Budgeting water resources

Integrated water management from the treasurer's perspective

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Preface

The following thesis is the final component of a long academic journey. This journey started in Wageningen and is about to end in Delft. In and outside my studies, I have met many interesting people. Some of who have become very dear to me. A lot of interesting lessons were learned along the way. It has taught me much about what I like and perhaps even more about what I do not like. In this section I want to take the opportunity to thank:

- God: for coming so that I may have life, and have it to the full (John 10:10).
- Peter-Jules: for providing an interesting thesis topic, for guiding me in the process of conducting proper research and for giving me the freedom to focus on what I found interesting.
- Suzanne: for listening, giving her thoughts and for sharing her beauty with me.
- Mirjam en Tamar: for barging into our lives and being Mirjam and Tamar.
- My family and friends: for their support and interest.

Summary

In this thesis, the concept of water budgeting is discussed. This concept is based on a comparison between water resources and financial resources. It aims to approach water resources management problems more like a treasurer would. Water resources can be distributed in such a way as to optimise the chance of achieving a desired goal. Depending on what the most important goal of the water manager is, different 'water budgets' are possible. The concept of water budgeting is: to distribute the available water resources in such a way as to optimally achieve a certain objective. Model Predictive Control is considered a potential tool for water budgeting. This tool can translate the desired objectives into operational water management. The objective for the water system, in the form of penalties and constraints, are used as input for the Model Predictive Controller. The controller then determines the operational water management, which is most successful at achieving the desired goals.

The concept of water budgeting is applied to the South-Western Delta in order to test its usefulness. Different goals are set for the area, and these different goals result in different operational water management strategies. During the application of the water budgeting concept several shortcomings became apparent. These shortcomings follow from the fact that: the comparison between water resources and financial resources is complicated by the physical properties of water. Two very important properties of water in this respect are: water is bulky and water is fugitive. These properties result in: water being difficult to store and transport, in comparison to financial resources. Because water is difficult to handle, it is not straightforward to budget water. The water budgets become very variable in time and space. Due to this variability in time and space the sum of the water distribution does not tell the whole story. The moment at which the water resources are used is equally, or might be even more, important.

The application of Model Predictive Control, as a tool for water budgeting, has also proven to be limited. The most important limitation of using Model Predictive Control is: the reduced transparency of the decision making process. It is difficult to trace back why the controller 'chooses' certain control actions. This reduces the predictability of the operational water management. Reduced predictability of the operational water management, results in a less predictable water system. This will make it harder for stakeholders to be dependant on the water system.

The application of Model Predictive Control to a water system of this size and without a very clear (single) objective is relatively new. During the research it became clear that: it is very important to be able to control all the (large) in and outflow structures, and that it is important to included the parameter that needs to be controlled in the internal model. In the case used, it was not possible to control the Maeslantkering. This resulted in limited control over the water bodies connected to the Nieuwe Waterweg. In the internal model water salinity was not included. This made it very hard to control salinity. Penalties for the controller were developed that were assumed to influence salinity. These penalties were however not sufficient to prevent salinities to become too high in certain areas. This shows that the controller needs to be able to directly predict what the salinities will be.

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1 Introduction

This thesis suggests the treasures' perspective on water management. A treasurer considers the goals he wishes to achieve and he prioritises these goals. After this process of determining the goals and their respective importance, the available resources are assigned accordingly. The financial resources are assigned in such a way as to optimize the chance of achieving the most important goal(s). In this thesis an attempt is made to approach water resources management problems more like a treasurer would. Water resources are distributed in such a way as to optimize the achievement of the goal with the highest priority. The way water resources are distributed is referred to as 'water budgets'. The process of determining the priorities is one of a political nature and as such is better left for politicians. Water resources engineers however come in when it comes to 'water budgeting'. They can provide the knowledge needed for determining the way resources should be assigned in order to achieve the desired goals.

Not deliberately starting the decision making process from an objectives perspective, and having a narrow scope in the decision making process, can significantly limit the decision options. This is illustrated by the recent decision making with regard to the Volkerak-Zoommeer. After the floods of 1953, that took place in large parts of the South West of The Netherlands, the Dutch decided to improve water safety in the South-Western Delta. The constructions that followed were named: the Delta-works. The Delta-works were successful in terms of improving the water safety in the South-Western Delta. However they introduced new problems. Among others, the newly created lakes: Krammer-Volkerak and the Zoommeer, are facing water quality problems.

A long residence time and high nutrient inflow causes blue-green algae blooms during the summer in the Krammer-Volkerak and the Zoommeer (Verspagen et al, 2006). These algae produce toxins, which make the water unsuitable for swimming and agricultural use. The first logical solution to the algae problem would be: to flush the lakes with fresh water from the rivers. This solution was not considered feasible, since there is not sufficient fresh water available for flushing the lakes. Another proposed solution to these water quality problems is the construction of a large opening in the Phillipsdam (BOKV, 2009). This opening will allow water to be exchanged from the Oosterschelde to the Krammer-Volkerak. The Volkerak-Zoommeer becomes saline and there will be damped tidal movement. Due to the increased salinity the blue-green algae will not be able to survive.

This thesis argues that: the way the water quality problems in the Volkerak-Zoommeer were framed, inevitably led to: turning the lake saline being the 'most suitable' solution. It is not so much the proposed solution that this thesis wishes to question. The thesis wishes to provide an alternative to the decision making process: a broader and objective oriented approach, similar to the way a treasurer would work. In the case of the Volkerak-Zoommeer the issue was addressed from a status quo perspective. With this status quo perspective, it is meant that the fresh water availability in the surrounding areas should remain the same. So, this implies that: the algae bloom problem can be solved in any way, as long as this solution does not (negatively) effect surrounding areas or water bodies.

From a treasurer’s perspective: the distribution (‘budgeting’) of the available fresh water resources is regularly evaluated. The re-evaluation of the water resources budgets can provide new means of solving water management problems. In the Volkerak-Zoommeer case: the treasurer’s perspective could include a possible shift of fresh water resources from other functions to the Volkerak-Zoommeer as a logical alternative. Taking a treasurer’s perspective on water management, in other words: budgeting water resources, can help to introduce more creative ways to achieve the desired goals and avoid tunnel vision. In this report the water budgeting concept is elaborated on and its usefulness is evaluated by applying it to the South-Western Delta.

2 Research objective and approach

In the introduction the example of the Volkerak-Zoommeer is given. In this example the water resources management problem was approached from a status quo perspective. The distribution of the fresh water inflow from the rivers was considered fixed. This approach left very little room to solve the problems in the Volkerak-Zoommeer, because there was no fresh water left that could be used. The fact that the fresh water distribution is considered fixed might lead to good solutions being missed. These solutions are not considered because they influence the fresh water distribution. The problem definition for this thesis is:

> *"Good options for solving water resources management problems are not considered, because the fresh water distribution is considered fixed."*

In order to illustrate this problem the example of the Volkerak-Zoommeer is used. The example shows how: the assumption that the fresh water distribution should remain fixed, limits the possible solutions to the blue-green algae problems significantly. For this research the specific example of the Volkerak-Zoommeer in itself is not very important. The example is only used to indicate how inflexible water resources distribution, limits the solutions available for water management problems.

2.1 Objective

In order to provide a solution to the problem defined above, this research considers an alternative way of approaching water resources management problems. In this thesis a more flexible approach is considered in the form of 'water budgeting'. The water budgeting concept is introduced and elaborated on. The concept assumes that water could be managed more like a treasurer would manage financial resources. The treasures perspective, on water management, could provide alternative solutions for water management problems. By looking at water management: at a larger scale and taking the desired objectives as starting point, more room is created in which alternative solutions can be found. The question is: can some of the principles we apply to finances, also be applied to water? This question results in the following research objective:

> *"To evaluate the usefulness of the water budgeting concept for integrated water resources management."*

By nature, water resources management involves conflicting stakes and limited possibilities to distribute water. Stakeholders in the water system will have different objectives for the water system and these objectives are often conflicting with each other. The possibilities to distribute water are limited by the water management infrastructure and water availability. These characteristics of water resource management call for some type of constrained optimisation. The Delft University of Technology has valuable experience in applying Model Predictive Control to water management problems (Overloop, 2006).

Model Predictive Control is considered as a potential tool for water budgeting. This tool can translate the desired state of the water system into operational water management. Since the application of Model Predictive Control for water budgeting has not been done before, the following sub objective is formulated:

> *"To evaluate the effectiveness of Model Predictive Control as a tool for water budgeting."*

2.2 Approach

To determine the water budgets, a Model Predictive Controller is developed. Model Predictive Control can translate the objectives of the water management authority into operational water management. This controller will generate the actions that need to be taken by water control structures. The actions taken by the water control structures, in turn, result in a certain water distribution. This distribution of the water is referred to as the water budgets in this report. These controlled structures, the structures that receive input from the controller, are selected. In order to keep the computational load for the controller low, the number of controlled structures that it has to generate actions for, is kept to a minimum. The number of controlled structures is reduced by only including the structures that have a significant influence on the water system. In order to simulate the effects of the control actions: an existing detailed water quantity and water quality model is used.

In order to deal with the water resources management issues in an integrated manner, the entire South-Western Delta is considered as the study area. Integrated water resource management in this thesis consists of: looking at different types of water use and looking at water management at a large spatial scale. This large area needs to be taken into account in order to be able to distribute all the fresh water from the rivers Rhine and Meuse. The importance of distributing fresh water optimally is highest in dry periods. When river discharges are high the fresh water availability is not limiting and most objectives can be met without much trouble. For this reason it is more relevant to look at a time of low river discharges in this research. The simulation period is the first 7 days, in September 2000. This is a time in which fresh water availability is low: the river discharges are low and it is a period, which is preceded by low discharges.

Different sets of penalties and constraints for the controller are used. These sets of constraints and penalties reflect the desired objectives that the controller is required to achieve. The resulting operational water management for these different objectives are referred to as different strategies. In this research three different strategies are considered: one which aims to improve the ecological state of the area, one which aims to provide the right conditions for navigation and one which aims to have the highest fresh water availability in the area. The control actions generated by the controller are implemented into the existing water quantity and quality model. These control actions result in a certain state of the water system. The final stage of the research is: the evaluation of the control actions and the resulting water system. This is done by comparing the outcome of the different water budgets, with the objective that was set for that particular strategy.

3 Area description

The study area in this research is the 'South-Western Delta', see Figure 1 for an overview of the study area. As the name indicates, the area is located in the south western part of the Netherlands. It is the area in which the rivers Rhine and Meuse flow into the North Sea. During the second half of the previous century the construction of the Deltaworks started. The Deltaworks have separated the, previously open, estuary delta into several, fresh or salt, water bodies. Figure 1 shows the salinity and tidal dynamics of the water bodies. In this research the Westerschelde will not be considered, because there are no structures in this area that can be controlled. The following parts of this chapter will deal with the control structures in the area. First an overview of the existing water control structures in the area is given. After this, the structures that are going to be controlled in the water budgeting examples are selected.

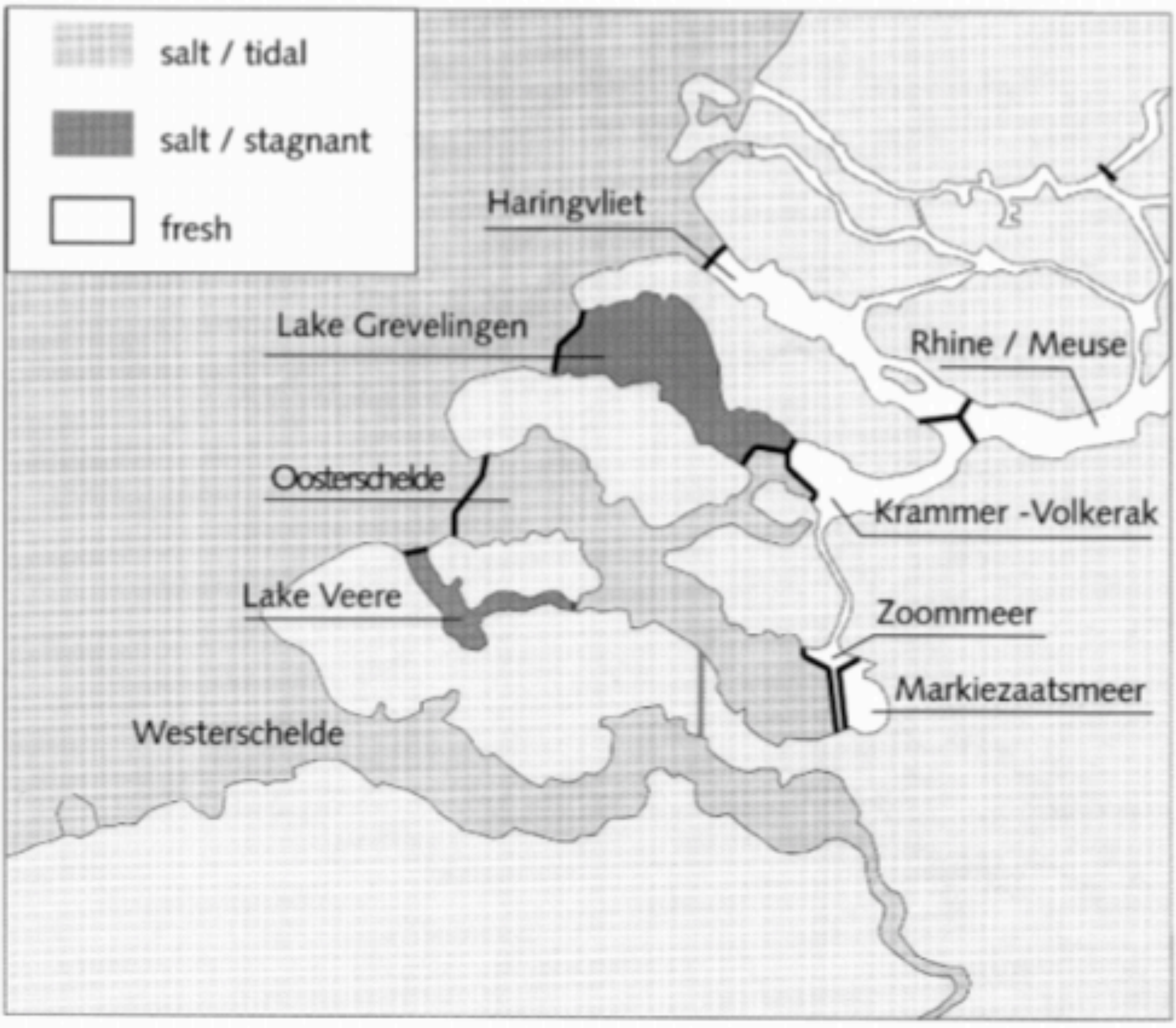

Figure 1: water bodies in the South-Western Delta (source: de Vries et al, 1996)

3.1 Water management structures

An overview of the different water management structures in the South-Western Delta is shown in Figure 2. In the following section a short description is given for all the structures. The information about these structures is obtained from the 'Delta verkenner' website (public.deltares.nl).

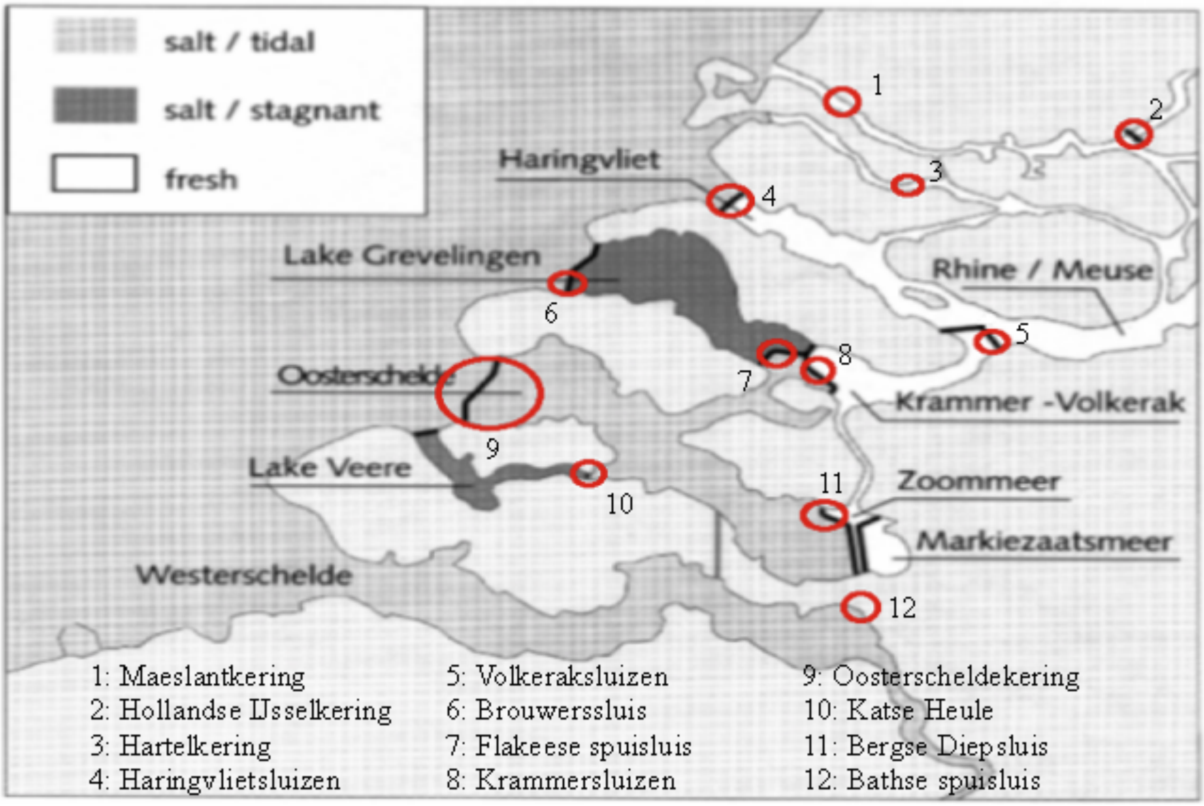

Figure 2: Water managment infrastructure in the South-Western Delta (modified from: de Vries et al, 1996)

1: Maeslantkering

The Maeslantkering is a storm surge barrier in the Nieuwe Waterweg. It consists of two circular gates, which are floated from their docks into the canal. When they touch in the middle the gates are filled with water to sink them. When a storm tide of more then 3 meters above NAP is expected, the barrier is closed. Closing the barrier takes about 4 hours. The width of Nieuwe Waterweg at the Maeslantkering is 360 meters and the bottom is located at -17 meters NAP.

2: Hollandse IJsselkering

The Hollandse IJsselkering is a storm surge barrier, which is meant to protect the area along the Hollandse Ijssel (North of the barrier) against high water. This area is among the lowest areas of the Netherlands. It also is a densely populated area. The barrier consists of two large gates, which can be lowered into the water. The gates are 80 meters wide and the weir crest is located at -6.5 meters NAP.

3: Hartelkering

The Hartelkering is a storm surge barrier similar to the Hollandse IJsselkering. Two large gates can be lowered to close of the Hartelkanaal. The gates are closed when a storm tide of more than 3 meters above NAP is expected. Closing the Hartelkering takes about one hour. The gates combined width, is: 200 meters and the weir crest is located at -6 meters NAP.

4: Haringvlietsluizen

The Haringvlietsluizen serve two purposes: protection against high water at sea and regulating the discharges through the Nieuwe Waterweg and the Haringvliet. When river discharges are low, the water flows through the Nieuwe Waterweg. At increasing discharges the Haringvlietsluizen are opened to prevent the water levels upstream from rising. The gates of the Haringvlietsluizen can be set to any desired opening. The gates combined width, is: 993 meters and the weir crest is located at -5.5 meters NAP.

5: Volkeraksluizen

Besides shipping locks, the Volkeraksluizen also has gates for providing the Krammer-Volkerak with water from the Hollandsche Diep. These gates served the purpose of flushing the Volkerak-Zoommeer to make it a freshwater lake. At the moment they are not used. The total area of flow through these gates is 300 squared meters.

6: Brouwerssluis

The Brouwerssluis was constructed to create a possibility to exchange water between the Grevelingen and the North Sea. This gate is usually open. It is only occasionally closed to keep the water level in the Grevelingen at the desired level. The area of flow through this gate is approximately 65 squared meters.

7: Flakeese spuisluis

The Flakeese spuisluis was used during the construction of the Deltaworks. It served the purpose of keeping the salinity in the northern part of the Oosterschelde high. At the moment the Flakeese spuisluis is not used for water management purposes. The area of flow through this gate is approximately 61 squared meters.

8: Krammersluizen

The Krammersluizen are shipping locks. They make it possible for transport and recreational ships to travel from the Krammer-Volkerak to the Oosterschelde. The total width of the shipping locks is 66 meters. The average depth of the weir over the different locks is at -5.28 meters NAP.

9: Oosterscheldekering

The Oosterscheldekering is a large storm surge barrier. It consists of three series of gates. These gates are closed when high water at sea is expected. The largest gate takes 82 minutes to close. Besides protection against flooding it currently serves no other water management purpose. The gates combined width, is 3223 meters, and the average weir crest is at -6.59 meters NAP.

10: Katse Heule

The Katse Heule is a structure used to increase the exchange of water between the Oosterschelde and the Lake Veere. This exchange increases the water quality in Lake Veere significantly. The area of flow through this gate is 39 squared meters.

11: Bergse Diepsluis

The Bergse Diepsluis is a shipping lock for recreational ships. It has facilities to keep the salt water from the Oosterschelde from entering the Zoommeer. It does not serve any water management purposes. The width of this shipping lock is 6.5 meters, and the crest level is at -2.5 meters NAP.

12: Bathse spuisluis

The Bathse Spuisluis is used to discharge excess water from the Volkerak-Zoommeer to the Westerschelde. It has six gates, which can be either open or closed. The area of flow through this gate is approximately 66 squared meters.

3.2 Structures controlled in the water budgeting examples

In order to reduce the complexity of the problem, only a few of the structures in the study area will be controlled. If all of the structures are controlled, the computer simulation of the system would become too complex, resulting in very long computational times. The research will focus on fresh water distribution in times of low rivers discharges. This will make some of the structures irrelevant for this research.

The Oosterschelde is considered to remain saline, so it is not very relevant in this research. If the situation in times of high river discharges would be considered, then it could provide extra storage. The water level in the Oosterschelde could be kept low to provide storage of excess river water. Since this research is focussed on low river discharges, controlling the Oosterscheldekering does not provide much use.

Since the Oosterschelde is considered to remain saline, there are some lakes, which will have no direct connection to any fresh water bodies. These lakes are: Lake Grevelingen and Lake Veere. Controlling the structures connected to these lakes is also not relevant in this research.

Some other structures are not very useful to control for other reasons. The Maeslantkering for example takes a very long time to open or close. Due to its construction it also is not able to prevent water from flowing towards the Noths Sea. This makes the Maeslantkering unsuitable for daily water management. Besides the limited usefulness of the Maeslantkering it was also very difficult to properly implement the structure in the internal model. The Bergse Diepsluis is only a small shipping lock, which will not have much influence on the water system as a whole. The Hollandse IJsselkering could be used to control water levels at the Hollandse Ijssel. This area however is not considered in this research, so there is little use in controlling the Hollandse IJsselkering.

The structures, which are selected as controlled structures, are: the Hartelkering, the Haringvlietsluizen, the Volkeraksluizen, the Krammersluizen and the Bathse Spuisluis. The locations of these controlled structures are shown in Figure 3: Structures controlled in water budgeting examples (modified from: de Vries et al, 1996)Figure 3. Of the remaining structures only the Bergse Diepsluis is considered closed. The other structures are all modelled as being fully opened.

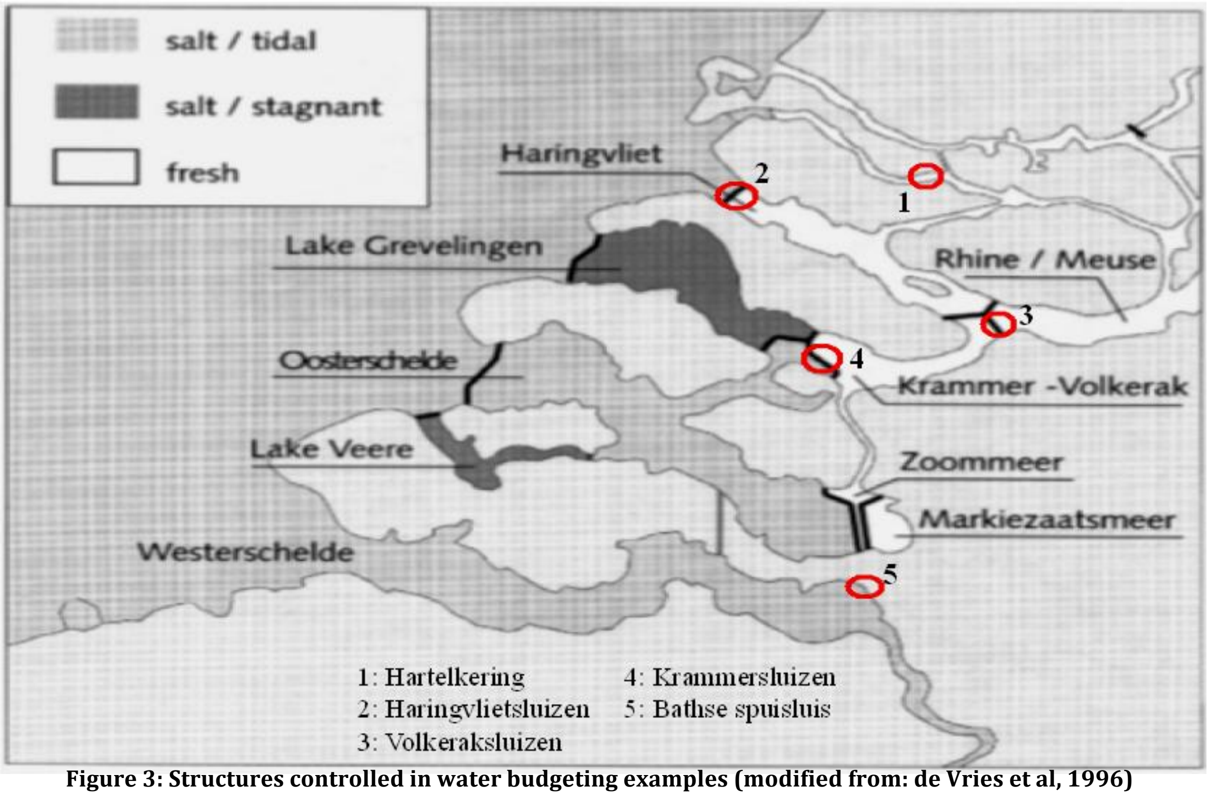

Figure 3: Structures controlled in water budgeting examples (modified from: de Vries et al, 1996)

3.3 Decision-making in the Volkerak-Zoommeer

This section will discuss the developments in the Krammer-Volkerak and the Zoommeer. These lakes together are referred to as: Volkerak-Zoommeer, in the rest of the report. Not only the physical developments in the Volkerak-Zoommeer will be discussed, but also the decision making process that the water management authorities went through, will be illustrated.

Until the year 1990, the ecological development of the Volkerak-Zoommeer progressed nicely. The water was very clear, despite its high nutrient content. From 1994 onwards it became clear that the ecological development of the lakes was following an unwanted trajectory. The receding water quality resulted in increasing numbers of blue-green algae (Cyanobacteria). These toxic blue-green algae are a threat to the ecology and other uses of the lakes. The algae reduce the amount of light that can penetrate into the water, making it impossible for other aquatic plants to develop. The biggest problems, however, occur when the algae die. When the algae decompose, toxins are released. This usually occurs in summer and autumn. At this time, the algae form thick layers floating on the water surface. The toxins released are dangerous for water fauna, including birds. In the autumn of 2002 around 5000 birds died due to these algae toxins. (Sliepen&Tosserams, 2003)

Not only do these blue-green algae have detrimental effects on the ecological functioning of the water system, they also cause problems relating to the recreational use of the water. Health risks prevent the water from being suitable for swimming, when the algae form floating layers on the water surface. The water also becomes unsuitable for irrigational use in agriculture. Besides these effects the recurring algae blooms also prevent building projects for adjacent municipalities. The decomposition of the algae causes stench, which is a nuisance for the surroundings. (Sliepen&Tosserams, 2003)

The conditions which make it possible for these blue-green algae blooms to occur are: high nutrient inflow from surrounding brooks, and long residence times in the lake (Sliepen&Tosserams, 2003, Verspagen et al, 2006). The high nutrient content, originating from agricultural areas, provides the algae with enough resources to grow rapidly. The long residence time allows the blue-green algae to dominate the algae population even though they have a slower growth rate as the competing (non toxic) species.

At the end of the nineties the political pressure to find structural solutions for the algae bloom problems increased. In 2001 the national water management authority (Rijkswaterstaat) started the project Exploring solutions Volkerak-Zoommeer (Verkenning oplossingsrichtingen Volkerak-Zoommeer). The goal of this project was: to provide solutions for reaching the long-term goals, solving the blue-green algae problems on the medium and long term and providing the directions for these solutions. The exploration should result in a number of possible solutions, consisting of different measures. These solutions should result in a sustainable, self-regulating, Volkarak-Zoommeer by the year 2035. (Sliepen&Tosserams, 2003)

The report by Sliepen and Tosserams (2003) is the result of this exploration. They list eight possible scenarios, which result in the Volkerak-Zoommeer being a healthy water body without blue-green algae blooms. With the help of different stakeholders in the area, three scenarios with the highest chance of success are formulated:

- Estuary Dynamics:
    Fresh water enters the Volkerak from Hollandsche Diep (the rivers: Rhine and Meuse) and saline water enters the Zoommeer from the Oosterschelde. The Volkerak-Zoommeer will have a tide of 1 to 1.5 meters and there will be a transition between fresh and saline water.
- Dynamic Bay:
    The Volkerak-Zoommeer is turned in a saline water body with a tide. Water from the Hollandsche Diep is only used to prevent saline water entering the Hollandsche Diep.
- River Dynamics:
    The Volkerak-Zoommeer is flushed with fresh water from Hollandsche Diep. Keeping the Volkerak-Zoommeer as a fresh water reservoir.

In 2005 a so-called ‘Planstudie’ started to access the effectiveness of the proposed scenario’s and their effect on the environment. During the first phase of this study, the focus was mainly on the River Dynamics scenario. The investigation of the fresh Volkerak-Zoommeer scenario was finished in 2006 and they concluded that this scenario was not effective enough. The effectiveness of flushing the Volkerak-Zoommeer with fresh water was not satisfactory, and there was not enough fresh water available for flushing. (BOKV, 2009)

According to Verspagen et al (2006), the blue-green algae blooms could be prevented both by flushing with fresh water as well as turning the Volkerak-Zoommeer into a saline lake. A later study by Boderie et al. (2006) conclude that even when flushing with 150m^3/s from the Haringvliet, algae blooms will not be sufficiently prevented. The research done by Boderie et al used the same model as the one used by Verspagen et al, but Boderie et al implemented the model in combination with a 2d hydrodynamic model. In the research done by Verspagen et al. the entire Volkerak-Zoommeer was modelled as a single reservoir, which was completely mixed. During a meeting with (international) experts on aquatic ecology it was shown that residence times within the Volkerak-Zoommeer varied significantly (van Duren et al, 2006). The 2d model clearly showed that residence times in the deeper parts of the lake were much lower than those in the shallow areas. This resulted in the flushing strategy being effective in the deep channels of the lake but the shallow parts remained relatively stagnant and were thus still susceptible to the occurrence of algae blooms. The experts also suggested that increasing the dynamics in a salt Volkerak-Zoommeer increases the chance it will be a successful measure in preventing the algae blooms (van Duren et al, 2006). This increase in dynamics can be achieved by increasing the tidal range (difference between high and low tide). It will decrease algae bloom chances by reducing the residence time in the lake.

In order to determine the amount of water available, Jacobs and Bruggers (2006) investigated how much fresh water from the Hollandsche Diep could be used, without causing fresh water shortage in other areas. The Nieuwe Waterweg is the only remaining open connection between the rivers Rhine and Meuse, and the North Sea. In order to keep the saline seawater from intruding up the rivers, a minimum discharge of 1200m^3/s is required to go through the Nieuwe Waterweg. There are several drinking water and agricultural water intake points in the area. Whenever the discharge in the rivers is insufficient to keep the salt water out, (some of) the intake points will not be able to take in fresh water any more. The conclusions drawn by Jacobs and Bruggers (2006) with respect to fresh water availability are summarized in Table 1. From this table it is clear that there will often be insufficient water available for flushing the Volkerak-Zoommeer. When looking at the scenario in which the Volkerak-Zoommeer is turned saline, the fresh water requirements are much lower, making this scenario more attractive.

Table 1: availability of fresh water for the Volkerak-Zoommeer

Required amount of fresh water (m^3/s)	Time the amount is available during summer (%)
30	90
50	75
100	43
150	17

In the 'Milieu Effecten Rapportage' (BOKV, 2009) the scenario in which the Volkerak-Zoommeer is flushed with fresh water from the Hollandsche Diep is considered ineffective in preventing algae blooms in the future. The report then continues by determining the effects, of turning the Volkerak-Zoommeer saline, on the environment and on the stakeholders in the area. The scenario 'Estuary Dynamics' does not seem to be considered in the 'Milieu Effecten Rapportage'.

Borm and Huijgens (2010) send in a plan to improve water management in The Netherlands on a national scale. Their idea consists (among others) of closing of the Nieuwe Waterweg in order to have more fresh water available for the southern part of the delta. The fresh water that is no longer needed to keep the salt water out at the Nieuwe Waterweg can be used to flush the Volkerak-Zoommeer. In this way the Volkerak-Zoommeer can remain a fresh water reservoir. A reaction to this plan by Rijkswaterstaat (the national water management authority) and research institute Deltares is given in Rijkswaterstaat Zeeland (2010). They reply that their research shows that flushing with fresh water will only be effective when more than 200-300m^3/s of water is used. With a lower flushing discharge, blue-green algae blooms will still occur. They argue that this water is not available and that discharging these quantities of fresh water into the Oosterschelde will have negative ecological effects. Currently the Oosterschelde is a saline water body; inflow of large amounts of fresh water will cause marine species (mainly shellfish) to die.

3.4 The Volkerak-Zoommeer case summarized

A summary of the developments and the decision making process in the Volkerak-Zoommeer:

1. The blue-green algae blooms were considered a problem and it was decided to search for a solution.
2. The causes for the algae blooms were: high nutrient input and a high residence time.
3. Three scenarios were considered: Estuary Dynamics, Dynamic Bay, and River Dynamics. Of these scenarios the Estuary Dynamics scenario does not appear in the final report (BOKV, 2009).
4. It was (implicitly) decided that a solution to the algae problem should not change current fresh water availability and any adverse effect would have to be compensated.
5. In order to access the effect of the two remaining scenarios (Dynamic Bay and River Dynamics) on the fresh water availability in surrounding areas a study was conducted (Jakobs&Bruggers, 2006).
6. Finally the solution that would require the least amount of fresh water was selected. Any detrimental effects of a saline Volkerak-Zoommeer would have to be compensated by other means.

During the decision making process the water management authorities decided (perhaps not explicitly) that water management in the surrounding water bodies should not be effected by the solution to the algae bloom problem. This resulted in the study done by Jakobs and Bruggers (2006) to access the impact of the different solutions on the fresh water availability in the surrounding water bodies. One could say that what they actually did was: looking for leftover fresh water that could be used for the solution of their algae problem. Even in the Netherlands there are times when fresh water is scarce, especially since the growing season is the dry season. With a densely populated area as the Netherlands it would be a miracle to find leftover water resources being unused in the dry season. So if there would be any water unused it would be a clear indication that the water management in The Netherlands is not very effective.

4 The treasurers’ approach

Any treasurer can tell you that there is little use in looking for any leftover budget for a long-term project. If there is leftover money on a regular basis then the treasurer is not doing his job right and the organisation would do well to look for a more capable treasurer. When we consider this logical in the case of finances, why not apply this to our water resources? Why not apply some sort of budgeting to our water resources?

In the Volkerak-Zoommeer the distribution of the water resources was considered static. This inevitably led to the most suitable solution being the solution that would require the least amount of (fresh) water, since there was no leftover water. In this way the other costs in terms of construction costs and costs for compensating adverse effects of the saline lake, were made subordinate to the costs in terms of water resources. A treasurer however evaluates on a regular basis whether the chosen distribution of (financial) resources has the desired effect and whether or not the resources are used effectively.

The concept of budgeting water is not entirely new, Molden (1997) introduces the concept accounting for water use. The underlying concept for water accounting is the water balance. Using water balances, insight can be gained into what the water in a certain basin is used for. The amounts of water can be accounted for in this way. By discerning between productive and unproductive use of water, wastes of water can be identified. Once it is known where water is wasted, measures can be taken to prevent these wastes and the productive water use can be increased (Molden&Sakthivadivel, 1999). The concept of budgeting water, which will be elaborated on, can be considered as a further development of the water accounting principle.

In order to illustrate the concept of water budgeting the analogy of a treasurer is used. A treasurer sets or receives a list of priorities. These priority lists will differ, depending on the organisation the treasurer is working for. For most commercial organisations the main priority will be to maximise profit. There are however different routes to achieve this goal. Possible strategies could be: keeping existing customers by providing a high level of service, increasing the number of costumers by advertising, or decreasing (future) production costs by investing in research. With a given list of goals and their respective priority, the treasurer will allocate (financial) resources. The resources are distributed in such a way that the goals with the highest priority will have the highest chance of being achieved. On a regular basis, the treasurer will access the progress that has been made concerning the different goals. When required, he will adjust the distribution of resources using the results of this assessment.

In a similar way as the treasurer distributes financial resources, the water manager can distribute water resources. With a given set of goals the water manager can allocate the incoming water according to the priorities set for all the desired goals. The process of determining the goals for the water system and their respective priorities is a process of political nature. As such, this process is better left to politicians. Water managers can provide input into this process by giving indications of the possibilities and constraints of the water system. After the objectives of the water system are determined and their respective priority has been decided upon, the water manager can translate them into a certain water distribution. The water manager can start budgeting the water. Budgeting water is somewhat less straightforward then budgeting finances. Knowledge on the functioning of the water system is essential in order to be able to get the water to the required location.

Keeney (1992) indicates that in many cases decisions are made while focussing on alternatives. When people have to decide they very quickly start to formulate the alternatives they have to choose from. After determining the alternatives, the best one is chosen. In the Volkerak-Zoommeer case a similar approach is applied. The decision makers start by determining their objective: a sustainable, self-regulating, Volkarak-Zoommeer by the year 2035 (Sliepen&Tosserams, 2003). Very soon after the formulation of this objective, however they start determining the available alternatives. Keeney (1992) argues that this approach, which he calls the alternative focused thinking, limits the decision making process. In general only the readily available, or obvious alternatives are considered.

The concept of water budgeting takes the objectives as a starting point. The value-focused thinking advocated by Keeney (1992), is similar in this respect. In value-focused thinking one starts with formulating what values one considers as important. After determining the most important values one starts to investigate how these values can be achieved. Water budgeting is similar with respect to the fact that it first formulates the objective(s) for the water system. Only after formulating the objectives the water manager will investigate the feasibility of achieving these goals. As a starting point to achieving the objective the operational water management is considered. When changing operational water management is not sufficient for achieving the objectives, investments in water management infrastructure can be considered. According to Keeney (1992) value-focused thinking will stimulate creativity in the decision making process. This creativity is stimulated by: looking beyond the obvious or readily available alternatives, and searching for ways to achieve several goals at once. Water budgeting could similarly stimulate creative thinking for water management issues.

Like the treasurer, the water manager should evaluate the performance of his water budgeting on a regular basis. Are the objectives met? Are there other options to achieve the same objectives with fewer resources? Are all resources used? These are the type of questions the water manager should ask regularly. Likewise, politicians should evaluate whether the goals and their relative importance still reflect their political agenda and the societal needs. This evaluation process is represented in Figure 4. This figure also illustrates the division in tasks between the politicians and the water managers. The priorities given to the objectives should be open for discussion. Just like there should be room to discuss the financial budgeting of an organisation. In this way the water budgets for the different objectives are not static, but they reflect what society considers important at that moment in time.

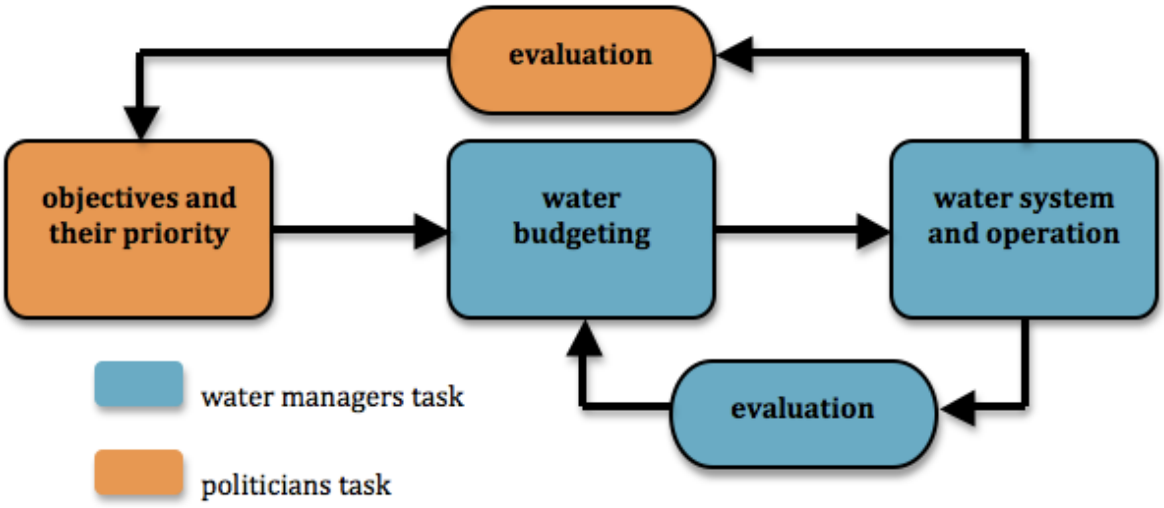

Figure 4: representation of the evaluation process and tasks, for the water budgeting concept

Since a water system is not the same as a spreadsheet, the analogy of the treasurer has its limitations. Water use does not always result in the required water being lost after use. Water can for instance be used for cooling or be required to maintain a minimum depth for navigation. In these examples, water used for one objective might be reused further downstream for another purpose. On the other hand, using water for cooling, results in a higher water temperature. This higher temperature might reduce the ecological value of the water. So the water might not be used in the sense that it is no longer available, but it might be used in the sense that it is no longer suitable. In this respect water pollution is very important. A factory might not use much water, but when it introduces pollutants to the water, it may render much more water unsuitable then the amount it actually uses. The fact that water only flows downhill also complicates the situation and limits the comparison between a treasurer and a water manager. Water may be abundant in one area, but the topography can prevent the water from being transported to a water scarce area. So unlike money, the possibilities to transport water are significantly limited by physical laws.

This calls for water managers with proper knowledge on how the water system functions. They need to be able to know the possibilities and limitations of the system. An understanding of the effects of certain measures is also essential. However, for more detail on how the water system responds computer models can be very useful. Even experts on the water system in question will not be able to predict how the system reacts to every possible adjustment. With respect to water budgeting, computer models can play an important role. Especially Model Predictive Control could be an important tool. The details on the way Model Predictive Control functions will be dealt with later in this report. Here, it will suffice to say that it could be useful in translating desired goals and priorities into operational water management. The objectives and their respective importance are used as input into the (Model Predictive) controller, in the form of penalties and constraints. The controller will then provide the actions that need to be taken to achieve the objectives as best as possible. These actions result in a certain water distribution. This water distribution is referred to as the water budgets.

As mentioned, Model Predictive Control (MPC) may provide a valuable tool for translating objectives and priorities into operational water management. In this thesis the concept of water budgeting is applied. The resulting water system, water distribution and the operational water management are evaluated. With the experience obtained from applying the concept some conclusions are drawn. The application of water budgeting is evaluated as well as the use of MPC as a water budgeting tool.

5 Model Predictive Control

In order to determine the optimal water management strategy for a given set of priorities Model Predictive Control (MPC) is used. Camacho and Bordons (2004) give a clear description of what Model Predictive Control is composed of:

- “Explicit use of a model to predict output at future time instants (horizon);
- Calculation of a control sequence minimizing an objective; and
- Receding strategy, so that at each instant the horizon is displaced towards the future, which involves the application of the first control signal of the sequence calculated at each step.”

In the following section, these three components are discussed in more detail with respect to this research.

The internal model developed for this research is able to calculate what happens to the water system given a certain starting situation and predictions of the future boundary conditions. Besides these initial and boundary conditions, the future state of the water system is also influenced by the settings of the water management infrastructure. The internal model calculates the future states for different settings of the infrastructure. The prediction horizon used in this research was 36 hours.

After obtaining the predictions, the best setting needs to be selected. In order to do this, an optimisation is conducted. For this optimisation, optimisation rules are applied. These rules indicate the penalty that is applied when a certain undesired state occurs. The optimisation then selects the set of infrastructure settings that results in the least total penalty. In this case penalties could be applied when: water levels exceed a certain maximum or drop below a minimum and penalties can be applied to changing the setting of gates or sluices. The determination of these penalties will directly influence the results of the MPC, so setting them is an important part of the development of the control system.

The infrastructure settings that resulted in the lowest total penalty are implemented in reality. In the case of this research, a detailed computer model is used to represent reality. This detailed model is implemented in the water modelling software package: Sobek. After a certain time interval (sampling interval) the initial and boundary conditions are determined again (in our case taken from the Sobek model). The internal model is rerun with these updated states, and the optimisation is conducted on the new predictions. In this way, the MPC is kept up-to-date; it also implies that the internal model should be simple. In order to keep the MPC up-to-date the sampling interval needs to be small, and in order for the sampling interval to be as small as possible, the calculation times should be kept to a minimum. Especially in a case like this, with many states and a complex system this is quite a challenge. In this research the internal model was run every 12 hours, so the sampling interval was 12 hours. The control actions generated by the controller were not fixed for 12 hours in a row. The control actions were determined per hour. So every twelve hours the controller would generate 12 control actions for each controller, one control action for each of the coming 12 hours.

Overloop (2006, p35) argues that there are two important reasons why modern water systems require more advanced control methods than classic feedback and feedforward: "First, the constraints of the control structures limit the performance of the present controlled water system. … Second, the demands on the flexibility of a controlled water system increase over time due to socio-economic development." These two reasons also apply to the situation in the South-Western Delta.

Limitations on the capacity of the water management infrastructure not only require measuring the disturbances (feed forward), but also determining the effect of these disturbances on the water system. When a flood wave, too big for the existing infrastructure to handle, is coming, one needs to be able to predict what the effect of this flood wave will be on the water levels in the delta. When water levels are likely to exceed unwanted thresholds, MPC can help to increase storage in the water system before the flood wave actually arrives. When only applying classic feedback and/or feed forward the control system would act too late in such a case.

In the South Western Delta many different stakeholders are present who all have different priorities with respect to the water system. MPC can help to incorporate these different stakes in the control system. Water management authorities, for example, would like their structures to be operated in the most cost effective way. Shipping companies want the water to have a certain minimum depth in order for ships to pass. MPC can help to reduce the number of changes in the settings of the infrastructure without resulting in the water depths becoming too small. With the help of predictions MPC could, for example, anticipate on an increased inflow in the future. This would make it unnecessary to decrease the outflow, where feedback and feed forward only consider the present situation and would react by closing the outflow structure.

In order to be able to deal with more complex objectives the application of MPC to water management, as done in Overloop (2006), had to be extended. In order to implement the desired objectives, new states are created. These new states can then be penalised. More details on these extra states can be found in the penalties and constraints section, later in this chapter.

5.1 Internal Model

For the construction of the internal model, data from the Delta-model was used. This Delta-model is a hydrodynamic and water quality model implemented in the Sobek software package. For a description of the Delta-model see Meijers and Groot (2007). In order to make the internal model simpler, all the reaches were assigned one averaged cross section. In the Delta-model some of the reaches had several branches. These branches were added together to form one branch in the internal model. Some of the structures in the system were not (or only partly) incorporated in the Delta-model. These structures are not used for water management at the moment, so there was little use to put them (correctly) in the Delta-model. For this research, these structures were included in both the Delta-model and the internal model. The dimensions of these structures were obtained from the 'Delta verkenner' website (public.deltares.nl). See Figure 5 for a schematic representation of the internal model. The extent of the internal model is the same as that of the Delta-model, except for the Westerschelde, which is not included in the internal model. In Annex A, the schematic representations of the internal model with node and reach numbers can be found. The calculation time step for the internal model is one hour. The prediction horizon is 36 hours, and the internal model is run every 12 hours.

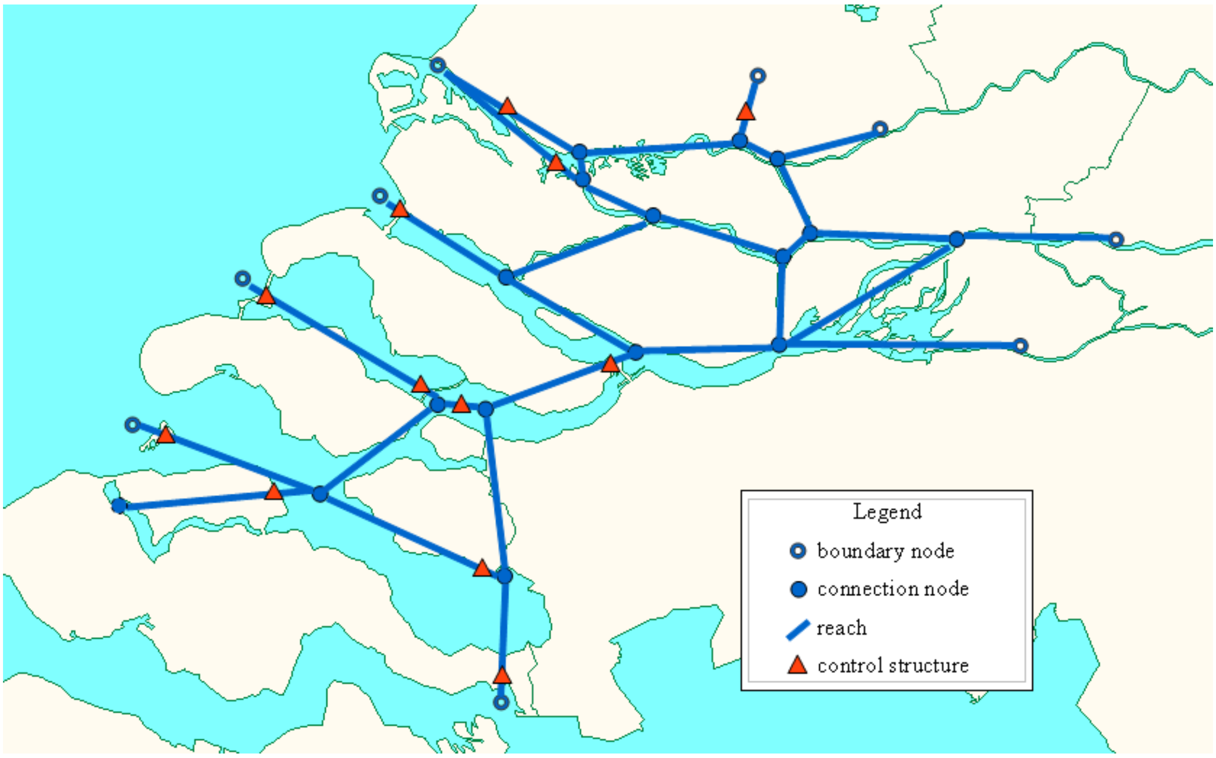

Figure 5: schematic representation of the internal model

5.1.1 Mathematics

For the internal model, the de Saint-Venant equations are approximated using the staggered conservative grid of Stelling and Duinmeijer (2003). With respect to the time integration a θ-scheme with: θ=1 is used. This θ results in an implicit scheme, an explicit scheme would result in strict limitations of the time and space discretisation step. With an explicit scheme the Courrant number would limit Δt and Δx, because they would have to comply with formula 1. In formula 1: Δt is the computational time step in seconds, Δx is the distance between calculation points in the internal model in meters, ν is the wave speed in the system in meters per second.

$$\frac{\Delta t \cdot v}{\Delta x} < 1 \qquad (1)$$

The mathematical structure used in the internal model is a state space model. It is similar to the state space model used in Overloop (2006), but it is slightly altered to include the implicit scheme. The state space model becomes:

$$x(k+1)=\theta \cdot E(k+1)^{-1} \cdot ((1-\theta) \cdot A(k) \cdot x(k)+B_u(k) \cdot u(k)+B_d(k) \cdot d(k)) \qquad (2)$$

In which x is a vector of the states of the water system (the water levels). The matrices A and E are system matrices with respect to time step k and time step k+1 respectively. Matrix B_u is the control input matrix, with u the vector with the control structure settings (discharges). The disturbance matrix is B_d, with d being the disturbances (in vector form). The matrices B_u and B_d are time dependant because the surface area of each calculation point depends on the water level, this water level in turn varies in time.

5.1.2 Calibration

In order for the internal model to be accurate, it needs to be calibrated to the real situation or, in this case, the detailed Sobek model. As the calibration parameter the Chezy friction coefficient has been used. It is assumed that: the dimensions of the different reaches, and the storage in some of the nodes, are more or less similar to the detailed model. Since the data used to determine these dimensions is obtained from the detailed model, this assumption seems reasonable. In the calibration process, discrepancies between the internal model and the Sobek model, due to simplification, are reduced to a minimum. The Chezy coefficient is allowed to vary between 10 and 100, which are not very realistic values. This wide range is used to compensate for loss of detail in the conversion from the Sobek model to the internal model. This loss of detail is needed to get a simple model, which is required for the optimization process.

For the calibration process several techniques have been used and the model was run with all structures fully opened. These different techniques result in different Chezy coefficients. The different techniques are as follows:

Calibration method 1:

a) The friction coefficients for all the reaches are set to 10.
b) The simulation is run, and the squared difference between the discharges in the internal model and the discharges in the Sobek model are calculated.
c) All friction coefficients are increased by one
d) The simulation is run again, and the squared errors are calculated.
e) For each reach, the Chezy value that results in the least squared error is taken.
f) The process is repeated from b to e, until all the reaches have the least squared error in the first calculation (no improvement when the Chezy value is increased by one), or when the maximum number of repetitions has occurred (this maximum was set to 90).

Calibration method 2:

Is the same as method 1 except for the fact that it started at a Chezy value of 100, and is reduced with one, with every calculation loop.

Calibration method 3:

a) The friction coefficients are set to 55. The lower and upper Chezy values are 10 and 100 respectively.
b) The simulation is run.
c) When the absolute discharge (for all the reaches together) in the internal model is lower than that of the Sobek model, the new Chezy value is the average between the upper Chezy value and the last used Chezy value. The new lower Chezy value will be the previously used Chezy value. Whenever the absolute discharge is higher than that in the Sobek model the new Chezy value is the average between the old Chezy value and the lower Chezy value. The new upper Chezy value will be the previously used Chezy value. This method is referred to as bi-sectional method.

d) Steps b and c are repeated for 9 times. In this method all reaches are assigned the same Chezy value.

Calibration method 4:

Is the same as method 3 except in this case all the reaches are dealt with separately, so all reaches will have their own Chezy value.

The different techniques clearly resulted in different calibration results. This was caused by the fact that the methods used were different, but also due to the fact that the starting situation for the techniques differed. Since, the flow in one of the reaches has an influence on the flows in all the reaches connected to it, changing one friction value has an influence on much more than just that one reach. Even though the methods 1 and 2 differed only in their starting situation, the results they produced were very different. With this many different states, all influencing each other, it is very well possible that there are several different optima. Of course the best results would be obtained by trying every possible combination of Chezy coefficient values. However, if the values were to range from 10 to 100, this method would result in 90^{29} possible combinations. Since it was impossible to calculate all these combinations within the time available for this thesis, this method was not an option. After applying the different methods, the remaining squared errors were compared (see Table 2).

Table 2: Total squared error per calibration method

Method	Total squared error ($[m^3/s)]^2$)
1	$1.479*10^{10}$
2	$1.452*10^{10}$
3	$1.841*10^{10}$
4	$1.671*10^{10}$

From Table 2 it is clear that method 2 results in the least squared error. The comparison between the internal model and the Sobek model for calibration method 2 can be found in Annex B. For the rest of the research, the Chezy values that were obtained by calibration method 2, are used. These Chezy coefficient values can also be found in Annex B.

5.2 Optimisation

In order to find the optimal control settings an objective function has to be formulated. In this objective function, all the sub-objectives are added up. To each of these sub-objectives a relative weight is given. The controller will minimize the objective function. The objective function has the following form:

$$J = \tfrac{1}{2} X^T \cdot Q \cdot X + U^T \cdot R \cdot U \tag{3}$$

In which X is the vector of the states of the water system. Q is the weight matrix. In the Q matrix the penalties that are applied to any unwanted states are defined. The matrix U represents the control input into the system. Penalties to this control input are given in the R matrix. The penalties in the R matrix can prevent the control actions to change too much in one time step. The ease of operating the structures is not considered in this research. This results in very low penalties in the R matrix. In the following section the unwanted states and the corresponding penalties (the Q matrix) are discussed.

5.3 Penalties and constraints

For the water budgeting examples, the following three stakeholders or objectives were selected: ecology, shipping and fresh water supply. More objectives for the South-Western Delta can be thought of, but these three are in this research considered the most important. The wanted and undesired states for these different objectives are discussed in the following sections.

Ecology is considered to benefit most when the natural dynamics of the sea and rivers is the least restricted. This restriction is the lowest when all structures are set at the largest gate openings. A simulation was run in which all gates in the area are fully opened. In the ecology objective the difference between the occurring water levels and the water levels with all gates fully opened is penalized. In order to be able to penalize this difference a new state had to be defined. This new state is the difference between the occurring water level and the water level, calculated beforehand, that occurs with all the gates fully opened. For the comparison of these two water levels, three locations were selected: Oude Maas, Hollandsche Diep, and Lake Volkerak. These are respectively: nodes 11, 15, and 18 of the internal model (see Annex A for the exact locations).

In order to provide the best situation for transportation through shipping there are certain minimum and maximum water levels. According to van Maldegem (2008) the minimum depth for ships in the connection between the Scheldt and the Rhine, is 5.6 meters. Van Maldegem also mentions that the maximum water level in the Volkrak-Zoommeer is 0.5m above NAP. This maximum water level is caused by the height of bridges. In order for the bigger ships to be able to pass these bridges, the water levels in the area should remain below 0.5m above NAP. The Scheldt-Rhine connection is considered to consist of the areas between nodes 8, 14, 15, 18, and 21 of the internal model (see Annex A for their locations). The requirements for shipping in the South-Western Delta are summarized in Table 3. There is also a penalty on discharging through the Krammer shipping locks.

Table 3: water level requirements for shipping

node of internal model	minimum water level (mNAP)	maximum water level (mNAP)
8	-0.03	
14	-0.03	
15	-1.39	
18	-0.85	0.5
21	-0.39	0.5

The maximum availability of fresh water is achieved, when saline water is kept out of the area as much as possible. For the optimisation this means that there is a penalty on water flowing from the sea through a controlled structure. The structures that are penalized for letting in (salt) water are: Haringvliet sluices, Krammer sluice and the Bathse Spuisluis. A penalty is also required to prevent too much water from entering through the Nieuwe Waterweg. In this research, it was not possible to create a new state, which could be used to implement such a penalty. Some sort of penalty that would dictate that: for every litre of salt water coming in, a certain amount of fresh water would have to go out, to push it back, seems impossible to create in the current set up.

6 Results

As water budgeting examples, three different strategies were implemented. In each of these strategies the emphasis is put on one of the three objectives mentioned in the previous chapter. So there is a strategy in which priority is given to ecology, one in which shipping is most important and finally one in which the availability of fresh water has the highest priority. The simulation period is: the first week of September of the year 2000. This period was chosen because it is after a long period of low river discharge and the discharge is at its lowest in this week. In this chapter the results and the required water management for the different strategies will be discussed.

6.1 Water levels

The water levels that occur with the different water management strategies are given in Figure 6 and Figure 7. The graphs show the water levels at node 14 and 21 respectively. These locations were chosen to give the results for two different areas. On the one hand there is the area that is very much influenced by the fact that there is an open connection with the sea, through the Nieuwe Waterweg. Water levels in this area cannot be fully controlled and these areas are represented by node 14 (Figure 6). On the other hand there is the Volkerak-Zoommeer. These water bodies do not have any open connections with surrounding water bodies. In this area water levels can be fully controlled by structures. This area is represented by node 21 (Figure 7). Water levels at other nodes at which there are water levels objectives (nodes 8, 11, 15, 18), can be found in Annex C.

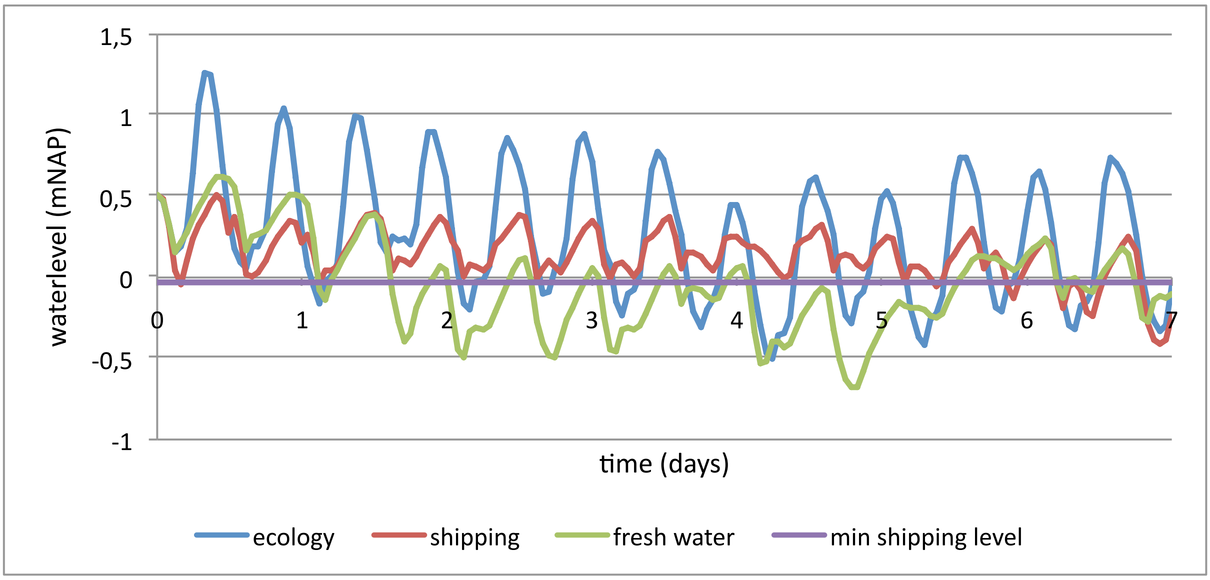

Figure 6: water levels at node 14 for the three strategies

From Figure 6 it is clear that the ecology strategy shows the most variation in water level. In this case, MPC appears to be able to achieve its goal. The shipping strategy is able to keep the water level above the minimum shipping depth for 6 days. After this period it is not able to comply with the minimum shipping depth. It is remarkable that after this time the shipping strategy performs even worse then the fresh water strategy. In Figure 8 the cause for this bad performance is shown. The shipping strategy discharges much water into the North Sea at the end of the simulation period. With respect to the fresh water strategy Figure 6 and Figure 7 do not show us much, since this strategy is more about water flows than it is about water levels.

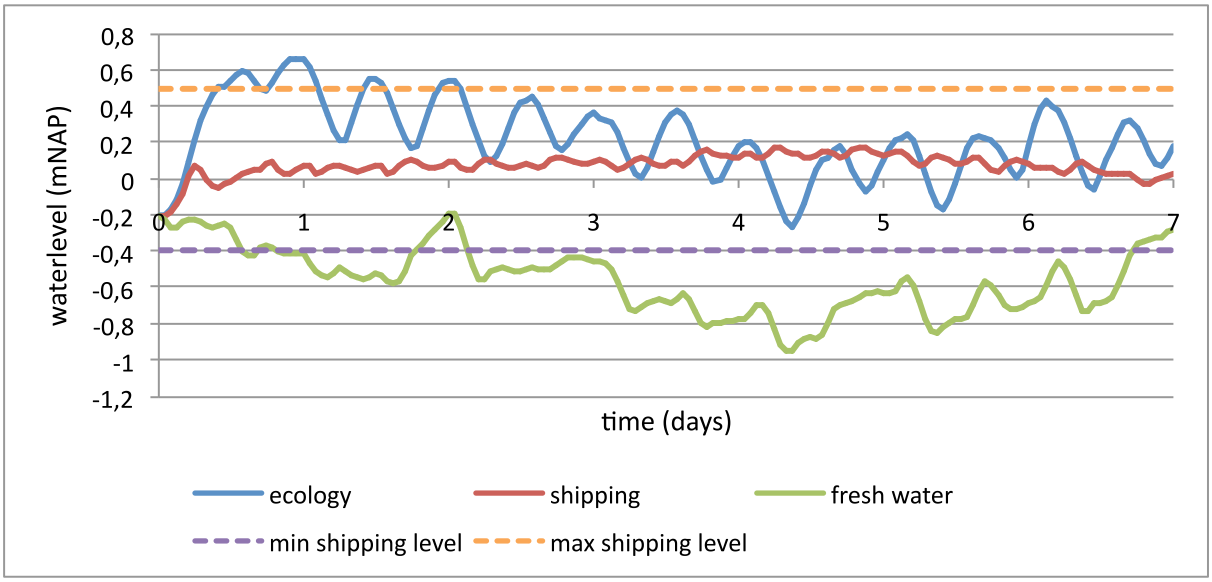

Figure 7: water levels at node 21 for the three strategies

In the water bodies that can be fully controlled, the ecology strategy also shows most tidal variation. The shipping strategy is able to keep the water levels between the maximum and minimum requirements. The water level requirements are not very strict, so this is not very surprising. The water levels in the fresh water strategy are much lower then those for the other two strategies. This is caused by high outflow of water, through the Bathse Spuisluis and the Krammersluizen, and limited inflow through the Volkeraksluizen.

6.2 Structure flows

The discharges of the Haringvlietsluizen and the Bathse Spuisluis are shown in Figure 8 and Figure 9 respectively. For the Haringvlietsluizen, positive flow is from the Haringvliet to the North Sea. In the case of the Bathse Spuisluis, positive flow is from the Zoommeer to the Westerschelde. The discharges through other controlled structures are shown in Annex D.

From Figure 8 it is clear that the ecology strategy results in the highest discharges through the Haringvlietsluizen. Although in the positive direction (towards the North sea), the discharges are not at the maximum. For the performance of the shipping strategy, this figure does not tell much. This strategy is mainly concerned with water levels. As mentioned before it does show why the water levels at node 14 are low at the end of the simulation period. The fresh water strategy seems to function properly, since there is only positive flow at this structure. So there is no saline water coming in through the Haringvlietsluizen.

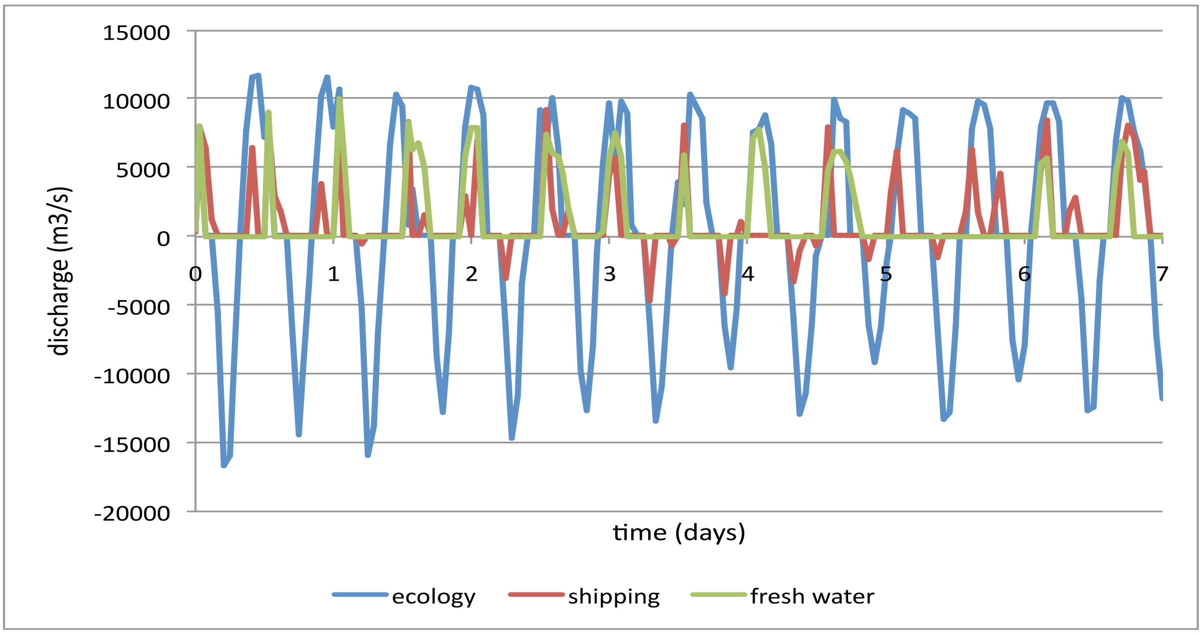

Figure 8: discharge of Haringvlietsluizen for the three strategies

For some reason Figure 9 shows almost no positive flow for the ecology strategy. In this strategy the Bathse Spuisluizen are mainly used to get water from the Westerschelde to the Zoommeer. In the shipping strategy the Bathse Spuisluis is primarily used to discharge Zoommeer water to the Westerschelde. The fresh water strategy shows some flaws. At the Bathse Spuisluis the gates are kept open too long. This causes (saline) water to flow in from the Westerschelde when the tide rises. The water level in the Westerschelde becomes higher than the water level in the Zoommeer, resulting in water flowing from the Westerscheld to the Zoommeer. The controller keeps the gate open too long because of incorrect predictions. These incorrect predictions are a result of the fact that the structure flows in the internal model are calculated explicitly. So the internal model uses an outdated water level to calculate the structure flow.

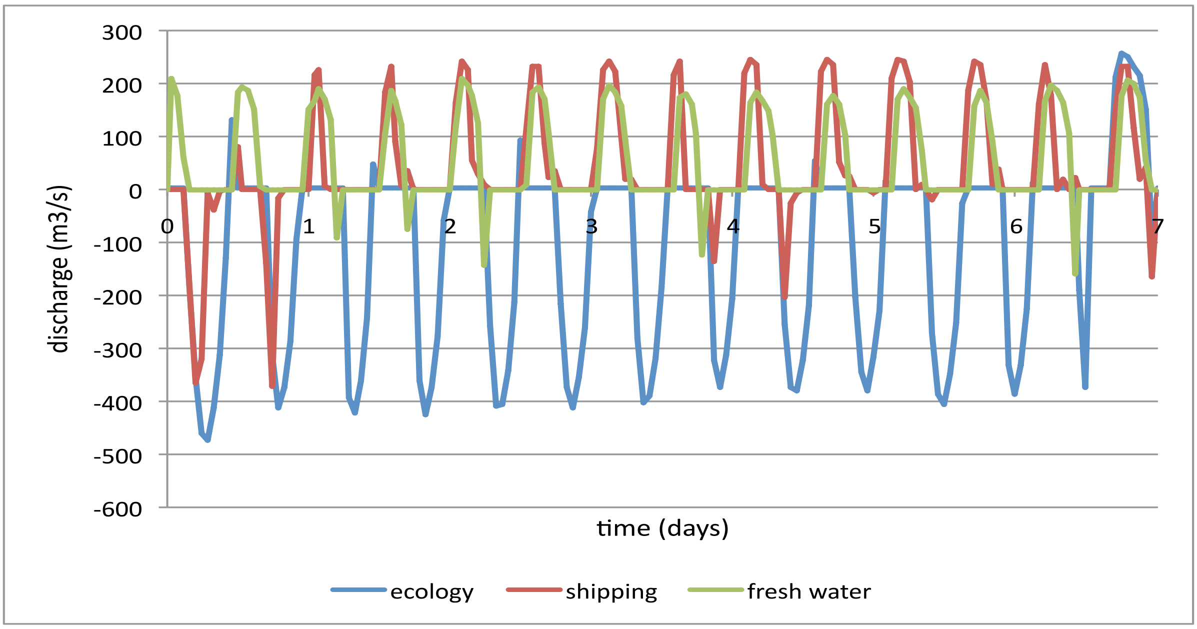

Figure 9: discharge of Bathse Spuisluis for the three strategies

6.3 Salinity

The Sobek model used to calculate the salinities is a one-dimensional model. This means that the salinities may not be very accurate, but they at least give an impression. The salinity at node 11 for the three strategies is given in Figure 10 below. The reference strategy is the situation, which occurs when applying the current operational water management. Node 11 is located close to a large drinking water treatment plant. The water in this location needs to be fresh in order for the drinking water plant to be operational. The fresh water strategy clearly fails to keep the salinity at this location low. Both of the other strategies perform much better.

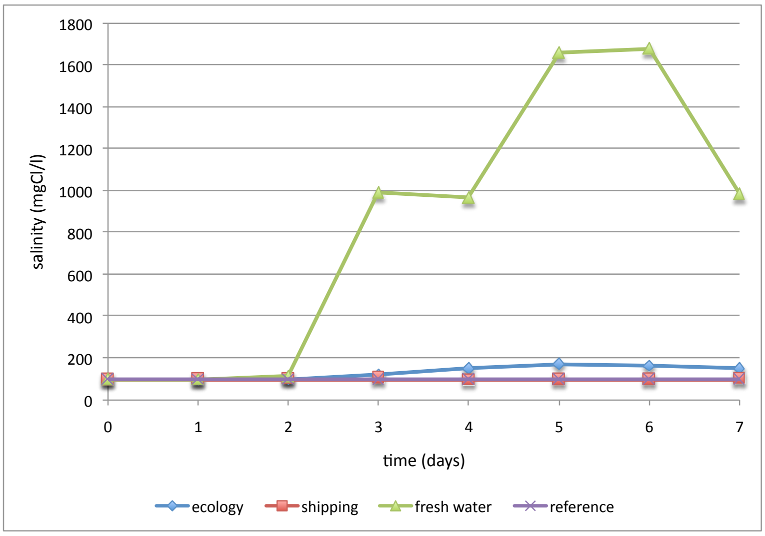

Figure 10: salinity at node 11 for the three strategies

6.4 Water budgets

The water budgets for the different strategies can be seen in Figure 11 through Figure 14. These figures show the relative net outflow through 3 different structures. The total outflow differs slightly from strategy to strategy. This is caused by the difference in storage in the system. If the average water level in the system is increased over the simulation period, the net outflow is lower. The differences between the net outflows of the strategies, is not very large. The lowest net outflow (reference strategy) is 89% of the highest net outflow (shipping strategy). It is clear that in all three the alternative strategy's, more water is diverted to the Volkeraksluizen than in the reference strategy. The shipping strategy is closest to the reference strategy, with respect to the discharge through the Volkeraksluizen.

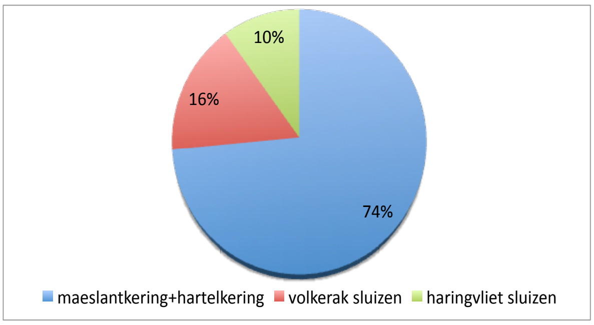

Figure 11: relative net outflow for ecology strategy

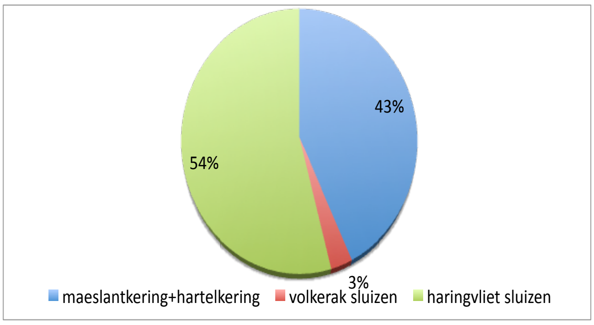

Figure 12: relative net outflow for shipping strategy

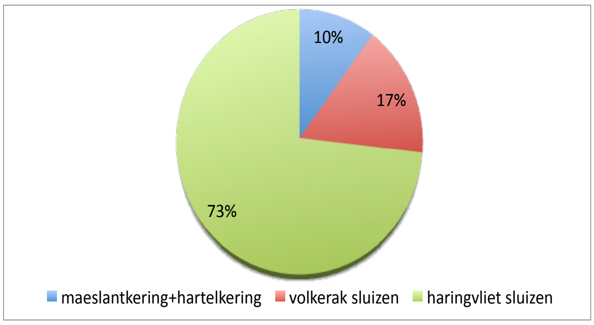

Figure 13: relative net outflow for fresh water strategy

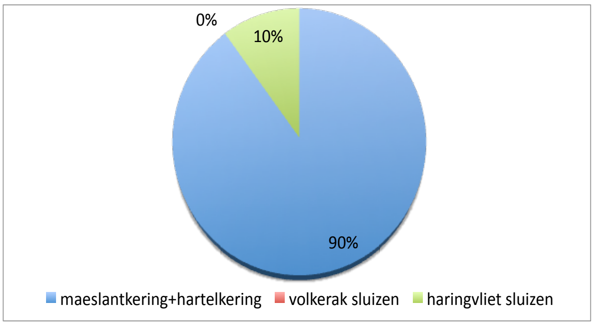

Figure 14: relative net outflow for reference strategy

In Figure 13 it is shown why the fresh water strategy fails to keep the salinity low. The controller prevents water from flowing into the controlled structures, but it does nothing to compensate for the inflow of salt water, through the Maeslantkering. Most water is discharged through the Haringvlietsluizen, while it could instead be used to flush out the salt water coming in through the Nieuwe Waterweg.

7 Discussion

This chapter will discuss the application of the water budgeting concept on the South-Western Delta. Improvements of the approach used in this research will be dealt with. There are however, some more fundamental issues in relation to using MPC as a water budgeting tool. These issues will also be dealt with. Finally the concept of water budgeting will be revisited. The experience from applying the concept will be used to discuss the usefulness of the concept.

7.1 Performance of MPC as a water budgeting tool

The results clearly show that the strategies do not all perform equally well. Especially the fresh water strategy does not improve the availability of fresh water. The other two strategies seem to perform reasonable well. Even those two strategies show some flaws however. In the ecology strategy not all structures are fully opened all the time. This can be seen in Figure 8 and Figure 9. The shipping strategy does not perform better with respect to improving shipping conditions some of the time (see Figure 6).

7.1.1 Possible improvements of the controller

In the set up used in this research, the control actions were generated for every 12 hours. In between there was no check to see whether or not the predictions of the internal model were correct. The performance of the controller could be improved by including a check to see whether the control structures are operating properly. This could for example eliminate inflow of salt water in the fresh water strategy (see Figure 9). Incorrect predictions of the water levels cause the structure gate to be opened when it should be closed. Some sort of check could prevent the gate to be opened when the Zoommeer water level is lower then the water level in the Westerschelde. Another options would be to shorten the sampling interval. For this research that was not feasible, since it would result in the calculation time being too long.

As mentioned, the fresh water strategy performed especially bad. A simple way to improve this strategy would be to also penalize the outflow of fresh water through controlled structures. This would result in: all of the net outflow going through the Nieuwe Waterweg. In this way the salt intrusion in this area would be minimized. The reason for not penalizing outflow through controlled structures was: to be able to flush the Volkerak-Zoommeer. If outflow were penalized, no fresh water would flow through the Volkerak-Zoommeer. Outflow through the Haringvlietsluizen could still be penalized without preventing flushing of the Volkerak-Zoommeer.

Another way to improve the performance of the fresh water strategy would be to include some sort of flushing rule. This flushing rule would be something like: for every litre of (salt) water coming in through the Nieuwe Waterweg, x litres of (fresh) water need to go out. As mentioned before, it was not possible to create a penalty that would penalize any diversion from such a flushing rule. When this flushing rule was to be implemented, any excess water could be used for flushing the Volkerak-Zoommeer. The best solution would however be to extend the internal model of the controller. When salinity would be included into the internal model, one could directly penalize any salinity that is above the maximum allowed salinity.

In terms of increasing the tidal range in the South-Western Delta, the ecological strategy is successful. This does not necessarily mean that the ecological status of the area is improved. In order to access the effectiveness of the ecological strategy more specific objectives are needed. The occurrence of certain species for instance could be an objective. In order to be able to use this objective into MPC, one needs to model it. This ecological modelling could be done by: extending the internal model with an ecological model.

One of the things that became clear from the research is the need to be able to control all the crucial structures. In this research it was not possible to control the Maeslantkering. This made it very difficult to achieve the desired goals. Especially in the case of the fresh water strategy this became apparent. Without the possibility to control all the in and outflow structures. MPC performs much less effective. This becomes clear by comparing Figure 6 and Figure 7. All the structures in the case of Figure 7 are controlled. This clearly shows in the different strategies following a much more distinct trajectory. In Figure 6 on the other hand, the limited control is clear from the fact that, even though the strategies serve different objective, the resulting water levels are much closer to each other.

In this research MPC was applied to a case in which the objectives are more complex. Not much work has been done on similar control problems. In many cases the objective of the controller is very clear, for instance: keep the water level above, or below a certain threshold. In many cases the MPC controller is used to replace a classic feedback or feed forward controller. So the goal of the MPC controller is to achieve its goal better than the previous controller. In this research MPC was not applied to replace an existing controller. Of course there are operational rules for the control structures in the area, but they all serve their own objective and are controlled separately.

Further research with more simple (virtual) cases could provide ways to improve the functioning of MPC in water budgeting. It could provide a way to incorporate more information in the internal model. It could for example include water quality and ecological aspects. In this way the controller can be evaluated when it is able to directly predict all the objectives that it has to achieve. In a simpler case the internal model can be extended without resulting in the calculation times becoming too long. Future developments in computing technology could provide means to handle more complicated models without increasing the calculation time.

7.1.2 Shortcomings of MPC as a budgeting tool

As mentioned, some of the shortcomings of the use of MPC in water budgeting could be overcome by: improving or expanding the model that is used. This will in turn result in new problems. The time needed to solve the optimisation problem will increase exponentially. Also the problem will become much more complex. The chance of mistakes in the model increases, but also the chance that these mistakes are detected decreases. The problem will become extremely complex. It will be very hard for any person to determine whether the model is performing properly. In this case it was already difficult to determine the proper values for the different penalties. This was especially difficult because there where different aspects that needed to be penalized. How does one compare a discharge with a water level? In other words: how undesirable is one extra meter of water level compared to a certain amount of cubic meters discharge. The values of the penalties were determined by trial and error. With a certain penalty value the simulation is run. The results of this simulation run are compared to the desired or expected results. The penalty value is adjusted in such a way that the chance of achieving the desired results is increased. With the adjusted value the simulation is run again. Adjusting the penalty value and rerunning the simulation continues until the desired results are obtained.

In order to be able to check whether MPC is doing what it is supposed to do, one needs to keep its objective simple. In this example this was especially the case since the MPC had to be developed during this research. While developing the controller one needs to be able to check whether it is really optimizing what one wants it to optimize. Even when the controller is finished and it is used for a new objective, it is necessary to be able to check the outcome. With simple objectives it might still be difficult to get an idea of why the controller takes certain actions. In Figure 6 for example, the shipping strategy performs worse than the fresh water strategy at a certain moment. It is very difficult to determine why the controller performs worse than it (apparently) could. It is clear from Figure 8 that the discharge through the Haringvlietsluizen is higher in the shipping strategy than that in the fresh water strategy. There are no clues however as to why the MPC discharged more in this strategy. The way MPC functions in this respect is more or less a black box. You know what you put in: a model of the system, a prediction of the river inflows, the tide, and the penalties on undesired states. You know what you get out: a set of control actions, which in turn result in a certain state of the system. In the end, however, you cannot really track what happens in between.

Using the computer to determine the best water management strategy results in reduced transparency in the decision making process. It is not clear why the computer chooses a certain strategy. In a democratic society reduced transparency in decision-making is not very desirable. People will want to know why things happen in order to determine whether or not they think it is a good decision. It is also desirable for the water management decisions to be (more or less) predictable. If the water system is predictable, stakeholders can more easily adjust to it and rely on it. Even if not every stakeholder gets the best conditions, they might be able to adjust to these less favourable conditions. With the reduced predictability that is introduced by MPC, it will be harder for stakeholders to adjust to, and to rely on the operational water management of the system.

7.2 Water budgeting revisited

While trying to apply the water budgeting principle to the South-Western Delta some of its shortcomings became clear. The most important aspect of the water budgeting concept is the comparison between water resources and financial resources. There are however some very important differences between money and water, which make the application of water budgeting difficult.

The limited usefulness of water budgeting, as a water management strategy, is indicated by Figures 11-14. Although these figures show the distribution of the water over the simulation period, it tells very little about the system in general. In order to get an idea of the state of the system, a lot more information is needed then only the water budgets for the entire period. It is impossible to say that one budget is better than the other, merely on the total amount. The timing at which water is released is just as important as the amount of water that is released. The same amount might be used much more effectively by improving the timing at which it is used. This calls for a good investigation of the achievements of the goals with a certain water budget. It might be an idea to determine a rate between the amount of water used and how much the goal is achieved. This rate will tell you how effective a water budgeting option is with respect to a certain objective. Even this rate might not be very informative if there are alternatives to solve a certain problem. In the current situation, fresh water is used to flush out salt water from the Nieuwe Waterweg. This flushing requires a lot of fresh water. An alternative solution could be to close of the Nieuwe Waterweg. This would prevent any salt water from intruding and thus reduces the water needed for flushing.

An important difference between financial resources and water resources is the amount of control you have over them. Finances can be stored and distributed exactly according to your wishes. Physical laws however, restrict the storage and distribution of water. The structures in the system restrict the amount of water that can be discharged at any moment. These structures are in turn limited by the water levels up and downstream of the structure. It takes a lot of energy to transport water against the force of gravity. Combined with the fact that you usually have to deal with large quantities of water makes it costly to move water upstream. Savenije (2002) refers to this characteristic of water, as it being bulky. Another aspect of water, which makes it more difficult to control, is the fact that water is fugitive (Savenije, 2002). Water is not a stock, but a flux. Unless it is stored somehow, water will flow away. The combination with the fact that generally large quantities of water are required makes this characteristic problematic. Because large quantities are required, it is difficult to store the water that is required for a long period. This is especially the case in a delta area. In low-lying areas there is little head difference available for storing water. Due to this lack of storage available you are limited by the amount of water discharged by the rivers. Unlike money, which can be stored and spend whenever one likes, water can only be stored for a very limited amount to be used later in time.

The characteristics mentioned in the previous paragraph can be seen in Figure 6 and Figure 7. The graphs in Figure 6 show how fugitive water is. There is no way to close of the Nieuwe Waterweg, so the water will flow freely with the tide. In Figure 7 the water levels are much more controlled. This figure shows that the possibilities to store water are limited. In the Volkerak-Zoommeer the amount of water that can be stored is only about 1.3 meters (when considering the minimum and maximum shipping levels). This in turn is about 11% of the net outflow in the reference strategy. The amount of water that could be stored in the Volkerak-Zoommeer in this case, is less than the net outflow of one day.

All of the above implies that water budgeting is not as straightforward as it may seem. The similarities between finances and water are outnumbered by the amount of differences between them. The concept of water budgeting might however still provide an alternative way of approaching water management issues. It can provide insight in the way (fresh) water is distributed and it can help to think in an objective oriented manner. The combination of the distribution and the achievement of the desired goals will indicate the effectiveness of the water distribution. One very important aspect to keep in mind however is that: not all problems are solved by, simply, assigning more water to it. In some cases a more suitable solution might be found in better timing of the water supply. In other cases improving water management infrastructure can provide the best solution. In cases where input of fresh water is essential to achieving a goal, water budgeting can play a role. In these situations, water budgeting can be a tool to quantify the priorities given to each of the objectives.

8 Conclusions

The goal of this research was: to evaluate the usefulness of the water budgeting concept, and to determine the effectiveness of Model Predictive Control as a tool for water budgeting. The water budgeting concept is based on the assumption that: the way finances are handled could be applied to water resources management. From the work done in this research it is clear that: there are some very important differences between water and finances that complicate water budgeting. Especially the facts that water is bulky and fugitive are important in this respect. These two characteristics of water make it very hard to handle. Exercising control over water and moving it to the desired location at the desired time is much more difficult than it is for money. The differences between money and water imply that being a good treasurer does not necessarily make you a good water manager. In order to properly budget water, thorough knowledge about water is necessary. The water manager needs to know how the water system functions and how water, in general, behaves. This knowledge is vital in order to determine where and when (fresh) water is needed. It helps to determine in which cases the achievement of the desired objectives is not best served by increasing water supply. Some cases require water management infrastructure to be improved, or in some cases water of another quality might serve the purpose just as well.

The application of Model Predictive Control in this research does not show very impressive results. This is mainly caused by the fact that the objectives needed to be kept simple. Especially while developing the controller it is important to be able to check whether or not the results make any sense. In order to do this it must be possible to easily check the generated outcome. This causes the outcome of the controller to be fairly trivial. Perhaps once a controller is fully developed it can be used to test more complicated objectives or penalty settings. In this research the required time to do more strategies was missing however.

The results of this research also show the requirement to be able to control all the important structures. It was not possible to control the Maeslantkering. The fact that this structure could not be controlled was caused by: the long closing (and opening) time and the fact that it cannot prevent water flowing towards the North Sea (due to the way it is constructed). These two characteristics made it difficult to properly model the structure, but they also limit the usefulness of the Maeslantkering for (daily) water management. Because the Maeslantkering could not be closed the controller had only limited control over the water bodies connected to the Nieuwe Waterweg. This resulted in the controller not performing optimally for these areas. Better results with Model Predictive Control for water budgeting, can be achieved when all the (large) in and outflow structures are controlled.

The research was successful at implementing a new type of objective. For the ecology strategy, a water level objective that varied with time was implemented by creating a new state in the internal model. More complex objectives still need to be included, especially for the fresh water scenario. These new type of objectives could increase the usefulness of applying Model Predictive Control to water budgeting.

A different kind of issue that is raised by the use of Model Predictive Control is: transparency. That fact that the computer decides what the best water management will be, reduces the transparency of the decision making process. It is not always clear, why the controller produces a certain output. In a situation where there are many (conflicting) objectives for the same water system, transparency becomes important. In order for stakeholders of rely on the water system, they need to know what they can expect. In this respect having a transparent water management is more important than having the optimal water management.

As mentioned in the explanation of the water budgeting concept, this thesis wanted to extend the concept of water accounting. With regard to this objective the research has failed to achieve this. The water budgeting concept has not yet moved beyond being an evaluation tool. However, the concept of water budgeting can stimulate creative thinking in water management decision making. This can be done by focusing on the objectives that the water system has to achieve, instead of looking at (readily available) alternatives. Considering what one considers important, before looking at the possibilities, can stimulate looking for solutions that are not the most obvious and that might serve more than one objective.

With respect to Model Predictive Control as a tool to look for solutions: it seems that the South Western Delta has proven to be too complex. This thesis can, however, provide input for future research. The application of Model Predictive Control to water management problems of this scale and with multiple (conflicting) objectives is relatively new. This research provides valuable knowledge for future research aimed at applying Model Predictive Control to similar cases.

The research shows that it is crucial for the internal model to be able to model the desired objective. In this research it was clear that without modelling salinity in the internal model, the controller is not be able to achieve the desired salinity. A simpler (virtual) test case could provide the possibility to include more parameters into the internal model. The internal model could be extended with water quality and ecological parameters. These extensions would provide the possibility for the controllers to directly predict and control, for example, salinity. It is expected that this would greatly increase the effectiveness of the controller. Improving the controller would increase the usefulness of the water budgeting concept. Future research, on simpler cases, could provide ways to improve the water budgeting concept and its application.

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Annex A: Internal model node and reach numbering

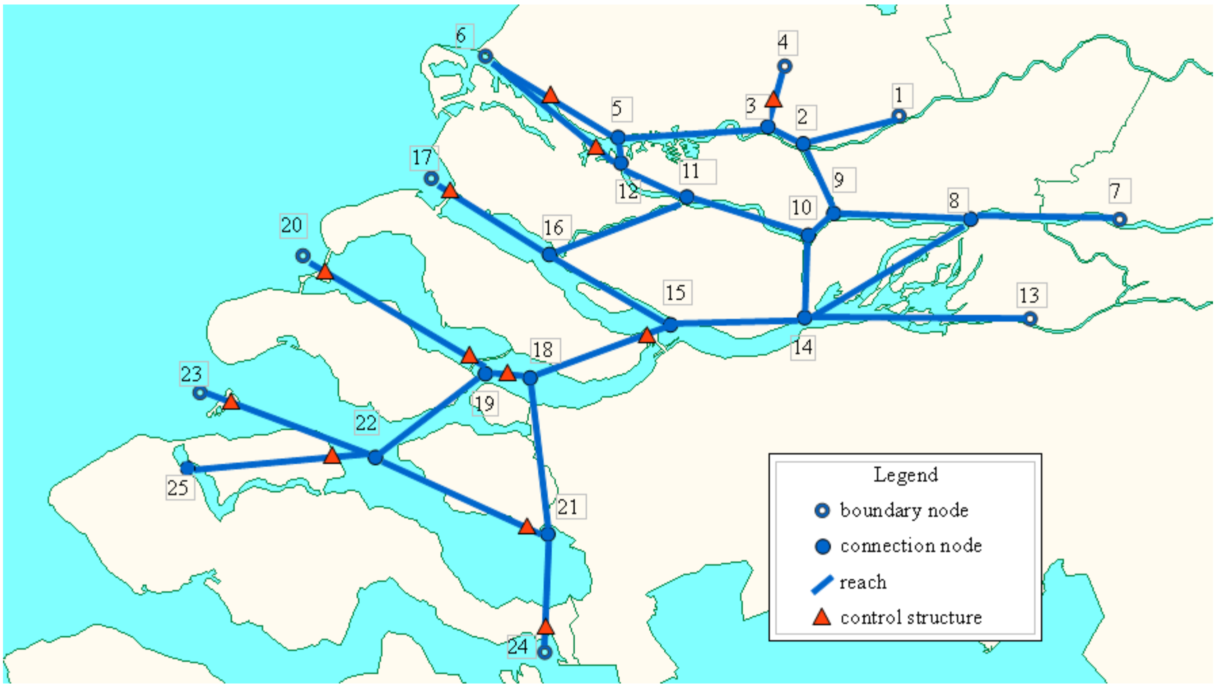

Figure A1: Internal model schematisation, with node numbers

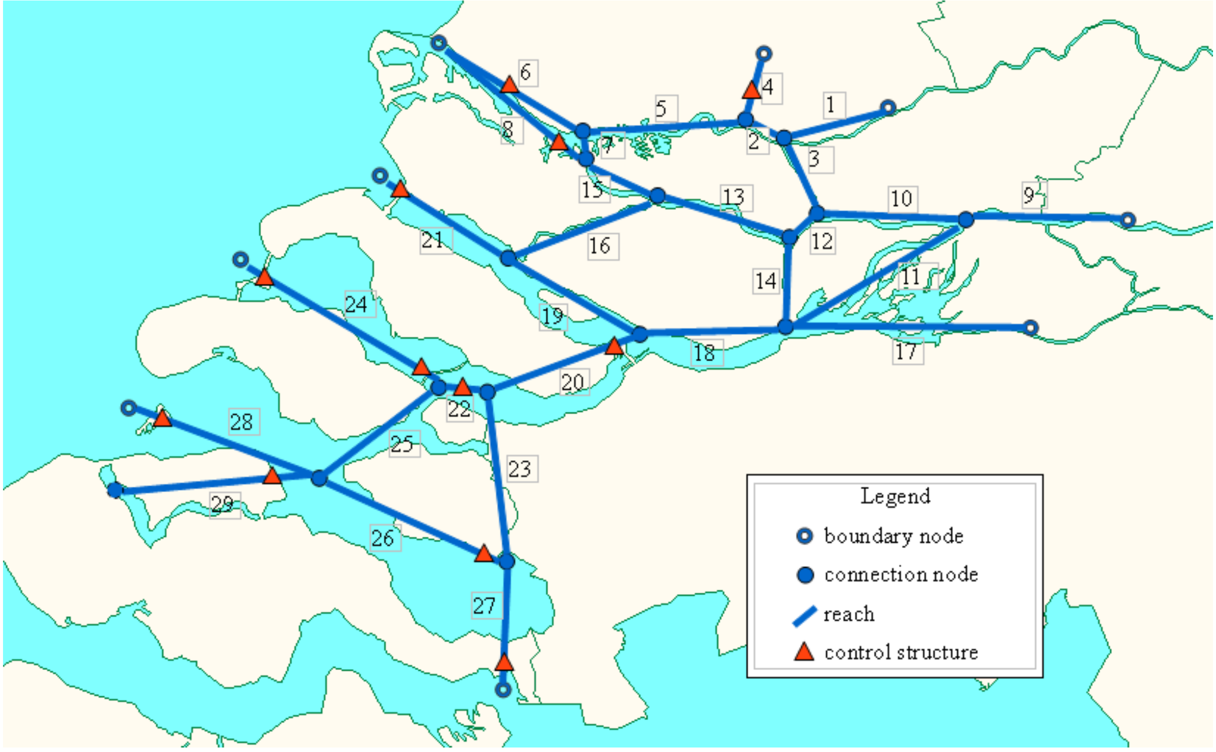

Figure A2: Internal model schematisation, with reach numbers

Annex B: Results of calibration method 2

Table B1: Chezy coefficient value per reach

Reach	Chezy coefficient value
1	49
2	52
3	76
4	100
5	67
6	77
7	99
8	51
9	44
10	39
11	53
12	48
13	42
14	60
15	97
16	21
17	58
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27	43
28	45
29	25

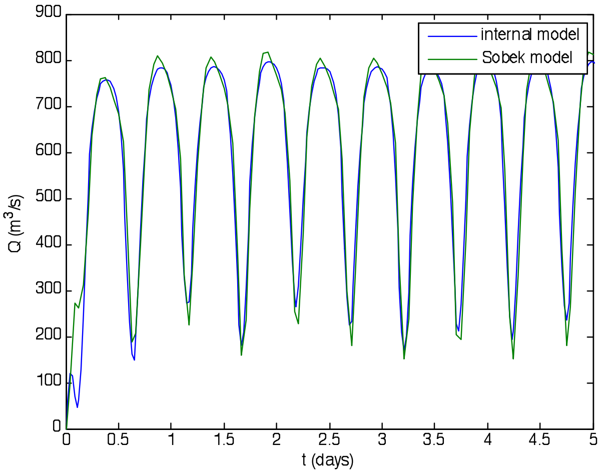

Figure B1: Calibration results reach 1

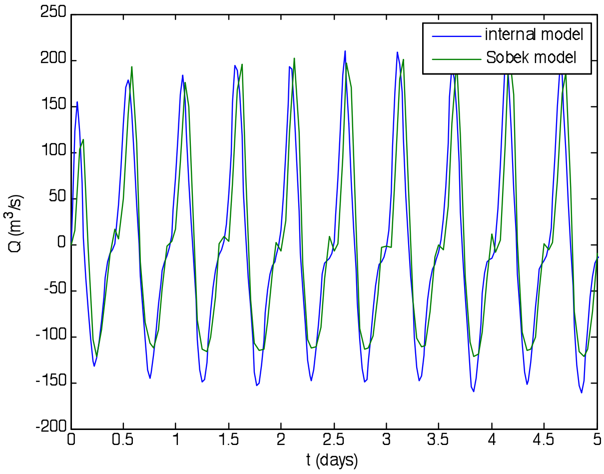

Figure B4: Calibration results reach 4

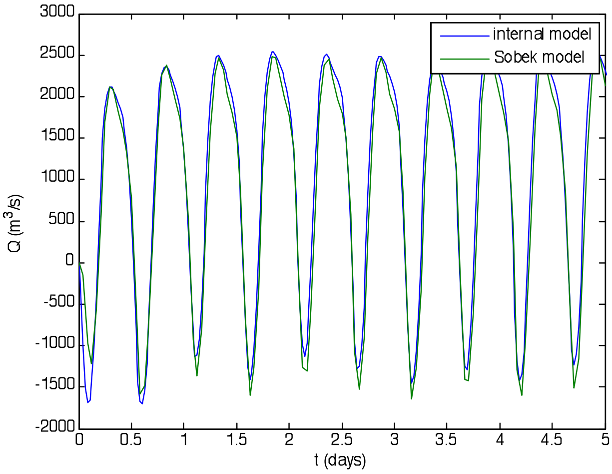

Figure B2: Calibration results reach 2

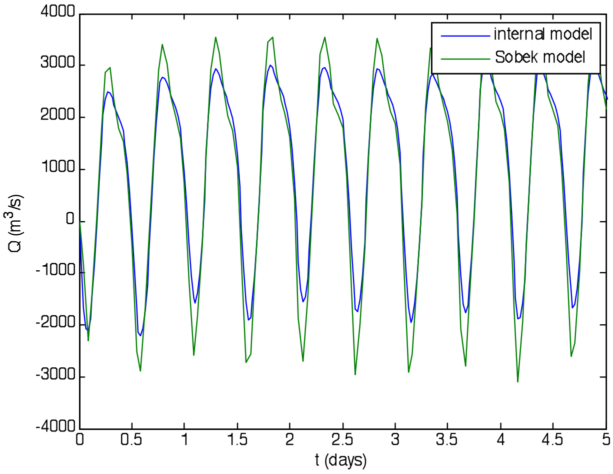

Figure B5: Calibration results reach 5

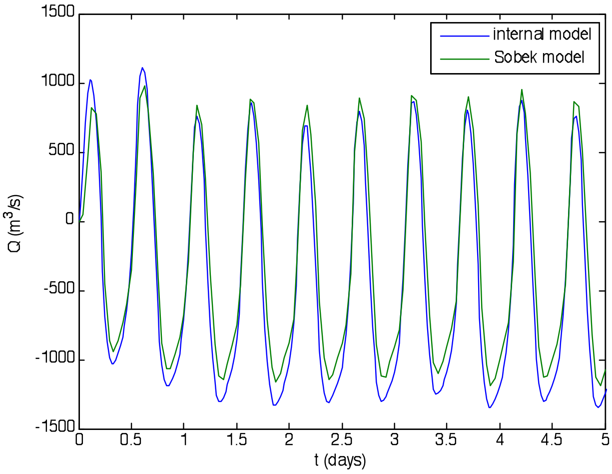

Figure B3: Calibration results reach 3

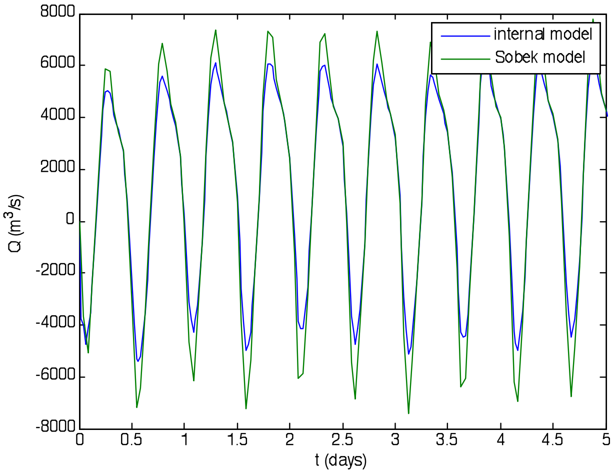

Figure B6: Calibration results reach 6

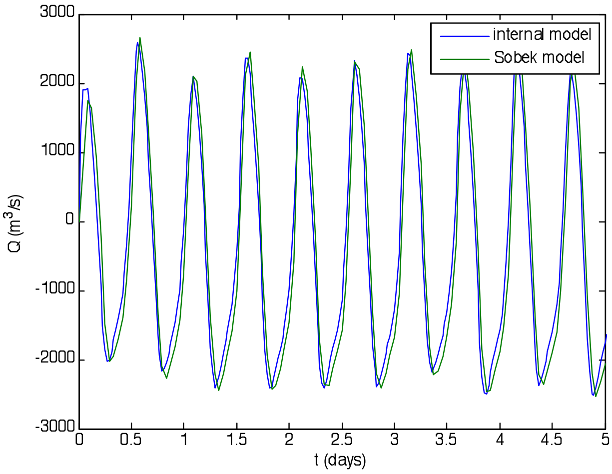

Figure B7: Calibration results reach 7

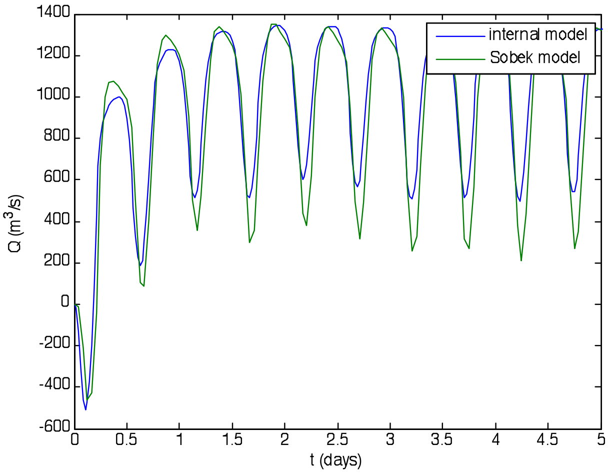

Figure B10: Calibration results reach 10

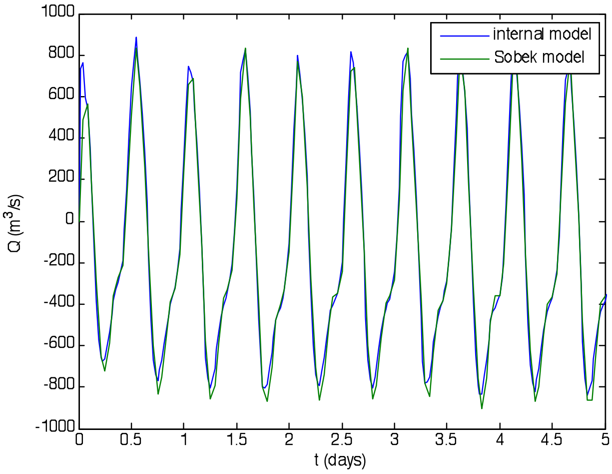

Figure B8: Calibration results reach 8

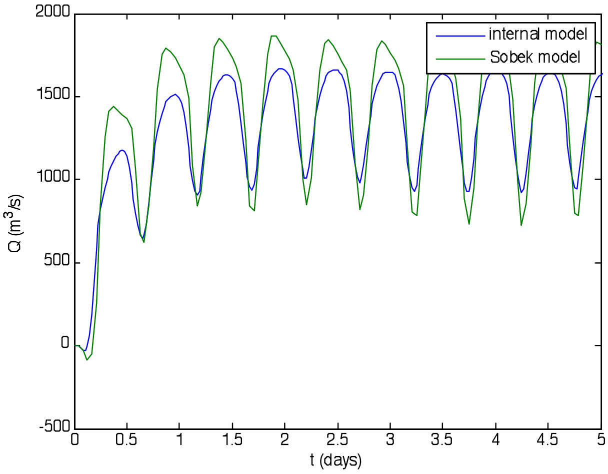

Figure B11: Calibration results reach 11

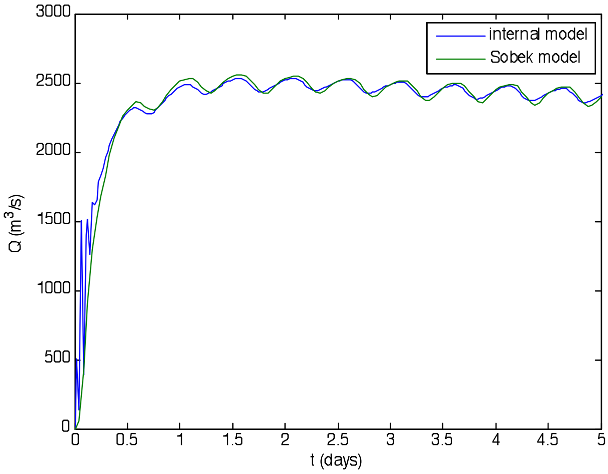

Figure B9: Calibration results reach 9

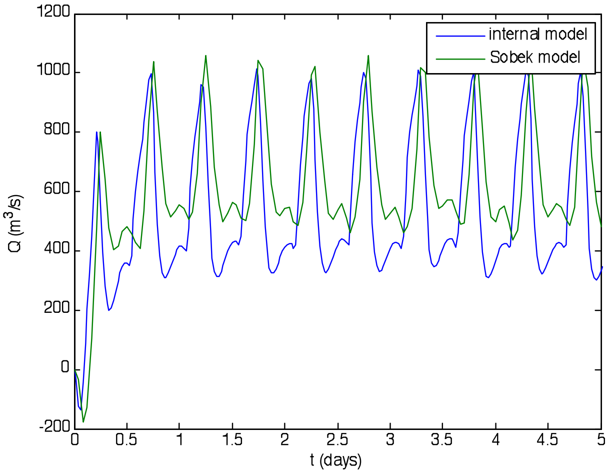

Figure B12: Calibration results reach 12

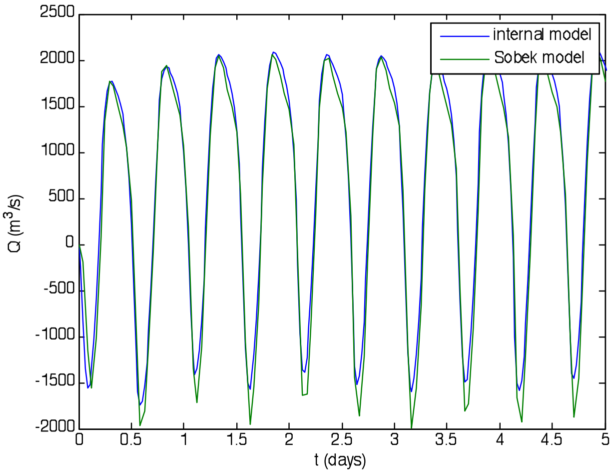

Figure B13: Calibration results reach 13

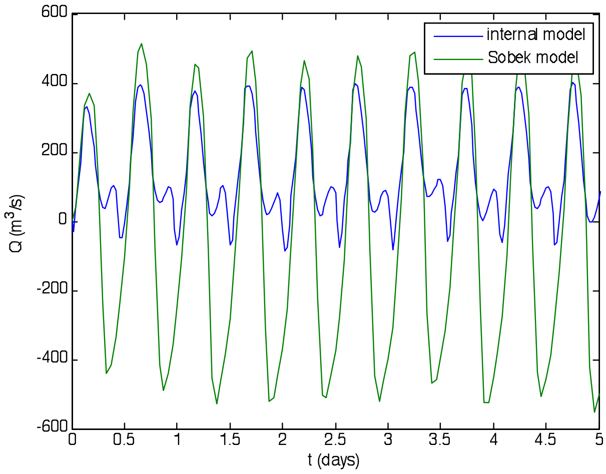

Figure B16: Calibration results reach 16

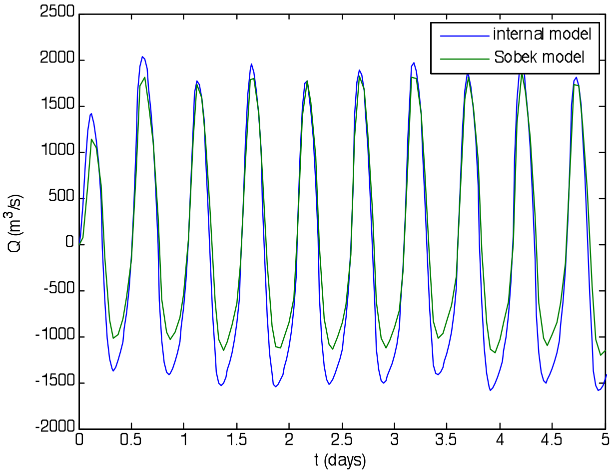

Figure B14: Calibration results reach 14

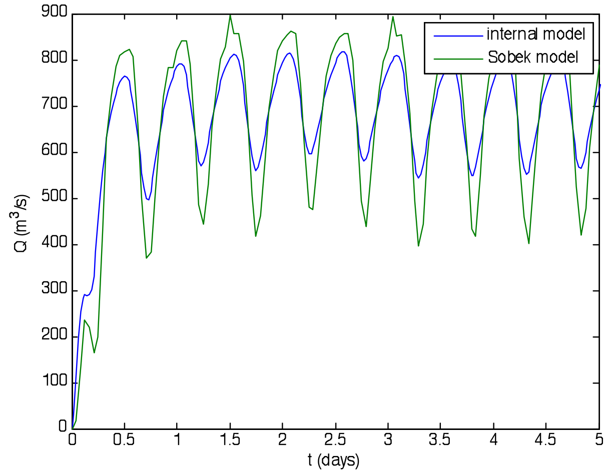

Figure B17: Calibration results reach 17

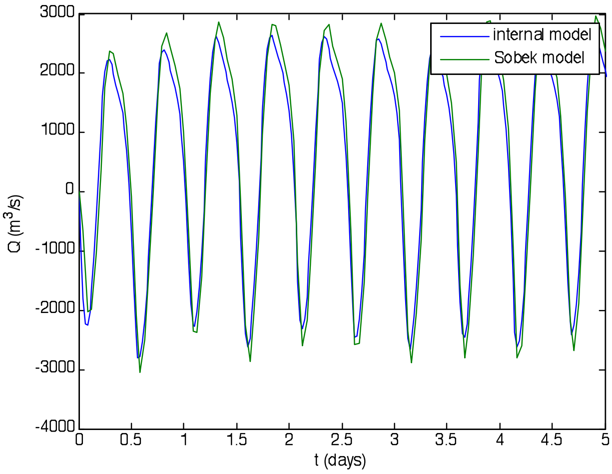

Figure B15: Calibration results reach 15

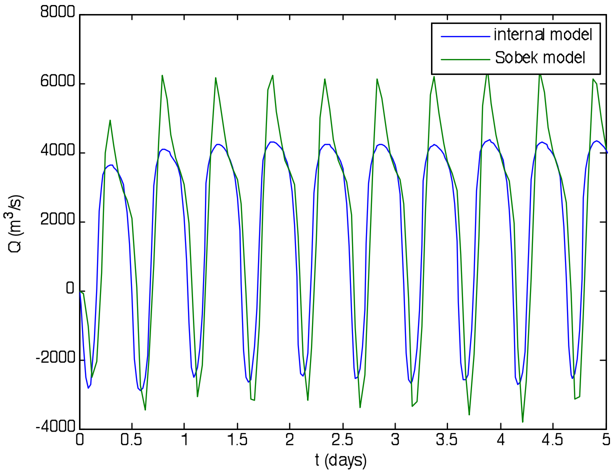

Figure B18: Calibration results reach 18

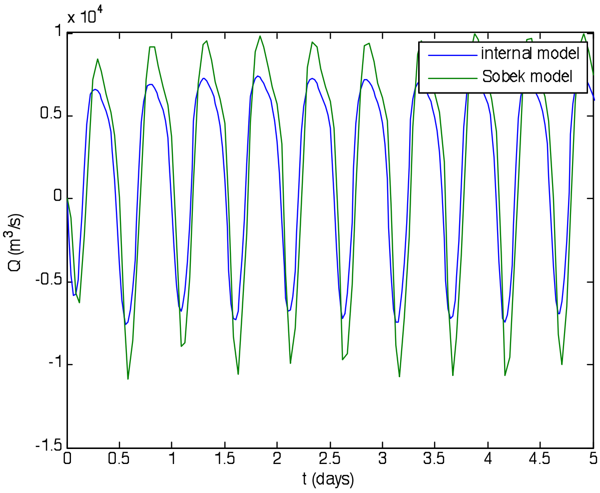

Figure B19: Calibration results reach 19

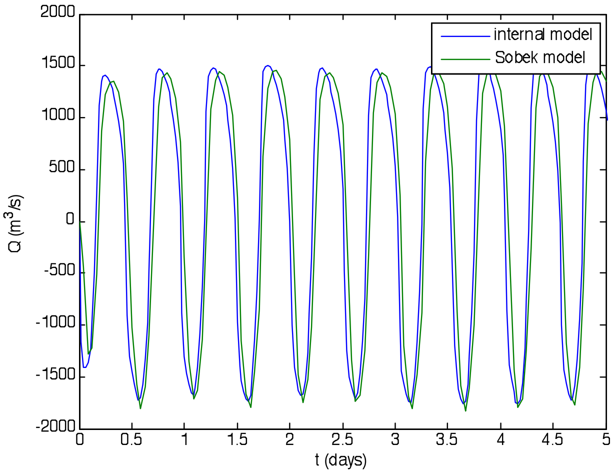

Figure B22: Calibration results reach 22

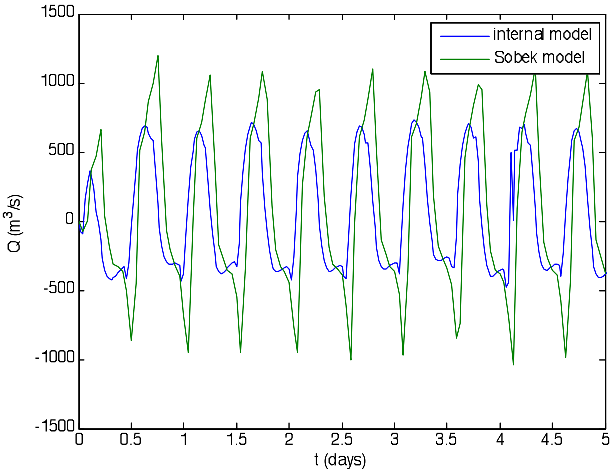

Figure B20: Calibration results reach 20

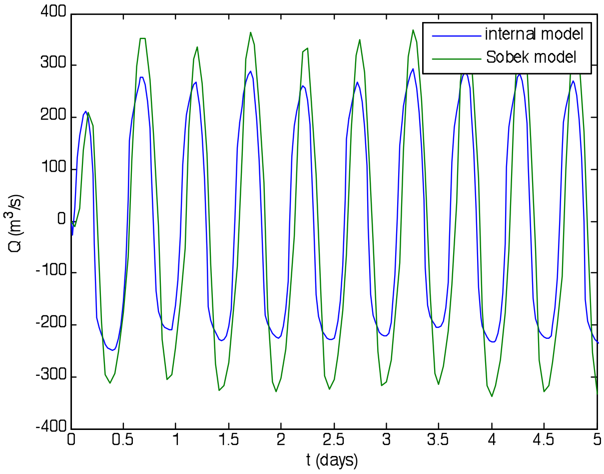

Figure B23: Calibration results reach 23

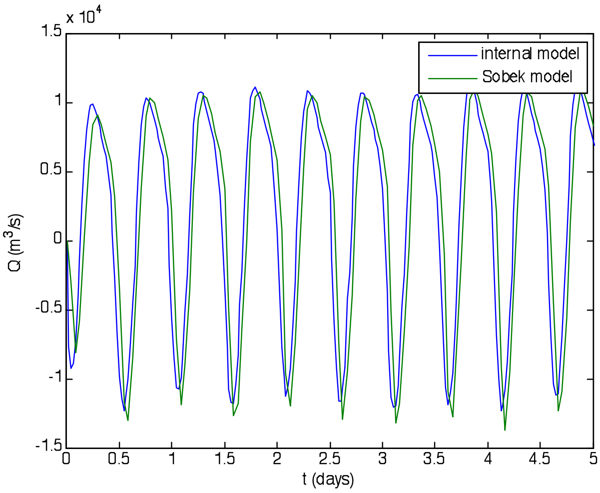

Figure B21: Calibration results reach 21

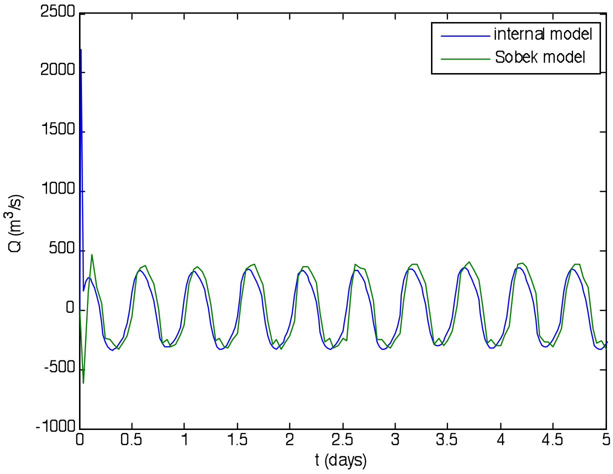

Figure B24: Calibration results reach 24

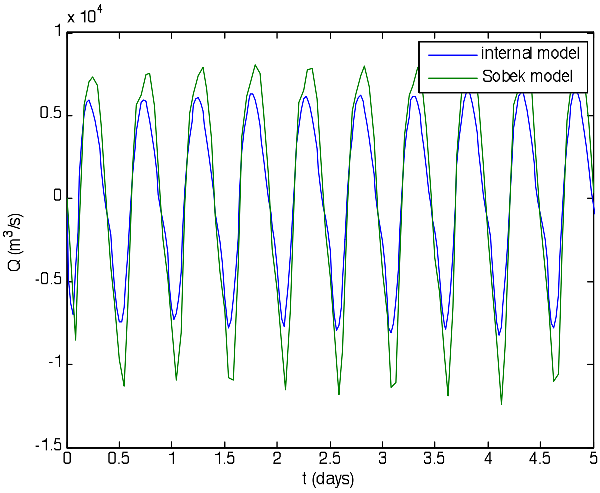

Figure B25: Calibration results reach 25

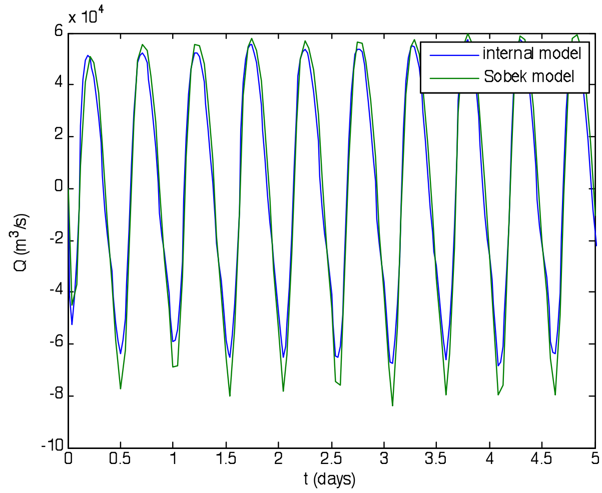

Figure B28: Calibration results reach 28

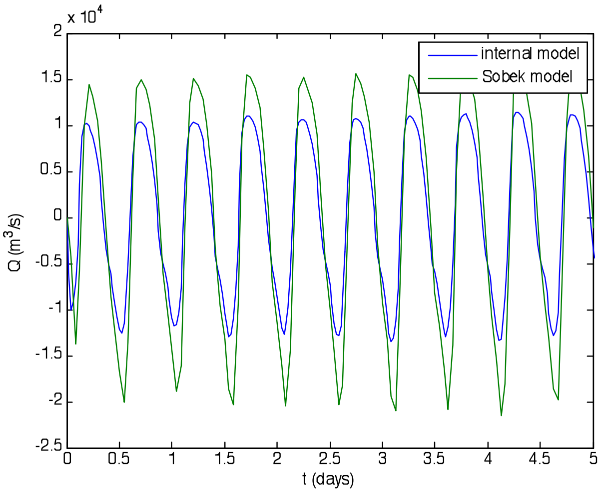

Figure B26: Calibration results reach 26

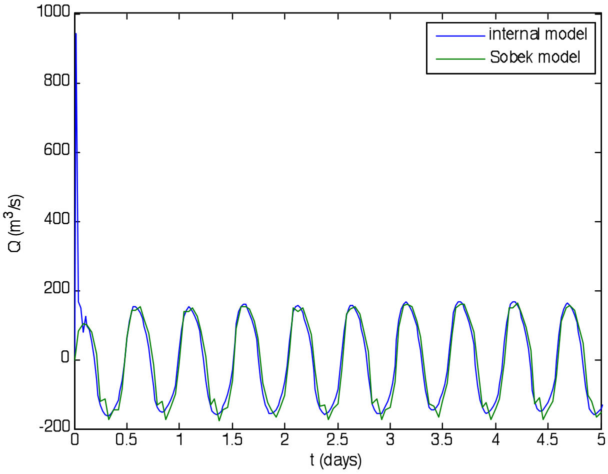

Figure B29: Calibration results reach 29

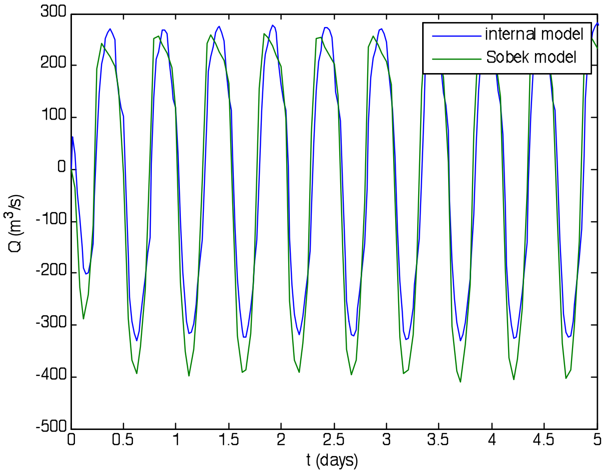

Figure B27: Calibration results reach 27

Annex C: Water level results

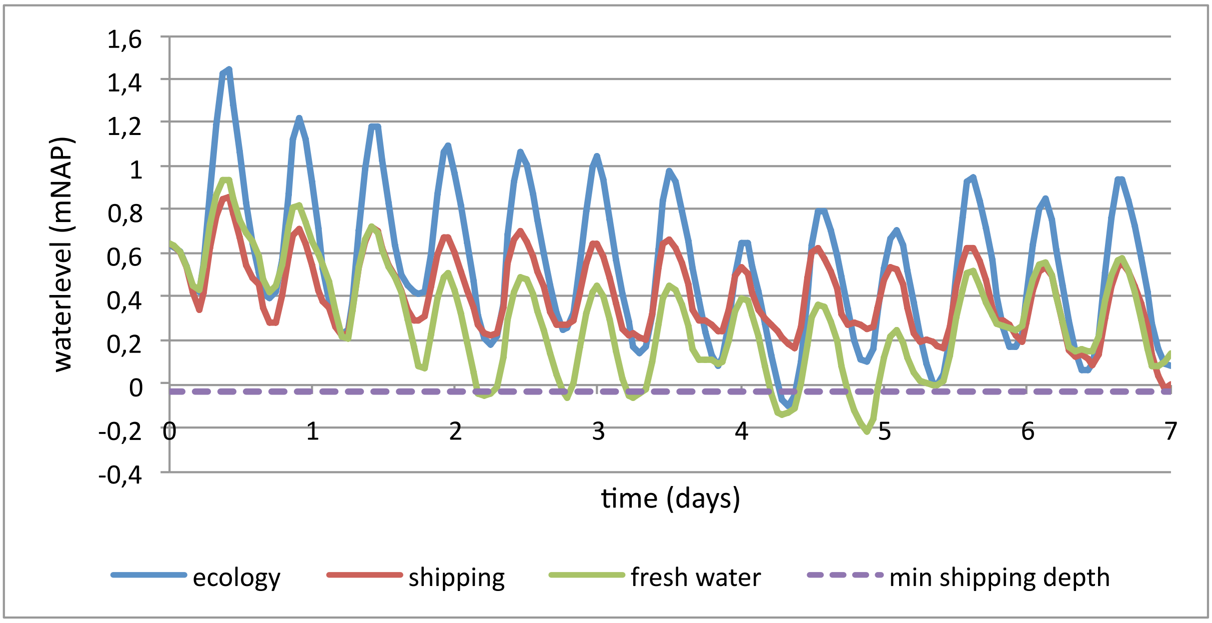

Figure C1: Water levels at node 8 for the three strategies

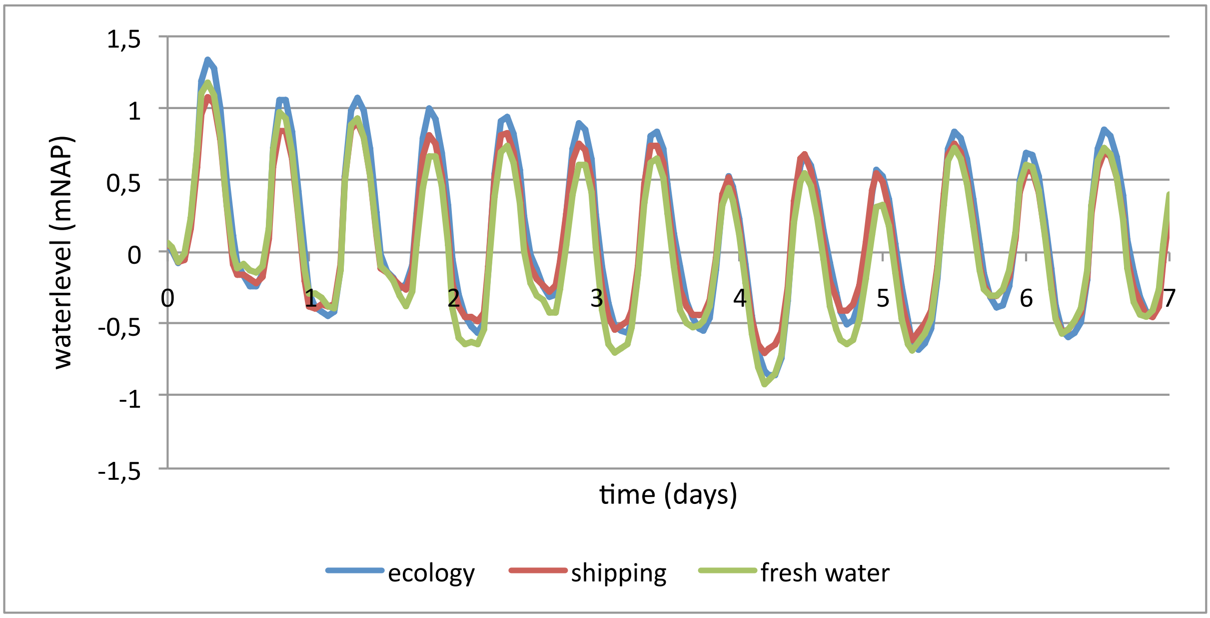

Figure C2: Water levels at node 11 for the three strategies

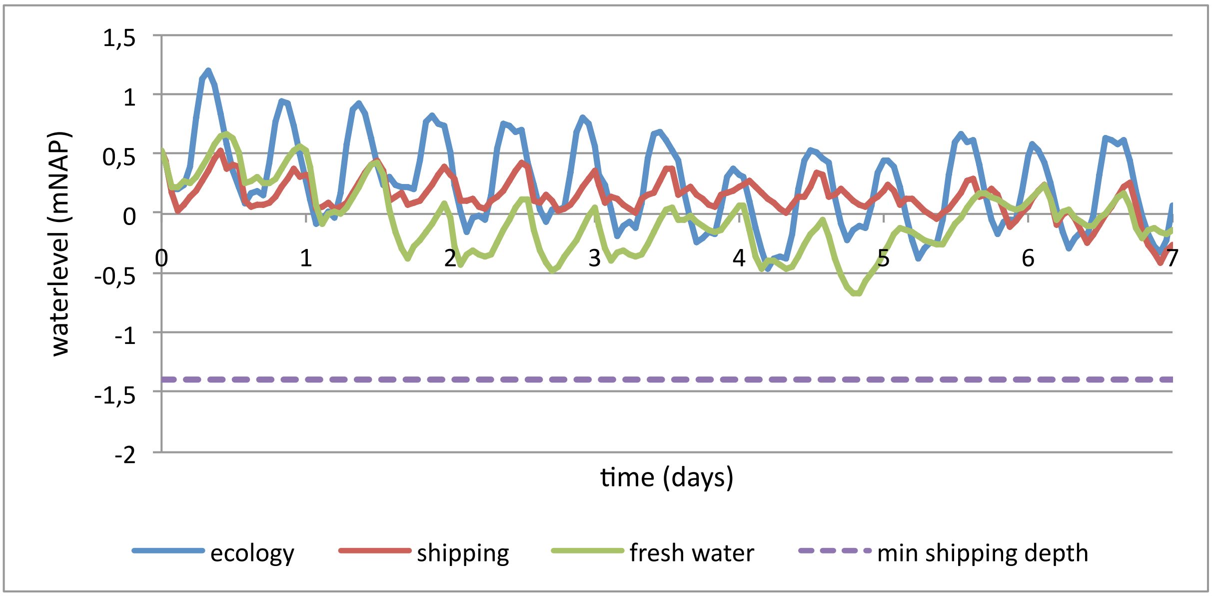

Figure C3: Water levels at node 15 for the three strategies

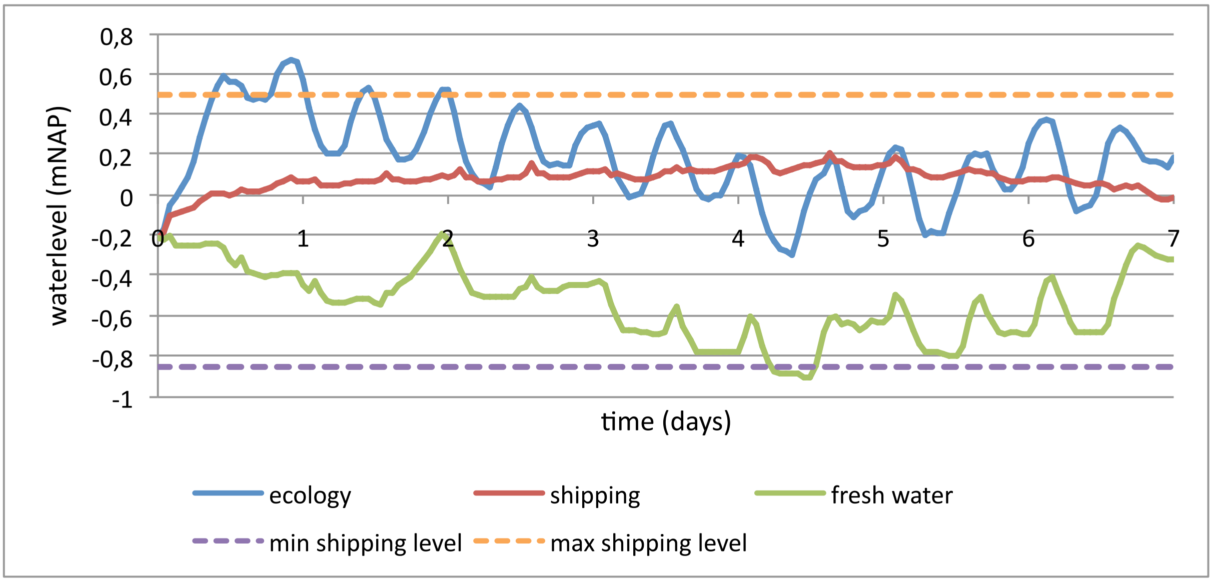

Figure C4: Water levels at node 18 for the three strategies

Annex D: Results at controlled structures

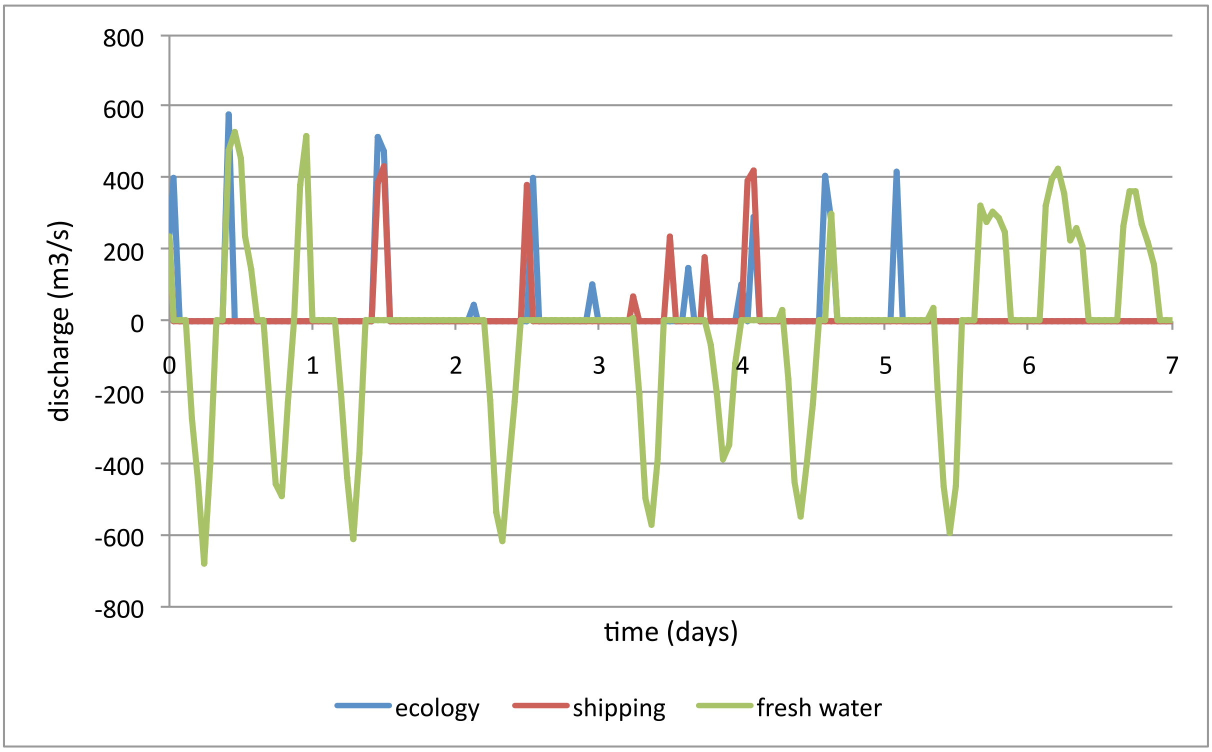

Figure D1: discharge of the Hartelkering (positive flow is towards North Sea)

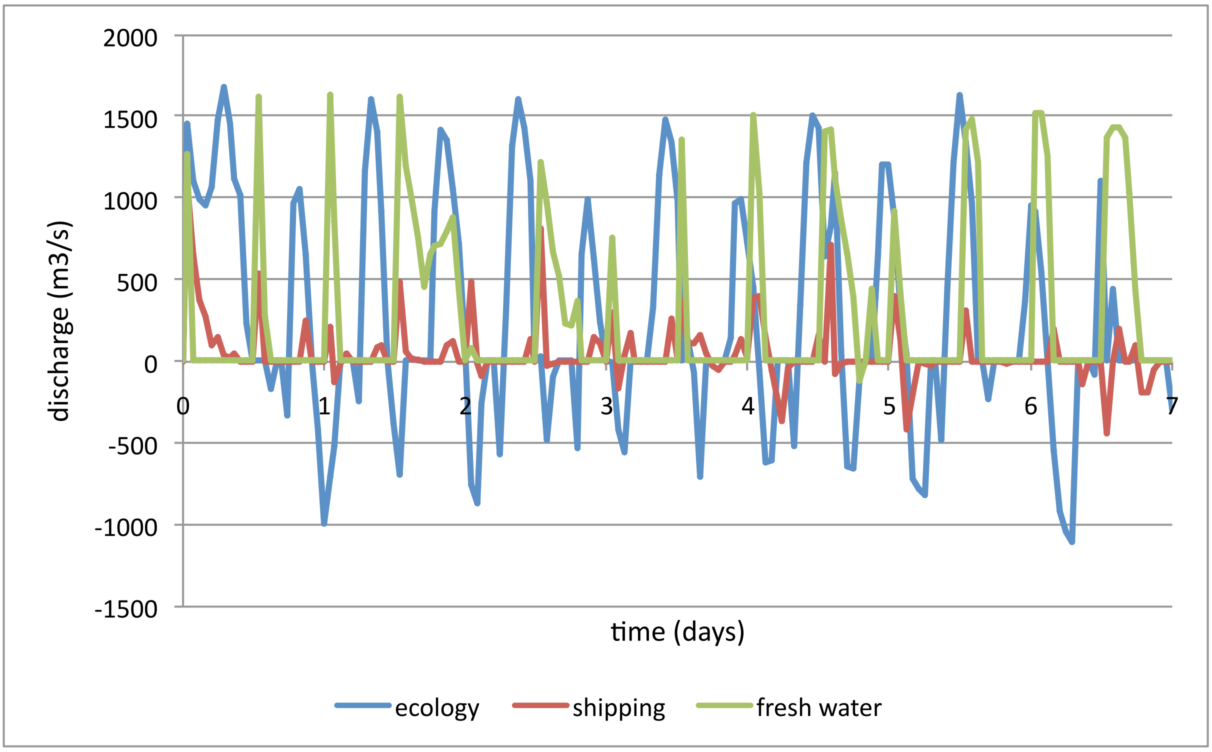

Figure D2: discharge of the Volkeraksluizen (positive flow is towards Volkerak-Zoommeer)

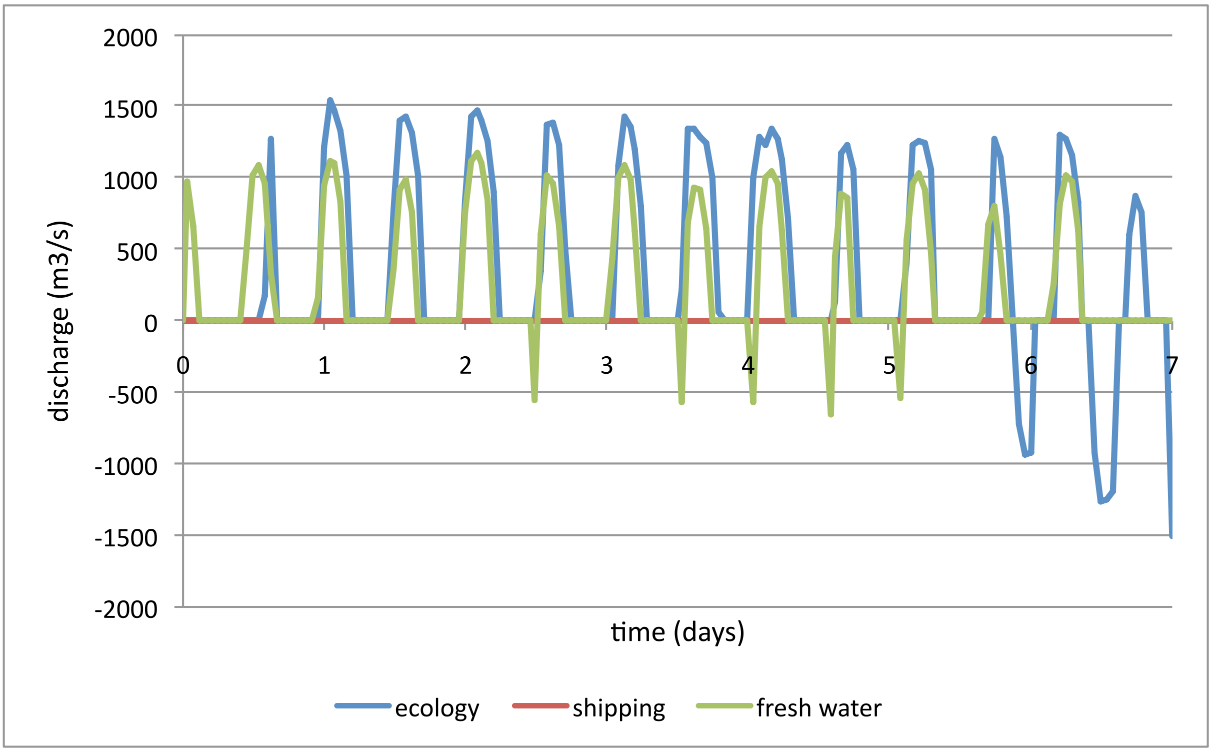

Figure D3: discharge of the Krammersluizen (positive flow is towards Oosterschelde)