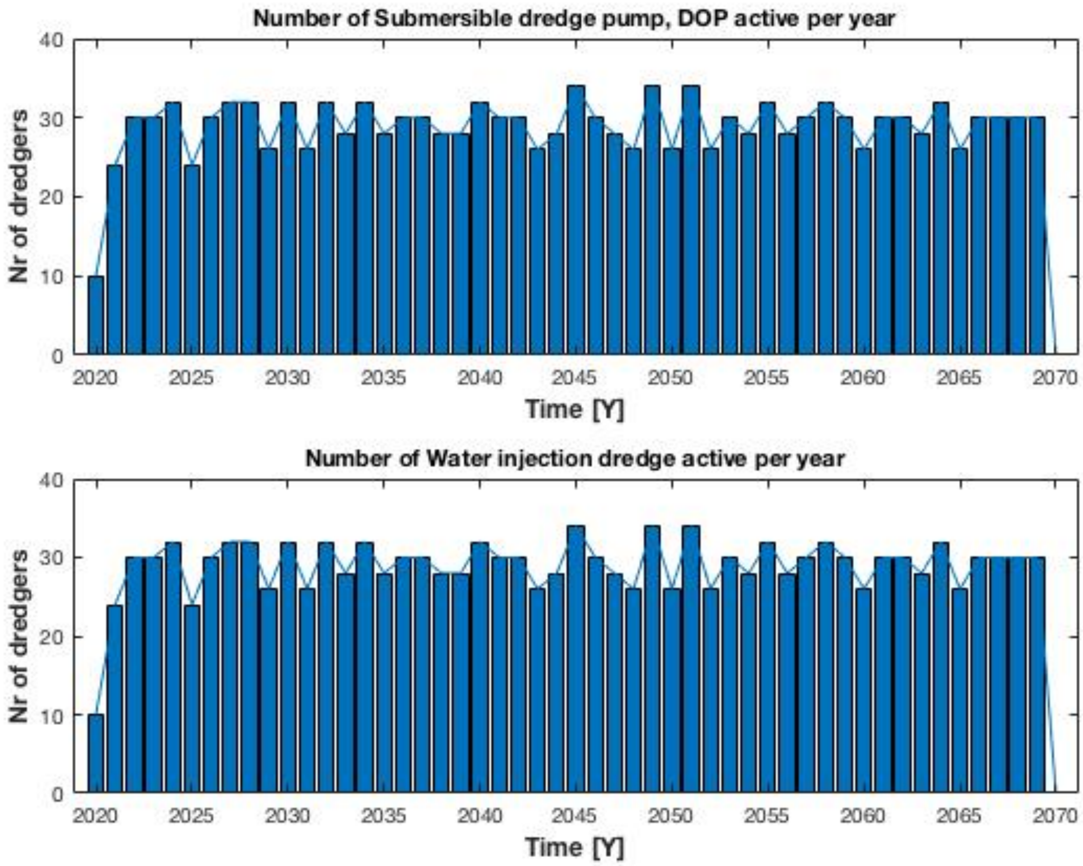


Figure 8-13: Dredging activities per year [4-5]

Table 8-1: Project outlook

Projects/year	Total	Max projects per year
Method 1: Suction dredger	1452	36
Method 2: Cutter suction dredge 1	1442	36
Method 3: Grab dredge	1448	34
Method 3: Submersible dredge pump, DOP	1450	34
Method 5: Water injection dredge	1450	34

Table 8-2: Average project duration

Project	Duration [weeks]
Method 1: Suction dredger	5.81
Method 2: Cutter suction dredge 1	2.42
Method 3: Grab dredge	4.54
Method 3: Submersible dredge pump, DOP	2.53
Method 5: Water injection dredge	2.82

8.4. Dredging costs

An important part of the final policy advice whether or not to deploy dredging equipment in the case reservoir is the direct dredging costs. The scope of the projects is first assessed, after which the direct costs will be discussed. Flushing will not be considered here, since sediment will settle near the river mouth, instead of any significant sediment aggregations near the dam.

8.4.1. Dredging scope

Figure 8-14 toFigure 8-15 show the expected purchase planning for the Ke Go reservoir. The five feasible methods show slight to significant differences over the 50-year period. A number of reasons cause these differences:

1. Deprecation time of equipment is different per method.
2. Difference in project durations can have impact on available dredging capacity.
3. Different efficiencies for different soil types.

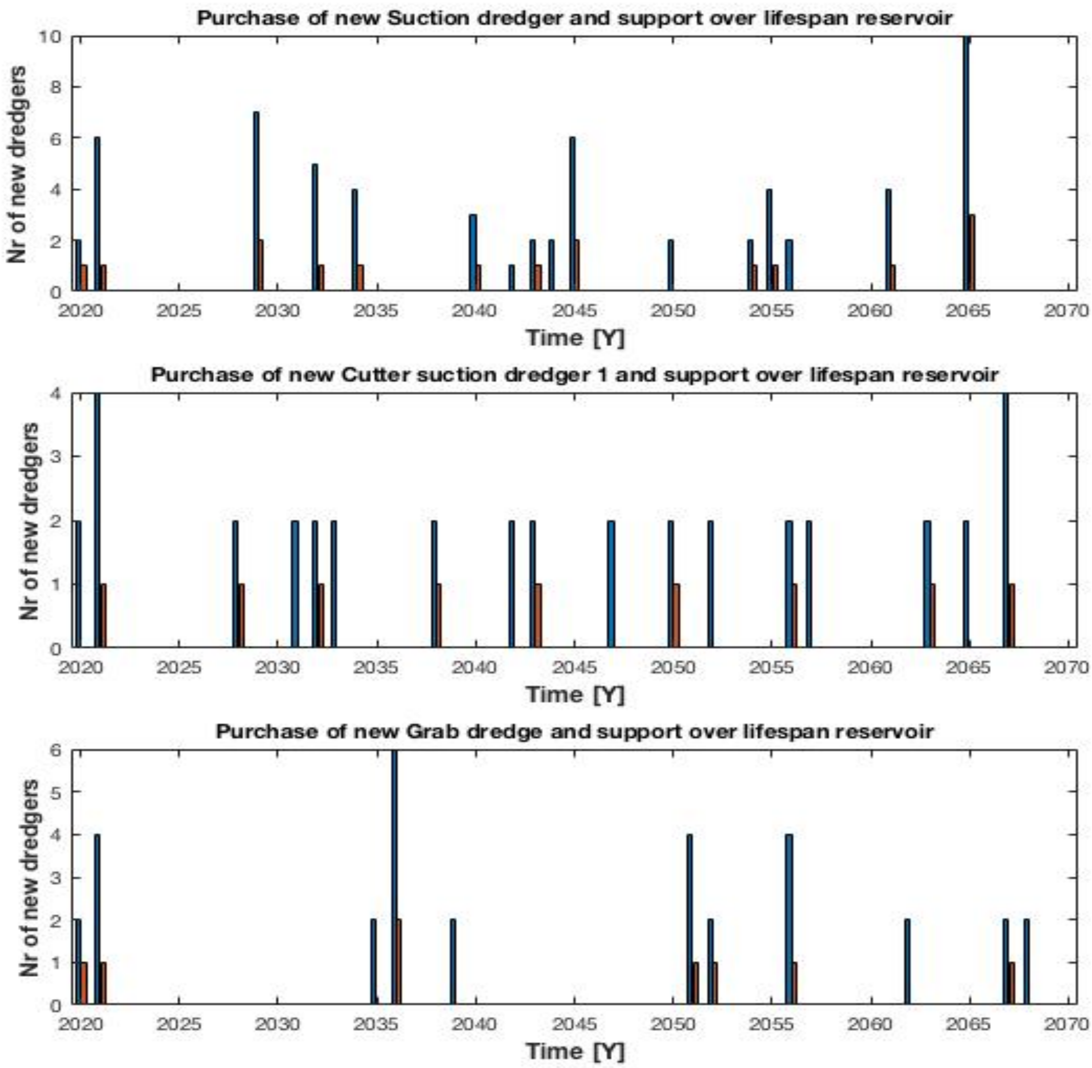
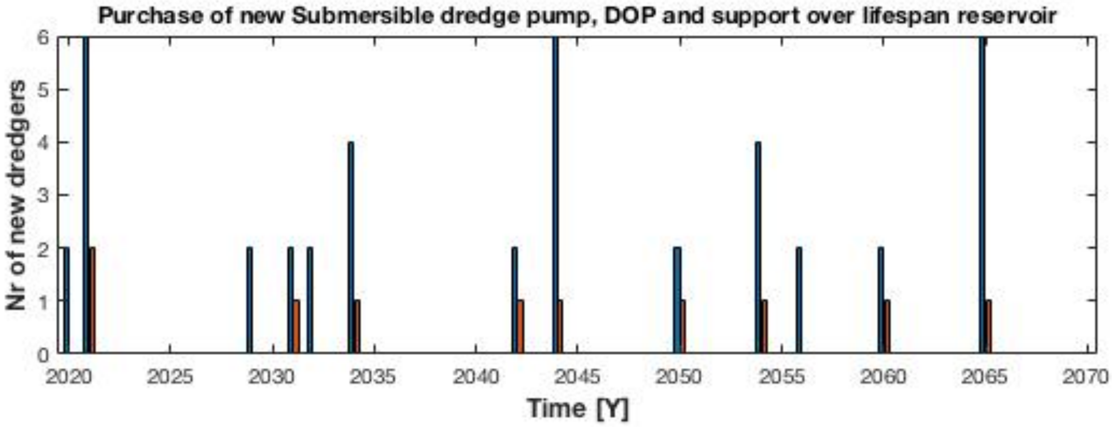


Figure 8-14: Investment outlook for dredging and support equipment [1-3]

Cash flow can be decisive under certain circumstances. Cutter Suction dredger (1) has a relatively smooth purchase progress, while other methods show steep spikes. The suction dredgers show an unfavourable investment plan with purchase of 10 units near the end of the lifespan. In general, reviewing all expected sediment management operations will need to be examined over and over. The forecast as presented in this thesis will not be accurate enough to precisely schedule purchases over a reservoir lifespan. However, it is a tool to predict and estimate the project scope and costs.



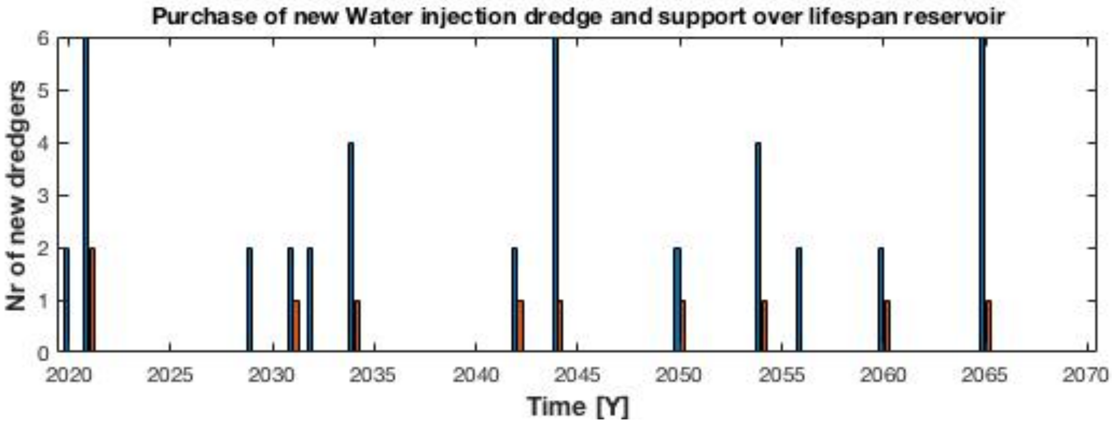


Figure 8-15: Investment outlook for dredging and support equipment [4-5]

Table 8-3: Total required dredging equipment

New required equipment	Total	Max Units per year
Method 1: Suction dredger	62	10
Support eq. method 1	16	3
Method 2: Cutter Suction Dredger 1	38	4
Support eq. method 2	9	1
Method 3: Grab dredge	32	6
Support eq. method 3	8	2
Method 4: Submersible dredge pump, DOP	42	6
Support eq. method 3	10	2
Method 5: WID	42	6
Support eq. method 3	10	2

8.4.2. Dredging costs

Figure 8-16 shows the cost estimation for the five different feasible dredging methods. The most important result is the net real valuation of dredging operations. It is assumed that 50 percent of the dredged material can be used for fertilization or other industrial purposes. Important to note is that the processing of sediment on shore is not yet included. If the cost and benefits of sediment is included, all dredging alternatives show negative net values between – €50 to – €200 million. The submersible dredge pump (DOP) and cutter suction dredge (1) have the highest and very comparable net values, respectively €-194 and €-195 million. Differences in CAPEX and OPEX are small and deprecation periods are the same.

Final evaluation of the optimum alternative will therefore be based on expected complexity of implementation, transport modes and ultimately personal considerations of policymakers. Submersible dredge pumps are relatively easy to transport by trucks, especially compared to a cutter suction dredger (even though cutter dredgers can be divided in to individual modules, for example standardized IHC Beavers). Transport of sediment through pipelines can be beneficial too. Because most dredging operations will be executed in a small area, pipelines can remain in place and operations would probably be relatively efficient compared to continuous barge transport. The purchase plan for the cutter suction dredger is the most uniform, hence beneficial in terms of cash flow and pressure on maintenance works. Still, the expect accuracy of the purchase plan is low and the purchase plan for the submersible dredge pump does not differ much from the CSD (1). The submersible dredge pump is therefore considered best for the Ke Go case and adopted in further evaluation of reservoir performance.

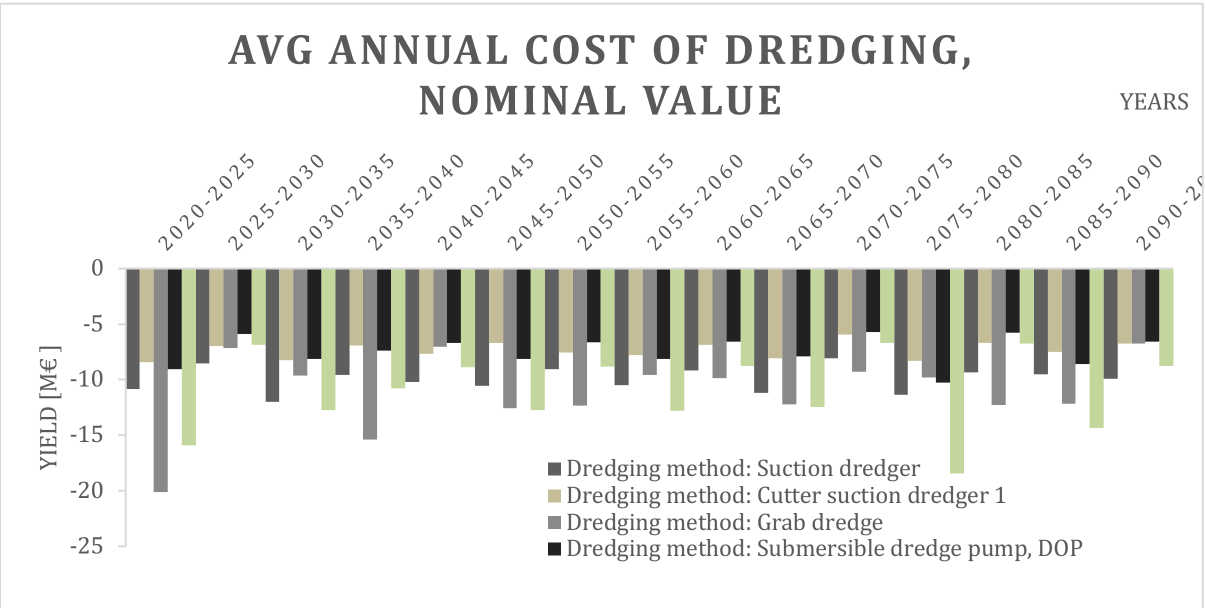


Figure 8-16: Annual (nominal) dredging costs

Table 8-4: Dredging method: Suction dredger [*106]

Core equipment	**€ -40.31**
Dredge equipment	€ -35.83
On - Offloading barge	€ -
Discharge pipe	€ -4.48
Boosters	€ -
Support equipment	**€ -9.17**
Equipment pontoon	€ -
Tug	€ -
Workboat	€ -9.17
OPEX	**€ -213.27**
Labour cost	€ -16.99
Fuel cost	€ -69.45
Storage cost	€ -63.42
Transport cost	€ -63.42
Subtotal	**€ -262.75**

Table 8-5: Dredging method: Cutter suction dredge 1 [*10^6]

Core equipment	**€ -35.09**
Dredge equipment	€ -32.39
On - Offloading barge	€ -
Discharge pipe	€ -2.70
Boosters	€ -
Support equipment	**€ -5.54**
Equipment pontoon	€ -
Tug	€ -
Workboat	€ -5.54
OPEX	**€ -153.27**
Labour cost	€ -7.00
Fuel cost	€ -20.40
Storage cost	€ -62.94
Transport cost	€ -62.94
Subtotal	**€ -193.90**

Table 8-6: Dredging method: Grab dredge [*10^6]

Core equipment	**€ -121.50**
Dredge equipment	€ -81.00
On - Offloading barge	€ -40.50
Discharge pipe	€ -
Boosters	€ -
Support equipment	**€ -15.92**
Equipment pontoon	€ -5.31

Tug	€ -10.61
Workboat	€ -
OPEX	**€ -178.14**
Labour cost	€ -11.89
Fuel cost	€ -39.79
Storage cost	€ -63.23
Transport cost	€ -63.23
Subtotal	**€ -315.56**

Table 8-7: Dredging method: Submersible dredge pump, DOP [*10^6]

Core equipment	**€ -39.95**
Dredge equipment	€ -36.88
On - Offloading barge	€ -
Discharge pipe	€ -3.07
Boosters	€ -
Support equipment	**€ -6.33**
Equipment pontoon	€ -
Tug	€ -
Workboat	€ -6.33
OPEX	**€ -148.24**
Labour cost	€ -7.39
Fuel cost	€ -14.10
Storage cost	€ -63.38
Transport cost	€ -63.38
Subtotal	**€ -194.52**

Table 8-8: Dredging method: Water injection dredge [*10^6]

Core equipment	**€ -113.71**
Dredge equipment	€ -110.64
On - Offloading barge	€ -
Discharge pipe	€ -3.07
Boosters	€ -
Support equipment	**€ -6.33**
Equipment pontoon	€ -
Tug	€ -
Workboat	€ -6.33
OPEX	**€ -173.09**
Labour cost	€ -8.23
Fuel cost	€ -38.11
Storage cost	€ -63.38
Transport cost	€ -63.38
Subtotal	**€ -293.93**

9. Results – CBA

This chapter reviews the expected costs and benefits by operating a multifunctional reservoir, including sediment management. This involves both dredge costs and sediment processing or disposal costs, as specified in chapter 6.

9.1. *Reservoir construction costs*

The construction cost and maintenance cost are predefined, mainly based on known construction costs of other reservoirs. The Ke Go dam is earth filled, which is a relatively cost-efficient type of dam. The actual cost of construction may deviate, but Table 9-1 provides with an educated guess about the amount of costs that new construction entails.

Table 9–1: Reservoir cost [$*10^6$]

Maintenance cost	€	-267.30
Construction cost	€	-9,681
Total	**€**	**-9,948**

9.2. *Dredge and disposal costs*

Table 9-2 shows a summary of dredging costs, as reviewed in chapter 8. The submersible dredge has been chosen based on flexibility and total expected dredge costs.

Table 9–2: Summary PV dredging alternatives without waste dumping [$*10^6$]

Total present value Suction dredger	€	-262.75
Total present value Cutter suction dredge 1	€	-193.90
Total present value Grab dredge	€	-315.56
Total present value Submersible dredge pump, DOP	**€**	**-194.52**
Total present value Water injection dredge	€	-293.13

Apart from the fact that dredging operations would be substantial in a reservoir such as Ke Go, dredged material still needs to be transported and processed on shore. The results of the costs and benefits of dredged material are solely based on the specification earlier; 50% of the material is considered waste, the remaining material is divided proportionally for fertilization and industrial purposes. The present value of sediment processing costs and benefits is shown in Table 9-3. The net result of sediment processing is approximately €150 million with the current settings. In the worst case, this would be €-300 million. That is if none of the material could be used and all of it would have been considered waste.

Table 9-3: Sediment processing benefits/costs (PV, [$*10^6$])

Dredge waste [cost]	€	-170
Dredged sediment for fertilization/topsoil [benefits]	€	107
Dredged sediment for industrial purposes [benefits]	€	212.50
Total	**€**	**149.50**

9.3. (In)direct costs and benefits

Table 9-4 shows the included indirect costs and benefits. Primary functions, i.e. hydropower generation, irrigation and water supply for consumption purposes add up to approximately €20 billion. On the other hand, the total cost of dredging will add up to €50 million. Dredging costs are very little in percentage of the total real yields, but still substantial. It will be particularly important in the future to provide reservoir owners and operators with the positive effects of early sediment management and its extended value for both the primary functions and the ecological footprint.

The costs incurred at the early stages of a reservoir due to obligated moving is substantial, especially when compared in real monetary value. The costs cannot be distributed over a longer period and can therefore not be discounted. Proper maintenance of a reservoir will at least postpone the occurrence of comparable costs in the future. Besides the high costs incurred, it is socially extremely undesirable to oblige residents to move.

Hydropower generation is by far the most important primary function of the case reservoir and accounts for more than 60 percent of the total yields. Initial negative effects of the decline in water storage is limited. Once the hydropower generation becomes limited, the Ke Go reservoir will likely very rapidly lose its economic and social value.

Table 9-4: (In)direct costs & benefits [$*10^9$] - 50 years

Hydropower generation [benefits]	€ 12.60
Irrigation (agricultural) [benefits]	€ 1.99
Freshwater (drinking water) [benefits]	€ 4.97
Loss of land [cost]	€ -1.12
Total social costs & benefits	€ 18.27
NET present costs & benefits (opt.)	**€ 8.18**

9.4. Flushing

Flushing without first dredging the material seems impossible, however it can be considered an alternative after the material has been dredged. Dredged material can be flushed partially by transporting it from dredge location to the dam. A prescribed concentration is allowed during flushing, see Assumption 4-D. Flushing at a rate of 5 grams of dredged material per litre of discharge is beneficial and not considered a threat for the downstream river system. Flushed materials only reach the primary river system and fertilization of the ecological system downstream is not possible since flood events are considered excluded after flood control of the reservoir.

The discharge available for flushing is initially estimated at 10.52 $m^3.s^{-1}$ (39 % of the annual reservoir discharge). Therefore, the flushing capacity is approximately 52.62 kg/s, or 1.66 million tons of sediment annually. Flushing therefore can reduce waste surplus. The annual sedimentation rate is pre-set at 1% of the reservoir capacity, flushing can reduce this rate by approximately 0.25%. Flushing can only contribute to this amount if it can be performed permanently and at an average rate of 5 grams per litre.

The previous section clearly shows that dredging keeps up with the sedimentation. Therefore, long term average dredging production equals the sedimentation rate. Waste is estimated to be 50% of the dredged material, which equals 0.5% of the reservoir capacity on an annual basis. Approximately half of the waste can be flushed, half of the waste must be dumped and stored ashore. Dumping somewhere else in the reservoir is not considered beneficial, since long term effects will be negative (replacing the original problem).

Table 9-5: Flush capacity

Total dredged waste [m^3] @ c=0.6	104,650,000
Flushing capacity [m^3] @ c=0.6	52,183,000
Residual waste to dump [m^3]	52,467,000

The waste that needs to dumped is practically halved when flushing is considered feasible for the earth fill dam (Table 9-5). While sediment in this case is considered small enough, larger particles can obstruct the flow near the sluice-gates. The dam must also be designed with flush gates, since the sluice-gates for hydropower generation are usually not suitable for a process like this. Real savings will add up to approximately €85 million and can be deducted from the cost of dredge waste dumping.

9.5. *Scenarios*

A great number of influenceable parameters can be adjusted to check the robustness of alternatives and to check optimization opportunities.
The following figures show the impact of application of dredging on the performance of the Ke Go reservoir. Each primary function will be reviewed and its performance is compared to a situation without sediment management.

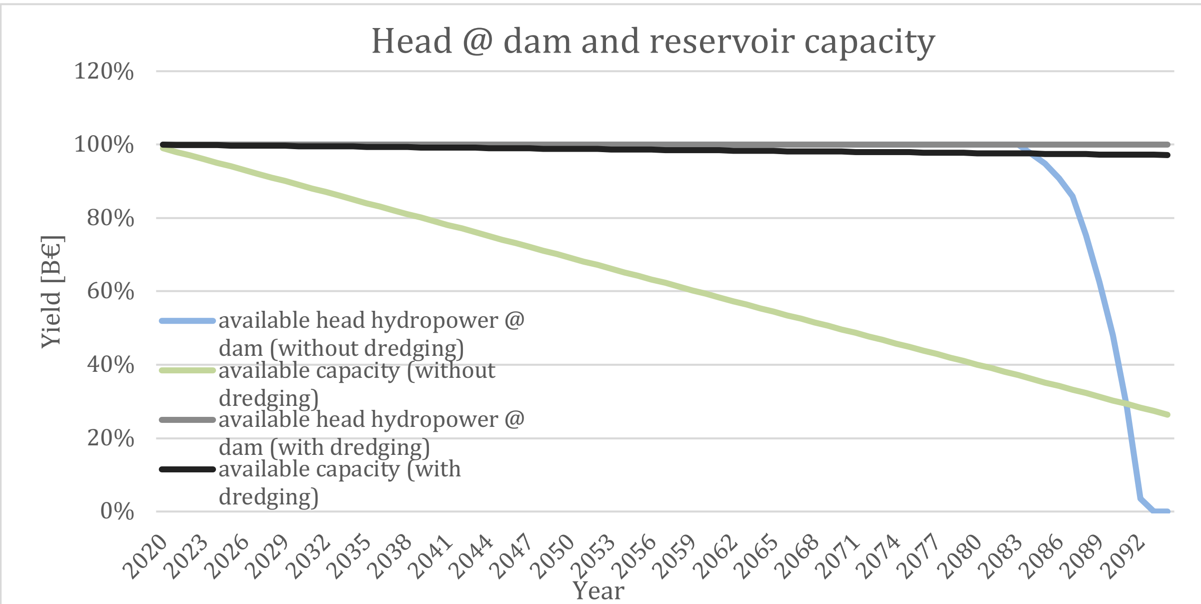


Figure 9-1: Head and capacity development with and without sediment management

Decline in water storage capacity is gradually without sediment management. On the other hand, hydropower generation will more or less vanish and possibly without a sufficiently long period to overcome the regional deficit in energy supply. This emphasizes the seemingly unbranded effects at first, but with truly large effects on the long term.

9.5.1. Reservoir lifespan

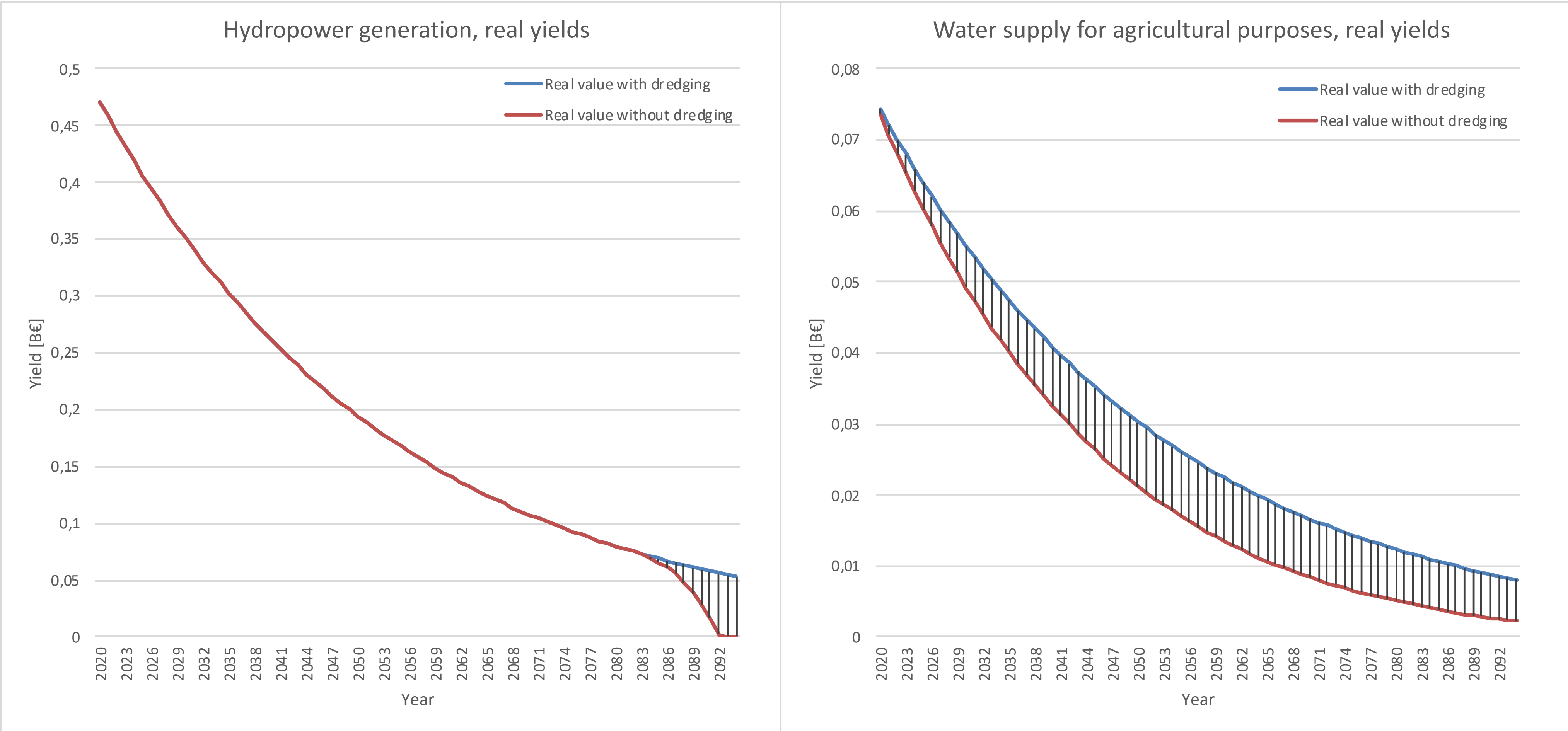


Figure 9-2: Real annual yields; hydropower and water supply for agricultural purposes

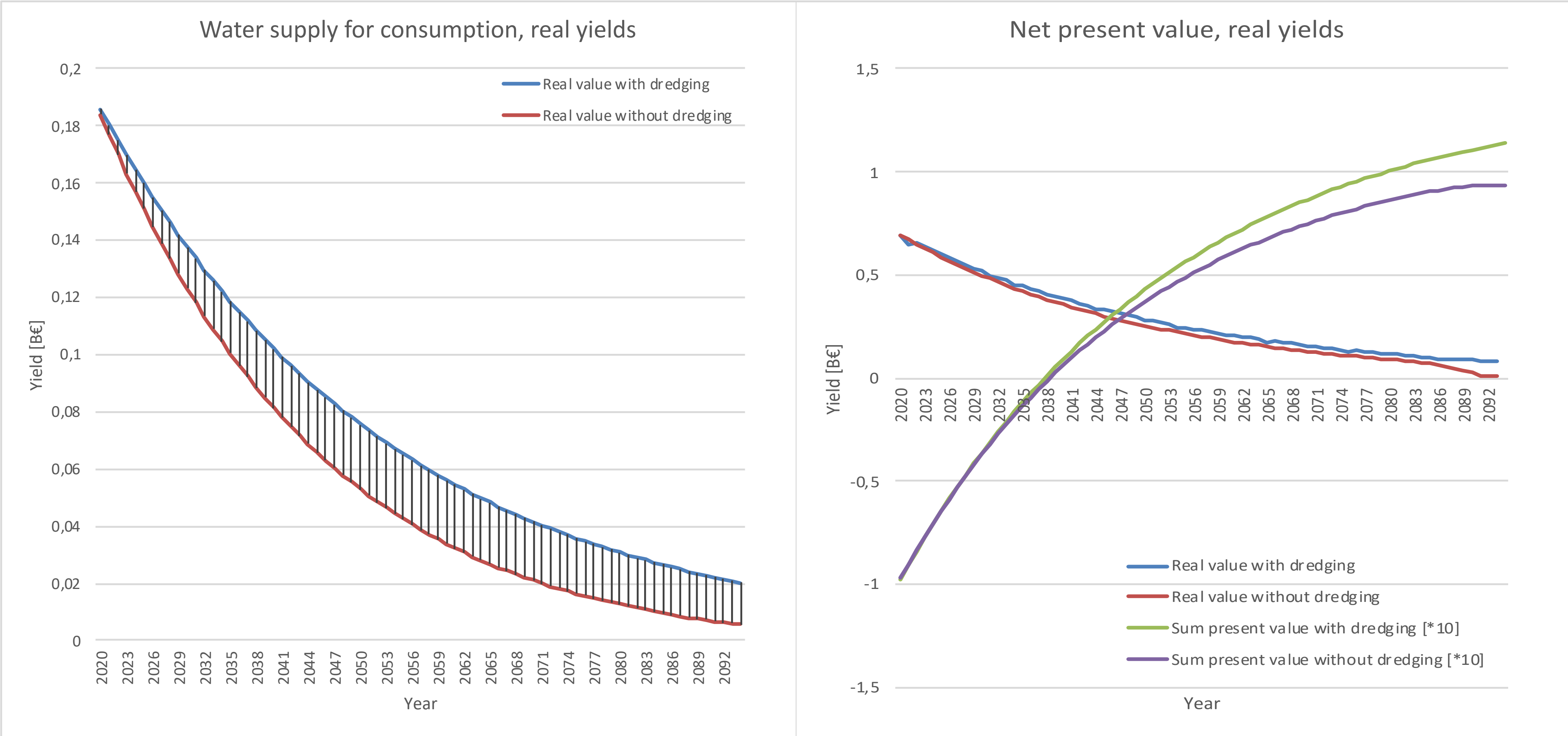


Figure 9-3: Real annual yields; water supply for consumption and net present value reservoir operations

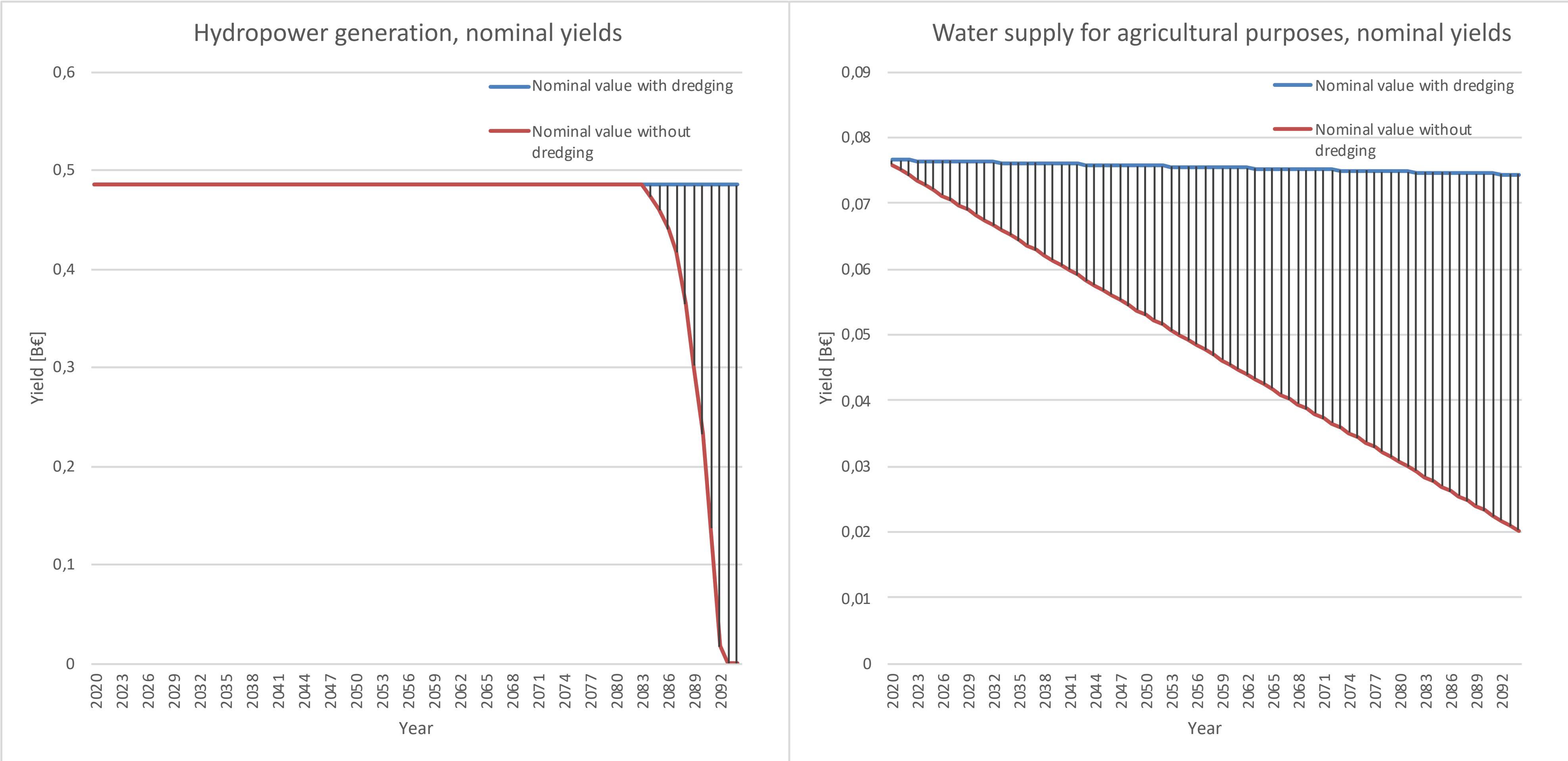
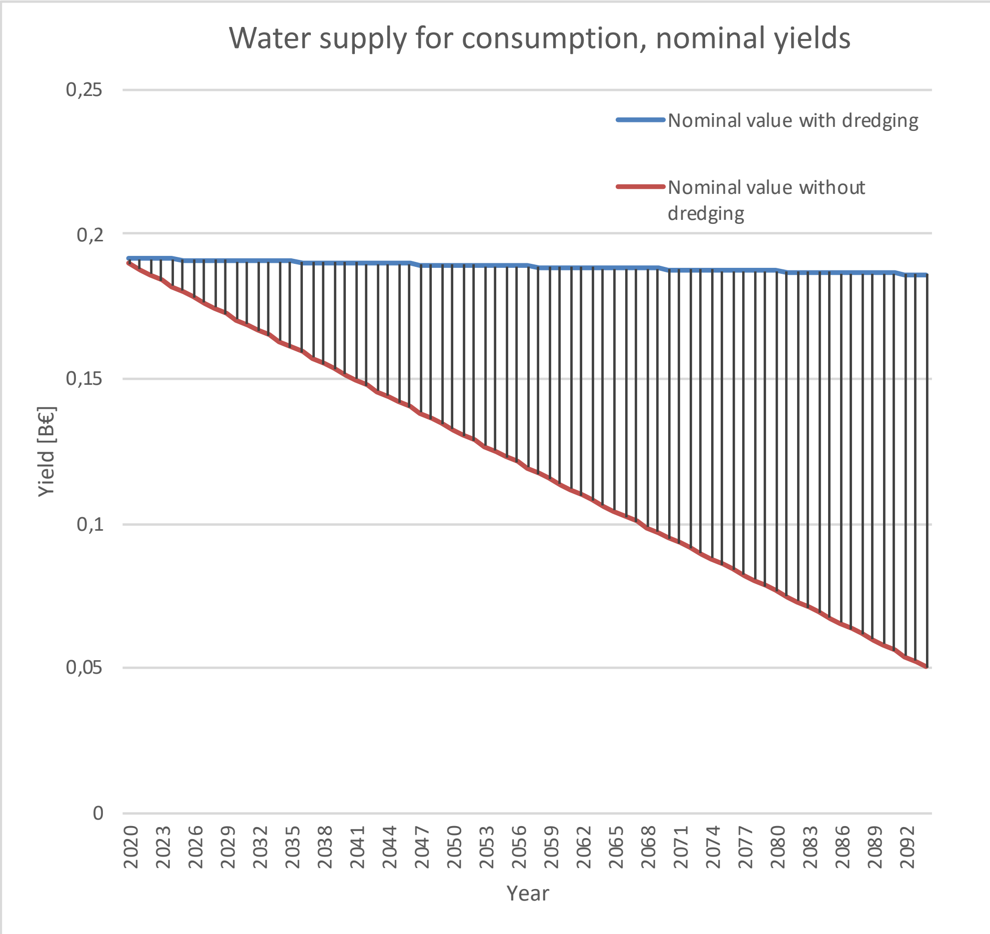


Figure 9-4: Nominal annual yields; hydropower and water supply for agricultural purposes



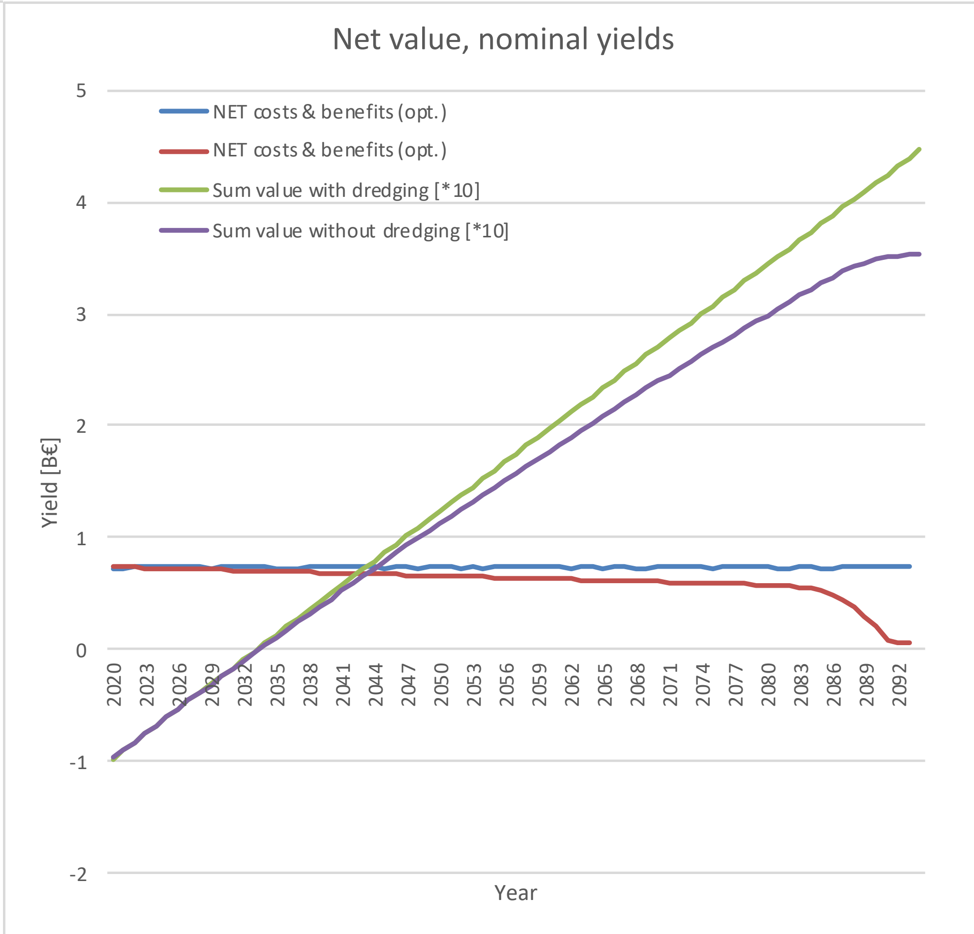


Figure 9-5: Nominal annual yields; water supply for consumption and net value reservoir operations

9.5.2. Sediment handling

Typical usability rates of dredged material from reservoirs are between 10 and 90 percent. The use of sediment is discussed earlier and numerous. To keep results transparent, dredged material is considered usable or not. Usable sediment can be applied for fertilization (top soil) or construction. Dredge waste will be partially dumped on shore and flushed as much as the system can handle environmentally friendly. Dredging costs will be low compared to the reservoir overall performance numbers, but remain substantial. Figure 9-6 shows again that dredging is favourable in the long run, no matter how low usability rates are. The maximum difference in terms of monetary value will be approximately €200 million, however necessary to overcome long term negative effects of sedimentation (after 75 years maximum approx. €3.5 billion nominal).

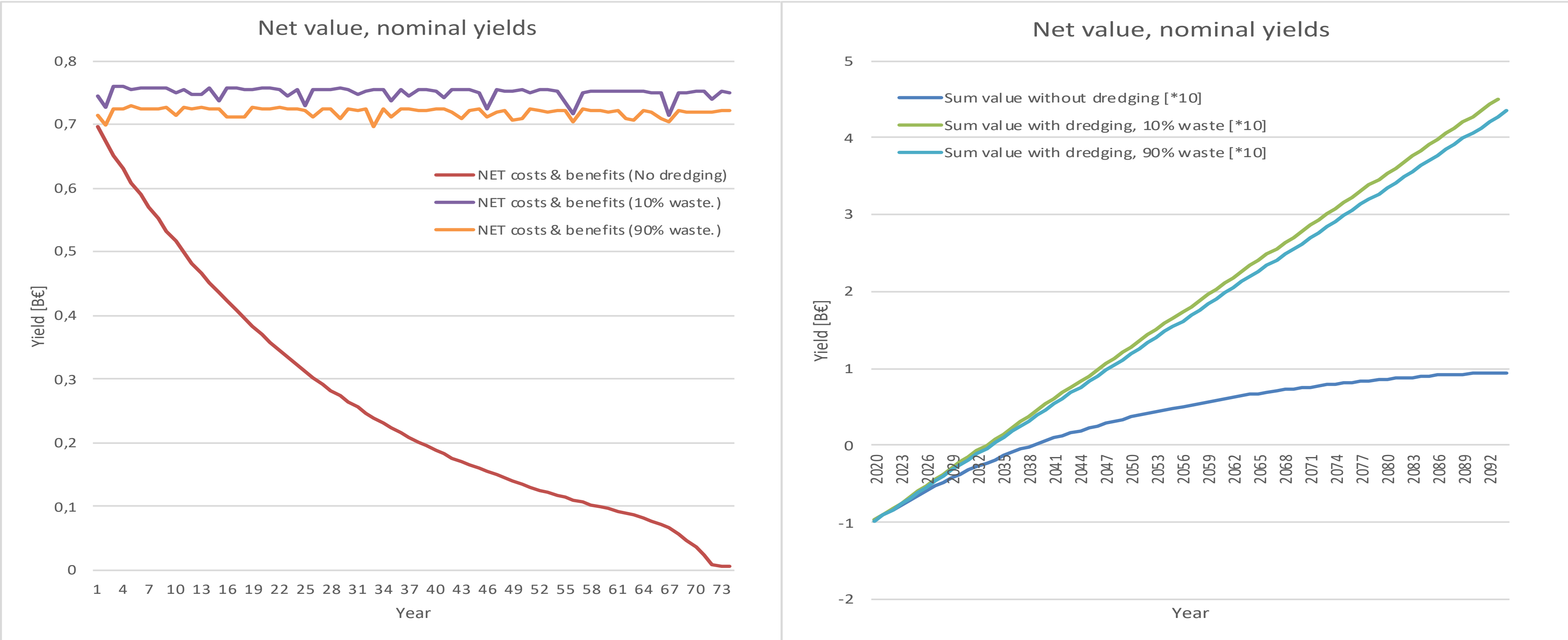


Figure 9-6 a, b: Nominal yield, variation of usability of dredged material.

9.5.3. Dredge depth

The total depth of the Ke Go reservoir is known (37 metres). Varying the head for hydropower generation and the maximum dredging depth are opportunities to optimize reservoir operations and review sensitivity.

The impact of four alternatives are reviewed:

- Changing base height of the hydropower generation sluice gate (10 to 1 metre);
- Changing base height of the hydropower generation sluice gate (10 to 20 metre);
- Changing maximum dredging depth (50% to 100% of dead storage);
- Changing upstream depth of river mouth (10 to 5 metre).

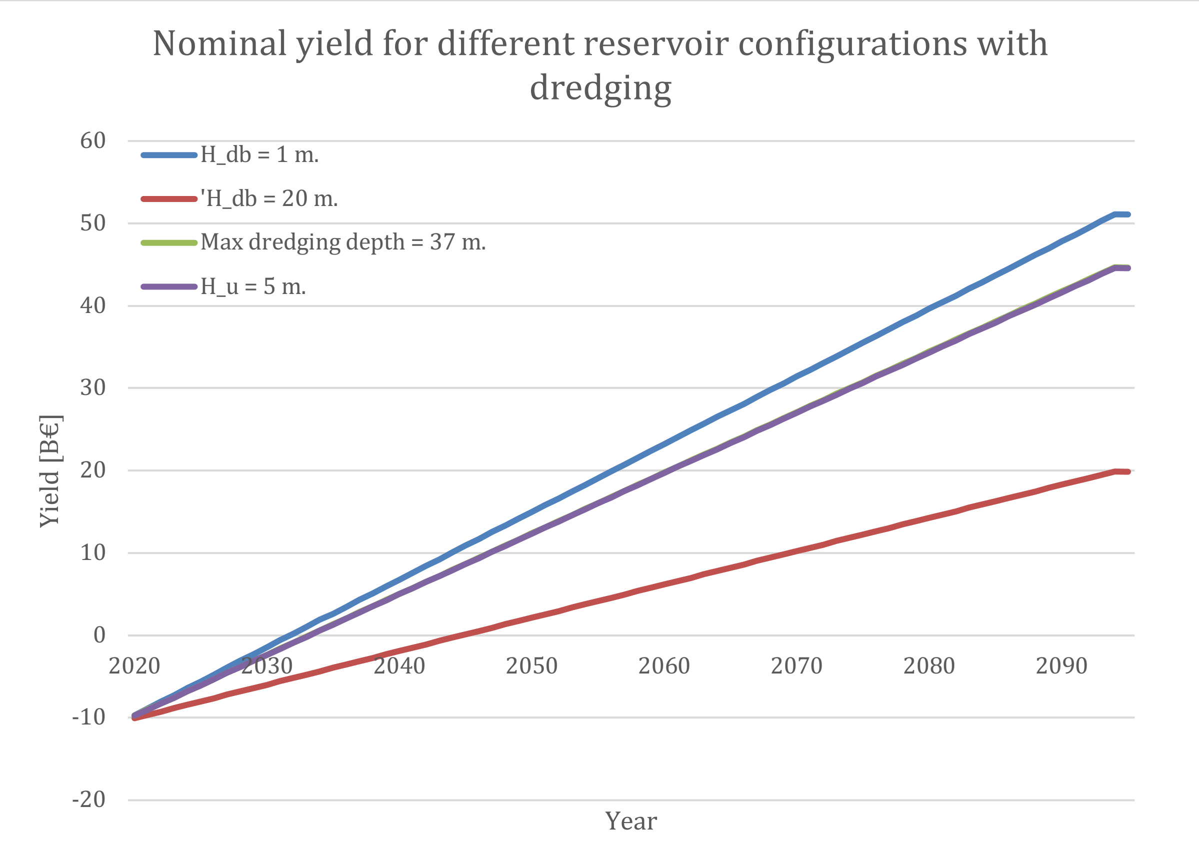


Figure 9-7: Sensitivity to river depth and sluicegate dimensions, including dredging/sediment management.

The base height of the sluice gates has the greatest impact on reservoir performance. With the sluice gates positioned as low as technically feasible, the larger available head will result in the highest achievable hydropower generation yields. On the other hand, lower positioned sluice gates will face sedimentation issues in an earlier stage. Sedimentation will probably concentrate near the inlet and only gradually develop towards the dam. Therefore, hydropower generation will continue for at least 50 - 60 years without major sedimentation problems. Once sedimentation becomes significant near the dam, it will rapidly reach heights beyond the sluice gates. Consequently, higher positioned sluice gates will in all probability not be an effective alternative. Flushing without support of dredging will only become noticeable when sedimentation effects reach the dam. By then, sedimentation velocity near the dam will rise rapidly and the flushing capacity alone will certainly not be effective to prevent the continuation of sedimentation. Flushing at undesirable high concentration could significantly decline sedimentation height, but completely halting the process would probably no longer an option. Additionally, flushing at higher average concentrations (>5gr.l^{-1}) disturbs the environment and is rejected as qualified alternative.

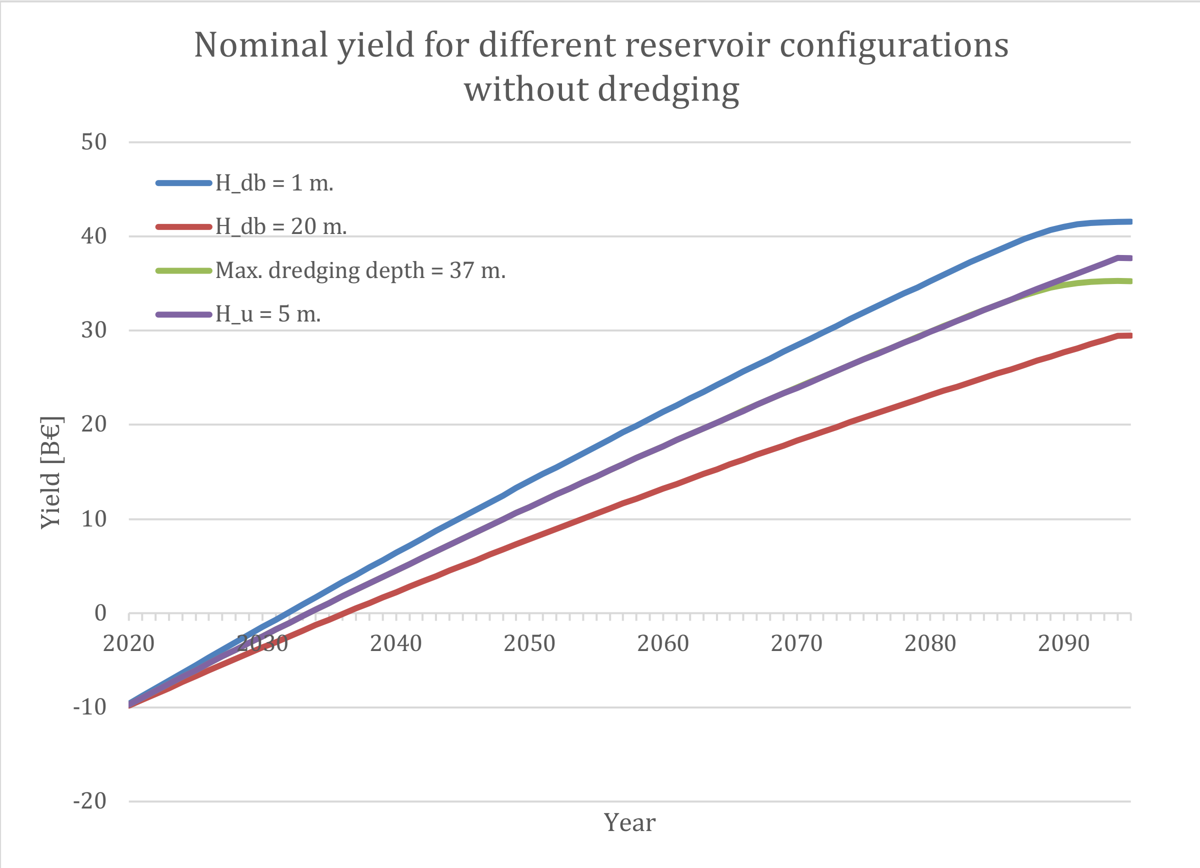


Figure 9-8: Sensitivity to river depth and sluicegate dimensions, without dredging/sediment management.

9.5.4. Combined scenarios

As discussed, dredging is worthwhile in the long run. The best operational and sustainable reservoir performance can be expected if sediment management is truly integrated in the operational lifespan. Postponing dredging operation is undesirable, since a substantial amount of the initial reservoir capacity will be lost irreversibly and requires more dredging equipment than needed initially. Early adoption of sediment management implies that sedimentation effects occur in a limited area, which is beneficial for both reservoir operations and dredging costs. Residual sedimentation effects will be less, which increases the maximum achievable lifespan of a reservoir. With timely introduction of dredging, a reservoir can remain operation without a foreseeable lifespan and would at least be significantly larger than the current average lifespan of 40 – 50 years.

Optimization of the primary functions in the Ke Go reservoir or comparable reservoirs can mainly achieved by the following consideration:

- Timely introduction of dredging operations;
- Flushing is highly recommendable, but should never reach an average concentration beyond 5 $gr.l^{-1}$;
- Hydropower generation is the major driver behind the economic performance. Therefore, the head available for hydropower should be maximized;
- Wear out at the inlet/upstream river mouth is undesirable and could increase further scattering of sediment in the reservoir. Application of a weir or sill at the could possibly counteract wear and promote earlier settling.

Figure 9-9 shows the potential discounted yields from a typical reservoir with active sediment management, such as Ke Go could be. The NPV value after 50 years reaches a positive amount of €15 billion and remains unaltered operational.

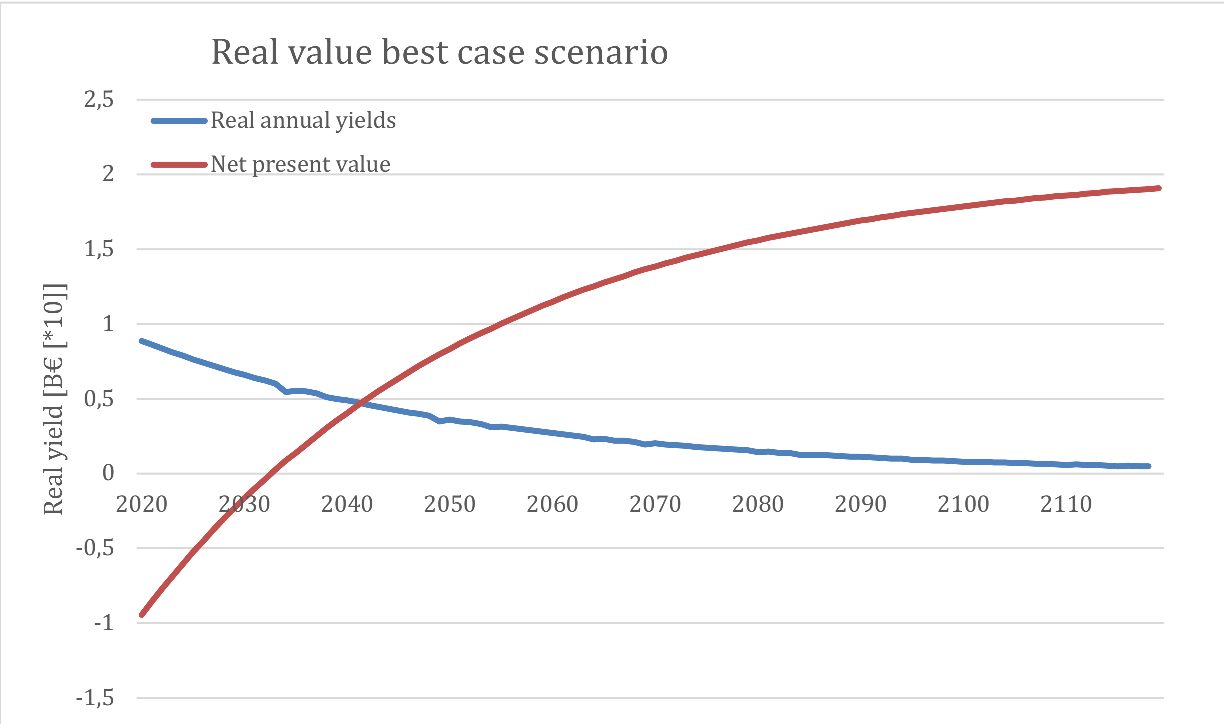


Figure 9-9: Net present value and real annual yield over a period of 100 years.

10. Conclusion

Going through this master thesis, an answer to the following main research question has been sought: “To what extent are active sediment management alternatives worthwhile for the functional value of reservoirs, while environmental consequences are mitigated?” The matter has been viewed primarily from the perspective of an owner, while operating companies are closely related. Active sediment management in this research are a number of dredging methods and flushing.

10.1. Reservoir sedimentation

Forecasting real sedimentation rates is a particularly complex task. The river system like it was before the development of the reservoir can lead to important information about sediment transport rates. Another opportunity to forecast transport rates is to measure rates in comparable reservoirs or rivers. Sedimentation in reservoirs is mainly affected by the shape, length and discharge of a reservoir. While artificial reservoirs usually have simpler shapes, naturally formed shapes are complex and this makes it hard to predict the strength of prevalent currents and long-term morphological changes. Adoption of a constant assumed sedimentation rate in this study necessarily simplifies, but simultaneously leads to a rough estimate for the entire reservoir lifespan. The sedimentation rate seems high for the case that is analysed (Ke Go, Vietnam), especially because the case is characterized by a low discharge rate.

A three-dimensional computational fluid dynamics model has been developed to predict sediment aggregations in the reservoir. The approach needs a lot of computing power and can only be used for short simulated periods. The bottom allows sediment to fall through and gives information about the distribution of settled sediment in a reservoir. Since the modelling approach can be used for very short periods only (practically up to a day), the results are extended with a timeseries analysis to longer periods (50 – 100 years). The CFD model is valuable to estimate sedimentation patterns and it gives an educated guess about the intensity of sedimentation through the reservoir. However, its limited predictive power must be recognized, especially for the long-examined periods in this research.

The general area of sediment aggregation is noticed first. Once sediment reaches the reservoir, it settles over a short distance. The settling velocity of particles is affected by the horizontal velocity component in the reservoir. Even if the total annual discharge of a reservoir is relatively large (up to 1000 percent of the gross reservoir capacity), the settling patterns remain broadly the same in the simulation. Settling near the dam is extremely limited, unless the examined reservoir lifespan is extended to a period of more than 60 years. Without dredging, settling continuous to reach further into the reservoir, eventually reaching the dam. A reservoir such as the Ke Go (case) can probably operate for at least 60 years with active sediment management. By then, a significant part of the original storage capacity would be lost. During this period, the quality and water supply capacity will gradually decline. As a consequence of sedimentation, hydropower generation will rapidly decline just after the 60-year period. Hydropower generation accounts for more than 60 percent of the annual yields in Ke Go, which is reason to consider a typical reservoir written off shortly after the 60-year period.

The results of the simulation are fairly comparable to the real-life Ke Go case. The top view of the Ke Go reservoir shows siltation upstream and near the entrance of the reservoir. The reservoir has an age of 47 years and clearly shows significant effects of sedimentation. Timely replacement of the various reservoir functions or restoring to the initial functional performance must be considered.

The depth of the upstream river and the base height of the sluice gates are essential parameters for the economic functioning of the reservoir. Measurement of the depth of the upstream river at the mouth is not always unequivocal. Wear out causes the transition zone between river and reservoir to become longer. Based on the modelling, it is beneficial to maintain a steep bottom gradient at the inlet. A steep slope near the inlet causes the current to slow down rapidly and improves settling directly after entering the reservoir. An alternative to investigate is a weir sill. Application of a weir sill near the inlet could improve the predictability of the flow characteristics and prevents wear of the river mouth.

10.2. Economic value of reservoirs and the application of sediment management

Typical for reservoirs are the substantially high sunk costs (often much more than € 10 Billion) before operations can commence. Development of a reservoir has become a politically charged question, especially in combination with all potential environmental drawbacks. The next conclusions are drawn from the examined Ke Go reservoir case.

The payback period is between 12 to 20 years. The costs of dredging are small compared to the initial sunk cost and primary function yields. Theoretically, the value of sediment can be greater than the total cost of dredging. The turning point for this is approximately 35 percent usability. Usability of less than 35 percent increases sediment management (dredging, transport and dumping). Usability larger than 35 percent can fully cover the costs of sediment management.

A substantial amount of dredged material can be flushed at a rate of 5 grams per litre. Flushing is an especially interesting option if the usability of dredged material is relatively low. So far, flushing is treated as a method to get rid of sediment. Flushing may also be a good alternative redistribute sediment downstream of a dam. In the valuation of flushing, the benefits of redistribution should also be considered, but is currently not included as such.

In the Ke Go case, it is not possible to flush only. More generally, it is unlikely that sediment management can be performed sufficiently with flushing only. Dredging is inescapable and the large quantities of sediment cannot be flushed all, unless the environment will be threatened seriously. The production costs for the submersible dredge pump are the least, starting from approximately €1.50 per m^3 in-situ material (fine sand).

Sediment management will be favourable whether a reservoir will be functional for 50 years or 100 years. After a period of 50 years, the difference between NPV with and without sediment management will add up to approximately 2 Billion. With the outlook that reservoirs can remain in service for extended periods, this difference will grow steadily with time. To really be able to extend the lifespan, appropriate sediment management must be carried out in a timely manner.

In short, dredging is highly recommendable to suppress sedimentation. Even with lower sediment usability, the financial and environmental performance of a reservoir is likely to be much better when sedimentation is prevented or reduced. Suggested dredging projects in this research are substantial and on an ongoing basis, but will lead to a stable regional driver while mitigating at least partially the external environmental drawbacks.

11. Recommendations

The results of this thesis are limited to comparable reservoir shapes as simulated. To really develop a robust framework, the models should be able to include more complex reservoir shapes. This chapter discusses opportunities to improve this work and to apply the work in real policy issues.

11.1. Current opportunities

Organizations and governments do not always introduce or give proper attention to sedimentation issues and associated opportunities. The terms for operating licences should include sediment management and transfer requirements after the licensed period.

The lifespan of current operating reservoirs could potentially be lengthened significantly. All parties involved should be invited to collaborate to improve operation of reservoirs and to adjust it for a sustainable future. Dredging in combination with appropriate flushing and application in industry and agriculture lead to a more valuable project.

The developed CFD model provides with a rough estimate about sediment concentration distribution in a reservoir. This result is then extended to a reservoir lifespan and shows an estimate of reservoir sedimentation. Little to no attention is given to morphological changes in a reservoir, such as the development of channels and local erosion/pick up. Accuracy of the expected sedimentation development could be improved greatly. By introducing morphological effects, possibly even designing a sequence of CFD and morphological models that follow each other up gives a vastly more accurate outlook.

11.2. Sustainability considerations

Flushing appears to be a means to improve the biodiversity. A decrease in flow variation will lead to a decline in natural fertilization in flood plains. However, flushing is a valid alternative to improve the soil characteristics of river banks downstream. Maximum concentration is defined at 5 gr. $L.^{-1}$, but is based on limited knowledge about its impact on the biodiversity downstream. As it impacts both the environment and dredging costs, it would be very useful to research maximum flushing concentrations in different seasonal patterns and environments.

11.3. Future research

The CFD and NPV models are bounded within certain limits. A number of research opportunities could improve the current models and would make prediction more precise and generalizable to different types and sizes of reservoirs.

1. Review the CFD grid to generalize applicability to other reservoir shapes, including initial bottom slope;
2. Development of morphological model;
3. Research the potential utility of a weir/submerged sill to prevent weir out of the upstream river mouth;
4. Research the challenges to adapt organizational structures to implement appropriate sediment management/dredging. Create awareness about long term sedimentation issues and apparent opportunities with owners and operating companies.

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A. Problem analysis

A.1. System analysis

The system analysis is of great importance for the problem demarcation and for deepening knowledge in the systematic dependencies. The analysis starts with a short description of the system that is being considered. After this, the system is completely and thoroughly evaluated to assess importance of external factors and the power of certain resources on specified criteria.

The objectives tree in Figure A. 1 (below) is actor specific and for this thesis specifically constructed for public government. The actor analysis shows that in most cases public government plays a significant role and has the legal right to influence policy making in a multi actor environment. The objectives tree is a tool to analyse and break down objectives into smaller and more manageable parts and is a tool to investigate opportunities for an improved overall system. Characterizing in the objectives is that not all objectives can be reached at once. There is very often a dilemma involved; if the one objective is met, other objectives might be less likely fulfilled. Examining the objectives tree on higher level, a dilemma between economic growth and living environment is present. Even within the objective of enhancing economic growth resides a dilemma. Efficient production of a hydroelectric power generation dam could result to unnatural patterns in the flow, which would result in a decline in fish population or touristic appeal.

It is not particularly useful to only investigate the higher-level objectives. Higher-level objectives are characterized by a more general description. Lower level objectives are more specific and define precise criteria that are preferable to measure and address situations with complex dilemmas.

For this thesis it is given that building a reservoir and dam once was a solution to a situation. From the analysis of the cases in section A.2.1. can be concluded that many dam projects are the cause for serious problems for nature, certain business sectors and living environment for inhabitants.

A dam project can cause conflicts with the following criteria in the objectives tree, figure A.1.

- Improving water quality;
- Preserve river delta downstream (natural flow of sediment);
- Increase hydropower storage/generator capacity;
- Extend functional lifespan reservoir;
- Supply of nutrients;
- Prevent obligatory moving;
- Preserve and protect archaeological and cultural sites.

The last two criteria are influenced during construction and commissioning of a reservoir and dam project. The situation cannot be improved dramatically in that area for existing reservoirs and is less interesting to investigate in this scope of research, since the aim is on addressing problems for existing reservoirs.

This however is not meant to undermine the preferences of inhabitants with potential new dam projects. The matter is more subject of civil planning and shall not be addressed here.

Table A. 1: Specified objectives

Living Environment	Economy
Improving Water Quality	Increase Hydropower Storage
Preserve Natural Flow of Sediment	Increase Generator Capacity
Supply of Nutrients	Increase Functional Life Reservoir

The remaining criteria show a breakdown into two types. On the one hand economy related criteria and on the other hand living environment related criteria. Economy related criteria suffer from inefficiency while living environmental criteria suffer from overusing and/or heavy burdening raw or natural materials.

At first sight, it seems that both types contradict heavily. Efficiency is a cost for environment, while preservation of nature could reduce productivity. However, when considering the longer-term effects of sedimentation and reduced quality of water, the economic value of a dam also reduces and the effect on both environment and economy is negatively influenced. The expected functional life might reduce, but the longer term of bad sedimentation management can change bathymetry in a reservoir drastically and puts power generation at risk.

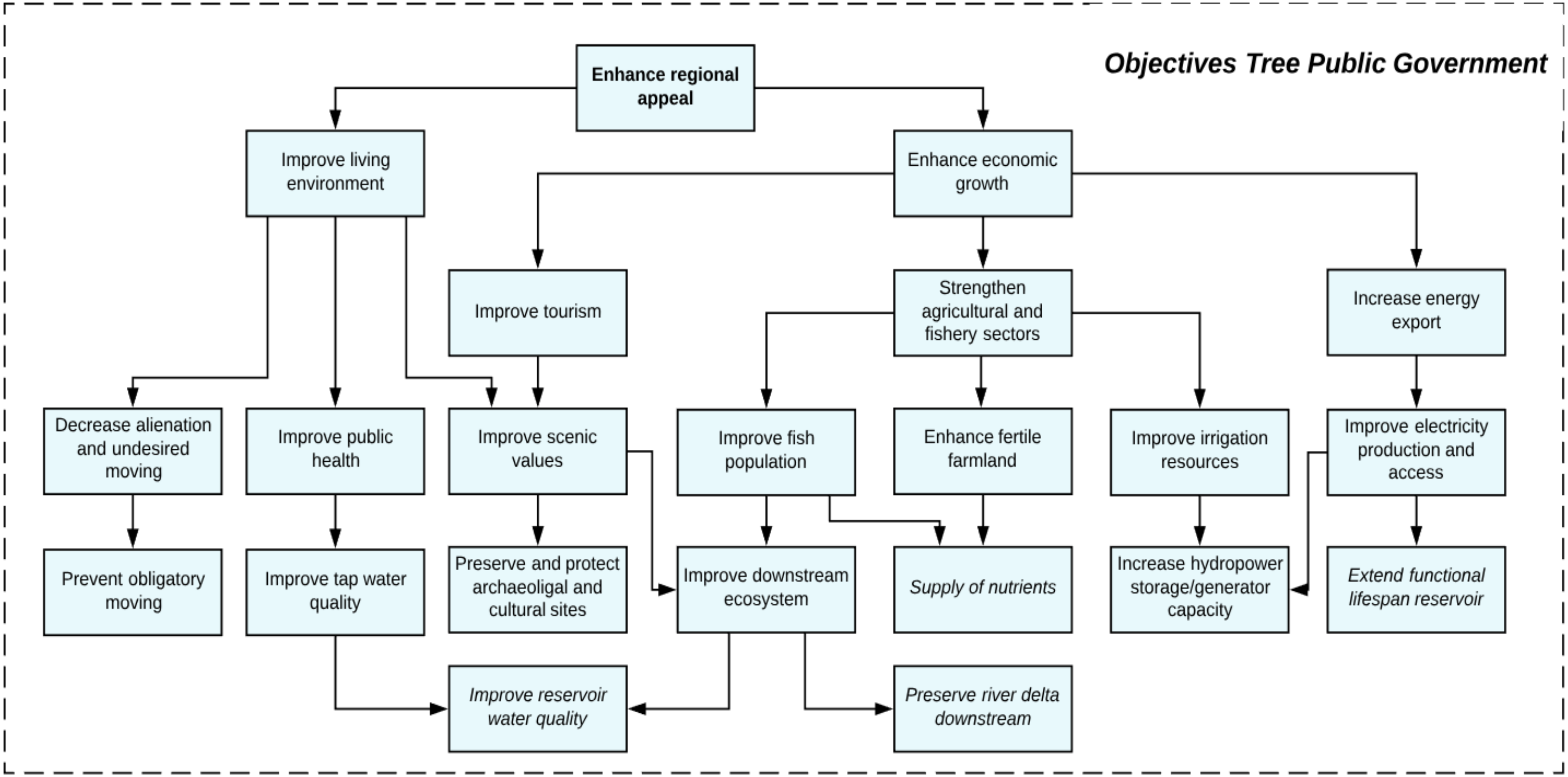

Figure A. 1: Objectives tree (Public Government)

The insight that downstream ecosystem and general environment preservation could coincide with economy optimization is further elaborated in Figure A. 2, the system diagram. The diagram consists of the following components:

- Criteria;
  Identified specified objectives to meet in a desirable situation.
- Factors;
  Causal factors can be influenced with resources available to a stakeholder. External factors can impact causal factors too.
- External factors;
  Causal factors cannot be influenced, however do influence the system of consideration. External factors result in uncertainty and show potential risk from across demarcated boundaries. External factors included in the system analysis are as follows:
  1. Water supply. Change of water supply can result in excess or shortage. Especially shortages can result in problems. Both electricity generation and a water shortage for irrigation are problematic for the revenues. At the same time is a long-term shortage in supply a problem for downstream environment. This external factor is not necessarily caused by climate change, but can also be the result of human interference. (Ali, R. R.)
  2. Global warming. Global warming can result in a significant change in seasonal patterns in water supply, but may also result in change in soil characteristics upstream. An example for this is the water-year stream flow in the Colorado River (McCabe, G. J.). Less winter precipitation falls as snow and the melting of winter snow occurs earlier in springy (Barnett, T. P.), while irrigation demand grows with rising temperature.
  3. Supply of sediment and average PSD (particle size diameter) from upstream river. Sediment transport from upstream rivers is often the cause for change in bathymetry in a reservoir. At the same time, sediment accumulation in a reservoir may put the functionality of the dam and reservoir at risk and sediment shortages may result downstream of the dam. Spatial distribution of sediments in a reservoir is also often and depends on multiple parameters including particle size diameter, speed of flow, density and hang.
  4. Change in population. Increase in population increases demand for water and living space. The river dam project faces more challenges to produce adequate amounts of energy and water. Increase in economic activities in the region around the reservoir has positive impact on population growth.
  5. Global opinion on energy transition. Multilateral agreements about sustainability goals may increase or decrease demand for carbon neutral energy, among which hydroelectric power generation.
- Resources;
  Stakeholder have resources specific for their power or professional occupation. Stakeholders specifically have interest in applying resources to influence their own perception. Cooperation between stakeholders (mixed use of resources) can result in unexpected enhanced outcomes with more focus on long-term effects and regional or central governments can actively influence the deployment of resources. Resources are numerous and, in this dam-reservoir case in general as follows:
  1. Change water use. Water can be used for irrigation, drinking water and hydroelectric power generation. Changing the ratio of use results in a redistribution of water supply across the different functions.
  2. Change seasonal schedule of hydroelectric power generation. Changing the schedule back to a reflection of natural flows saves ecosystems and delta.
  3. Change total flow rate.
  4. Replace generation capacity with other energy generation plant, either carbon neutral (solar, wind, nuclear) or not (coal).
  5. Maintain bathymetry. Maintenance not only to mechanical parts, but especially active maintenance to the bathymetry in both rivers and reservoir has positive effect on

environmental factors (ecosystems, fish/animal habitat) and economic use of a hydroelectric power plant.
6. Prohibit access to local area. Unburden the over-use of a reservoir from recreation activities and other use.
7. Regulate fishery. A natural fish population keeps natural balance in reservoir and rivers. Individual fishing quotas are means to regulate fishing.

Table A. 2: Qualitative consequences table (resources – criteria)

Criteria / **Resources**	**High generator production**	**Improved water storage**	**Extended functional life**	**Sufficient supply of nutrients**	**Natural flow of sediment**	**Improved water quality**
Change user ratio: generation--> storage	-	-	±	-	-	-
Increase flow rate @ dam	+	+	±	+	+	+
Replace generation capacity with other plant	-	+	±	-	-	-
Improve generation schedule	-	±	±	+	+	+
Maintain bathymetry	**+**	**+**	**+**	**+**	**+**	**+**
Regulate fishery				+		+
Prohibit access to local area						+

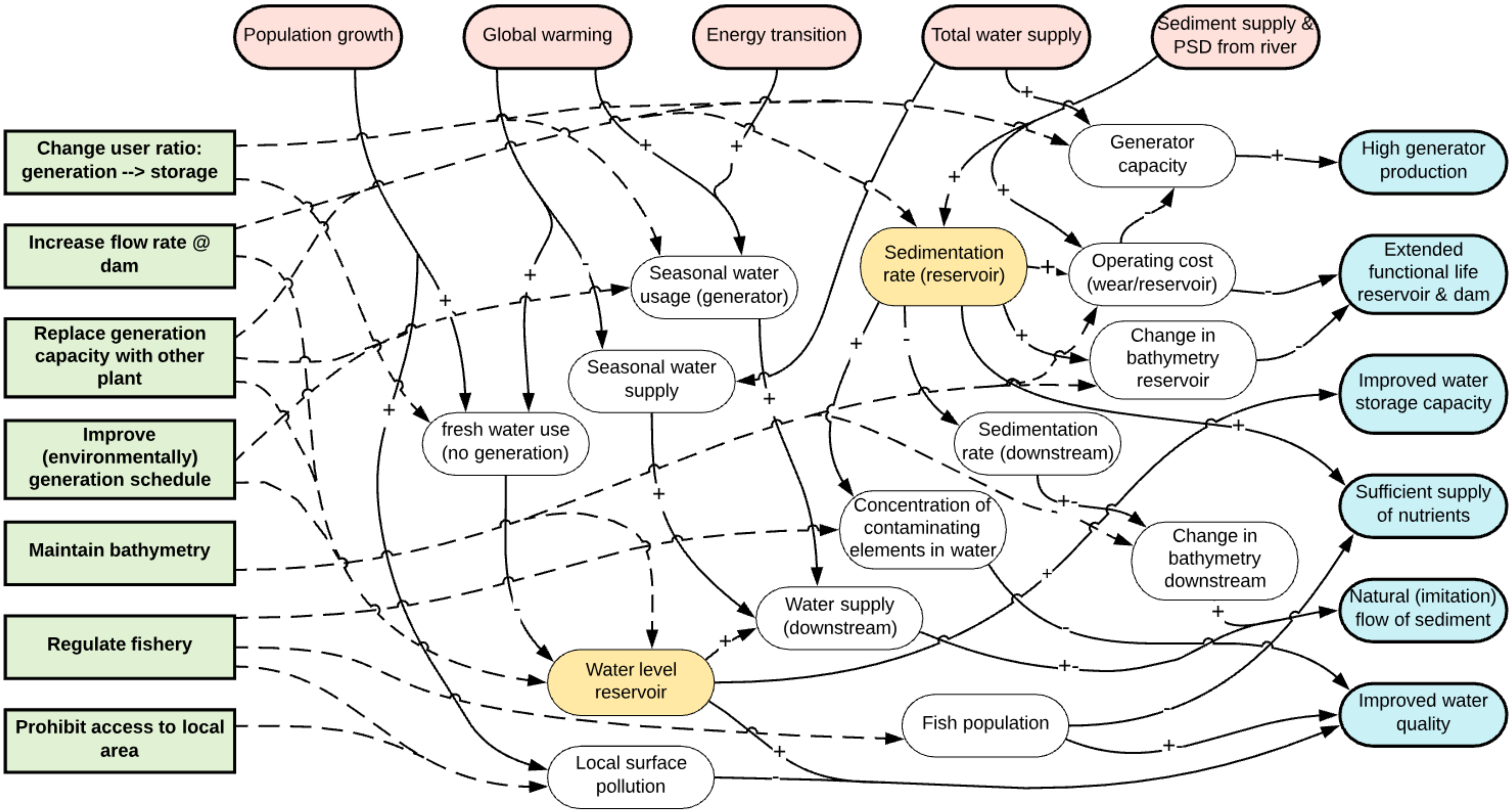

Figure A. 2: System Diagram

A.2. Actor analysis

The actor analysis is based on literature research. Literature research involves reviewing a number of different cases and sources that specifically devote attention to stakeholder networks. The cases are selected such that various types of reservoirs reflect a complete basis for analysis. A structured approach results in the necessary information regarding stakeholder networks and shows power and resource distribution across different actors. Section 1 and 2 sum up literature sources and identify different stakeholders. The in-depth analysis is part of section 3 and ends with a conclusion for further research development.

A.2.1. Cases

The stakeholder analysis is based on a number of different reservoirs. The reservoirs are selected based on significant capacity and unique geographical location. The result is that most of the continents are represented in the list, while the significant capacity of reservoirs guarantees professional stakeholder networks instead of smaller non-organized groups of stakeholders.

Alqueva Reservoir, Portugal

The Alqueva reservoir is a relatively young reservoir, finished in 2002 (source). The dam is arch typed and it impounds the river Guadiana in Southern Portugal. The reservoir is quite large with a 518 MW power station that was commissioned in 2004 – 2013. The reservoir also serves as fresh water resource throughout the region.

The feasibility of the reservoir was first researched in the 1960s by the general ministry of Portugal. The government finally made the decision to build in the 1990s. Local inhabitants were affected heavily due to identified potential flood zones. A complete village was relocated to a safer zone. On the other hand, the community now takes benefit from the hydro-power stations and fresh water supply. The European Union is stakeholder as financer, while management of the reservoir and dam are with a state-owned company. Total cost of construction was approximately 1.5B USD.

Actors with resources and/or power are:

- Government of Portugal;
- EDIA (Empresa de Desenvolvimento e Infra-Estruturas do Alqueva), state company responsible for the management of Alqueva system);
- Local and regional inhabitants;
- Agriculture, SISAP (crop suitability support system): irrigation;
- Utility, electricity and/or freshwater companies;
- Industry;

Kariba Dam, Zimbabwe

The Kariba Dam was the largest dam and artificial lake when constructed (1950s) and still is the largest man-made reservoir by volume. About 57,000 people had to move which still is a shortcoming for the Tonga and Korekore people. The Victoria Falls, part of the reservoir, is considered to be the largest waterfall in the world, surpassing even the Niagara Falls and Iguacu Falls. The flow strongly depends on the season and during the annual dry season most of the supply is diminished. The capacity is primarily used for hydroelectric power generation. However, supply is now used to serve many users. Environmental threats are present, such as weeds, water pollution and drought and flood events. The Kariba Dam is owned by Zambezi River Authority, a corporation jointly and equally owned by the government of Zambia and Zimbabwe. Financing of the dam is in public hands. The dam now needs rehab/maintenance works after 60 years of production. The European Union, the government of Sweden, the World Bank and the African Development Bank are expected to support the project financially.

Important actors involved in the Kariba reservoirs case are

- Inhabitants (Tonga/Korekore People);
- Zambezi River Authority
- Government of Sweden;
- European Union;
- African Development Bank;
- The World Bank;
- Government;
- Fishery;
- Agriculture;
- Flora/fauna foundations;
- World Health Organization (GET 2020 strategy)

Bratsk Dam, Russia

The Bratsk Dam is a gravity-fill dam on the Angara River. The reservoir and dam were completed in 1963 and has a capacity of around 11 million cubic metres. The dam includes a hydroelectric power generation plant with a capacity of 4,500 MW. Remarkable fact is that the dam not only provides significant power supply, but also serves as important infrastructural network point. Studies show that after the construction of the dam new problems arose. Specifically, problems after the construction were related to the use of water, biological quality, and sustainable socioeconomic development of the region. Different elements were found in fresh water supply and in some food fish. Power Company Irkutskenergo is owner of the dam and operates the generation plants. Irkutskenergo is privately owned with 10% of the shares free tradable on the Moscow Stock Exchange.

Important stakeholders involved in the Bratsk dam and reservoir are

- Local inhabitants;
- Government of Russia;
- Tourists (emphasizing over use of land, space and water, leading to environmental risks) and tourism;
- Non-governmental environmental organizations (Such as Greenpeace);
- Local and regional political parties;
- Fishery;
- Irkutskenergo;

Daniel Johnson Dam, Canada

The Daniel Johnson Dam is a multi arch dam with a height of over 200 meter. The reservoir's general structure was created roughly 214 million years ago by the impact of a meteor. The main purpose of the dam was to generate electricity from hydropower (MANIC-5) with a capacity of over 2500 MW under favourable conditions. As with most reservoirs and dams, the system is government-owned. The first hydrological studies were carried out in the earlier 1920s. The construction then took a long period to start and was eventually finished in 1970 after eleven years of building. Construction of the dam was complex, with the advantage that less concrete was needed. This still is a great accomplishment for the engineers and contractors involved. The dam is publicly owned by Hydro-Québec, which manages the generation, transmission and distribution of electricity of electricity in Québec.

Important stakeholders involved in the construction and now during its functional life phase are

- The government of Canada;
- Construction and engineering companies;
- Inhabitants;
- Politics;

- Hydro-Québec;
- Government of Québec;

Guri Dam, Venezuela

The Guri Dam in Venezuela was finished in 1969 after only 6 years of construction. The dam impounds the Guri reservoir with an area of 4,250 kilometres. The system is owned by the state electric company (EDELCA), but is under supervision of the Venezuelan government. EDELCA awarded HITACHI the contract to build and install the hydropower generation plants. Due to government policy 74% of Venezuelan Electricity comes from sustainable sources. This is in line with efforts to minimize the use of hydrocarbons. The countries great dependence on hydropower generation appeared to be a threat during periods of drought. In 2010 export agreements could not be met and Venezuelan inhabitants were obliged to use as little electricity as possible. Droughts (especially after dam and reservoir construction) also have extreme impact on ecological systems. Fish and other benthic animals suffer from reduced inputs of dissolved nutrients. This has impact on fishery and other primary industries throughout the region.
Important actors involved are

- Venezuelan government;
- EDELCA (electric company);
- Inhabitants;
- Export countries;
- Non-governmental environmental organizations
- Contractors (HITACHI, but also other involved companies);
- Fishery and primary industries.

Aswan High Dam, Egypt

The Aswan High Dam was constructed in the 1960s across the river Nile. Main purposes of the dam are to manage flood risks, increase fresh water storage and to generate hydro electricity. The dam has significant impact on the regional economy, but also culture. Flood risk management is extremely important in the region. Crop would be destroyed in case of flood, but the same applies to extreme droughts. On the other hand, floods are required to distribute natural nutrients and minerals. Where as many reservoirs and dams are the cause for harm to ecological systems, the Aswan High Dam is one that actually contributes on this subject significantly. Sardine population has declined slightly since the opening of the High Dam. It is still not certain whether or not the dam is the cause for this decline. The Soviet Union/Russia financed the dam after the United States, Great Britain and the World Bank withdrew offers. Politics played an important role and had impact on the choice and withdrawal of offers.

Involved actors in the Aswan High Dam are

- Government of Egypt;
- Soviet Union;
- Contractors;
- Inhabitants;
- Agriculture;
- Fishery and industries;
- Tourism;

W.A.C Bennett Dam, Canada

As for most reservoirs of this size, the main purpose of the W.A.C. Bennett Dam is hydroelectric-power generation. The W.A.C Bennett Dam impounds the river Peace and is one the largest earth fill dams in the world. The dam was constructed between 1961 and 1968 and is named after the Premier of British Columbia, W. A. C. Bennett (active 1952 – 1972). Political policy during that

period focused on developing large-scale state-directed public resources for British Columbia. The purpose of W.A.C. Bennett was to develop especially the regional economy with less focus on country policy. Economic potential of the dam was great, while the effects for the downstream river was not at all positive. Both plants and animals were affected by the less drastic fluctuations in water levels. Complete landscapes changed and flood plains dried up. Minorities and agriculture industry faced significant problems. Development of the reservoir led to isolation, dependence, alienation and even illness. Fishing grounds were severely impacted. The W.A.C Bennett dam and reservoir are a great example of a combination of initial great economic profits, while the long-term effects are overshadowed with negative impact on various subjects.
Involved actors for this case are

- Government of British Columbia;
- Central Government of Canada;
- Inhabitants;
- Fishery;
- Agriculture;
- Non-Government Organizations (NGO) for nature;
- World Health Organization;
- Construction related stakeholders.

<u>The Three Gorges Reservoir, China</u>
The hydroelectricity gravity dam was the world’s greatest in terms of power (22,500 MW) until 2016. The dam was completed in 2012 and is a measure to limit greenhouse gas emissions. The construction of the dam was also with the intentions to increase shipping capacity and reduce flood risk downstream. The dam has both positive and negative external effects. The project was socially and economically as success at first, but construction also was the cause for the loss of cultural and archaeological sites. 1.3 million people had to move and risk of landslides increased. Active flood and water level management was the cause for changes in regional ecological systems and therefor cannot be seen as sheer positive. China Yangtze Power (state owned) is the owner of the dam and has operational responsibility over the dam.
Involved actors in this case are

- Government of China;
- China Yangtze Power
- Inhabitants;
- Agriculture;
- Non-Governmental Organizations;
- Fishery;
- Archaeology/Cultural preservation organizations;

A.2.2. Identified actors

It is clear from the cases in A.2.2. that numerous ownership and financing structures are possible. Environmental problems, obliged moving and loss of archaeological or cultural heritage are also often applicable to reservoirs and dams. The next list identifies the variety of actors that must be included for the integral approach in the thesis.

- Countries Government;
  In most cases central Government of a country is involved.

- Regional and local Government;
  Regional government does not always share objectives with central government and there may be competition. While the location is in a region, public ownership can be directly controlled from central government.
- Multilateral organizations with political influence;
  Some continents have far-reaching multilateral cooperation with political influence.
- Investors, either private or public;
  Financing can be private or public.
- Owners, either private or public;
  Reservoirs are often publicly owned, but sometimes private ownership is possible.
- Power and power distribution companies;
  Operational responsibility is often in the hands of power companies.
- Inhabitants;
  Inhabitants are often severely affected by a reservoir and dam. Economic growth, stable power supply is beneficial. Mandatory moving, health issues, loss of nature is disadvantageous.
- Visitors, tourists;
  Can be positive or negative. The dam itself is often an impressive structure, while loss of nature can result in decrease of tourism.
- Farmers and organized agriculture;
  Organized irrigation, while the long-term effects can be negative due to decrease in nutrients/vitamins etc.
- Fishery;
- In most cases fishery is negatively affected by a reservoir.
- Other industries;
  Stable supply of power and water. Overall increase in economic activity due to construction and maintenance of dam.
- Cultural and/or religious minorities;
  Loss of cultural or religious material and immaterial goods.
- NGO’s representing nature and environment;
  Often a negative impact on nature and ecosystem.
- NGO’s representing healthcare;
  In some cases, reservoirs are a cause for increase in health issues among inhabitants.
- Construction companies;
  Temporarily immense increase in work on a project basis.
- Maintenance companies;
  Both dam and reservoirs, i.e. mechanical components, sedimentation and other types of maintenance/rehab works.

A.2.2.3 Actor networks

A.2.1. Cases show that a great number of actors (sometimes stakeholders) is affected by de development and production of dams and reservoirs. This section discusses the relations between actors and their power or resources.

The (in)formal chart in

Figure A. 3 shows cooperation opportunities and interdependencies. At the same time, the chart gives a graphical representation of solution directions. Different actors certainly don’t always have the same problem perceptions. While inhabitants may wish to improve living environment, a power company could lean more toward profit maximization. The actor analysis shows possible solution directions where power and resources are mixed in a way that multiple problem perceptions across different actors are addressed. Additionally, not one case is exactly similar to another.

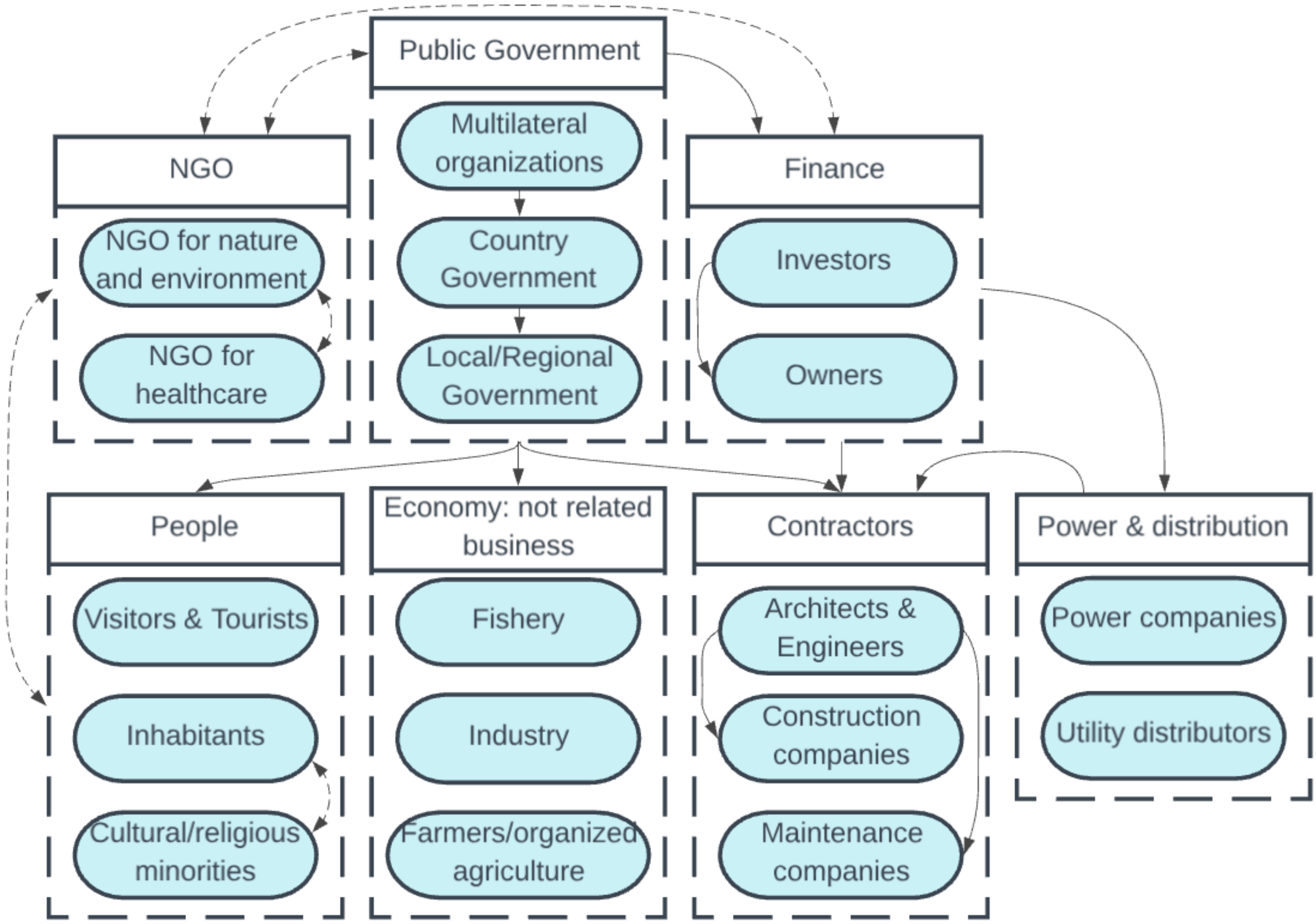

Figure A. 3: (In)formal Chart. Formal and informal interdependencies. Informal relations are shown with dashed lines and are directed both ways.

From the formal relations can be seen that public government plays an important role in scheduling and addressing situations. In most cases central government of a country is actively involved in the design phases. There are however examples that regional government has the leading role in assessing feasibility and giving approval for such extensive projects. The W.A.C. Bennett Dam is an example for this. Nevertheless, public government plays an important role in almost every dam project. State-owned power and distribution companies often organize production, which gives public government the ultimate tool for policymaking and decisions. There are again examples that a dam is privatized after construction, most notably the Bratsk Dam in Russia.

The decision to build a dam is in most cases to generate electricity from hydropower. However the main purpose is in many cases overshadowed with negative side effects, such as droughts, ecological changes, health issues and impact on primary industries. Feasibility studies do not always research downstream effects thoroughly and results often in unexpected negative effects.

The question is how more awareness can be created for problems that seem small at first but appear to be significant after time. The idea for a reservoir usually starts at the government. That can be a rational decision from policy makers, but political influence is usually large for large sunk cost that face great impact on inhabitants and therefor voters. On the other hand, engineers and consultants should perform feasibility assessment with awareness for long-term effects on the entire region. There seems to be too much pressure on short-term financial and political benefits for contractors, owners/investors and political parties.

The (in)formal chart quickly sketches the following opportunities to influence the government, financial sector, contractors and owners.

- Non-Governmental Organizations (NGO) and professional organized groups of minorities, inhabitants, industries can lobby and create awareness for external effects. This can be compared with the situation that feasibility studies nowadays not always present the complete effects and the results may be pushed towards exaggerating the positive short-term side to enhance the position of a construction contractor;
- A government may change views on existing reservoirs, since maintenance become increasingly important and urgent. Publishing research on combining necessary maintenance on bathymetry of components and addressing negative side effects can result in a shift in both the view of people and government.

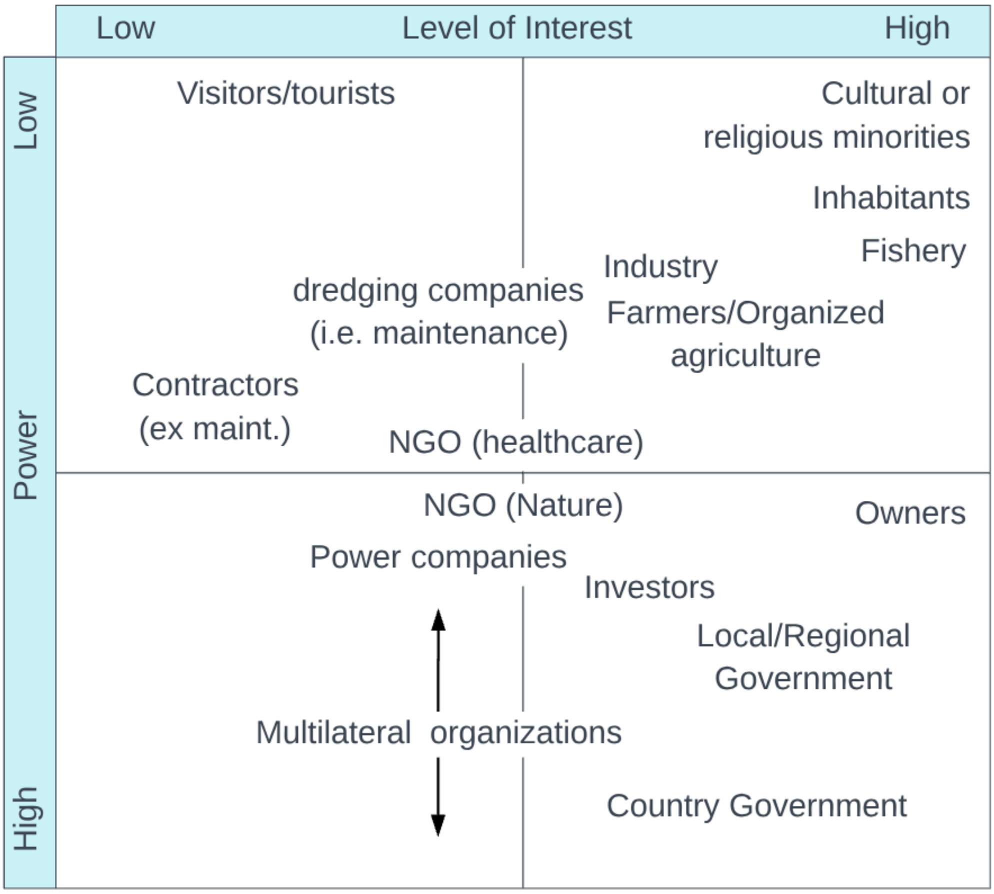

Figure A. 4: PI Grid for involved actors

The PI Grid in

Figure A. 4 shows an assessment of the distribution of actors with interest and/or power to actually affect a situation. It must be underlined that the graph does not represent every case exactly. Power of actors (stakeholder if more power) is strongly affected by privatization, Governmental structures, financing, ownership structure and other factors. Interest in a situation mainly depends on the effects that are being experienced by an actor.

Public Government plays a major role in assessing problems. A Government either has own resources or has the power to mobilize resources from an actor. There seems to be little incentives for contractors to design and build dams in way that it is environmentally friendly or less damaging. The actors facing the largest side-effects show low to very low power in figure

Figure A. 4, which shows the complexity of the problem. Large companies, stakeholders and even the government may take of has taken far-reaching policy decision without noticing problems for minorities or observant actors.

A.3. Scenario analysis

The scenario analysis starts with the identified external factors in the systems analysis. External factors are the identified sources for possible future events or developments. Characterizing for the scenario analysis is that it will never be able to include all aspects completely. The scenario analysis tries to map the currently known uncertainties. The result will be an estimate how the future of a current or expected dam/reservoir project might be impacted by a mixture of uncertainties.

Table A. 3: External Factors- Criteria dependence

Criteria / **Ext. Factors**	**High generator production**	**Improved water storage**	**Extended functional life reservoir/dam**	**Sufficient supply of nutrients**	**Natural flow of sediment**	**Improved water quality**
Population growth		-				-
Climate change		-			-	±
Energy transition	+	±			±	±
Total water supply	+	+		+	±	±
Sediment supply & PSD from river	**-**	**-**	**-**	**+**	±	±

Table A. 3 shows the assessed impact in the system diagram of external factors on criteria. Not all external factors have severe impact on all criteria, but almost all criteria do have impact on water storage in the reservoir, flow of sediment and water quality. Sediment supply from the river and hinterland and its particle size distribution (PSD) affects all criteria. The total water supply from rivers has impact on all criteria except for the functional lifespan of the reservoir and dam. The water supply would only affect the functional life span in case diminishes severely, for example by changing the upstream river course or by adding dam(s) upstream.

Reviewing the external factors, there is the uncertainty of global warming, sediment supply (PSD) and total water supply that impacts the natural supply for a sustainable reservoir – dam project. On the other hand, there is population growth and energy transition and affects the demand side in a reservoir – dam project. The greatest uncertainties are on the supply side, based on table XX. Sediment supply and PSD and water supply are closely related to each other because of the positive relation between the speed of water flow and sediment transport. The critical speed (speed for which sediment at a particular diameter size goes in to suspended mode) will be achieved for a greater number of diameters when the flow increases. Bottom sediment transport also increases with an increase in water flow.

The next list gives a short explanation about the different external factors and expected development over the next 50-100 years.

- Population growth: in many cases after development enhanced growth in the region where the dam in located. The reasons are as follows, a reservoir – dam project usually increases economic growth in the region, which is a cause for a lower unemployment rate. Secondly, hydropower development that comes with a dam is often a start for a thorough improvement of local and regional electricity networks. Traffic and transport networks are often relatively good, since development was already needed for development of the dam. It is not always about immigration to the region, but resettling is also an essential part of population growth. Many cases show significant number of people that had to move and make place for the reservoir development. Resettling indirectly also has impact on population density. The conclusion is that mega engineering of dams and reservoirs has a positive impact on population growth. This positive impact has works back too; not always is a significant change in population growth anticipated. The demand for water increases (whether the function of the water use is hydropower generation, irrigation or other sorts of fresh water use) and can result in negative impact on the environment (i.e. overuse and pollution). The final impact of population growth is for this study less relevant, since the core aim is on existing reservoirs. The change in demand should however always be assessed to determine long-term reservoir water supply.
- Climate change: a much-discussed topic. The general trend is a global increase in temperature and on average an increase in precipitation. Global precipitation averages are not quantitative usable in this thesis. Especially the change in precipitation in the region around reservoirs and upstream is interesting. Precipitation upstream in the form of snow is changing due to increasing temperatures. More rain is falling and the resulting snowfall is melting earlier in spring. Faster snow thaw can result in significant increase in upstream river flow and can therefor also increase sediment supply. The continuous supply towards the reservoir becomes more abrupt, which is not favourable for the local environment or stable electricity generation. The expected effects due to climate change should be considered in further analysis, especially the change in water-year stream flow.
- Energy transition: a very politically charged topic and often influenced by multilateral governance. Climate debates and the resulting agreements are a push toward more green carbon-neutral

energy generation. The energy transition depends not only on the political perceptions and societal willingness to pay, but depends on available sustainable generation solutions too. Many barriers exist for a sustainable transition then. One of which is the often-slow development of new renewable niche-innovation, which has to coincide with windows of opportunities in politics. Already existing solutions, in this case generating dams, show significant growth in times of political consent (Verbong, G. Geels, F.)The external factors shall be used in further analysis as general and uncertain input to assess the monetary value considering both economic and environmental effects. General expectations about the change in demand and supply due to external factors must be integrated to attain a valuable model.

B. Literature research

Upstream processes

Irrigation schemes and civil works is often associated with an increase in intensity of human activity in areas surrounding the reservoir and basin. People move into the area around a reservoir as a result of increased economic and are directly engaged in irrigation or other activities. Agriculture becomes more intensive rain fed and grows quicker than before. Greater use of forests, particularly for fuel wood, leads to deforestation and destabilizing top soil. All these activities increase erosion in the area by decreasing vegetative cover which will have a detrimental effect on the local fertility and ecology as well as contribute to sediment related problems. Because irrigated land is wetter, it absorbs less rainfall and runoff will therefore be higher.

Mitigating actions can be put in place relatively easily with forethought as to problems that might arise. For example, allowance should be made for livestock, fuel wood or vegetable gardens within the layout of an irrigation scheme. Alternatively, protection of vulnerable areas may be necessary.

River morphology

The capacity and shape of a river results from its flow, the river bed and bank material, and the sediment carried by the flow. A fast-flowing river has more energy and is able to carry higher sediment loads (both more and larger particles) than a slow-moving river. Hence, sediments settle out in reservoirs and in deltas where the flow velocity decreases. A river is said to be in regime when the amount of sediment carried by the flow is constant so that the flow is not erosive nor is sediment being deposited. The regime condition changes through the year with changing flows. The PSD can vary from much smaller than 1 mm for very fine materials to a diameter greater than 200 mm. This depends on a great number of factors, such as river basin, flow velocities and bed slope.

Median diameter of bed material

The wide spread of potential particle size diameters is the main cause for multiple sediment transport modes (suspended and bottom transport). Suspended sediment transport is the foremost important type of transport in which a larger spatial distribution is created in the reservoir. The CFD model setup and grid is chosen such that it is able to generate useful data about suspended transport (smaller PSD), but is less valid for bottom transport.

Downstream sedimentation

Bottom transport is cancelled out due to very low speeds in the reservoir;
Suspended transport in a downstream reservoir is also diminished as the reservoir acts as a barrier for the throughput of any type of sediment, velocities drop after water enters the reservoir. The discussed types of dredging and sediment management techniques can be a solution under certain system characteristics.

- type of dam;
- newbuild/already existing
- spatial characteristics of sediment aggregations;
- mud flows;

B.1. Reservoir sedimentation and dredging

The following methods are included:

- Suction Dredge;
  Based on suction under water only, no rotating cutter heads applied. At first sight applicable for settled sediment such as gravel, sand, clay, silt and other minerals.
  https://dredging.org/media/ceda/org/documents/resources/othersonline/vlasblom4-the-plain-suction-dredgers.pdf
- Cutter Suction Dredge;
  Cutter heads applied for cutting of harder and larger soils and rock.
  https://www.iadc-dredging.com/ul/cms/fck-uploaded/documents/PDF%20Facts%20About/facts-about-cutter-suction-dredgers.pdf
- Grab Dredge;
  Also Clamshell Dredge, picks up seabed material with a clamshell bucket. This type of dredging always includes a barge or comparable structure. The barge functions as base for the crane and has a cargo hold for dredged material.
  https://www.royalihc.com/en/products/dredging/other-dredging/grab-hopper-dredger
- Backhoe Dredge;
  The backhoe dredge is a stationary floating type of dredging, anchored by three spuds. A backhoe crane is position on a barge and removes sediment from the bottom. This type of dredging is limited to about 18 meters depth.
  https://dredging.org/media/ceda/org/documents/resources/othersonline/vlasblom8-the-backhoe-or-dipper-dredger.pdf
  http://www.fao.org/3/i1883e/i1883e06.pdf
- Submersible Dredging Pump (DOP);
  DOP pumps are compact submersible pumps dedicated to slurry transport. Flexible method in terms of size of equipment and maximum dredging depth.
  https://dopdredgepumps.com/en/
- Water Injection Dredge;
  This type of dredging is based on a series of nozzles on a horizontal jetbar injecting large volumes of water at low pressure to fluidize the sediment.
  https://www.vanoord.com/activities/water-injection-dredger

C. Models

C.1. Details of intermediate velocity

$u_{i+\frac{1}{2},j,k} = \frac{u_{i+1,j,k}+u_{i,j,k}}{dx}$, $u_{i-\frac{1}{2},j,k} = \frac{u_{i-1,j,k}+u_{i,j,k}}{dx}$, $v_{i+\frac{1}{2},j,k} = \frac{v_{i+1,j,k}+v_{i,j,k}}{dx}$, $v_{i-\frac{1}{2},j,k} = \frac{v_{i-1,j,k}+v_{i,j,k}}{dx}$,
$w_{i+\frac{1}{2},j,k} = \frac{w_{i+1,j,k}+w_{i,j,k}}{dx}$, $w_{i-\frac{1}{2},j,k} = \frac{w_{i-1,j,k}+w_{i,j,k}}{dx}$
$u_{i,j+\frac{1}{2},k} = \frac{u_{i,j+1,k}+u_{i,j,k}}{dy}$, $u_{i,j-\frac{1}{2},k} = \frac{u_{i,j-1,k}+u_{i,j,k}}{dy}$, $v_{i,j+\frac{1}{2},k} = \frac{v_{i,j+1,k}+v_{i,j,k}}{dy}$, $v_{i,j-\frac{1}{2},k} = \frac{v_{i,j-1,k}+v_{i,j,k}}{dy}$,
$w_{i,j+\frac{1}{2},k} = \frac{w_{i,j+1,k}+w_{i,j,k}}{dy}$, $w_{i,j-\frac{1}{2},k} = \frac{w_{i,j-1,k}+w_{i,j,k}}{dy}$
$u_{i,j,k+\frac{1}{2}} = \frac{u_{i,j,k+1}+u_{i,j,k}}{dy}$, $u_{i,j,k-\frac{1}{2}} = \frac{u_{i,j,k-1}+u_{i,j,k}}{dy}$, $v_{i,j,k+\frac{1}{2}} = \frac{v_{i,j,k+1}+v_{i,j,k}}{dy}$, $v_{i,j,k-\frac{1}{2}} = \frac{v_{i,j,k-1}+v_{i,j,k}}{dy}$,
$w_{i,j,k+\frac{1}{2}} = \frac{w_{i,j,k+1}+w_{i,j,k}}{dy}$, $w_{i,j,k-\frac{1}{2}} = \frac{w_{i,j,k-1}+w_{i,j,k}}{dy}$

$$(\tau_{xx})^n_{i+\frac{1}{2},j,k} = 2\mu\frac{\partial u^n}{\partial x}_{i+\frac{1}{2},j,k}, (\tau_{yy})^n_{i,j+\frac{1}{2},k} = 2\mu\frac{\partial u^n}{\partial y}_{i,j+\frac{1}{2},k}, (\tau_{zz})^n_{i,j,k+\frac{1}{2}} = 2\mu\frac{\partial u^n}{\partial z}_{i,j,k+\frac{1}{2}}$$
$$(\tau_{xx})^n_{i-\frac{1}{2},j,k} = 2\mu\frac{\partial u^n}{\partial x}_{i-\frac{1}{2},j,k}, (\tau_{yy})^n_{i,j-\frac{1}{2},k} = 2\mu\frac{\partial u^n}{\partial y}_{i,j-\frac{1}{2},k}, (\tau_{zz})^n_{i,j,k-\frac{1}{2}} = 2\mu\frac{\partial u^n}{\partial z}_{i,j,k-\frac{1}{2}}$$

$$(\tau_{xy})^n_{i+\frac{1}{2},j,k} = \mu(\frac{\partial v^n}{\partial x}_{i+\frac{1}{2},j,k} + \frac{\partial u^n}{\partial y}_{i+\frac{1}{2},j,k}), (\tau_{xy})^n_{i,j+\frac{1}{2},k} = \mu(\frac{\partial v^n}{\partial x}_{i,j+\frac{1}{2},k} + \frac{\partial u^n}{\partial y}_{i,j+\frac{1}{2},k}),$$
$$(\tau_{xy})^n_{i,j,k+\frac{1}{2}} = \mu(\frac{\partial v^n}{\partial x}_{i,j,k+\frac{1}{2}} + \frac{\partial u^n}{\partial y}_{i,j,k+\frac{1}{2}})$$
$$(\tau_{xz})^n_{i+\frac{1}{2},j,k} = \mu(\frac{\partial u^n}{\partial z}_{i+\frac{1}{2},j,k} + \frac{\partial w^n}{\partial x}_{i+\frac{1}{2},j,k}), (\tau_{xz})^n_{i,j+\frac{1}{2},k} = \mu(\frac{\partial u^n}{\partial z}_{i,j+\frac{1}{2},k} + \frac{\partial w^n}{\partial x}_{i,j+\frac{1}{2},k}),$$
$$(\tau_{xz})^n_{i,j,k+\frac{1}{2}} = \mu(\frac{\partial u^n}{\partial z}_{i,j,k+\frac{1}{2}} + \frac{\partial w^n}{\partial x}_{i,j,k+\frac{1}{2}})$$
$$(\tau_{yz})^n_{i+\frac{1}{2},j,k} = \mu(\frac{\partial v^n}{\partial z}_{i+\frac{1}{2},j,k} + \frac{\partial w^n}{\partial y}_{i+\frac{1}{2},j,k}), (\tau_{yz})^n_{i,j+\frac{1}{2},k} = \mu(\frac{\partial v^n}{\partial z}_{i,j+\frac{1}{2},k} + \frac{\partial w^n}{\partial y}_{i,j+\frac{1}{2},k}),$$
$$(\tau_{yz})^n_{i,j,k+\frac{1}{2}} = \mu(\frac{\partial v^n}{\partial z}_{i,j,k+\frac{1}{2}} + \frac{\partial w^n}{\partial y}_{i,j,k+\frac{1}{2}})$$
$$(\tau_{xy})^n_{i-\frac{1}{2},j,k} = \mu(\frac{\partial v^n}{\partial x}_{i-\frac{1}{2},j,k} + \frac{\partial u^n}{\partial y}_{i-\frac{1}{2},j,k}), (\tau_{xy})^n_{i,j-\frac{1}{2},k} = \mu(\frac{\partial v^n}{\partial x}_{i,j-\frac{1}{2},k} + \frac{\partial u^n}{\partial y}_{i,j-\frac{1}{2},k}),$$
$$(\tau_{xy})^n_{i,j,k-\frac{1}{2}} = \mu(\frac{\partial v^n}{\partial x}_{i,j,k-\frac{1}{2}} + \frac{\partial u^n}{\partial y}_{i,j,k-\frac{1}{2}})$$
$$(\tau_{xz})^n_{i-\frac{1}{2},j,k} = \mu(\frac{\partial u^n}{\partial z}_{i-\frac{1}{2},j,k} + \frac{\partial w^n}{\partial x}_{i-\frac{1}{2},j,k}), (\tau_{xz})^n_{i,j-\frac{1}{2},k} = \mu(\frac{\partial u^n}{\partial z}_{i,j-\frac{1}{2},k} + \frac{\partial w^n}{\partial x}_{i,j-\frac{1}{2},k}),$$
$$(\tau_{xz})^n_{i,j,k-\frac{1}{2}} = \mu(\frac{\partial u^n}{\partial z}_{i,j,k-\frac{1}{2}} + \frac{\partial w^n}{\partial x}_{i,j,k-\frac{1}{2}})$$
$$(\tau_{yz})^n_{i-\frac{1}{2},j,k} = \mu(\frac{\partial v^n}{\partial z}_{i-\frac{1}{2},j,k} + \frac{\partial w^n}{\partial y}_{i-\frac{1}{2},j,k}), (\tau_{yz})^n_{i,j-\frac{1}{2},k} = \mu(\frac{\partial v^n}{\partial z}_{i,j-\frac{1}{2},k} + \frac{\partial w^n}{\partial y}_{i,j-\frac{1}{2},k}),$$
$$(\tau_{yz})^n_{i,j,k-\frac{1}{2}} = \mu(\frac{\partial v^n}{\partial z}_{i,j,k-\frac{1}{2}} + \frac{\partial w^n}{\partial y}_{i,j,k-\frac{1}{2}})$$

$$\left.\frac{\partial u^n}{\partial x}\right|_{i+\frac{1}{2},j,k} = \frac{u^n_{i+1,j,k}-u^n_{i,j,k}}{dx}, \left.\frac{\partial v^n}{\partial y}\right|_{i,j+\frac{1}{2},k} = \frac{v^n_{i,j+1,k}-v^n_{i,j,k}}{dy}, \left.\frac{\partial w^n}{\partial z}\right|_{i,j,k+\frac{1}{2}} = \frac{w^n_{i,j,k+1}-w^n_{i,j,k}}{dz}$$

$$\left.\frac{\partial u^n}{\partial x}\right|_{i-\frac{1}{2},j,k} = \frac{u^n_{i,j,k}-u^n_{i-1,j,k}}{dx}, \left.\frac{\partial v^n}{\partial y}\right|_{i,j-\frac{1}{2},k} = \frac{v^n_{i,j,k}-v^n_{i,j-1,k}}{dy}, \left.\frac{\partial w^n}{\partial z}\right|_{i,j,k-\frac{1}{2}} = \frac{w^n_{i,j,k}-w^n_{i,j,k-1}}{dz},$$

$$\left.\frac{\partial u^n}{\partial y}\right|_{i+\frac{1}{2},j,k} = 2\left(\frac{u^n_{i+1,j+1,k}-u^n_{i+1,j-1,k}}{2\,dy}+\frac{u^n_{i,j+1,k}-u^n_{i,j-1,k}}{2\,dy}\right), \left.\frac{\partial u^n}{\partial y}\right|_{i-\frac{1}{2},j,k} = 2\left(\frac{u^n_{i-1,j+1,k}-u^n_{i-1,j-1,k}}{2\,dy}+\frac{u^n_{i,j+1,k}-u^n_{i,j-1,k}}{2\,dy}\right)$$

$$\left.\frac{\partial u^n}{\partial z}\right|_{i+\frac{1}{2},j,k} = 2\left(\frac{u^n_{i+1,j,k+1}-u^n_{i+1,j,k-1}}{2\,dz}+\frac{u^n_{i,j,k+1}-u^n_{i,j,k-1}}{2\,dz}\right), \left.\frac{\partial u^n}{\partial z}\right|_{i-\frac{1}{2},j,k} = 2\left(\frac{u^n_{i-1,j,k+1}-u^n_{i-1,j,k-1}}{2\,dz}+\frac{u^n_{i,j,k+1}-u^n_{i,j,k-1}}{2\,dz}\right)$$

$$\left.\frac{\partial v^n}{\partial x}\right|_{i,j+\frac{1}{2},k} = 2\left(\frac{v^n_{i+1,j+1,k}-v^n_{i-1,j+1,k}}{2\,dx}+\frac{v^n_{i+1,j,k}-v^n_{i-1,j,k}}{2\,dx}\right), \left.\frac{\partial v^n}{\partial x}\right|_{i,j-\frac{1}{2},k} = 2\left(\frac{v^n_{i+1,j-1,k}-v^n_{i-1,j-1,k}}{2\,dx}+\frac{v^n_{i+1,j,k}-v^n_{i-1,j,k}}{2\,dx}\right)$$

$$\left.\frac{\partial v^n}{\partial z}\right|_{i,j+\frac{1}{2},k} = 2\left(\frac{v^n_{i,j+1,k+1}-v^n_{i,j+1,k-1}}{2\,dz}+\frac{v^n_{i,j,k+1}-v^n_{i,j,k-1}}{2\,dz}\right), \left.\frac{\partial v^n}{\partial z}\right|_{i,j-\frac{1}{2},k} = 2\left(\frac{v^n_{i,j-1,k+1}-v^n_{i,j-1,k-1}}{2\,dz}+\frac{v^n_{i,j,k+1}-v^n_{i,j,k-1}}{2\,dz}\right)$$

$$\left.\frac{\partial w^n}{\partial x}\right|_{i,j,k+\frac{1}{2}} = 2\left(\frac{w^n_{i+1,j,k+1}-w^n_{i-1,j,k+1}}{2\,dx}+\frac{w^n_{i+1,j,k}-w^n_{i-1,j,k}}{2\,dx}\right), \left.\frac{\partial w^n}{\partial x}\right|_{i,j,k-\frac{1}{2}} = 2\left(\frac{w^n_{i+1,j,k-1}-w^n_{i-1,j,k-1}}{2\,dx}+\frac{w^n_{i+1,j,k}-w^n_{i-1,j,k}}{2\,dx}\right)$$

$$\left.\frac{\partial w^n}{\partial y}\right|_{i,j,k+\frac{1}{2}} = 2\left(\frac{w^n_{i,j+1,k+1}-w^n_{i,j-1,k+1}}{2\,dy}+\frac{w^n_{i,j+1,k}-w^n_{i,j-1,k}}{2\,dy}\right), \left.\frac{\partial w^n}{\partial y}\right|_{i,j,k-\frac{1}{2}} = 2\left(\frac{w^n_{i,j+1,k-1}-w^n_{i,j-1,k-1}}{2\,dy}+\frac{w^n_{i,j+1,k}-w^n_{i,j-1,k}}{2\,dy}\right)$$

C.2. Boundary specifications

For the 3D grid with one inlet and one outlet a total of 31 different mesh-blocks are identified, based on types of boundaries. The following list below contains the different boundary locations:

1. 4 bottom corner mesh blocks;
2. 4 top corner mesh blocks;
3. 4 series of mesh blocks in the XY-plane at the bottom (for X direction and Y direction 2 x 2);
4. 4 series of mesh blocks in the XY-plane at the top (for X direction and Y direction 2 x 2);
5. 2 series of mesh blocks in the YZ-plane at X = 0 in Y direction;
6. 2 series of mesh blocks in the YZ-plane at X=L_R in Y direction;
7. 6 series of mesh blocks to fill up every boundary plane at minimum or maximum axis values.
8. 1 type of mesh blocks for the centre in the reservoir;
9. 1 type of mesh blocks at the top in the XY-plane at X = 0, due to the inlet;
10. 1 type of mesh blocks at X = 0 in the YZ-plane, due to the inlet;
11. 1 type of mesh blocks at the top in the XY-plane at X = L_R, due to the outlet;
12. 1 type of mesh blocks at X = L_R in the YZ-plane, due to the outlet;

- The number of mesh blocks corresponding to the height (w.r.t. depth reservoir) of the outlet is determined with variable r*.*
- The inlet is at free surface height and located in the centre of the width of the reservoir.
- The outlet is at specified height (bottom sluice gates at H_{db}) and located in the centre of the width of the reservoir.

Table C-1: Specification of boundaries with locations and conditions (appendix C.) shows the complete identification and specification of locations and conditions for the boundaries. The following (coordinate) characteristics are essential to span the 3D grid.

- The grid is divided in m mesh blocks in X direction, the number identified with variable *i*.
- The grid is divided in n mesh blocks in Y direction, the number identified with variable *j*.
- The grid is divided in r mesh blocks in Z direction, the number identified with variable *k*.

- The boundary conditions for the basis reservoir have to be calculated first in the code. Only after this is complete, the boundary conditions for the in- and outlet can be calculated.
- The number of mesh blocks corresponding to the depth of the inlet is determined with variable *r_up.*
- The number of mesh blocks corresponding to the width of the inlet is determined with variable *n_up.*
- The number of mesh blocks corresponding to the depth of the outlet is determined with variable *r_down*
- The number of mesh blocks corresponding to the width of the outlet is determined with variable n_down*.*
- The number of mesh blocks corresponding to the height (w.r.t. depth reservoir) of the outlet is determined with variable n_downb*.*
- The inlet is at the height of the free surface of the reservoir and located in the centre of the width of the reservoir.
- The outlet is at specified height and located in the centre of the width of the reservoir.

Table C–1: Specification of boundaries with locations and conditions

Boundary ID	***i***	***j***	***k***	***Boundary Conditions***
1	1	1	1	$u_{i-0.5} = 0$; $v_{i-0.5} = 0$; $w_{i-0.5} = 0$; $u_{j-0.5} = 0$; $v_{j-0.5} = 0$; $w_{j-0.5} = 0$; $u_{k-0.5} = 0$; $v_{k-0.5} = 0$; $w_{k-0.5} = 0$; $tau_{xx,i-0.5} = 0$; $tau_{zz,z-0.5} = 0$; $tau_{yy,j-0.5} = 0$; $u_{x,i-0.5} = 0$; $v_{y,i-0.5} = 0$; $w_{z,i-0.5} = 0$; $v_{x,i-0.5} = 2*v(i,j,k)/dx$; $w_{x,i-0.5} = 2*w(i,j,k)/dx$; $u_{x,j-0.5} = 0$; $v_{y,j-0.5} = 0$; $w_{z,j-0.5} = 0$; $u_{y,j-0.5} = 2*u(i,j,k)/dy$; $w_{j,j-0.5} = 2*w(i,j,k)/dy$; $u_{x,z-0.5} = 0$; $v_{y,z-0.5} = 0$; $w_{z,z-0.5} = 0$; $u_{z,k-0.5} = 2*u(i,j,k)/dz$; $v_{z,k-0.5} = 2*v(i,j,k)/dz$;
2	1	n	1	$u_{i-0.5} = 0$; $v_{i-0.5} = 0$; $w_{i-0.5} = 0$; $u_{j+0.5} = 0$; $v_{j+0.5} = 0$; $w_{j+0.5} = 0$; $u_{k-0.5} = 0$; $v_{k-0.5} = 0$; $w_{k-0.5} = 0$; $tau_{xx,i-0.5} = 0$; $tau_{zz,z-0.5} = 0$; $tau_{yy,j+0.5} = 0$; $u_{x,i-0.5} = 0$; $v_{y,i-0.5} = 0$; $w_{z,i-0.5} = 0$; $v_{x,i-0.5} = 2*v(i,j,k)/dx$; $w_{x,i-0.5} = 2*w(i,j,k)/dx$; $u_{x,j+0.5} = 0$; $v_{y,j+0.5} = 0$; $w_{z,j+0.5} = 0$; $u_{y,j+0.5} = 2*-u(i,j,k)/dy$; $w_{j,j+0.5} = 2*-w(i,j,k)/dy$; $u_{x,z-0.5} = 0$; $v_{y,z-0.5} = 0$; $w_{z,z-0.5} = 0$; $u_{z,k-0.5} = 2*u(i,j,k)/dz$; $v_{z,k-0.5} = 2*v(i,j,k)/dz$;
3	1	1	r	$u_{i-0.5} = 0$; $v_{i-0.5} = 0$; $w_{i-0.5} = 0$; $u_{j-0.5} = 0$; $v_{j-0.5} = 0$; $w_{j-0.5} = 0$; $u_{k+0.5} = u(i,j,k)$; $v_{k+0.5} = v(i,j,k)$; $w_{k+0.5} = 0$;

				$tau_{xx,i-0.5} = 0$; $tau_{zz,z+0.5} = 0$; $tau_{yy,j-0.5} = 0$; $u_{x,i-0.5} = 0$; $v_{y,i-0.5} = 0$; $w_{z,i-0.5} = 0$; $v_{x,i-0.5} = 2*v(i,j,k)/dx$; $w_{x,i-0.5} = 2*w(i,j,k)/dx$; $u_{x,j-0.5} = 0$; $v_{y,j-0.5} = 0$; $w_{z,j-0.5} = 0$; $u_{y,j-0.5} = 2*u(i,j,k)/dy$; $w_{j,j-0.5} = 2*w(i,j,k)/dy$; $u_{x,z+0.5} = 0$; $v_{y,z+0.5} = 0$; $w_{z,z+0.5} = 0$; $u_{z,k+0.5} = 2*-u(i,j,k)/dz$; $v_{z,k+0.5} = 2*-v(i,j,k)/dz$;
4	1	n	r	$u_{i-0.5} = 0$; $v_{i-0.5} = 0$; $w_{i-0.5} = 0$; $u_{j+0.5} = 0$; $v_{j+0.5} = 0$; $w_{j+0.5} = 0$; $u_{k+0.5} = u(i,j,k)$; $v_{k+0.5} = v(i,j,k)$; $w_{k+0.5} = 0$; $tau_{xx,i-0.5} = 0$; $tau_{zz,z+0.5} = 0$; $tau_{yy,j+0.5} = 0$; $u_{x,i-0.5} = 0$; $v_{y,i-0.5} = 0$; $w_{z,i-0.5} = 0$; $v_{x,i-0.5} = 2*v(i,j,k)/dx$; $w_{x,i-0.5} = 2*w(i,j,k)/dx$; $u_{x,j+0.5} = 0$; $v_{y,j+0.5} = 0$; $w_{z,j+0.5} = 0$; $u_{y,j+0.5} = 2*-u(i,j,k)/dy$; $w_{j,j+0.5} = 2*-w(i,j,k)/dy$; $u_{x,z+0.5} = 0$; $v_{y,z+0.5} = 0$; $w_{z,z+0.5} = 0$; $u_{z,k+0.5} = 2*-u(i,j,k)/dz$; $v_{z,k+0.5} = 2*-v(i,j,k)/dz$;
5	m	1	1	$u_{i+0.5} = 0$; $v_{i+0.5} = 0$; $w_{i+0.5} = 0$; $u_{j-0.5} = 0$; $v_{j-0.5} = 0$; $w_{j-0.5} = 0$; $u_{k-0.5} = 0$; $v_{k-0.5} = 0$; $w_{k-0.5} = 0$; $tau_{xx,i+0.5} = 0$; $tau_{zz,z-0.5} = 0$; $tau_{yy,j-0.5} = 0$; $u_{x,i+0.5} = 0$; $v_{y,i+0.5} = 0$; $w_{z,i+0.5} = 0$; $v_{x,i+0.5} = 2*-v(i,j,k)/dx$; $w_{x,i+0.5} = 2*-w(i,j,k)/dx$; $u_{x,j-0.5} = 0$; $v_{y,j-0.5} = 0$; $w_{z,j-0.5} = 0$; $u_{y,j-0.5} = 2*u(i,j,k)/dy$; $w_{j,j-0.5} = 2*w(i,j,k)/dy$; $u_{x,z-0.5} = 0$; $v_{y,z-0.5} = 0$; $w_{z,z-0.5} = 0$; $u_{z,k-0.5} = 2*u(i,j,k)/dz$; $v_{z,k-0.5} = 2*v(i,j,k)/dz$;
6	m	n	1	$u_{i+0.5} = 0$; $v_{i+0.5} = 0$; $w_{i+0.5} = 0$; $u_{j+0.5} = 0$; $v_{j+0.5} = 0$; $w_{j+0.5} = 0$; $u_{k-0.5} = 0$; $v_{k-0.5} = 0$; $w_{k-0.5} = 0$; $tau_{xx,i+0.5} = 0$; $tau_{zz,z-0.5} = 0$; $tau_{yy,j+0.5} = 0$; $u_{x,i+0.5} = 0$; $v_{y,i+0.5} = 0$; $w_{z,i+0.5} = 0$; $v_{x,i+0.5} = 2*-v(i,j,k)/dx$; $w_{x,i+0.5} = 2*-w(i,j,k)/dx$; $u_{x,j+0.5} = 0$; $v_{y,j+0.5} = 0$; $w_{z,j+0.5} = 0$; $u_{y,j+0.5} = 2*-u(i,j,k)/dy$; $w_{j,j+0.5} = 2*-w(i,j,k)/dy$;

				$u_{x,z-0.5} = 0$; $v_{y,z-0.5} = 0$; $w_{z,z-0.5} = 0$; $u_{z,k-0.5} = 2*u(i,j,k)/dz$; $v_{z,k-0.5} = 2*v(i,j,k)/dz$;
7	m	1	r	$u_{i+0.5} = 0$; $v_{i+0.5} = 0$; $w_{i+0.5} = 0$; $u_{j-0.5} = 0$; $v_{j-0.5} = 0$; $w_{j-0.5} = 0$; $u_{k+0.5} = u(i,j,k)$; $v_{k+0.5} = v(i,j,k)$; $w_{k+0.5} = 0$; $tau_{xx,i+0.5} = 0$; $tau_{zz,z+0.5} = 0$; $tau_{yy,j-0.5} = 0$; $u_{x,i+0.5} = 0$; $v_{y,i+0.5} = 0$; $w_{z,i+0.5} = 0$; $v_{x,i+0.5} = 2*-v(i,j,k)/dx$; $w_{x,i+0.5} = 2*-w(i,j,k)/dx$; $u_{x,j-0.5} = 0$; $v_{y,j-0.5} = 0$; $w_{z,j-0.5} = 0$; $u_{y,j-0.5} = 2*u(i,j,k)/dy$; $w_{j,j-0.5} = 2*w(i,j,k)/dy$; $u_{x,z+0.5} = 0$; $v_{y,z+0.5} = 0$; $w_{z,z+0.5} = 0$; $u_{z,k+0.5} = 2*-u(i,j,k)/dz$; $v_{z,k+0.5} = 2*-v(i,j,k)/dz$;
8	m	n	r	$u_{i+0.5} = 0$; $v_{i+0.5} = 0$; $w_{i+0.5} = 0$; $u_{j+0.5} = 0$; $v_{j+0.5} = 0$; $w_{j+0.5} = 0$; $u_{k+0.5} = u(i,j,k)$; $v_{k+0.5} = v(i,j,k)$; $w_{k+0.5} = 0$; $tau_{xx,i+0.5} = 0$; $tau_{zz,z+0.5} = 0$; $tau_{yy,j-0.5} = 0$; $u_{x,i+0.5} = 0$; $v_{y,i+0.5} = 0$; $w_{z,i+0.5} = 0$; $v_{x,i+0.5} = 2*-v(i,j,k)/dx$; $w_{x,i+0.5} = 2*-w(i,j,k)/dx$; $u_{x,j+0.5} = 0$; $v_{y,j+0.5} = 0$; $w_{z,j+0.5} = 0$; $u_{y,j+0.5} = 2*-u(i,j,k)/dy$; $w_{j,j+0.5} = 2*-w(i,j,k)/dy$; $u_{x,z+0.5} = 0$; $v_{y,z+0.5} = 0$; $w_{z,z+0.5} = 0$; $u_{z,k+0.5} = 2*-u(i,j,k)/dz$; $v_{z,k+0.5} = 2*-v(i,j,k)/dz$;
9	1	2 … n – 1	1	$u_{i-0.5} = 0$; $v_{i-0.5} = 0$; $w_{i-0.5} = 0$; $u_{k-0.5} = 0$; $v_{k-0.5} = 0$; $w_{k-0.5} = 0$; $tau_{xx,i-0.5} = 0$; $tau_{zz,z-0.5} = 0$; $u_{x,i-0.5} = 0$; $v_{y,i-0.5} = 0$; $w_{z,i-0.5} = 0$; $v_{x,i-0.5} = 2*v(i,j,k)/dx$; $w_{x,i-0.5} = 2*w(i,j,k)/dx$; $u_{x,z-0.5} = 0$; $v_{y,z-0.5} = 0$; $w_{z,z-0.5} = 0$; $u_{z,k-0.5} = 2*u(i,j,k)/dz$; $v_{z,k-0.5} = 2*v(i,j,k)/dz$;
10	2 … m – 1	1	1	$u_{j-0.5} = 0$; $v_{j-0.5} = 0$; $w_{j-0.5} = 0$; $u_{k-0.5} = 0$; $v_{k-0.5} = 0$; $w_{k-0.5} = 0$; $tau_{yy,j-0.5} = 0$; $tau_{zz,z-0.5} = 0$; $u_{x,j-0.5} = 0$; $v_{y,j-0.5} = 0$; $w_{z,j-0.5} = 0$; $u_{y,j-0.5} = 2*u(i,j,k)/dy$; $w_{y,j-0.5} = 2*w(i,j,k)/dy$; $u_{x,z-0.5} = 0$; $v_{y,z-0.5} = 0$; $w_{z,z-0.5} = 0$; $u_{z,k-0.5} = 2*u(i,j,k)/dz$; $v_{z,k-0.5} = 2*v(i,j,k)/dz$;
11	2 … m – 1	n	1	$u_{j+0.5} = 0$; $v_{j+0.5} = 0$; $w_{j+0.5} = 0$; $u_{k-0.5} = 0$; $v_{k-0.5} = 0$; $w_{k-0.5} = 0$;

				$tau_{yy,j+0.5}$ = 0; $tau_{zz,z-0.5}$ = 0; $u_{x,j+0.5}$ = 0; $v_{y,j+0.5}$ = 0; $w_{z,j+0.5}$ = 0; $u_{y,j+0.5}$ = 2*-u(i,j,k)/dy; $w_{y,j+0.5}$ = 2*-w(i,j,k)/dy; $u_{x,z-0.5}$ = 0; $v_{y,z-0.5}$ = 0; $w_{z,z-0.5}$ = 0; $u_{z,k-0.5}$ = 2*u(i,j,k)/dz; $v_{z,k-0.5}$ = 2*v(i,j,k)/dz;
12	m	2 … n – 1	1	$u_{i+0.5}$ = 0; $v_{i+0.5}$ = 0; $w_{i+0.5}$ = 0; $u_{k-0.5}$ = 0; $v_{k-0.5}$ = 0; $w_{k-0.5}$ = 0; $tau_{xx,i+0.5}$ = 0; $tau_{zz,z-0.5}$ = 0; $u_{x,i+0.5}$ = 0; $v_{y,i+0.5}$ = 0; $w_{z,i+0.5}$ = 0; $v_{x,i+0.5}$ = 2*-v(i,j,k)/dx; $w_{x,i+0.5}$ = 2*-w(i,j,k)/dx; $u_{x,z-0.5}$ = 0; $v_{y,z-0.5}$ = 0; $w_{z,z-0.5}$ = 0; $u_{z,k-0.5}$ = 2*u(i,j,k)/dz; $v_{z,k-0.5}$ = 2*v(i,j,k)/dz;
13	1	2 … n – 1	r	$u_{i-0.5}$ = 0; $v_{i-0.5}$ = 0; $w_{i-0.5}$ = 0; $u_{k+0.5}$ = u(i,j,k); $v_{k+0.5}$ = v(i,j,k); $w_{k+0.5}$ = 0; $tau_{xx,i-0.5}$ = 0; $tau_{zz,z+0.5}$ = 0; $u_{x,i-0.5}$ = 0; $v_{y,i-0.5}$ = 0; $w_{z,i-0.5}$ = 0; $v_{x,i-0.5}$ = 2*v(i,j,k)/dx; $w_{x,i-0.5}$ = 2*w(i,j,k)/dx; $u_{x,z+0.5}$ = 0; $v_{y,z+0.5}$ = 0; $w_{z,z+0.5}$ = 0; $u_{z,k+0.5}$ = 2*-u(i,j,k)/dz; $v_{z,k+0.5}$ = 2*-v(i,j,k)/dz;
14	2 … m – 1	1	r	$u_{j-0.5}$ = 0; $v_{j-0.5}$ = 0; $w_{j-0.5}$ = 0; $u_{k+0.5}$ = u(i,j,k); $v_{k+0.5}$ = v(i,j,k); $w_{k+0.5}$ = 0; $tau_{yy,j-0.5}$ = 0; $tau_{zz,z+0.5}$ = 0; $u_{x,j-0.5}$ = 0; $v_{y,j-0.5}$ = 0; $w_{z,j-0.5}$ = 0; $u_{y,j-0.5}$ = 2*u(i,j,k)/dy; $w_{y,j-0.5}$ = 2*w(i,j,k)/dy; $u_{x,z+0.5}$ = 0; $v_{y,z+0.5}$ = 0; $w_{z,z+0.5}$ = 0; $u_{z,k+0.5}$ = 2*-u(i,j,k)/dz; $v_{z,k+0.5}$ = 2*-v(i,j,k)/dz;
15	2 … m – 1	n	r	$u_{j+0.5}$ = 0; $v_{j+0.5}$ = 0; $w_{j+0.5}$ = 0; $u_{k+0.5}$ = u(i,j,k); $v_{k+0.5}$ = v(i,j,k); $w_{k+0.5}$ = 0; $tau_{yy,j+0.5}$ = 0; $tau_{zz,z+0.5}$ = 0; $u_{x,j+0.5}$ = 0; $v_{y,j+0.5}$ = 0; $w_{z,j+0.5}$ = 0; $u_{y,j+0.5}$ = 2*-u(i,j,k)/dy; $w_{y,j+0.5}$ = 2*-w(i,j,k)/dy; $u_{x,z+0.5}$ = 0; $v_{y,z+0.5}$ = 0; $w_{z,z+0.5}$ = 0; $u_{z,k+0.5}$ = 2*-u(i,j,k)/dz; $v_{z,k+0.5}$ = 2*-v(i,j,k)/dz;
16	m	2 … n – 1	r	$u_{i+0.5}$ = 0; $v_{i+0.5}$ = 0; $w_{i+0.5}$ = 0; $u_{k+0.5}$ = u(i,j,k); $v_{k+0.5}$ = v(i,j,k); $w_{k+0.5}$ = 0; $tau_{xx,i+0.5}$ = 0; $tau_{zz,z+0.5}$ = 0; $u_{x,i+0.5}$ = 0; $v_{y,i+0.5}$ = 0; $w_{z,i+0.5}$ = 0; $v_{x,i+0.5}$ = 2*-v(i,j,k)/dx; $w_{x,i+0.5}$ = 2*-w(i,j,k)/dx; $u_{x,z+0.5}$ = 0; $v_{y,z+0.5}$ = 0; $w_{z,z+0.5}$ = 0; $u_{z,k+0.5}$ = 2*-u(i,j,k)/dz; $v_{z,k+0.5}$ = 2*-v(i,j,k)/dz;
17	1	1	2 … r – 1	$u_{i-0.5}$ = 0; $v_{i-0.5}$ = 0; $w_{i-0.5}$ = 0; $u_{j-0.5}$ = 0; $v_{j-0.5}$ = 0; $w_{j-0.5}$ = 0;

				$tau_{xx,i-0.5} = 0$; $tau_{yy,j-0.5} = 0$; $u_{x,i-0.5} = 0$; $v_{y,i-0.5} = 0$; $w_{z,i-0.5} = 0$; $v_{x,i-0.5} = 2*v(i,j,k)/dx$; $w_{x,i-0.5} = 2*w(i,j,k)/dx$; $u_{x,j-0.5} = 0$; $v_{y,j-0.5} = 0$; $w_{z,j-0.5} = 0$; $u_{y,j-0.5} = 2*u(i,j,k)/dy$; $w_{j,j-0.5} = 2*w(i,j,k)/dy$;
18	1	n	2 … r – 1	$u_{i-0.5} = 0$; $v_{i-0.5} = 0$; $w_{i-0.5} = 0$; $u_{j+0.5} = 0$; $v_{j+0.5} = 0$; $w_{j+0.5} = 0$; $tau_{xx,i-0.5} = 0$; $tau_{yy,j+0.5} = 0$; $u_{x,i-0.5} = 0$; $v_{y,i-0.5} = 0$; $w_{z,i-0.5} = 0$; $v_{x,i-0.5} = 2*v(i,j,k)/dx$; $w_{x,i-0.5} = 2*w(i,j,k)/dx$; $u_{x,j+0.5} = 0$; $v_{y,j+0.5} = 0$; $w_{z,j+0.5} = 0$; $u_{y,j+0.5} = 2*-u(i,j,k)/dy$; $w_{j,j+0.5} = 2*-w(i,j,k)/dy$;
19	m	1	2 … r – 1	$u_{i+0.5} = 0$; $v_{i+0.5} = 0$; $w_{i+0.5} = 0$; $u_{j-0.5} = 0$; $v_{j-0.5} = 0$; $w_{j-0.5} = 0$; $tau_{xx,i+0.5} = 0$; $tau_{yy,j-0.5} = 0$; $u_{x,i+0.5} = 0$; $v_{y,i+0.5} = 0$; $w_{z,i+0.5} = 0$; $v_{x,i+0.5} = 2*-v(i,j,k)/dx$; $w_{x,i+0.5} = 2*-w(i,j,k)/dx$; $u_{x,j-0.5} = 0$; $v_{y,j-0.5} = 0$; $w_{z,j-0.5} = 0$; $u_{y,j-0.5} = 2*u(i,j,k)/dy$; $w_{j,j-0.5} = 2*w(i,j,k)/dy$;
20	m	n	2 … r – 1	$u_{i+0.5} = 0$; $v_{i+0.5} = 0$; $w_{i+0.5} = 0$; $u_{j+0.5} = 0$; $v_{j+0.5} = 0$; $w_{j+0.5} = 0$; $tau_{xx,i+0.5} = 0$; $tau_{yy,j-0.5} = 0$; $u_{x,i+0.5} = 0$; $v_{y,i+0.5} = 0$; $w_{z,i+0.5} = 0$; $v_{x,i+0.5} = 2*-v(i,j,k)/dx$; $w_{x,i+0.5} = 2*-w(i,j,k)/dx$; $u_{x,j+0.5} = 0$; $v_{y,j+0.5} = 0$; $w_{z,j+0.5} = 0$; $u_{y,j+0.5} = 2*-u(i,j,k)/dy$; $w_{j,j+0.5} = 2*-w(i,j,k)/dy$;
21	1	2 … n – 1	2 … r – 1	$u_{i-0.5} = 0$; $v_{i-0.5} = 0$; $w_{i-0.5} = 0$; $tau_{xx,i-0.5} = 0$; $u_{x,i-0.5} = 0$; $v_{y,i-0.5} = 0$; $w_{z,i-0.5} = 0$; $v_{x,i-0.5} = 2*v(i,j,k)/dx$; $w_{x,i-0.5} = 2*w(i,j,k)/dx$;
22	2 … m – 1	1	2 … r – 1	$u_{j-0.5} = 0$; $v_{j-0.5} = 0$; $w_{j-0.5} = 0$; $tau_{yy,j-0.5} = 0$; $u_{x,j-0.5} = 0$; $v_{y,j+0.5} = 0$; $w_{z,j-0.5} = 0$; $u_{y,j-0.5} = 2*u(i,j,k)/dy$; $w_{j,j-0.5} = 2*w(i,j,k)/dy$;
23	2 … m – 1	2 … n – 1	1	$u_{k-0.5} = 0$; $v_{k-0.5} = 0$; $w_{k-0.5} = 0$; $u_{x,z-0.5} = 0$; $v_{y,z-0.5} = 0$; $w_{z,z-0.5} = 0$; $u_{z,k-0.5} = 2*u(i,j,k)/dz$; $v_{z,k-0.5} = 2*v(i,j,k)/dz$;
24	2 … m – 1	n	2 … r – 1	$u_{j+0.5} = 0$; $v_{j+0.5} = 0$; $w_{j-+.5} = 0$; $tau_{yy,j+0.5} = 0$; $u_{x,j+0.5} = 0$; $v_{y,j+0.5} = 0$; $w_{z,j+0.5} = 0$; $u_{y,j+0.5} = 2*-u(i,j,k)/dy$; $w_{j,j-0.5} = 2*-w(i,j,k)/dy$;

25	2 … m – 1	2 … n – 1	r	$u_{k+0.5}$ = 0; $v_{k+0.5}$ = 0; $w_{k+0.5}$ = 0; $u_{x,z+0.5}$ = 0; $v_{y,z+0.5}$ = 0; $w_{z,z+0.5}$ = 0; $u_{z,k+0.5}$ = 2*-u(i,j,k)/dz; $v_{z,k+0.5}$ = 2*-v(i,j,k)/dz;
26	m	2 … n – 1	2 … r – 1	$u_{i+0.5}$ = 0; $v_{i+0.5}$ = 0; $w_{i+0.5}$ = 0; $tau_{xx,i+0.5}$ = 0; $u_{x,i+0.5}$ = 0; $v_{y,i+0.5}$ = 0; $w_{z,i+0.5}$ = 0; $v_{x,i+0.5}$ = 2*-v(i,j,k)/dx; $w_{x,i+0.5}$ = 2*-w(i,j,k)/dx;
27	1	floor((n-(ceil(n*W_u/L_y))/2) … floor((n-(ceil(n*W_u/L_y))/2)+ceil(n*W_u/L_y))/2	r	$u_{i-0.5}$ = 0; $v_{i-0.5}$ = 0; $w_{i-0.5}$ = 0; $u_{k+0.5}$ = u(i,j,k); $v_{k+0.5}$ = v(i,j,k); $w_{k+0.5}$ = 0; $tau_{xx,i-0.5}$ = 0; $tau_{zz,z+0.5}$ = 0; $u_{x,i-0.5}$ = 0; $v_{y,i-0.5}$ = 0; $w_{z,i-0.5}$ = 0; $v_{x,i-0.5}$ = 2*v(i,j,k)/dx; $w_{x,i-0.5}$ = 2*w(i,j,k)/dx; $u_{x,z+0.5}$ = 0; $v_{y,z+0.5}$ = 0; $w_{z,z+0.5}$ = 0; $u_{z,k+0.5}$ = 2*-u(i,j,k)/dz; $v_{z,k+0.5}$ = 2*-v(i,j,k)/dz;
28	1	floor((n-(ceil(n*W_u/L_y))/2) … floor((n-(ceil(n*W_u/L_y))/2)+ceil(n*W_u/L_y))/2	2 … r – 1	$u_{i-0.5}$ = 0; $v_{i-0.5}$ = 0; $w_{i-0.5}$ = 0; $tau_{xx,i-0.5}$ = 0; $u_{x,i-0.5}$ = 0; $v_{y,i-0.5}$ = 0; $w_{z,i-0.5}$ = 0; $v_{x,i-0.5}$ = 2*v(i,j,k)/dx; $w_{x,i-0.5}$ = 2*w(i,j,k)/dx;
29	m	floor((n-(ceil(n*W_d/L_y))/2) … floor((n-(ceil(n*W_d/L_y))/2)+ceil(n*W_d/L_y))/2	r	$u_{i+0.5}$ = 0; $v_{i+0.5}$ = 0; $w_{i+0.5}$ = 0; $u_{k+0.5}$ = u(i,j,k); $v_{k+0.5}$ = v(i,j,k); $w_{k+0.5}$ = 0; $tau_{xx,i+0.5}$ = 0; $tau_{zz,z+0.5}$ = 0; $u_{x,i+0.5}$ = 0; $v_{y,i+0.5}$ = 0; $w_{z,i+0.5}$ = 0; $v_{x,i+0.5}$ = 2*-v(i,j,k)/dx; $w_{x,i+0.5}$ = 2*-w(i,j,k)/dx; $u_{x,z+0.5}$ = 0; $v_{y,z+0.5}$ = 0; $w_{z,z+0.5}$ = 0; $u_{z,k+0.5}$ = 2*-u(i,j,k)/dz; $v_{z,k+0.5}$ = 2*-v(i,j,k)/dz;
30	m	floor((n-(ceil(n*W_d/L_y))/2) … floor((n-(ceil(n*W_d/L_y))/2)+ceil(n*W_d/L_y))/2	2 … r – 1	$u_{i+0.5}$ = 0; $v_{i+0.5}$ = 0; $w_{i+0.5}$ = 0; $tau_{xx,i+0.5}$ = 0; $u_{x,i+0.5}$ = 0; $v_{y,i+0.5}$ = 0; $w_{z,i+0.5}$ = 0; $v_{x,i+0.5}$ = 2*-v(i,j,k)/dx; $w_{x,i+0.5}$ = 2*-w(i,j,k)/dx;
31	2 … m – 1	2 … n – 1	2 … r – 1	No.

C.3. Derivation of the Poisson Matrix

The derivation of the Poisson matrix starts with the right-hand-side of Eq. 4-18:

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2} \qquad \text{Eq. C-1}$$

Written out without boundaries:

$$\frac{p_{i+1,j,k}^{n+1}}{(\Delta x)^2}-2\,\frac{p_{i,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}}{(\Delta y)^2}-2\,\frac{p_{i,j,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}}{(\Delta z)^2}-2\,\frac{p_{i,j,k}^{n+1}}{(\Delta z)^2}+\frac{p_{i,j,k-1}^{n+1}}{(\Delta z)^2} \qquad \text{Eq. C-2}$$

This formula will now be adjusted to become a multiplication of an array p^{n+1} and two-dimensional Poisson matrix A.

The next list of formulas shows the application of Eq. C-1 in the specified locations:

Front (j =1)

i = 1; z = 1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}$$

i = 2…m-1; z = 1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}$$

i = m; z = 1;

$$-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}$$

i = 1; z = 2…k-1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = 2…m-1; z = 2…k-1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = m; z = 2…k-1;

$$\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = 1; z = k;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = 2…m-1; z = k;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = m; z = k;

$$\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

Middle (j=2…n-1)

i = 1; z = 1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}$$

i = 2…m-1; z = 1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}$$

i = m; z = 1;

$$-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}$$

i = 1; z = 2…k-1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$ *If inlet at location!*

i = 2…m-1; z = 2…k-1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2} \quad \text{(Eq. C-2)}$$

i = m; z = 2…k-1;

$$-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$ *if outlet at location!*

i = 1; z = k;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = 2…m-1; z = k;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = m; z = k;

$$-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}+\frac{p_{i,j+1,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

Back (j=n)

i = 1; z = 1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}$$

i = 2…m-1; z = 1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}$$

i = m; z = 1;

$$-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}$$

i = 1; z = 2…k-1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = 2…m-1; z = 2…k-1;

$$\frac{p_{i+1,j,k}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = m; z = 2…k-1;

$$-\frac{p_{i,j,k}^{n+1}-p_{i-1,j,k}^{n+1}}{(\Delta x)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j-1,k}^{n+1}}{(\Delta y)^2}+\frac{p_{i,j,k+1}^{n+1}-p_{i,j,k}^{n+1}}{(\Delta z)^2}-\frac{p_{i,j,k}^{n+1}-p_{i,j,k-1}^{n+1}}{(\Delta z)^2}$$

i = 1; z = k;

$$\frac{p^{n+1}_{i+1,j,k}-p^{n+1}_{i,j,k}}{(\Delta x)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i,j-1,k}}{(\Delta y)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i,j,k-1}}{(\Delta z)^2}$$

i = 2…m-1; z = k;

$$\frac{p^{n+1}_{i+1,j,k}-p^{n+1}_{i,j,k}}{(\Delta x)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i-1,j,k}}{(\Delta x)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i,j-1,k}}{(\Delta y)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i,j,k-1}}{(\Delta z)^2}$$

i = m; z = k;

$$-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i-1,j,k}}{(\Delta x)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i,j-1,k}}{(\Delta y)^2}-\frac{p^{n+1}_{i,j,k}-p^{n+1}_{i,j,k-1}}{(\Delta z)^2}$$

Structure of Poisson Matrix and cell locations:
Size A: m X n X r
Location of grid cell in matrix A: A(i+(j-1)*m+(k-1)*m*n, i+(j-1)*m+(k-1)*m*n)
Location of grid cell i_{-1} in matrix A: A(i+(j-1)*m+(k-1)*m*n, i+(j-1)*m+(k-1)*m*n-1)
Location of grid cell i_{+1} in matrix A: A(i+(j-1)*m+(k-1)*m*n, i+(j-1)*m+(k-1)*m*n+1)
Location of grid cell j_{-1} in matrix A: A(i+(j-1)*m+(k-1)*m*n, i+(j-1)*m+(k-1)*m*n-m)
Location of grid cell j_{+1} in matrix A: A(i+(j-1)*m+(k-1)*m*n, i+(j-1)*m+(k-1)*m*n+m)
Location of grid cell k_{-1} in matrix A: A(i+(j-1)*m+(k-1)*m*n, i+(j-1)*m+(k-1)*m*n-m*n)
Location of grid cell k_{+1} in matrix A: A(i+(j-1)*m+(k-1)*m*n, i+(j-1)*m+(k-1)*m*n+m*n)

D. Results

D.1. Purchase of dredgers

New required equipment/Year	Method 1: Suction dredger	Support eq. method 1	Method 2: Cutter suction dredger 1	Support eq. method 2	Method 3: Grab dredge	Support eq. method 3	**Method 4: Submersible dredge pump, DOP**	**Support eq. method 4**	Method 5: Water injection dredge	Support eq. method 5
2020	2	1	2	0	2	1	**2**	**0**	2	0
2021	6	1	4	1	4	1	**6**	**2**	6	2
2022	0	0	0	0	0	0	**0**	**0**	0	0
2023	0	0	0	0	0	0	**0**	**0**	0	0
2024	0	0	0	0	0	0	**0**	**0**	0	0
2025	0	0	0	0	0	0	**0**	**0**	0	0
2026	0	0	0	0	0	0	**0**	**0**	0	0
2027	0	0	0	0	0	0	**0**	**0**	0	0
2028	0	0	2	1	0	0	**0**	**0**	0	0
2029	7	2	0	0	0	0	**2**	**0**	2	0
2030	0	0	0	0	0	0	**0**	**0**	0	0
2031	0	0	2	0	0	0	**2**	**1**	2	1
2032	5	1	2	1	0	0	**2**	**0**	2	0
2033	0	0	2	0	0	0	**0**	**0**	0	0
2034	4	1	0	0	0	0	**4**	**1**	4	1
2035	0	0	0	0	2	0	**0**	**0**	0	0
2036	0	0	0	0	6	2	**0**	**0**	0	0
2037	0	0	0	0	0	0	**0**	**0**	0	0
2038	0	0	2	1	0	0	**0**	**0**	0	0
2039	0	0	0	0	2	0	**0**	**0**	0	0
2040	3	1	0	0	0	0	**0**	**0**	0	0
2041	0	0	0	0	0	0	**0**	**0**	0	0
2042	1	0	2	0	0	0	**2**	**1**	2	1

2043	2	1	2	1	0	0	**0**	**0**	0	0
2044	2	0	0	0	0	0	**6**	**1**	6	1
2045	6	2	0	0	0	0	**0**	**0**	0	0
2046	0	0	0	0	0	0	**0**	**0**	0	0
2047	0	0	2	0	0	0	**0**	**0**	0	0
2048	0	0	0	0	0	0	**0**	**0**	0	0
2049	0	0	0	0	0	0	**0**	**0**	0	0
2050	2	0	2	1	0	0	**2**	**1**	2	1
2051	0	0	0	0	4	1	**0**	**0**	0	0
2052	0	0	2	0	2	1	**0**	**0**	0	0
2053	0	0	0	0	0	0	**0**	**0**	0	0
2054	2	1	0	0	0	0	**4**	**1**	4	1
2055	4	1	0	0	0	0	**0**	**0**	0	0
2056	2	0	2	1	4	1	**2**	**0**	2	0
2057	0	0	2	0	0	0	**0**	**0**	0	0
2058	0	0	0	0	0	0	**0**	**0**	0	0
2059	0	0	0	0	0	0	**0**	**0**	0	0
2060	0	0	0	0	0	0	**2**	**1**	2	1
2061	4	1	0	0	0	0	**0**	**0**	0	0
2062	0	0	0	0	2	0	**0**	**0**	0	0
2063	0	0	2	1	0	0	**0**	**0**	0	0
2064	0	0	0	0	0	0	**0**	**0**	0	0
2065	10	3	2	0	0	0	**6**	**1**	6	1
2066	0	0	0	0	0	0	**0**	**0**	0	0
2067	0	0	4	1	2	1	**0**	**0**	0	0
2068	0	0	0	0	2	0	**0**	**0**	0	0
2069	0	0	0	0	0	0	**0**	**0**	0	0
2070	0	0	0	0	0	0	**0**	**0**	0	0
Total	62	16	38	9	32	8	**42**	**10**	42	10

D.2. Dredging activities

The table below shows the draft dredging plan for during the 50 years of lifespan. This schedule is based on the initial dredging plan, i.e. scenarios are not included.

Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth
1	25	288	475	27	17	881	1438	425	27	23	1721	1438	475	27
2	25	288	525	27	18	881	1438	575	27	24	1721	1438	525	27
1	28	288	425	27	11	885	288	475	27	21	1726	288	375	27
2	28	288	575	27	12	885	288	525	27	22	1726	288	625	27
1	37	288	475	27	11	892	863	475	27	21	1731	288	425	27
2	37	288	525	27	12	892	863	525	27	22	1731	288	575	27
1	42	288	425	27	13	893	288	425	27	23	1732	288	475	27
2	42	288	575	27	14	893	288	575	27	24	1732	288	525	27
1	50	288	475	27	11	897	288	475	27	23	1744	288	475	27
2	50	288	525	27	12	897	288	525	27	24	1744	288	525	27
1	55	288	425	27	11	901	1438	475	27	25	1744	863	475	27
2	55	288	575	27	12	901	1438	525	27	26	1744	863	525	27
1	62	288	475	27	11	904	863	425	27	27	1745	288	425	27
2	62	288	525	27	12	904	863	575	27	28	1745	288	575	27
3	63	863	425	27	11	907	288	425	27	29	1745	863	425	27
4	63	863	575	27	12	907	288	575	27	30	1745	863	575	27
1	69	288	425	27	13	909	288	475	27	23	1757	288	475	27
2	69	288	575	27	14	909	288	525	27	24	1757	288	525	27
3	71	288	375	27	11	916	288	375	27	25	1759	288	425	27
4	71	288	625	27	12	916	288	625	27	26	1759	288	575	27
1	74	288	475	27	11	921	288	425	27	23	1762	288	375	27
2	74	288	525	27	12	921	288	575	27	24	1762	288	625	27
1	82	863	475	27	13	922	288	475	27	25	1763	288	325	27
2	82	863	525	27	14	922	288	525	27	26	1763	288	675	27
3	83	288	425	27	11	933	863	475	27	27	1763	1438	425	27
4	83	288	575	27	12	933	863	525	27	28	1763	1438	575	27
1	86	288	475	27	13	934	288	425	27	23	1769	288	475	27
2	86	288	525	27	14	934	288	475	27	24	1769	288	525	27
1	94	863	425	27	15	934	288	525	27	23	1772	288	425	27
2	94	863	575	27	16	934	288	575	27	24	1772	288	575	27
1	97	288	425	27	17	935	863	425	27	23	1777	863	425	27
2	97	288	575	27	18	935	863	575	27	24	1777	863	575	27

3	99	288	475	27	11	944	288	325	27	23	1781	288	475	27
Dredger ID	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**
4	99	288	525	27	12	944	288	675	27	24	1781	288	525	27
1	106	288	375	27	13	944	1438	425	27	23	1784	863	475	27
2	106	288	625	27	14	944	1438	575	27	24	1784	863	525	27
1	110	288	425	27	15	946	288	475	27	25	1786	288	425	27
2	110	288	575	27	16	946	288	525	27	26	1786	288	575	27
3	111	288	475	27	11	948	288	425	27	23	1793	288	475	27
4	111	288	525	27	12	948	288	575	27	24	1793	288	525	27
1	122	863	475	27	11	951	288	375	27	23	1797	288	375	27
2	122	863	525	27	12	951	288	625	27	24	1797	288	625	27
3	123	288	475	27	11	958	288	475	27	23	1800	288	425	27
4	123	288	525	27	12	958	288	525	27	24	1800	288	575	27
5	124	288	425	27	11	962	288	425	27	23	1803	1438	475	27
6	124	288	575	27	12	962	288	575	27	24	1803	1438	525	27
1	125	288	325	27	11	966	863	425	27	23	1806	288	475	27
2	125	288	675	27	12	966	863	575	27	24	1806	288	525	27
7	125	863	425	27	11	971	288	475	27	25	1808	863	425	27
8	125	863	575	27	12	971	288	525	27	26	1808	863	575	27
9	125	1438	425	27	13	973	863	475	27	23	1813	288	425	27
10	125	1438	575	27	14	973	863	525	27	24	1813	288	575	27
1	136	288	475	27	11	976	288	425	27	23	1818	288	475	27
2	136	288	525	27	12	976	288	575	27	24	1818	288	525	27
3	138	288	425	27	11	983	288	475	27	23	1825	863	475	27
4	138	288	575	27	12	983	288	525	27	24	1825	863	525	27
1	141	288	375	27	13	983	1438	475	27	25	1826	288	325	27
2	141	288	625	27	14	983	1438	525	27	26	1826	288	675	27
1	148	288	475	27	11	987	288	375	27	27	1826	1438	425	27
2	148	288	525	27	12	987	288	625	27	28	1826	1438	575	27
1	152	288	425	27	13	989	288	425	27	29	1827	288	425	27
2	152	288	575	27	14	989	288	575	27	30	1827	288	575	27
1	156	863	425	27	11	995	288	475	27	23	1830	288	475	27
2	156	863	575	27	12	995	288	525	27	24	1830	288	525	27
1	160	288	475	27	11	998	863	425	27	25	1832	288	375	27
2	160	288	525	27	12	998	863	575	27	26	1832	288	625	27
1	163	863	475	27	11	1003	288	425	27	23	1839	863	425	27
2	163	863	525	27	12	1003	288	575	27	24	1839	863	575	27

3	163	1438	475	27	11	1007	288	325	27	25	1841	288	425	27
4	163	1438	525	27	12	1007	288	675	27	26	1841	288	575	27
Dredger ID	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**
5	165	288	425	27	13	1007	1438	425	27	23	1843	288	475	27
6	165	288	575	27	14	1007	1438	575	27	24	1843	288	525	27
1	172	288	475	27	15	1008	288	475	27	23	1855	288	425	27
2	172	288	525	27	16	1008	288	525	27	24	1855	288	475	27
1	177	288	375	27	11	1014	863	475	27	25	1855	288	525	27
2	177	288	625	27	12	1014	863	525	27	26	1855	288	575	27
3	179	288	425	27	11	1017	288	425	27	29	1865	863	475	27
4	179	288	575	27	12	1017	288	575	27	30	1865	863	525	27
1	185	288	475	27	11	1020	288	475	27	31	1867	288	375	27
2	185	288	525	27	12	1020	288	525	27	32	1867	288	475	27
3	187	863	425	27	13	1022	288	375	27	33	1867	288	525	27
4	187	863	575	27	14	1022	288	625	27	34	1867	288	625	27
1	188	288	325	27	11	1029	863	425	27	29	1868	288	425	27
2	188	288	675	27	12	1029	863	575	27	30	1868	288	575	27
5	188	1438	425	27	13	1031	288	425	27	31	1870	863	425	27
6	188	1438	575	27	14	1031	288	575	27	32	1870	863	575	27
1	193	288	425	27	11	1032	288	475	27	29	1879	288	475	27
2	193	288	575	27	12	1032	288	525	27	30	1879	288	525	27
1	197	288	475	27	11	1044	288	425	27	29	1882	288	425	27
2	197	288	525	27	12	1044	288	475	27	30	1882	288	575	27
1	203	863	475	27	13	1044	288	525	27	29	1885	1438	475	27
2	203	863	525	27	14	1044	288	575	27	30	1885	1438	525	27
1	207	288	425	27	11	1055	863	475	27	29	1889	288	325	27
2	207	288	575	27	12	1055	863	525	27	30	1889	288	675	27
3	209	288	475	27	13	1057	288	375	27	31	1889	1438	425	27
4	209	288	525	27	14	1057	288	475	27	32	1889	1438	575	27
1	212	288	375	27	15	1057	288	525	27	29	1892	288	475	27
2	212	288	625	27	16	1057	288	625	27	30	1892	288	525	27
1	219	863	425	27	11	1058	288	425	27	29	1896	288	425	27
2	219	863	575	27	12	1058	288	575	27	30	1896	288	575	27
3	220	288	425	27	13	1060	863	425	27	29	1901	863	425	27
4	220	288	575	27	14	1060	863	575	27	30	1901	863	575	27
1	222	288	475	27	11	1065	1438	475	27	31	1902	288	375	27
2	222	288	525	27	12	1065	1438	525	27	32	1902	288	625	27

1	234	288	425	27	11	1069	288	475	27	29	1904	288	475	27
2	234	288	475	27	12	1069	288	525	27	30	1904	288	525	27
3	234	288	525	27	13	1070	288	325	27	31	1906	863	475	27
Dredger ID	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**
4	234	288	575	27	14	1070	288	675	27	32	1906	863	525	27
1	244	863	475	27	15	1070	1438	425	27	29	1910	288	425	27
2	244	863	525	27	16	1070	1438	575	27	30	1910	288	575	27
3	245	1438	475	27	11	1072	288	425	27	29	1916	288	475	27
4	245	1438	525	27	12	1072	288	575	27	30	1916	288	525	27
5	246	288	475	27	11	1081	288	475	27	29	1923	288	425	27
6	246	288	525	27	12	1081	288	525	27	30	1923	288	575	27
1	247	288	375	27	11	1086	288	425	27	29	1929	288	475	27
2	247	288	625	27	12	1086	288	575	27	30	1929	288	525	27
3	248	288	425	27	13	1091	863	425	27	29	1932	863	425	27
4	248	288	575	27	14	1091	863	575	27	30	1932	863	575	27
1	250	863	425	27	15	1092	288	375	27	29	1937	288	425	27
2	250	863	575	27	16	1092	288	625	27	30	1937	288	575	27
3	251	288	325	27	17	1093	288	475	27	31	1938	288	375	27
4	251	288	675	27	18	1093	288	525	27	32	1938	288	625	27
5	251	1438	425	27	13	1095	863	475	27	29	1941	288	475	27
6	251	1438	575	27	14	1095	863	525	27	30	1941	288	525	27
1	258	288	475	27	13	1099	288	425	27	29	1946	863	475	27
2	258	288	525	27	14	1099	288	575	27	30	1946	863	525	27
1	261	288	425	27	13	1106	288	475	27	29	1951	288	425	27
2	261	288	575	27	14	1106	288	525	27	30	1951	288	575	27
1	271	288	475	27	13	1113	288	425	27	31	1952	288	325	27
2	271	288	525	27	14	1113	288	575	27	32	1952	288	675	27
1	275	288	425	27	13	1118	288	475	27	33	1952	1438	425	27
2	275	288	575	27	14	1118	288	525	27	34	1952	1438	575	27
1	281	863	425	27	13	1122	863	425	27	35	1953	288	475	27
2	281	863	575	27	14	1122	863	575	27	36	1953	288	525	27
3	282	288	375	27	13	1127	288	425	27	29	1964	863	425	27
4	282	288	625	27	14	1127	288	575	27	30	1964	863	575	27
5	283	288	475	27	15	1128	288	375	27	31	1965	288	425	27
6	283	288	525	27	16	1128	288	625	27	32	1965	288	475	27
1	284	863	475	27	13	1130	288	475	27	33	1965	288	525	27
2	284	863	525	27	14	1130	288	525	27	34	1965	288	575	27

1	289	288	425	27	13	1133	288	325	27	29	1967	1438	475	27
2	289	288	575	27	14	1133	288	675	27	30	1967	1438	525	27
1	295	288	475	27	15	1133	1438	425	27	29	1973	288	375	27
2	295	288	525	27	16	1133	1438	575	27	30	1973	288	625	27
Dredger ID	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**
1	303	288	425	27	13	1136	863	475	27	29	1978	288	425	27
2	303	288	575	27	14	1136	863	525	27	30	1978	288	475	27
1	308	288	475	27	13	1140	288	425	27	31	1978	288	525	27
2	308	288	525	27	14	1140	288	575	27	32	1978	288	575	27
1	312	863	425	27	13	1143	288	475	27	29	1987	863	475	27
2	312	863	575	27	14	1143	288	525	27	30	1987	863	525	27
3	314	288	325	27	13	1147	1438	475	27	29	1990	288	475	27
4	314	288	675	27	14	1147	1438	525	27	30	1990	288	525	27
5	314	1438	425	27	13	1153	863	425	27	31	1992	288	425	27
6	314	1438	575	27	14	1153	863	575	27	32	1992	288	575	27
1	316	288	425	27	15	1154	288	425	27	29	1995	863	425	27
2	316	288	575	27	16	1154	288	575	27	30	1995	863	575	27
3	317	288	375	27	17	1155	288	475	27	29	2002	288	475	27
4	317	288	625	27	18	1155	288	525	27	30	2002	288	525	27
1	320	288	475	27	13	1163	288	375	27	29	2006	288	425	27
2	320	288	525	27	14	1163	288	625	27	30	2006	288	575	27
1	325	863	475	27	13	1167	288	475	27	31	2008	288	375	27
2	325	863	525	27	14	1167	288	525	27	32	2008	288	625	27
3	327	1438	475	27	15	1168	288	425	27	29	2015	288	325	27
4	327	1438	525	27	16	1168	288	575	27	30	2015	288	475	27
1	330	288	425	27	15	1176	863	475	27	31	2015	288	525	27
2	330	288	575	27	16	1176	863	525	27	32	2015	288	675	27
3	332	288	475	27	15	1179	288	475	27	33	2015	1438	425	27
4	332	288	525	27	16	1179	288	525	27	34	2015	1438	575	27
1	343	863	425	27	15	1182	288	425	27	29	2019	288	425	27
2	343	863	575	27	16	1182	288	575	27	30	2019	288	575	27
3	344	288	425	27	15	1185	863	425	27	29	2026	863	425	27
4	344	288	475	27	16	1185	863	575	27	30	2026	863	575	27
5	344	288	525	27	15	1192	288	475	27	31	2027	288	475	27
6	344	288	575	27	16	1192	288	525	27	32	2027	288	525	27
1	353	288	375	27	15	1195	288	425	27	33	2028	863	475	27
2	353	288	625	27	16	1195	288	575	27	34	2028	863	525	27

1	357	288	475	27	17	1196	288	325	27	29	2033	288	425	27
2	357	288	525	27	18	1196	288	675	27	30	2033	288	575	27
3	358	288	425	27	19	1196	1438	425	27	29	2039	288	475	27
4	358	288	575	27	20	1196	1438	575	27	30	2039	288	525	27
1	365	863	475	27	15	1198	288	375	27	29	2043	288	375	27
Dredger ID	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**
2	365	863	525	27	16	1198	288	625	27	30	2043	288	625	27
1	369	288	475	27	15	1204	288	475	27	29	2047	288	425	27
2	369	288	525	27	16	1204	288	525	27	30	2047	288	575	27
3	371	288	425	27	17	1209	288	425	27	31	2049	1438	475	27
4	371	288	575	27	18	1209	288	575	27	32	2049	1438	525	27
1	374	863	425	27	17	1216	288	475	27	29	2051	288	475	27
2	374	863	575	27	18	1216	288	525	27	30	2051	288	525	27
1	377	288	325	27	19	1216	863	425	27	29	2057	863	425	27
2	377	288	675	27	20	1216	863	575	27	30	2057	863	575	27
3	377	1438	425	27	21	1217	863	475	27	29	2061	288	425	27
4	377	1438	575	27	22	1217	863	525	27	30	2061	288	575	27
1	381	288	475	27	17	1223	288	425	27	29	2064	288	475	27
2	381	288	525	27	18	1223	288	575	27	30	2064	288	525	27
1	385	288	425	27	17	1229	288	475	27	29	2068	863	475	27
2	385	288	575	27	18	1229	288	525	27	30	2068	863	525	27
1	388	288	375	27	19	1229	1438	475	27	29	2074	288	425	27
2	388	288	625	27	20	1229	1438	525	27	30	2074	288	575	27
1	393	288	475	27	17	1233	288	375	27	31	2076	288	475	27
2	393	288	525	27	18	1233	288	625	27	32	2076	288	525	27
1	399	288	425	27	17	1237	288	425	27	29	2078	288	325	27
2	399	288	575	27	18	1237	288	575	27	30	2078	288	675	27
1	406	288	475	27	17	1241	288	475	27	33	2078	1438	425	27
2	406	288	525	27	18	1241	288	525	27	34	2078	1438	575	27
3	406	863	425	27	17	1247	863	425	27	31	2079	288	375	27
4	406	863	475	27	18	1247	863	575	27	32	2079	288	625	27
5	406	863	525	27	17	1250	288	425	27	29	2088	288	425	27
6	406	863	575	27	18	1250	288	575	27	30	2088	288	475	27
1	409	1438	475	27	17	1253	288	475	27	31	2088	288	525	27
2	409	1438	525	27	18	1253	288	525	27	32	2088	288	575	27
1	413	288	425	27	17	1257	863	475	27	33	2088	863	425	27
2	413	288	575	27	18	1257	863	525	27	34	2088	863	575	27

1	418	288	475	27	19	1259	288	325	27	29	2100	288	475	27
2	418	288	525	27	20	1259	288	675	27	30	2100	288	525	27
1	423	288	375	27	21	1259	1438	425	27	31	2102	288	425	27
2	423	288	625	27	22	1259	1438	575	27	32	2102	288	575	27
1	426	288	425	27	17	1264	288	425	27	29	2109	863	475	27
2	426	288	575	27	18	1264	288	575	27	30	2109	863	525	27
Dredger ID	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**
1	430	288	475	27	19	1265	288	475	27	29	2113	288	475	27
2	430	288	525	27	20	1265	288	525	27	30	2113	288	525	27
1	437	863	425	27	17	1268	288	375	27	31	2114	288	375	27
2	437	863	575	27	18	1268	288	625	27	32	2114	288	625	27
1	440	288	325	27	17	1278	288	425	27	29	2116	288	425	27
2	440	288	425	27	18	1278	288	475	27	30	2116	288	575	27
3	440	288	575	27	19	1278	288	525	27	29	2119	863	425	27
4	440	288	675	27	20	1278	288	575	27	30	2119	863	575	27
5	440	1438	425	27	21	1278	863	425	27	29	2125	288	475	27
6	440	1438	575	27	22	1278	863	575	27	30	2125	288	525	27
1	443	288	475	27	17	1290	288	475	27	29	2129	288	425	27
2	443	288	525	27	18	1290	288	525	27	30	2129	288	575	27
1	446	863	475	27	19	1292	288	425	27	31	2131	1438	475	27
2	446	863	525	27	20	1292	288	575	27	32	2131	1438	525	27
1	454	288	425	27	17	1298	863	475	27	29	2137	288	475	27
2	454	288	575	27	18	1298	863	525	27	30	2137	288	525	27
3	455	288	475	27	17	1302	288	475	27	29	2141	288	325	27
4	455	288	525	27	18	1302	288	525	27	30	2141	288	675	27
1	458	288	375	27	19	1304	288	375	27	31	2141	1438	425	27
2	458	288	625	27	20	1304	288	625	27	32	2141	1438	575	27
1	467	288	425	27	17	1305	288	425	27	33	2143	288	425	27
2	467	288	475	27	18	1305	288	575	27	34	2143	288	575	27
3	467	288	525	27	17	1309	863	425	27	31	2149	288	375	27
4	467	288	575	27	18	1309	863	575	27	32	2149	288	625	27
5	468	863	425	27	19	1311	1438	475	27	33	2149	863	475	27
6	468	863	575	27	20	1311	1438	525	27	34	2149	863	525	27
1	479	288	475	27	17	1315	288	475	27	35	2150	288	475	27
2	479	288	525	27	18	1315	288	525	27	36	2150	288	525	27
3	481	288	425	27	17	1319	288	425	27	37	2151	863	425	27
4	481	288	575	27	18	1319	288	575	27	38	2151	863	575	27

Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth
1	487	863	475	27	17	1322	288	325	27	31	2157	288	425	27
2	487	863	525	27	18	1322	288	675	27	32	2157	288	575	27
1	491	1438	475	27	19	1322	1438	425	27	31	2162	288	475	27
2	491	1438	525	27	20	1322	1438	575	27	32	2162	288	525	27
3	492	288	475	27	17	1327	288	475	27	31	2171	288	425	27
4	492	288	525	27	18	1327	288	525	27	32	2171	288	575	27
1	494	288	375	27	21	1333	288	425	27	31	2174	288	475	27
2	494	288	625	27	22	1333	288	575	27	32	2174	288	525	27
3	495	288	425	27	21	1338	863	475	27	31	2182	863	425	27
4	495	288	575	27	22	1338	863	525	27	32	2182	863	575	27
1	499	863	425	27	23	1339	288	375	27	33	2184	288	375	27
2	499	863	575	27	24	1339	288	475	27	34	2184	288	425	27
1	503	288	325	27	25	1339	288	525	27	35	2184	288	575	27
2	503	288	675	27	26	1339	288	625	27	36	2184	288	625	27
3	503	1438	425	27	27	1340	863	425	27	31	2186	288	475	27
4	503	1438	575	27	28	1340	863	575	27	32	2186	288	525	27
5	504	288	475	27	21	1346	288	425	27	31	2190	863	475	27
6	504	288	525	27	22	1346	288	575	27	32	2190	863	525	27
1	509	288	425	27	21	1351	288	475	27	31	2198	288	425	27
2	509	288	575	27	22	1351	288	525	27	32	2198	288	575	27
1	516	288	475	27	21	1360	288	425	27	33	2199	288	475	27
2	516	288	525	27	22	1360	288	575	27	34	2199	288	525	27
1	522	288	425	27	21	1364	288	475	27	31	2204	288	325	27
2	522	288	575	27	22	1364	288	525	27	32	2204	288	675	27
1	528	863	475	27	21	1372	863	425	27	33	2204	1438	425	27
2	528	863	525	27	22	1372	863	575	27	34	2204	1438	575	27
3	529	288	375	27	23	1374	288	375	27	31	2211	288	475	27
4	529	288	475	27	24	1374	288	425	27	32	2211	288	525	27
5	529	288	525	27	25	1374	288	575	27	33	2212	288	425	27
6	529	288	625	27	26	1374	288	625	27	34	2212	288	575	27
7	530	863	425	27	21	1376	288	475	27	35	2213	863	425	27
8	530	863	575	27	22	1376	288	525	27	36	2213	863	575	27
1	536	288	425	27	21	1379	863	475	27	37	2213	1438	475	27
2	536	288	575	27	22	1379	863	525	27	38	2213	1438	525	27
1	541	288	475	27	21	1385	288	325	27	31	2219	288	375	27
2	541	288	525	27	22	1385	288	675	27	32	2219	288	625	27

3	550	288	425	27	23	1385	1438	425	27	31	2223	288	475	27
4	550	288	575	27	24	1385	1438	575	27	32	2223	288	525	27
3	553	288	475	27	21	1388	288	425	27	33	2225	288	425	27
4	553	288	525	27	22	1388	288	475	27	34	2225	288	575	27
3	561	863	425	27	23	1388	288	525	27	31	2230	863	475	27
4	561	863	575	27	24	1388	288	575	27	32	2230	863	525	27
3	564	288	375	27	21	1393	1438	475	27	31	2236	288	475	27
4	564	288	425	27	22	1393	1438	525	27	32	2236	288	525	27

Dredger ID	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**	**Dredger ID**	**Start [week]**	**X-location**	**Y-location**	**Initial depth**
5	564	288	575	27	21	1400	288	475	27	31	2239	288	425	27
6	564	288	625	27	22	1400	288	525	27	32	2239	288	575	27
7	565	288	475	27	23	1401	288	425	27	31	2244	863	425	27
8	565	288	525	27	24	1401	288	575	27	32	2244	863	575	27
9	566	288	325	27	21	1403	863	425	27	31	2248	288	475	27
10	566	288	675	27	22	1403	863	575	27	32	2248	288	525	27
11	566	1438	425	27	21	1409	288	375	27	31	2253	288	425	27
12	566	1438	575	27	22	1409	288	625	27	32	2253	288	575	27
3	568	863	475	27	21	1413	288	475	27	33	2255	288	375	27
4	568	863	525	27	22	1413	288	525	27	34	2255	288	625	27
3	573	1438	475	27	23	1415	288	425	27	31	2260	288	475	27
4	573	1438	525	27	24	1415	288	575	27	32	2260	288	525	27
3	577	288	425	27	21	1419	863	475	27	31	2267	288	325	27
4	577	288	575	27	22	1419	863	525	27	32	2267	288	425	27
5	578	288	475	27	21	1425	288	475	27	33	2267	288	575	27
6	578	288	525	27	22	1425	288	525	27	34	2267	288	675	27
5	590	288	475	27	21	1429	288	425	27	35	2267	1438	425	27
6	590	288	525	27	22	1429	288	575	27	36	2267	1438	575	27
7	591	288	425	27	21	1434	863	425	27	31	2271	863	475	27
8	591	288	575	27	22	1434	863	575	27	32	2271	863	525	27
5	593	863	425	27	21	1437	288	475	27	33	2272	288	475	27
6	593	863	575	27	22	1437	288	525	27	34	2272	288	525	27
5	599	288	375	27	21	1443	288	425	27	31	2275	863	425	27
6	599	288	625	27	22	1443	288	575	27	32	2275	863	575	27
5	602	288	475	27	23	1445	288	375	27	31	2280	288	425	27
6	602	288	525	27	24	1445	288	625	27	32	2280	288	575	27
5	605	288	425	27	21	1448	288	325	27	31	2285	288	475	27
6	605	288	575	27	22	1448	288	675	27	32	2285	288	525	27

Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth
5	609	863	475	27	23	1448	1438	425	27	31	2290	288	375	27
6	609	863	525	27	24	1448	1438	575	27	32	2290	288	625	27
5	615	288	475	27	25	1450	288	475	27	31	2294	288	425	27
6	615	288	525	27	26	1450	288	525	27	32	2294	288	575	27
5	619	288	425	27	21	1456	288	425	27	33	2295	1438	475	27
6	619	288	575	27	22	1456	288	575	27	34	2295	1438	525	27
5	624	863	425	27	21	1460	863	475	27	31	2297	288	475	27
6	624	863	575	27	22	1460	863	525	27	32	2297	288	525	27
5	627	288	475	27	23	1462	288	475	27	31	2306	863	425	27
6	627	288	525	27	24	1462	288	525	27	32	2306	863	575	27
7	629	288	325	27	21	1465	863	425	27	33	2308	288	425	27
8	629	288	675	27	22	1465	863	575	27	34	2308	288	575	27
9	629	1438	425	27	21	1470	288	425	27	31	2309	288	475	27
10	629	1438	575	27	22	1470	288	575	27	32	2309	288	525	27
5	632	288	425	27	21	1474	288	475	27	33	2311	863	475	27
6	632	288	575	27	22	1474	288	525	27	34	2311	863	525	27
7	634	288	375	27	23	1475	1438	475	27	31	2322	288	425	27
8	634	288	625	27	24	1475	1438	525	27	32	2322	288	475	27
5	639	288	475	27	21	1480	288	375	27	33	2322	288	525	27
6	639	288	525	27	22	1480	288	625	27	34	2322	288	575	27
11	646	288	425	27	21	1484	288	425	27	31	2325	288	375	27
12	646	288	575	27	22	1484	288	575	27	32	2325	288	625	27
11	649	863	475	27	23	1486	288	475	27	31	2330	288	325	27
12	649	863	525	27	24	1486	288	525	27	32	2330	288	675	27
13	651	288	475	27	21	1496	863	425	27	33	2330	1438	425	27
14	651	288	525	27	22	1496	863	575	27	34	2330	1438	575	27
11	655	863	425	27	23	1498	288	425	27	31	2334	288	475	27
12	655	863	575	27	24	1498	288	575	27	32	2334	288	525	27
13	655	1438	475	27	21	1499	288	475	27	33	2335	288	425	27
14	655	1438	525	27	22	1499	288	525	27	34	2335	288	575	27
11	660	288	425	27	23	1501	863	475	27	31	2338	863	425	27
12	660	288	575	27	24	1501	863	525	27	32	2338	863	575	27
11	664	288	475	27	21	1511	288	325	27	31	2346	288	475	27
12	664	288	525	27	22	1511	288	425	27	32	2346	288	525	27
11	670	288	375	27	23	1511	288	475	27	31	2349	288	425	27
12	670	288	625	27	24	1511	288	525	27	32	2349	288	575	27

Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth
11	673	288	425	27	25	1511	288	575	27	31	2352	863	475	27
12	673	288	575	27	26	1511	288	675	27	32	2352	863	525	27
11	676	288	475	27	27	1511	1438	425	27	31	2358	288	475	27
12	676	288	525	27	28	1511	1438	575	27	32	2358	288	525	27
11	686	863	425	27	21	1515	288	375	27	33	2360	288	375	27
12	686	863	575	27	22	1515	288	625	27	34	2360	288	625	27
13	687	288	425	27	21	1523	288	475	27	31	2363	288	425	27
14	687	288	575	27	22	1523	288	525	27	32	2363	288	575	27
15	688	288	475	27	23	1525	288	425	27	31	2369	863	425	27
16	688	288	525	27	24	1525	288	575	27	32	2369	863	575	27
11	690	863	475	27	21	1527	863	425	27	33	2371	288	475	27
12	690	863	525	27	22	1527	863	575	27	34	2371	288	525	27
13	692	288	325	27	21	1536	288	475	27	31	2377	288	425	27
14	692	288	675	27	22	1536	288	525	27	32	2377	288	575	27
15	692	1438	425	27	21	1539	288	425	27	33	2377	1438	475	27
16	692	1438	575	27	22	1539	288	575	27	34	2377	1438	525	27
11	700	288	475	27	23	1541	863	475	27	31	2383	288	475	27
12	700	288	525	27	24	1541	863	525	27	32	2383	288	525	27
13	701	288	425	27	21	1548	288	475	27	35	2390	288	425	27
14	701	288	575	27	22	1548	288	525	27	36	2390	288	575	27
11	705	288	375	27	23	1550	288	375	27	37	2392	863	475	27
12	705	288	625	27	24	1550	288	625	27	38	2392	863	525	27
11	713	288	475	27	21	1553	288	425	27	35	2393	288	325	27
12	713	288	525	27	22	1553	288	575	27	36	2393	288	675	27
13	715	288	425	27	21	1557	1438	475	27	39	2393	1438	425	27
14	715	288	575	27	22	1557	1438	525	27	40	2393	1438	575	27
11	717	863	425	27	23	1559	863	425	27	37	2395	288	475	27
12	717	863	575	27	24	1559	863	575	27	38	2395	288	525	27
11	725	288	475	27	21	1560	288	475	27	35	2396	288	375	27
12	725	288	525	27	22	1560	288	525	27	36	2396	288	625	27
11	728	288	425	27	21	1566	288	425	27	35	2400	863	425	27
12	728	288	575	27	22	1566	288	575	27	36	2400	863	575	27
13	730	863	475	27	21	1572	288	475	27	35	2404	288	425	27
14	730	863	525	27	22	1572	288	525	27	36	2404	288	575	27
11	737	288	475	27	23	1574	288	325	27	35	2407	288	475	27
12	737	288	525	27	24	1574	288	675	27	36	2407	288	525	27

Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth
13	737	1438	475	27	25	1574	1438	425	27	35	2418	288	425	27
14	737	1438	525	27	26	1574	1438	575	27	36	2418	288	575	27
11	740	288	375	27	21	1580	288	425	27	37	2420	288	475	27
12	740	288	625	27	22	1580	288	575	27	38	2420	288	525	27
13	742	288	425	27	23	1582	863	475	27	35	2431	288	375	27
14	742	288	575	27	24	1582	863	525	27	36	2431	288	625	27
11	748	863	425	27	21	1585	288	375	27	37	2431	863	425	27
12	748	863	575	27	22	1585	288	475	27	38	2431	863	575	27
13	750	288	475	27	23	1585	288	525	27	39	2432	288	425	27
14	750	288	525	27	24	1585	288	625	27	40	2432	288	475	27
11	755	288	325	27	21	1590	863	425	27	41	2432	288	525	27
12	755	288	675	27	22	1590	863	575	27	42	2432	288	575	27
13	755	1438	425	27	21	1594	288	425	27	43	2433	863	475	27
14	755	1438	575	27	22	1594	288	575	27	44	2433	863	525	27
15	756	288	425	27	21	1597	288	475	27	35	2444	288	475	27
16	756	288	575	27	22	1597	288	525	27	36	2444	288	525	27
11	762	288	475	27	21	1607	288	425	27	37	2445	288	425	27
12	762	288	525	27	22	1607	288	575	27	38	2445	288	575	27
11	770	288	425	27	23	1609	288	475	27	35	2456	288	325	27
12	770	288	575	27	24	1609	288	525	27	36	2456	288	675	27
13	771	863	475	27	21	1621	288	375	27	37	2456	1438	425	27
14	771	863	525	27	22	1621	288	425	27	38	2456	1438	575	27
11	774	288	475	27	23	1621	288	575	27	39	2457	288	475	27
12	774	288	525	27	24	1621	288	625	27	40	2457	288	525	27
13	775	288	375	27	25	1621	863	425	27	35	2459	288	425	27
14	775	288	625	27	26	1621	863	575	27	36	2459	288	575	27
11	780	863	425	27	27	1622	288	475	27	37	2459	1438	475	27
12	780	863	575	27	28	1622	288	525	27	38	2459	1438	525	27
11	783	288	425	27	29	1622	863	475	27	35	2462	863	425	27
12	783	288	575	27	30	1622	863	525	27	36	2462	863	575	27
11	786	288	475	27	21	1634	288	475	27	35	2466	288	375	27
12	786	288	525	27	22	1634	288	525	27	36	2466	288	625	27
11	797	288	425	27	23	1635	288	425	27	35	2469	288	475	27
12	797	288	575	27	24	1635	288	575	27	36	2469	288	525	27
13	799	288	475	27	21	1637	288	325	27	35	2473	288	425	27
14	799	288	525	27	22	1637	288	675	27	36	2473	288	575	27

Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth	Dredger ID	Start [week]	X-location	Y-location	Initial depth
11	811	288	375	27	25	1637	1438	425	27	37	2473	863	475	27
12	811	288	425	27	26	1637	1438	575	27	38	2473	863	525	27
13	811	288	475	27	23	1639	1438	475	27	37	2481	288	475	27
14	811	288	525	27	24	1639	1438	525	27	38	2481	288	525	27
15	811	288	575	27	21	1646	288	475	27	37	2486	288	425	27
16	811	288	625	27	22	1646	288	525	27	38	2486	288	575	27
17	811	863	425	27	21	1649	288	425	27	37	2493	288	475	27
18	811	863	475	27	22	1649	288	575	27	38	2493	288	525	27
19	811	863	525	27	21	1652	863	425	27	39	2493	863	425	27
20	811	863	575	27	22	1652	863	575	27	40	2493	863	575	27
11	818	288	325	27	21	1656	288	375	27	37	2500	288	425	27
12	818	288	675	27	22	1656	288	625	27	38	2500	288	575	27
13	818	1438	425	27	23	1658	288	475	27	39	2501	288	375	27
14	818	1438	575	27	24	1658	288	525	27	40	2501	288	625	27
15	819	1438	475	27	21	1662	288	425	27	37	2506	288	475	27
16	819	1438	525	27	22	1662	288	575	27	38	2506	288	525	27
11	823	288	475	27	23	1663	863	475	27	37	2514	288	425	27
12	823	288	525	27	24	1663	863	525	27	38	2514	288	575	27
13	825	288	425	27	21	1671	288	475	27	39	2514	863	475	27
14	825	288	575	27	22	1671	288	525	27	40	2514	863	525	27
11	836	288	475	27	21	1676	288	425	27	37	2518	288	475	27
12	836	288	525	27	22	1676	288	575	27	38	2518	288	525	27
13	838	288	425	27	21	1683	288	475	27	39	2519	288	325	27
14	838	288	575	27	22	1683	288	525	27	40	2519	288	675	27
11	842	863	425	27	23	1683	863	425	27	41	2519	1438	425	27
12	842	863	575	27	24	1683	863	575	27	42	2519	1438	575	27
11	846	288	375	27	21	1690	288	425	27	37	2524	863	425	27
12	846	288	625	27	22	1690	288	575	27	38	2524	863	575	27
13	848	288	475	27	23	1691	288	375	27	37	2528	288	425	27
14	848	288	525	27	24	1691	288	625	27	38	2528	288	575	27
11	852	288	425	27	21	1695	288	475	27	39	2530	288	475	27
12	852	288	575	27	22	1695	288	525	27	40	2530	288	525	27
13	852	863	475	27	21	1700	288	325	27	37	2536	288	375	27
14	852	863	525	27	22	1700	288	675	27	38	2536	288	625	27
11	860	288	475	27	23	1700	1438	425	27	37	2541	288	425	27
12	860	288	525	27	24	1700	1438	575	27	38	2541	288	575	27

11	866	288	425	27	21	1703	863	475	27	39	2541	1438	475	27
12	866	288	575	27	22	1703	863	525	27	40	2541	1438	525	27
11	872	288	475	27	23	1704	288	425	27	41	2543	288	475	27
12	872	288	525	27	24	1704	288	575	27	42	2543	288	525	27
13	873	863	425	27	21	1707	288	475	27	37	2555	288	425	27
14	873	863	575	27	22	1707	288	525	27	38	2555	288	475	27
11	880	288	425	27	21	1714	863	425	27	39	2555	288	525	27
12	880	288	575	27	22	1714	863	575	27	40	2555	288	575	27
13	881	288	325	27	21	1717	288	425	27	41	2555	863	475	27
14	881	288	375	27	22	1717	288	575	27	42	2555	863	525	27
15	881	288	625	27	21	1720	288	475	27	43	2556	863	425	27
16	881	288	675	27	22	1720	288	525	27	44	2556	863	575	27

D.3. NPV base without dredging/sediment management

Model results with data about dredge costs.

D.3.1. NPV 50 years

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reservoir cost	**€ -9,691.01**	**€ -9.71**	**€ -9.43**	**€ -9.15**	**€ -8.88**	**€ -8.63**	**€ -8.37**	**€ -8.13**	**€ -7.89**	**€ -7.66**	**€ -7.44**
Construction cost [M€]	€ -9,681.01	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -10.00	€ -9.71	€ -9.43	€ -9.15	€ -8.88	€ -8.63	€ -8.37	€ -8.13	€ -7.89	€ -7.66	€ -7.44
Hydropower generation [benefits] [B€]	€ 0.47	€0.46	€0.44	€0.43	€0.42	€0.41	€0.39	€0.38	€0.37	€0.36	€0.35
Irrigation (agricultural) [benefits] [B€]	€ 0.07	€0.07	€0.07	€0.07	€0.06	€0.06	€0.06	€0.06	€0.05	€0.05	€0.05
Freshwater (drinking water) [ben.] [B€]	€ 0.18	€0.18	€0.17	€0.16	€0.16	€0.15	€0.14	€0.14	€0.13	€0.13	€0.12
Loss of land [cost] [B€]	€-1.12	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Total social costs & benefits	**€-0.39**	**€0.71**	**€0.68**	**€0.66**	**€0.64**	**€0.62**	**€0.60**	**€0.58**	**€0.56**	**€0.54**	**€0.52**
NET present costs & benefits (opt.) [B€]	**€ -10.08**	**€0.70**	**€0.67**	**€0.65**	**€0.63**	**€0.61**	**€0.59**	**€0.57**	**€0.55**	**€0.53**	**€0.52**

Year	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
Reservoir cost	**€ -7.22**	**€ -7.01**	**€ -6.81**	**€ -6.61**	**€ -6.42**	**€ -6.23**	**€ -6.05**	**€ -5.87**	**€ -5.70**	**€ -5.54**	**€ -5.38**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -7.22	€ -7.01	€ -6.81	€ -6.61	€ -6.42	€ -6.23	€ -6.05	€ -5.87	€ -5.70	€ -5.54	€ -5.38
Hydropower generation [benefits] [B€]	€ 0.34	€ 0.33	€ 0.32	€ 0.31	€ 0.30	€ 0.29	€ 0.29	€ 0.28	€ 0.27	€ 0.26	€ 0.25
Irrigation (agricultural) [benefits] [B€]	€ 0.05	€ 0.05	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.03	€ 0.03	€ 0.03
Freshwater (drinking water) [ben.] [B€]	€ 0.12	€ 0.11	€ 0.11	€ 0.10	€ 0.10	€ 0.10	€ 0.09	€ 0.09	€ 0.08	€ 0.08	€ 0.08
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Total social costs & benefits	**€ 0.51**	**€ 0.49**	**€ 0.47**	**€ 0.46**	**€ 0.44**	**€ 0.43**	**€ 0.41**	**€ 0.40**	**€ 0.39**	**€ 0.37**	**€ 0.36**
NET present costs & benefits (opt.) [B€]	**€ 0.50**	**€ 0.48**	**€ 0.47**	**€ 0.45**	**€ 0.44**	**€ 0.42**	**€ 0.41**	**€ 0.39**	**€ 0.38**	**€ 0.37**	**€ 0.36**

Year	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052
Reservoir cost	**€ -5,22**	**€ -5,07**	**€ -4,92**	**€ -4,78**	**€ -4,64**	**€ -4,50**	**€ -4,37**	**€ -4,24**	**€ -4,12**	**€ -4,00**	**€ -3,88**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -5,22	€ -5,07	€ -4,92	€ -4,78	€ -4,64	€ -4,50	€ -4,37	€ -4,24	€ -4,12	€ -4,00	€ -3,88
Hydropower generation [benefits] [B€]	€ 0,25	€ 0,24	€ 0,23	€ 0,23	€ 0,22	€ 0,21	€ 0,21	€ 0,20	€ 0,19	€ 0,19	€ 0,18
Irrigation (agricultural) [benefits] [B€]	€ 0,03	€ 0,03	€ 0,03	€ 0,03	€ 0,03	€ 0,02	€ 0,02	€ 0,02	€ 0,02	€ 0,02	€ 0,02
Freshwater (drinking water) [ben.] [B€]	€ 0,07	€ 0,07	€ 0,07	€ 0,07	€ 0,06	€ 0,06	€ 0,06	€ 0,06	€ 0,05	€ 0,05	€ 0,05
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Total social costs & benefits	**€ 0,35**	**€ 0,34**	**€ 0,33**	**€ 0,32**	**€ 0,31**	**€ 0,30**	**€ 0,29**	**€ 0,28**	**€ 0,27**	**€ 0,26**	**€ 0,25**
NET present costs & benefits (opt.) [B€]	**€ 0,35**	**€ 0,33**	**€ 0,32**	**€ 0,31**	**€ 0,30**	**€ 0,29**	**€ 0,28**	**€ 0,27**	**€ 0,26**	**€ 0,26**	**€ 0,25**

Year	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063
Reservoir cost	**€ -3.77**	**€ -3.66**	**€ -3.55**	**€ -3.45**	**€ -3.35**	**€ -3.25**	**€ -3.16**	**€ -3.07**	**€ -2.98**	**€ -2.89**	**€ -2.81**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -3.77	€ -3.66	€ -3.55	€ -3.45	€ -3.35	€ -3.25	€ -3.16	€ -3.07	€ -2.98	€ -2.89	€ -2.81
Hydropower generation [benefits] [B€]	€ 0.18	€ 0.17	€ 0.17	€ 0.16	€ 0.16	€ 0.15	€ 0.15	€ 0.14	€ 0.14	€ 0.14	€ 0.13
Irrigation (agricultural) [benefits] [B€]	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01
Freshwater (drinking water) [ben.] [B€]	€ 0.05	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.03	€ 0.03	€ 0.03	€ 0.03
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Total social costs & benefits	**€ 0.24**	**€ 0.23**	**€ 0.23**	**€ 0.22**	**€ 0.21**	**€ 0.21**	**€ 0.20**	**€ 0.19**	**€ 0.19**	**€ 0.18**	**€ 0.17**
NET present costs & benefits (opt.) [B€]	**€ 0.24**	**€ 0.23**	**€ 0.22**	**€ 0.22**	**€ 0.21**	**€ 0.20**	**€ 0.20**	**€ 0.19**	**€ 0.18**	**€ 0.18**	**€ 0.17**

Year	2064	2065	2066	2067	2068	2069	2070	Total
Reservoir cost	**€ -2.72**	**€ -2.64**	**€ -2.57**	**€ -2.49**	**€ -2.42**	**€ -2.35**	**€ -2.28**	**€ -9.948.31**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -9.681.01
Maintenance cost [M€]	€ -2.72	€ -2.64	€ -2.57	€ -2.49	€ -2.42	€ -2.35	€ -2.28	€ -267.30
Hydropower generation [benefits] [B€]	€ 0.13	€ 0.12	€ 0.12	€ 0.12	€ 0.11	€ 0.11	€ -	€ 12.49
Irrigation (agricultural) [benefits] [B€]	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ -	€1.59
Freshwater (drinking water) [ben.] [B€]	€ 0.03	€ 0.03	€ 0.03	€ 0.02	€ 0.02	€ 0.02	€ -	€3.97
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -1.12
Total social costs & benefits	**€ 0.17**	**€ 0.16**	**€ 0.16**	**€ 0.15**	**€ 0.15**	**€ 0.14**	**€ -**	**€ 16.93**
NET present costs & benefits (opt.) [B€]	**€ 0.16**	**€ 0.16**	**€ 0.15**	**€ 0.15**	**€ 0.14**	**€ 0.14**	**€ -0.00**	**€6.98**

D.3.2. NPV 75 years

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reservoir cost	**€ -9,691.01**	**€ -9.71**	**€ -9.43**	**€ -9.15**	**€ -8.88**	**€ -8.63**	**€ -8.37**	**€ -8.13**	**€ -7.89**	**€ -7.66**	**€ -7.44**
Construction cost [M€]	€ -9,681.01	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -10.00	€ -9.71	€ -9.43	€ -9.15	€ -8.88	€ -8.63	€ -8.37	€ -8.13	€ -7.89	€ -7.66	€ -7.44
Hydropower generation [benefits] [B€]	€ 0.47	€0.46	€0.44	€0.43	€0.42	€0.41	€0.39	€0.38	€0.37	€0.36	€0.35
Irrigation (agricultural) [benefits] [B€]	€ 0.07	€0.07	€0.07	€0.07	€0.06	€0.06	€0.06	€0.06	€0.05	€0.05	€0.05
Freshwater (drinking water) [ben.] [B€]	€ 0.18	€0.18	€0.17	€0.16	€0.16	€0.15	€0.14	€0.14	€0.13	€0.13	€0.12
Loss of land [cost] [B€]	€ -0.74	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Total social costs & benefits	**€ -0.02**	**€0.71**	**€0.68**	**€0.66**	**€0.64**	**€0.62**	**€0.60**	**€0.58**	**€0.56**	**€0.54**	**€0.52**
NET present costs & benefits (opt.) [B€]	**€ -9.71**	**€0.70**	**€0.67**	**€0.65**	**€0.63**	**€0.61**	**€0.59**	**€0.57**	**€0.55**	**€0.53**	**€0.52**

Year	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
Reservoir cost	**€ -7.22**	**€ -7.01**	**€ -6.81**	**€ -6.61**	**€ -6.42**	**€ -6.23**	**€ -6.05**	**€ -5.87**	**€ -5.70**	**€ -5.54**	**€ -5.38**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -7.22	€ -7.01	€ -6.81	€ -6.61	€ -6.42	€ -6.23	€ -6.05	€ -5.87	€ -5.70	€ -5.54	€ -5.38
Hydropower generation [benefits] [B€]	€ 0.34	€ 0.33	€ 0.32	€ 0.31	€ 0.30	€ 0.29	€ 0.29	€ 0.28	€ 0.27	€ 0.26	€ 0.25
Irrigation (agricultural) [benefits] [B€]	€ 0.05	€ 0.05	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.03	€ 0.03	€ 0.03
Freshwater (drinking water) [ben.] [B€]	€ 0.12	€ 0.11	€ 0.11	€ 0.10	€ 0.10	€ 0.10	€ 0.09	€ 0.09	€ 0.08	€ 0.08	€ 0.08
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Total social costs & benefits	**€ 0.51**	**€ 0.49**	**€ 0.47**	**€ 0.46**	**€ 0.44**	**€ 0.43**	**€ 0.41**	**€ 0.40**	**€ 0.39**	**€ 0.37**	**€ 0.36**
NET present costs & benefits (opt.) [B€]	**€ 0.50**	**€ 0.48**	**€ 0.47**	**€ 0.45**	**€ 0.44**	**€ 0.42**	**€ 0.41**	**€ 0.39**	**€ 0.38**	**€ 0.37**	**€ 0.36**

Year	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052
Reservoir cost	**€ -5.22**	**€ -5.07**	**€ -4.92**	**€ -4.78**	**€ -4.64**	**€ -4.50**	**€ -4.37**	**€ -4.24**	**€ -4.12**	**€ -4.00**	**€ -3.88**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -5.22	€ -5.07	€ -4.92	€ -4.78	€ -4.64	€ -4.50	€ -4.37	€ -4.24	€ -4.12	€ -4.00	€ -3.88
Hydropower generation [benefits] [B€]	€ 0.25	€ 0.24	€ 0.23	€ 0.23	€ 0.22	€ 0.21	€ 0.21	€ 0.20	€ 0.19	€ 0.19	€ 0.18
Irrigation (agricultural) [benefits] [B€]	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02
Freshwater (drinking water) [ben.] [B€]	€ 0.07	€ 0.07	€ 0.07	€ 0.07	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.05	€ 0.05	€ 0.05
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Total social costs & benefits	**€ 0.35**	**€ 0.34**	**€ 0.33**	**€ 0.32**	**€ 0.31**	**€ 0.30**	**€ 0.29**	**€ 0.28**	**€ 0.27**	**€ 0.26**	**€ 0.25**
NET present costs & benefits (opt.) [B€]	**€ 0.35**	**€ 0.33**	**€ 0.32**	**€ 0.31**	**€ 0.30**	**€ 0.29**	**€ 0.28**	**€ 0.27**	**€ 0.26**	**€ 0.26**	**€ 0.25**

Year	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063
Reservoir cost	**€-3.77**	**€-3.66**	**€-3.55**	**€-3.45**	**€-3.35**	**€-3.25**	**€-3.16**	**€-3.07**	**€-2.98**	**€-2.89**	**€-2.81**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€-3.77	€-3.66	€-3.55	€-3.45	€-3.35	€-3.25	€-3.16	€-3.07	€-2.98	€-2.89	€-2.81
Hydropower generation [benefits] [B€]	€ 0.18	€ 0.17	€ 0.17	€ 0.16	€ 0.16	€ 0.15	€ 0.15	€ 0.14	€ 0.14	€ 0.14	€ 0.13
Irrigation (agricultural) [benefits] [B€]	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01
Freshwater (drinking water) [ben.] [B€]	€ 0.05	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.03	€ 0.03	€ 0.03	€ 0.03
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Total social costs & benefits	**€ 0.24**	**€ 0.23**	**€ 0.23**	**€ 0.22**	**€ 0.21**	**€ 0.21**	**€ 0.20**	**€ 0.19**	**€ 0.19**	**€ 0.18**	**€ 0.17**
NET present costs & benefits (opt.) [B€]	**€ 0.24**	**€ 0.23**	**€ 0.22**	**€ 0.22**	**€ 0.21**	**€ 0.20**	**€ 0.20**	**€ 0.19**	**€ 0.18**	**€ 0.18**	**€ 0.17**

Year	2064	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074
Reservoir cost	**€-2.72**	**€-2.64**	**€-2.57**	**€-2.49**	**€-2.42**	**€-2.35**	**€-2.28**	**€-2.21**	**€ -2.15**	**€ -2.09**	**€ -2.03**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€-	€ -	€ -	€ -
Maintenance cost [M€]	€-2.72	€-2.64	€-2.57	€-2.49	€-2.42	€-2.35	€-2.28	€-2.21	€ -2.15	€ -2.09	€ -2.03
Hydropower generation [benefits] [B€]	€ 0.13	€ 0.12	€ 0.12	€ 0.12	€ 0.11	€ 0.11	€ 0.11	€0.10	€ 0.10	€ 0.10	€ 0.10
Irrigation (agricultural) [benefits] [B€]	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€0.01	€ 0.01	€ 0.01	€ 0.01
Freshwater (drinking water) [ben.] [B€]	€ 0.03	€ 0.03	€ 0.03	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€0.02	€ 0.02	€ 0.02	€ 0.02
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€-	€ -	€ -	€ -
Total social costs & benefits	**€ 0.17**	**€ 0.16**	**€ 0.16**	**€ 0.15**	**€ 0.15**	**€ 0.14**	**€ 0.14**	**€0.13**	**€ 0.13**	**€ 0.12**	**€ 0.12**
NET present costs & benefits (opt.) [B€]	**€ 0.16**	**€ 0.16**	**€ 0.15**	**€ 0.15**	**€ 0.14**	**€ 0.14**	**€ 0.13**	**€0.13**	**€ 0.13**	**€ 0.12**	**€ 0.12**

Year	2075	2076	2077	2078	2079	2080	2081	2082	2083	2084	2085
Reservoir cost	**€ -1.97**	**€ -1.91**	**€ -1.85**	**€ -1.80**	**€ -1.75**	**€ -1.70**	**€ -1.65**	**€ -1.60**	**€ -1.55**	**€ -1.51**	**€ -1.46**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -1.97	€ -1.91	€ -1.85	€ -1.80	€ -1.75	€ -1.70	€ -1.65	€ -1.60	€ -1.55	€ -1.51	€ -1.46
Hydropower generation [benefits] [B€]	€ 0.09	€ 0.09	€ 0.09	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.07	€ 0.07	€ 0.07
Irrigation (agricultural) [benefits] [B€]	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Freshwater (drinking water) [ben.] [B€]	€ 0.02	€ 0.02	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Total social costs & benefits	**€ 0.12**	**€ 0.11**	**€ 0.11**	**€ 0.10**	**€ 0.10**	**€ 0.10**	**€ 0.09**	**€ 0.09**	**€ 0.09**	**€ 0.08**	**€ 0.08**
NET present costs & benefits (opt.) [B€]	**€ 0.11**	**€ 0.11**	**€ 0.11**	**€ 0.10**	**€ 0.10**	**€ 0.10**	**€ 0.09**	**€ 0.09**	**€ 0.09**	**€ 0.08**	**€ 0.08**

Year	2086	2087	2088	2089	2090	2091	2092	2093	2094	2095	Total
Reservoir cost	**€ -1.42**	**€ -1.38**	**€ -1.34**	**€ -1.30**	**€ -1.26**	**€ -1.23**	**€ -1.19**	**€ -1.16**	**€ -1.12**	**€ -1.09**	**€ -9.988**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -9.681
Maintenance cost [M€]	€ -1.42	€ -1.38	€ -1.34	€ -1.30	€ -1.26	€ -1.23	€ -1.19	€ -1.16	€ -1.12	€ -1.09	€-307.02
Hydropower generation [benefits] [B€]	€ 0.06	€ 0.06	€ 0.05	€ 0.04	€ 0.03	€ 0.02	€ 0.00	€ -	€ -	€ -	€14.13
Irrigation (agricultural) [benefits] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ -	€ 1.71
Freshwater (drinking water) [ben.] [B€]	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ -	€ 4.27
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€-0.74
Total social costs & benefits	**€ 0.07**	**€ 0.07**	**€ 0.06**	**€ 0.05**	**€ 0.04**	**€ 0.03**	**€ 0.01**	**€ 0.01**	**€ 0.01**	**€ -**	**€19.36**
NET present costs & benefits (opt.) [B€]	**€ 0.07**	**€ 0.07**	**€ 0.06**	**€ 0.05**	**€ 0.04**	**€ 0.02**	**€ 0.01**	**€ 0.01**	**€ 0.01**	**€ -0.00**	**€ 9.37**

D.3.3. NPV base with dredging method 4 – 50 Years

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reservoir cost	**€ -9,691.01**	**€ -9.71**	**€ -9.43**	**€ -9.15**	**€ -8.88**	**€ -8.63**	**€ -8.37**	**€ -8.13**	**€ -7.89**	**€ -7.66**	**€ -7.44**
Construction cost [M€]	€ -9,681.01	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -10.00	€ -9.71	€ -9.43	€ -9.15	€ -8.88	€ -8.63	€ -8.37	€ -8.13	€ -7.89	€ -7.66	€ -7.44
Core dredging equipment	**€ -3.16**	**€ -3.06**	**€ -8.92**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -2.35**
Dredge equipment [M€]	€ -2.91	€ -2.83	€ -8.24	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -2.17
Discharge pipe [M€]	€ -0.24	€ -0.24	€ -0.69	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -0.18
Support equipment [M€]	**€ -0.97**	**€ -**	**€ -1.83**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Workboat [M€]	€ -0.97	€ -	€ -1.83	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
OPEX [M€]	€ -2.01	€ -4.67	€ -5.28	€ -5.85	€ -5.67	€ -3.78	€ -5.33	€ -5.17	€ -4.70	€ -4.25	€ -4.71
labour cost [M€]	€ -0.15	€ -0.34	€ -0.37	€ -0.40	€ -0.38	€ -0.25	€ -0.34	€ -0.33	€ -0.29	€ -0.26	€ -0.28
Fuel cost [M€]	€ -0.19	€ -0.43	€ -0.49	€ -0.55	€ -0.53	€ -0.35	€ -0.50	€ -0.48	€ -0.44	€ -0.40	€ -0.44
Storage cost [M€]	€ -0.84	€ -1.95	€ -2.21	€ -2.45	€ -2.38	€ -1.59	€ -2.24	€ -2.18	€ -1.98	€ -1.80	€ -1.99
Transport cost [M€]	€ -0.84	€ -1.95	€ -2.21	€ -2.45	€ -2.38	€ -1.59	€ -2.24	€ -2.18	€ -1.98	€ -1.80	€ -1.99
Benefits [M€]	€ 4.16	€ 9.70	€ 10.98	€ 12.18	€ 11.83	€ 7.90	€ 11.15	€ 10.83	€ 9.85	€ 8.93	€ 9.91
Fertilization purposes [M€]	€ 1.39	€ 3.23	€ 3.66	€ 4.06	€ 3.94	€ 2.63	€ 3.72	€ 3.61	€ 3.28	€ 2.98	€ 3.30
Construction purposes [M€]	€ 2.77	€ 6.46	€ 7.32	€ 8.12	€ 7.89	€ 5.26	€ 7.43	€ 7.22	€ 6.57	€ 5.95	€ 6.60
Subtotal	**€ -1.98**	**€ 1.96**	**€ -5.06**	**€ 6.33**	**€ 6.16**	**€ 4.12**	**€ 5.82**	**€ 5.66**	**€ 5.16**	**€ 4.68**	**€ 2.85**
Hydropower generation [benefits] [B€]	€ 0.47	€ 0.46	€ 0.44	€ 0.43	€ 0.42	€ 0.41	€ 0.39	€ 0.38	€ 0.37	€ 0.36	€ 0.35
Irrigation (agricultural) [benefits] [B€]	€ 0.07	€ 0.07	€ 0.07	€ 0.07	€ 0.07	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.06
Freshwater (drinking water) [ben.] [B€]	€ 0.19	€ 0.18	€ 0.18	€ 0.17	€ 0.17	€ 0.16	€ 0.16	€ 0.15	€ 0.15	€ 0.14	€ 0.14
Loss of land [cost] [B€]	€ -1.12	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Dredge waste [cost] [B€]	€ -0.00	€ -0.01	€ -0.01	€ -0.01	€ -0.01	€ -0.00	€ -0.01	€ -0.01	€ -0.01	€ -0.00	€ -0.01
Total social costs & benefits	**€ -0.39**	**€ 0.71**	**€ 0.68**	**€ 0.66**	**€ 0.64**	**€ 0.63**	**€ 0.61**	**€ 0.59**	**€ 0.57**	**€ 0.56**	**€ 0.54**
NET present costs & benefits (opt.) [B€]	**€ -10.09**	**€ 0.69**	**€ 0.65**	**€ 0.66**	**€ 0.64**	**€ 0.62**	**€ 0.60**	**€ 0.59**	**€ 0.57**	**€ 0.55**	**€ 0.53**

Year	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
Reservoir cost	**€ -7.22**	**€ -7.01**	**€ -6.81**	**€ -6.61**	**€ -6.42**	**€ -6.23**	**€ -6.05**	**€ -5.87**	**€ -5.70**	**€ -5.54**	**€ -5.38**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -7.22	€ -7.01	€ -6.81	€ -6.61	€ -6.42	€ -6.23	€ -6.05	€ -5.87	€ -5.70	€ -5.54	€ -5.38
Core dredging equipment	**€ -**	**€ -2.21**	**€ -2.15**	**€ -**	**€ -4.05**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Dredge equipment [M€]	€ -	€ -2.04	€ -1.98	€ -	€ -3.74	€ -	€ -	€ -	€ -	€ -	€ -
Discharge pipe [M€]	€ -	€ -0.17	€ -0.17	€ -	€ -0.31	€ -	€ -	€ -	€ -	€ -	€ -
Support equipment [M€]	**€ -**	**€ -0.68**	**€ -**	**€ -**	**€ -0.62**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Workboat [M€]	€ -	€ -0.68	€ -	€ -	€ -0.62	€ -	€ -	€ -	€ -	€ -	€ -
OPEX [M€]	€ -3.42	€ -4.42	€ -3.75	€ -4.16	€ -3.78	€ -3.67	€ -3.56	€ -3.22	€ -3.12	€ -3.24	€ -3.35
labour cost [M€]	€ -0.20	€ -0.25	€ -0.21	€ -0.22	€ -0.20	€ -0.19	€ -0.18	€ -0.16	€ -0.15	€ -0.15	€ -0.15
Fuel cost [M€]	€ -0.32	€ -0.42	€ -0.36	€ -0.39	€ -0.36	€ -0.35	€ -0.34	€ -0.31	€ -0.30	€ -0.31	€ -0.32
Storage cost [M€]	€ -1.45	€ -1.88	€ -1.60	€ -1.77	€ -1.61	€ -1.57	€ -1.52	€ -1.38	€ -1.34	€ -1.39	€ -1.44
Transport cost [M€]	€ -1.45	€ -1.88	€ -1.60	€ -1.77	€ -1.61	€ -1.57	€ -1.52	€ -1.38	€ -1.34	€ -1.39	€ -1.44
Benefits [M€]	€ 7.21	€ 9.34	€ 7.93	€ 8.80	€ 8.01	€ 7.78	€ 7.55	€ 6.84	€ 6.64	€ 6.91	€ 7.16
Fertilization purposes [M€]	€ 2.40	€ 3.11	€ 2.64	€ 2.93	€ 2.67	€ 2.59	€ 2.52	€ 2.28	€ 2.21	€ 2.30	€ 2.39
Construction purposes [M€]	€ 4.81	€ 6.22	€ 5.29	€ 5.87	€ 5.34	€ 5.19	€ 5.03	€ 4.56	€ 4.43	€ 4.61	€ 4.77
Subtotal	**€ 3.79**	**€ 2.02**	**€ 2.03**	**€ 4.64**	**€ -0.44**	**€ 4.11**	**€ 4.00**	**€ 3.63**	**€ 3.52**	**€ 3.67**	**€ 3.80**
Hydropower generation [benefits] [B€]	€ 0.34	€ 0.33	€ 0.32	€ 0.31	€ 0.30	€ 0.29	€ 0.29	€ 0.28	€ 0.27	€ 0.26	€ 0.25
Irrigation (agricultural) [benefits] [B€]	€ 0.05	€ 0.05	€ 0.05	€ 0.05	€ 0.05	€ 0.05	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04
Freshwater (drinking water) [ben.] [B€]	€ 0.13	€ 0.13	€ 0.13	€ 0.12	€ 0.12	€ 0.12	€ 0.11	€ 0.11	€ 0.11	€ 0.10	€ 0.10
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Dredge waste [cost] [B€]	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00
Total social costs & benefits	**€ 0.52**	**€ 0.51**	**€ 0.49**	**€ 0.48**	**€ 0.47**	**€ 0.45**	**€ 0.44**	**€ 0.43**	**€ 0.41**	**€ 0.40**	**€ 0.39**
NET present costs & benefits (opt.) [B€]	**€ 0.52**	**€ 0.50**	**€ 0.48**	**€ 0.48**	**€ 0.45**	**€ 0.45**	**€ 0.44**	**€ 0.42**	**€ 0.41**	**€ 0.40**	**€ 0.39**

Year	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052
Reservoir cost	**€ -5.22**	**€ -5.07**	**€ -4.92**	**€ -4.78**	**€ -4.64**	**€ -4.50**	**€ -4.37**	**€ -4.24**	**€ -4.12**	**€ -4.00**	**€ -3.88**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -5.22	€ -5.07	€ -4.92	€ -4.78	€ -4.64	€ -4.50	€ -4.37	€ -4.24	€ -4.12	€ -4.00	€ -3.88
Core dredging equipment	**€ -**	**€ -1.60**	**€ -**	**€ -4.52**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -1.26**	**€ -**
Dredge equipment [M€]	€ -	€ -1.48	€ -	€ -4.17	€ -	€ -	€ -	€ -	€ -	€ -1.17	€ -
Discharge pipe [M€]	€ -	€ -0.12	€ -	€ -0.35	€ -	€ -	€ -	€ -	€ -	€ -0.10	€ -
Support equipment [M€]	**€ -**	**€ -0.49**	**€ -**	**€ -0.46**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -0.39**	**€ -**
Workboat [M€]	€ -	€ -0.49	€ -	€ -0.46	€ -	€ -	€ -	€ -	€ -	€ -0.39	€ -
OPEX [M€]	€ -2.64	€ -2.96	€ -2.68	€ -3.15	€ -2.70	€ -2.27	€ -2.37	€ -2.63	€ -2.23	€ -2.62	€ -1.95
labour cost [M€]	€ -0.12	€ -0.13	€ -0.11	€ -0.13	€ -0.11	€ -0.09	€ -0.09	€ -0.10	€ -0.08	€ -0.09	€ -0.07
Fuel cost [M€]	€ -0.25	€ -0.28	€ -0.26	€ -0.30	€ -0.26	€ -0.22	€ -0.23	€ -0.25	€ -0.21	€ -0.25	€ -0.19
Storage cost [M€]	€ -1.14	€ -1.27	€ -1.15	€ -1.36	€ -1.16	€ -0.98	€ -1.02	€ -1.14	€ -0.97	€ -1.14	€ -0.85
Transport cost [M€]	€ -1.14	€ -1.27	€ -1.15	€ -1.36	€ -1.16	€ -0.98	€ -1.02	€ -1.14	€ -0.97	€ -1.14	€ -0.85
Benefits [M€]	€ 5.65	€ 6.32	€ 5.73	€ 6.76	€ 5.79	€ 4.87	€ 5.09	€ 5.65	€ 4.80	€ 5.66	€ 4.20
Fertilization purposes [M€]	€ 1.88	€ 2.11	€ 1.91	€ 2.25	€ 1.93	€ 1.62	€ 1.70	€ 1.88	€ 1.60	€ 1.89	€ 1.40
Construction purposes [M€]	€ 3.76	€ 4.22	€ 3.82	€ 4.50	€ 3.86	€ 3.25	€ 3.39	€ 3.77	€ 3.20	€ 3.77	€ 2.80
Subtotal	**€ 3.00**	**€ 1.28**	**€ 3.06**	**€ -1.38**	**€ 3.09**	**€ 2.60**	**€ 2.72**	**€ 3.03**	**€ 2.57**	**€ 1.38**	**€ 2.25**
Hydropower generation [benefits] [B€]	€ 0.25	€ 0.24	€ 0.23	€ 0.23	€ 0.22	€ 0.21	€ 0.21	€ 0.20	€ 0.19	€ 0.19	€ 0.18
Irrigation (agricultural) [benefits] [B€]	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03
Freshwater (drinking water) [ben.] [B€]	€ 0.10	€ 0.09	€ 0.09	€ 0.09	€ 0.09	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.07	€ 0.07
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Dredge waste [cost] [B€]	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00
Total social costs & benefits	**€ 0.38**	**€ 0.37**	**€ 0.36**	**€ 0.35**	**€ 0.34**	**€ 0.33**	**€ 0.32**	**€ 0.31**	**€ 0.30**	**€ 0.29**	**€ 0.28**
NET present costs & benefits (opt.) [B€]	**€ 0.38**	**€ 0.36**	**€ 0.35**	**€ 0.33**	**€ 0.33**	**€ 0.32**	**€ 0.31**	**€ 0.31**	**€ 0.30**	**€ 0.28**	**€ 0.28**

Year	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063
Reservoir cost	**€ -3.77**	**€ -3.66**	**€ -3.55**	**€ -3.45**	**€ -3.35**	**€ -3.25**	**€ -3.16**	**€ -3.07**	**€ -2.98**	**€ -2.89**	**€ -2.81**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Maintenance cost [M€]	€ -3.77	€ -3.66	€ -3.55	€ -3.45	€ -3.35	€ -3.25	€ -3.16	€ -3.07	€ -2.98	€ -2.89	€ -2.81
Core dredging equipment	**€ -**	**€ -**	**€ -2.24**	**€ -**	**€ -1.06**	**€ -**	**€ -**	**€ -**	**€ -0.94**	**€ -**	**€ -**
Dredge equipment [M€]	€ -	€ -	€ -2.07	€ -	€ -0.98	€ -	€ -	€ -	€ -0.87	€ -	€ -
Discharge pipe [M€]	€ -	€ -	€ -0.17	€ -	€ -0.08	€ -	€ -	€ -	€ -0.07	€ -	€ -
Support equipment [M€]	**€ -**	**€ -**	**€ -0.35**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -0.29**	**€ -**	**€ -**
Workboat [M€]	€ -	€ -	€ -0.35	€ -	€ -	€ -	€ -	€ -	€ -0.29	€ -	€ -
OPEX [M€]	€ -2.18	€ -1.97	€ -2.19	€ -1.86	€ -1.93	€ -1.87	€ -1.94	€ -1.53	€ -1.48	€ -1.77	€ -1.61
labour cost [M€]	€ -0.07	€ -0.07	€ -0.07	€ -0.06	€ -0.06	€ -0.06	€ -0.06	€ -0.04	€ -0.04	€ -0.05	€ -0.04
Fuel cost [M€]	€ -0.21	€ -0.19	€ -0.21	€ -0.18	€ -0.19	€ -0.18	€ -0.19	€ -0.15	€ -0.14	€ -0.17	€ -0.16
Storage cost [M€]	€ -0.95	€ -0.86	€ -0.95	€ -0.81	€ -0.84	€ -0.82	€ -0.85	€ -0.67	€ -0.65	€ -0.77	€ -0.70
Transport cost [M€]	€ -0.95	€ -0.86	€ -0.95	€ -0.81	€ -0.84	€ -0.82	€ -0.85	€ -0.67	€ -0.65	€ -0.77	€ -0.70
Benefits [M€]	€ 4.71	€ 4.26	€ 4.73	€ 4.02	€ 4.18	€ 4.06	€ 4.20	€ 3.32	€ 3.22	€ 3.85	€ 3.50
Fertilization purposes [M€]	€ 1.57	€ 1.42	€ 1.58	€ 1.34	€ 1.39	€ 1.35	€ 1.40	€ 1.11	€ 1.07	€ 1.28	€ 1.17
Construction purposes [M€]	€ 3.14	€ 2.84	€ 3.16	€ 2.68	€ 2.79	€ 2.71	€ 2.80	€ 2.21	€ 2.15	€ 2.57	€ 2.33
Subtotal	**€ 2.53**	**€ 2.29**	**€ -0.04**	**€ 2.16**	**€ 1.19**	**€ 2.19**	**€ 2.27**	**€ 1.79**	**€ 0.51**	**€ 2.08**	**€ 1.89**
Hydropower generation [benefits] [B€]	€ 0.18	€ 0.17	€ 0.17	€ 0.16	€ 0.16	€ 0.15	€ 0.15	€ 0.14	€ 0.14	€ 0.14	€ 0.13
Irrigation (agricultural) [benefits] [B€]	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02
Freshwater (drinking water) [ben.] [B€]	€ 0.07	€ 0.07	€ 0.07	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.05	€ 0.05
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Dredge waste [cost] [B€]	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00
Total social costs & benefits	**€ 0.27**	**€ 0.27**	**€ 0.26**	**€ 0.25**	**€ 0.24**	**€ 0.24**	**€ 0.23**	**€ 0.22**	**€ 0.22**	**€ 0.21**	**€ 0.20**
NET present costs & benefits (opt.) [B€]	**€ 0.27**	**€ 0.26**	**€ 0.25**	**€ 0.25**	**€ 0.24**	**€ 0.23**	**€ 0.23**	**€ 0.22**	**€ 0.21**	**€ 0.21**	**€ 0.20**
Year	**2064**	**2065**	**2066**	**2067**	**2068**	**2069**	**2070**	**Total**			

Reservoir cost	**€ -2.72**	**€ -2.64**	**€ -2.57**	**€ -2.49**	**€ -2.42**	**€ -2.35**	**€ -2.28**	**€ -9,948.31**
Construction cost [M€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	**€ -9,681.01**
Maintenance cost [M€]	€ -2.72	€ -2.64	€ -2.57	€ -2.49	€ -2.42	€ -2.35	€ -2.28	**€ -267.30**
Core dredging equipment	**€ -**	**€ -**	**€ -2.43**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -39.95**
Dredge equipment [M€]	€ -	€ -	€ -2.24	€ -	€ -	€ -	€ -	**€ -36.88**
Discharge pipe [M€]	€ -	€ -	€ -0.19	€ -	€ -	€ -	€ -	**€ -3.07**
Support equipment [M€]	**€ -**	**€ -**	**€ -0.25**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -6.33**
Workboat [M€]	€ -	€ -	€ -0.25	€ -	€ -	€ -	€ -	**€ -6.33**
OPEX [M€]	€ -1.67	€ -1.21	€ -1.47	€ -1.52	€ -1.38	€ -1.34	€ -	**€ -148.24**
labour cost [M€]	€ -0.04	€ -0.03	€ -0.04	€ -0.04	€ -0.03	€ -0.03	€ -	**€ -7.39**
Fuel cost [M€]	€ -0.16	€ -0.12	€ -0.14	€ -0.15	€ -0.14	€ -0.13	€ -	**€ -14.10**
Storage cost [M€]	€ -0.73	€ -0.53	€ -0.64	€ -0.67	€ -0.61	€ -0.59	€ -	**€ -63.38**
Transport cost [M€]	€ -0.73	€ -0.53	€ -0.64	€ -0.67	€ -0.61	€ -0.59	€ -	**€ -63.38**
Benefits [M€]	€ 3.63	€ 2.64	€ 3.20	€ 3.32	€ 3.02	€ 2.93	€ -	**€ 314.92**
Fertilization purposes [M€]	€ 1.21	€ 0.88	€ 1.07	€ 1.11	€ 1.01	€ 0.98	€ -	**€ 104.97**
Construction purposes [M€]	€ 2.42	€ 1.76	€ 2.14	€ 2.21	€ 2.01	€ 1.96	€ -	**€ 209.94**
Subtotal	**€ 1.96**	**€ 1.43**	**€ -0.95**	**€ 1.80**	**€ 1.64**	**€ 1.59**	**€ -**	**€ 120.39**
Hydropower generation [benefits] [B€]	€ 0.13	€ 0.12	€ 0.12	€ 0.12	€ 0.11	€ 0.11	€ 0.11	**€ 12.60**
Irrigation (agricultural) [benefits] [B€]	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	**€ 1.99**
Freshwater (drinking water) [ben.] [B€]	€ 0.05	€ 0.05	€ 0.05	€ 0.05	€ 0.04	€ 0.04	€ 0.04	**€ 4.97**
Loss of land [cost] [B€]	€ -	€ -	€ -	€ -	€ -	€ -	€ -	**€ -1.12**
Dredge waste [cost] [B€]	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -0.00	€ -	**€ -0.17**
Total social costs & benefits	**€ 0.20**	**€ 0.19**	**€ 0.19**	**€ 0.18**	**€ 0.18**	**€ 0.17**	**€ 0.17**	**€ 18.27**
NET present costs & benefits (opt.) [B€]	**€ 0.20**	**€ 0.19**	**€ 0.18**	**€ 0.18**	**€ 0.17**	**€ 0.17**	**€ 0.16**	**€ 8,34**

D.3.4. NPV base with dredging method 4 – 75 years

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reservoir cost	**-€ 9,691.01**	**-€ 9.71**	**-€ 9.43**	**-€ 9.15**	**-€ 8.88**	**-€ 8.63**	**-€ 8.37**	**-€ 8.13**	**-€ 7.89**	**-€ 7.66**	**-€ 7.44**
Construction cost [M€]	-€ 9,681.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Maintenance cost [M€]	-€ 10.00	-€ 9.71	-€ 9.43	-€ 9.15	-€ 8.88	-€ 8.63	-€ 8.37	-€ 8.13	-€ 7.89	-€ 7.66	-€ 7.44
Core dredging equipment	**-€ 3.16**	**-€ 3.06**	**-€ 8.92**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**-€ 2.35**
Dredge equipment [M€]	-€ 2.91	-€ 2.83	-€ 8.24	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	-€ 2.17
Discharge pipe [M€]	-€ 0.24	-€ 0.24	-€ 0.69	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	-€ 0.18
Support equipment [M€]	**-€ 0.97**	**€ 0.00**	**-€ 1.83**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
Workboat [M€]	-€ 0.97	€ 0.00	-€ 1.83	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
OPEX [M€]	-€ 2.01	-€ 4.67	-€ 5.28	-€ 5.85	-€ 5.67	-€ 3.78	-€ 5.33	-€ 5.17	-€ 4.70	-€ 4.25	-€ 4.71
labour cost [M€]	-€ 0.15	-€ 0.34	-€ 0.37	-€ 0.40	-€ 0.38	-€ 0.25	-€ 0.34	-€ 0.33	-€ 0.29	-€ 0.26	-€ 0.28
Fuel cost [M€]	-€ 0.19	-€ 0.43	-€ 0.49	-€ 0.55	-€ 0.53	-€ 0.35	-€ 0.50	-€ 0.48	-€ 0.44	-€ 0.40	-€ 0.44
Storage cost [M€]	-€ 0.84	-€ 1.95	-€ 2.21	-€ 2.45	-€ 2.38	-€ 1.59	-€ 2.24	-€ 2.18	-€ 1.98	-€ 1.80	-€ 1.99
Transport cost [M€]	-€ 0.84	-€ 1.95	-€ 2.21	-€ 2.45	-€ 2.38	-€ 1.59	-€ 2.24	-€ 2.18	-€ 1.98	-€ 1.80	-€ 1.99
Benefits [M€]	€ 4.16	€ 9.70	€ 10.98	€ 12.18	€ 11.83	€ 7.90	€ 11.15	€ 10.83	€ 9.85	€ 8.93	€ 9.91
Fertilization purposes [M€]	€ 1.39	€ 3.23	€ 3.66	€ 4.06	€ 3.94	€ 2.63	€ 3.72	€ 3.61	€ 3.28	€ 2.98	€ 3.30
Construction purposes [M€]	€ 2.77	€ 6.46	€ 7.32	€ 8.12	€ 7.89	€ 5.26	€ 7.43	€ 7.22	€ 6.57	€ 5.95	€ 6.60
Subtotal	**-€ 1.98**	**€ 1.96**	**-€ 5.06**	**€ 6.33**	**€ 6.16**	**€ 4.12**	**€ 5.82**	**€ 5.66**	**€ 5.16**	**€ 4.68**	**€ 2.85**
Hydropower generation [benefits] [B€]	€ 0.47	€ 0.46	€ 0.44	€ 0.43	€ 0.42	€ 0.41	€ 0.39	€ 0.38	€ 0.37	€ 0.36	€ 0.35
Irrigation (agricultural) [benefits] [B€]	€ 0.07	€ 0.07	€ 0.07	€ 0.07	€ 0.07	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.06
Freshwater (drinking water) [ben.] [B€]	€ 0.19	€ 0.18	€ 0.18	€ 0.17	€ 0.17	€ 0.16	€ 0.16	€ 0.15	€ 0.15	€ 0.14	€ 0.14
Loss of land [cost] [B€]	-€ 0.74	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Dredge waste [cost] [B€]	€ 0.00	-€ 0.01	-€ 0.01	-€ 0.01	-€ 0.01	€ 0.00	-€ 0.01	-€ 0.01	-€ 0.01	€ 0.00	-€ 0.01
Total social costs & benefits	**-€ 0.02**	**€ 0.71**	**€ 0.68**	**€ 0.66**	**€ 0.64**	**€ 0.63**	**€ 0.61**	**€ 0.59**	**€ 0.57**	**€ 0.56**	**€ 0.54**
NET present costs & benefits (opt.) [B€]	**-€ 9.71**	**€ 0.69**	**€ 0.65**	**€ 0.66**	**€ 0.64**	**€ 0.62**	**€ 0.60**	**€ 0.59**	**€ 0.57**	**€ 0.55**	**€ 0.53**

Year	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
Reservoir cost	**-€ 7.22**	**-€ 7.01**	**-€ 6.81**	**-€ 6.61**	**-€ 6.42**	**-€ 6.23**	**-€ 6.05**	**-€ 5.87**	**-€ 5.70**	**-€ 5.54**	**-€ 5.38**
Construction cost [M€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Maintenance cost [M€]	-€ 7.22	-€ 7.01	-€ 6.81	-€ 6.61	-€ 6.42	-€ 6.23	-€ 6.05	-€ 5.87	-€ 5.70	-€ 5.54	-€ 5.38
Core dredging equipment	**€ 0.00**	**-€ 2.21**	**-€ 2.15**	**€ 0.00**	**-€ 4.05**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
Dredge equipment [M€]	€ 0.00	-€ 2.04	-€ 1.98	€ 0.00	-€ 3.74	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Discharge pipe [M€]	€ 0.00	-€ 0.17	-€ 0.17	€ 0.00	-€ 0.31	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Support equipment [M€]	**€ 0.00**	**-€ 0.68**	**€ 0.00**	**€ 0.00**	**-€ 0.62**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
Workboat [M€]	€ 0.00	-€ 0.68	€ 0.00	€ 0.00	-€ 0.62	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
OPEX [M€]	-€ 3.42	-€ 4.42	-€ 3.75	-€ 4.16	-€ 3.78	-€ 3.67	-€ 3.56	-€ 3.22	-€ 3.12	-€ 3.24	-€ 3.35
labour cost [M€]	-€ 0.20	-€ 0.25	-€ 0.21	-€ 0.22	-€ 0.20	-€ 0.19	-€ 0.18	-€ 0.16	-€ 0.15	-€ 0.15	-€ 0.15
Fuel cost [M€]	-€ 0.32	-€ 0.42	-€ 0.36	-€ 0.39	-€ 0.36	-€ 0.35	-€ 0.34	-€ 0.31	-€ 0.30	-€ 0.31	-€ 0.32
Storage cost [M€]	-€ 1.45	-€ 1.88	-€ 1.60	-€ 1.77	-€ 1.61	-€ 1.57	-€ 1.52	-€ 1.38	-€ 1.34	-€ 1.39	-€ 1.44
Transport cost [M€]	-€ 1.45	-€ 1.88	-€ 1.60	-€ 1.77	-€ 1.61	-€ 1.57	-€ 1.52	-€ 1.38	-€ 1.34	-€ 1.39	-€ 1.44
Benefits [M€]	€ 7.21	€ 9.34	€ 7.93	€ 8.80	€ 8.01	€ 7.78	€ 7.55	€ 6.84	€ 6.64	€ 6.91	€ 7.16
Fertilization purposes [M€]	€ 2.40	€ 3.11	€ 2.64	€ 2.93	€ 2.67	€ 2.59	€ 2.52	€ 2.28	€ 2.21	€ 2.30	€ 2.39
Construction purposes [M€]	€ 4.81	€ 6.22	€ 5.29	€ 5.87	€ 5.34	€ 5.19	€ 5.03	€ 4.56	€ 4.43	€ 4.61	€ 4.77
Subtotal	**€ 3.79**	**€ 2.02**	**€ 2.03**	**€ 4.64**	**-€ 0.44**	**€ 4.11**	**€ 4.00**	**€ 3.63**	**€ 3.52**	**€ 3.67**	**€ 3.80**
Hydropower generation [benefits] [B€]	€ 0.34	€ 0.33	€ 0.32	€ 0.31	€ 0.30	€ 0.29	€ 0.29	€ 0.28	€ 0.27	€ 0.26	€ 0.25
Irrigation (agricultural) [benefits] [B€]	€ 0.05	€ 0.05	€ 0.05	€ 0.05	€ 0.05	€ 0.05	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04
Freshwater (drinking water) [ben.] [B€]	€ 0.13	€ 0.13	€ 0.13	€ 0.12	€ 0.12	€ 0.12	€ 0.11	€ 0.11	€ 0.11	€ 0.10	€ 0.10
Loss of land [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Dredge waste [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Total social costs & benefits	**€ 0.52**	**€ 0.51**	**€ 0.49**	**€ 0.48**	**€ 0.47**	**€ 0.45**	**€ 0.44**	**€ 0.43**	**€ 0.41**	**€ 0.40**	**€ 0.39**
NET present costs & benefits (opt.) [B€]	**€ 0.52**	**€ 0.50**	**€ 0.48**	**€ 0.48**	**€ 0.45**	**€ 0.45**	**€ 0.44**	**€ 0.42**	**€ 0.41**	**€ 0.40**	**€ 0.39**

Year	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052
Reservoir cost	**-€ 5.22**	**-€ 5.07**	**-€ 4.92**	**-€ 4.78**	**-€ 4.64**	**-€ 4.50**	**-€ 4.37**	**-€ 4.24**	**-€ 4.12**	**-€ 4.00**	**-€ 3.88**
Construction cost [M€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Maintenance cost [M€]	-€ 5.22	-€ 5.07	-€ 4.92	-€ 4.78	-€ 4.64	-€ 4.50	-€ 4.37	-€ 4.24	-€ 4.12	-€ 4.00	-€ 3.88
Core dredging equipment	**€ 0.00**	**-€ 1.60**	**€ 0.00**	**-€ 4.52**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**-€ 1.26**	**€ 0.00**
Dredge equipment [M€]	€ 0.00	-€ 1.48	€ 0.00	-€ 4.17	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	-€ 1.17	€ 0.00
Discharge pipe [M€]	€ 0.00	-€ 0.12	€ 0.00	-€ 0.35	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	-€ 0.10	€ 0.00
Support equipment [M€]	**€ 0.00**	**-€ 0.49**	**€ 0.00**	**-€ 0.46**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**-€ 0.39**	**€ 0.00**
Workboat [M€]	€ 0.00	-€ 0.49	€ 0.00	-€ 0.46	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	-€ 0.39	€ 0.00
OPEX [M€]	-€ 2.64	-€ 2.96	-€ 2.68	-€ 3.15	-€ 2.70	-€ 2.27	-€ 2.37	-€ 2.63	-€ 2.23	-€ 2.62	-€ 1.95
labour cost [M€]	-€ 0.12	-€ 0.13	-€ 0.11	-€ 0.13	-€ 0.11	-€ 0.09	-€ 0.09	-€ 0.10	-€ 0.08	-€ 0.09	-€ 0.07
Fuel cost [M€]	-€ 0.25	-€ 0.28	-€ 0.26	-€ 0.30	-€ 0.26	-€ 0.22	-€ 0.23	-€ 0.25	-€ 0.21	-€ 0.25	-€ 0.19
Storage cost [M€]	-€ 1.14	-€ 1.27	-€ 1.15	-€ 1.36	-€ 1.16	-€ 0.98	-€ 1.02	-€ 1.14	-€ 0.97	-€ 1.14	-€ 0.85
Transport cost [M€]	-€ 1.14	-€ 1.27	-€ 1.15	-€ 1.36	-€ 1.16	-€ 0.98	-€ 1.02	-€ 1.14	-€ 0.97	-€ 1.14	-€ 0.85
Benefits [M€]	€ 5.65	€ 6.32	€ 5.73	€ 6.76	€ 5.79	€ 4.87	€ 5.09	€ 5.65	€ 4.80	€ 5.66	€ 4.20
Fertilization purposes [M€]	€ 1.88	€ 2.11	€ 1.91	€ 2.25	€ 1.93	€ 1.62	€ 1.70	€ 1.88	€ 1.60	€ 1.89	€ 1.40
Construction purposes [M€]	€ 3.76	€ 4.22	€ 3.82	€ 4.50	€ 3.86	€ 3.25	€ 3.39	€ 3.77	€ 3.20	€ 3.77	€ 2.80
Subtotal	**€ 3.00**	**€ 1.28**	**€ 3.06**	**-€ 1.38**	**€ 3.09**	**€ 2.60**	**€ 2.72**	**€ 3.03**	**€ 2.57**	**€ 1.38**	**€ 2.25**
Hydropower generation [benefits] [B€]	€ 0.25	€ 0.24	€ 0.23	€ 0.23	€ 0.22	€ 0.21	€ 0.21	€ 0.20	€ 0.19	€ 0.19	€ 0.18
Irrigation (agricultural) [benefits] [B€]	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03
Freshwater (drinking water) [ben.] [B€]	€ 0.10	€ 0.09	€ 0.09	€ 0.09	€ 0.09	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.07	€ 0.07
Loss of land [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Dredge waste [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Total social costs & benefits	**€ 0.38**	**€ 0.37**	**€ 0.36**	**€ 0.35**	**€ 0.34**	**€ 0.33**	**€ 0.32**	**€ 0.31**	**€ 0.30**	**€ 0.29**	**€ 0.28**
NET present costs & benefits (opt.) [B€]	**€ 0.38**	**€ 0.36**	**€ 0.35**	**€ 0.33**	**€ 0.33**	**€ 0.32**	**€ 0.31**	**€ 0.31**	**€ 0.30**	**€ 0.28**	**€ 0.28**

Year	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063
Reservoir cost	**-€ 3.77**	**-€ 3.66**	**-€ 3.55**	**-€ 3.45**	**-€ 3.35**	**-€ 3.25**	**-€ 3.16**	**-€ 3.07**	**-€ 2.98**	**-€ 2.89**	**-€ 2.81**
Construction cost [M€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Maintenance cost [M€]	-€ 3.77	-€ 3.66	-€ 3.55	-€ 3.45	-€ 3.35	-€ 3.25	-€ 3.16	-€ 3.07	-€ 2.98	-€ 2.89	-€ 2.81
Core dredging equipment	**€ 0.00**	**€ 0.00**	**-€ 2.24**	**€ 0.00**	**-€ 1.06**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**-€ 0.94**	**€ 0.00**	**€ 0.00**
Dredge equipment [M€]	€ 0.00	€ 0.00	-€ 2.07	€ 0.00	-€ 0.98	€ 0.00	€ 0.00	€ 0.00	-€ 0.87	€ 0.00	€ 0.00
Discharge pipe [M€]	€ 0.00	€ 0.00	-€ 0.17	€ 0.00	-€ 0.08	€ 0.00	€ 0.00	€ 0.00	-€ 0.07	€ 0.00	€ 0.00
Support equipment [M€]	**€ 0.00**	**€ 0.00**	**-€ 0.35**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**-€ 0.29**	**€ 0.00**	**€ 0.00**
Workboat [M€]	€ 0.00	€ 0.00	-€ 0.35	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	-€ 0.29	€ 0.00	€ 0.00
OPEX [M€]	-€ 2.18	-€ 1.97	-€ 2.19	-€ 1.86	-€ 1.93	-€ 1.87	-€ 1.94	-€ 1.53	-€ 1.48	-€ 1.77	-€ 1.61
labour cost [M€]	-€ 0.07	-€ 0.07	-€ 0.07	-€ 0.06	-€ 0.06	-€ 0.06	-€ 0.06	-€ 0.04	-€ 0.04	-€ 0.05	-€ 0.04
Fuel cost [M€]	-€ 0.21	-€ 0.19	-€ 0.21	-€ 0.18	-€ 0.19	-€ 0.18	-€ 0.19	-€ 0.15	-€ 0.14	-€ 0.17	-€ 0.16
Storage cost [M€]	-€ 0.95	-€ 0.86	-€ 0.95	-€ 0.81	-€ 0.84	-€ 0.82	-€ 0.85	-€ 0.67	-€ 0.65	-€ 0.77	-€ 0.70
Transport cost [M€]	-€ 0.95	-€ 0.86	-€ 0.95	-€ 0.81	-€ 0.84	-€ 0.82	-€ 0.85	-€ 0.67	-€ 0.65	-€ 0.77	-€ 0.70
Benefits [M€]	€ 4.71	€ 4.26	€ 4.73	€ 4.02	€ 4.18	€ 4.06	€ 4.20	€ 3.32	€ 3.22	€ 3.85	€ 3.50
Fertilization purposes [M€]	€ 1.57	€ 1.42	€ 1.58	€ 1.34	€ 1.39	€ 1.35	€ 1.40	€ 1.11	€ 1.07	€ 1.28	€ 1.17
Construction purposes [M€]	€ 3.14	€ 2.84	€ 3.16	€ 2.68	€ 2.79	€ 2.71	€ 2.80	€ 2.21	€ 2.15	€ 2.57	€ 2.33
Subtotal	**€ 2.53**	**€ 2.29**	**-€ 0.04**	**€ 2.16**	**€ 1.19**	**€ 2.19**	**€ 2.27**	**€ 1.79**	**€ 0.51**	**€ 2.08**	**€ 1.89**
Hydropower generation [benefits] [B€]	€ 0.18	€ 0.17	€ 0.17	€ 0.16	€ 0.16	€ 0.15	€ 0.15	€ 0.14	€ 0.14	€ 0.14	€ 0.13
Irrigation (agricultural) [benefits] [B€]	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02
Freshwater (drinking water) [ben.] [B€]	€ 0.07	€ 0.07	€ 0.07	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.05	€ 0.05
Loss of land [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Dredge waste [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Total social costs & benefits	**€ 0.27**	**€ 0.27**	**€ 0.26**	**€ 0.25**	**€ 0.24**	**€ 0.24**	**€ 0.23**	**€ 0.22**	**€ 0.22**	**€ 0.21**	**€ 0.20**
NET present costs & benefits (opt.) [B€]	**€ 0.27**	**€ 0.26**	**€ 0.25**	**€ 0.25**	**€ 0.24**	**€ 0.23**	**€ 0.23**	**€ 0.22**	**€ 0.21**	**€ 0.21**	**€ 0.20**

Year	2064	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074
Reservoir cost	**-€ 2.72**	**-€ 2.64**	**-€ 2.57**	**-€ 2.49**	**-€ 2.42**	**-€ 2.35**	**-€ 2.28**	**-€ 2.21**	**-€ 2.15**	**-€ 2.09**	**-€ 2.03**
Construction cost [M€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Maintenance cost [M€]	-€ 2.72	-€ 2.64	-€ 2.57	-€ 2.49	-€ 2.42	-€ 2.35	-€ 2.28	-€ 2.21	-€ 2.15	-€ 2.09	-€ 2.03
Core dredging equipment	**€ 0.00**	**€ 0.00**	**-€ 2.43**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
Dredge equipment [M€]	€ 0.00	€ 0.00	-€ 2.24	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Discharge pipe [M€]	€ 0.00	€ 0.00	-€ 0.19	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Support equipment [M€]	**€ 0.00**	**€ 0.00**	**-€ 0.25**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
Workboat [M€]	€ 0.00	€ 0.00	-€ 0.25	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
OPEX [M€]	-€ 1.67	-€ 1.21	-€ 1.47	-€ 1.52	-€ 1.38	-€ 1.34	-€ 1.39	-€ 0.93	-€ 1.31	-€ 1.27	-€ 1.08
labour cost [M€]	-€ 0.04	-€ 0.03	-€ 0.04	-€ 0.04	-€ 0.03	-€ 0.03	-€ 0.03	-€ 0.02	-€ 0.03	-€ 0.03	-€ 0.02
Fuel cost [M€]	-€ 0.16	-€ 0.12	-€ 0.14	-€ 0.15	-€ 0.14	-€ 0.13	-€ 0.14	-€ 0.09	-€ 0.13	-€ 0.12	-€ 0.11
Storage cost [M€]	-€ 0.73	-€ 0.53	-€ 0.64	-€ 0.67	-€ 0.61	-€ 0.59	-€ 0.61	-€ 0.41	-€ 0.58	-€ 0.56	-€ 0.48
Transport cost [M€]	-€ 0.73	-€ 0.53	-€ 0.64	-€ 0.67	-€ 0.61	-€ 0.59	-€ 0.61	-€ 0.41	-€ 0.58	-€ 0.56	-€ 0.48
Benefits [M€]	€ 3.63	€ 2.64	€ 3.20	€ 3.32	€ 3.02	€ 2.93	€ 3.04	€ 2.03	€ 2.86	€ 2.78	€ 2.36
Fertilization purposes [M€]	€ 1.21	€ 0.88	€ 1.07	€ 1.11	€ 1.01	€ 0.98	€ 1.01	€ 0.68	€ 0.95	€ 0.93	€ 0.79
Construction purposes [M€]	€ 2.42	€ 1.76	€ 2.14	€ 2.21	€ 2.01	€ 1.96	€ 2.03	€ 1.35	€ 1.91	€ 1.85	€ 1.57
Subtotal	**€ 1.96**	**€ 1.43**	**-€ 0.95**	**€ 1.80**	**€ 1.64**	**€ 1.59**	**€ 1.65**	**€ 1.10**	**€ 1.55**	**€ 1.51**	**€ 1.28**
Hydropower generation [benefits] [B€]	€ 0.13	€ 0.12	€ 0.12	€ 0.12	€ 0.11	€ 0.11	€ 0.11	€ 0.10	€ 0.10	€ 0.10	€ 0.10
Irrigation (agricultural) [benefits] [B€]	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02
Freshwater (drinking water) [ben.] [B€]	€ 0.05	€ 0.05	€ 0.05	€ 0.05	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04	€ 0.04
Loss of land [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Dredge waste [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Total social costs & benefits	**€ 0.20**	**€ 0.19**	**€ 0.19**	**€ 0.18**	**€ 0.18**	**€ 0.17**	**€ 0.17**	**€ 0.16**	**€ 0.16**	**€ 0.15**	**€ 0.15**
NET present costs & benefits (opt.) [B€]	**€ 0.20**	**€ 0.19**	**€ 0.18**	**€ 0.18**	**€ 0.17**	**€ 0.17**	**€ 0.16**	**€ 0.16**	**€ 0.15**	**€ 0.15**	**€ 0.15**

Year	2075	2076	2077	2078	2079	2080	2081	2082	2083	2084	2085
Reservoir cost	**-€ 1.97**	**-€ 1.91**	**-€ 1.85**	**-€ 1.80**	**-€ 1.75**	**-€ 1.70**	**-€ 1.65**	**-€ 1.60**	**-€ 1.55**	**-€ 1.51**	**-€ 1.46**
Construction cost [M€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Maintenance cost [M€]	-€ 1.97	-€ 1.91	-€ 1.85	-€ 1.80	-€ 1.75	-€ 1.70	-€ 1.65	-€ 1.60	-€ 1.55	-€ 1.51	-€ 1.46
Core dredging equipment	**-€ 1.24**	**-€ 2.41**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
Dredge equipment [M€]	-€ 1.15	-€ 2.23	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Discharge pipe [M€]	-€ 0.10	-€ 0.19	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Support equipment [M€]	**-€ 0.19**	**-€ 0.37**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
Workboat [M€]	-€ 0.19	-€ 0.37	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
OPEX [M€]	-€ 1.12	-€ 1.23	-€ 0.77	-€ 1.09	-€ 0.99	-€ 0.96	-€ 0.94	-€ 0.85	-€ 0.82	-€ 0.91	-€ 0.78
labour cost [M€]	-€ 0.02	-€ 0.02	-€ 0.01	-€ 0.02	-€ 0.02	-€ 0.02	-€ 0.02	-€ 0.01	-€ 0.01	-€ 0.01	-€ 0.01
Fuel cost [M€]	-€ 0.11	-€ 0.12	-€ 0.08	-€ 0.11	-€ 0.10	-€ 0.09	-€ 0.09	-€ 0.08	-€ 0.08	-€ 0.09	-€ 0.08
Storage cost [M€]	-€ 0.49	-€ 0.54	-€ 0.34	-€ 0.48	-€ 0.44	-€ 0.43	-€ 0.41	-€ 0.38	-€ 0.36	-€ 0.40	-€ 0.34
Transport cost [M€]	-€ 0.49	-€ 0.54	-€ 0.34	-€ 0.48	-€ 0.44	-€ 0.43	-€ 0.41	-€ 0.38	-€ 0.36	-€ 0.40	-€ 0.34
Benefits [M€]	€ 2.46	€ 2.70	€ 1.70	€ 2.40	€ 2.18	€ 2.12	€ 2.06	€ 1.86	€ 1.81	€ 2.01	€ 1.71
Fertilization purposes [M€]	€ 0.82	€ 0.90	€ 0.57	€ 0.80	€ 0.73	€ 0.71	€ 0.69	€ 0.62	€ 0.60	€ 0.67	€ 0.57
Construction purposes [M€]	€ 1.64	€ 1.80	€ 1.13	€ 1.60	€ 1.45	€ 1.41	€ 1.37	€ 1.24	€ 1.21	€ 1.34	€ 1.14
Subtotal	**-€ 0.10**	**-€ 1.31**	**€ 0.92**	**€ 1.30**	**€ 1.19**	**€ 1.15**	**€ 1.12**	**€ 1.02**	**€ 0.99**	**€ 1.09**	**€ 0.93**
Hydropower generation [benefits] [B€]	€ 0.09	€ 0.09	€ 0.09	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.07	€ 0.07	€ 0.07
Irrigation (agricultural) [benefits] [B€]	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01
Freshwater (drinking water) [ben.] [B€]	€ 0.04	€ 0.04	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03
Loss of land [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Dredge waste [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Total social costs & benefits	**€ 0.14**	**€ 0.14**	**€ 0.13**	**€ 0.13**	**€ 0.13**	**€ 0.12**	**€ 0.12**	**€ 0.12**	**€ 0.11**	**€ 0.11**	**€ 0.11**
NET present costs & benefits (opt.) [B€]	**€ 0.14**	**€ 0.13**	**€ 0.13**	**€ 0.13**	**€ 0.13**	**€ 0.12**	**€ 0.12**	**€ 0.12**	**€ 0.11**	**€ 0.11**	**€ 0.11**

Year	2086	2087	2088	2089	2090	2091	2092	2093	2094	2095	Total
Reservoir cost	**-€ 1.42**	**-€ 1.38**	**-€ 1.34**	**-€ 1.30**	**-€ 1.26**	**-€ 1.23**	**-€ 1.19**	**-€ 1.16**	**-€ 1.12**	**-€ 1.09**	**-€ 9.988**
Construction cost [M€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**-€ 9.681**
Maintenance cost [M€]	-€ 1.42	-€ 1.38	-€ 1.34	-€ 1.30	-€ 1.26	-€ 1.23	-€ 1.19	-€ 1.16	-€ 1.12	-€ 1.09	**-€ 307.02**
Core dredging equipment	**€ 0.00**	**-€ 1.74**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**-€ 0.38**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**-€ 45.72**
Dredge equipment [M€]	€ 0.00	-€ 1.61	€ 0.00	€ 0.00	€ 0.00	€ 0.00	-€ 0.35	€ 0.00	€ 0.00	€ 0.00	**-€ 42.21**
Discharge pipe [M€]	€ 0.00	-€ 0.13	€ 0.00	€ 0.00	€ 0.00	€ 0.00	-€ 0.03	€ 0.00	€ 0.00	€ 0.00	**-€ 3.52**
Support equipment [M€]	**€ 0.00**	**-€ 0.27**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**-€ 0.12**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**-€ 7.28**
Workboat [M€]	€ 0.00	-€ 0.27	€ 0.00	€ 0.00	€ 0.00	€ 0.00	-€ 0.12	€ 0.00	€ 0.00	€ 0.00	**-€ 7.28**
OPEX [M€]	-€ 0.75	-€ 0.89	-€ 0.66	-€ 0.69	-€ 0.76	-€ 0.69	-€ 0.67	-€ 0.65	-€ 0.55	€ 0.00	**-€ 171.01**
labour cost [M€]	-€ 0.01	-€ 0.01	-€ 0.01	-€ 0.01	-€ 0.01	-€ 0.01	-€ 0.01	-€ 0.01	-€ 0.01	€ 0.00	**-€ 7.80**
Fuel cost [M€]	-€ 0.07	-€ 0.09	-€ 0.06	-€ 0.07	-€ 0.08	-€ 0.07	-€ 0.07	-€ 0.06	-€ 0.05	€ 0.00	**-€ 16.34**
Storage cost [M€]	-€ 0.33	-€ 0.39	-€ 0.29	-€ 0.30	-€ 0.34	-€ 0.31	-€ 0.30	-€ 0.29	-€ 0.24	€ 0.00	**-€ 73.44**
Transport cost [M€]	-€ 0.33	-€ 0.39	-€ 0.29	-€ 0.30	-€ 0.34	-€ 0.31	-€ 0.30	-€ 0.29	-€ 0.24	€ 0.00	**-€ 73.44**
Benefits [M€]	€ 1.66	€ 1.95	€ 1.45	€ 1.52	€ 1.68	€ 1.53	€ 1.49	€ 1.44	€ 1.21	€ 0.00	**€ 364.91**
Fertilization purposes [M€]	€ 0.55	€ 0.65	€ 0.48	€ 0.51	€ 0.56	€ 0.51	€ 0.50	€ 0.48	€ 0.40	€ 0.00	**€ 121.64**
Construction purposes [M€]	€ 1.10	€ 1.30	€ 0.97	€ 1.01	€ 1.12	€ 1.02	€ 0.99	€ 0.96	€ 0.81	€ 0.00	**€ 243.27**
Subtotal	**€ 0.90**	**-€ 0.94**	**€ 0.79**	**€ 0.83**	**€ 0.92**	**€ 0.84**	**€ 0.32**	**€ 0.79**	**€ 0.66**	**€ 0.00**	**€ 140.90**
Hydropower generation [benefits] [B€]	€ 0.07	€ 0.07	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.06	€ 0.05	€ 0.05	€ 0.05	**€ 14.47**
Irrigation (agricultural) [benefits] [B€]	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	**€ 2.28**
Freshwater (drinking water) [ben.] [B€]	€ 0.03	€ 0.03	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	€ 0.02	**€ 5.71**
Loss of land [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**-€ 0.74**
Dredge waste [cost] [B€]	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**-€ 0.19**
Total social costs & benefits	**€ 0.10**	**€ 0.10**	**€ 0.10**	**€ 0.09**	**€ 0.09**	**€ 0.09**	**€ 0.09**	**€ 0.08**	**€ 0.08**	**€ 0.08**	**€ 21.52**
NET present costs & benefits (opt.) [B€]	**€ 0.10**	**€ 0.09**	**€ 0.10**	**€ 0.09**	**€ 0.09**	**€ 0.09**	**€ 0.08**	**€ 0.08**	**€ 0.08**	**€ 0.08**	**€ 11.56**