2020

Assessment of alternative pumping regimes for the Noordoostpolder

BACHELOR ASSIGNMENT CIVIL ENGINEERING

BAKKER, O.S. (OSCAR, STUDENT B-CE)

Colophon

Student
Name: Oscar Bakker
Student number: S1935291
E-mail address: o.s.bakker@student.utwente.nl

Internal supervisor
Name: Matthijs Gensen
Function: PhD candidate University of Twente
E-mail address: m.r.a.gensen@utwente.nl

Second internal supervisor
Name: K. Gkiotsalitis
Function: Assistant professor transport engineering University of Twente
E-mail address: k.gkiotsalitis@utwente.nl

External supervisor
Name: Rudolf Versteeg
Function: Senior advisor hydrology Zuiderzeeland regional water authority
E-mail address: r.versteeg@zuiderzeeland.nl

Host organization
Waterschap Zuiderzeeland
Lindelaan 20 Lelystad
E-mail address: waterschap@zuiderzeeland.nl

Preface

In front of you, the reader, lies the bachelor report *Assessment of alternative Noordoostpolder pumping regimes*. This report has been made as my graduation assignment for the bachelor civil engineering at the University of Twente. In the winter of 2019, I contacted the Zuiderzeeland regional water authority for the first time with the question if they had room for a civil engineering student interested in water topics. Luckily, I was welcomed warmly by Marijke Visser and Rudolf Versteeg, who offered ample opportunity for me to do my bachelor assignment at Zuiderzeeland. Unfortunately, it would turn out to be my only visit to the Zuiderzeeland: there is no need for an extensive explanation about the Corona virus. It is a pity that I have not had the opportunity to work at the Zuiderzeeland itself and work with my colleagues there face to face. Yet, working from home proved no to be a hindrance as large as thought beforehand. First of all, I want to thank my external supervisor Rudolf Versteeg for his guidance and help. Rudolf has always stood ready with good advice and answers to my many questions and never failed to come up with a new research direction. My (hydrology) colleagues at the Zuiderzeeland have given me invaluable advice, information and help. I would especially like to thank Cees Bakker. Cees has provided me with information regarding the inner workings of the Noordoostpolder pumping regimes and has always quickly answered any emails I fired at him. Likewise, I want to thank my internal supervisor Matthijs Gensen. Matthijs has always kept a good overview off the entire project whenever I got stuck and has helped me in shaping my research and report in what it has now become. Last, I would like to thank my friends, family and (former) housemates, who were always open to give advice, tips and some 'gezelligheid' so now and then. I hope that I have made a valuable contribution to the Zuiderzeeland regional water authority on the subject of pumping regime.

I hope that all readers enjoy reading this report and gain new insights on this interesting subject.

Oscar Bakker,

Hengelo, 8-7-2020

Table of contents

Table of figures

Table of tables

Summary

The aim of this bachelor thesis is to assess various alternative pumping regimes for the Noordoostpolder. The assessment focusses on three aspects: the costs of electricity, the number of operating hours and the water level fluctuations. A pumping regime is the overarching term for all measures and policies used to control the water level in an area. In this case, this area is the entire Noordoostpolder, part of the IJsselmeerpolders in the central part of the Netherlands. The Zuiderzeeland regional water authority is responsible for water management and pumping regimes in the Noordoostpolder. The Zuiderzeeland regional water authority has previously conducted minor research into the subject of pumping regime, combined with a pilot at one of their Noordoostpolder pumping stations, Buma. This study was conducted on behalf of STOWA, a research collective of Dutch regional water authorities. However, this particular study had a quite narrow focus, modelling solely the use of the Buma pumping station and the use of advanced steering software. Therefore, the Zuiderzeeland regional water authority wants to gain more insight in this subject by researching more and diverse alternative pumping regimes.

The report consists of nine different chapters. In the first chapter an introduction is given about the subject of pumping regimes, the motivation behind this research and a description of the Noordoostpolder study area. Furthermore, the core tasks of a regional water authority are briefly explained. In chapter 2, the research scope, research questions and the relevance of this research are explained. Chapter 3 consists of the methodology used for every research question. Chapter 4 contains the results for the electricity costs, number of operating hours and the water level fluctuations per pumping regime. In chapter 5, the results, the report and the research process are discussed while in chapter 6, the final conclusions are given based on the results of chapter 4. In chapter 7, recommendations for further research are put forward. In chapter 8 and 9, the appendices and references are stored.

The research into alternative pumping regimes has been done by using different methods and approaches. To gain more insight in the requirements of the Noordoostpolder water system, the Noordoostpolder pumping stations and the policies and rules of the local water management a literature research was conducted, supported by the consultation of Zuiderzeeland regional water authority experts. Practical information about electricity prices and electricity pricing trends was also gathered by conducting a literature research. Using this information and the input from hydrologists at the Zuiderzeeland, seven alternative pumping regimes were defined. These alternative pumping regimes tested several different steering mechanisms and ideas: different forms of steering mechanisms were applied, while some pumping regimes included modifications to the model input. A MATLAB model has been made to simulate these alternative pumping regimes. The settings of the pumping regimes have been calibrated with historical data sets made available by the regional water authority. The data output from the MATLAB model were used for the calculations of the operating hours, the costs of electricity and for the evaluation of the water level fluctuations.

The results showed that concerning the aspect of electricity prices, the pumping regime which incorporated a steering mechanism based on the day ahead electricity price resulted in the lowest yearly electricity costs, while using almost no time-based steering mechanism at all resulted in the highest electricity costs. However, the same pumping regime that used a minimum of time-based steering control had the most stable water level course in the Noordoostpolder. For the number of operating hours: the pumping regime that used a decreased inlet of water during the dry summer and spring seasons had the lowest number of active operating pumping hours.

1. Introduction

1.1. Background

Before the construction of the Afsluitdijk and the creation of the IJsselmeer, the Zuiderzee was an inner sea between the Holland and Friesland provinces. Although the Zuiderzee had a large economical importance for the region, inhabitants of the coastal areas surrounding the Zuiderzee suffered regularly from floods. In 1916, a storm surge flooded large areas surrounding the Zuiderzee, causing fatalities and large economic damages. This disaster combined with a need for more arable land in the midst of the first world war created the perfect environment to realize the long desire of damming in the Zuiderzee. In 1918, the Zuiderzee act was passed, clearing the way for the construction of the IJsselmeerpolders (Waterschap Zuiderzeeland, 2020a). In 1927, the Zuiderzee works commenced with the construction of the Afsluitdijk. One of the IJsselmeerpolders is the Noordoostpolder, situated in the eastern part of the IJsselmeer (Figure 1). It has been reclaimed from the sea in 1942 and has since been a fertile ground for agriculture. The Noordoostpolder is a part of the province of Flevoland since 1986, with 47.000 inhabitants living on 59.347 hectares of land.

The Noordoostpolder is part of the area under control by the Zuiderzeeland Regional water authority. The Zuiderzeeland regional water authority (RWA) is responsible for the whole province of Flevoland, thus including Eastern Flevoland and Western Flevoland as depicted in Figure 1. The Zuiderzeeland regional water authority has the responsibility over four main tasks:

1. Maintaining a sufficient level of water quality in the open water bodies
2. Purification of wastewater
3. Protection against flooding
4. Maintaining appropriate water levels

In its core vision (Waterschap Zuiderzeeland, 2020b), the Zuiderzeeland RWA strives to fulfill these tasks in such a way that it incorporates sustainability, adaptation to climate change and stakeholder participation.

Figure 1 Ijsselmeer polders

1.2. Problem description

As mentioned in paragraph 1.1, one of the core tasks of the Zuiderzeeland RWA is the control and maintenance of proper water levels within its borders. On average, the polder lies at a depth of 5 meters below NAP level. This low elevation height means that during the year certain surpluses of water must be pumped out of the polder in order to retain proper water levels. The Zuiderzeeland RWA controls the water levels inside the polder via a network of pumping stations, sluices, weirs and other structures (*see paragraph 1.3).* The management of these structures related to the control of water levels and the control of the water levels inside a certain area is the definition of a pumping regime.

The Zuiderzeeland RWA has had several different water pumping regimes in place in the Noordoostpolder. According to the pumping policy plans for the period 2011-2020 as determined in (Waterschap Zuiderzeeland, 2010a) and according to consulted experts at the RWA, the pumping stations are mainly used during off-peak periods at night. The use of pumping stations over the course of a full day is regulated by using different pump initiation and termination water levels for off-peak and peak periods. Before 2019, off-peak periods were defined as the period between 23:00 and 07:00. After the expiration of the old energy contracts, new energy contracts were concluded, expanding the off-peak period to 20:00- 08:00 in 2020. Test trials in 2018 and 2019 showed that taking an even less rigid approach to time-based pumping resulted in decreased electricity costs, expanding pumping activity to the day-time period.

These test trials were part of a study conducted on behalf of STOWA *(Stichting Toegepast Onderzoek Waterbeheer),* a research collective of Dutch regional water authorities. The subject of this research was the implementation of a system called 'Slim malen' (Pothof et al, 2019). '*Slim malen*', or smart pumping in English, is an initiative to reduce the energy use of current pumping by optimizing the steering of pumping stations for regional water authorities using more advanced and improved software. Practically, the aim is to pump less and to only use the pumping stations during favorable conditions. Favorable conditions for pumping depend on the pre-defined main goals of each regional water authority. Those goals can range from reducing the emissions of CO_2 to reducing the financial costs of pumping activity.

The use of this improved steering software is tested in a pilot at four Dutch regional water authorities, among them the Zuiderzeeland RWA. Three main goals were formulated: reducing the financial costs of pumping, increasing the use of renewable energy used by pumping stations and reducing the amount of used energy. For the pilot, the use of the Buma pumping station was modelled. First, pumping based on decreasing the use of energy caused the pumping station to use less power but in turn lead to an increase in the duration of pumping activity. Secondly, steering on increasing the use of renewable energy sources reduced the financial costs significantly, mostly based on the fact that the researchers assumed wind energy to be cost-free. Thirdly, steering based on reducing financial costs achieved the highest reduction in energy costs.

However, the report does not give an exact cost valuation, nor information about the timing and duration of pumping activity. Also, no large-scale research has been done towards researching whether electricity costs of pumping can be decreased by using pumping regimes with different approaches to steering and water management. The Zuiderzeeland RWA is curious to know whether alternative pumping regimes would affect overall electricity costs and operating hours for pumping activity in the Noordoostpolder. This not only includes time- and electricity price based steering but also varying with the share of each pumping station in the total discharge and the type of energy contract.

Furthermore, the RWA lacks clarity about the effects of their current pumping regime on the fluctuation of the water levels inside the polder. Various reports and sightings by farmers and Zuiderzeeland RWA experts indicate that the increased irregularity in the use of pumping station Buma causes damage to vegetation close to waterways and disadvantageous circumstances for the discharge of mowed vegetation (clippings). Therefore, the Zuiderzeeland RWA wants to take into account the aspects of water levels and water level fluctuations in the evaluation of the alternative pumping regimes.

1.3. Study area characteristics

The basic water balance for the Noordoostpolder is summarized in this equation (Rommens & Bosma, 2013):

Precipitation + Seepage water + inlet water + effluents from wastewater treatment plans = evaporation + discharge

Water is discharged from and into the Noordoostpolder by three large pumping stations and a sluice complex, all in service of the Zuiderzeeland regional water authority (Figure 2). The water system connected to these four hydraulic structures occupies roughly 1% of the Noordoostpolder surface area (Waterschap Zuiderzeeland, 2020a), a percentage typical for the IJsselmeer polders. In older Dutch polders, higher percentages of the total surface area have been designated for water ways. Those water ways are part of an elaborate drainage system designed to control the (ground)water level. Precipitation infiltrating into ground is drained by drainage tubes and discharged to ditches and smaller canals who ultimately discharge water into the main canals. The regional water authority is not directly responsible for the drainage of privately owned lands itself, such as agricultural plots. That is the responsibility of the owner. The regional water authorities responsibilities begin at the smaller canals and ditches. The main waterways are the Urkervaart, Lemstervaart and Zwolse vaart (Peilbesluit Hoge en Lage afdeling (Noordoostpolder), 2003). Figure 3 shows the general overview of the draining system used in the Noordoostpolder. The arrows show the direction of the water flow (Stapel, 2018).

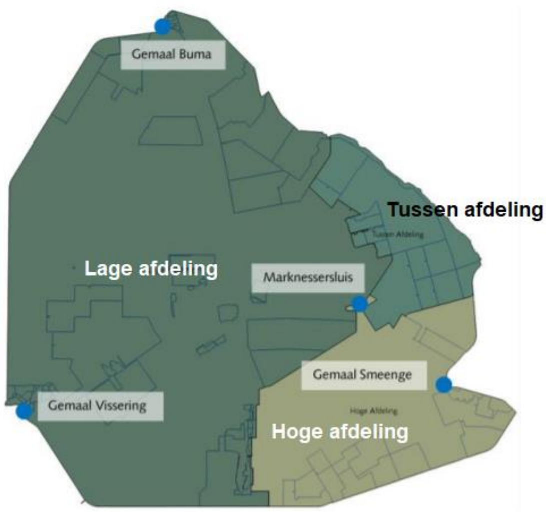

Figure 2 Noordoostpolder

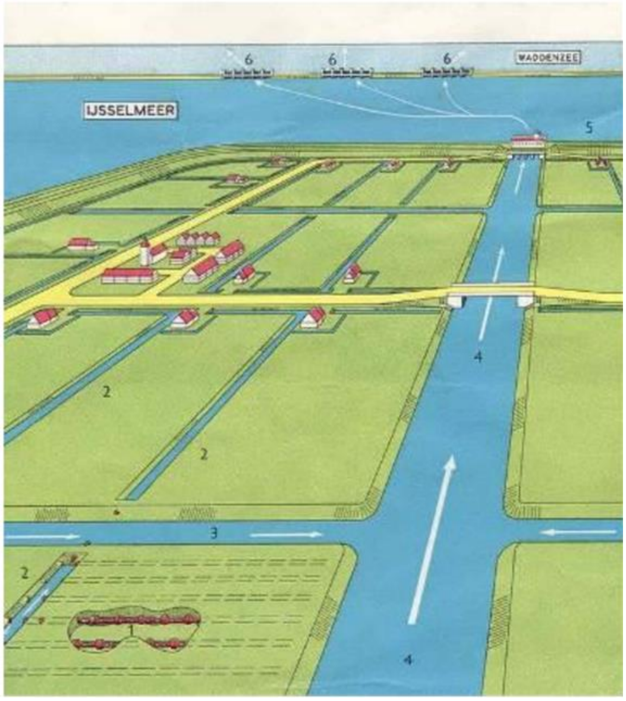

Figure 3 Drainage system Noordoostpolder (Stapel, 2018)

The water system is connected to three pumping stations and one internal sluice complex. Two of these pumping stations, Smeenge and Buma, are powered by electricity while the third pumping station, Vissering, is powered by two large gas turbines. The Marknessersluis only uses energy to open and close the lock paddles. Figure 2 shows that the Noordoostpolder has been divided in three areas based on differences in elevation height: a lower lying area in the west (*Lage afdeling*) , a more elevated area in the east (*Hoge afdeling*) and an in-between area in the north-east (*Tussen afdeling).*

The Hoge afdeling is serviced by the pumping stations Vissering and Buma. The Lage afdeling is serviced by pumping station Smeenge. The Tussen afdeling is not directly supported by any pumping station or sluice, but water from the Tussen afdeling generally flows towards the Lage afdeling. Discharge from the Hoge afdeling into the Lage afdeling is supported by a sluice complex: the Marknessersluis. Water flows from both the Hoge and Tussen afdeling towards the Lage afdeling, meaning that the water streams inside the polder generally follow a western to north western direction. Two other types of hydraulic structures are also used to control water inside the polder: inlets and weirs. Inlets are used to discharge water into the polder in dry (summer) times, while weirs facilitate the proper distribution of water over specific area inside the polder.

2. Research objectives

2.1. Research goal and questions

The main research aim of this research is formulated as such:

What are the effects of different pumping regimes on the financial costs of electricity, the operating hours of pumping stations and water level fluctuations in the Noordoostpolder?

The research is structured into four research questions. The first research question is formulated as such:

1. What are the requirements for pumping activities in the Noordoostpolder?

The first research question will analyze the water management and pumping policy in the Noordoostpolder. Several more specific questions regarding this subject have been formulated:

- Which factors influence and determine the pumping requirements?
- When is there a need to pump?
- How much water needs to be pumped in case the maximum allowable water levels have been reached?
- What is the share of each pumping station in the total discharge of water into the Ijsselmeer?
- What is the pumping capacity and electricity use per unit of pumped water of each pumping station?
- What is the influence of the water level in the Ijsselmeer on the ability of pumping stations to discharge water from the Noordoostpolder?

2. What are the electricity prices for different times of the day and for which relevant period should they be determined?

The second question will treat the subject of electricity prices. Aspects like which data should be taken, which time scale should be used and in which manner from that data average prices per hour for different relevant periods (period long enough that a conclusion can be taken) can be derived will be part of this question, including any energy contracts and other agreements the regional water authority has with its energy supplier. This information forms the basis for the later quantification of the electricity costs per pumping regime.

3. What are the electricity costs and operating hours for each pumping regime in the Noordoostpolder?

The third question will answer two of the three main aspects of this research. Based on the information gathered in the first and second research questions, the total energy costs per pumping regime will be calculated for different relevant periods. For the same relevant periods, the operating hours are determined per pumping regime.

4. What are the water level fluctuations per pumping regime in the Noordoostpolder?

The fourth research question treats the subject of water level fluctuations and the general course of water levels per pumping regime. The water level fluctuations are quantified for the same relevant periods used in research question 3.

2.2. Research scope

The research scope encompasses the assessment of various pumping regimes in the Noordoostpolder on the effects of electricity costs and water level fluctuations. Seven different alternative pumping regimes will be used for the assessment. The pumping regimes are constructed based on the wishes and input from the Zuiderzeeland RWA (hydrology) experts. The pumping regimes are bound by the requirements and physical characteristics of the local Noordoostpolder water system. Therefore, the research will focus on the main elements of this water system. In Figure 2, the important objects and waterways in the Noordoostpolder water system are displayed (Immerzeel, Graafstal, & Loeve, 2006).

The discharge of water is taken care of by three pumping stations and a sluice complex. Two pumping stations are electrically powered, and one is not: pumping station Vissering. Pumping station Vissering is powered by a combination of gas and diesel turbines, which generates power for the pumps. The scope of this research concerns the costs of electricity costs. However, the Zuiderzeeland RWA has plans to renovate Vissering in the coming years, replacing the diesel and gas turbines by electrical power. Besides that, without taking into account the energy costs of Vissering, it is impossible to gain an appropriate view of the energy costs of a pumping regime. Therefore, Vissering will be taken into account for the total costs of electricity and the amount of operating hours. Regarding the Marknessersluis: since the Marknessersluis only uses energy to open and close the lock paddles, this is not part of the quantification of the electricity costs per pumping regime.

2.3. Relevance of research

Keeping the electricity costs down is important for the Zuiderzeeland RWA. In the future, the water level of the IJsselmeer is expected to increase to levels up to 1.5 meter compared to the contemporary average water level. Combined with an expected increase in precipitation and extreme weather conditions, this means that pumping stations have to increase their activities, resulting in a higher electricity use (Waterschap Zuiderzeeland, 2010a). Since 16 % of the total energy costs by the Zuiderzeeland RWA is used for pumping activity (Van Boldrik, 2015), a reduction in these costs is useful for the durability of the Zuiderzeeland RWA finances in the long term.

3. Methodology for research

The methodology describes the methods and strategies employed to answer the research questions.

3.1. Methodology research question 1

A literature research is conducted to research the requirements and conditions for pumping activity in the Noordoostpolder. Most of the literature is available in the digital workplace of the Zuiderzeeland regional water authority. A wide range of literature is used to form an overview of the subject. The main sources of information are the documents containing the "*peilbesluiten*", since these documents contain the necessary information about the factors important in the formation of water management and pumping regimes by the regional water authority. In particular the document *Peilbesluit hoge en lage afdeling* (Peilbesluit Hoge en Lage afdeling (Noordoostpolder), 2003) proves to be useful. A multitude of these documents are available online. Since some of these documents are 15 to 20 years old, their relevance is checked by consulting the external supervisor. Using the information derived from the peilbesluiten, the main interests and factors concerning water management are identified. Per factor, extra literature research was done for the sake of deepening the knowledge already found in the peilbesluiten. Most of this information is found in documents like the *Gemalenplan 2011-2020, WaterTakenPlan Noordoostpolder* and in medium term policy plans such as in the *Waterbeheerplan*. Concerning the search for technical information of the pumping stations: recently, the Zuiderzeeland RWA conducted an investigation aimed at finding ways to save on energy costs. This report (*Energie-aspecten poldergemalen Noordoostpolder)* proved to be an excellent source for technical information about the pumping stations.

3.2. Methodology research question 2

The aim of this question is to determine the correct electricity prices per hour per day and the period needed to evaluate the pumping regimes later in research question 3. The relevant information is retrieved by a combination of literature research into internal Zuiderzeeland documents and expert consultation. The first step is to research under which energy contracts the Zuiderzeeland RWA operates. This was achieved by consulting an energy expert of the Zuiderzeeland, Cees Bakker. For pumping station Smeenge, fixed prices are found for the period 2017 up to and including 2020. For pumping station Buma, the electricity prices depend fully on the Dutch APX electricity exchange. Electricity prices per hour for the APX are only available for the full year of 2018 and a part of 2019. To research the pumping regimes on electricity costs for Buma beyond this period, a trendline is composed, clarifying the relation between the electricity price and the time of day. To do this, a random sub-set of the available electricity price data from 2018 is taken, containing 125 days with 24 hourly price values each. The average electricity price per time interval is calculated, as is the total daily average over 125 days. A sample size of 125 days is chosen for several reasons. According to (NAO, 2001) as a rule of thumb a sample should contain a 50 to 100 values per variable. Normally the Cochran formula is used to calculate the correct sample size, requiring among other things the size of the set from which the sample set would be picked. This is however impossible to determine in a proper way.

The average prices per hour and the average daily price over all 3000 (125*24) values are calculated. Using these values, the relative differences between the average daily price and the hourly prices could be determined. A graph containing both the daily average and the hourly averages is made, showing the general trend of electricity prices over the day. This graph is used for the validation of the electricity price trend, by conducting a literature research into the dynamics of electricity prices per hour.

By adding the value of 1 to all relative difference values, 24 conversion factors are determined. These conversion factors enable the determination of hourly electricity prices from daily electricity prices. These daily electricity prices were retrieved from EMI, short for Energiemarktinfo (Marktinformatie, 2020). The specific price data concerns the day-ahead prices from the Dutch APX energy exchange. EMI is an independent research centrum for the Dutch energy market. EMI granted permission to the use of this data under the condition that proper citation is provided. The hourly electricity prices are calculated for the duration of the research period. The appropriate research period of 3 years and 4 months is determined in consultation with the external supervisor. This period is chosen for both hydrological and energy related reasons. First, a more lengthy period is favored over several separate smaller periods. A longer term period has the advantage of continuity and encompasses several hydrological patterns (dry, wet, average) at once. Secondly, data about fixed electricity prices is only available from the year 2017 onwards.

3.3. Methodology research questions 3 & 4

Research question 3, about the quantification of the costs of energy and research question 4, consisting of the evaluation of water level fluctuations, are both answered by building a simplified model of the Noordoostpolder water system and using data output from a SOBEK Rural model made available by the Zuiderzeeland RWA. Figure 4 shows the main parts of the MATLAB model. The modelling and definition of the alternative pumping regimes are explained on basis of these three main parts.

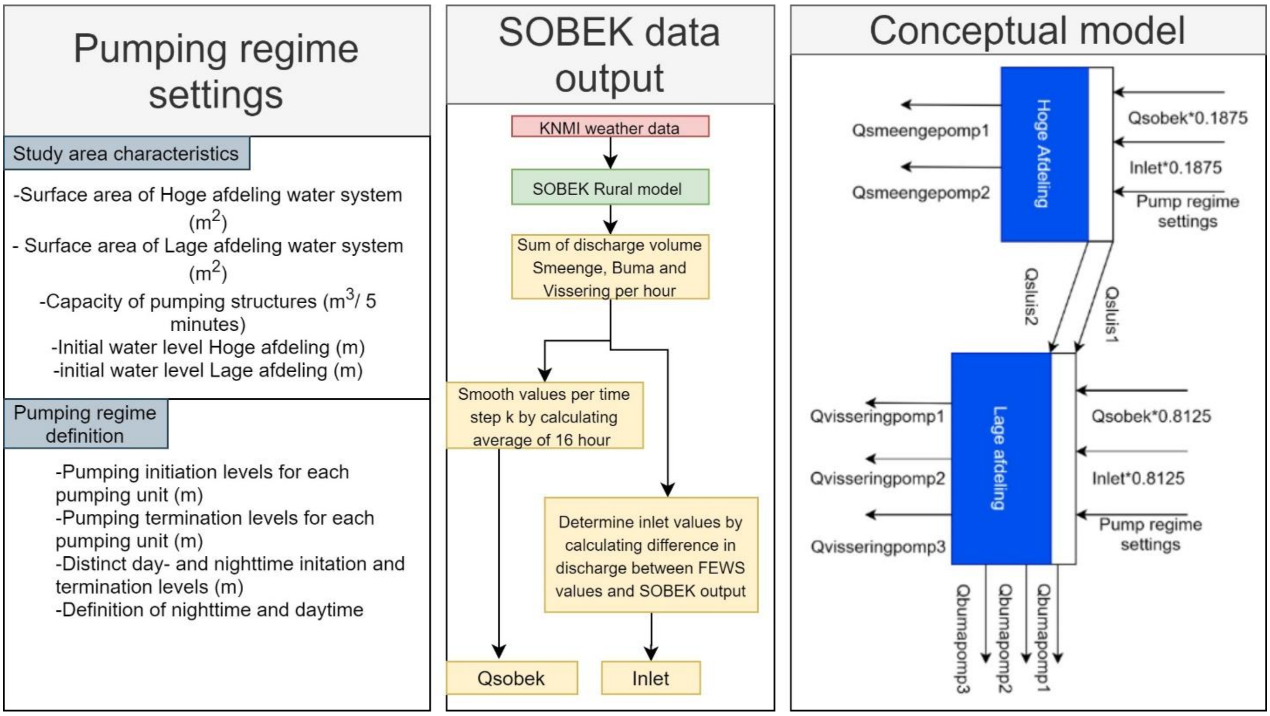

Figure 4 Modelling steps

3.3.1. Pumping regime settings

Seven different alternative pumping regimes are defined. The settings of each pumping regime determine to a large degree the differences between the alternative pumping regimes. Alterations in other variables like the inlet input or the steering also determine the pumping regime characteristics.

The pumping regime settings are divided in two parts: the study area characteristics and the pumping regime definitions.

Study area characteristics

The study area characteristics are fixed for each pumping regime. These characteristics are the surface area of the water system, the values of the initial water levels and the pumping capacities of the pumping structures. According to (Hoes & Van de Giesen, 2015), the average percentage of area occupied by the water system in the IJsselmeerpolders is 1 %. The Hoge afdeling has a surface area of 9000 Ha and the Lage afdeling has a surface area of 39000 Ha. Using the 1% factor, the Hoge afdeling water system surface area is 900.000 m^2 and 3.900.000 m^2 for the Lage afdeling. The initial water level values of the Hoge and Lage afdeling are taken as the target water levels: -4.5 m + NAP for the Hoge afdeling and -5.7 m + NAP for the Lage afdeling. The model works in such a way that if the pumps and outlets are activated, they only work at full capacity. As explained in paragraph 4.1.4, the efficiency and thus the electricity use of pumps depends partially on the capacity of the pump. The optimal rpm for these pumps is close to full capacity (Rommens & Bosma, 2013). Letting pumps run at half speed would impact the electricity costs negatively. The capacity values are displayed in Table 1.

Table 1 Capacity

Hydraulic unit	Capacity (m^3 / 5 minutes)
Smeenge pump 1	3100
Smeenge pump 2	3100
Buma pump 1	3600
Buma pump 2	3600
Buma pump 3	3600
Vissering pump 1	4000
Vissering pump 2	4000
Vissering pump 3	3600
Marknessersluis lock paddle 1	1000
Marknessersluis lock paddle 2	1000

Pumping regime definition

Seven alternative pumping regimes are created for the evaluation in questions 3 and 4. Each alternative pumping regime is defined in this paragraph. Table 2 gives an overview of the seven alternative pumping regimes and their defining characteristic. The reasons behind the establishment of every alternative pumping regime are explained, combined with the pumping regime settings. These pumping regime settings are included in tables. These tables contain the pump initiation and termination levels for both the off-peak (nighttime) and peak (daytime) period. The Marknessersluis uses a different definition of off-peak and peak time. This definition is used for all seven pumping regimes: the off-peak time for the Marknessersluis runs from 22:00 to 06:00.

Table 2 Overview of pumping regimes

Pumping regime (name)	Main defining characteristic
1 (Basic)	Basic pumping regime
2 (Smeenge high)	Increased share of Smeenge
3 (Day ahead)	1 day ahead price based steering
4 (Relaxed time steering)	Relaxation in time-based steering on water levels
5 (Decreased inlet)	Decreased inlet
6 (3 days ahead)	3 days ahead price based steering
7 (Increased bandwidth)	1 day ahead price based steering with increased bandwidth for allowable water levels

Pumping regime 1 (Basic)

Pumping regime 1 is based on the pumping regime that is currently in use by the Zuiderzeeland RWA. The off-peak period for the pumping stations is defined as the period between 23:00 and 07:00. Table 3 shows the initiation and termination water levels for each pumping unit for each defined period of time. The electricity costs for this pumping regime will be calculated for three variants of this basic regime: one variant simply called pumping regime 1 Basic, for which the electricity prices are determined according to the current electricity contracts for each pumping station. The second variant is called pumping regime 1 APX, which will calculate the electricity costs according to the APX electricity price contracts for each of the three pumping stations. The third variant is called pumping regime 1 Fixed prices: all electricity costs are calculated by using the fixed price contracts for all pumping stations.

Table 3 Pumping regime 1 settings

Pumping unit	Pump stages	Values peak period (m + NAP)	Values off-peak period (m + NAP)
Marknessersluis lock paddle 1	Initiation level	-4.31	-4.465
	Termination level	-4.565	-4.575
Marknessersluis lock paddle 2	Initiation level	-4.31	-4.44
	Termination level	-4.565	-4.575
Smeenge pump 1	Initiation level	-4.34	-4.37
	Termination level	-4.58	-4.60
Smeenge pump 2	Initiation level	-4.342	-4.368
	Termination level	-4.58	-4.60
Buma pump 1	Initiation level	-5.595	5.647
	Termination level	-5.72	-5.8
Buma pump 2	Initiation level	-5.59	-5.643
	Termination level	-5.71	-5.785
Buma pump 3	Initiation level	-5.57	-5.62
	Termination level	-5.70	-5.77
Vissering pump 1	Initiation level	-5.61	-5.635
	Termination level	-5.72	-5.97
Vissering pump 2	Initiation level	-5.605	-5.616
	Termination level	-5.71	-5.78
Vissering pump 3	Initiation level	-5.58	-5.59
	Termination level	-5.70	-5.765

Pumping regime 2 (Smeenge high)

Pumping regime 2 is quite similar compared to pumping regime 1. The main difference is that the share of pumping station Smeenge in the total amount of pumped water is increased, by altering the pump stage levels for Smeenge. As explained in paragraph 4.1.3. *Use of pumping stations*, the use of Smeenge is discouraged by the Zuiderzeeland RWA due to fact that Smeenge often discharges water of a lower water quality. By ignoring that fact in this pumping regime, the regional water authority wants to see what the financial impact is of that decision. Table 4 shows the settings of each pumping unit. The off-peak period for the pumping stations is defined as 23:00-07:00.

Table 4 Pumping regime 2 settings

Pumping unit	Pump stages	Values peak period (m + NAP)	Values off-peak period (m + NAP)
Marknessersluis lock paddle 1	Initiation level	-4.31	-4.465
	Termination level	-4.565	-4.575
Marknessersluis lock paddle 2	Initiation level	-4.31	-4.44
	Termination level	-4.565	-4.575
Smeenge pump 1	Initiation level	-4.35	-4.405
	Termination level	-4.58	-4.60
Smeenge pump 2	Initiation level	-4.345	-4.395
	Termination level	-4.58	-4.60
Buma pump 1	Initiation level	-5.595	5.647
	Termination level	-5.72	-5.8
Buma pump 2	Initiation level	-5.59	-5.643
	Termination level	-5.71	-5.785
Buma pump 3	Initiation level	-5.57	-5.62
	Termination level	-5.70	-5.77
Vissering pump 1	Initiation level	-5.61	-5.635
	Termination level	-5.72	-5.97
Vissering pump 2	Initiation level	-5.605	-5.616
	Termination level	-5.71	-5.78
Vissering pump 3	Initiation level	-5.58	-5.59
	Termination level	-5.70	-5.765

Pumping regime 3 (Day ahead)

The values for the pump stages in pumping regime 3 are the same as the pump stage values defined in pumping regime 1. The main difference is that for pumping regime 3, steering based on the price of electricity is incorporated into the model design. To a large extent, the development of current and past pumping regimes is predominantly influenced by the desire to keep the financial costs down. Therefore, they would like to see an alternative pumping regime that would test price based steering even more explicitly. That pumping regime will be pumping regime 3. This pumping regime controls the activity of Buma and Vissering based on the comparison between the average electricity price of the current day and the day-ahead electricity price. Smeenge is not part of this price-based steering system, since it does not pump at a regular basis but is only used at moments with high water levels in the Hoge afdeling. Adding a price-based steering mechanism to Smeenge would hamper its efforts during this peak water level moments. This pumping regime requires a change in the general MATLAB model algorithm. The paragraph *Model algorithm* explains this addition. Table 5 shows the initiation and termination water levels for each defined period. The off-peak period for pumping stations is defined as 23:00-07:00.

Table 5 Pumping regime 3 settings

Pumping unit	Pump stages	Values peak period (m + NAP)	Values off-peak period (m + NAP)
Marknessersluis lock paddle 1	Initiation level	-4.31	-4.465
	Termination level	-5.51	-5.51
Marknessersluis lock paddle 2	Initiation level	-4.31	-4.44
	Termination level	-5.51	-5.51
Smeenge pump 1	Initiation level	-4.35	-4.405
	Termination level	-5.51	-5.51
Smeenge pump 2	Initiation level	-4.345	-4.395
	Termination level	-5.51	-5.51
Buma pump 1	Initiation level	-5.595	5.647
	Extreme initiation level	-5.51	-5.51
	Termination level	-5.72	-5.8
Buma pump 2	Initiation level	-5.59	-5.643
	Extreme initiation level	-5.51	-5.51
	Termination level	-5.71	-5.785
Buma pump 3	Initiation level	-5.57	-5.62
	Extreme initiation level	-5.51	-5.51
	Termination level	-5.70	-5.77
Vissering pump 1	Initiation level	-5.61	-5.635
	Extreme initiation level	-5.51	-5.51
	Termination level	-5.72	-5.79
Vissering pump 2	Initiation level	-5.605	-5.616
	Extreme initiation level	-5.51	-5.51
	Termination level	-5.71	-5.78
Vissering pump 3	Initiation level	-5.58	-5.59
	Extreme initiation level	-5.51	-5.51
	Termination level	-5.70	-5.765

Pumping regime 4 (Relaxed time steering)

The regional water authority expressed the wish to test an alternative pumping regime that largely ignores time based steering and instead focusses on the regular use of pumping stations and on maintaining a steady water level course in the Noordoostpolder. Therefore, pumping regime 4 does not use a distinction between off-peak and peak pump stages for Buma, Smeenge and Vissering. Instead, one uniform set of pump stages is formulated (Table 6) for these structures. Thus, there is no distinction between the off-peak and peak period. In this pumping regime, there will still be a difference between off-peak and peak pump stages for the Marknessersluis, based on reasons explained in paragraph 4.1.2. *Use of pumping stations*.

Table 6 Pumping regime 4 settings

Pumping unit	Pump stages	Off-peak values (m + NAP)	Peak values (m + NAP)	Values (m + NAP)
Marknessersluis lock paddle 1	Initiation level	-4.465	-4.31	/
	Termination level	-4.575	-4.565	/
Marknessersluis lock paddle 2	Initiation level	-4.44	-4.31	/
	Termination level	-4.575	-4.565	/
Smeenge pump 1	Initiation level	/	/	-4.37
	Termination level	/	/	-4.60
Smeenge pump 2	Initiation level	/	/	-4.68
	Termination level	/	/	-4.60
Buma pump 1	Initiation level	/	/	-5.647
	Termination level	/	/	-5.8
Buma pump 2	Initiation level	/	/	-5.643
	Termination level	/	/	-5.785
Buma pump 3	Initiation level	/	/	-5.62
	Termination level	/	/	-5.77
Vissering pump 1	Initiation level	/	/	-5.635
	Termination level	/	/	-5.79
Vissering pump 2	Initiation level	/	/	-5.616
	Termination level	/	/	-5.78
Vissering pump 3	Initiation level	/	/	-5.59
	Termination level	/	/	-5.765

Pumping regime 5 (Decreased inlet)

Pumping regime 5 uses the same set of pump stages as pumping regime 1 (Table 3). The same is true for the definition of the off-peak period: 23:00-07:00 for the pumping stations. The feature that differentiates it from the other pumping regimes is that the inlet input is decreased by 20%. The reason behind this alteration is that the Zuiderzeeland RWA currently discharges large quantities of water into the Noordoostpolder during the spring and summer. This is done to maintain a proper level of water quality in the Noordoostpolder. Yet, the Zuiderzeeland RW does not exactly know what the financial impact of that amount of water inlet is.

Pumping regime 6 (3 Days ahead)

This pumping regime uses the same settings of pumping regime 3 (Day ahead). The difference between this two pumping regimes is that instead of basing the decision whether to pump or not on the comparison between the current day electricity price and the day-ahead electricity price, the comparison period is extent: in this pumping regime, the decision to pump or not to pump is based on the comparison between the average price of the current day and the expected price 3 days ahead. The Zuiderzeeland RWA wants to find out whether looking even further in the future would yield more financial gains compared to looking only at the day-ahead prices. For Smeenge, Buma and Vissering, the off-peak period is 23:00-07:00. The 3 days ahead price steering mechanism is not used for Smeenge for the same reason as explained in the paragraph *Pumping regime 3 (Day ahead)*.

Pumping regime 7 (Increased bandwidth)

Pumping regime 7 uses the same day-ahead price based steering as used in pumping regime 3. What makes it different from pumping regime 3 is that the extreme initiation level, set up to prevent that the water level exceeds the upper water level limit (-5.5 m + NAP), is adjusted to a level of -5.45 m + NAP (Table 7). This modification is spurred by the question of the Zuiderzeeland RWA whether maintaining their strict bandwidth would hamper pumping regimes like pumping regime 3 in finding the optimal time and date to activate their pumps. The off-peak period runs from 23:00 to 07:00. The day ahead price steering mechanism is not used for Smeenge for the same reason as explained in the paragraph *Pumping regime 3 (Day ahead)*.

Table 7 Pumping regime 7 settings

Pumping unit	Pump stages	Values peak period (m + NAP)	Values off-peak period (m + NAP)
Marknessersluis lock paddle 1	Initiation level	-4.31	-4.465
	Termination level	-5.51	-5.51
Marknessersluis lock paddle 2	Initiation level	-4.31	-4.44
	Termination level	-5.45	-5.45
Smeenge pump 1	Initiation level	-4.35	-4.405
	Termination level	-5.45	-5.45
Smeenge pump 2	Initiation level	-4.345	-4.395
	Termination level	-5.45	-5.45
Buma pump 1	Initiation level	-5.595	5.647
	Extreme initiation level	-5.45	-5.45
	Termination level	-5.72	-5.8
Buma pump 2	Initiation level	-5.59	-5.643
	Extreme initiation level	-5.45	-5.45
	Termination level	-5.71	-5.785
Buma pump 3	Initiation level	-5.57	-5.62
	Extreme initiation level	-5.45	-5.45
	Termination level	-5.70	-5.77
Vissering pump 1	Initiation level	-5.61	-5.635
	Extreme initiation level	-5.45	-5.45
	Termination level	-5.72	-5.79
Vissering pump 2	Initiation level	-5.605	-5.616
	Extreme initiation level	-5.45	-5.45
	Termination level	-5.71	-5.78
Vissering pump 3	Initiation level	-5.58	-5.59
	Extreme initiation level	-5.45	-5.45
	Termination level	-5.70	-5.765

3.3.2. SOBEK data output

The Zuiderzeeland RWA made available a SOBEK Rural model for the calculation of the water input values for the MATLAB model. SOBEK Rural is a software system made for the modelling of hydrological processes in polders. The SOBEK Rural model supplied by the RWA consists of the complete water system network of the Noordoostpolder, including all major hydraulic structures mentioned in this report. in theory, this model is used to model the different pumping regimes. However according to hydrologists at the Zuiderzeeland RWA, this model was only created by an external consultancy organization to simulate extreme conditions, making it unfit to be used for simulating the different pumping regimes within the scope of this research. Therefore the model is only used to extract the required data input for the MATLAB models. The SOBEK Rural model required two input variables: the hourly precipitation values and the daily evapotranspiration values. The data for the precipitation and evapotranspiration values are taken from the KNMI meteorological weather station Marknesse in the Noordoostpolder. The output data consists of the sums of the hourly discharge values for the three pumping stations Smeenge, Vissering and Buma. Since the results showed that the use of 1 hour time steps in the model leads to very abrupt differences in discharge from hour to hour, the data is smoothed for the first SOBEK output variable, *Qsobek*. This is done by calculating the value for each timestep by taking the average of all values during 8 hour intervals in Excel. The same method is used taking a 12 hour interval, but it did not lead to different results. The variable *Qsobek* uses these values as input values for the MATLAB model.

The second output variable is the inlet. The Zuiderzeeland RWA discharges water into the Noordoostpolder to sustain a proper water balance during dry times. The SOBEK Rural model however does not take this factor into account. To determine the proper inlet values, the real world discharge measurements of all three pumping stations are taken from the RWA databank FEWS. The consulted expert of the RWA defined the inlet period as being between the beginning of may till the end of September. The discharge values of SOBEK are subtracted from the discharge values from FEWS for each timestep. Within the research period, there are four inlet periods: three full inlet periods in the years 2017,2018,2019 and the first month of the 2020 inlet period. for each inlet period, the average difference between the FEWS and SOBEK discharge is calculated. This average is used for all the values of that individual inlet period for the sake of continuity.

3.3.3. MATLAB model

The water system of the Noordoostpolder is simulated in a MATLAB bucket model. The Hoge and Lage afdeling are modelled like a bucket, with an inflow and outflow (Figure 4, under *MATLAB model*). The goal of the MATLAB model is to determine the water level fluctuations in the Noordoostpolder and to simulate the discharge per time unit of the four major hydraulic structures: Buma, Smeenge, Vissering and Marknessersluis. Three components of the MATLAB model are explained: time, the course of the water levels and the model algorithm.

Modelling course of water levels

Two equations are constructed for the two Noordoostpolder areas in order to calculate the change in water level for every time step k. Due to practical constraints, the water level fluctuations are not calculated for several locations in each afdeling. Instead, the so-called indicative polder water level is used. An indicative polder water level is a method in use for eastern and southern Flevoland (part of the Zuiderzeeland RWA jurisdiction) that calculates the average water level per time period based on several measurements at different locations in the polder. The water levels WP_{hoog} and WP_{laag} are thus indicative polder water levels. The variables *Qsobek* and *Inlet* have a factor added to them. The factor divides the water inflow of these two variables based on the share of surface area. The total surface area of the Lage and Hoge afdeling combined is 9000+39000=48000 Ha. For the Hoge afdeling, the factor is 9000/48000= 0.1875. For the Lage afdeling, the factor is 39000/48000=0.8125.

Equation 1 Hoge afdeling

$$wp_{hoog(k)} = \left(Qsobek(k) * \frac{0.1875}{area_{hoog}}\right) + (Inlet(k) * \frac{0.1875}{area_{hoog}}) - \left(\frac{Qsluis1(k)}{area_{hoog}}\right) - \left(\frac{Qsluis2(k)}{area_{hoog}}\right) - \left(\frac{Qsmeengepomp1(k)}{area_{hoog}}\right) - (\frac{Qsmeengepomp2(k)}{area_{hoog}})$$

Equation 2 Lage afdeling

$$wp_{laag(k)} = \left(Qsobek(k) * \frac{0.8125}{area_{laag}}\right) + (Inlet(k) * \frac{0.8125}{area_{laag}}) + \left(\frac{Qsluis1(k)}{area_{laag}}\right) + \left(\frac{Qsluis2(k)}{area_{laag}}\right) - \left(\frac{Qbumapomp1(k)}{area_{laag}}\right) - \left(\frac{Qbumapomp2(k)}{area_{laag}}\right) - \left(\frac{Qbumapomp3(k)}{area_{laag}}\right) - \left(\frac{Qvisseringpomp1(k)}{area_{laag}}\right) - \left(\frac{Qvisseringpomp2(k)}{area_{laag}}\right) - (\frac{Qvisseringpomp3(k)}{area_{laag}})$$

Time

The run time of the model is three years and four months, as determined in paragraph 3.3.1 . The timesteps k are set at 5 minutes. Time steps of 5 minutes are chosen for the reason that small timesteps allow a larger degree of control over pumping activity than larger time steps.

Model algorithm

Three different MATLAB algorithms have been developed to model the alternative pumping regimes. Figure 5 shows algorithm 1. Algorithm 1 is the general algorithm in use for modelling the pumping activity of Smeenge, Buma and Vissering based on the pump stage levels defined in paragraph 3.3.1. . The second algorithm (algorithm 2) is used to model the pumping activity for the Marknessersluis (appendix C, Figure 25). Since the Marknessersluis is instructed to shut down every time Smeenge is activated, an extra code had to be added. The most complex of all is algorithm 3 (Figure 6). This algorithm models the price based steering mechanism. Basically, this algorithm is an extended version of algorithm 1. The main difference is that compared to algorithm 1, algorithm 3 has more conditions to be met before pumping activity can start. Arguments are added to the MATLAB code that evaluate whether the electricity prices of the current day are smaller than those of the future day of interest. If not, there will be no pumping activity unless the water level reaches the extreme initiation water level. Adding this code makes it possible to research the impact of steering directly on electricity costs. Figure 26 in appendix C gives an overview of which algorithm is used for which pumping station for every alternative pumping regime. Figure 27, Figure 28 and Figure 29 (all appendix C) provide a more detailed description of algorithms 1, 2 and 3 respectively.

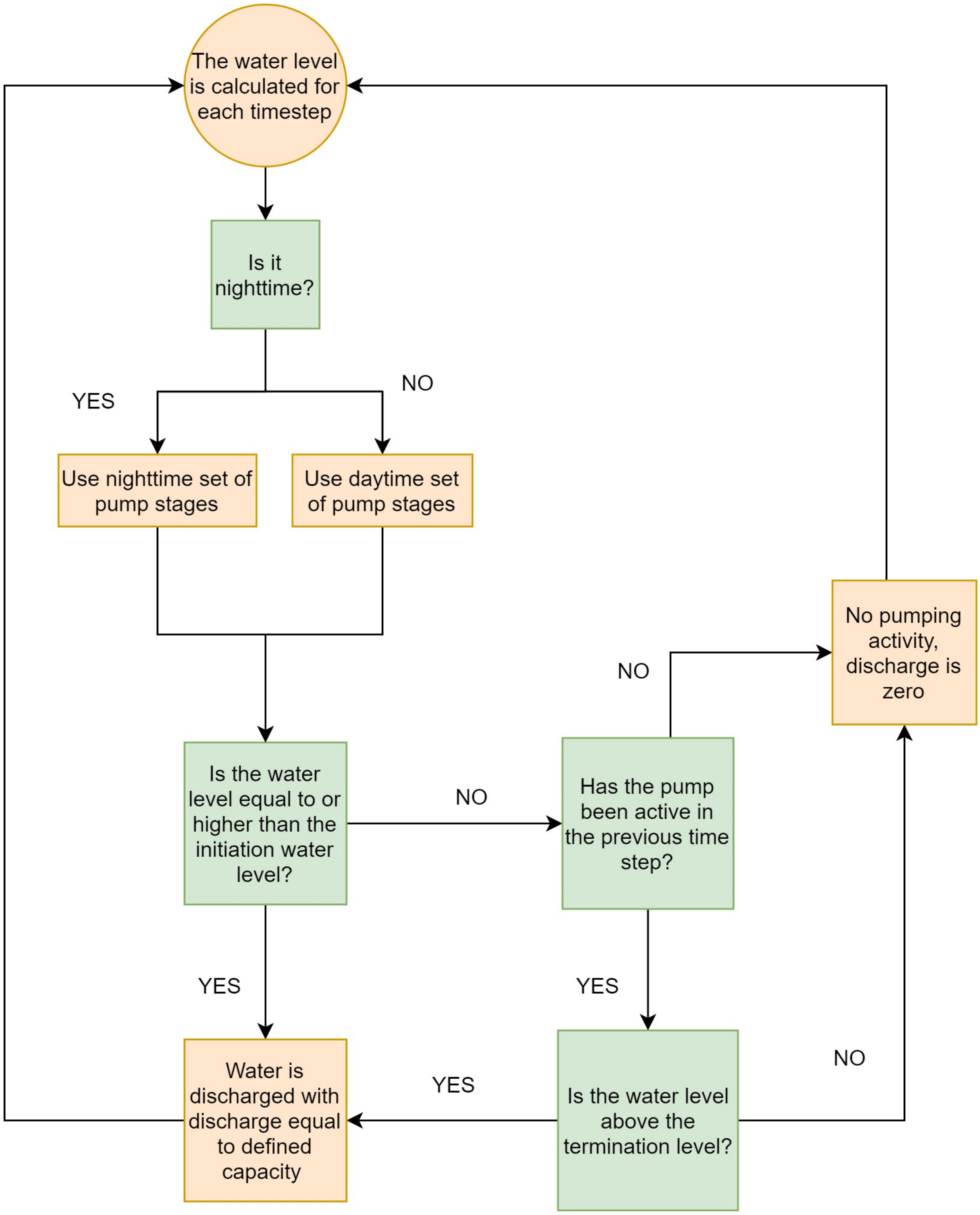

Figure 5 Algorithm 1

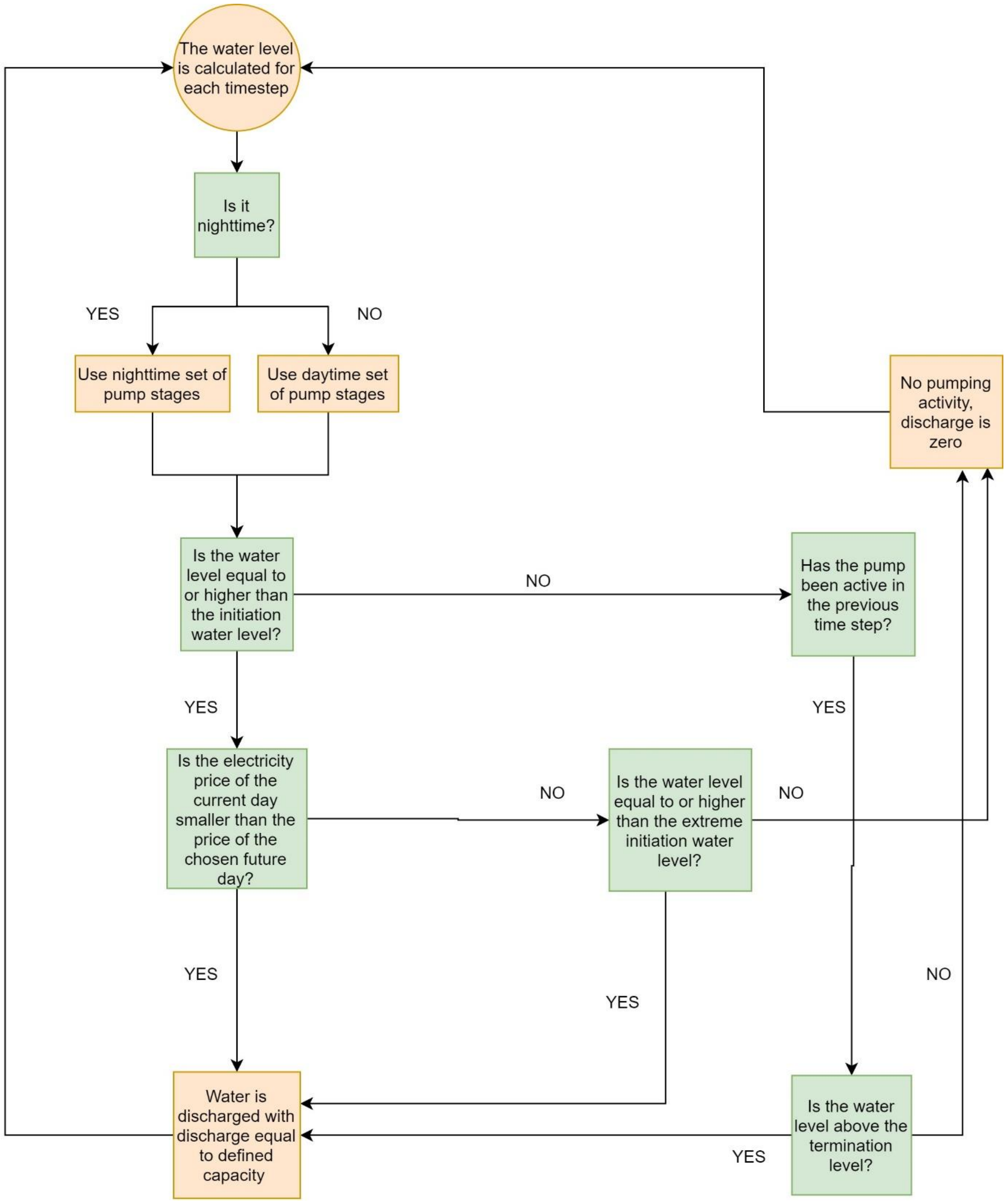

Figure 6 Algorithm 3

3.3.4. Calibration of MATLAB model

The MATLAB model is calibrated on four aspects:

- Total amount of activity
- Ratio between peak and off-peak period activity
- Timing of activity
- Water levels in each accompanying section (afdeling)

These aspects have a large influence on the model results and are therefore included in the calibration of the MATLAB model. Data for these four aspects is available at the FEWS databank. The pump initiation and termination water levels are the model parameters used for the calibration of the MATLAB model. The model is calibrated for the years 2017, 2018 and 2019, while in that period one uniform off-peak and peak period definition was used. That makes it possible to more accurately compare model results with the FEWS measurements. First, the discharge data from FEWS for the pumping stations Smeenge, Vissering and Buma is taken. In Excel, the total amount of active hours for each individual off-peak and peak period is calculated for both MATLAB and FEWS. The second step is to retrieve the relevant water level data from FEWS. For the Hoge afdeling, the water level data from the Marknessersluis is used. For the Lage afdeling, measurement point *Havenstraat* provides the water level data. It should be noted that these measurement point only provide a general indication of the average water level course in their respective sectors. Also, the Zuiderzeeland RWA retains a high degree of flexibility in their control op pump termination and initiation levels. Therefore, the decisions is made to base the course of water levels in MATLAB on the periods in FEWS that fits that description the best. By using the pump stages from Table 9 and by making numerous iterations, the correct set of initiation and termination water levels for each pumping structure is determined. These settings are used for the settings of the first alternative pumping regime.

3.3.5. Calculation of electricity costs

The MATLAB models calculate the discharge for each individual pump for each timestep. In Excel, the total discharge for every pumping station per timestep is calculated. The next step is to calculate the electricity consumption per timestep. This is done by using the average electricity consumption of each pumping station per 1000 m^3 of discharged water as determined in research question 1. The results of this step are multiplied with the electricity MWH hour price of that timestep. The total electricity costs are presented as the total costs of electricity per year. The electricity costs are calculated for the wet season, dry season and average season periods as defined in paragraph 4.2.2. The operating hours are part of this research question. The operating hours are calculated by assigning the value of 1 to each time step with an discharge in Excel and a 0 to all timesteps without any discharge. This is done on an individual basis for each pump. Taking the sum of all the timesteps with active pumps and dividing it by 12 (12 sets of 5 minutes per hour) yields the number of operating hours. The operating hours are likewise calculated for the same research periods as the costs of electricity.

3.3.6. Water level and water level fluctuations

The MATLAB models calculate the water levels for each timestep for both the Hoge and Lage afdeling. The results are given in two categories: the water levels and the water level fluctuations. To quantify the water level, four water level intervals are defined for each 'Afdeling'. Two of these water level intervals cover the water levels outside the upper and lower boundaries of the water level allowable bandwidth (see also 4.1.2. paragraph *Target water levels*). The other two respectively cover the 10 cm below the upper boundary and the 10 cm above the lower boundary. Figure 7 provides a visualization of these intervals in relation to the water levels. For each water level interval, the percentage of time for which the water levels falls within that interval is calculated. The results of these calculation give an indication to the question how stable the average water level course is for every alternative pumping regime.

The fluctuations itself are also part of the results. For each 24 hour period between 12 o' clock in the afternoon, the maximum and minimum water level is determined using Excel. The difference between these values is taken as the fluctuation. To evaluate this data properly, the fluctuations are sorted for each pumping regime, from high to low. This allows for a more clear overview of the results.

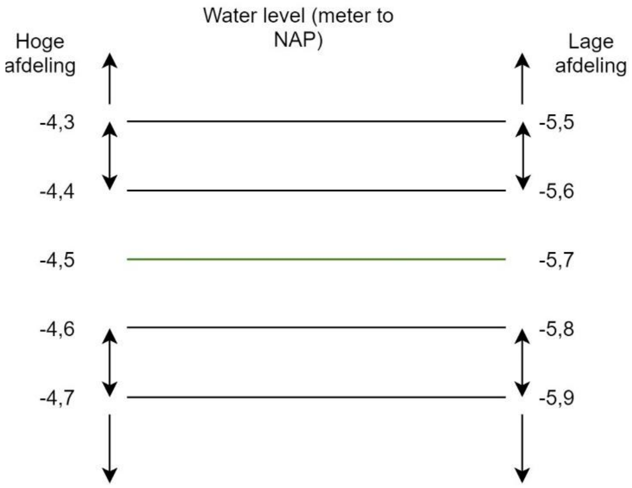

Figure 7 Interval water level for quantification research question 4

4. Results

4.1. Results research question 1

The water management policies of the Zuiderzeeland regional water authority are derived from the four main tasks assigned by law (in the *Waterwet,* or water law) to the institution of a regional water authority (Petie & Borneman, 2019). These four tasks (as mentioned in paragraph 1.1) determine the responsibilities for the Zuiderzeeland RWA concerning water level management in the Noordoostpolder. Three out of the four tasks mentioned in paragraph 1.1 are relevant for water level management in the Noordoostpolder:

1. Protection against flooding
2. Maintaining appropriate water levels
3. Maintaining a sufficient level of water quality in the open water bodies

In particular task 2 is important for the determination of '*streefpeilen',* or target water levels inside polders. Target water levels are established by measure of a *'peilbesluit'.* A *peilbesluit,* or loosely translated water level decree, is a comprehensive document containing the target water levels per specific area. A clarification of the determination of the target water levels is given in four parts as part of the peilbesluit: the legal framework, relevant policies and agreements, a description of the area and the examination of the area functions for the `*ontwateringsdiepte*` and `*drooglegging*` values.

The target water level is determined on grounds of the `*ontwateringsdiepte*` and `*drooglegging*` values for the different user functions and interests in an area. In Figure 8, a cross section of a generalized part of the polder is displayed, clarifying some of the water management terms used in this report. The `*ontwateringsdiepte*`, or drain depth in English, is the distance between the ground level (´*maaiveld*´) and the peak of the bulging water ('*opbolling'*). Maintaining the right drain depth is important for farmers in relation to the yield of their crops. The curvature of the water depends on the quality of the drainage system in place. If the correct drainage system is in place, the curvature of the groundwater level below the field will be smaller (Zuiderzeeland, 2010c). The '*drooglegging'*, or drainage, is the distance between the surface water level and the ground level. For the proper control of the relation between surface and groundwater, the regional water authority uses '*droogleggingsnormen'*, or drainage norms. The determination of target water levels is supported by the GGOR methodology, explained in appendix A1, paragraph *GGOR.*

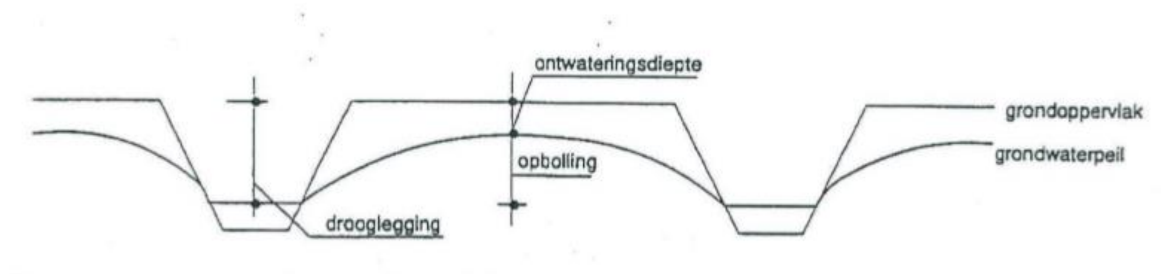

Figure 8 Cross section polder

4.1.1. Factors and functions

As mentioned in paragraph 4.1.1, several factors are important in shaping the management and maintenance in (ground)water levels. Table 8 shows the factors and functions shaping water management (Peilbesluit Hoge en Lage afdeling (Noordoostpolder), 2003) & (Nota Peilbeheer, 2008). In this paragraph, the most important functions and factors for the Noordoostpolder are explained: water quality, agriculture, integrity of canal banks, CO2 emissions and costs of energy. The other functions are briefly explained in appendix A1.

Table 8 Functions and factors pumping regimes

Function
Water quality
Agriculture
Infrastructure
Safety and flood defenses
(Terrestrial nature)
Drainage and sewage systems
Archaeological and historical objects
Land subsidence
Canal banks
CO2 emissions
Financial costs of energy consumption

Water quality

Maintaining the quality of water is one of the core tasks of the Zuiderzeeland regional water authority. The control of the right water levels is important, since water quality is intrinsically linked to water quantity (Rijtema, 1978). The quality of water depends on three things: the source of water, the hydrological variability and in-stream processes (Deparment of agriculture and water resources, 2013). Water levels are part of the second aspect. The EU water framework directive, or abbreviated to KRW in Dutch, determines the boundary conditions by which the water quality of artificial surface water bodies must comply with.

Different water levels have different effects on the water quality. Low water levels have more negative consequences than high water levels. Because of high water levels, substances from pesticides and fertilizers used in agriculture can flow from the land into the water system, causing a drop in water quality (Mettrop et al, 2012). There are several negative effects to low water levels. A possible negative effect is that low water levels create circumstances in which there is a higher chance of eutrophication (Van den Berg et al, 2002). This is predominantly the case in water systems with a relatively balanced amount of nutrients: in water bodies with on average either extreme high or low nutrient concentrations, water level changes have little to no effect.

Another effect of a low water level is an increased inflow of seepage water. Due to the elevation and geology of the Noordoostpolder, seepage water constitutes up to about 1/3 of the total inflow of water into the Noordoostpolder (Peilbesluit Hoge en Lage afdeling (Noordoostpolder), 2003). Depending on the source of this seepage water, the amount of phosphates, chlorides, and nitrates in Noordoostpolder surface water can either decrease or increase. However, due to the fact the

Noordoostpolder is situated on the bottom of a former open sea, seepage water tends to increase the concentration of chlorides. It is a relevant issue for the Noordoostpolder: the Zuiderzeeland RWA discharges water with a relative high concentration of nutrients into nearby lakes like the Vollenhovermeer (Waterschap Zuiderzeeland, 2010a). In times of low water levels, this water including the nutrients can seep back into the polder.

A low groundwater level also impacts the quality of the groundwater (Mettrop et al, 2012). A low groundwater increases the occurrence of nitrification processes, causing the acidification of water and sub-soil.

Canal banks

The stability of the banks of canals and ditches is influenced by the frequency of water level fluctuations (Van den Berg et al, 2002). In the Noordoostpolder, these banks are covered by a combination of grasses and other types of small vegetation like reed. Vegetation supports the stability of canal banks through their roots. Large fluctuations in the form of waves erode canal and riverbanks. Those kind of water level fluctuations do not exist in the Noordoostpolder. Only water level fluctuations with a magnitude of several decimeters per full day occur. It has not been researched yet what the effect of these relatively small water level fluctuations is to the stability of canal banks and the vegetation according to both the report *Ecologische effecten van peilbeheer* (Van den Berg et al, 2002) and experts from the Rijkswaterstaat Waterdienst (RWS-Waterdienst, 2020), water side vegetation. The Zuiderzeeland RWA however suspects that there might be negative consequences from water level fluctuations in the current pumping regime.

Agriculture

Agriculture strongly depends on maintaining the correct groundwater levels and proper drainage system. The optimal water levels depend on the type of subsoil, type of agriculture and type of crop present. In the Noordoostpolder, the most common types of agriculture are field crops, horticulture and fruit growing. Livestock is less common. For smaller crops with smaller roots, the optimal drain depth is about 0,8 to 1 meter below ground level, while for larger plants like fruit trees, the drain depth varies from 1 to 2 meters below ground level (Zuiderzeeland, 2010c). According to (Van den Berg et al, 2002), drought and low groundwater levels can lead to a lower crop yield for farmers. On the other hand, high groundwater levels also cause lower crop yields, causing among other things difficulties for farmer in working their lands and rot in the crops. Water level fluctuations impact crop yields in a similar way: continuous and large fluctuation in groundwater levels cause decreases in crop yield regardless of whether the groundwater levels stay within their appropriate boundaries according to the *Polders* report (Hoes & Van de Giesen, 2015).

On behalf of the Zuiderzeeland RWA, Tauw BV has conducted a study into the effects of altering the current pumping regime (Rommens & Bosma, 2013). A part of that study consisted of measuring the effects of increasing the target water level bandwidth (see paragraph 4.1.3.1.) with ± 10 centimeters. The financial implications of this increased water level flexibility for farmers has been tested for three types of agriculture and crops: potatoes, wetland, and summer vegetables. In appendix A2, Figure 21, the average damage to potato crops has been calculated for the old water level regime and the new (bar charts with *nieuw*). For both the dry and wet scenarios, an increased flexibility for water level management would lead to larger damages, especially in damages incurred due to extreme wetness (purple bars). The results are the largely the same for summer vegetables (appendix A2, Figure 22). For wetlands, the most potential damage is caused by an increased bandwidth in a wet scenario (appendix A2, Figure 23)

CO_2 emissions

The Zuiderzeeland regional water authority desires to reduce its CO_2 emissions (Stapel, 2018). Of all the Dutch regional water authorities, the relative amount of CO_2 emissions emitted to control the local water system in relation to the complete CO_2 consumption of a regional water authority is by far the highest for the Zuiderzeeland RWA: more than 50% of their CO_2 emissions goes towards the regulation and management of their water systems. This is caused by the simple fact that most of their area lies 5 meter below sea level. On average, the Zuiderzeeland RWA emits an estimated 14000 tons of CO_2 per year (Rommens & Bosma, 2013).

Their aim is to achieve a reduction of 30% in greenhouse gasses in the year 2020 compared to 1990 (Rommens & Bosma, 2013). This goal has several ramifications for the Noordoostpolder pumping regime. The most relevant for this report is the reduction in CO_2 emissions, which is directly related to the operating hours of the pumping stations. A decrease in the number of operating hours leads to a decrease in CO_2 emissions.

Financial costs of electricity consumption

As mentioned in the paragraph 2.3. *Relevance of research,* the energy costs of regulating the water system are 16 % of the total energy consumption by the Zuiderzeeland RWA. Although the regulation and control of water levels in the Noordoostpolder according to the water level decree is the most important priority in pumping regimes and local water management, keeping the costs of electricity down at an acceptable level is a close second. According to hydrologists at the regional water authority, the direction of the Zuiderzeeland RWA has recently made it clear that in the coming years a considerable reduction in energy costs has to be achieved, although no clear target has been set as of yet, according to hydrologists at the Zuiderzeeland RWA.

4.1.2. Pumping requirements

Target water levels

The pumping requirements for the Noordoostpolder are area specific, according to the corresponding water level decree of these areas. In Figure 9, the target water levels for Flevoland are displayed. In this report, the focus is on target water levels directly related to the three pumping stations in the Noordoostpolder. In the Noordoostpolder, a dynamic water level management is in place since 2015 (Waterschap Zuiderzeeland, 2015). Dynamic water level management allows water levels to fluctuate within a certain bandwidth. The Zuiderzeeland RWA uses dynamic water level management to mitigate the effects of dry and wet periods.

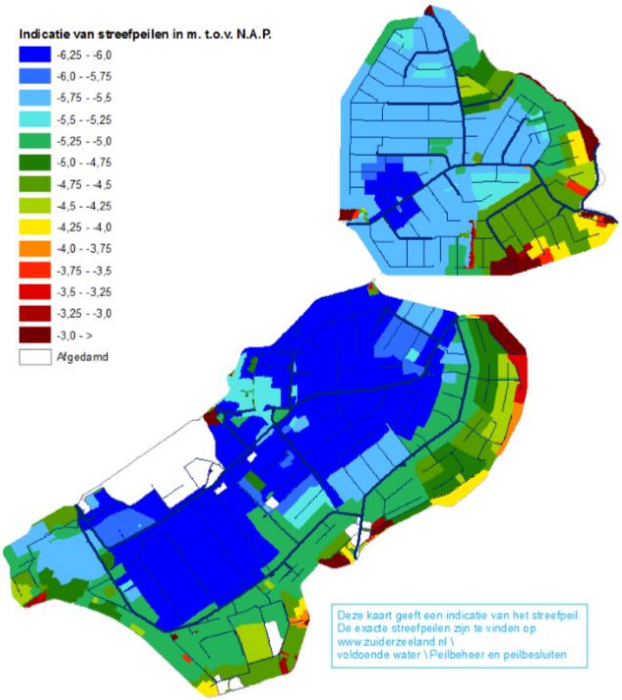

Figure 9 Target water levels Flevoland

The general target water levels for the areas in the vicinity of the hydraulic structures are displayed in Table 9, as derived from the general water decree for both the low and high sections of the Noordoostpolder (Peilbesluit Hoge en Lage afdeling (Noordoostpolder), 2003). The Zuiderzeeland RWA uses a bandwidth of ± 0.2 meters for target water levels, but the pumps start before that threshold has been reached as is clarified with the pump initiation level in Table 9. The Zuiderzeeland RWA only allows exceedances of this bandwidth during extraordinary weather conditions, for 10 to 20 days per year (Peilbesluit Hoge en Lage afdeling (Noordoostpolder), 2003). Once the pump initiation level has been reached the water level is brought back to the pump termination level. Different pump initiation and termination levels are in use for off-peak and peak periods. Lower pump initiation levels are used in off-peak hours, in order to stimulate the use of pumping stations while energy costs are lower. Depending on the hydrological circumstances, the Zuiderzeeland RWA decides which levels are appropriate. In case of prolonged and/or heavy precipitation, the pump initiation levels are close to or the same as the target water levels. Within hydraulic structures, different initiation and termination are applied to the different pumps or lock paddles. The values of Table 9 are therefore indicative averages.

Table 9 Target water levels and pump stages

Hydraulic structures	Target water level (m + NAP)	Pump initiation level (m + NAP)	Pump termination level (m + NAP)
Buma	-5.70	-5.60/-5.70	-5.80/-5.90
Vissering	-5.70	-5.60/-5.70	-5.80/-5.90
Smeenge	-4.50	-4.40/-4.50	-4.60/-4.70
Marknessersluis	-4.50	-4.40/-4.50	-4.60/-4.70

Quantity of waterflows in the Noordoostpolder

The basic water balance of the Noordoostpolder is explained in paragraph 1.3. Based on information derived from the *WaterTakenPlan Noordoostpolder* (Stapel, 2018), the value for the total yearly Noordoostpolder water discharge by pumping stations is displayed in Table 10. It should be noted that the values for the in- and outflowing streams are different each year. This table thus provides only a general indication.

Table 10 Water balance

Inflowing streams (in million m^3/year		Outflowing streams (in million m^3/year)	
Precipitation	310	Pumping	350
Seepage	175	Evapotranspiration	220
Inlet + other sources	85		

Use of pumping stations

The approximately 350 million cubic meter of water discharged out of the Noordoostpolder by pumping stations is not distributed equally over Buma, Smeenge and Vissering. According to the Zuiderzeeland RWA pumping policy (Waterschap Zuiderzeeland, Gemalenplan 2011-2020, 2010a), the regional water authority has taken this approach for various reasons. Of all pumping stations, Smeenge is used the least. The reason behind this policy is that Smeenge discharges water with a relatively low water quality into the Vollenhovermeer. This matters, because water from the Vollenhovermeer is used by farmers, especially those in the fruit picking sector. Besides that, the Vollenhovermeer is part of a designated Natura 2000 area, thus falling under the KRW directive for water quality. On average, Smeenge is used 200 to 500 hours per year (Waterschap Zuiderzeeland, 2015). For the Hoge afdeling, the most frequently used structure is the Marknessersluis, responsible for up to 90 % of the Hoge afdeling discharge according to the experts at the RWA. However, if one of the pumps of Smeenge is activated, the Marknessersluis ceases all its activities at once. Also, the Marknessersluis is used almost exclusively between 22:00 and 06:00. The reason behind this is that the use of the sluice complex beyond this hours obstructs shipping through the sluice itself. Only in rare occasions is the Marknessersluis used beyond this time limit, according to experts at the RWA. Pumping station Vissering is the second most active pumping station. Vissering is powered by diesel instead of electricity and is therefore officially designated as a minor power plant. In summer times, the use of Buma is preferred over the use of Vissering due to the fact that Vissering does not have to produce power for sources other than the regional water authority. In the winter, that policy is reversed: Vissering will be put into action first, before Buma. Vissering is used approximately 2500 hours per year and Buma an approximate 6000 to 7000 hours per year (Waterschap Zuiderzeeland, 2015).

4.1.3. Technical characteristics hydraulic structures

The energy consumption of pumping stations is determined by three factors:

- Efficiency of the pumps
- The amount of water that needs to be pumped
- The pumping head

The pumping head is the difference between the water level inside the Noordoostpolder and the water level of the surrounding lakes. The IJsselmeer has water levels between -0.2 and -0.4 m + NAP (Rommens & Bosma, 2013). A large pumping head means that the pumps need more power to pump water and thus use more energy. Although the IJsselmeer water level is expected to increase in the coming decades, the Zuiderzeeland RWA does not see any problems in the medium turn for the ability of pumping stations to pump the required volumes of water (Waterschap Zuiderzeeland, 2010a). Therefore, the factor of pumping head is not taken into account in the modelling of pumping regimes in this report. The efficiency of pumps differs per pumping station and thus has an impact on the energy consumption of the pumping station. In Table 11, the electricity use in KwH per 1000 cubic meters of pumped water is displayed, as is the discharge in cubic meters per minute. For Vissering, relevant data about the specific electricity consumption is not available yet. Therefore it is assumed that the average electricity use of Vissering is similar to that of Buma, since both pumping stations are roughly equal in size and capacity. The Marknessersluis does not use pumps. The values for the electricity use were taken from (Rommens & Bosma, 2013) and are averages calculated by a consultancy firm commissioned by the Zuiderzeeland RWA. The pumping capacities were taken from (Waterschap Zuiderzeeland, 2010a).

Table 11 Data pumping stations

Pumping station	Energy source of pump	Pumps and power output	Maximum discharge capacity per pump (m^3/minute)	Average electricity use (KWH/1000 m^3 water)
Buma	Electricity	P1100 (850 kW)	720	21.5
	Electricity	P1200 (850 kW)	720	
	Electricity	P1300 (850 kW)	720	
Smeenge	Electricity	P1100 (630 kW)	620	17.5
	Electricity	P1200 (630 kW)	620	
Vissering	Gas	P1100 (1070 kW)	800	21.5
	Diesel	P1200 (1110 kW)	720	
	Gas	P1300 (1070 kW)	800	
Marknessersluis	/	Lock paddle 1	200	/
		Lock paddle 2	200	

4.2. Results research question 2

4.2.1. Electricity prices

The Zuiderzeeland regional water authority has two different types of electricity contracts according to the consulted Zuiderzeeland RWA expert. For pumping station Buma, electricity prices depend on the hourly electricity prices as determined by the Dutch APX electricity market. For pumping station Smeenge, the electricity costs are determined by fixed prices for off-peak and peak periods. After the renovation of Vissering is completed, the pumping station is planned to use the same fixed price contract as Smeenge. Therefore, the fixed price contracts are also used for Vissering.

As mentioned before in paragraph 1.2, most pumping is done in the off-peak period between 20:00 and 08:00, at least for pumping station Smeenge. Before 2020, the off-peak period was defined as 23:00-07:00. For each year, new fixed prices are determined. Table 12 shows the prices for the period 2017-2020.

Table 12 Fixed electricity prices

Year	Peak price (€)	Off-peak price (€)
2017	50.66	34.61
2018	44.42	29.50
2019	43.81	31.83
2020	61.41	46.85

Based on the APX hourly electricity prices from 2018, a graph (Figure 10) was constructed that compares the hourly average electricity prices to the daily average electricity price. The hourly prices based on the APX exchange price rates are stored in excel sheets, providing all the price data needed to quantify the costs of energy in research question 3. The electricity prices used for the quantification of the electricity costs for pumping stations Smeenge and Buma are the bare prices: taxes and any other surcharges are not included.

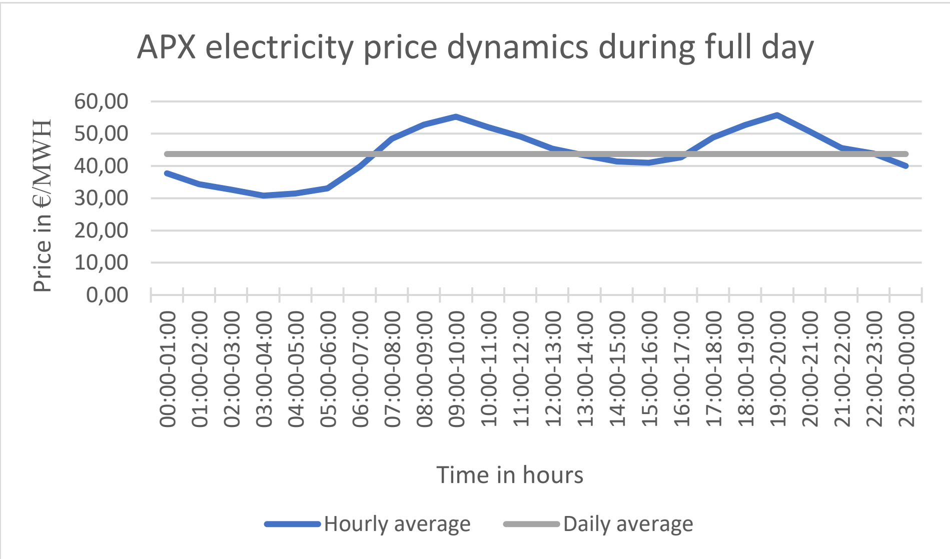

Figure 10 APX electricity price dynamics during a full day

In Figure 24, the daily electricity price dynamics graph of the Dutch energy market in the year 2016 is displayed (Roland Berger Consultancy, 2017). Overall, the electricity price trend from Figure 24 closely resembles the electricity price dynamics trendline constructed in Figure 10.

4.2.2. Research period

To research the effects of the pumping regimes on electricity costs and water level fluctuations, a period of 3 years and 4 months has been chosen, corresponding with the period running from 1 January 2017 to the 30th of April, 2020. Figure 11 shows the balance between precipitation and evapotranspiration for each month of the research period. Besides the whole three year and four month period, three smaller periods with a duration of four months each will also be used to evaluate the effects of pumping regimes. These three periods are a comparatively wet period, a dry period an average period.

For the wet season period, the months 9, 10, 11 and 12 are used, translating to the months of September, October, November and December in 2017. For the dry season period, the months 29, 30, 31 and 32 are used: the months of May, June, July and August in 2019. For the average season period, the months 20, 21,22 and 23 are the most suitable: August, September, October and November 2018.

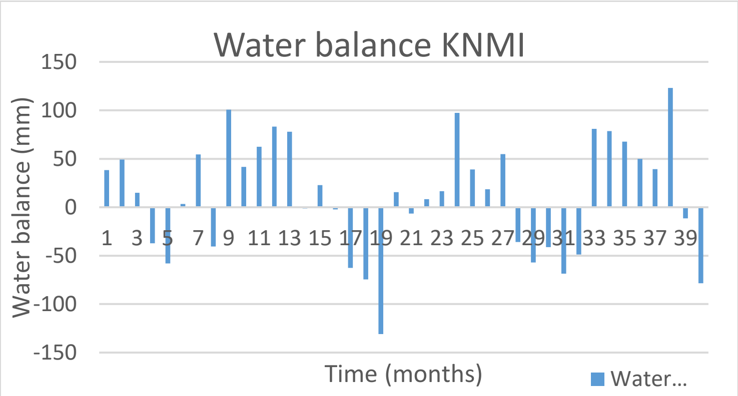

Figure 11 Graph water balance KNMI data

4.3. Results research question 3

4.3.1. Data validation

Figure 12 shows the discharge values from the SOBEK Rural model the values taken from the FEWS databank. The results of SOBEK closely resemble the values from FEWS, although the SOBEK values are smaller. This is mainly the case in the dry seasons. The reasons behind this phenomenon is likely that data from only a single KNMI meteorological station was available. Since this periods coincides with the inlet period of the Zuiderzeeland RWA, the difference between FEWS and SOBEK is used to create an inlet input factor (Figure 13).

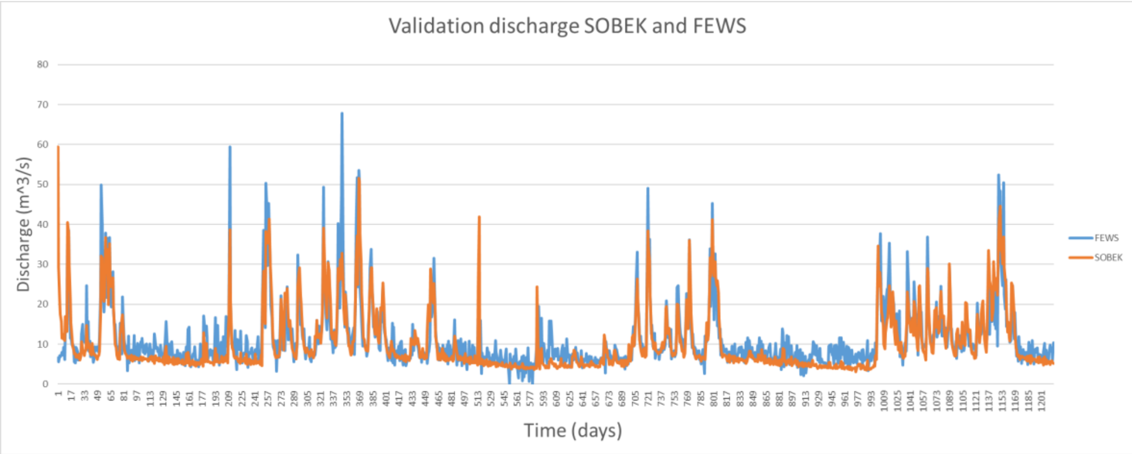

Figure 12 Validation SOBEK versus FEWS

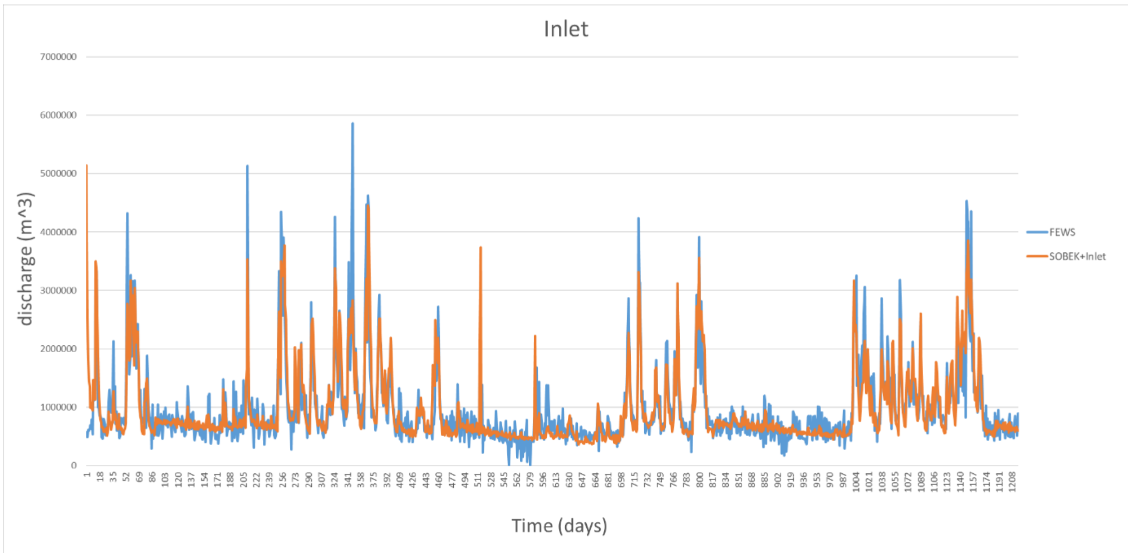

Figure 13 Inlet

4.3.2. Calibration MATLAB model

Figure 14 shows the pumping activity over the course of three years. The activity as determined by the MATLAB settings for Smeenge closely resembles the activity measured by FEWS. The ratio off-peak and peak period activity (see Table 17) is the basically the same as in FEWS. Figure 30 and Figure 31 (appendix E) show the course of the water levels in the Hoge afdeling. As Figure 30 shows, in reality the Zuiderzeeland RWA uses three different sets of pump stages: winter, summer and an intermediate set. The intermediate set is taken as the set of water levels the model should approximate, since the intermediate set fluctuates most consistently around the target water level for the Hoge afdeling. Figure 31 shows a more detailed look at the course of water levels. The water levels calculated by the MATLAB model display a so called 'sawtooth' pattern: increasing water levels during the day and a decrease during the night due to pumping activity. The pumping activity of Vissering (Figure 33, appendix E) as modelled in MATLAB also approaches the pumping activity as it was measured in reality. Buma (Figure 32, appendix E) pumps more consistently in the MATLAB model than in reality due to the flexible handling of pump stages by the RWA. Both pumping stations have a well tuned total activity and off-peak/peak period ratio (Table 17, appendix E). The water level course of the Lage afdeling (Figure 34 and Figure 35, appendix E) displays the correct night and day 'sawtooth' pattern as required.

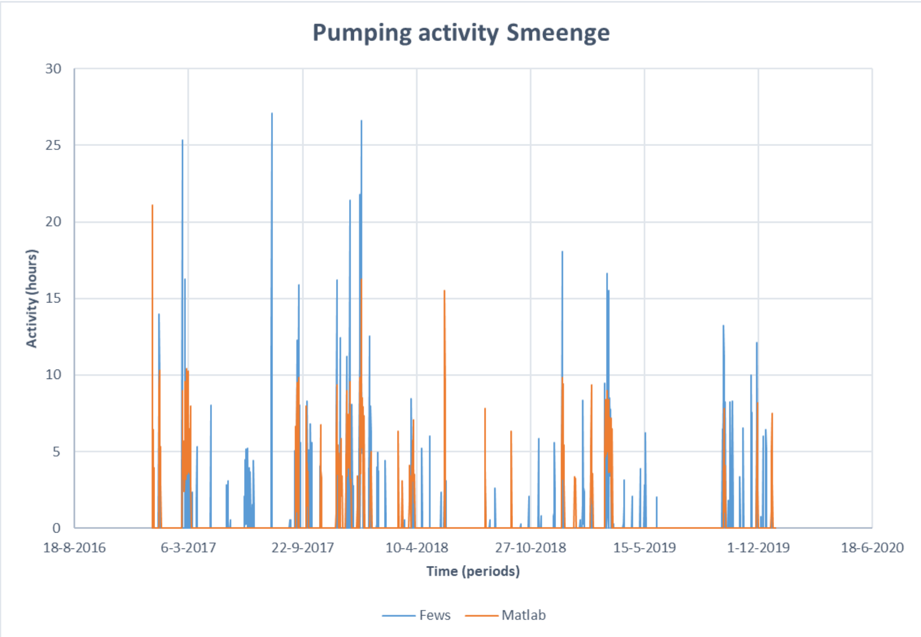

Figure 14 Pumping activity Smeenge

4.3.3. Costs of electricity

Figure 15 shows the costs of electricity on a yearly basis for each of the alternative pumping regimes. Pumping regime 3 '*Day ahead*' has the lowest yearly electricity costs, at €259047. This is a decrease of slightly more than €38000 compared to the basis scenario of pumping regime 1 ´*Basic*´. Pumping regime 3 '*Day ahead'* is followed at a distance by pumping regime 7 ´*Increased bandwidth*´, which shows a €11700 decrease in electricity costs compared to the basic pumping regime 1. Pumping regime 4 '*Relaxed time steering*' has the highest overall yearly costs: €316703. An interesting result is the difference between pumping regime 1 ´*APX*´ and pumping regime 1 ´*Fixed prices*´. The results show that using only the APX prices could result in a small reduction in electricity costs, while using solely the fixed price contracts has the opposite effect. Between the two other pumping regimes incorporating the price steering mechanism (pumping regimes 6 and 7), it is interesting to see that increasing the bandwidth for allowable water levels in pumping regime 7 leads to a larger reduction in costs than steering on 3 day ahead electricity prices in pumping regime 6. It should be noted that the y-axis of Figure 15 does not start at zero, putting more emphasis on the differences between the pumping regimes. This is also applied to all the other graphs used in this paragraph.

The costs of electricity have also been calculated for three smaller periods: a wet season, a dry season and an average season (see also paragraph 4.2.2 *Research period*). For the wet season research period (Figure 36, appendix F), the results are quite similar to the results of Figure 15. There are small differences however: looking at this period, pumping regime 5 ´*Decreased inlet*´ and pumping regime 2 ´*Smeenge high*´ perform slightly better than pumping regime 7, but only in a magnitude of several hundred up to a thousand Euros. The dry season results (Figure 37, appendix F) show that pumping regime 3 ´*Day ahead*´ again performs the best of all pumping regimes on electricity costs, also under dry season conditions. Pumping regime 4 on its part also remains the most expensive pumping regime. For the average season, the most interesting results concerns the difference in costs between pumping regime 1 ´*APX*´ and pumping regime 1 ´*Fixed prices*´ (Figure 38, appendix F). Pumping regime 1 ´*Fixed prices*´ performs the best of all pumping regimes with an electricity cost of only €48367. On the other hand the nominally more cost-effective pumping regime 1 '*APX*' has electricity costs of €78004, only trumped by pumping regime 4.

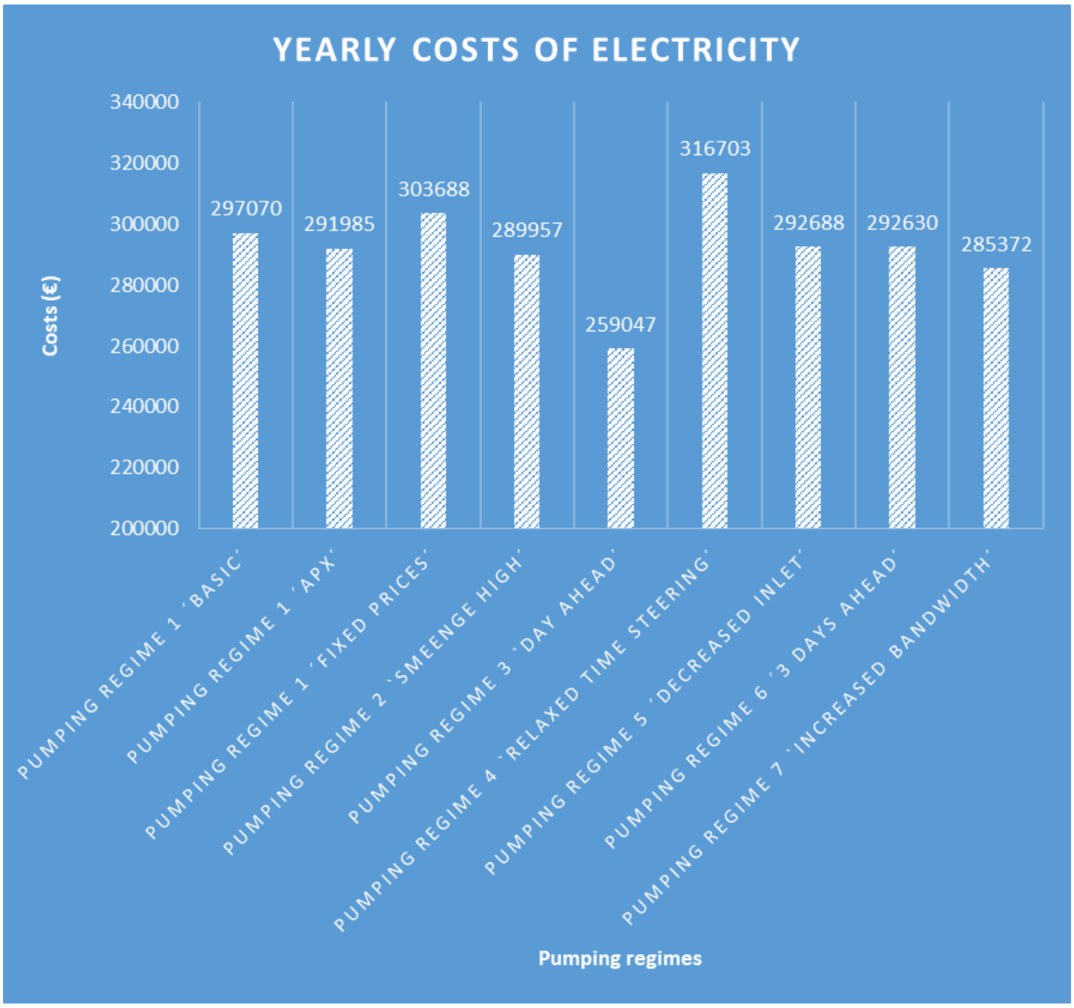

Figure 15 Yearly costs of electricity

Figure 16 shows the number of active operating hours per year for each pumping regime. Pumping regimes 1 ´*Basic*´, ´*APX*´ and ´*Fixed prices*´ are all represented by pumping regime 1 in this graph. Pumping regime 5 ´*Decreased inlet*´ has the lowest number of operating hours for the pumping stations, at 7831 hours. That is an decrease of 73 hours compared to pumping regime 1. The largest reduction of costs in pumping regime 3 ´*Day ahead*´ does not automatically lead to a reduction in operating hours compared to the basic pumping regime 1, but rather to a small increase of 47 hours. Pumping regime 4 ´*Relaxed time steering*´ has the largest amount of operating hours, at 8223 hours. Increasing the share of Smeenge in pumping regime 2 ´*Smeenge high*´ leads also to a relatively sharp increase in operating hours: 8142 hours. The three pumping regimes operating on a price-steering mechanism (pumping regimes 3, 6 and 7) show remarkable little difference in operating hours among themselves. It should be noted that the y-axis of Figure 16 does not start at zero, putting more emphasis on the differences between the pumping regimes. This is also applied to all the other graphs used in this paragraph.

Using different research periods does not lead to considerably different results. Figure 39, Figure 40 and Figure 41 (all appendix F) show the operating hours per pumping regime for respectively the wet, dry and average seasons. An interesting result is that during the dry period instead of pumping regime 4 ‘*Relaxed time steering*’, pumping regime 2 ‘*Smeenge high*’ needs to most operating hours for the pumping stations.

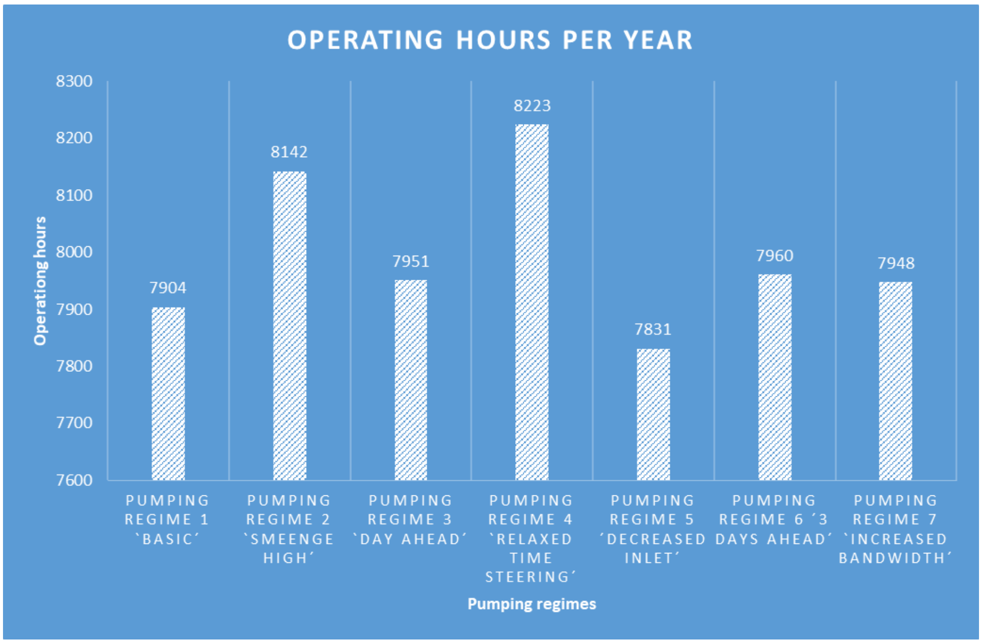

Figure 16 Operating hours per year

4.4. Results research question 4

4.4.1. Water level

For both the Hoge and Lage afdeling, the share in time that their respective water levels are located within a certain water level range is expressed in a percentage per pumping regime. Table 13 shows these values for the Hoge afdeling. Clearly, the water level for all seven pumping regime never exceeds the upper boundary of -4.3 m + NAP. The same is true for the lower boundary of -4.7 m + NAP. The two 10 cm intervals close to both boundaries do show different results. Most of the time, the water levels are located between the -4.4 to -4.6 m + NAP interval (not shown in this table), staying closely to the target water level of -4.5 m + NAP. The water level barely touches the lowest 10 cm interval (-4.6 to -4.7 m + NAP). That is different for the -4.4 to -4.3 m + NAP interval. Here, the table shows that pumping regime 2 ´*Smeenge high*´ has the highest percentage of time (13.16%) that its water levels fall within this range. Pumping regime 4 ´*Relaxed time steering*´ has the lowest percentage (3.57%), due to its relaxed time steering. The rest of the pumping regimes score roughly the same.

Table 14 shows the values for the Lage afdeling. The water levels of all pumping regimes do not exceed the -5.8 m + NAP limit. However, the water levels of pumping regime 7 ´*Increased bandwidth*´ does exceed the Lage afdeling upper boundary of -5.5 m + NAP 23.98 % of the time, as the only pumping regime. For the range of -5.6 to -5.5 m + NAP, it has a lower but still considerably high percentage of 13.73 %. Pumping regime 3 ´*Day ahead*´ and pumping regime 6 ´*3 Days ahead*´ do not exceed the upper boundary, but show with equally high percentages that their water levels fall within the higher water level range: 36.68% and 38.35% respectively. The water levels of pumping regime 4 ´*Relaxed time steering*´ do not appear in any of the four categories, showing the stability of this pumping regime regarding water levels. Pumping regimes 1 ´*Basic*´, 2 ´*Smeenge high*´, and 5 ´*Decreased inlet*´ also stay in close proximity to the target water level.

Table 13 Water level Hoge afdeling

Water level Hoge afdeling (m to NAP)	Pumping regime 1 (Basic)	Pumping regime 2 (Smeenge high)	Pumping regime 3 (Day ahead)	Pumping regime 4 (Relaxed time steering)	Pumping regime 5 (Decreased inlet)	Pumping regime 6 (3 Days ahead)	Pumping regime 7 (Increased bandwidth)
> -4.3	0 %	0 %	0 %	0 %	0 %	0 %	0 %
Between -4.4 and -4.3	4.88 %	13.16 %	4.88 %	3.57 %	4.95 %	4.88 %	4.88 %
Between -4.6 and -4.7	0.05 %	0.77 %	0.05 %	0.07 %	0.05 %	0.05 %	0.05 %
Water level <-4.7	0 %	0 %	0 %	0 %	0 %	0 %	0 %

Table 14 Water level Lage afdeling

Water level Lage afdeling (m to NAP)	Pumping regime 1 (Basic)	Pumping regime 2 (Smeenge high)	Pumping regime 3 (Day ahead)	Pumping regime 4 (Relaxed time steering)	Pumping regime 5 (Decreased inlet)	Pumping regime 6 (3 Days ahead)	Pumping regime 7 (Increased bandwidth)
> -5.5	0 %	0 %	0 %	0 %	0 %	0 %	23.98 %
Between -5.6 and -5.5	0.41 %	0.24 %	36.68 %	0 %	0.38 %	38.35 %	13.73 %
Between -5.8 and -5.9	0 %	0 %	0 %	0 %	0 %	0 %	0 %
Water level <-5.9	0 %	0 %	0 %	0 %	0 %	0 %	0 %

4.4.2. Water level fluctuations

Figure 17 shows the sorted water level fluctuation values for the Hoge afdeling for the full research period. Although the highest fluctuation values initially belong to pumping regimes 1 '*Basic*', 3 *'Day ahead'*, 5 '*Decreased inlet*', 6 *'3 Day ahead'* and 7 '*Increased bandwidth*', overall pumping regime 2 '*Smeenge high*' consistently shows the largest fluctuation values over the course of the full research period. Pumping regimes 1, 3, 6 and 7 all have the same pumping regime settings for the Hoge afdeling. The fluctuations of pumping regime 4 '*Relaxed time steering*' are initially somewhat smaller than the rest of the pumping regimes, but converges after some time with the rest of pumping regimes 1, 3, 5, 6 and 7. The same pattern occurs during the wet, dry and average seasons (Figure 42, Figure 43 and Figure 44, appendix G).

Figure 18 shows the sorted water level fluctuation values for the Lage afdeling. Pumping regime 7 '*Increased bandwidth*' has the highest fluctuation values seen over the complete research period. Pumping regime 7 is closely followed by the two other pumping regimes based on the price steering mechanism: pumping regime 3 '*Day ahead*' and Pumping 6 '*3 Days ahead'*. The most consistent and stable pumping regime is pumping regime 4 '*Relaxed time steering*'. Pumping regimes 1 , pumping regime 2 and pumping regime 5 are shown to have slightly larger fluctuations than pumping regime 4. An interesting result is that during the average season (appendix G, Figure 46), pumping regime 2 is the most stable pumping regime instead of pumping regime 4.

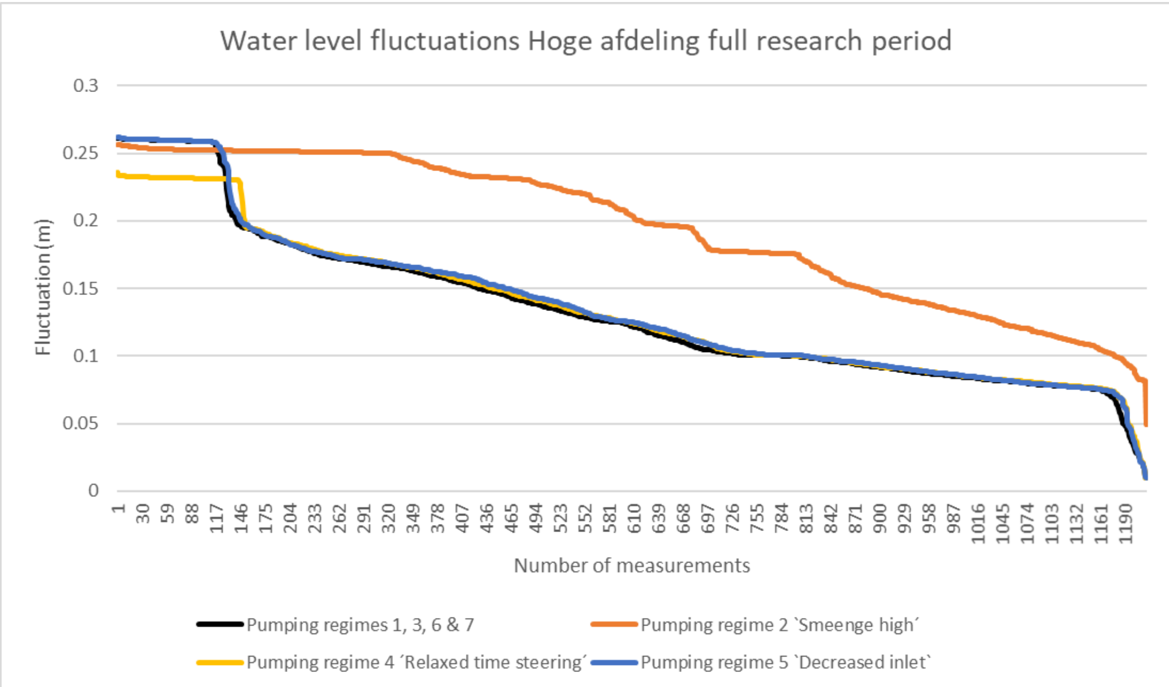

Figure 17 Water level fluctuations Hoge afdeling

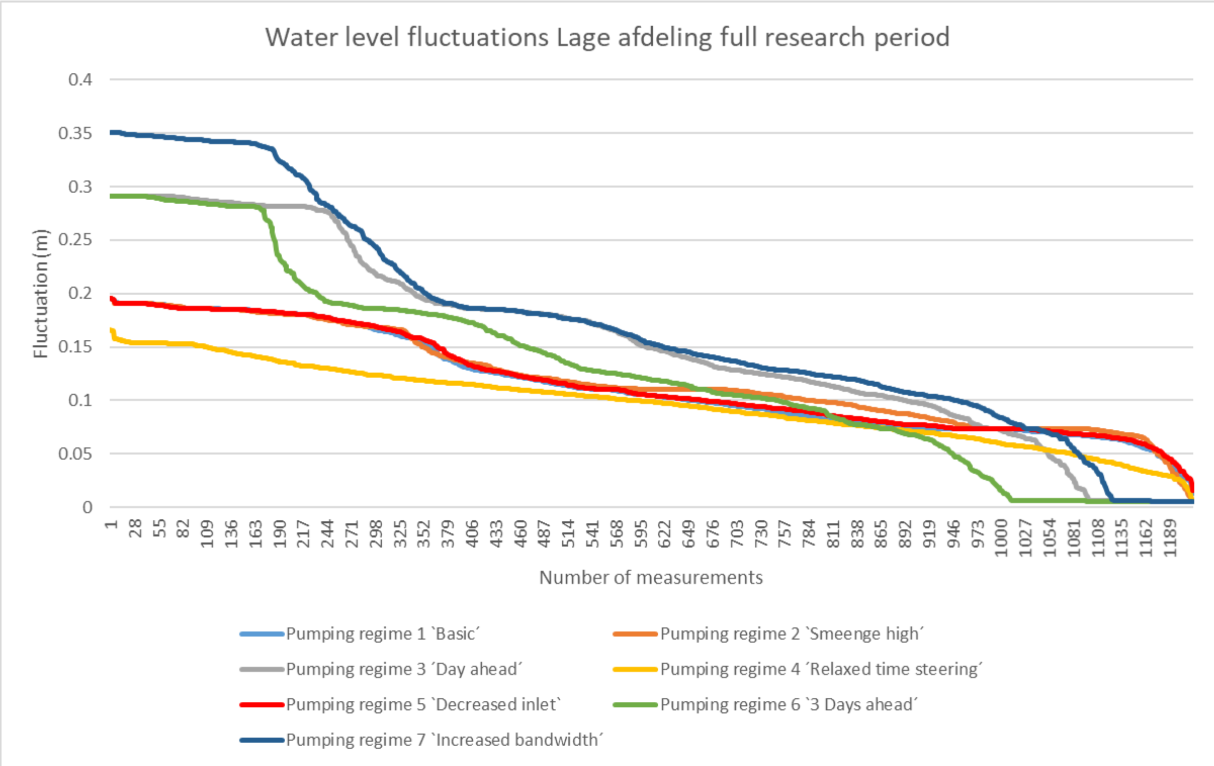

Figure 18 Water level fluctuations Lage afdeling

5. Discussion

In this chapter the methodology, working process, results and the report as a whole are critically examined.

Processing information from Zuiderzeeland RWA experts

At the start of the bachelor thesis process, the plan was to further elaborate on the research done by STOWA (Pothof et al, 2019) and the pilots executed by the regional water authority itself with regard to the establishment of new alternative pumping regimes. However as it turned out during impromptu planned meetings with the hydrologists from the RWA, the hydrologists tendered some very interesting and practical ideas for alternative pumping regimes based on their working experience and knowledge from other colleagues. Their advice was quite successfully incorporated into the design of alternative pumping regimes. The way it is done now might not appear to be very structured or clear to the average reader who is not completely knowledgeable in this subject and in the inner workings of regional water authorities. In hindsight, taking official interviews with Zuiderzeeland RWA hydrologists and other experts might have been a more structured choice.

Modelling and calibration of water level

The MATLAB model is a bucket model, meaning that the Hoge and Lage afdeling are represented like buckets where water flows in and out. For both the Hoge and Lage afdeling, one water level is calculated and used. In reality, there is no uniform water level in the two Noordoostpolder sectors. Pumping activity influences the water levels 10 kilometers away from a pumping station differently than at a further distance of for example 20 kilometers. Before the start of this report, the pumping regimes were meant to be modelled in SOBEK Rural, a software program that included the necessary fluid dynamics to model water levels at different location in the same 'afdeling'. However, because it turned out that the available SOBEK Rural model was not fit to model the pumping regimes in the first place, this had to be scrapped in favor of constructing a MATLAB bucket model. Due to practical constraints, it was not possible to include fluid dynamics in the MATLAB models. This limited the evaluation of the water level and water level fluctuations in research question 4. Also, it impacts to a certain degree the accuracy of the results in research question 3, because the activation and de-activation of pumps is directly linked to the water level. In practice, the pumps in the Noordoostpolder are controlled by water level measurements 10 to 20 kilometers away from their location. In the current model setup, an indicative general polder water level had to be used, similar to pumping regimes in Southern and Western Flevoland.

To model the water level similar to the water levels in reality, the model had to be calibrated. For both the Hoge and Lage afdeling, one water level measurement point from FEWS was taken to retrieve the historical water level data. These points were chosen on advice from the external supervisor, for the reason that these points represented the average water levels in both sector the most realistically in the absence of data for an average water level historical data set for each sector. It is the question how much different the real average water level courses are compared to real average water levels in the Hoge and Lage afdeling.

Time variability pumping regimes

In all pumping regimes except for pumping regime 4, the off-peak and peak period for the pumping stations Buma, Smeenge and Vissering is the same: 23:00 to 07:00 for the off-peak period and vice versa for the peak period. The same off-peak period definition is used in the current and past pumping regimes in the Noordoostpolder. At first, the planned approach for designing the alternative pumping regimes involved to a large degree alternations in the definition of the off-peak period. The plan was to use an off-peak period of 22:00-08:00 off-peak period definition, as is consistent with the current off-peak period in use for the prolonged pumping station Buma pilot since this year. This was also consequentially tried for several alternative pumping regimes not used in this report. However, the initial results for the ratio day and night activity showed that this ratio turned out be highly skewered in favor of pumping activity during day hours, something the experts of the waterboard set would never occur at this rate. Unfortunately, the model turned out to be too sensitive to implement changes in the off-peak period definition. This limited the variety of alternative pumping regimes that could be test. Therefore, the old off-peak definition 23:00-07:00 on which the model also was calibrated had to be used for six out of the seven pumping regimes.

Evaluation of water level fluctuations

For the evaluation of the water level fluctuations in paragraph 4.4.2, the water level fluctuations was calculated for each 24 hour period between 12 in the afternoon. At first sight, the more logical option would have been to simply every single day as the standard 24 hour period for minimum and maximum water levels and the subsequent calculation of the daily water level fluctuation. However, as mentioned in the calibration paragraph, there is a so called ‘sawtooth’ pattern in the Noordoostpolder water level: during the night, the water levels decrease, while they increase again during the day time period. Taking this period would yield relatively similar results since the peaks and throughs would occur in a roughly similar pattern.

6. Conclusion

The main question research question of this report was: *What are the effects of different pumping -regimes on the financial costs of electricity, the operating hours of pumping stations and water level fluctuations in the Noordoostpolder?.* Four smaller research questions have been formulated to answer the main research question:

1. What are the requirements for pumping activities in the Noordoostpolder?
2. What are the electricity prices for different times of the day and for which relevant period should they be determined?
3. What are the electricity costs and operating hours for each pumping regime in the Noordoostpolder?
4. What are the water level fluctuations per pumping regime in the Noordoostpolder?

In this concluding paragraph, several conclusions will be drawn about the merits and performance of these alternative pumping regimes based on the results and analyses made in this report. The first two research questions lay the groundwork for answering the main research question in research questions 3 and 4. Some of the aspects treated in the research questions only bear relevance for the practical completion and data input for the models. These aspects do not require further attention in this conclusion. Research into the first research question revealed that a large number of factors and interests influence the requirements with which a Noordoostpolder pumping regime should comply. There are two kinds of factors and interests at play: interests and factors that are part of the water level decrees and interest and factors that are relevant because of general Zuiderzeeland RWA objectives. The water level decree establishes the appropriate target water level for an area based on these factors and interests. The main interests in the Noordoostpolder water level decrees are agriculture, water quality, land subsidence and safety. These interests and factors require that the water level stays close to the determined target water level. Pumping regimes must be able to maintain to a stable course of water levels in the Noordoostpolder. Outside the scope of the water level decree, two other main interests have been identified: costs of electricity and CO2 emissions. CO2 emissions. The Zuiderzeeland RWA is focused on keeping both the CO2 emissions and costs of electricity down. In the context of this report, keeping CO2 emissions down means that the operating hours of the pumping stations should be as low as possible. Concluding, there are three important performance indicators for a pumping regime:

-Keeping the costs of electricity down
-Keeping the number of operating hours low
-The ability to maintain stable water levels

The experts of the Zuiderzeeland RWA have proposed various changes and/or additions to the current pumping regime. This information was used to define seven alternative pumping regimes, among which one pumping regime for which the electricity costs have been calculated with different electricity contracts. Table 15 shows the overall performance of the alternative pumping regimes for the three performance indicators as determined in research questions 3 and 4. The color dark green means that this particular pumping regimes scores very well on that specific category. Lighter green means that it scores relatively well on that category. Dark red means that this particular pumping regime score is performs mediocre to poor, while the lighter red suggest that a pumping regime scores slightly to moderately lower than average. The 'scores' for the alternative pumping regimes in Table 15 have been given based on the comparison with the basic pumping regime, pumping regime 1 '*Basic'.* Pumping regime 3 '*Day ahead*' is the pumping regime with the lowest amount of electricity costs.

Pumping regime 5 '*Decreased inlet*' has the lowest number of operating hours. Pumping regime 4 '*Relaxed time steering'* has the most stable water level regime in both the Lage and Hoge afdeling. Overall, pumping regime 5 '*Decreased inlet'* has the best performance taking into account all three performance indicators. Pumping regimes that use time steering mechanisms score above average on the costs of electricity. However, that is exactly the opposite for their results on their ability to maintain a stable water level regime in the Noordoostpolder.

Table 15 Conclusion

Pumping regimes	Costs of electricity	Operating hours per year	Water level
Pumping regime 1 'Basic'	Average amount of costs	Average number of operating hours	Stable water level regime
Pumping regime 1 'APX'	Costs slightly lower than average	See pumping regime 1 'basic'	See pumping regime 1 'basic'
Pumping regime 1 \`Fixed prices´	Higher than average	See pumping regime 1 'basic'	See pumping regime 1 'basic'
Pumping regime 2 'Smeenge high'	Costs lower than average	Large number of operating hours	Unstable water level regime, only in Hoge afdeling
Pumping regime 3 'Day ahead'	Cheapest pumping regime	Slightly more operating hours than average	Unstable water level regime
Pumping regime 4 'Relaxed time steering'	Most expensive pumping regime	Highest number of operating hours	Most stable pumping regime
Pumping regime 5 'Decreased inlet'	Costs slightly lower than average	Lowest number of operating hours	Stable water level regime
Pumping regime 6 '3 Days ahead'	Costs slightly lower than average	Slightly more operating hours than average	Quite unstable water level regime
Pumping regime 7 'Increased bandwidth'	Costs lower than average	Slightly more operating hours than average	Pumping regime with the most unstable water level course

7. Recommendations

7.1. Recommendations for further research

In this paragraph, recommendations for further research into the subject are put forward

Fluid dynamics

For deeper research into this topic, it is recommendable to either add fluid dynamics to the current MATLAB models or to use a revised SOBEK Rural model. This addition would improve the accuracy and depth of the results of this report and would give ample opportunity to go more in depth on the local variations in water level inside the Noordoostpolder and the Hoge and Lage afdeling themselves.

Optimization of pumping regimes

Within this report alternative pumping regimes have been created to evaluate the effects of additions and alterations to the current pumping regime on the three main performance indicators. It might be an idea to work the other way around. Future research could use the results of this report as a starting point to optimize the current pumping regime based on the electricity costs, water level fluctuations and operating hours.

Connecting alternative pumping regimes

In this report, the alternative pumping regimes have been used separately for each research period. The results have shown that there are differences however in the performance of each pumping regime. It is therefore interesting to research what the effects would be of using different pumping regimes for different hydrological periods (wet, dry, et cetera) over a long term research period.

Time flexibility

In the current MATLAB model, there is little room for adjustments to the time settings of the off-peak and peak periods. Future students and researchers could use the MATLAB models used in this report as a basis for further improvements on the aspect of time flexibility.

Pumping

In this report, the pumping capacities of the used pumps are static: they either work at a fixed capacity or they do not work. In reality, the Zuiderzeeland RWA is a little bit more flexible with the power of their pumps. As explained in paragraph 4.1.3, every individual pump has a power output that delivers the most efficient pumping operations in terms of electricity use. Future research could include the implementation of more variability in the use and capacity of individual pumps based on the expected amount of water that needs to be discharged. By extension, there is also the aspect of the pumping head (‘opvoerhoogte’): the difference in water level inside and outside the polder, mainly concerning lake IJssel. Climate change will not only cause rising water levels on the oceans, but it will also impact the water levels in lake IJssel. As explained in paragraph 4.1.3., for this report the assumption was made that the pump head is relatively static. The difference in pumping head is of importance for the costs of electricity, since a larger pumping head means that more electricity is required to discharge water. This is an aspect that could be included in a follow-up on this report.

Seasonality

The water levels have been calibrated for the average water level as registered at the water level measurement locations in the Noordoostpolder, using one set of pump stages for the entire research period. The Zuiderzeeland RWA uses different sets of initiation and termination levels during the year, as they see fit. This creates an pattern of seasonal differences in the course of Noordoostpolder water levels, or seasonality in other words. Due to practical constraints, it was chosen not to model water levels to this level of accuracy. Future research could apply the factor of seasonality to the modelling of water levels to the alternative pumping regimes used in this report. It would be interesting so see how the alternative pumping regimes would behave when this factor would be applied.

7.2. Recommendations for the use of pumping regimes

This paragraph puts forward recommendations regarding the management and use of pumping regimes by the Zuiderzeeland RWA. The results of the costs of electricity resulted in some interesting observation. One example is the difference in electricity costs between pumping regime 1 '*APX*' and pumping regime 1 '*Fixed prices*' during the average season period (appendix F, Figure 38), where it turned out that taking the electricity prices from the fixed price contracts resulted in a considerable decrease in electricity costs, even more than that any modification to the pumping regime itself could bring forth. Therefore, the Zuiderzeeland RWA might want to consider more flexibility with regards to their current management of electricity contracts. For example, it might be beneficial for them to use different contracts for different pumping stations for different periods per year. However, the question of course remains whether their current energy supplier, or any energy supplier for that matter, would allow such practices.

8. References

(2018). *Beleid peilbeheer en peilbesluiten.* Waterschap Noorderzijlvest.

Benjamin, E., & Wendt, T. (2010). *Handleiding GGOR-methodiek.* Lelystad: Waterschap Zuiderzeeland.

Cabral, L., Booth, B., & Peterson, C. (2020, May 12). *California wholesale electricity prices are higher at the beginning and end of the day*. Retrieved from eia.gov: https://www.eia.gov/todayinenergy/detail.php?id=32172

Claessen, F., Spiers, B., & Prak, H. (2003). *Werken met GGOR.* RIZA: Commissie Integraal waterbeheer.

Deparment of agriculture and water resources. (2013). *Characterising the relationship between water quality and water quantity.* Canberra: Water quality Austrialia.

Hoes, O., & Van de Giesen, N. (2015). *Polders.* Delft: TU Delft.

Immerzeel, W., Graafstal, H., & Loeve, R. (2006). *Evaluatie wateraanvoer in de noordoostpolder.* Wageningen: FutureWater.

Marktinformatie. (2020, may 11). Retrieved from energiemarktinformatie.nl: https://www.energiemarktinformatie.nl/beurzen/elektra/

Meijerink, J. (2017). *Nota Ijsselmeerpolders.* Lelystad: Waterschap Zuiderzeeland.

Mettrop et al. (2012). *Een meer natuurlijk peilbeheer: relaties tussen geohydrologie, ecosysteem-dynamiek en Natura 2000.* Driebergen: Ministerie van EL&I.

NAO. (2001). *A practical guide to sampling.* London: National Audit Office.

(2008). *Nota Peilbeheer.* Leiden: Hoogheemraadschap Rijnland.

(2003). *Peilbesluit Hoge en Lage afdeling (Noordoostpolder).* Lelystad: Waterschap Zuiderzeeland.

(2004). *Peilbesluit stedelijk gebied gemeente Noordoostpolder.* Lelystad: Waterschap Zuiderzeeland.

Petie, K., & Borneman, J. (2019). *Peilbesluit Havenkwartier.* Lelystad: Waterschap Zuiderzeeland.

Pothof et al. (2019). *Slim malen- Energie besparen?* Amersfoort: STOWA.

Rijtema, P. (1978). Algemeen overzicht over de realitie tussen waterkwaliteit en waterkwantiteit. *Lezing "Samenhang tuseen waterkwaliteit en -kwantiteit bij studies van oppervlaktewateren'*, (p. 3). Wageningen.

Roland Berger Consultancy. (2017). *Energiespotmarktprijzen vs. vaste prijzen per jaar.* Amsterdam: Roland Berger Consultancy.

Rommens, K., & Bosma, A. (2013). *Energie-aspecten poldergemalen waterschap Zuiderzeeland.* Deventer: Tauw bv.

Rutten, E. (2018, 11 3). *Huizen scheuren door droogte: steeds meer klachten bij gemeenten*. Retrieved from Gelderlander: https://www.gelderlander.nl/zevenaar/huizen-scheuren-door-droogte-steeds-meer-klachten-bij-gemeenten~af2a284b/?referrer=https://www.google.com/

RWS-Waterdienst. (2020, May 5). *Maatregel: peilbeheer*. Retrieved from Helpdeskwater: https://www.helpdeskwater.nl/onderwerpen/water-ruimte/ecologie/meren/ingreep-fysica/peilbeheer/

Stapel, W. (2018). *WaterTakenPlan Noordoostpolder.* Amersfoort: RoyalHaskoning DHV.

UK Day Ahead Auction Prices . (2020, May 10). Retrieved from Nordpoolgroup.com: https://www.nordpoolgroup.com/Market-data1/GB/Auction-prices/UK/Hourly/?view=table

Van Boldrik, M. (2015). *Energiebesparingspotentieel Watersysteem en overige waterschapstaken.* Deventer: Tauw.

Van den Akker, J. (2020, May 4). *Verdroging en problemen bij veen- en kleikaden*. Retrieved from wur.nl: https://www.wur.nl/nl/artikel/Verdroging-en-problemen-bij-veen-en-kleikaden.htm

Van den Berg et al. (2002). *Ecologische effecten van peilbeheer.* Lelystad: RIZA.

Verruijt et al. (2020, May 4). *Beïnvloeden stijghoogte en stroming van grondwater- bijzondere toepassingen constructies*. Retrieved from helpdeskwater.nl: https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/primaire/technische-leidraden/zoeken-technische/@192660/beinvloeden/

Waterschap Zuiderzeeland. (2010a). *Gemalenplan 2011-2020.* Lelystad: Waterschap Zuiderzeeland afdeling zuivering en gemalen.

Waterschap Zuiderzeeland. (2010b). *Waterbeheerplan 2010-2015.* Lelystad.

Waterschap Zuiderzeeland. (2015). *Basisgegevens gemalen 2014.* Lelystad: Waterschap Zuiderzeeland.

Waterschap Zuiderzeeland. (2015). *Waterbeheerplan 2016-2021.* Lelystad: Waterschap Zuiderzeeland.

Waterschap Zuiderzeeland. (2020a, March 9). *1942-De Noordoostpolder drooggegelegd*. Retrieved from ww.Zuiderzeeland.nl: https://www.zuiderzeeland.nl/over_ons/organisatie/geschiedenis/waterschapscanon/waterschapscanon/1942-noordoostpolder/

Waterschap Zuiderzeeland. (2020a, March 5). *Waterschapscanon*. Retrieved from www.Zuiderzeeland.nl: https://www.zuiderzeeland.nl/over_ons/organisatie/geschiedenis/waterschapscanon/

Waterschap Zuiderzeeland. (2020b, May 2). *Organisatieverhaal*. Retrieved from www.Zuiderzeeland.nl: https://www.zuiderzeeland.nl/over_ons/organisatieverhaal/

Zuiderzeeland, W. (2010c). *Onderbemaling Tollebeek.* Lelystad: Waterschap Zuiderzeeland.

9. Appendix

Appendix A1

GGOR

As mentioned before in the introduction of this chapter, in the water level decrees the target water levels are determined. However, those target water levels only apply directly to surface water levels, not to groundwater levels. Since groundwater levels are dependent on surface water levels, it is important for the Zuiderzeeland regional water authority to include both the influence of the target water level on the groundwater levels and accompanying interests of stakeholders (as part of the water level decree), as well as groundwater level management itself. The instrument of GGOR helps to combine those interests into an integrated water management.

GGOR, short for "*Gewenst Grond- en Oppervlaktewater Regime"* or "desirable ground- and surface water level regime", is according to the *Handleiding GGOR-Methodiek* (Benjamin & Wendt, 2010) three things in one: a way of thinking, a method and a final product in the realm of water management. It is a new way of thinking in the sense that GGOR provides a new paradigm for water management. The GGOR method argues that the management of water systems and bodies should be determined and carried out with an integral approach to both surface- and groundwater systems. In more practical terms, GGOR helps to align the interests of multiple user functions related to both surface- and groundwater systems, often in spite of the conflicting character of those interests. GGOR is a method in the sense that a pre-determined set of steps and actions should be followed to define the optimal water level regime for all functions involved. The final product is a desirable ground- and surface water regime, supported by clarifying charts and text. In 1998, the *Vierde nota Waterhuishouding* proposed that the Dutch provinces should determine a "desirable groundwater situation", or GGS (Claessen, Spiers, & Prak, 2003). The aim was to mitigate the effects of drought more effectively. Over the years, this evolved to GGOR. GGOR has been made compulsory by the national policy agreement water (NBW) in 2008 (Waterschap Zuiderzeeland, 2010b), but only for rural areas.

To summarize the GGOR process itself shortly: GGOR identifies several key factors and function who interact and influence with surface- and groundwater level management. As part of the method, GGOR derives the optimal ground water level per factor, also known as OGOR, or optimal surface- and groundwater regime. Part of the later process is to weigh all the interests and determine a compromise water level regime (final product GGOR) that is considered appropriate to all the functions and parameters. The identification of these area specific functions is most important for this report and for the completion of research question 5. According to (Benjamin & Wendt, 2010), the four most important functions in the Noordoostpolder are:

- Agriculture
- Water quality (as per *Kaderrichtlijn Water* or *KRW)*
- Archeology
- Terrestrial nature

It should be noted that these functions are only for rural areas. The exact relevance of these functions for water level management, combined with other factors identified in literature will be explained in paragraph 4.1.2. The results of the GGOR method itself are not binding: the water level decree is still the legally binding document, but the results of GGOR analyses are often adopted by water level decrees (Claessen, Spiers, & Prak, 2003).

Safety and flood defenses

Water levels inside the polder influence the safety of the inhabitants in two ways:

- Extremely high (ground)water levels
- Low groundwater levels for a prolonged period near flood defenses

The consequences of extreme high-water levels inside the Noordoostpolder would be that the water levels increase to levels so high that the inner water system cannot cope with it, resulting in the flooding of housing and fields. The second problem forms the occurrence of low groundwater levels for a prolonged period of time. If the soil of which a dike is made of gets too dry, cracks in the dike will start to form, critically weakening the flood defense (Van den Akker, 2020). Another possibility for failure is that due to low groundwater levels, seepage under the dike will increase, which can ultimately result in piping and dike failure (Verruijt et al, 2020).

(Terrestrial) nature

Terrestrial nature means all vegetation that lives on dry land, as opposed to aquatic nature. The groundwater level effects nature in different ways. Groundwater is an important source of water for plants and helps with conservation of the soil quality by discharging and supplying nutrients and other substances (Mettrop et al, 2012). For terrestrial nature, the concentration of oxygen in the soil is rated as highly important. Both the quality and quantity of groundwater thus determine a precarious balance of species. The relation between groundwater and nature is displayed in Figure 19. In that figure, it is visible that the quality of water influences the soil acidity and nutrient concentration. The Zuiderzeeland RWA does not want to alter the composition of species in current nature areas, so it is imperative that the groundwater level and quality must be relatively stable. Low groundwater levels would lead to the destruction of certain vegetation types due to drought. Lower quality of groundwater can also be a side effect of that. High groundwater levels would increase the chances on eutrophication (Van den Berg et al, 2002).

Archaeological and historical objects

In the Noordoostpolder, various archaeological and historical objects are present, an example being the former island of Schokland. The EU wide Valletta treaty demands that these objects are protected (Beleid peilbeheer en peilbesluiten, 2018). These historical and archaeological sites face danger from the processes of erosion and weathering if exposed to open air or drought conditions. Therefore, the optimal ground water level for these objects is as high as possible, which often conflicts with other interests such as agriculture. Also, another aspect important to the preservation of the historical objects is the water quality. Certain concentrations of oxygen and chlorides coupled with the acidity of water can be harmful (Benjamin & Wendt, 2010). No drainage norm has been determined as of yet (Peilbesluit Hoge en Lage afdeling (Noordoostpolder), 2003).

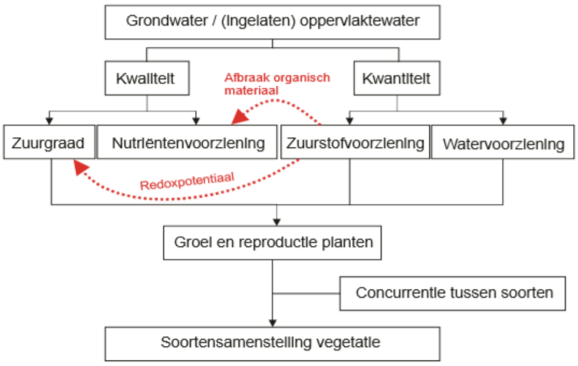

Figure 19 Influence of groundwater on terrestrial nature

Land subsidence

Another hazard of low groundwater levels is the subsidence of land. Low (ground)water levels affect land subsidence in two ways: through settlement and through soil oxidation. Settlement occurs when water is drained (Stapel, 2018). Settlement can occur anywhere. Oxidation of soil takes place in peat or predominantly peaty subsoils. The organic materials of which these peat layers consist will undergo oxidation because of exposure to air, leading to soil subsidence. In Figure 20, the prognosis for land subsidence in the Noordoostpolder for the period of 2011-2050 is displayed. Especially the areas in the south-western corner of the Noordoostpolder are at risk of substantial land subsidence in the coming decades. The processes of oxidation and settlement are irreversible.

Figure 20 Land subsidence predictions Noordoostpolder

Infrastructure

Different types of infrastructure are affected by groundwater levels. Objects that fall into this category are buildings, bridges, roads, transport over water and cables (Peilbesluit Hoge en Lage afdeling (Noordoostpolder), 2003). For housing, regional water authorities strive for a drain depth (*ontwateringsdiepte*) between 1 and 1.2 meters (Nota Peilbeheer, 2008). Higher groundwater levels would flood the so-called crawl spaces, directly below the ground level of Dutch houses. Consistent low groundwater levels would cause the settlement of soil, thereby putting the structural stability of houses and structures alike at risk (Rutten, 2018). For roads, a similar drain depth is used. Roads need a minimum drain depth to prevent instability and make sure proper drainage is possible (Peilbesluit stedelijk gebied gemeente Noordoostpolder, 2004). Cables need a smaller drain depth. Therefore, the drain depth of roads is often taken as a reference point. In the Noordoostpolder, transport over water takes places in the larger, central canals (*vaarten*). A certain minimum water depth is therefore required.

Drainage and sewage systems

The surface water level of ditches and smaller canals is important for the proper drainage of fields in the polder. Drainage tubes discharge water into the ditches and smaller canals surrounding the plot of land (Peilbesluit stedelijk gebied gemeente Noordoostpolder, 2004). If the surface water level is higher then the discharge points of the drainage tubes, the areas dependent on these drainage tubes cannot drain. Thus, it is imperative that the outfalls of drainage tubes are situated well above the target water levels. For urban areas in the Noordoostpolder, the optimal drain depth is considered to be around the 1,10 meters below ground level.

For sewage systems, it is the other way around. If the surface water level gets too high compared to the sewage tubes, surface water will be discharged into the sewer pipes.

Appendix A2

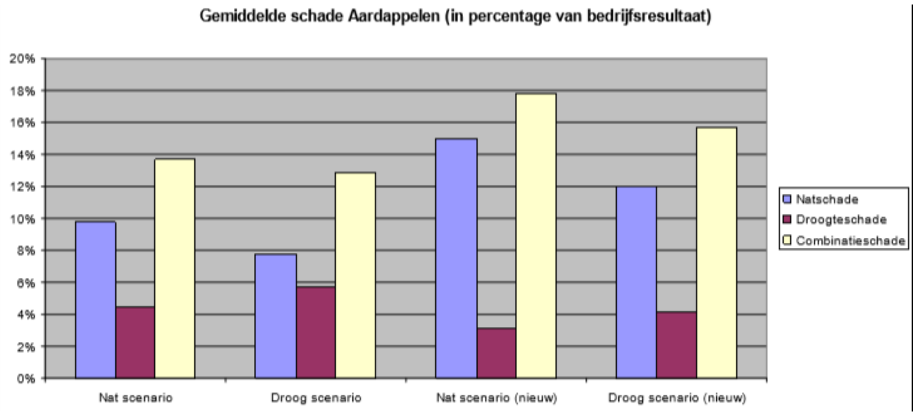

Figure 21 Average financial damage to potatoes

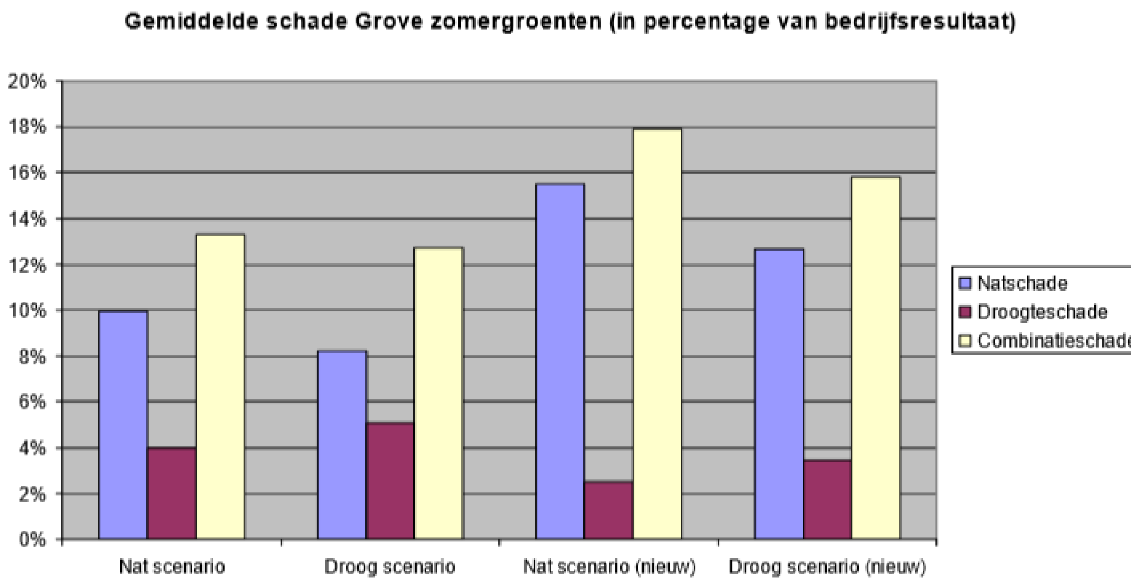

Figure 22 Average financial damage to summer vegetables

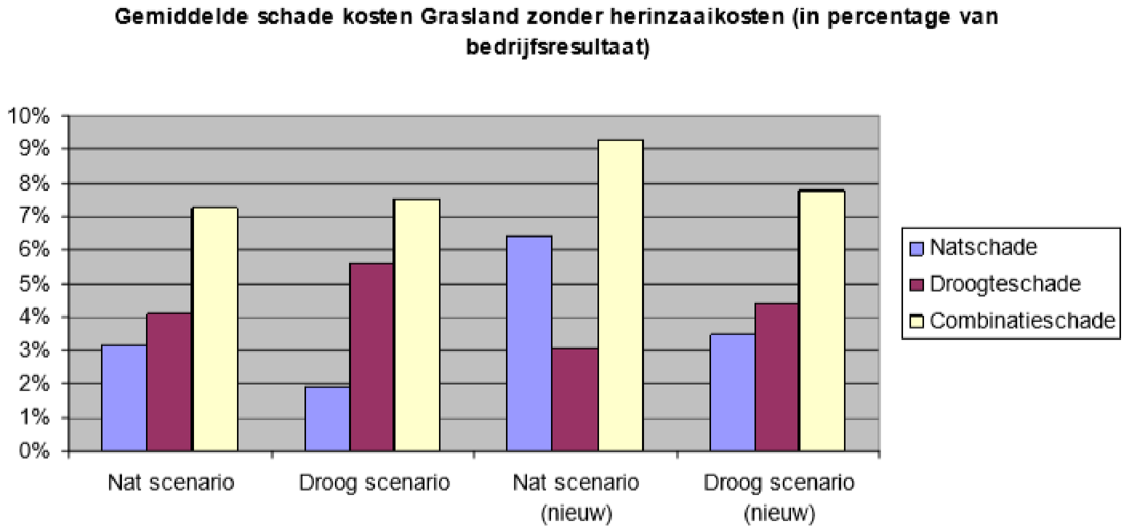

Figure 23 Average financial damage to wetlands

Appendix B

Table 16 Conversion factors for electricity prices

Time interval	Factor for conversion
00:00-01:00	0.863
01:00-02:00	0.786
02:00-03:00	0.747
03:00-04:00	0.705
04:00-05:00	0.721
05:00-06:00	0.758
06:00-07:00	0.910
07:00-08:00	1.109
08:00-09:00	1.208
09:00-10:00	1.265
10:00-11:00	1.191
11:00-12:00	1.125
12:00-13:00	1.038
13:00-14:00	0.991
14:00-15:00	0.948
15:00-16:00	0.938
16:00-17:00	0.976
17:00-18:00	1.118
18:00-19:00	1.205
19:00-20:00	1.276
20:00-21:00	1.160
21:00-22:00	1.041
22:00-23:00	1.005
23:00-00:00	0.916

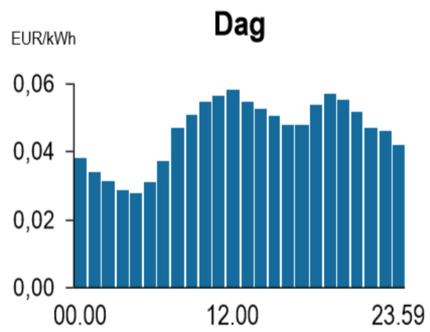

Figure 24 Electricity price dynamics (Roland Berger Consultancy, 2017)

Appendix C

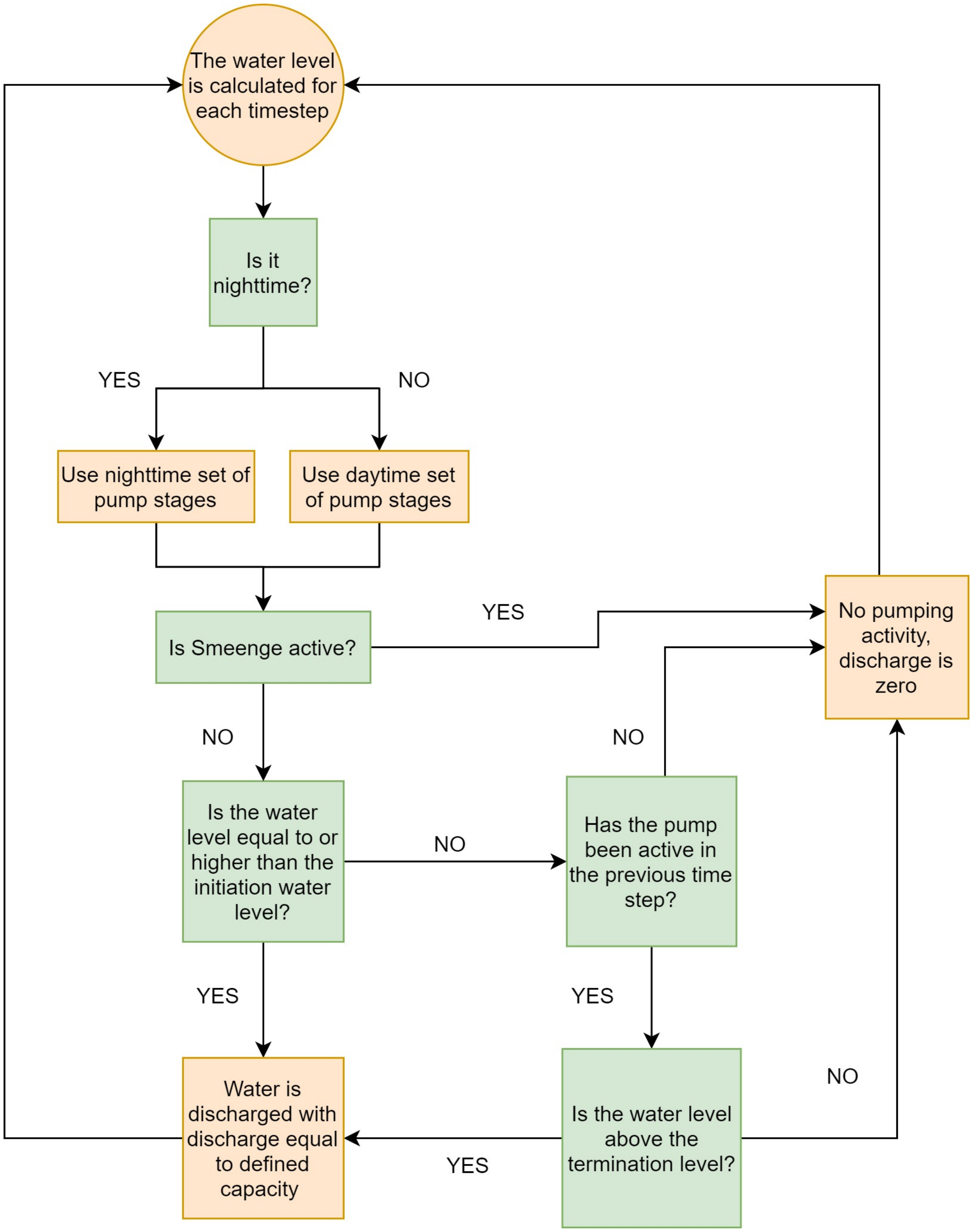

Figure 25 Algorithm 2

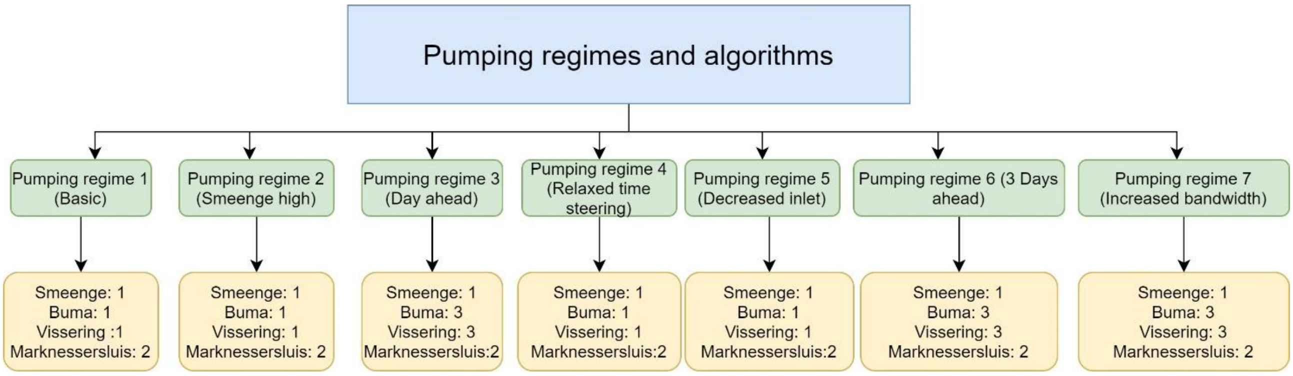

Figure 26 Pumping regimes and algorithms

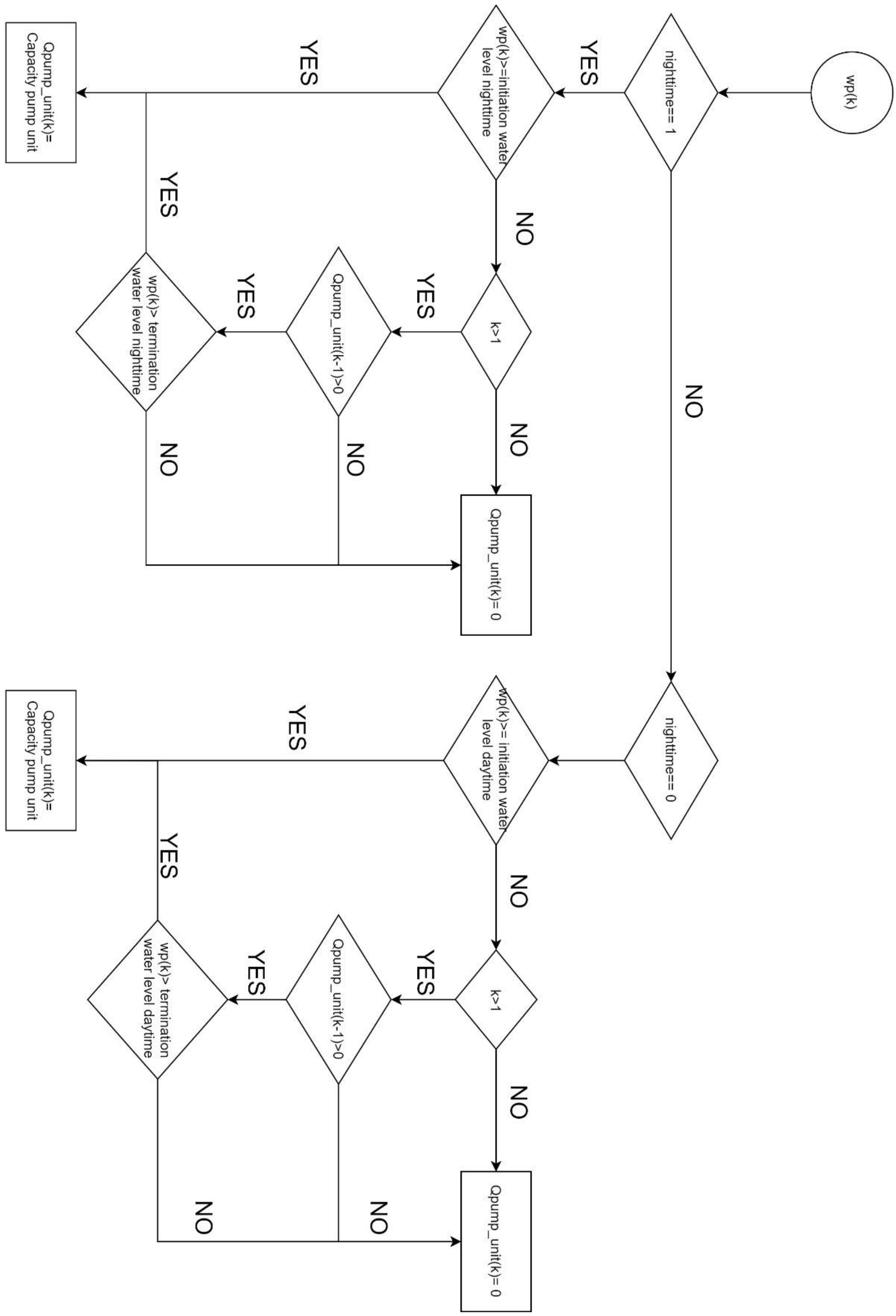

Figure 27 Detailed algorithm 1

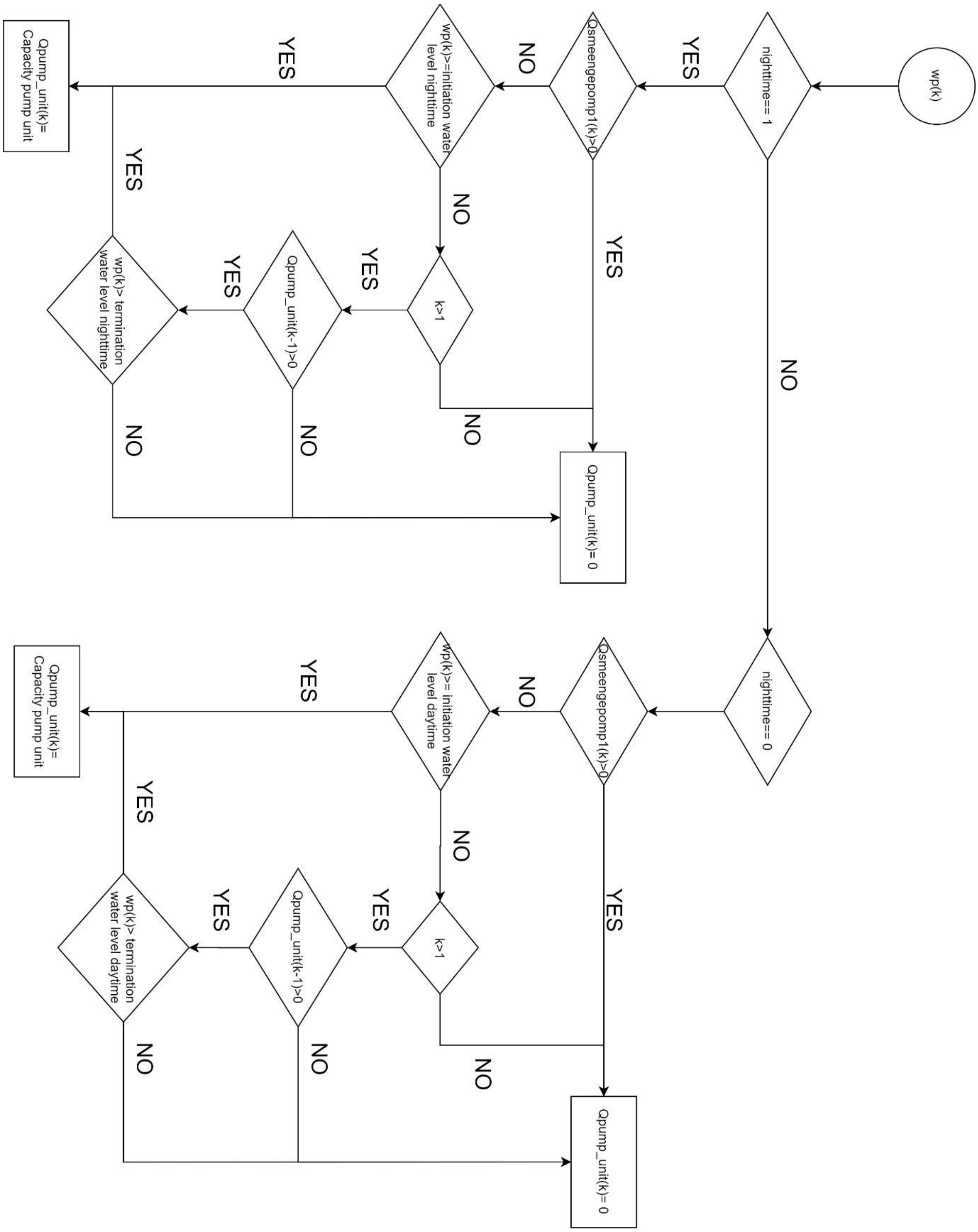

Figure 28 Detailed algorithm 2

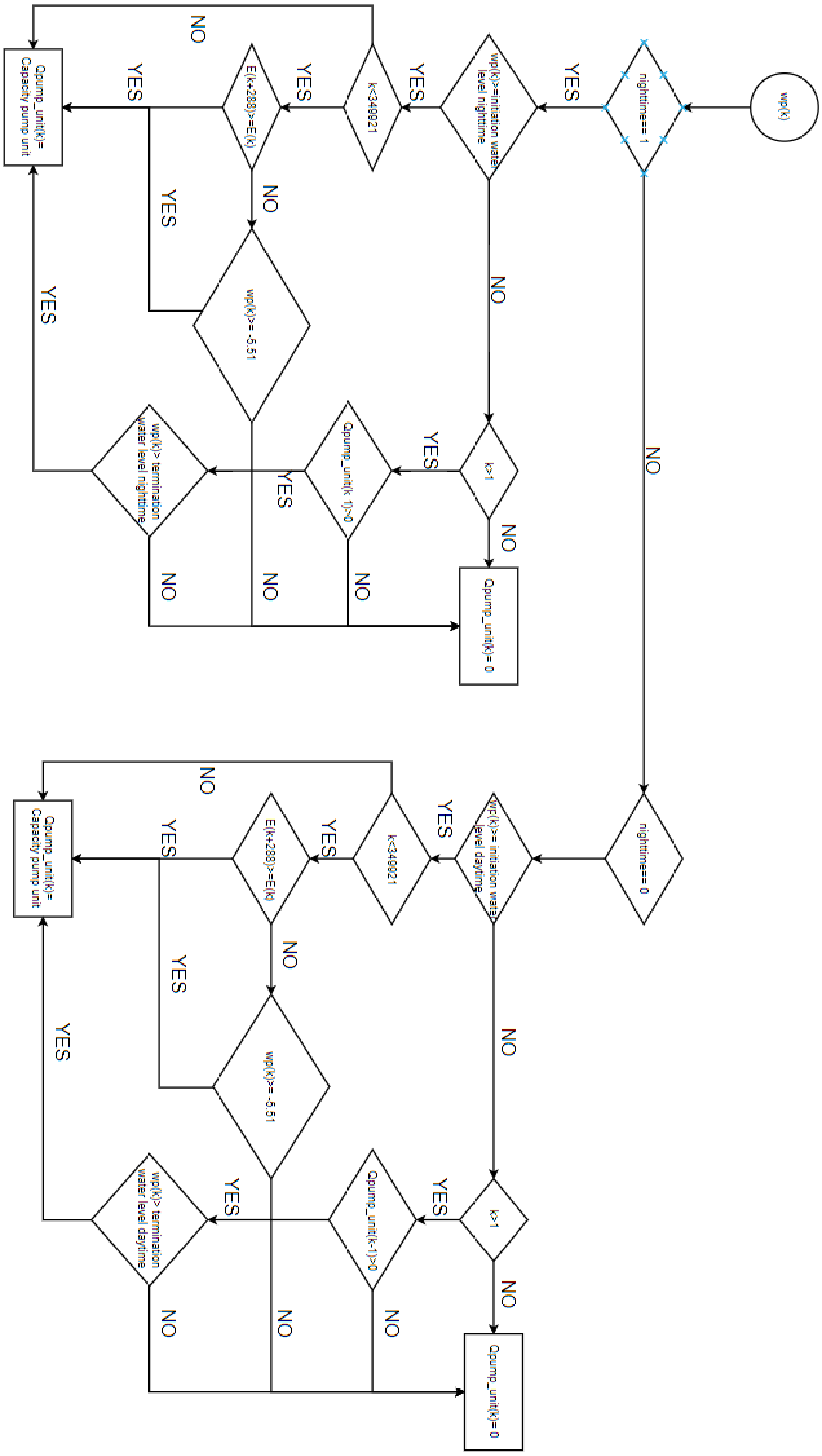

Figure 29 Detailed algorithm 3

Appendix D MATLAB script

```
clear , clc, clf
%format shortG
%BEMALINGSREGIME 1

%% time
%time interval
T1= datetime(2017,1,1,0,0,0);
T2= datetime(2020,4,30,23,55,0);
deltaT= minutes(5); %tijdstappen van vijf minuten
dates=T1:deltaT:T2;

%Off peak en peak periodes
nighttime=zeros(1,length(dates));
nighttime_sluis=zeros(1,length(dates));

for i = 1: length(dates)
    if dates(i).Hour >= 23 || dates(i).Hour <7
        nighttime(i) = 1;
    else
        nighttime(i) = 0;
    end
end

for i = 1: length(dates)
    if dates(i).Hour >= 22 || dates(i).Hour <6
        nighttime_sluis(i) = 1;
    else
        nighttime_sluis(i) = 0;
    end
end


%% Water invoer
Qsobek = load('Qsobek8.txt');
Inlet = load('Inlaat.txt');
%% Hoge afdeling
%initialisatie hoge afdeling
wp_hoog(1)= -4.5; %Begin- en streefpeil (m)
area_hoog= 900000; %Wateroppervlakte(M^2)
Qsmeengepomp1=zeros(1,length(dates)); %Initialiseren
Qsmeengepomp2=zeros(1,length(dates)); %Initialiseren
Qsluis1=zeros(1,length(dates)); %Initialiseren
Qsluis2=zeros(1,length(dates)); %Initialiseren
Csmeenge=3100; %Capaciteit van 1 pomp Smeenge(M^3/5 minuten)
Csluis= 1000; %Capaciteit Marknessersluis (M^3/5 minuten)

%Nachtpeilen hoge afdeling
 %Inslagpeilen
IPsluis1_nacht=-4.465; %Inslagpeil eerste uitlaat Marknessersluis (m)75
IPsluis2_nacht= -4.44; %Inslagpeil tweede uitlaat Marknessersluis (m)
IPsmeengepomp1_nacht= -4.37; %Inslagpeil pomp 1 Smeenge (m)
IPsmeengepomp2_nacht= -4.368; %Inslagpeil pomp 2 Smeenge (m)
 %Uitslagpeilen
UPsluis1_nacht=-4.575; %Uitslagpeil eerste uitlaat Marknessersluis (m)
UPsluis2_nacht=-4.575; %Uitslagpeil tweede uitlaat Marknessersluis (m)
UPsmeengepomp1_nacht= -4.60; %Uitslagpeil pomp 1 Smeenge (m)
UPsmeengepomp2_nacht= -4.60; %Uitslagpeil pomp 2 Smeenge (m)

%Dagpeilen hoge afdeling
 %Inslagpeilen
```

```
IPsluis1_dag= -4.31; %Inslagpeil eerste uitlaat Marknessersluis (m)
IPsluis2_dag= -4.31; %Inslagpeil tweede uitlaat Marknessersluis (m)
IPsmeengepomp1_dag= -4.34; %Inslagpeil pomp 1 Smeenge (m)
IPsmeengepomp2_dag= -4.342; %Inslagpeil pomp 2 Smeenge (m)
 %Uitslagpeilen
UPsluis1_dag= -4.565; %Uitslagpeil eerste uitlaat Marknessersluis (m)
UPsluis2_dag= -4.565; %Uitslagpeil tweede uitlaat Marknessersluis (m)
UPsmeengepomp1_dag= -4.58; %Uitslagpeil pomp 1 Smeenge (m)
UPsmeengepomp2_dag= -4.58; %Uitslagpeil pomp 2 Smeenge (m)

%% Lage afdeling
%initialisatie lage afdeling
wp_laag(1)= -5.7; %Begin- en streefpeil lage afdeling (m)
area_laag= 3900000; %Wateroppervlakte (m^2)
Qbumapomp1= zeros(1,length(dates)); %Initialiseren
Qbumapomp2= zeros(1,length(dates)); %Initialiseren
Qbumapomp3= zeros(1,length(dates)); %Initialiseren
Qvisseringpomp1= zeros(1,length(dates)); %Initialiseren
Qvisseringpomp2= zeros(1,length(dates)); %Initialiseren
Qvisseringpomp3= zeros(1,length(dates)); %Initialiseren
Cbuma=3600; %Capaciteit van 1 pomp Buma (M^3/5 minuten)
Cvissering_gas=4000; %Capaciteit van 1 gaspomp Vissering (M^3/5 minuten)
Cvissering_diesel=3600; %Capaciteit van 1 dieselpomp Vissering (M^3/5
minuten)

%Nachtpeilen Lage afdeling
 %Inslagpeilen
IPbumapomp1_nacht= -5.647; %Inslagpeil pomp 1 Buma (m)
IPbumapomp2_nacht= -5.643; %Inslagpeil pomp 2 Buma (m)
IPbumapomp3_nacht= -5.62; %Inslagpeil pomp 3 Buma (m)
IPvisseringpomp1_nacht= -5.635; %Inslagpeil pomp 1 Vissering (m)
IPvisseringpomp2_nacht= -5.616; %Inslagpeil pomp 2 Vissering (m)
IPvisseringpomp3_nacht= -5.59; %Inslagpeil pomp 3 Vissering (m)
 %Uitslagpeilen
UPbumapomp1_nacht= -5.8; %Uitslagpeil pomp 1 Buma (m)
UPbumapomp2_nacht= -5.785; %Uitslagpeil pomp 2 Buma (m)
UPbumapomp3_nacht= -5.77; %Uitslagpeil pomp 3 Buma (m)
UPvisseringpomp1_nacht= -5.79; %Uitslagpeil pomp 1 Vissering (m)
UPvisseringpomp2_nacht= -5.78; %Uitslagpeil pomp 2 Vissering (m)
UPvisseringpomp3_nacht= -5.765; %Uitslagpeil pomp 3 Vissering (m)

%Dagpeilen Lage afdeling
 %Inslagpeilen
IPbumapomp1_dag= -5.595; %Inslagpeil pomp 1 Buma (m)
IPbumapomp2_dag= -5.59; %Inslagpeil pomp 2 Buma (m)
IPbumapomp3_dag= -5.57; %Inslagpeil pomp 3 Buma (m)
IPvisseringpomp1_dag= -5.61; %Inslagpeil pomp 1 Vissering (m)
IPvisseringpomp2_dag= -5.605; %Inslagpeil pomp 2 Vissering (m)
IPvisseringpomp3_dag= -5.58; %Inslagpeil pomp 3 Vissering (m)
 %Uitslagpeilen
UPbumapomp1_dag= -5.72; %Uitslagpeil pomp 1 Buma (m)
UPbumapomp2_dag= -5.71; %Uitslagpeil pomp 2 Buma (m)
UPbumapomp3_dag= -5.70; %Uitslagpeil pomp 3 Buma (m)
UPvisseringpomp1_dag= -5.72; %Uitslagpeil pomp 1 Vissering (m)
UPvisseringpomp2_dag= -5.71; %Uitslagpeil pomp 2 Vissering (m)
UPvisseringpomp3_dag= -5.70; %Uitslagpeil pomp 3 Vissering (m)


%% berekeningen
for k=1:length(dates)-1 %index array failure voorkomen
    if nighttime(k) == 1
```

```
%% Nacht Hoge afdeling
if wp_hoog(k)>= IPsmeengepomp1_nacht
    Qsmeengepomp1(k)= Csmeenge;
elseif wp_hoog(k)< IPsmeengepomp1_nacht
    if k>1
        if Qsmeengepomp1(k-1)>0
            if wp_hoog(k)> UPsmeengepomp1_nacht
                Qsmeengepomp1(k)= Csmeenge;
            end
        end
    end
end

if wp_hoog(k)>= IPsmeengepomp2_nacht
    Qsmeengepomp2(k)= Csmeenge;
elseif wp_hoog(k)< IPsmeengepomp2_nacht
    if k>1
        if Qsmeengepomp2(k-1)>0
            if wp_hoog(k)> UPsmeengepomp2_nacht
                Qsmeengepomp2(k)= Csmeenge;
            end
        end
    end
end


%% Nacht lage afdeling
if wp_laag(k)>= IPbumapomp1_nacht
    Qbumapomp1(k)= Cbuma;
elseif wp_laag(k)< IPbumapomp1_nacht
    if k>1
        if Qbumapomp1(k-1)>0
            if wp_laag(k)> UPbumapomp1_nacht
                Qbumapomp1(k)= Cbuma;
            end
        end
    end
end

if wp_laag(k)>= IPbumapomp2_nacht
    Qbumapomp2(k)= Cbuma;
elseif wp_laag(k)< IPbumapomp2_nacht
    if k>1
        if Qbumapomp2(k-1)>0
            if wp_laag(k)> UPbumapomp2_nacht
                Qbumapomp2(k)= Cbuma;
            end
        end
    end
end

if wp_laag(k)>= IPbumapomp3_nacht
    Qbumapomp3(k)= Cbuma;
elseif wp_laag(k)< IPbumapomp3_nacht
    if k>1
        if Qbumapomp3(k-1)>0
            if wp_laag(k)> UPbumapomp3_nacht
                Qbumapomp3(k)= Cbuma;
            end
        end
    end
```

```
        end

        if wp_laag(k)>= IPvisseringpomp1_nacht
            Qvisseringpomp1(k)= Cvissering_gas;
        elseif wp_laag(k)< IPvisseringpomp1_nacht
            if k>1
                if Qvisseringpomp1(k-1)>0
                    if wp_laag(k)> UPvisseringpomp1_nacht
                        Qvisseringpomp1(k)= Cvissering_gas;
                    end
                end
            end
        end

        if wp_laag(k)>= IPvisseringpomp2_nacht
            Qvisseringpomp2(k)= Cvissering_gas;
        elseif wp_laag(k)< IPvisseringpomp2_nacht
            if k>1
                if Qvisseringpomp2(k-1)>0
                    if wp_laag(k)> UPvisseringpomp2_nacht
                        Qvisseringpomp2(k)= Cvissering_gas;
                    end
                end
            end
        end

        if wp_laag(k)>= IPvisseringpomp3_nacht
            Qvisseringpomp3(k)= Cvissering_diesel;
        elseif wp_laag(k)< IPvisseringpomp3_nacht
            if k>1
                if Qvisseringpomp3(k-1)>0
                    if wp_laag(k)> UPvisseringpomp3_nacht
                        Qvisseringpomp3(k)= Cvissering_diesel;
                    end
                end
            end
        end

    elseif nighttime(k) ==0
        %% Dag hoge afdeling
        if wp_hoog(k)>= IPsmeengepomp1_dag
            Qsmeengepomp1(k)= Csmeenge;
        elseif wp_hoog(k)< IPsmeengepomp1_dag
            if k>1
                if Qsmeengepomp1(k-1)>0
                    if wp_hoog(k)> UPsmeengepomp1_dag
                        Qsmeengepomp1(k)= Csmeenge;
                    end
                end
            end
        end

        if wp_hoog(k)>= IPsmeengepomp2_dag
            Qsmeengepomp2(k)= Csmeenge;
        elseif wp_hoog(k)< IPsmeengepomp2_dag
            if k>1
                if Qsmeengepomp2(k-1)>0
                    if wp_hoog(k)> UPsmeengepomp2_dag
                        Qsmeengepomp2(k)= Csmeenge;
                    end
                end
```

```
    end
end

%% Dag lage afdeling
if wp_laag(k)>= IPbumapomp1_dag
    Qbumapomp1(k)= Cbuma;
elseif wp_laag(k)< IPbumapomp1_dag
    if k>1
        if Qbumapomp1(k-1)>0
            if wp_laag(k)> UPbumapomp1_dag
                Qbumapomp1(k)= Cbuma;
            end
        end
    end
end

if wp_laag(k)>= IPbumapomp2_dag
    Qbumapomp2(k)= Cbuma;
elseif wp_laag(k)< IPbumapomp2_dag
    if k>1
        if Qbumapomp2(k-1)>0
            if wp_laag(k)> UPbumapomp2_dag
                Qbumapomp2(k)= Cbuma;
            end
        end
    end
end

if wp_laag(k)>= IPbumapomp3_dag
    Qbumapomp3(k)= Cbuma;
elseif wp_laag(k)< IPbumapomp3_dag
    if k>1
        if Qbumapomp3(k-1)>0
            if wp_laag(k)> UPbumapomp3_dag
                Qbumapomp3(k)= Cbuma;
            end
        end
    end
end

if wp_laag(k)>= IPvisseringpomp1_dag
    Qvisseringpomp1(k)= Cvissering_gas;
elseif wp_laag(k)< IPvisseringpomp1_dag
    if k>1
        if Qvisseringpomp1(k-1)>0
            if wp_laag(k)> UPvisseringpomp1_dag
                Qvisseringpomp1(k)= Cvissering_gas;
            end
        end
    end
end

if wp_laag(k)>= IPvisseringpomp2_dag
    Qvisseringpomp2(k)= Cvissering_gas;
elseif wp_laag(k)< IPvisseringpomp2_dag
    if k>1
        if Qvisseringpomp2(k-1)>0
            if wp_laag(k)> UPvisseringpomp2_dag
                Qvisseringpomp2(k)= Cvissering_gas;
            end
        end
```

```
        end
    end

    if wp_laag(k)>= IPvisseringpomp3_dag
        Qvisseringpomp3(k)= Cvissering_diesel;
    elseif wp_laag(k)< IPvisseringpomp3_dag
        if k>1
            if Qvisseringpomp3(k-1)>0
                if wp_laag(k)> UPvisseringpomp3_dag
                    Qvisseringpomp3(k)= Cvissering_diesel;
                end
            end
        end
    end

end

%% Marksluis
if nighttime_sluis(k)==1
    if Qsmeengepomp1(k)>0
        Qsluis1(k)=0;
    elseif wp_hoog(k)>= IPsluis1_nacht
        Qsluis1(k)= Csluis;
    elseif wp_hoog(k)< IPsluis1_nacht
        if k>1
            if Qsluis1(k-1)>0
                if wp_hoog(k)> UPsluis1_nacht
                    Qsluis1(k)= Csluis;
                end
            end
        end
    end

    if Qsmeengepomp1(k)>0
        Qsluis2(k)=0;
    elseif wp_hoog(k)>= IPsluis2_nacht
        Qsluis2(k)= Csluis;
    elseif wp_hoog(k)< IPsluis2_nacht
        if k>1
            if Qsluis2(k-1)>0
                if wp_hoog(k)> UPsluis2_nacht
                    Qsluis2(k)= Csluis;
                end
            end
        end
    end

elseif nighttime_sluis(k)==0

    if Qsmeengepomp1(k)>0
        Qsluis1(k)=0;
    elseif wp_hoog(k)>= IPsluis1_dag
        Qsluis1(k)= Csluis;
    elseif wp_hoog(k)< IPsluis1_dag
        if k>1
            if Qsluis1(k-1)>0
                if wp_hoog(k)> UPsluis1_dag
                    Qsluis1(k)= Csluis;
                end
            end
        end
```

```
        end

        if Qsmeengepomp1(k)>0
            Qsluis2(k)=0;
        elseif wp_hoog(k)>= IPsluis2_dag
            Qsluis2(k)= Csluis;
        elseif wp_hoog(k)< IPsluis2_dag
            if k>1
                if Qsluis2(k-1)>0
                    if wp_hoog(k)> UPsluis2_dag
                        Qsluis2(k)= Csluis;
                    end
                end
            end
        end

    end

    %% Waterbalansen

wp_hoog(k+1)=wp_hoog(k)+((Qsobek(k)*0.1875)/area_hoog)+((Inlet(k)*0.1875)/a
rea_hoog)-(Qsluis1(k)/area_hoog)-(Qsluis2(k)/area_hoog)-
(Qsmeengepomp1(k)/area_hoog)-(Qsmeengepomp2(k)/area_hoog); %Waterbalans
hoge afdeling

wp_laag(k+1)=wp_laag(k)+((Qsobek(k)*0.8125)/area_laag)+((Inlet(k)*0.8125)/a
rea_laag)+(Qsluis1(k)/area_laag)+(Qsluis2(k)/area_laag)-
(Qbumapomp1(k)/area_laag)-(Qbumapomp2(k)/area_laag)-
(Qbumapomp3(k)/area_laag)-(Qvisseringpomp1(k)/area_laag)-
(Qvisseringpomp2(k)/area_laag)-(Qvisseringpomp3(k)/area_laag);
end
```

Appendix E

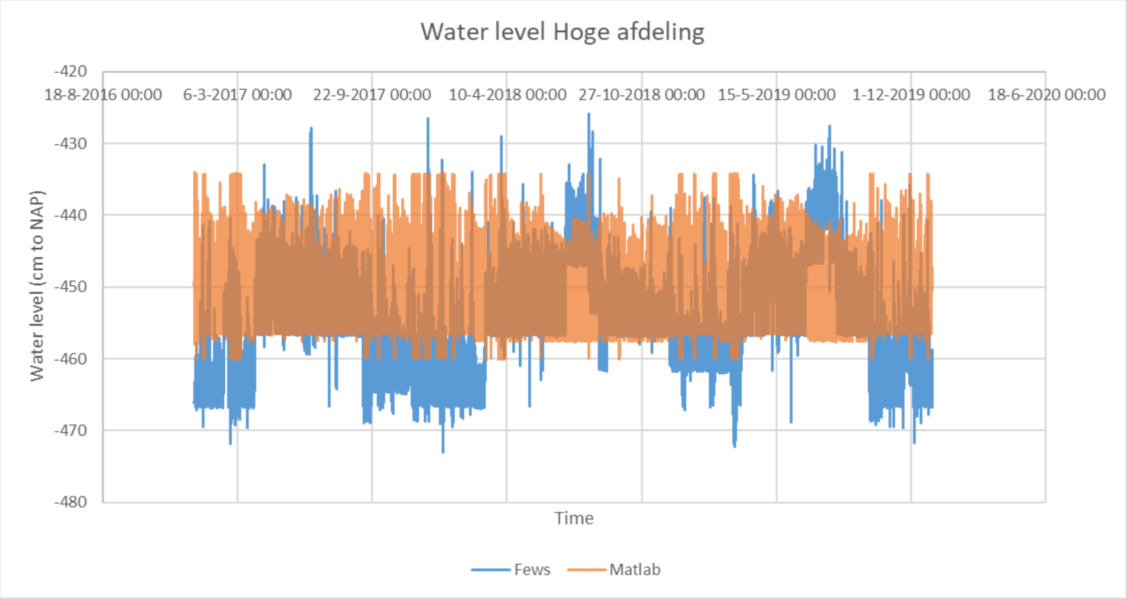

Figure 30 Water level Hoge afdeling

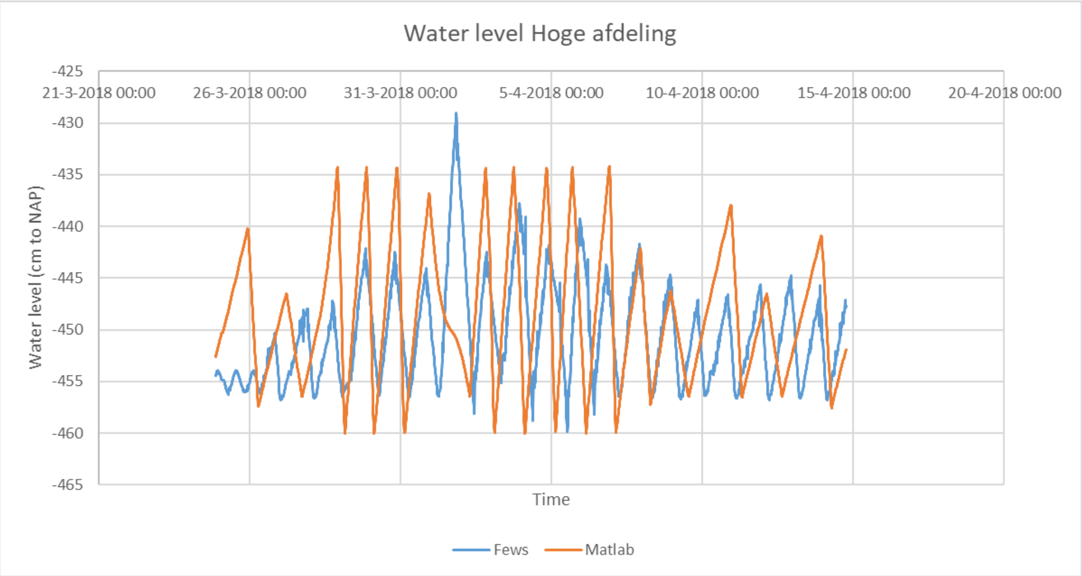

Figure 31 Water level Hoge afdeling (detailed)

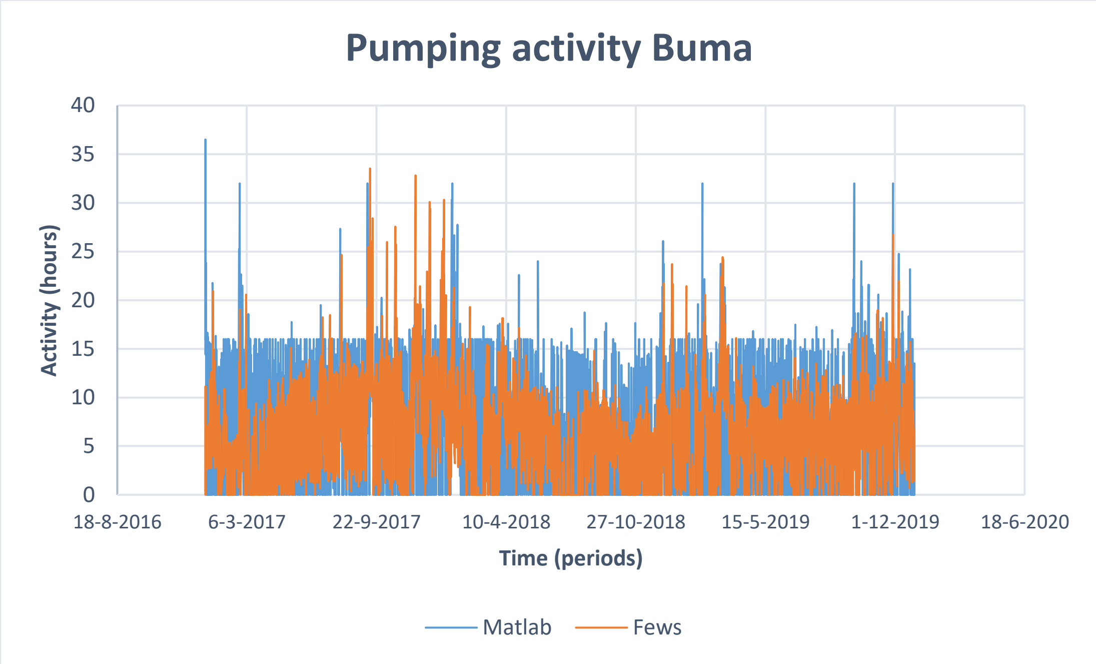

Figure 32 Pumping activity Buma

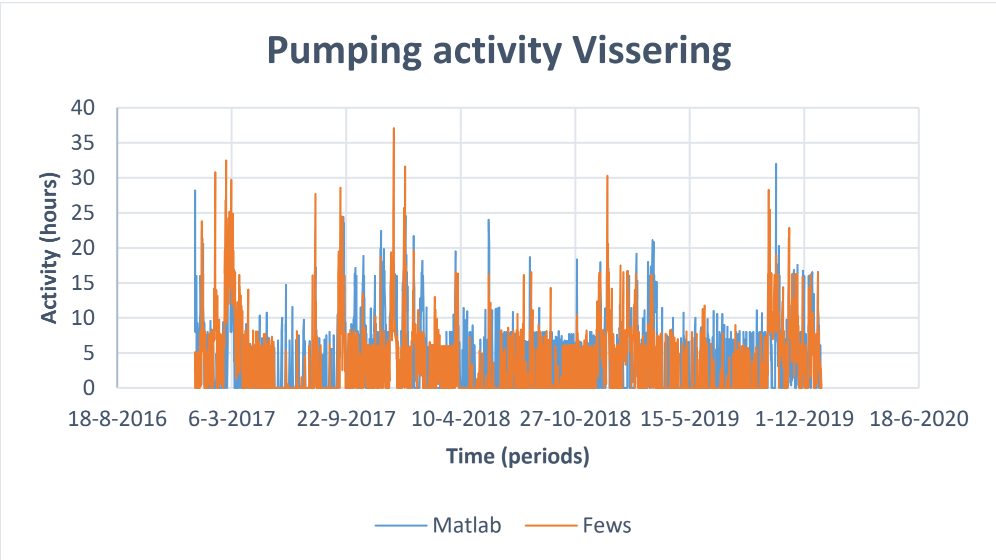

Figure 33 Pumping activity Vissering

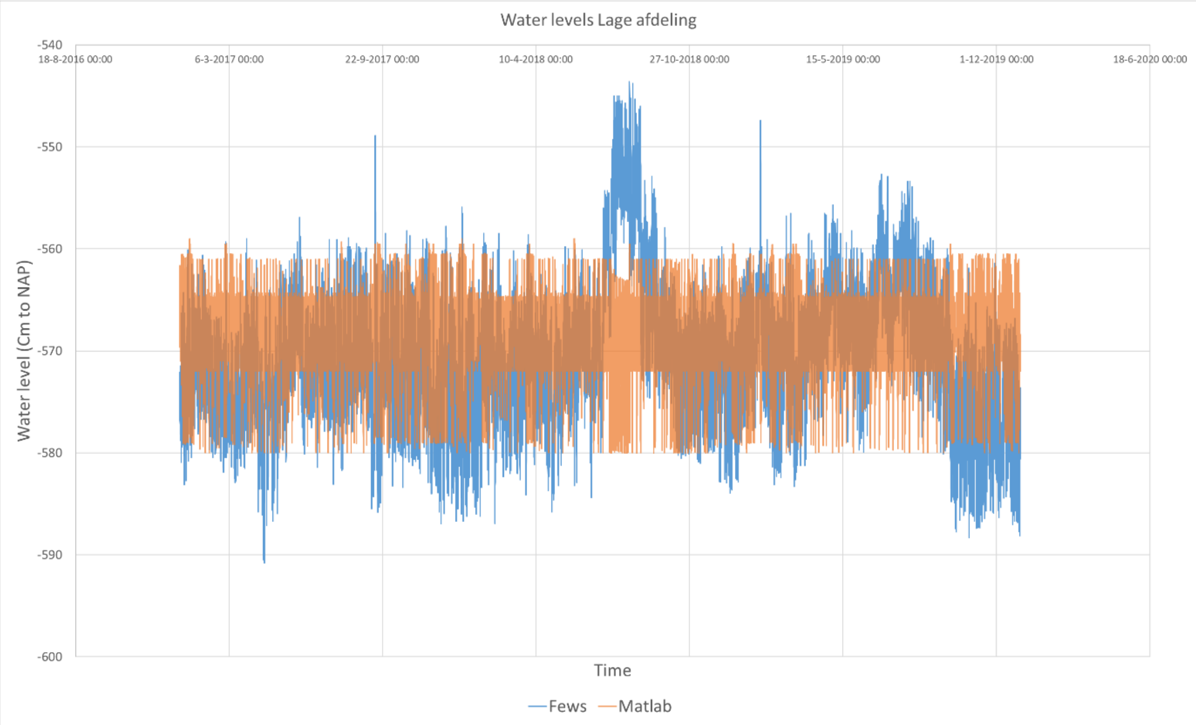

Figure 34 Water level Lage afdeling

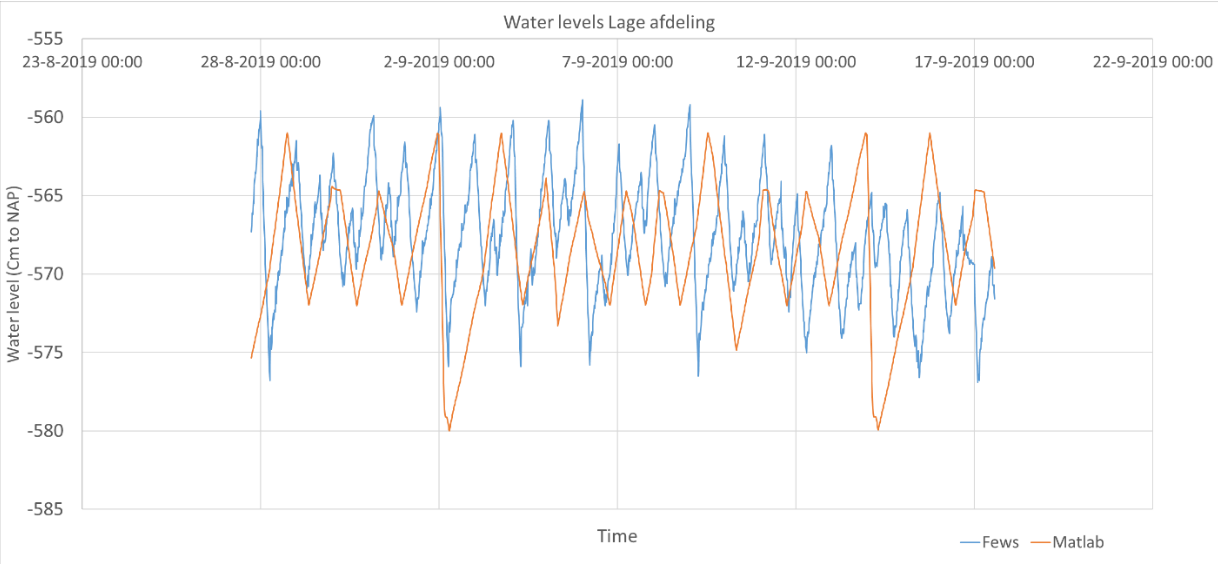

Figure 35 Water level Lage afdeling (detailed)

Table 17 Calibration activity data

Pumping station	Data source	Total activity (hours)	Percentage of off-peak period activity (%)	Percentage of peak period activity (%)
Smeenge	MATLAB model	1113.25	44.27	55.73
	FEWS	1255.95	44.57	55.43
Buma	MATLAB model	14364.8	61.8	38.2
	FEWS	14737.08	62.19	37.81
Vissering	MATLAB model	7725.83	54.68	45.32
	FEWS	7898.65	55.57	44.43

Appendix F

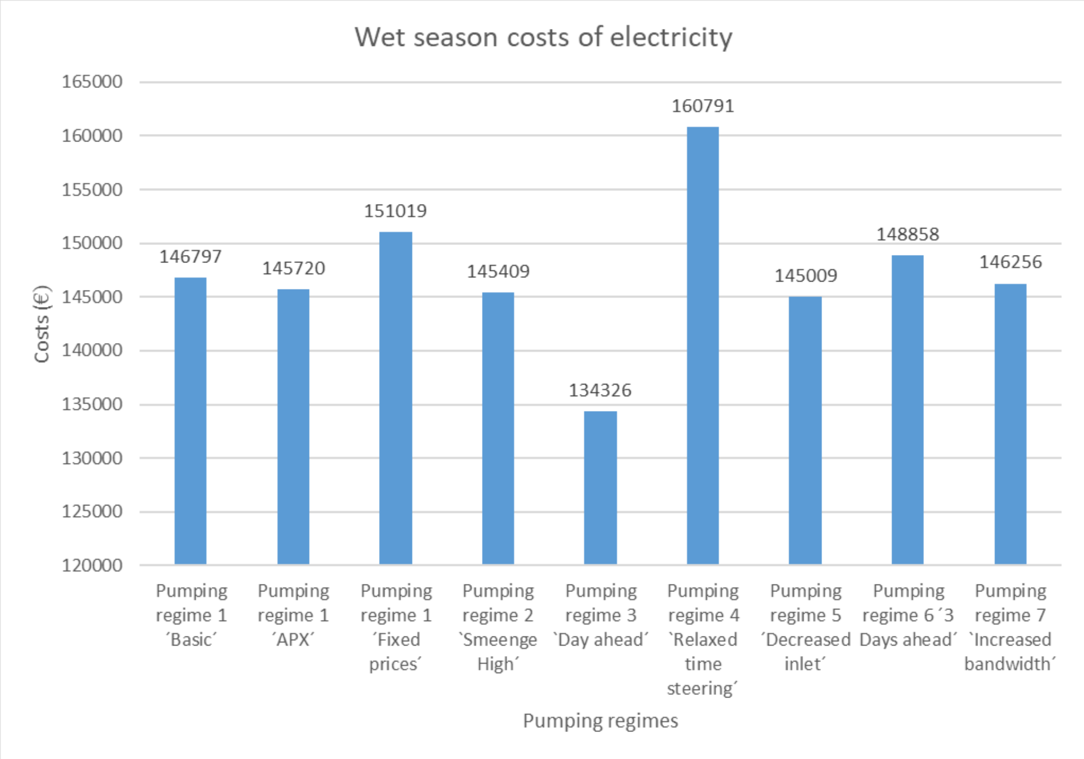

Figure 36 Wet season costs of electricity

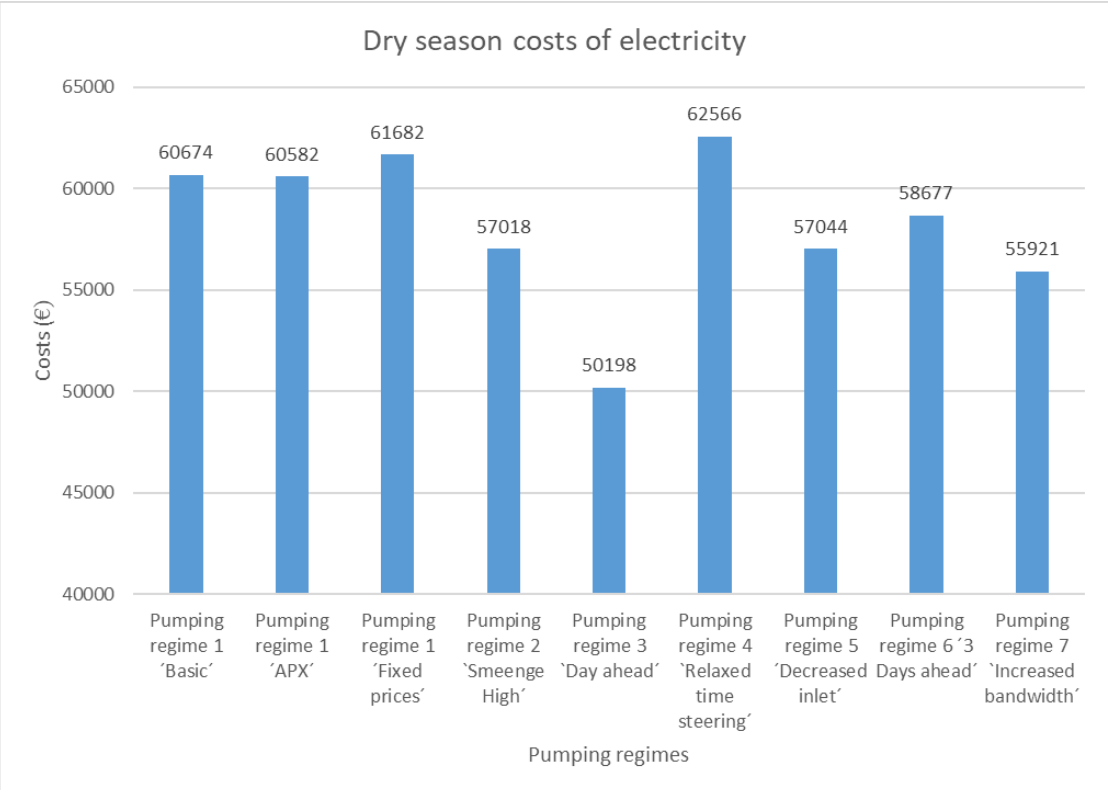

Figure 37 Dry season costs of electricity

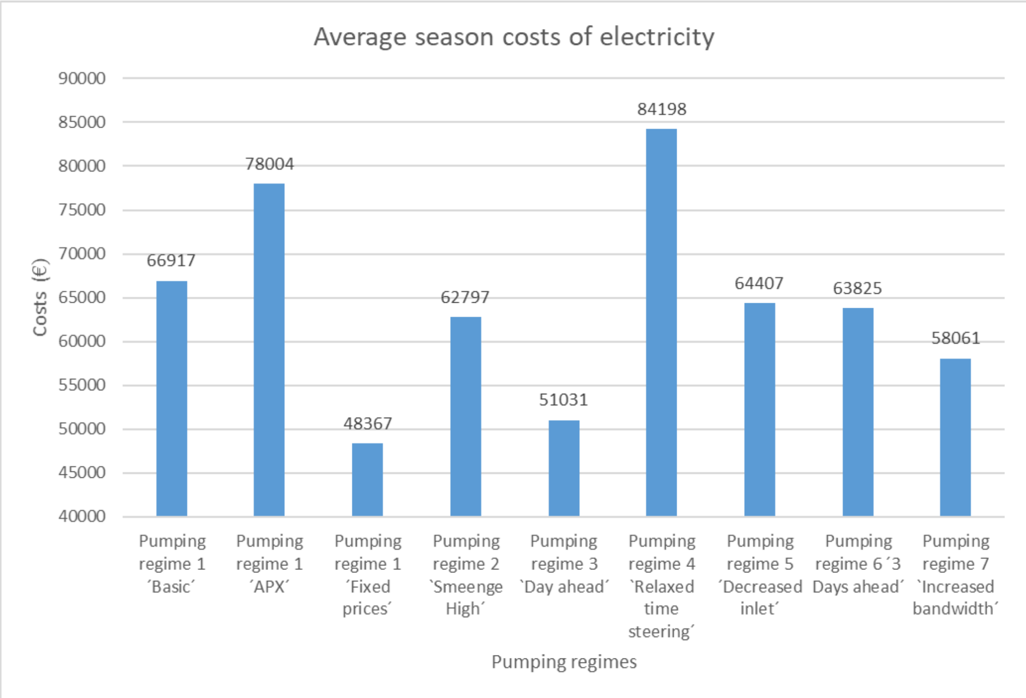

Figure 38 Average season costs of electricity

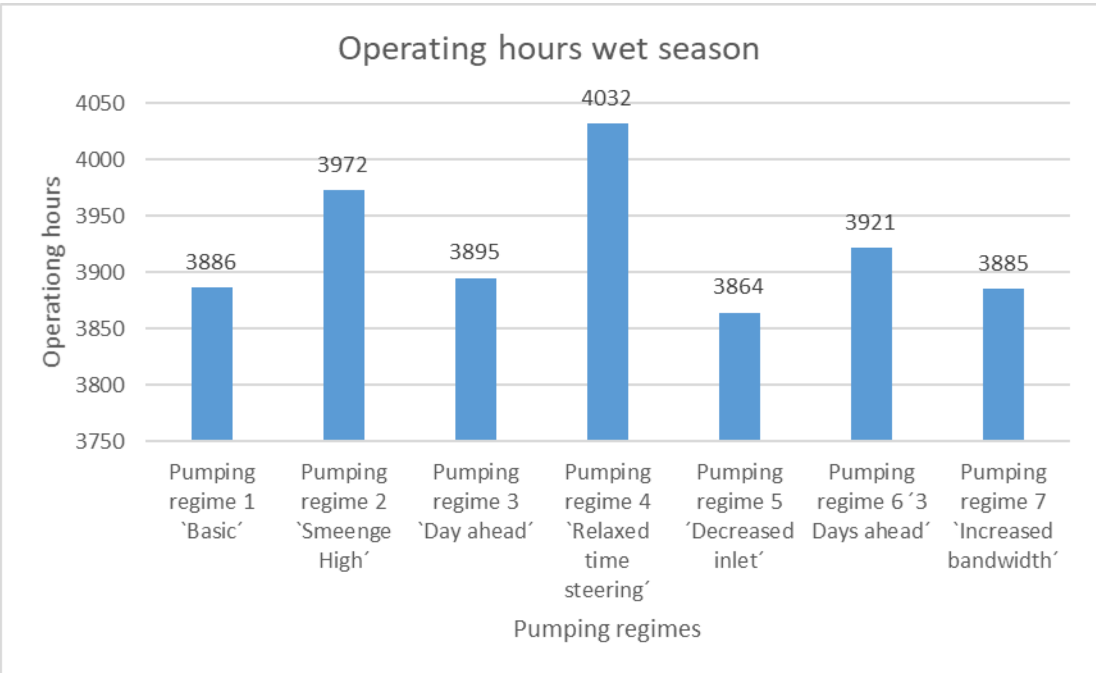

Figure 39 Operating hours wet season

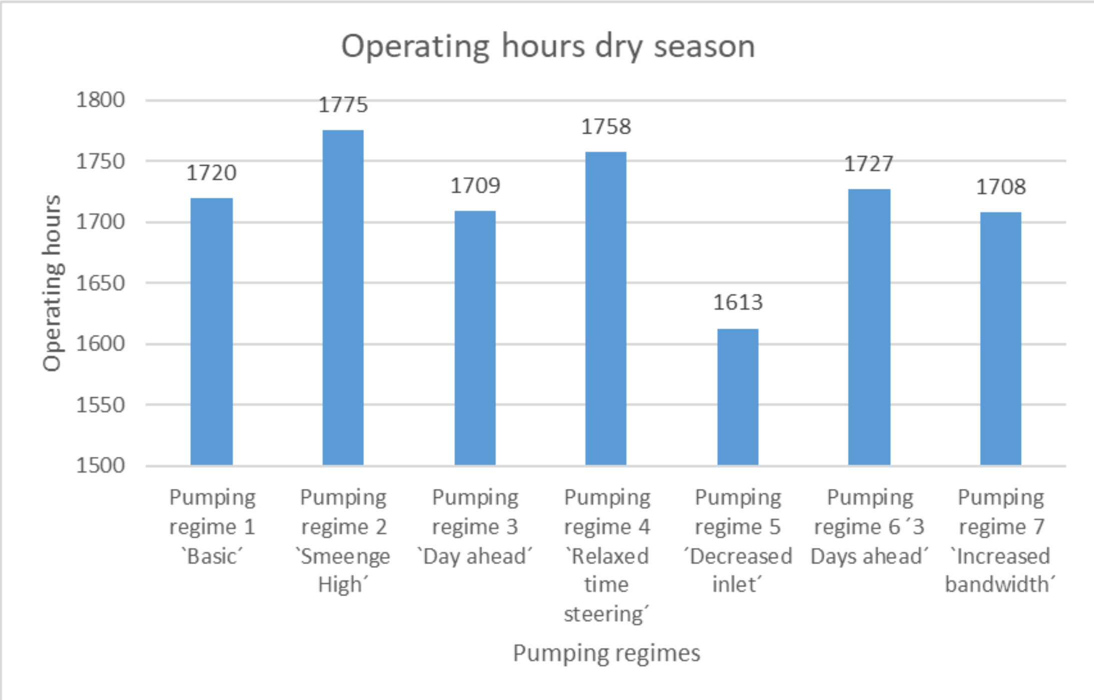

Figure 40 Operating hours dry season

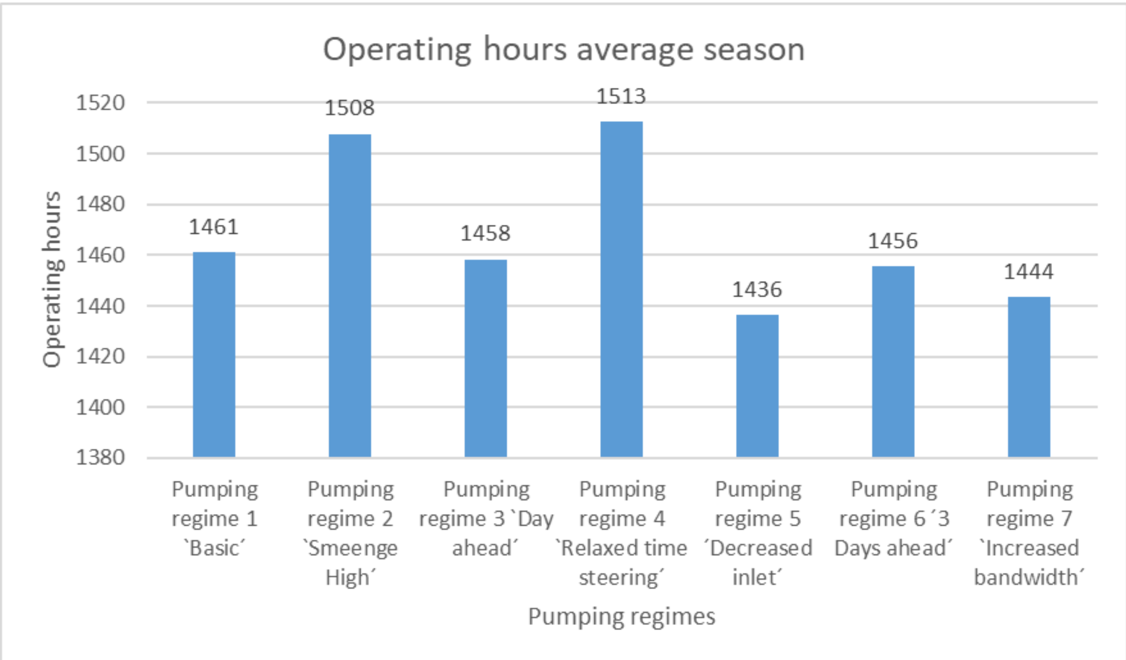

Figure 41 Operating hours average season

Appendix G

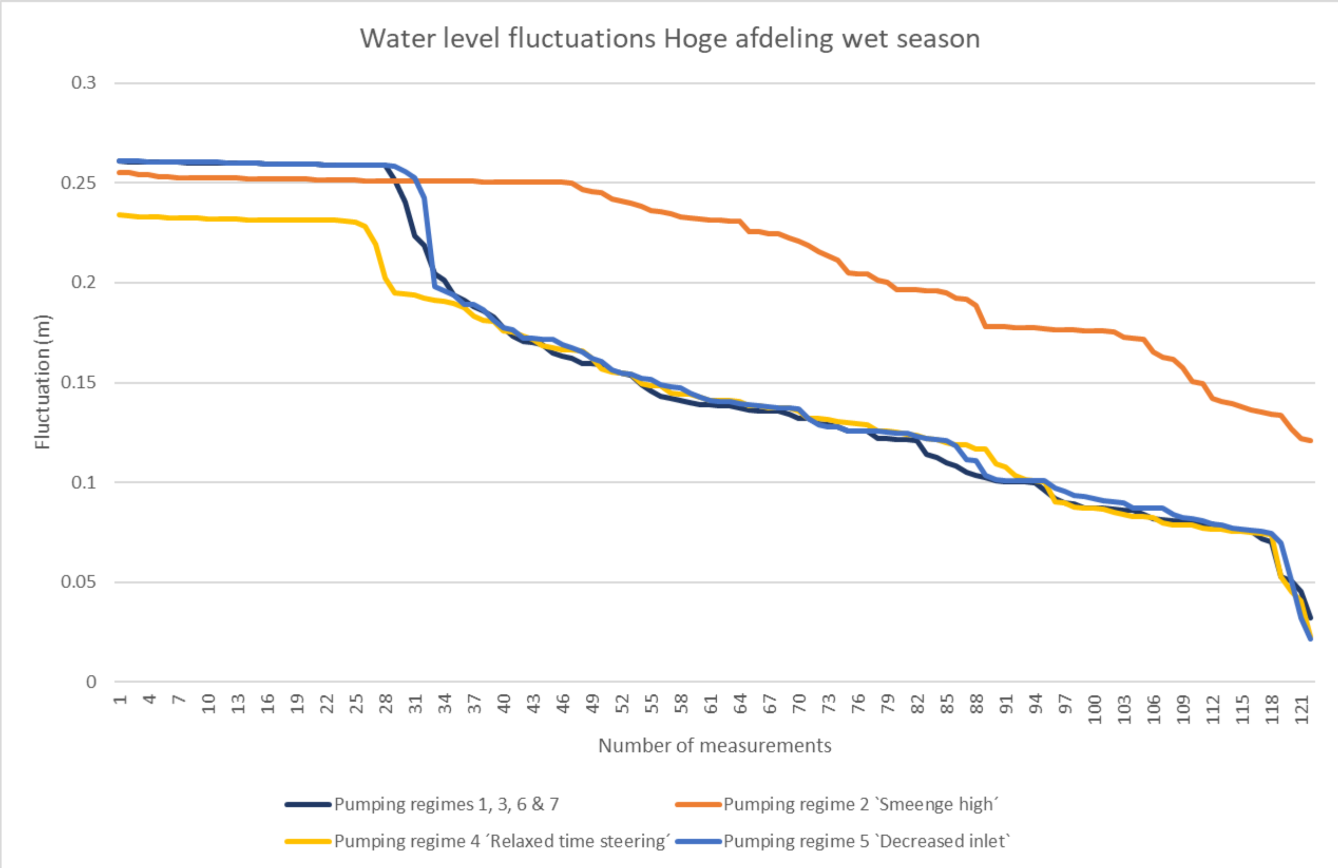

Figure 42 Water level fluctuations Hoge afdeling wet season

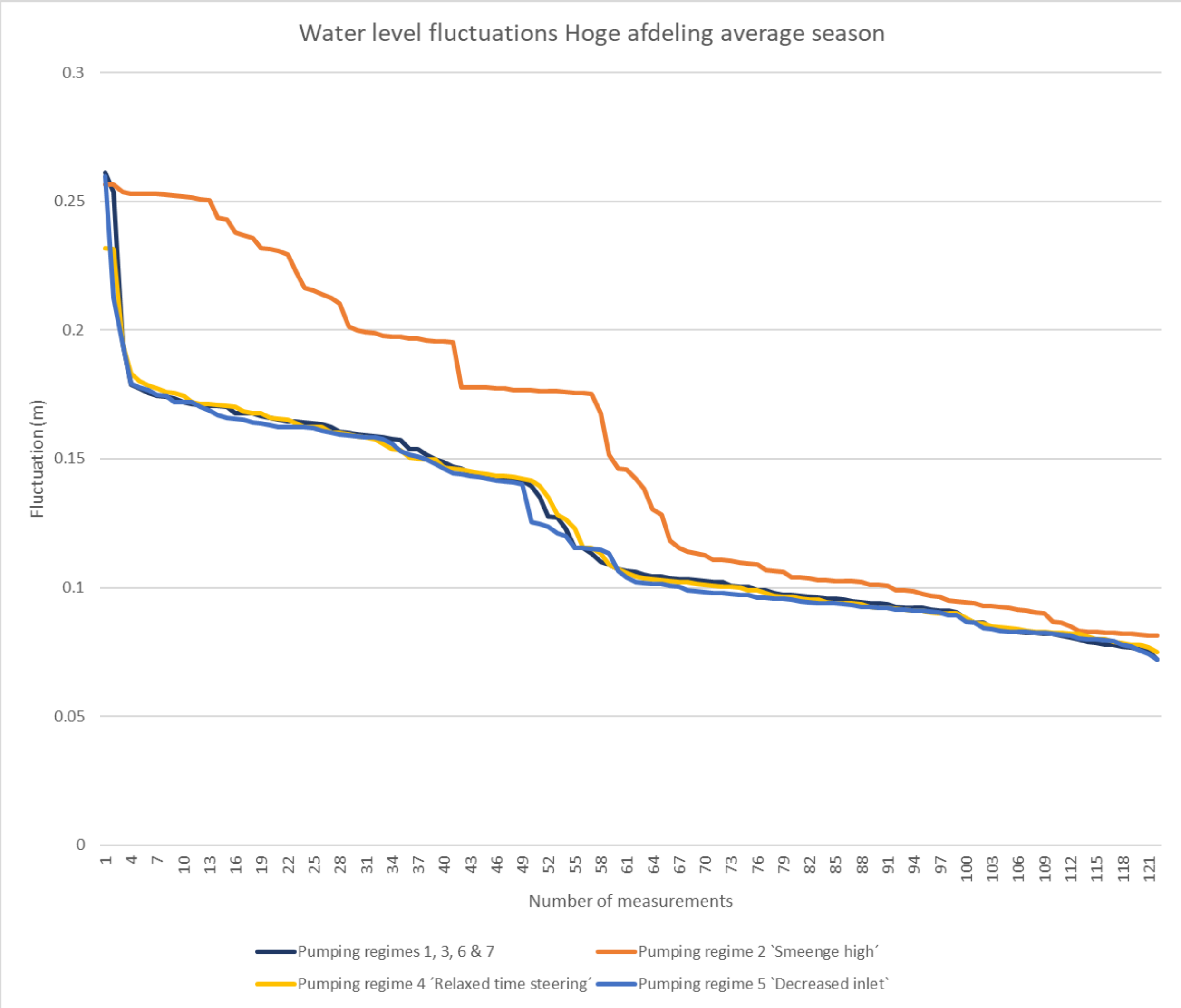

Figure 43 Water level fluctuations Hoge afdeling average season

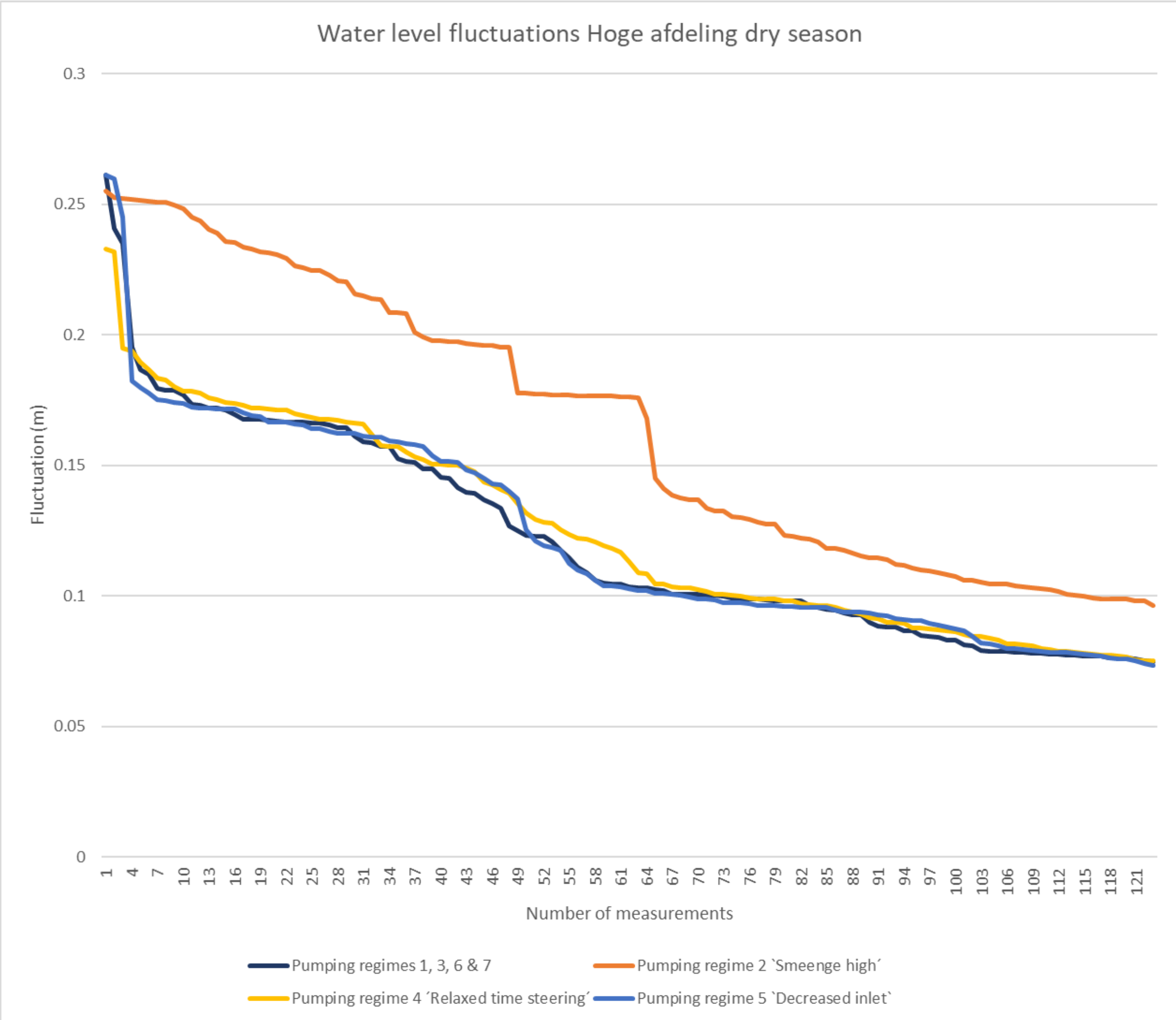

Figure 44 Water level fluctuations Hoge afdeling dry season

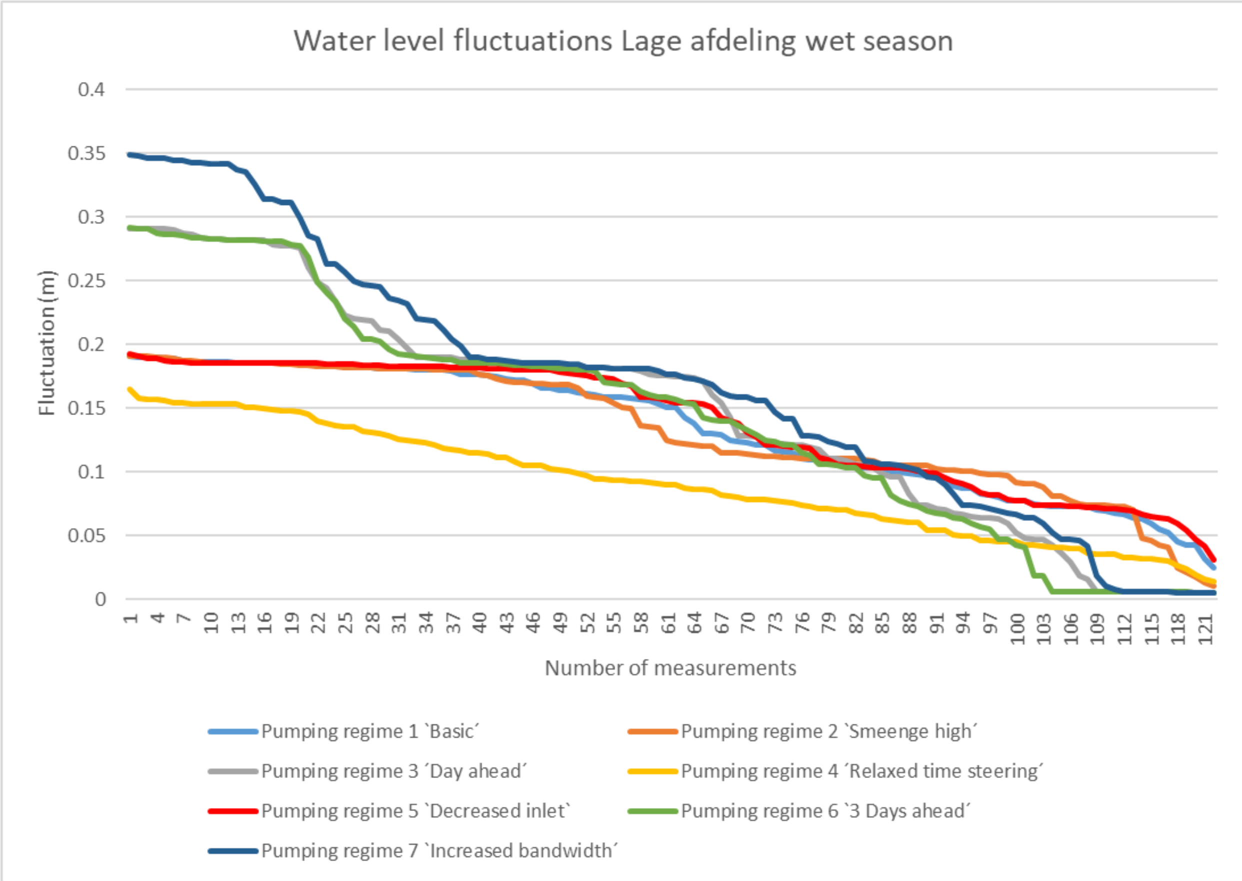

Figure 45 Water level fluctuations Lage afdeling wet season

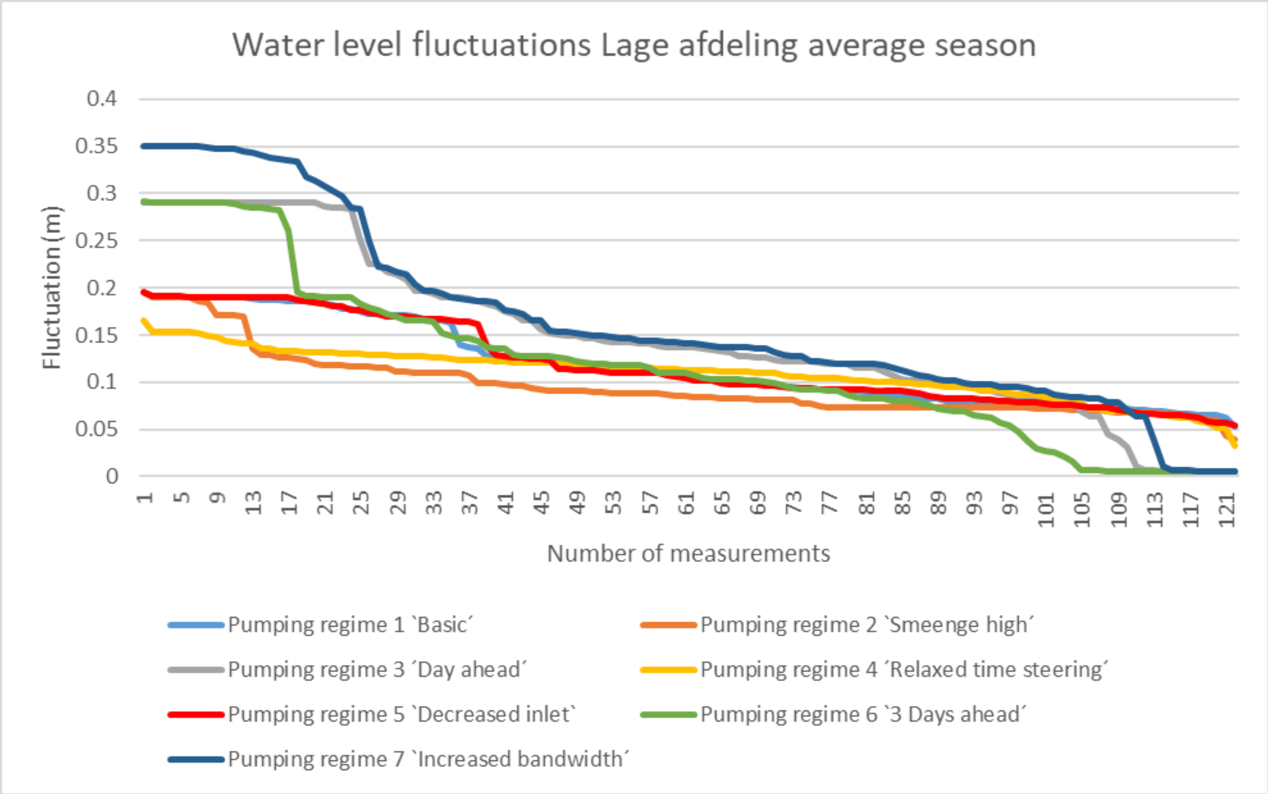

Figure 46 Water level fluctuations Lage afdeling average season

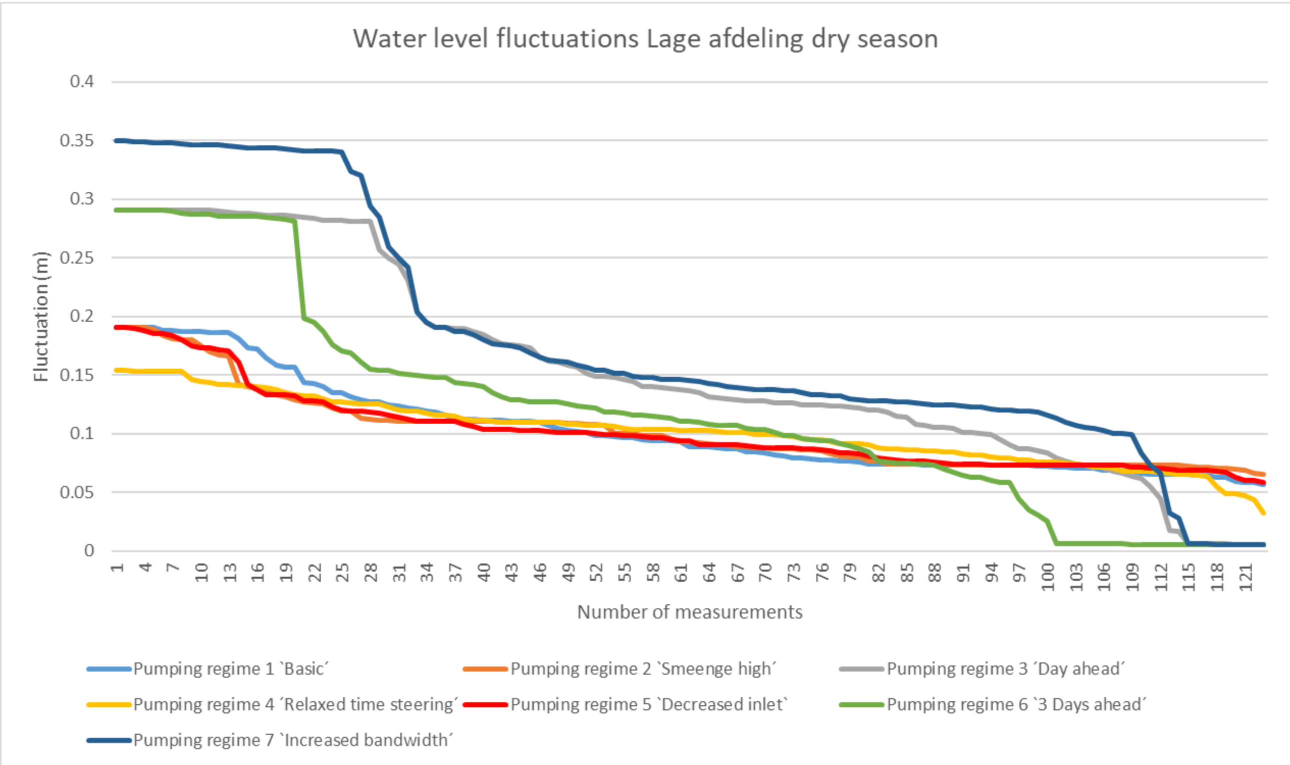

Figure 47 Water level fluctuations Lage afdeling dry season