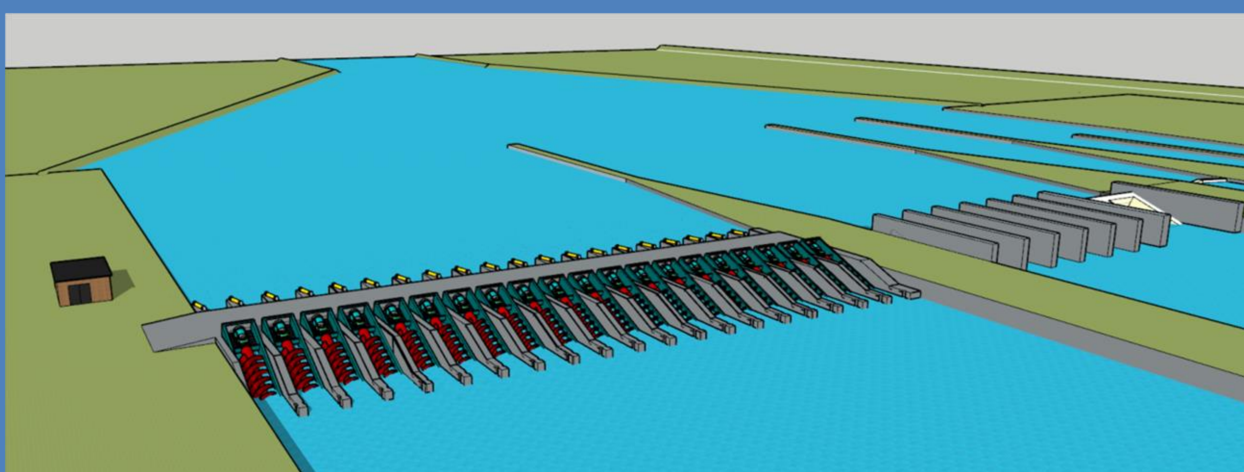
RIVER MEUSE: UTILIZING HYDROPOWER- AND ENERGY STORAGE POTENTIAL



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MSc Thesis

of

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PREFACE

In 2014 I started the bachelor Civil Engineering at Delft University of Technology (TU Delft) driven by a deep desire to obtain some exact/technological knowledge. After finishing the bachelor in 2017 hydropower engineering was the main magnet to go for a master as well. I am fascinated by dams and the principle of utilizing the head difference in a river for renewable energy purposes. Not surprisingly the course 'Waterpower Engineering' (together with the course 'Ocean Energy Technologies' and 'Offshore Wind Farms Design') were regarded as the most interesting as these courses are directly related to renewable energy.

At the end of the academic year 2017/2018 the dream graduation topic - related to hydropower on a weir at the Nederrijn - was available. Unfortunately, I was not allowed to start graduating because of not having earned enough ECTS's at that moment.

At the start of the academic year 2019/2020 I've searched extensively to comparable hydropower thesis subjects. The Netherlands contains some hydropower plants, of which two are located in the river Meuse. Reading an online news article, I discovered members of the local council in Boxmeer are interested in hydropower at the weir at Sambeek, currently not equipped for hydropower. This question is of interest to me as I've been wondering quite regularly why the hydropower potential of the river Meuse has not been fully utilized nowadays.

When writing a thesis proposal this question converged to additional questions of interest. These questions are related to pump-storage possibilities using the sections of the Meuse cascade as storage reservoirs and the possibility of pumping back locking water at periods of drought in order to avoid limited locking.

To write a thesis on these subjects combines a mix of my interests:

- River engineering: what is the available discharge for hydropower in the river Meuse?
- Hydraulic engineering: is it possible to construct a pump-storage power plant at a weir in the Meuse river within the flow regimes with varying water levels?
- Sustainability: is it possible to design a plant within Dutch environmental regulations regarding fish mortality?
- Mechanical engineering: what kind of turbines are applicable within the Dutch environmental regulations?
- Renewable energy: is it possible to utilize the full hydropower potential of the Meuse?
- Energy storage: is it possible to use the Meuse cascade for storage purposes?

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SUMMARY

The Meuse river has been made navigable for ships by the construction of a cascade of seven weirs. At only two weirs hydropower facilities exist. This implies the full hydropower potential of the Meuse is not utilized. The maximum cumulative fish mortality allowed in the river is 10 % which is already reached due to the Linne and Lith facilities. *Rijkswaterstaat* only provides additional permits when fish friendly turbines are used, or when the cumulative fish mortality does not exceed 10 %.

At periods of severe drought, the discharge in the Meuse river is too low to compensate for water losses at the weirs and locks, resulting in limited locking. Equipping a hydropower facility with pump-turbines can serve navigability by pumping back locking water upstream. Besides this, pump-turbines can be used for the purpose of energy storage by pumping water upstream at hours of low electricity demand which can be released through the turbines at hours of high demand. These purposes can be achieved by the construction of a Pumped-Storage Power plant (PSP-plant).

The objective of this report is to study if the full hydropower- and energy storage potential of the Meuse cascade can be utilized by the use of pump-turbines within Dutch environmental regulations. In order to meet the objective a conceptual design for a PSP-plant at Sambeek has been compiled. By using this design, an assessment of utilizing the full hydropower- and energy storage potential in the Meuse cascade has been performed. This assessment forms the essence of this report. For the assessment a numerical model has been constructed an applied.

Multiple turbines have been analyzed with respect to fish friendliness, the suitability for low head conditions and turbining- and pumping capabilities. The Archimedean screw has been selected for equipping the Sambeek conceptual design. This design has been scaled with respect to the head differences at the other weirs in the cascade by decreasing or extending the screw length.

As the cumulative fish mortality is expected to be lower than 10 % it can be assumed the full hydropower potential of the Meuse cascade can be utilized within Dutch environmental regulations using this conceptual design. Furthermore, the problem of limited locking is eliminated by using the pumps.

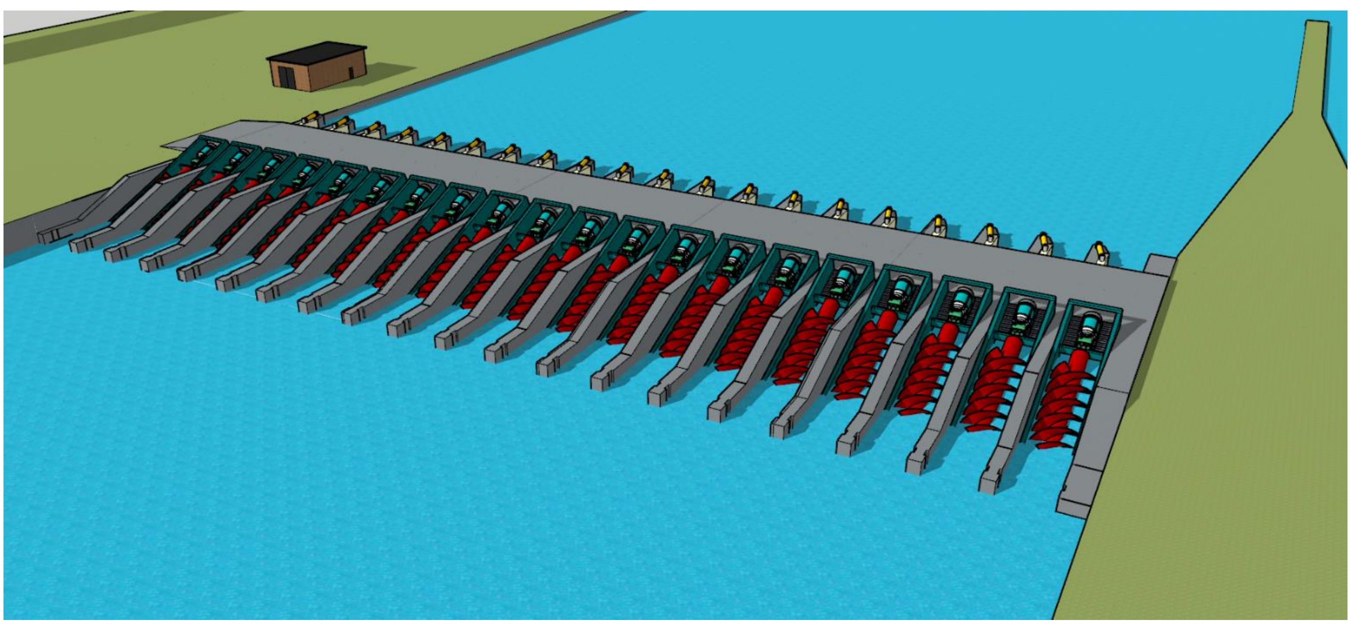

Figure 1: Conceptual design PSP-plant at Sambeek

The river bed slope in the Linne - Borgharen section causes restrictions for energy storage. As a result, energy storage in the Meuse cascade will start at the weir of Lith and will end at the Linne weir. At storage mode river water is discharged in the storage section Roermond-Linne. The river will store energy itself as well.

The number of screws per hydropower- and PSP-plant in the Meuse cascade is calculated using the 100-day design discharge related to a flow duration curve (FDC). This is common practice in the field of hydropower engineering with respect to run-of-river plants. The numerical Meuse model computes power production- and storage per FDC-day.

Using the design discharge the cumulative installed capacity throughout the cascade becomes 50.3 MW. This results in a hydropower Annual Energy Yield (AEY) of 205 GWh. The pumped-stored power AEY is 31.6 GWh processing a yearly surplus power of 56.2 GWh. Up to 59,000 households can be powered with hydro- and pumped-stored power.

To put the pumped-stored power AEY into perspective: 54 % of the yearly power surplus of the Offshore Windfarm Egmond aan Zee (OWEZ) can be processed, assuming the wind is blowing every night of the year. OWEZ is representative for a small size Dutch windfarm.

In order to utilize the complete energy storage potential of the cascade more pump capacity is needed. By using the maximum volumes the PSP-plants need to pump leads to more screws for the PSP-plants at Lith, Grave and Sambeek. The cumulative installed cascade capacity increases to 81 MW. The AEY on pumped-stored power increases to 77.2 GWh. Combined with the AEY on hydropower up to 75,000 households can be powered.

Downstream the Borgharen weir ships make use of the Juliana canal, as the river is not navigable between Linne and Borgharen. The Juliana canal shows a head difference of 23 meter. When – besides the Meuse cascade – the Juliana canal is included in the model the hydropower AEY increases to 393.1 GWh. The AEY on pumped-stored power increases to 129.3 GWh. Up to 131,000 households can be powered by pumped-stored power and hydropower.

LIST OF SYMBOLS

The symbols used in this thesis are ordered in alphabetical order. Greek symbols are preceded by alphabetical symbols.

Symbol	Description	Unit
A	Cross-sectional area	m^2
B	Width	m
D	Diameter screw	m
d	Diameter shaft	m
E	Energy	Joule (J)
g	Gravitational acceleration	m^2/s
GWh	Giga Watt hour	J
h	Head difference	m
H	Height	m
I	Screw end submergence	-
L	Length	m
L_b	Length screw	m
L_s	Length shaft screw	m
m	Mass	kg
$\dot{m}$	Mass flow rate	kg/s
MWh	Mega Watt hour	J
N	Number of blades	-
n	Rotational speed screw	rpm
P	Power	J/s or Watt (W)
PCP	Pump Chute Point	m
PFP	Pump Filling Point	m
Q	Discharge	m^3/s
R_i	Inner radius (radius shaft)	m
R_a	Outer radius (screw)	m
S	Pitch screw	m
TEP	Turbine Exit Point	m
TFP	Turbine Filling Point	m
v	Velocity	m/s
V	Volume	m^3
W	Watt	J/s

Greek symbols

α	Angle inclination screw turbine	°
β	Angle inclination screw pump	°
ρ	Density	$kg/_{m^3}$
μ	Efficiency	%
δ	Ratio d/D	-

TABLE OF CONTENTS

1. INTRODUCTION

This introductionary chapter contains a motivation and a description of the relevancy for the chosen subjects. Furthermore, the problem analysis and problem statement, the objective of the thesis, the methodology and the report outline are presented.

1.1 MOTIVATION

Nowadays climate change is a topic of concern throughout the world. To battle climate change 195 countries signed a international climate agreement on 12 December 2015. This agreement has two main targets for the year 2050: the increase in global warming to be maximally 2 degrees and the achievement of a balance between greenhouse gas emission and storage (Ministry Economic Affairs, 2019).

The Dutch economy is currently depending on fossil fuels which supply 95 % of the energy. To meet the goals of the climate agreement a shift is needed from fossil to renewable energy sources ("Communicating the energy", 2019).

In the next decade offshore wind farms in the North Sea are expected the generate electricity for at least five million households. By cooperating internationally, the Netherlands aims to use renewable energy sources like solar energy from Spain and hydropower energy from Norway (Ministry Economic Affairs, 2019).

However, hydropower energy does exist in the Netherlands as well. Two main rivers are entering the Netherlands which are the Rhine and the Meuse. Because of the flat topography of the Rhine and shipping purposes the potential for hydropower is limited. Currently one hydropower plant exists at Amerongen ("Rijkswaterstaat Waterinfo", 2019).

The river Meuse has been divided into multiple sections at the river trajectory Borgharen-Lith in order to make the river suitable for shipping purposes. To utilize the head difference at the weirs currently two hydropower plants exist. This means at only two of the seven weirs hydropower is generated in the river Meuse. The hydropower potential is not fully utilized because of environmental regulations ("Uitspraken in vergunningszaken", 2019).

In periods of severe drought, the navigability of the river Meuse is influenced by low river discharges. In these periods a locking process is put on hold until the whole lock chamber is filled with ships thereby reducing the loss of water. The maximum waiting time for ships is four hours ("Maatregelen vanwege lage", 2020).

Pumped-storage power is based on the movement of water between two reservoirs at different elevations. During periods of low energy demand excess electricity is pumped to an upper reservoir. At periods of high energy demand the water is released through the pump-turbines thereby generating electricity ("Pumped storage", 2019).

At hours of low energy demand excess energy could be used to pump back water into the sections of the Meuse cascade when the weirs are equipped with pumps thereby contributing to grid reliability and to avoid of the loss of this excess energy.

These considerations form the motivation (and objective) of this thesis: to study if the full hydropower and energy storage potential of the Meuse cascade can be utilized by using pump-turbines which can serve navigability in periods of drought as well.

1.2 RELEVANCY

In December 2019 the Dutch High Council (Dutch*: 'Hoge Raad der Nederlanden'*) ordered the government to decrease the output of CO_2 for the year 2020 to be 25 % lower compared to 1990 (Santen & Kos, 2019). Currently the hydropower potential of the Meuse river is not fully utilized. Utilizing this potential could contribute to lower CO_2 emissions and an increase of the use of renewable energy in the Netherlands.

In periods of drought the waiting time for ships increases at the locks in Meuse river in order to minimize the loss of locking water thereby maintaining the minimum waterdepth upstream. It might be of economic benefit to decrease this waiting time by pumping back locking water, thereby eliminating the need to put locking processes on hold.

Pumped-storage power is an effective solution to achieve grid reliability and to avoid the loss of excess electricity ("Pumped storage", 2019). Currently no pumped-storage power facilities exist in the Netherlands. This is mainly due to the unsuitable geography as the country is flat. However, it might be possible to use the sections of the Meuse cascade as reservoirs for pumped-storage power purposes.

1.3 PROBLEM ANALYSIS

In this paragraph a problem analysis of the Meuse cascade with respect to hydropower, navigability, pumped-storage power and the Dutch environmental regulations will be presented.

1.3.1 THE RIVER MEUSE

Two main rivers are entering the Netherlands which are the Rhine and the Meuse, shown in Figure 12 in chapter 4. The Meuse enters the Netherlands in the south at approximately NAP + 44 meter ("Rijkswaterstaat Waterinfo", 2019).

CANALISATION

This high NAP level is the main reason the river Meuse has been canalized into multiple sections which are called '*panden*' in Dutch. To make the river suitable for shipping the waterlevels at these sections is managed by the use of weirs. The weirs and their gross head together with existing hydropower facilities are presented in Table 1.

weir	gross head (meter)	Hydropower
Borgharen	5.2	no
Linne	4	yes: 11 MW
Roermond	2.7	no
Belfeld	3.0	no
Sambeek	3.2	no
Grave	2.5	no
Lith	4.2	yes: 14 MW

Table 1: Gross head and installed capacities at weirs in Meuse cascade (*De Limburgse Maas*, 2019)

As one can observe currently two hydropower plants exist in the river Meuse. The weir at Linne is equipped with a 11 MW facility and the weir at Lith with a 14 MW facility. These hydropower facilities can be described as so called 'run-of- river plants'. A run-of-river plant is characterized by an operational mode where inflow equals outflow. In appendix A an overview of the main types of hydropower plants can be found.

1.3.2 HYDROPOWER POTENTIAL RIVER MEUSE

As the Meuse has been canalized by the use of weirs the head difference is utilizable for energy generation. The general hydropower formula reads:

$$P = \rho * g * Q * H * \eta \qquad \text{formula (1)}$$

In which:

- P = Power (W)
- ρ = density water (kg/m^3)
- g = gravitational acceleration (m^2/s)
- Q = discharge (m^3/s)
- η = efficiency (-)

The derivation of this formula is shown in appendix A. Using this formula, the hydropower potential of the river Meuse is estimated to be 59 MW (assumption of a design discharge of 300 m^3/s as derived in chapter 4 with respect to the available discharge for the Sambeek weir, total head difference weirs 24,7 meter according to Table 1 and applying an efficiency of 80 %).

ENERGY MODE

Utilizing the whole hydropower potential with power plants at the weirs could lead to an operational mode called 'energy mode'. In this mode all the weirs in the Meuse are generating hydro-electricity.

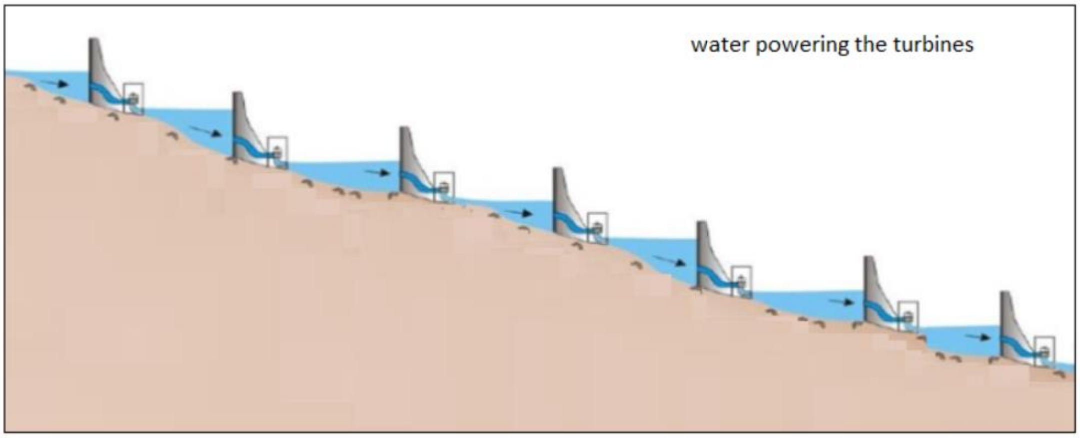

Figure 2: Energy mode, hydropower generation at weirs ("Types of hydropower", 2019)

1.3.3 NAVIGABILY RIVER MEUSE DURING DROUGHT

The discharge in the river Meuse varies throughout the seasons. Low discharge occurs in the period June-October and is approximately 80 m^3/s (Bruijn et al, 2012, p.182). In 2017,2018 and 2019 it decreased to just above 20 m^3/s, as will be explained in chapter 4 on the boundary conditions on discharge.

LOCKING PROCES

Low discharges at the Meuse cause several problems, which are amongst others increased waiting times at the locks due to limited locking in order to decrease the loss of locking water ("Hinder voor scheepvaart", 2019). In periods of drought a locking process is put on hold until the whole lock chamber is full with ships, with a maximum waiting time of four hours ("Maatregelen vanwege lage", 2020). This is done in order to maintain the water level upstream sufficiently high.

At the weirs in the Meuse it might be useful to pump back locking water thereby serving navigability by maintaining the water level and reducing large waiting times for ships during the locking process. These considerations suggest the use of pump-storage turbines at the weirs in the cascade could be useful to maintain the water level.

1.3.4 PUMPED-STORAGE POWER

In Figure 3 one can view the layout of a pumped-storage power facility of the Norwegian company Statkraft, which is a leading international hydropower company and Europe's biggest renewable energy supplier ("Pumped-storage hydropower", 2019). During periods of high demand the stored water is released through the turbine thereby generating electricity in the same way as a conventional hydropower plant ("Pumped storage", 2019). A pumped-storage hydropower facility is often called a PSP-plant (Pumped-Storage Power plant).

Pumped-stored hydropower is an effective solution to achieve grid reliability. It is proven to be a robust way of storing and generating energy. Nowadays in the US pumped-storage is an essential component of the electricity network with a capacity of 20 GW ("Pumped storage", 2019).

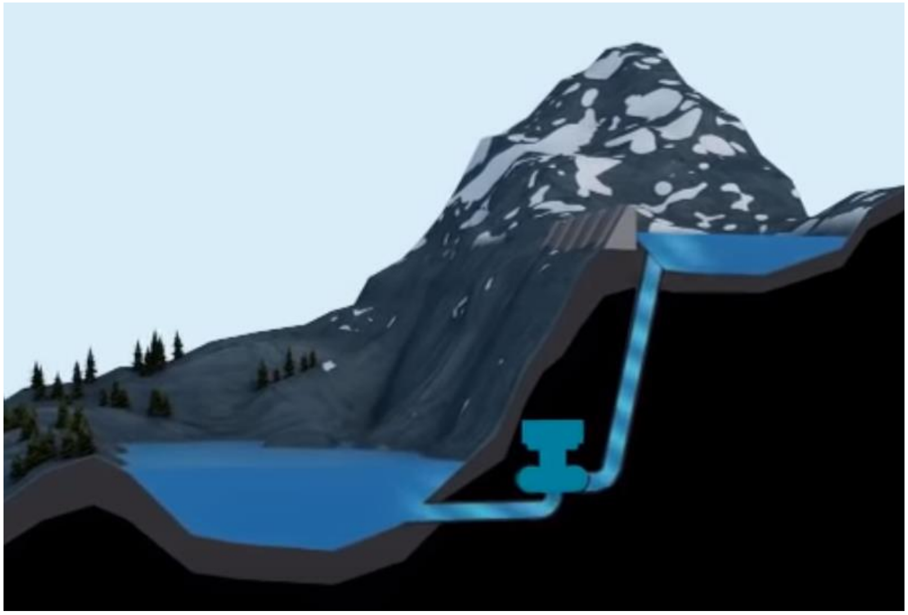

Figure 3: Norwegian pumped storage lay out ("Pumped-storage hydropower", 2019)

As explained in the (sub)section 'Canalization' the river Meuse has been made navigable for shipping purposes by dividing it into sections. The installation of pumped-storage turbines creates the opportunity to use these sections for energy storage.

STORAGE MODE

The installation of pump-turbines with the purpose of energy storage can be described by an operational mode called 'storage mode'. This is illustrated in Figure 4, in which energy is stored upstream the weirs in the Meuse cascade.

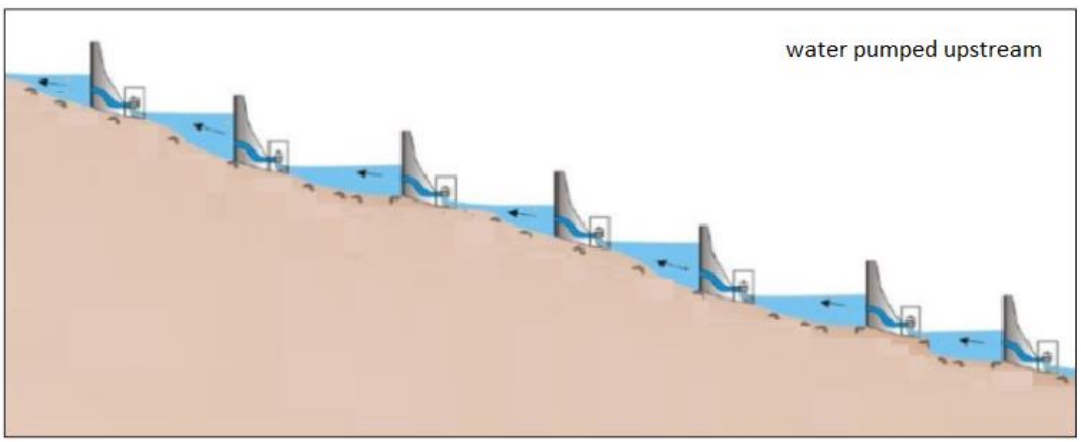

Figure 4: Energy stored upstream weirs, adjusted picture ("Types of hydropower", 2019)

1.3.5 ENVIRONMENTAL IMPACT ASSESSMENT

In this paragraph an Environmental Impact Assessment (EIA) on the river Meuse will be presented, as part of the problem analysis. The main environmental problems with respect to a hydropower/PSP-plant in the Meuse cascade are the fish mortality rates.

FISH MORTALITY

The primary mechanism leading to fish mortality is blade strike. Blade strike occurs when a fish is hit by a rotating blade from a turbine. The probability of being hit by a blade depends on (Amaral, 2019):

- The fish length.
- Relative velocity of fish to a blade.
- The spacing between the blades.
- The rotational speed of the turbine.

Furthermore, the thickness and shape of the blade are of influence on fish mortality.

Figure 5: fish struck by a turbine blade (Amaral, 2019)

Pressure-related injury potential (or barotrauma) is another fish mortality mechanism, which is mainly depending on (Amaral, 2019):

- How rapid the pressure changes from the entrance and exit of the turbine blades occur.
- How quickly a fish is able to adjust to this pressure changes.

DUTCH FISH MORTALITY REGULATIONS

Because of fish mortality the Dutch law has strict regulations considering hydropower plants. For a 'relevant area', which is the river Meuse in this perspective, one can obtain a license only when the power plant meets the requirements for downstream fish migration. A PSP-plant is therefore only permitted if the cumulative fish mortality in a 'relevant area' is lower than 10 % (Dronkers, 2015).

If the cumulative fish mortality is 10 % or more new permits for hydropower facilities are provided only if they are equipped with fish friendly turbines or experimental other measures aimed at reducing the fish mortality, or if the additional contribution to fish mortality is lower than 0.1 % ("Uitspraken in vergunningszaken", 2019).

The hydropower plants at Lith and Linne are equipped with Kaplan turbines, more specific bulb turbines. They are currently responsible for around 10 % percent of the fish mortality in the River Meuse ("Uitspraken in vergunningszaken", 2019).

1.4 PROBLEM STATEMENT

The main observations resulting from the problem analysis on the Meuse cascade are:

- The Meuse cascade consists of seven weirs. Only at two weirs (Lith and linne) hydropower facilities exist. This implies the full hydropower potential of the Meuse cascade has not been utilized.
- According to the Dutch environmental regulations the cumulative fish mortality due to hydropower generation in the Meuse cascade is maximally 10 %. The two power stations at Lith and Linne weirs are already responsible for 10 % fish mortality.
- In periods of severe drought locking processes are put on hold in order to maintain the water level upstream of a weir. It might be useful to equip a hydropower facility with pump-turbines in order to account for the water lost during locking processes. This might decrease waiting times for ships thereby serving navigability.
- The installation of pump-turbines could serve the goal of pumped-storage power. The sections of the Meuse cascade could function as reservoirs to store energy at periods of low demand. At hours of high demand, the stored water can be released thereby powering the turbines and producing electricity.

ESSENCE PROBLEM ANALYSIS

The essence of the problem analysis is Dutch environmental regulations block the construction of new hydropower plants at the weirs in the Meuse cascade. By doing so the full hydropower potential of the river Meuse cannot be utilized.

New permits are only provided when fish friendly turbines leading to an additional fish mortality of 0,1 % are used, or when the cumulative fish mortality stays beyond 10 %. When using fish friendly pump-turbines a PSP-plant might be feasible. Thereby the Meuse cascade can be used for energy storage and -production purposes. Pump-turbines can be used for pumping back locking water as well thereby eliminating the need for limited locking.

PROBLEM STATEMENT

It is not known whether and how the hydropower- and energy storage potential of the Meuse cascade can be fully utilized within Dutch environmental regulations using PSP-plants.

1.5 OBJECTIVE

The objective of this thesis is to study whether the full hydropower- and energy storage potential of the Meuse cascade can be utilized within Dutch environmental regulations. By building a model it will be studied whether this hydropower- and energy storage potential can be utilized using a conceptual design of a PSP-plant equipped with pump-turbines.

1.6 METHODOLOGY

The objective of this thesis should lead to an integrated approach for the Meuse cascade of:

- Utilizing the hydropower potential using pump-turbines.
- Create energy storage in the sections of the cascade.
- Increasing navigability by pumping back locking water.

The approach will be to compile a conceptual design of a PSP-plant for the weir at Sambeek. The PSP-plant will be designed with respect to the following operational modes:

- Energy mode (when hydropower is generated). This will be the main operational process.
- Storage mode (when water is pumped upstream for energy storage purposes). This will be the second operational process. The pumps can also be used to pump back locking water at periods of drought.

Using this conceptual design, the possibility of utilizing the full hydropower- and energy storage potential of the Meuse cascade will be researched. This is the essence of this report. This assessment will be carried out by constructing a numerical model which is capable of describing energy storage and energy production for the whole Meuse cascade.

METHODOLOGICAL STEPS

The methodological steps are based on the design steps used for hydraulic structures (Molenaar & Voorendt, 2020). The initial steps to work through are summed up below:

- Description of lock- and weir complexes Meuse cascade needed for the determination of boundary conditions.
- Formulation of the requirements on turbines, turbine configuration, PSP-plant and numerical Meuse model.
- Formulation of boundary conditions on discharges, waterlevels and storage volumes.
- Development and verification of concepts on turbines and turbine configuration.

After these steps the main methodical steps to meet the objective are:

- Development and verification on requirements of a conceptual PSP-plant using information obtained in initial steps.
- Construction of numerical model using this conceptual design in order to assess Meuse cascade on:
  -utilization of hydropower potential;
  -utilization of energy storage potential.

These steps are used as guideline for the chapters in the report outline, which is presented in paragraph 1.7.

Usually, a design is made in the rough-to-fine ('*grof-naar-fijn*') sequence. This sequence is followed throughout this report as well, for instance at the selection of the turbine to apply in the conceptual PSP-plant design. After a rough assessment of available turbines in chapter 7 and verification on requirements the selected turbine is analyzed more detailed in chapter 8, for instance on its efficiency.

The chapter on turbine configurations will follow the sequence of rough-to fine as well. Multiple turbine configurations are assessed in chapter 9. The selected turbine configuration is elaborated on into detail in chapter 10, in which it will be integrated in the conceptual design of the PSP-plant at the Sambeek weir.

Finally, for the model it is assumed PSP-plants like the conceptual design are present at the weirs in the Meuse cascade. The model will be used for the assessment of the Meuse cascade on the utilization of its hydropower- and energy storage potential.

As this report partly focuses on a technical functional design for the PSP-plant no attention will be paid to stakeholders or costs. For this reason, no evolutionary design phase will be performed. This will become a recommendation.

The location of Sambeek has been chosen as this lock- and weir complex is currently not equipped with a hydropower facility or PSP-plant. Furthermore, the local council of Boxmeer has shown an interest in utilizing the head at Sambeek for renewable energy purposes.

1.7 REPORT OUTLINE

The outline of the report is presented in Table 2. The first chapters are related to requirements and boundary conditions. After this the development- and verification of concepts will take place. The thesis will be finalized with a discussion of the results followed by conclusions.

Chapter :	Contains:
1) Introduction	Motivation, problem analysis, objectives, methodology, guide
2) Weir- and lock complexes Meuse	Further description complexes needed to determine boundary conditions
3) Requirements	Distinction in requirements on turbines, turbine configuration, conceptual design PSP-plant and Meuse cascade model
4) Boundary conditions on discharge	Flow duration curves and boundary conditions with respect to the purpose of hydropower for the weirs in the cascade
5) Boundary conditions on water levels	Analysis of water levels at different river modes for each weir resulting in boundary conditions for design PSP-plant and Meuse model
6) Boundary conditions on energy storage volumes	Determination energy storage capacities upstream weirs
7) Development of concept: turbines	Analysis of available and suitable fish friendly pump-turbines. Verification on requirements.
8)Development of concept: selected pump-turbine	In depth analysis selected turbine (Archimedean screw) needed for model and screw configuration
9) Development of concept: screw configuration	Multiple screw turbine configurations and verification on requirements
10) Development of concept: PSP-plant	Conceptual design PSP-plant and verification on requirements
11) Construction of Meuse cascade model	Design of model which verifies the hydropower- and energy storage potential Meuse cascade
12) Discussion	Discussion of the results
13) Conclusions and recommendations	Main conclusions thesis
Appendixes	Background information subjects
References	

Table 2: Outline final report based on methodology

2. BACKGROUND WEIR- AND LOCK COMPLEXES MEUSE CASCADE

In this chapter the lock- and weir complexes will be described more into detail which is needed to formulate the boundary conditions on discharge, waterlevels and storage volumes.

The complex at Sambeek will be described in a broader perspective compared to the other complexes in de Meuse cascade, as Sambeek will serve as location for the conceptual design of a PSP-plant. Furthermore, the complexes at Linne and Lith will be explained more into depth as these contain a hydropower facility currently.

2.1 MEUSE CASCADE AND WEIRS

The first weir upstream the cascade is located at Borgharen near the southern city of Maastricht. The last weir downstream the cascade is located at Lith (often called Alphen). The Meuse cascade is shown in the Figure 20 in chapter 5. In Table 1 one can observe gross heads per weir.

SAMBEEK

The construction of the lock- and weir complex at Sambeek in the 1920's was part of the canalization of the river Meuse in order to make it suitable for shipping and to control the water level. To guarantee a minimal waterdepth initially six weir complexes were built. In a later stage the seventh weir at Lith was constructed. The weir- and lock complex at Sambeek was put into use in 1929.

The Directorate-General for Public Works and Water Management (Dutch: '*Rijkswaterstaat'* abbreviated as RWS) is responsible for the maintenance and functionality of the weir- and lock complex Sambeek ("Stuwen Maas Sambeek", 2019). RWS is also responsible for the other weirs in the Meuse cascade.

In Figure 6 one can see an overview of the Sambeek weir- and lock complex. As one can observe three locks exist at Sambeek. After the second world war inland shipping has grown enormously. For this reason, two more locks were constructed in order to minimize waiting time for ships. In 2012 these two smaller locks were renovated with new gates and mechanical equipment. The big lock was increased in width from 14 to 16 meter in 2013 to be able to lock the new and bigger generation inland ships ("Stuwen Maas Sambeek", 2019).

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Figure 6: Aerial overview of lock- and weir complex Sambeek (Biezen, 2020)

TYPES OF WEIRS AT SAMBEEK

The weir is constructed using two types of weirs ("Stuwen Maas Sambeek", 2019). These are:

- Poirée weirs
- Stoney weirs

Figure 7: Poirée- and Stoney weir at Sambeek ("Stuwen Maas Sambeek", 2019)

The Poirée-weir consists of 13 openings of 4,85 meter between yokes. Every opening contains three gates which are placed above each other. When the discharge is less than 200 m^3/s the Poirée-weir is completely closed and the water level is controlled by the Stoney-weir. This Stoney-weir consists of two control gates which are placed in openings of 17-meter width. These control gates are able to move up and down in order to control the discharge and to maintain the desired water level ("Stuwen Maas Sambeek", 2019).

When the discharge is between 200 and 1070 m^3/s as much gates are removed from the Poirée-weir as needed to make it possible to control the water level with the movable gates of the Stoney-weir. When the discharge is reaching peak levels of more than 1070 m^3/s all gates from the Poirée-weir are removed. The gates in the Stoney weir are raised completely and the water level up- and downstream is equal ("Stuwen Maas Sambeek", 2019)

LINNE

The weir- and lock complex in Linne is constructed in 1921. Like the complex in Sambeek it is hosting Stoney- and Poirée weirs. Contrary to Sambeek three Stoney weirs exist at Linne. The Poirée weirs consist of 15 openings hosting the gates. Furthermore, a fish passage of 230 meter in length is present at Linne (de Jong, 2014).

The complex is currently hosting one of the two hydropower plants in the cascade. On overview of the power plant is shown in Figure 8. The power plant is equipped with horizontal Kaplan turbines. The technical specifications are ("Waterkrachtcentrale Linne", 2020):

- number of turbines: 4
- maximum power capacity per turbine: 3.5 MW processing a discharge of 102.5 m^3/s
- design discharge: 410 m^3/s
- rotational speed: 88.2 rpm
- gross head: 4.05 meter

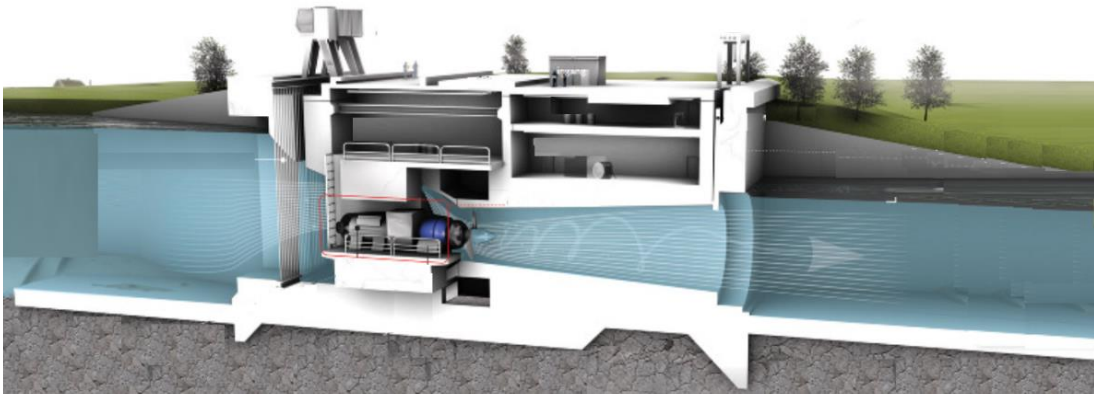


Figure 8: Adjusted pictures powerplant at Linne ("Waterkrachtcentrale Linne", 2020)

A problem for hydropower in the Meuse is the relatively low gross head when using Kaplan turbines. Even when the discharge is at full design capacity it is not possible for the plant to operate at full installed power. The efficiency reached under these conditions is just 69 % (Druten & Kruit, 2019).

Using an efficiency of 69 % is resulting in the following power output by applying formula 1 (Druten & Kruit, 2019):

$$P_{Linne} = \rho * g * Q * H * \eta$$

$$P_{Linne} = 1000 * 9.81 * 410 * 4.05 * 69\% = 11.2 \text{ MW}$$

This explains why Linne is called an '11MW' power plant.

LITH

Lock- and weir complex Lith is the other complex equipped with a hydropower plant. The water level at Lith is controlled by another type of weir. These are lifting gates with a width of 38 meter each. The complex became operational in 1935 (de Jong, 2014). It is shown in Figure 9:

Figure 9: Hydropower station at Lith (''Luchtfoto Maas'', 2020)

The type of hydropower plant and the technical specifications are similar to the facility at Linne. It operates at a maximum efficiency of 69 % as well. The main difference is the design discharge which is 450 m^3/s (Druten & Kruit, 2019). Lith is called a '14 MW' powerplant.

FISH MORTALITY AT LITH AND LINNE

According to chapter 1 the power plants at Lith and Linne are responsible for more than 10 % of the cumulative fish mortality in the Meuse cascade. More specifically this holds for young salmon (*smolts*) and *schieraal*. For the facility at Linne alone the mortality rates are (Bakker, 2020):

- schieraal: 13-24 %.
- smolts: 4-7 %
- other species: <5%

This had led to multiple initiatives to reduce the fish mortality, which are (Bakker, 2020):

- A test by the company Fish Flow Innovations 2006 using fish bypasses.
- Mechanical adjustments.
- Assessment of the application of fish friendly turbines.
- Migromat detection system.

The bypass system of Fish Flow Innovations has failed when testing in the Meuse. The main reason was the discharge flowing in the bypass being too low and the unwillingness of fish to swim into it (Bakker, 2020). Mechanical adjustments (like a trash rack with a reduced spacing in order to obstruct the fish) have not been realized in practice. On the one hand there was too much doubt about the effectiveness and on the other hand it was simply too costly with major effects on business operations (van den Berg et al, 2014)(Bakker, 2020).

The Migromat detection system is invented in Germany. It measures migration waves of fish. In the Meuse river every spring young salmon migrate to the North Sea. The Migromat system is used to stop the power plant from operating during periods of fish migration. Fish migration for schieraal occurs mainly during autumn ("Ministerie: Nuon vermaalt", 2020). The Migromat system is capable of reducing the fish mortality for schieraal with 69 %. It is in operation since 2017. However, it does not work for young salmon (Bakker, 2020).

Therefore, RWS has ordered to take additional measures to reduce fish mortality. This has resulted in ("Vergunning verleend voor", 2020):

- An experiment using fish friendly turbines at Linne, which are in the development phase.
- The objective of installation an additional early warning system for young salmon at Lith.

BELFELD

Lock- and weir complex Belfeld is constructed in the same way as Sambeek. Constructed in 1924 it is hosting two Stoney weirs and 13 openings containing Poirée weirs. A fish passage is present as well (like it is at every weir in the Meuse). The main functions of the weir are water level management and navigability regulation, in combination with discharging ice, water and sediment (de Jong, 2014).

GRAVE

The weir at Grave - in operation since 1926 - is a so called 'turned around Poirée weir'. The gates are supported by yokes. These yokes are connected to the bottom side of the bridge above the weir by hinges. At the bottom of the river these yokes are resting at concrete supports. These supports are needed to resist te vertical hydrostatic- and impulse force of the water loading the gates. The yokes are downed and pulled up using two mobile cranes.

In total this weir consists of 20 yokes and gates (de Jong, 2014). In appendix C one can view a figure of the (damaged) weir structure.

With respect to hydropower and Dutch environmental regulations the current project at the Grave weir is interesting to notice. Plans are developed to retrofit an old lock chamber - not in use anymore - with three screw turbines (which are considered fish friendly according to chapter 7) for the purpose of hydropower ("Stuw Grave geschikt", 2020).

Research on this project has been carried out by a group of local citizens, Royal Haskoning DHV and 'Oost NL' (which is a company focusing on sustainable innovation and investment). It is expected this hydropower initiative can generate 3,600 MWh per year. The initiative is currently examined by RWS for approval ("Stuw Grave geschikt", 2020).

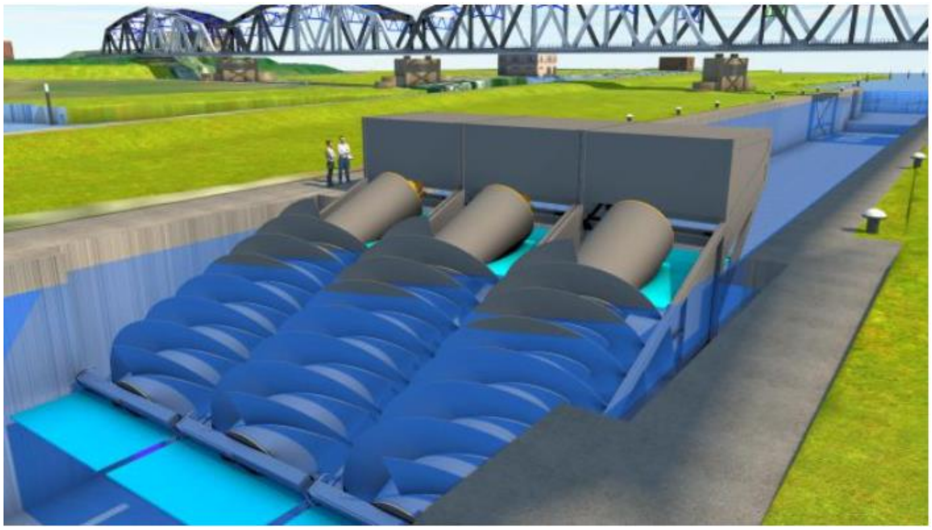


Figure 10: Screw turbines in Grave ("Stuw Grave geschikt", 2020)

BORGHAREN

The weir at Borgharen consists of four openings hosting three valve gates and one lifting gate. The biggest opening is containing the lifting gate. Above the weir a truss-bridge is present which can be used for a mobile crane for lifting purposes. The complex is in service since 1928 (de Jong, 2014). It is shown in Figure 11.

Figure 11: Weir at Borgharen (de Jong, 2014)

ROERMOND

The last weir which will be described shortly is the one at Roermond. This weir is similar to Sambeek as well. It is equipped with Stoney and Poirée weirs. The difference lies in the number of weirs: three Stoneys (17 meter) and 17 openings for the Poirée gates. The complex was built in 1921.

2.2 FUTURE PLANS

Most of the weirs in the Meuse have been constructed at the beginning of the 20th century. As they are approximately 100 years old the end of the technical lifespan of the weirs has been reached. Therefore, RWS wants to replace the weirs in the next decades, with an estimated cost of 1.5 billion euro (Bartholomeus, 2019). The weirs with the highest priority of replacement are the so called Poirée weirs. However, plans are still in the preliminary phase, no explicit designs have been made yet (Kortlever, interview, 2020 March 2).

Kortlever (interview, 2020 March 2) has explained the Poirée weirs will disappear in the future. Future weirs should have gates of up to 45 meter width in order to serve shipping purposes at high river discharges Furthermore, the Poirée weirs are considered to be unsafe for the workmen removing the gates at high discharges. Currently RWS is brainstorming on three types of weirs, which are:

- sector gates
- lifting gates (like installed at the weir in Grave)
- bellow weir (in Dutch: '*balgstuw*')

The weir at Borgharen is scheduled to be replaced in the period 2025 - 2030. The weirs at Belfeld, Sambeek and Grave are scheduled for replacement in the years 2030 - 2035. The weirs at Lith and Linne are planned to be replaced in the period 2035 - 2040 (de Jong, 2014).

2.3 CONCLUSIONS CHAPTER TWO

The weirs in the Meuse cascade are constructed in the years 1921 - 1935. The Dutch agency RWS is responsible for the maintenance and functionality of these complexes.

The complexes in Linne, Roermond, Belfeld and Sambeek are hosting Stoney- and Poirée weirs. At Grave 'turned around Poirée weirs' are installed. The Borgharen weir uses valve- and lifting gates, while the complex in Lith is using lifting gates only.

All the weirs in the cascade will be replaced in the coming decades as they have reached the end of their technical lifetime. It is not known yet which type of weirs will be used as a replacement. The first weir to be replaced is the one at Borgharen. After this the complexes hosting Poirée- and Stoney weirs are scheduled for replacement in the years 2030 - 2035. Lith and Linne are scheduled for replacement in the 2035 - 2040 period.

The weirs at Linne and Lith are currently equipped with hydropower facilities using Kaplan turbines. When processing the full design discharge these plants are not capable to operate at full installed power. The efficiency reached under these conditions is 69 %. The cumulative fish mortality caused by the power plants is exceeding the boundary limit of 10 % prescribed by RWS.

3. PROGRAM OF REQUIREMENTS

In this chapter the program of requirements needed for verification purposes is presented. This program is divided into four separate programs, considering:

- Requirements on turbine functions and capabilities.
- Configuration requirements with respect to the installation of the selected turbine.
- Requirements on the conceptual design of the PSP-plant.
- Requirements on the numerical Meuse model.

3.1 REQUIREMENTS ON TURBINES

The turbine requirements are shown in Table 3. The main requirements are the turbine should be capable of pumping as well and it should be fish friendly.

Requirements on turbine
Capable of pumping
Capable of turbining
Capable of processing a 'considerable' discharge per device
Maximum of 0.1 % additional fish mortality per weir in Meuse cascade in combination with current hydropower facilities at Lith and Linne
Maximum of 1.5 % fish mortality per weir when all the seven weirs are equipped with selected turbine
Suitable for the range in head differences in the Meuse cascade

Table 3: requirements on turbines

The 1.5 % fish mortality is explained by the fact the maximum cumulative fish mortality in the Meuse cascade is 10 %. As the cascade is hosting seven lock- and weir complexes the fish mortality per weir - in case every weir is equipped with the selected turbine - 1.49 % rounded off to 1.5 %.

If the current hydropower facilities are kept in place the maximum additional fish mortality per weir is 0.1 %, as Lith and Linne are already responsible for a combined mortality rate of 10 % according to theory of the second chapter.

With the requirement 'considerable discharge' is meant the selected device should be capable of processing an 'acceptable' amount of the design discharge.

3.2 REQUIREMENTS ON CONFIGURATION SELECTED TURBINE

In chapter 7 it will become clear the Archimedean screw turbine will be selected after verification on the turbine requirements. This particular device is turbining under a different angle of inclination with the horizontal compared to the situation when it is pumping. Therefore, multiple screw configurations need to be assessed and verified.

The requirements on the screw configurations are shown in Table 4. Technical terms (like for instance chute point, or angle of inclination β) are explained in the chapter on the Archimedean screw.

Requirements on screw configuration
Angle of inclination β at 30 ° when pumping
Pump chute point just above the upstream water level
Pump delivery point: at 0.3 D above pump chute point
Pump filling point just above the shaft of the screw at the downstream water level
Angle of inclination α at 22 ° when turbining
Turbine filling point located at the upstream water level
Turbine exit point located at downstream water level and optimized with respect to submergence and efficiency
Installable and maintainable

Table 4: requirements on screw configurations

3.3 REQUIREMENTS ON CONCEPTUAL DESIGN PSP-PLANT

The requirements on the PSP-plant are shown in Table 5. As this report is focusing on a conceptual design no verification on strength or stiffness in ultimate- and serviceability state will be performed. Furthermore, stakeholders and costs are not included in the list of requirements as explained in the paragraph on methodology in chapter 1.

Requirements on PSP-plant
PSP-plant should be able to host the selected turbines
Plant should be capable of hydropower generation in the main operational process: energy mode
Plant should be capable of pumping in the second operational process: storage mode
All components (screw, generator etc) should be installable
For this reason a mobile crane or crane vessel has to be maneuverable in position on- or in front of the PSP-plant
Closure measures are needed in order to close of compartments of the plant to allow workmen in
A closing measure is needed to close off the flow of water in case of a calamity
The PSP-plant should not suffer damage to electrical components like the generator in peak river mode
The PSP-plant should not reduce the current discharge capacity of the weirs
The structure should be 'robust' and sustainable. Thickness of walls and slabs need to be estimated using relevant rules of thumbs
The PSP-plant should be constructable within the head differences of every weir in the cascade

Table 5: requirements on conceptual design

3.4 REQUIREMENTS ON NUMERICAL MEUSE MODEL

The requirements on the numerical Meuse model are presented in Table 6. The term AEY (Annual Energy Yield) is used in chapter 11 and the energy assessment of the Meuse cascade.

Requirements on model
Capable of changing duration storage- and energy mode
Capable of adjusting width and thereby the volume of storage sections in the cascade
Capable of adjusting number of screws per weir in operation in order to increase PSP-capacity
Capable of describing AEY hydropower production individual weir
Capable of describing AEY pumped-stored power production per weir
Capable of describing surplus power used per weir
Capable of providing number of turbines in operation depending on river- and stored discharge
Capable of describing waterlevel increase due to pumping
Capable of providing number of screws in operation while pumping
Capable of providing surplus power used – and power produced based on some random discharge processed by PSP-plant
Capable of describing AEY pump-stored power cascade
Capable of describing AEY on hydropower whole cascade
Capable of describing surplus power used cascade
Capable of describing efficiency overall PSP-process cascade
Capable of providing total surplus power used – and total power produced depending on some random average discharge cascade
Take into account boundary conditions on discharge, waterlevels and storage volumes

Table 6: requirements on Meuse cascade model

4. DISCHARGE ANALYSIS MEUSE

In order to compile a conceptual design of a PSP-plant at the Sambeek weir and to construct the numerical Meuse model boundary conditions related to discharge are needed, like for instance the design discharge for hydropower purposes. These boundary conditions will be presented in chapter 4 using a discharge analysis of 20 years of data.

4.1 MEUSE AND TRIBUTARIES

RWS provides data from several measurement locations within the Meuse cascade. These locations are marked with a red dot in Figure 12. The locations of the weirs in the cascade are marked with a green dot. The only weir with a measurement location nearby is Borgharen, therefore it has a green/red dot. Furthermore, several tributaries are shown in the figure.

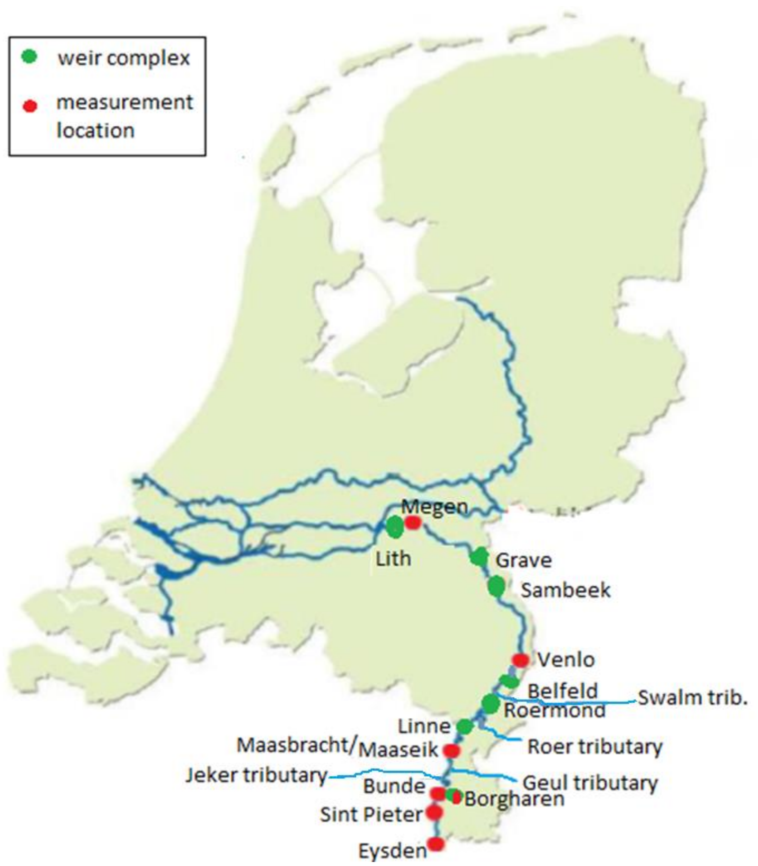


Figure 12: Discharge measurement locations and weirs Meuse, adjusted picture. ("Rivieren Nederland", 2020)

Just upstream of Borgharen the Zuid-Willems canal (Dutch: *'Zuid-Willemsvaart'*) is connected to the Maas resulting in some loss of discharge through this canal which is measured at the location of Smeermaas. Furthermore, just upstream of Borgharen some water is bypassed via the Juliana canal (Dutch: '*Julianakanaal*') which flows back in the Maas again at Maasbracht (located just downstream of Maaseik). The discharge through the Juliana canal is measured at Bunde.

Figures showing these canals and their measurement locations are shown in appendix B. The discharge flowing through these canals is small compared to the discharge in the Maas. However, it is not neglectable, certainly not at low discharge in the Meuse river. In periods of high discharge in February 2020 Borgharen processes 1634 m^3/s, Smeermaas processes 12.9 m^3/s and Bunde discharges 19.6 m^3/s. In periods of low discharge (May 2020) Borgharen shows 125.1 m^3/s, Smeermaas 13.6 m^3/s and Bunde discharges 24.0 m^3/s ("Rijkswaterstaat Waterinfo", 2020).

Several tributaries are discharging into the Meuse cascade. The four main tributaries are shown in Figure 12. These tributaries and their average discharges are:

- Jeker: 2 m^3/s (Kemper & de Bruijn, 2014)
- Geul: 4 m^3/s ("Geul rivier", 2020)
- Roer: 23 m^3/s ("Roer rivier", 2020)
- Swalm: 1.8 m^3/s ("Swalm", 2020)

The biggest tributary is the Roer. This river can reach discharges up to 120 m^3/s during periods of heavy rainfall in its catchment area (Hoogwaterbericht Maas, 2019).

4.2 FLOW DURATION CURVES AND DESIGN DISCHARGES

In this paragraph the flow duration curves for the Meuse cascade will be studied which are needed to determine the design discharge for hydropower purposes at each weir. It starts with the flow duration curve (FDC) for Venlo, as this is the measurement station most nearby the Sambeek weir for which the conceptual PSP-plant will be designed.

4.2.1 FDC VENLO

In order to construct the Venlo FDC data in the period 2000-2019 have been downloaded. Two methods for construction of the FDC have been applied.

FDC USING DAILY AVERAGES

The first FDC is constructed using daily discharges in the period 2000-2019. Flow duration curves have been constructed for each year. For these years the daily discharges are ordered from high to low. These daily discharges are average d to obtain the FDC. The FDC curves per year and the average daily FDC are shown in Figure 13.

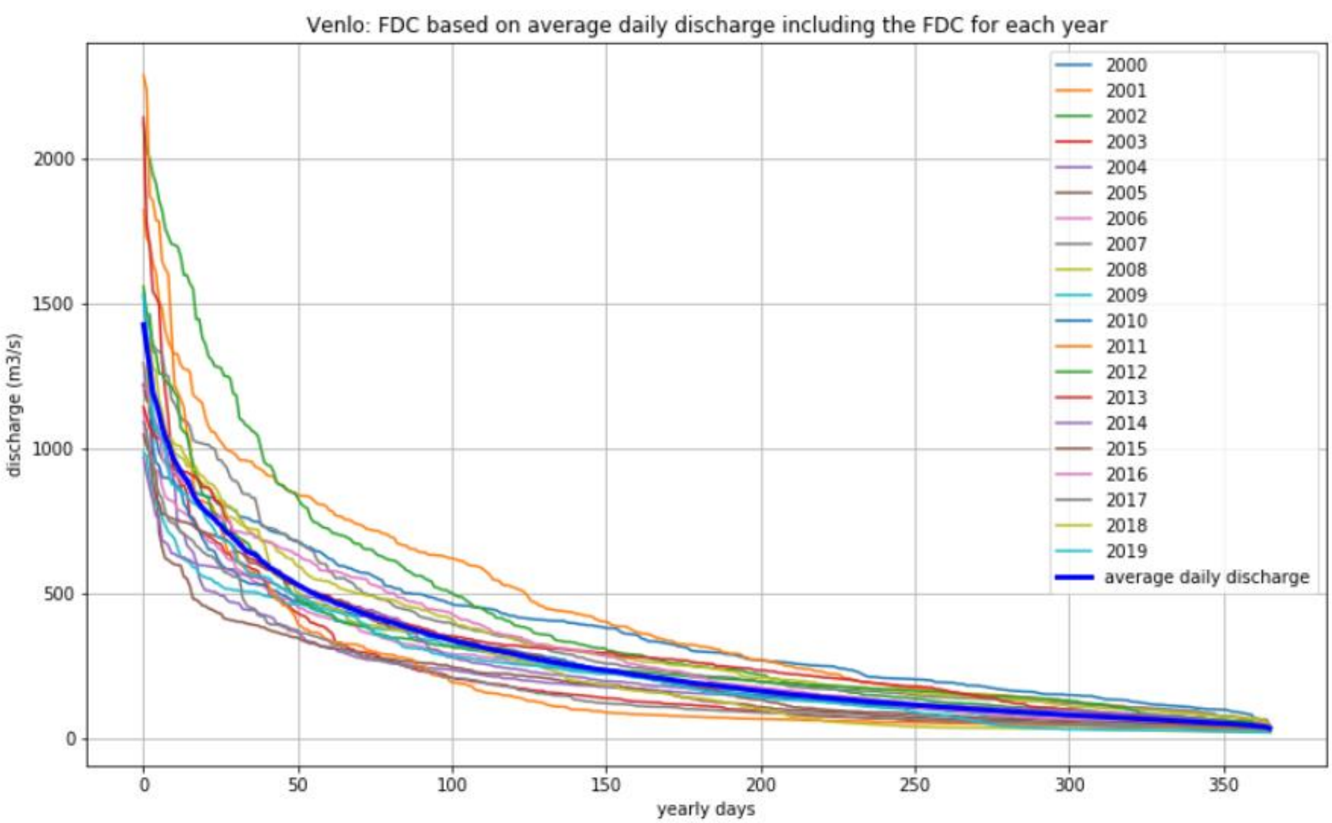


Figure 13: Yearly FDC's and the FDC based on average daily discharges for location of Venlo

FDC USING PEAK VALUES

The second FDC is constructed using the peak values per FDC day from 20 year of data are used. Again, the FDC's per year are used. These data are put together and ranked from high to low. This leads to an array of 7300 data points. For the peaks on the maximum discharge the highest values in the first half of this array (1- 3650) are used. In a similar way the peaks on the minimum discharge are obtained for the second half of this array (3651 - 7300). This method is explained to the detail in appendix B. The peak discharge FDC is shown in Figure 14.

4.2.2 DESIGN DISCHARGE VENLO

In order to determine the design discharge usually the 100-day discharge is used. For this purpose, both the peak- and daily average FDC can be used, as they can be assumed to be similar at the 100-day intersection as one can notice in Figure 14. The design discharge is determined by the intersection of the red lines and results in 335 m^3/s. However, this design discharge needs to be adjusted for several losses.

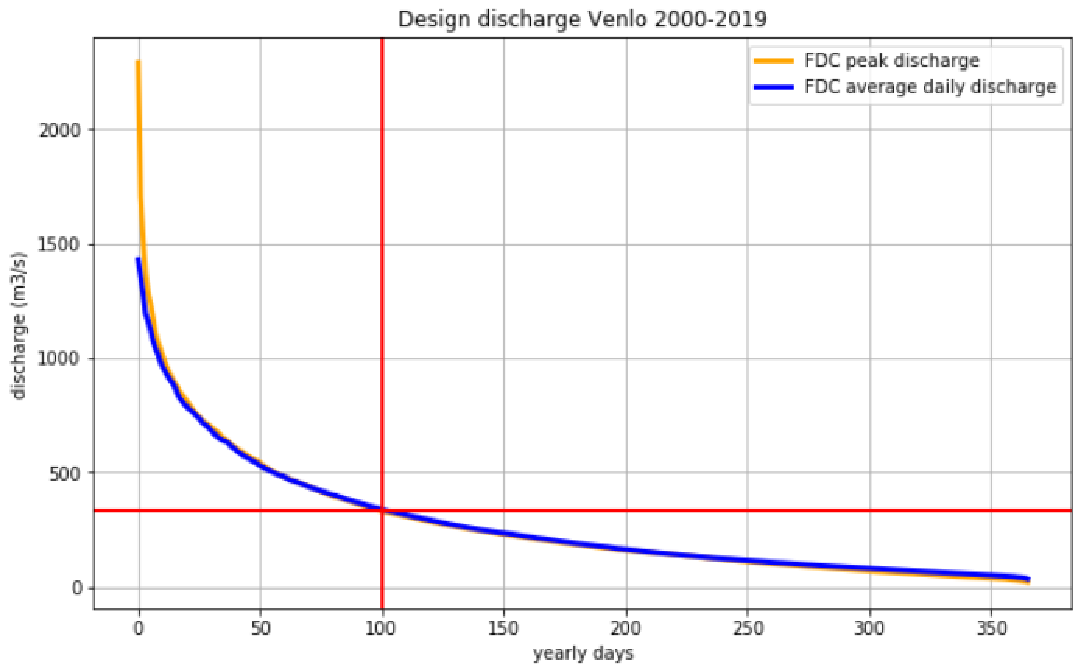


Figure 14: Flow duration curves and design discharge (335 m^3/s) at the location of Venlo

As one can observe in Figure 14 the FDC using peak discharge differs from the FDC using average daily discharge in the upper- and lower tail. Clearly visible is the difference in discharge at the upper tail. The peak maximum measured at Venlo is 2288.2 m^3/s. The highest average daily discharge measured is 1427.3 m^3/s. The peak minimum is 20.5 m^3/s, while the lowest average daily discharge is 34.7 m^3/s ("Rijkswaterstaat Waterinfo", 2019), explaining the average flow is higher than the peak flow at the right side of the graph. (In appendix B one find an extensive explanation on peak flow minima- and maxima.)

4.2.3 FDC'S AND DESIGN DISCHARGE BORGHAREN, MAASBRACHT AND MEGEN

As one can observe in Figure 12 no measurement stations are present nearby the weirs of Roermond, Belfeld, Sambeek and Grave. In order to account for the discharge of the relatively big Roer tributary the Venlo FDC will be used for these weirs. The weirs at Borgharen, Linne and Lith will use separate FDC's based on measurement locations nearby these weirs.

FDC BORGHAREN

The second FDC has been constructed using the measurement location of Borgharen, which is also representative for the weir at Borgharen. It would be wrong to use the measurement location of Sint-Pieter, as some discharge is directed to the Zuid-Willems canal and the Juliana canal, as explained in appendix B.

As one can observe in Figure 14 the FDC for peak - and daily average discharge is similar at the 100-day intersection. For this reason, for Borgharen only the FDC based on daily averages has been used. The design discharge is 280 m^3/s which is considerably lower than the design discharge at Venlo. The differences are explained by the presence of the tributaries and the canals.

This is underlined by a comparison of the average daily discharge over the period 2000 - 2019 which is shown in appendix B. The Borgharen FDC together with its design discharge is shown in appendix B as well.

FDC MAASBRACHT

The third FDC should be constructed for the measurement location of Maaseik located upstream of the Linne weir. However, downloading data has been persistently problematic. Either the data are not available for the last 20 years, or they contain too many outliers resulting in the need to remove complete days of unusable data.

Therefore, a shortcut has been applied. It was possible to download timeseries for the measurement station of Bunde in the Juliana canal, which location is shown in appendix B. This canal flows back in the Meuse river at the location of Maasbracht. By adding the data of Bunde to the data of Borgharen the FDC for Maasbracht has been constructed. This FDC – using daily averages - and its design discharge is shown in appendix B. The Maasbracht design discharge is 300 m^3/s.

FDC LITH

When observing Figure 12, the last relevant measurement location is located at Megen. The FDC for this location will be used to determine the design discharge for the Lith weir, which is the last weir in the cascade downstream. Megen shows the largest design discharge occurring in the cascade (360 m^3/s) which is explained by the fact it has the biggest catchment area compared to the other measurement locations. The FDC of Megen is presented in appendix B.

4.3 AVAILABLE DISCHARGE HYDROPOWER

The design discharge for each weir needs to be corrected for several losses resulting in the 'available discharge for hydropower'. These losses are related to locking processes, the presence of a fish passage and leakage losses.

4.3.1 AVAILABLE DISCHARGE SAMBEEK

This paragraph will start with an in-depth analysis of the available discharge for the Sambeek weir as this will be the location of the conceptual PSP-plant design. The gathered information will in turn be used for shorter assessment of the available discharge for the other weirs in the cascade.

INFLUENCE LOCKING PROCESS ON AVAILABLE DISCHARGE

The Meuse river is strongly depending on precipitation, contrary to the river Rhine which is fed by a combination of melting ice and precipitation. The Meuse has a capricious discharge pattern. At the location of Liège in Belgium the lowest discharge measured is 20 m^3/s, while the recorded peak discharge is more than 3000 m^3/s. This is a factor of 150 times higher. To compare: for the Rhine this factor is maximally 20 (Asselman et al, 2018).

During locking processes water is lost downstream of the weirs. At periods of drought these locking processes are put on hold (*'beperkt schutten'* translated by 'limited locking') at the lock- and weir complexes in the Meuse cascade. RWS indicates the maximum waiting time is 4 hours ("Maatregelen vanwege lage", 2020).

In order to determine what the boundary is for RWS to start limited locking discharge data from the measurement location of Venlo have been analyzed. At the 6th of August 2018 RWS started limited locking (Tiems, 2018). The discharge at this moment in time was about 24 m^3/s. At the 11th of September 2019 limited locking took place as well ("Maatregelen vanwege lage", 2020). The discharge at Venlo was about 22 m^3/s ("Rijkswaterstaat Waterinfo", 2019). In Figure 15 one can find an overview.

date:	discharge (m3/s):
8/3/2018	29.4
8/4/2018	28.4
8/5/2018	22
8/6/2018	**23.8**
8/7/2018	23.3
8/8/2018	24.2
8/9/2018	29

date:	discharge (m3/s):
9/8/2019	21.4
9/9/2019	20.5
9/10/2019	21.7
9/11/2019	**22.8**
9/12/2019	22
9/13/2019	23.9
9/14/2019	25

Figure 15: Periods of limited locking at low discharges in the Meuse

Based on these data one can assume limited locking starts at a discharge of roughly 25 m^3/s. This value is confirmed by Kortlever (interview, 2020 March 2).

In the problem analysis of chapter 1 it was suggested the use of pump turbines could be useful to maintain the minimum water level at periods of low discharges, thereby improving navigability. The theory and findings of this paragraph confirm this suggestion. As the waiting time for ships of 4 hours results in economic damage a PSP-plant capable of pumping back locking water seems to be of added value.

LOSS OF DISCHARGE BY LEAKAGE

At the weirs in the Meuse leakage losses occur as well. According to Kortlever (interview, 2020 March 2) one can estimate these losses at roughly 5 m^3/s for the Sambeek weir. During the severe drought of the summer of 2019 RWS improvised by sealing of the Poirée weir with a plastic foil to reduce the leakage. However, leakage losses are included in the discharge at which limited locking occurs. Limited locking occurs when the sum of water lost by leakage and the water lost by the locking process approaches the value of 25 m^3/s as derived in the previous subparagraph.

The construction of a PSP-plant will result in additional leakage losses. Based on the conceptual design in chapter 10 the leakage losses are estimated to increase with 7 m^3/s.

DISCHARGE NEEDED FOR FISH PASSAGE

The presence of a fish passage decreases the available discharge for hydropower purposes even more, although the influence is minor. Lanters (1995) evaluated the hydraulic characteristics of the fish passage at the Belfeld weir, which is of the same type as constructed for Sambeek. The graphical illustration used for this evaluation is shown in appendix B. The discharge on the fish passage was estimated to be 3 to 4 m^3/s (Lanters, 1995, p.8).

Note: at periods of drought the fish passage can be closed to avoid losing water downstream ("Maatregelen vanwege lage", 2020). However, the fish passages in the Meuse cascade are assumed to be open permanently in this report.

AVAILABLE DISCHARGE FOR HYDROPOWER PURPOSES

Using the design discharge, the water needed for the locking process, leakage losses and the discharge through the fish passage the available discharge for hydropower purposes at the weirs in the Meuse can be determined. (In appendix B one can observe a calculation for Sambeek). This will result in the first boundary condition on discharge. The available discharge can be described as:

$$Q_{available} = Q_{design} - Q_{locking} - Q_{leakage,weir} - Q_{fish\ passage} - Q_{leakage,PSP} \qquad \text{formula (2)}$$

MINIMUM DISCHARGE HYDROPOWER SAMBEEK

In chapter 7 the screw turbine - capable of processing 15 m³/s - will be selected as the device to use for the conceptual design of the PSP-plant. Chapter 8 will show this turbine has a flat efficiency curve. Even at 20 % filling capacity it can produce hydro-electricity (“Archimedean screw hydro", 2020). Therefore, the starting discharge (Q_{start}) to produce hydro-electricity using one screw turbine is assumed to be 20 % of 15 m³/s which is 3 m³/s.

This will result in the second boundary condition on discharge: the minimum flow at a weir (Q_{min})which is needed to start hydropowering. In formula terms this is described as:

$$Q_{min} = Q_{locking} + Q_{leakage,weir} + Q_{fish\ passage} + Q_{leakage,PSP} + Q_{start} \qquad \text{formula (3)}$$

4.3.2 AVAILABLE- AND MINIMUM DISCHARGE OTHER WEIRS CASCADE

Although the weirs are differing in design - as elaborated on in the second chapter - it will be assumed the losses due to limited locking per weir are equal to 'Sambeek'. Every weir in the cascade contains a fish passage. The loss of discharge via these passages is assumed to be equal to the one at Sambeek. Furthermore, the leakage losses through the weirs and the PSP-plants are assumed to be equal.

The exception is the Borgharen weir, as this weir does not contain lock chambers and therefore no losses due to limited locking occur. Ships are diverted to the Juliana canal which is located upstream of the Borgharen weir, as explained in appendix B. This implies Q_{start} at Borgharen is relatively low.

4.4 BOUNDARY CONDITIONS ON DISCHARGE

Finally, the boundary conditions on discharge for the weir in the Meuse cascade can be obtained. According to the theory of the previous paragraphs two boundary conditions have been formulated, which are:

- Boundary condition on available discharge (BC1)
- Boundary condition on minimum discharge to start hydropowering using one screw (BC2)

The boundary conditions for each weir in the present situation of the Meuse cascade are presented in Table 7.

Weir:	FDC to use:	Design discharge (m³/s:	Total leakage losses weir and PSP-plant (m³/s):	Locking process losses (m³/s):	Losses Fish passage (m³/s):	BC1: available discharge (m³/s):	BC2: minimum discharge (m³/s):
Borgharen	Borgharen	280	12	-	3	265	18
Linne	Maasbracht	300	12	20	3	265	38
Roermond	Venlo	335	12	20	3	300	38
Belfeld	Venlo	335	12	20	3	300	38
Sambeek	Venlo	335	12	20	3	300	38
Grave	Venlo	335	12	20	3	300	38
Lith	Megen	360	12	20	3	325	38

Table 7: Boundary conditions available- and minimum discharge per weir in present situation Meuse cascade

4.5 CONCLUSIONS CHAPTER FOUR

In this chapter FDC's have been constructed for the measurement locations of Borgharen, Maasbracht, Venlo and Megen. Using these FDC's the design discharge for hydropower purposes for each weir has been derived.

These discharges need to be adjusted for several losses due to the presence of a fish passage, leakage losses through the gates of the weirs and the PSP-plant, and water which is lost during locking processes. Leakage- and locking losses account for 32 m^3/s on average per year. The fish passage results in an additional loss of 3 m^3/s.

Two boundary conditions for the purpose of hydro-electricity production have been formulated. The first condition is related to the available discharge for hydropower purposes after adjusting the design discharge with the losses mentioned above. For the weir at Borgharen and Linne this is 265 m^3/s. For the weir at Lith it is 325 m^3/s. For the remaining weirs - including Sambeek - the available discharge is 300 m^3/s.

The second boundary condition is related to the minimum discharge needed to start hydropowering using one screw turbine. For the Borgharen weir this will be 18 m^3/s. For the other six weirs in the cascade this is 38 m^3/s.

5. WATERLEVEL ANALYSIS WEIRS

In order to determine the gross head - needed for hydro-electricity production at the weirs in the cascade - an analysis of the waterlevels up- and downstream is needed. This will result in additional boundary conditions. Furthermore, the analysis will be used for boundary conditions on storage volumes in chapter 6.

5.1 RIVER MODES

This first paragraph will analyze the different river modes occurring in the river Meuse. This is needed as the gross head will vary withing these river modes influencing the production of hydro-electricity. This analysis will be done in depth with respect to the Sambeek lock- and weir complex for which the PSP-plant will be designed.

5.1.1 FLOW REGIME AT SAMBEEK WEIR

According to Blom (2018) one can divide the flow regime of a river in two modes, which are base- and peak mode. However, based on chapter 2 the flow regime at the Sambeek weir appears to be a three-mode system:

- Base mode: Poirée weirs fully closed and water level controlled by Stoney weirs.
- Median mode: Poirée weirs partly removed and water level controlled by Stoney weirs.
- Peak mode: Poirée weirs completely removed and Stoney weirs fully opened leading to zero gross head.

Van Erp (2019) constructed a graphical illustration of the water surface between the weirs in the Nederrijn in his MSc thesis report, which is shown in the Figure 16.

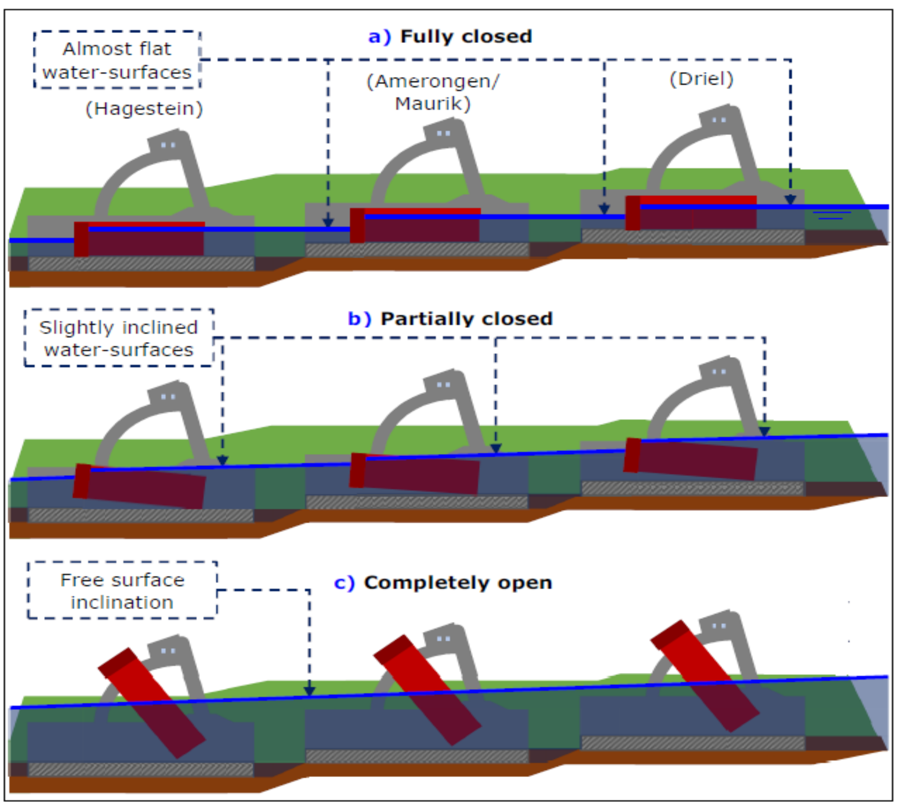


Figure 16: Water levels occurring at different flow regimes in the Nederrijn (Van Erp, 2019)

The illustration clearly visualizes the water inclination at the different flow regimes in the Nederrijn river. According to Kortlever (interview, 2020 March 2) the water level at the Sambeek weir shows a similar pattern. For hydropower purposes this has practical consequences as the necessary head difference at peak mode is not there anymore with equal water levels up- and downstream.

5.1.2 WATERLEVELS SAMBEEK WEIR

Data from RWS ("Rijkswaterstaat Waterinfo", 2020) on the waterlevels up- and downstream of Sambeek have been used in order to verify the theory on river modes. According to Kortlever (interview, 2020 March 2) the distance between up- and downstream is roughly 1000 to 2000 meter. In Figure 17 one can observe the average daily discharge and average daily waterlevels.

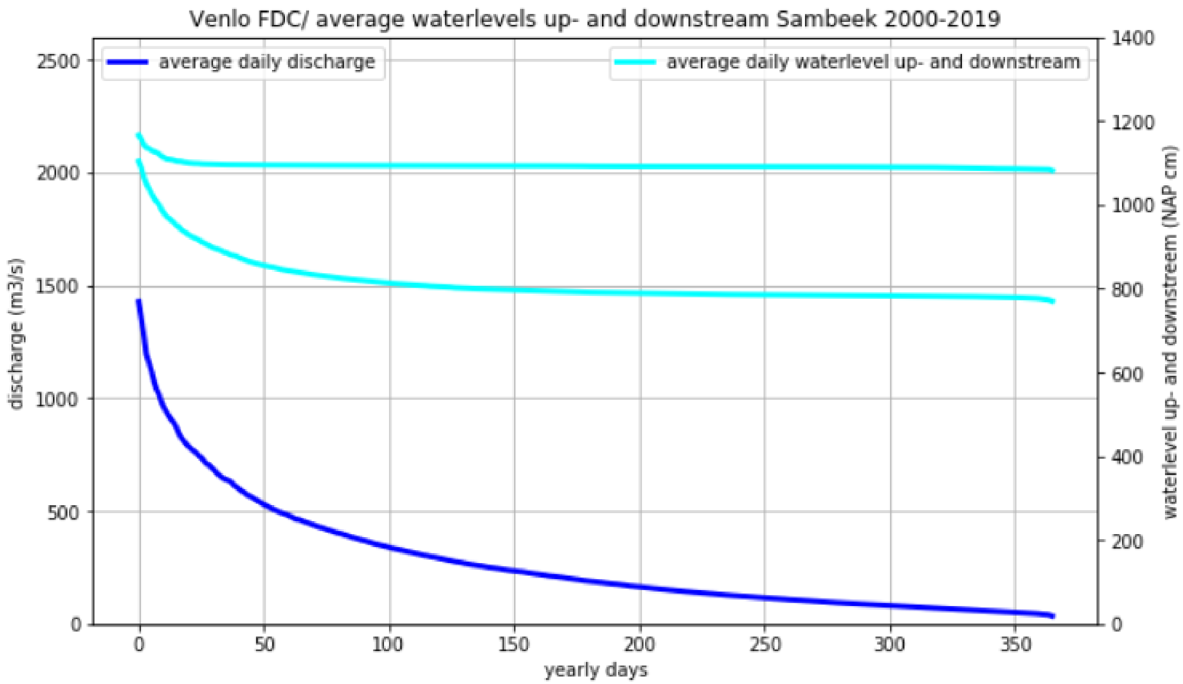


Figure 17: Sambeek average daily discharge and waterlevels, distance up- and downstream 1000 to 2000 meter

Based on Figure 17 and the analysis of the underlying data one can conclude:

- At base mode ($Q < 200$ m^3/s) the gross head lies in the range 3.01 - 3.15 meter.
- At median mode ($200 < Q < 1070$ m^3/s) the gross head varies in the range 1.07 - 3.01 meter.
- At peak mode ($Q > 1070$ m^3/s) the gross head varies in the range 0.63 - 1.07 meter.

The results are not completely in line with the theory of van Erp (2017) and the information provided by Kortlever (interview, 2020 March), which state the gross head should be zero at peak river mode.

Therefore, flood waves in the Meuse river which occurred before the time series 2000-2019 have been studied.

DATA FROM RIVER FLOOD WAVES BEFORE 2000

In 1926 the peak discharge at Borgharen was roughly 3000 m^3/s. In 1993 the discharge at this measurement station was 3039 m^3/s. At the flooding events of 1995 the discharge at Borgharen was 2746 m^3/s. These discharges were the highest ever recorded at Borgharen (IJpelaar, 2020).

These river flood waves - together with two flood waves occurring in 1980 of which one is shown in Figure 18- are analysed on waterlevels up- and downstream with respect to the Sambeek weir. By comparing the waterlevels up- and downstream one can analyse if equal waterlevels occur at peak river mode.

The graphical results on the analysis of these flood waves are shown in appendix C. The most relevant result is found in the data from 1995. The Meuse flooding of 1995 took place at the beginning of February. The water level upstream of Sambeek was NAP 1397.2 cm. The gross head was 8.3 cm at this moment in time.

Figure 18: Zero gross head Sambeek weir 1980 flood wave ("Hoogwater 1980 sluizen", 2020)

The remaining difference in water level can be explained by the distance between the measurement stations up- and downstream. According to Kortlever (interview, 2020 March 2) this distance is roughly 1000 to 2000 meter. The NAP water level decreases slightly between these locations due to the inclination of the water surface at peak river mode.

5.1.3 WATERLEVELS OTHER WEIRS CASCADE

For each weir in the Meuse cascade the waterlevels have been analysed. These waterlevels show similar patterns like occurring at Sambeek. In Figure 19 one can observe the waterlevels at the Borgharen weir which shows a relatively constant increase in waterlevels downstream during base- and median river mode. To avoid an excessive information load the figures of the other weirs are presented in appendix C.

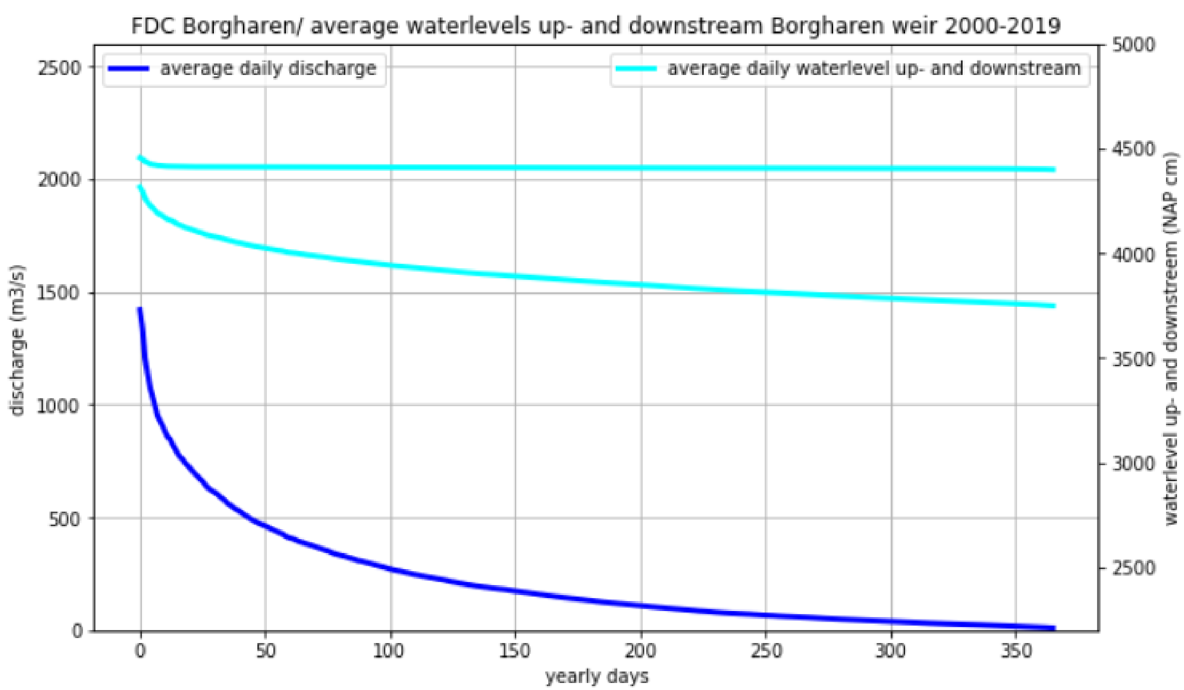


Figure 19: Waterlevels at Borgharen weir

5.2 HYDROPOWERING AT DIFFERENT RIVER MODES

In chapter 4 two boundary conditions related to hydropower have been obtained. This paragraph formulates an additional boundary condition considering hydropower and the influence of varying waterlevels in the Meuse.

PEAK RIVER MODE AT SAMBEEK

An overview of the discharge at each river mode ("Stuwen Maas Sambeek", 2019) together with the gross head for the Sambeek weir is presented in the Table 8:

Discharge Q (m3/s)	River mode	Weir configuration	Water surface	Gross head Sambeek
Q < 200	base	Poirée fully closed, water level controlled by Stoney	Almost flat	3.2 meter
200 < Q < 1070	median	Poirée partly closed, water level controlled by Stoney	Slightly inclined	Decreasing depending on discharge
Q > 1070	peak	Poirée removed and Stoney opened, free flow	Free surface inclination	0

Table 8: Discharge and gross head Sambeek

By analysing the Venlo FDC the following results are obtained:

- Base river mode (Q < 200 m^3/s) is covering 192 days of the FDC.
- Median river mode (200 < Q < 1070 m^3/s) covers 166 days.
- Peak river mode (Q > 1070 m^3/s) occurs 7 days a year within the curve.

This implies hydropower is not possible for one week (the duration of peak river mode) at the Sambeek weir as the head difference has disappeared. The impossibility to produce hydropower at peak river mode forms the third boundary condition.

PEAK RIVER MODE AT OTHER WEIRS CASCADE

The peak discharges at which the other weirs in the Meuse are fully opened differ. As these peak discharges differ the third boundary condition varies per weir. These peak discharges are (Schrojenstein Lantman, 2004):

- Borgharen: 1260 m^3/s
- Linne: 1250 m^3/s
- Roermond: 1040 m^3/s
- Belfeld: 850 m^3/s
- Grave: 1650 m^3/s
- Lith: 1070 m^3/s

The consequences for this boundary condition are presented in Table 9. For instance, peak mode last for 17 days at Belfeld. During this period the gross head is zero and hydropowering is not possible.

Note: it should be mentioned the production of hydro-electricity might not be possible in the last days of median mode as well. In the chapter on turbine selection, it will become clear the Archimedean screw will be selected. This turbine needs a minimum head difference which is related to the screw radius, as will be elaborated on in chapter 8.

5.3 DESIGN WATER LEVELS

In order to determine which waterlevels up- and downstream should be used as design levels for the conceptual PSP-plant at Sambeek target levels - provided by RWS - and the waterlevels obtained from the data have been analysed.

DESIGN LEVELS SAMBEEK WEIR

According to Figure 17 the waterlevels at base mode seems to be rather constant at Sambeek. The water level downstream slightly increases at bigger discharges. The average value of the waterlevels up- and downstream in base mode have been determined, as these could be useful as design waterlevels. These average waterlevels up- and downstream are:

- upstream: NAP 1092.4 cm
- downstream: NAP 783.8 cm

TARGET LEVEL ACCORDING TO RWS

RWS uses target levels (in Dutch: '*streefpeilen'*) as a guidance for the waterlevels in the Meuse cascade. These target levels are shown in the Figure 20 (written in Dutch) provided by Kortlever (interview, 2020 March 2).

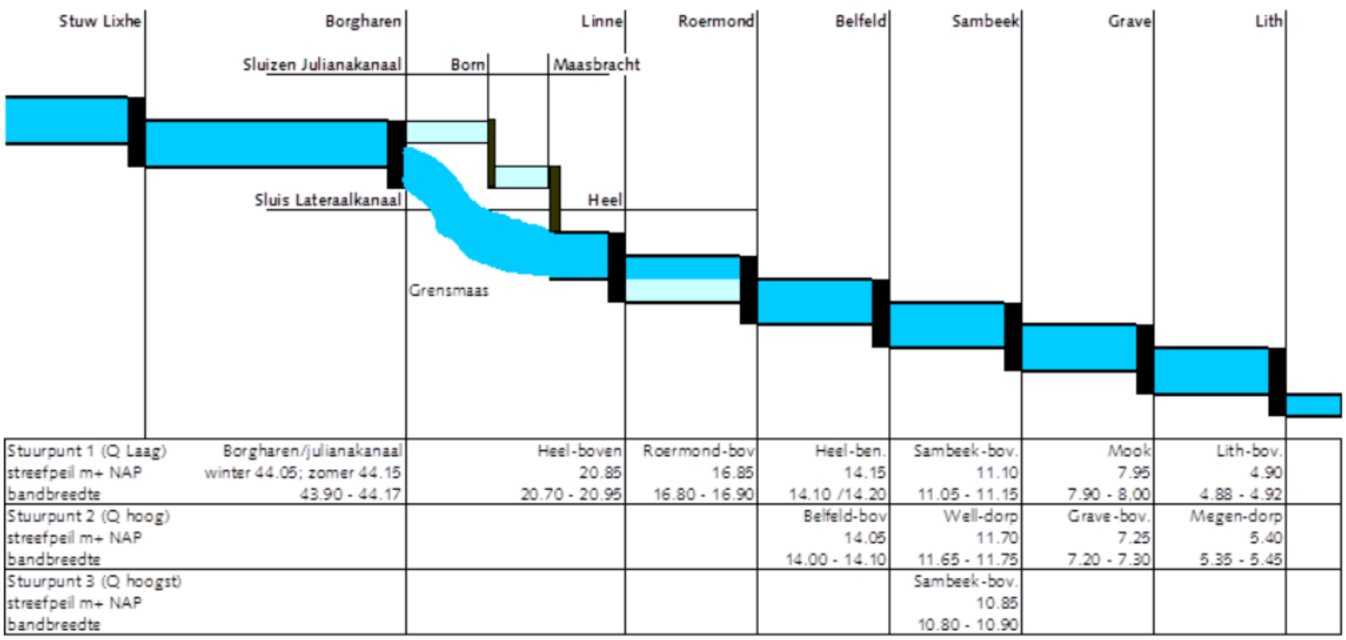


Figure 20: Target levels Meuse cascade used by RWS (W. Kortlever, interview, 2020 March 2)

The target levels for the Sambeek weir are:

- upstream: NAP 1110 cm
- downstream: NAP 795 cm

The average waterlevels in base mode obtained by the time series are slightly lower than the target levels used by RWS. As the target levels provided by RWS are the official guidelines they will be used as design waterlevels for the conceptual design of the Sambeek PSP-plant. These target levels will result in a boundary condition on waterlevels.

DESIGN WATERLEVELS OTHER WEIRS CASCADE

For the other weirs no conceptual design will be compiled. However, the target levels will be used as design levels in the chapter on storage volumes. The design levels per weir are presented in Table 9. Downstream target levels are not provided for Borgharen and Lith. These are obtained using Table 1.

5.4 BOUNDARY CONDITIONS ON WATERLEVELS

In chapter 4 two types of boundary conditions have been formulated, called BC1 (related to the available discharge for hydropower purposes) and BC2 (related to the minimum discharge to start hydropowering at least one turbine).

This chapter has formulated two additional boundary conditions which are called BC3 and BC4. However, these are related to peak river mode and the design waterlevels in the Meuse cascade. These boundary conditions comprise:

- The impossibility on hydro-electricity production at the duration of peak river mode. This is boundary condition three (BC3).
- The design waterlevels per weir based on the RWS target levels (BC4).

These boundary conditions are presented in Table 9.

Weir:	FDC to use:	Weir fully opened at (m^3/s):	BC3: duration peak river mode (days):	BC4: design level upstream (NAP cm):	BC4: design level downstream (NAP cm):	Gross head (m):
Borgharen	Borgharen	1260	3	4410	3890	5.2
Linne	Maasbracht	1250	2	2085	1685	4.0
Roermond	Venlo	1040	8	1685	1415	2.7
Belfeld	Venlo	850	17	1415	1110	3.05
Sambeek	Venlo	1070	7	1110	795	3.15
Grave	Venlo	1650	-	795	490	3.05
Lith	Megen	1070	8	490	70	4.2

Table 9: Boundary conditions on days of zero gross head and design waterlevels up- and downstream

5.5 CONCLUSIONS CHAPTER FIVE

Three river modes occur in the Meuse river, which are base-, median- and peak mode. Roughly at the start of median mode the gross head begins to decrease at increasing discharges. This implies the gross head at a weir in the Meuse river is not constant. It is varying throughout the year depending on the discharge.

Peak river mode conditions differ per weir. In times of peak mode, the waterlevels up- and downstream at a weir are equal resulting in zero gross head and no production of hydro-electricity. The duration of this peak mode period is translated into the first waterlevel related boundary condition of chapter 5.

Design waterlevels for each weir are based on the target levels provided by RWS. These target levels have resulted in the second boundary condition of this chapter. The target levels will also be used in the chapter on energy storage.

6. ANALYSIS STORAGE VOLUMES MEUSE CASCADE

For the purpose of energy storage in the Meuse cascade the storage volumes upstream the weirs need to be determined. These volumes will be assessed in chapter 6. It will result in additional boundary conditions to imply in the numerical Meuse model.

6.1 CROSS SECTION RIVER MEUSE

A typical cross section of a Dutch river is shown in Figure 21. One can notice summer- and winter dikes and floodplains. At periods of base- and (the majority of) median river mode the discharge is processed in the cross section bounded by the summer dikes. At periods of peak river mode the waterlevel rises so much the floodplains take effect. The river cross section increases and is bounded by the winter dikes.

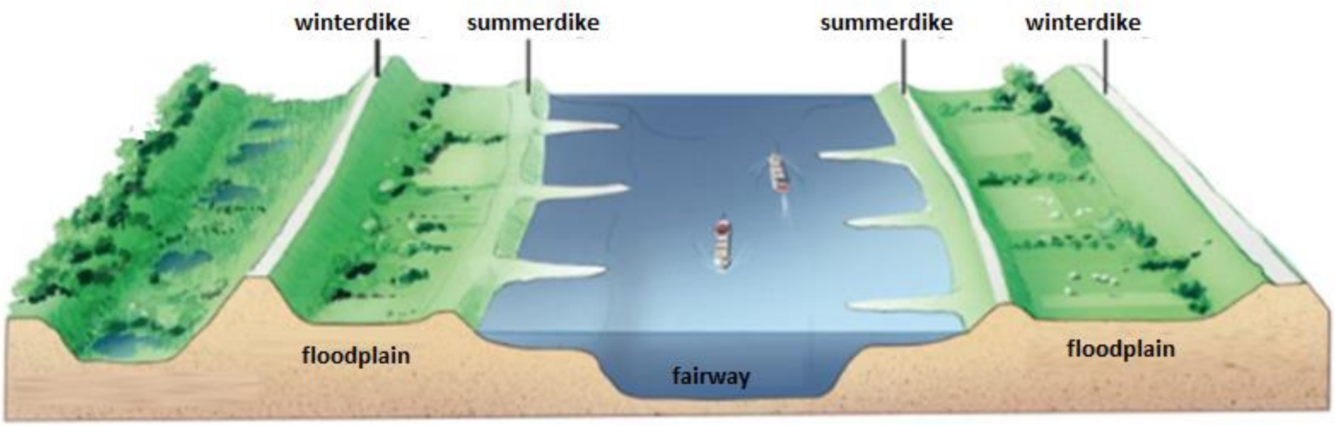


Figure 21: Cross-section Dutch river, adjusted picture (Bosman, 2020)

In Figure 21 one can observe groynes, which are usually constructed to protect the river bank against erosion and to divide flow to the fairway. After the construction of the weir complexes in the Meuse river those groynes not strictly necessary anymore were removed in order not to hinder the river flow at peak mode and corresponding high discharges ("Maas natuurvriendelijke oevers",2020).

CROSS SECTION TO USE FOR ENERGY STORAGE

The primary function of flood plains is the storage of water during river flood waves. The secondary function of the floodplains is agriculture. Nowadays some floodplains are serving nature development as well ("Uiterwaarden", 2020). According to Figure 21 one could use the cross section bounded by the winter dikes for energy storage. However, this would lead to flooding of the floodplains each time at storage mode with a major impact on agriculture.

Furthermore, water storage in the floodplains is currently not possible, as the water is not retained besides the weir structures. In order to do so dams should be constructed connecting the weir structure to the winter dikes. This would obstruct the flow of water at periods of peak river mode.

For these reasons the cross-section bounded by the summer dikes will be assessed primarily for the purpose of energy storage.

6.2 STORAGE WATERLEVELS

The storage volumes in the Meuse cascade are bounded with minimum- and maximum storage levels.

MINIMUM STORAGE WATERLEVEL CASCADE

In the chapter on waterlevels it is described RWS uses target levels as guidance for the minimum waterlevels in the Meuse cascade. These target levels are presented in Table 9. In order to maintain navigability waterlevels should not decrease below target levels, which is achieved by the use of the weir complexes in the Meuse cascade. Therefore, the minimum waterlevel at storage mode will be prescribed by these target levels.

With respect to energy storage this result in the 5th boundary condition of this report, and the first BC related to energy storage. The pumped volume at each weir is bounded by the volume pumped up at the weir downstream, in order to avoid a decrease in waterlevel below target level downstream.

MAXIMUM STORAGE WATERLEVEL CASCADE

At first sight one should expect the maximum waterlevel at storage mode is bounded by the height difference between the top of the summer dikes and the waterlevels in the trajectories of the Meuse cascade. Based on a fieldtrip to the Meuse this height is assumed to be 1.5 – 2 meter. However, the fieldtrip to the Sambeek weir made clear the maximum waterlevel for storage is determined by the height of the lock- and weir complex at the upstream side with respect to the waterlevel upstream. Based on this field trip it is assumed the upstream waterlevel can increase roughly 1.25 -1.5 meter before the locks will overflow.

In Figure 22 one can observe this height at the Sambeek weir. When pumping starts the waterlevel upstream a weir increases. When the waterlevel increases too much it will overflow the locks and water will flow back downstream.

Figure 22: Height lock complex with respect to upstream waterlevel at Sambeek (photo taken at fieldtrip)

This is further clarified when observing Figure 17. When peak river mode is approached mainly the waterlevel downstream a weir increases towards the waterlevel upstream. Ultimately the head difference disappears and the waterlevels become equal and both will rise. There is less room for an increase in waterlevel upstream before the locks will become submerged compared to the room for increase in waterlevel downstream.

This is substantiated using data presented in Figure 23 (including the highest peaks ever recorded at Sambeek). The horizontal green line marks an increase in the upstream waterlevel of the Sambeek weir of 1 meter with respect to its target level of 11.1 NAP m. As one can observe an increase of 1 meter upstream corresponds to peak river mode. Based on this, the assumption is made the maximum storage height is 1m, which will be a default value in the model of chapter 11.

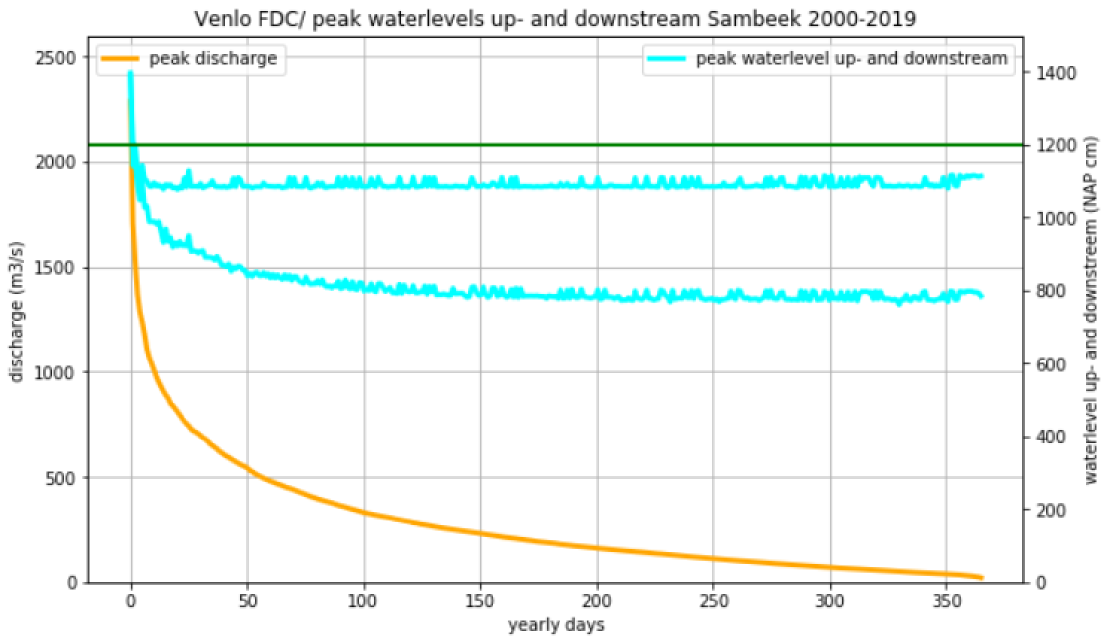


Figure 23: Increase in waterlevel of 1 meter upstream Sambeek weir

However, in the numerical model the distance between the summer dikes, and the storage height will become variables in order to assess increased storage volumes as well.

WIDTH BETWEEN SUMMER DIKES

According to Bodegraven (2009) the width between the summer dikes varies in the range 89 – 174 meters when considering the complete Meuse cascade. The width at the trajectory Borgharen – Linne is the lowest, which is explained by the relatively steep bed slope of this section which is elaborated on in the next paragraph. An increased bed slope will lead to a larger flow velocity resulting in the need of a smaller cross-section to process the discharge.

The width between the dikes at the Sambeek – Grave section (119 meter provided at the location of Gennep) is counterintuitively low compared to the surrounding sections (150 and 161 meter) (Bodegraven, 2009). By using Google Earth and by taking a view at the fieldtrip this distance is adjusted in 150 meter as it does not seem to differ from the surrounding cascade sections. Furthermore, the width at the Linne – Roermond section is set te be equal to the Roermond – Linne section as it is not provided by Bodegraven (2009).

6.3 RESTRICTIONS ON STORAGE

The length of the Meuse river is usually represented using the definition of 'river kilometers'. For instance, the distance one needs to sail on the trajectory Sambeek – Grave is 27 kilometers. The length in river kilometers of each section of the Meuse cascade is (Bodegraven, 2009)(Beurskens & van Dongen, 2018):

- Borgharen – Linne: 54 km
- Linne – Roermond: 13 km
- Roermond – Belfeld: 17 km
- Belfeld – Sambeek: 46 km
- Sambeek – Grave: 27 km
- Grave – Lith: 25 km

In Figure 85 in chapter 11 the Meuse cascade is shown. One can also observe the locking stations in the Juliana canal at Born and Maasbracht.

TRAJECTORY BORGHAREN - LINNE

In chapter 4 it became clear just upstream of the Borgharen weir ships are diverted to the Juliana canal. The reason for the presence of this canal is the steep river bed slope in the Meuse (This trajectory is called '*Grensmaas*' in Dutch) downstream of Borgharen. The waterlevel in the Meuse decreases from roughly NAP 44 meter at Borgharen to NAP 20 meter at Linne over a distance of 54 river kilometers, as can be observed in Figure 85. For this reason, some discharge of the Meuse is bypassed via the Juliana canal in order to serve shipping. Locking in this canal occurs at Born and Maasbracht.

The Meuse river can be considered to be in unsteady flow conditions within every particular trajectory of the cascade, as the waterdepth depends on the river modes throughout the year, although this occurs mainly in peak river mode. At every trajectory of the cascade the flow can be assumed to be uniform with equal waterdepth, with the exception of the trajectory Borgharen – Linne, in which the equilibrium waterdepth will vary according to the bed slope.

STORAGE UPSTREAM BORGHAREN WEIR

The bed slope in the Borgharen – Linne trajectory causes complications for energy storage. The waterlevels just downstream of the Borgharen weir have been studied by comparing data in the period 2014 – 2019 for the location of Lanaken and the Borgharen weir, which are shown in appendix D. The distance in river kilometers is roughly 3.5 kilometer ("Routeplanner Itteren-Borgharen", 2020). Over this distance the waterlevel drops 103 cm on average.

When the discharge in the Meuse becomes low water is pumped back at the locking complexes in the Julianacanal. By doing so the minimum discharge at Borgharen can be maintained at 10 m^3/s. It is important to maintain this discharge at periods of drought in order to avoid damage to the rare nature in this area ("Afvoer, 2020").

When the flow at the Borgharen weir is blocked and pumping starts it can be assumed (see detailed graph and explanation in appendix D) the river will fall dry within 4 hours. This is due to the combined effect of the river itself - which will flow downstream because of the bed slope - and the volume of water which is pumped upstream.

The Meuse river should not fall dry. It does not make sense to allow a fraction of the flow to pass the weir to prevent the river from falling dry, as the pumped volume always has to be bigger than the fraction of flow passed, otherwise no storage will occur upstream the weir. This will cause a limitation considering energy storage in the Meuse cascade. For the reasons mentioned above no storage will take place upstream the Borgharen weir.

STORAGE UPSTREAM LINNE WEIR

When the discharge is blocked at the Linne weir the waterlevel upstream will rise, depending on the discharge of the Meuse river and the pumping capacity of the PSP-plant. A backwater curve will develop. This is shown in a simplified manner in Figure 24.

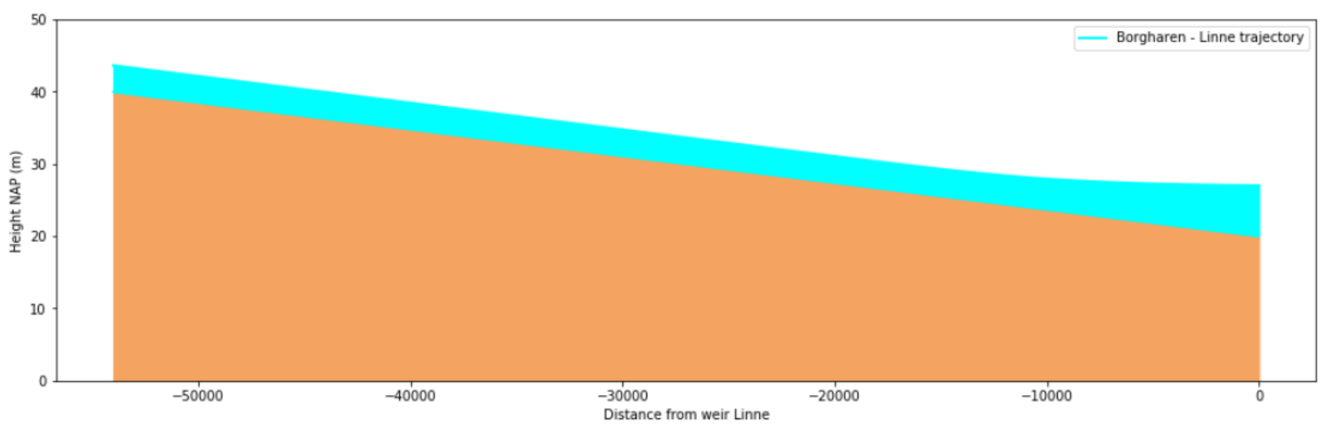


Figure 24: Backwater curve at Linne weir during storage mode

To exactly study the development of the backwater curve at varying discharges does not fall within the scope of this report. However, the backwater curve will cause another limitation for energy storage in the cascade. It can be assumed the storage volume above the Linne weir is limited, particularly when observing Figure 85.

At every trajectory downstream of the Linne weir 'rectangular' storage volumes are present as the cascade is canalized. Above Linne this is not the case as a consequence of the river bed slope and the presence of the backwater curve. Pumping up water at Linne could result in overflowing of the particular weir.

It is considered to be not economical to use sections in the Juliana canal above the Maasbracht and Born lock complexes for energy storage, as the discharge through this canal is 15.8 m^3/s on average for the period 2000 – 2019 ("Rijkswaterstaat Waterinfo", 2019). This would ask for the construction of PSP-plants which will not be used to utilize the bulk of the discharge of the Meuse river for hydropower but only for energy storage. Furthermore, it is questionable if the Juliana canal is capable of storing massive volumes of water.

Therefore, a second limitation for energy storage occurs. No water will be pumped upstream of the Linne weir. This implies energy storage in the Meuse cascade will start downstream at the Lith weir and will end at the Linne weir.

SUPPLY OF WATER

The river Meuse streams into the North Sea without the occurrence of any weir complex further downstream of Lith ("Project Over de Maas", 2020). This suggests 'enough' water should be available to pump upstream for storage purposes.

6.4 RIVER STORAGE AND PUMPED STORAGE

Energy storage in the Meuse cascade has an interesting aspect. Energy storage in the section Linne – Roermond occurs by pumping up water from the downstream side at the Roermond weir. However, the river will discharge water in this section from the upstream side at the Linne weir during storage mode. The river itself will store energy as well.

This implies the pumped volume in the section Linne - Roermond is bounded by the stored volume delivered by the river at storage mode. When the discharge increases the whole storage volume of the section Linne – Roermond will be filled with river water. As a result, in turn the pumped volume in the section Roermond – Belfeld will be bounded by the inflow of river water from upstream at Roermond.

This results in the 8th boundary condition of this report: pumped storage in a section of the Meuse cascade is bounded by river storage. Obviously, this phenomenon starts in the storage section most upstream in the cascade. The numerical Meuse model in chapter 11 is constructed in such a way it accounts for river- and pumped storage.

Note: river storage could be possible upstream the Borgharen weir. When the minimum discharge of 10 m^3/s (needed to avoid the river from falling dry and damaging nature) would be released at all time, the remaining discharge could be stored. However, when releasing this volume of water during energy mode an artificially created flood wave would be the result in the section Linne-Borgharen. This might lead to erosion of the river bed and dangerous situations along the border of the Meuse. Therefore, river storage upstream Borgharen is considered to be unfeasible.

6.5 STORAGE VOLUMES AND BOUNDARY CONDITIONS

Finally, the storage volumes of the Meuse cascade and the boundary conditions will be presented. The storage volumes are calculated by multiplying the length in river kilometers of a section by its summer dikes width and by using a storage height of 1 meter. BC5 does not apply for the section Grave – Lith as this is the section most downstream where pumping starts.

Storage section:	Length (m):	Width (m):	Height (m):	Storage Volume (m3):	BC5: pumping bounded by pumped volume downstream weir:	BC6: Storage volume bounded by height lock complex upstream:	BC7: Storage volume bounded by width between summer dikes:	BC8: pump storage bounded by river storage:
Linne - Roermond	13,000	150	1	1,950,000	applies	applies	applies	applies
Roermond - Belfeld	17,000	150	1	2,550,000	applies	applies	applies	applies
Belfeld - Sambeek	46,000	160	1	7,360,000	applies	applies	applies	applies
Sambeek - Grave	27,000	150	1	4,050,000	applies	applies	apllies	apllies
Grave - Lith	25,000	150	1	3,750,000	-	applies	applies	applies

Table 10: Storage volumes and boundary conditions on storage based on present situation Meuse cascade

6.6 CONCLUSIONS CHAPTER SIX

Storage volumes in the Meuse cascade are bounded by the summer dikes. The width between these dikes lies in the range 150 – 160 meters. It is assumed the waterlevel in a section can increase by 1 meter before the lock complexes will overflow. As a result, the storage volumes vary in the range 1,950,000 m^3 and 7,360,000 m^3.

In the numerical Meuse model, the distance between the summer dikes, and the storage height will become variables in order to assess increased storage volumes as well.

The pumped volume at each weir (with the exception of Lith) is bounded by the volume pumped up at the weir further downstream, in order to avoid a decrease in waterlevel downstream below target level.

The waterlevel in the Meuse decreases from roughly NAP 44 meter at the Borgharen weir to NAP 20 meter at the Linne weir. The bed slope in the Borgharen – Linne section causes limitations for energy storage. When the flow at the Borgharen weir is blocked and pumping starts the river will fall dry within approximately 4 hours. Therefore, no storage will occur upstream the Borgharen weir.

Upstream of the Linne weir a backwater curve will develop when the discharge is blocked and pumping starts. This might result in overflowing of this weir. For this reason, no water will be stored upstream the Linne weir. This implies energy storage in the Meuse cascade will start at the weir of Lith and will end at the weir of Linne.

The volume of pumped water into the upstream section(s) of the Meuse cascade is bounded by the inflow of river water during storage mode. Besides the PSP-plants the river itself will store energy as well.

7. TURBINE SELECTION

In this chapter the available low head turbines will be analyzed. This is the first design loop as a turbine is a design variable. The available turbines will be verified with respect to the requirements, like for instance fish friendliness and pumping capabilities. This verification will result in the selection of the device to be used for the conceptual design at the Sambeek weir.

7.1 AVAILABLE TURBINES

Usually, turbines are divided into three main categories. These categories together with their mortality rates are shown in the Table 11.

Type	Mortality rate
Pelton Wheel	100 %
Francis turbine	30 %
Kaplan turbine	10%

Table 11: main types of turbines (Bricker, 2018)

Table 11 provides a first impression of turbine types and fish mortality rates. However, other types of turbines have been developed especially aimed at reducing the fish mortality rates. Noortgaete et al (2016) performed an extensive study on the availability of turbines and their fish friendliness for a low head hydropower project in the Dutch province of Gelderland. The results of this study are briefly summarized below. Not every turbine from this study is described to avoid excessive information. For instance: Noortgate et al (2016) describe many variants of the waterwheel.

Additional information is provided about the pumping capabilities of the turbines, as the PSP-plants in the Meuse cascade should be equipped with pump-turbines. Furthermore, some other turbines are described not studied by Noorgeate et al (2016). The overview starts with the description of the Kaplan (Bulb) turbine.

BULB TURBINE

The bulb (Kaplan) turbine is currently equipping the hydropower facilities at the weir in Linne and Lith ("Uitspraken in vergunningszaken", 2019). A bulb turbine with variable guide vanes and runner blades has a capability of pumping ("Kaplan Turbines", 2020). The turbine is not fish friendly because of pressure-related injury (barotrauma) and high rotational velocities of the turbine leading to blade strike. According to Table 11 the fish mortality rate is 10 %. The main characteristics of the bulb turbine are (Noortgaete et al, 2016):

- power: 50 - 5000 kW
- head: 1 to 15 meter
- discharge capacity: 1 - 100 m^3/s
- fish friendliness: 10 % mortality rate
- capable of pumping: yes

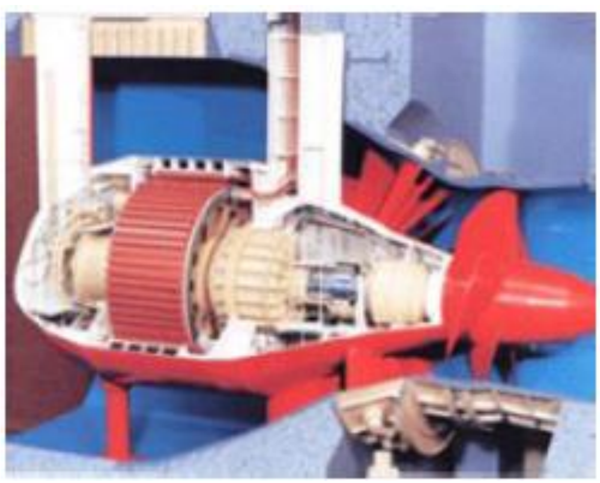


Figure 25: Kaplan bulb turbine (Noortgaete et al, 2016)

HORIZONTAL TURBINE

This turbine - a variant of the Kaplan turbine - is developed by the companies FishFlow Innovations and Pentair Fairbanks Nijhuis. It is especially designed to reduce the mortality of fish happening at a conventional Kaplan bulb turbine. Fish friendliness is achieved by the design of the impeller. This impeller (shown in Figure 26) causes a flow which is beneficiary for fish to migrate through the turbine safely. Basically: the occurrence of blade strike is minimized. However, the device is only tested by FishFlow Innovations ("Lagedruk Waterturbine", 2020). Information on pumping capabilities is not provided by the manufacturer. The main characteristics are (Noortgaete et al, 2016):

- power: 50 - 5000 kW
- head: 2 to 10 meter
- discharge: 1 - 50 m^3/s
- fish friendly: yes
- pumping capabilities: no information

Figure 26: horizontal turbine ("Lagedruk Waterturbine", 2020)

CROSS FLOW TURBINE

A cross flow (or Ossberger) turbine is an impulse turbine (like a Pelton wheel). The water runs transversely through this device. Turbine blades are passed twice increasing the efficiency (Noortgaete et al, 2016). However, as the turbine is powered by a water jet the device is not capable of pumping. Because of the high rotational velocity, a cross flow turbine is not fish friendly. The main characteristics are (Noortgaete et al, 2016):

- power: 10 - 3000 kW
- head: 2 to 200 meter
- discharge capacity: 0.04 - 13 m^3/s
- fish friendly: no
- pumping capabilities: no

Figure 27: Ossberger turbine (Noortgaete et al, 2016).

WATERWHEEL

A waterwheel is used for centuries (although with other purposes than electricity generation). This device collects water at the upper side in the compartments connected to the wheel, after which it starts turning due to gravity. The hydropower facility *'De Hamermolen'* in the Netherlands is powered by a waterwheel (Noortgaete et al, 2016). Due to its dependence on gravity and the design with compartments a waterwheel is not capable of turning around in order to pump. A waterwheel is considered to be fish friendly due to low rotational velocities. The characteristics of a waterwheel are (Noortgaete et al, 2016):

- power: 1 - 100 kW
- head: 2,5 to 10 meter
- discharge capacity: 0,1 to 2,5 m^3/s
- fish friendly: yes
- capable of pumping: no

Figure 28: Waterwheel (Noortgaete et al, 2016)

VERY LOW HEAD TURBINE

This relatively new turbine (the development started in 2002) is especially designed for low head sites which require a minimum of civil works and which demand fish friendliness. In order to reach this goal the axial turbine uses large Kaplan runners ("Next-Generation Small Hydro", 2020). The turbine is positioned in a frame with an angle to the horizontal of 30 ° to 50 ° (Noortgaete et al, 2016). The turbine is considered fish friendly due to the low pressure differences and low rotational velocities. The characteristics are:

- power: 100 - 500 kW
- head: 1,5 to 4,5 meter
- discharge capacity: 10 - 27 m^3/s
- fish friendly: yes
- pumping capabilities: no information

Figure 29: Very Low Head turbine ("Next-Generation Small Hydro", 2020)

GRAVITATION WATER VORTEX TURBINE

This turbine consists of a spiral formed basin hosting a turbine in its center. It is often called Zotlöterer-turbine based on the name of its inventor. The water vortex is the result of gravity and is concentrated to the turbine without the need of guidance equipment. The turbine is fish friendly as the result of the low rotational velocity (Noortgaete et al, 2016). However, due to its functioning by the use of gravity the turbine is incapable of pumping. The main characteristics are:

- power: 0,2 - 40 kW
- head: 0,7 to 2 m
- discharge: 0,02 - 20 m^3/s
- fish friendly: yes
- capable of pumping: no

Figure 30: Gravitational water vortex turbine (Noortgaete et al, 2016)

RONAMIC

The Ronamic is a device capable of pumping and turbining which is in the testing phase. The turbine is made of two unconventionally shaped rotors which are located in a concrete caisson ("RONAMIC Low head", 2020). This caisson can be integrated in a dam. The rotational velocity of the rotors is low making the device fish friendly (Noortgaete et al, 2016). However the maximum discharge which can be processed is limited. The characteristics of the device are (Noortgaete et al, 2016)("RONAMIC Low head", 2020):

- power: 60 - 120 kW (information not up to date, so might be higher)
- head: 1 to 10 meter
- discharge capacity: 6 - 8 m^3/s
- fish friendly: yes
- pumping possible: yes

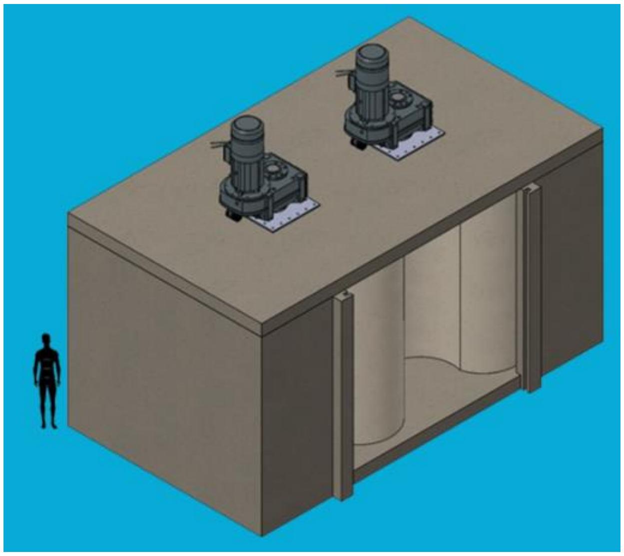


Figure 31: Ronamic ("RONAMIC Low head", 2020)

FRANCIS TURBINE

The Francis turbine is mentioned in the introductory chapter. This device is explained a bit more in depth as it is often used for pump-storage facilities as well.

Francis turbines are currently equipping four of the five highest capacity hydropower plants in the world. Francis turbines are very suitable for high head projects. For instance, the Three Gorges Dam in China is hosting 14 Francis turbines of 700 MW (!) each at a head difference of 80 meter ("Pump hydro turbine", 2019).

Although Francis turbines have been applied at heads up to 600 meter the best performance is reached using heads between 100 and 300 meter. This indicates Francis devices are high head turbines, while this report focuses on low head PSP-plants. The flow rate is often the limiting factor when using this kind of turbine. At higher heads the size of the turbines must fall and the flow must be large, and for low head projects the flow must be low to avoid the turbine to become very large. With an appropriate design a Francis turbine can utilize up to 95% of the energy available in the water (Breeze, 2020).

A Francis turbine is very suitable for pumping purposes. This is the main reason pump-storage facilities are usually equipped with Francis pump-turbines. However, the fish mortality rates are reaching 30 %, as shown in Table 11. The turbine can be considered to be fish unfriendly.

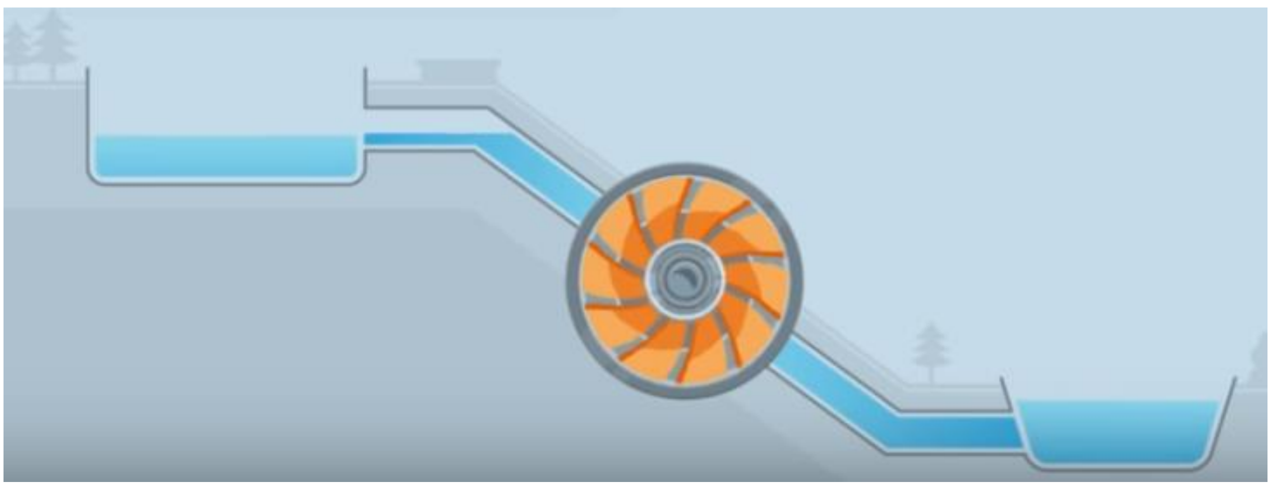


Figure 32: Francis turbine installed at PSP-plant bron ("Pump hydro turbine", 2019)

The main characteristics of a Francis turbine are:

- power: up to 700 MW
- head: up to 600 meter
- discharge capacity: depending on head difference
- fish friendly: no
- pumping possible: yes

RESTORATION HYDRO TURBINE

The potential for low head hydropower in the United Stated (US) is estimated to be 13 GW based on the hydropower potential of 54,000 existing dams. This could power up to 5 million homes within the country (Brown, 2020). However, in the US regulations on fish mortality are present like they are in the Netherlands.

Natel Energy is developing fish-friendly turbines. This company has designed the Restoration Hydro Turbine (RHT) with fish-safe blunt leading edges. These edges greatly reduce blade strike. Furthermore, the rotational velocity is designed to be low. The turbine allows 98% of fish up to 20 cm to pass the turbine unharmed at a 10-meter head test location. The characteristics are ("Restoration Hydro Turbines.", 2020):

- power: up to 1400 kW
- head: 2 to 10 meter
- discharge: approximately 14 m^3/s (reverse engineered)
- fish friendly: yes
- pumping possible: no information available

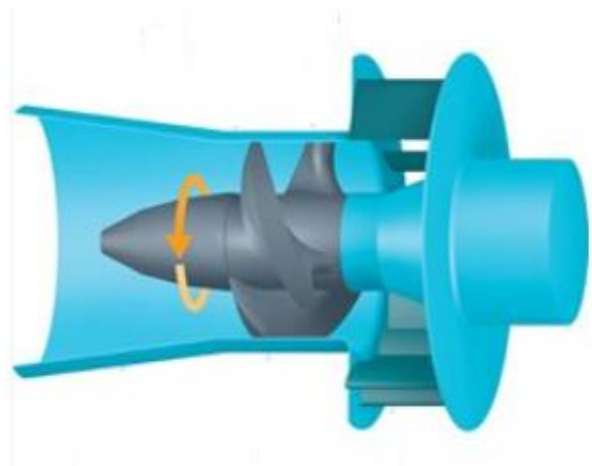


Figure 33: RHT-turbine ("Restoration Hydro Turbines.", 2020)

SCREW TURBINE

The last turbine that will be discussed is the screw turbine. The screw turbine has been developed inspired by the Archimedean screw pump. The turbine is rotating due to the flowing water thereby transferring energy to a drive unit, at which it is transformed into electricity by a generator (Spaans Babcock, 2019). A screw turbine can be considered fish friendly (Noortgaete et al, 2016). It can be used as pump as well thereby serving the purposes of a PSP-plant. The main characteristics of the screw turbine are (Spaans Babcock, 2019):

- power: 100 - 800 kW
- head: 1 to 12 meter
- discharge capacity: 0,25 to 15 m^3/s
- fish friendly: yes
- pumping capabilities: yes

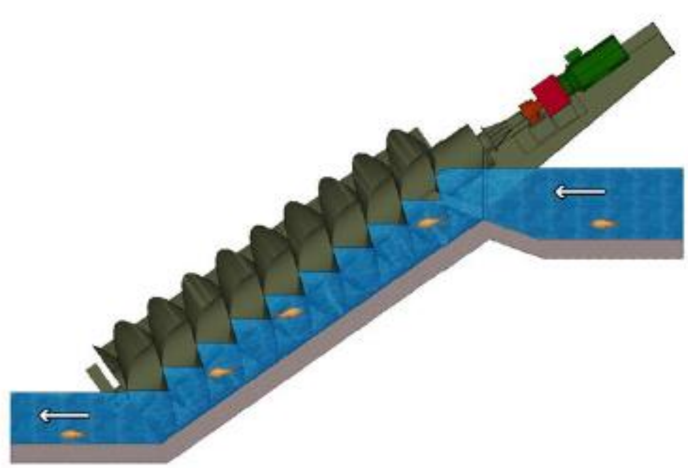


Figure 34: Screw turbine (Noortgaete et al, 2016)

This would imply a PSP-plant could indeed be equipped with screw turbines as the fish mortality rates are promising. Furthermore, the screw turbine seems to be tested on fish mortality in many studies when gathering information.

Vriese (2009) conducted a field test using a 700 mm screw turbine capable of discharging 35 m^3/hr. The test was rotating with 57 revolutions per minute (rpm). The test was conducted in the Dutch city of Medemblik on the shore of a canal. In total 99 fish consisting of several species passed the turbine resulting in zero fish mortality. The results are shown in Figure 35.

Fish specie	Length (cm)	No Injuries	Injured	Total number
Roach	13-24	33		33
Bream	10-50	33		33
Silver bream	15-32	5		5
Perch	15-18	3		3
Eel	55-82	23		23
Ruffe	13	1		1
Pike	44	1		1
		99	0	99

Figure 35: Test results fish mortality screw turbine (Vriese, 2009)

In appendix E the results on research on fish mortality by Charisiadis (2015) are shown. Again, the mortality is zero, however some injuries due to scale loss and hematoma occur.

According to Nagel (1968) the optimal rotational speed of a screw pump- and turbine decreases at increasing diameter. For the PSP-plant screws with the maximum diameter are needed to process the available discharge. This will minimize the rotational velocity.

In the introduction it was mentioned the probability of being hit by a blade depends among others on the rotational speed of a turbine (Amaral, 2019). Although a screw turbine does not have blades which can cause direct blade strike - like for instance Kaplan turbines have - it is reasonable to assume fish become safer at low rotational speed screws, either at pumping or at powering.

However, an additional fish mortality mechanism occurs at the Archimedean screw. Fish can be cached between the blade and the runner chamber, which is situated in the trough of the screw. Therefore, the gap between screw and trough should be minimized, which also should be done to minimize leakage losses through this gap.

7.2 VERIFICATION TURBINES ON REQUIREMENTS

In this paragraph the information on the turbines will be summarized and presented in Table 12. Using this table and the requirements from chapter 3 the pump-turbines will be verified. This verification will result in the selection of the pump-turbine to be used for the PSP-plant at Sambeek.

The turbine requirements are shown in chapter 3. Briefly summarized the requirements are:

- Capable of powering.
- Capable of pumping.
- Capable of processing a considerable discharge.
- Turbine has to meet Dutch environmental regulations on fish mortality.
- Suitable within the heads at the weirs in the Meuse cascade.

When observing Table 12 and the requirements the horizontal turbine, cross flow turbine, waterwheel, very low head turbine, gravitation vortex turbine and the restoration hydro turbine are eliminated from the list of potential turbines as these turbines are not capable of pumping, or if no information on pumping capabilities is available.

Type:	Power (kW):	Head (m):	Discharge (m^3/s):	Fish friendly:	Capable of pumping:
Kaplan bulb turbine	50 - 5000	1 - 15	1 - 100	no	yes
Horizontal turbine	50 - 5000	2 - 10	1 - 50	yes	no information
Cross flow turbine	10 - 3000	2 -200	0.04 - 13	no	no
Waterwheel	1 - 100 kW	2.5 - 10	0.1 - 2.5	yes	no
Very low head turbine	100 - 500 kW	1.5 - 4.5	10 - 27	yes	no information
Gravitation vortex turbine	0.2 - 40	0,7 - 2	0.02 - 20	yes	no
Ronamic	60 - 120	1 - 10	6 - 8	yes	yes
Francis turbine	up to 700 MW	up to 600	up to 875	no	yes
Restoration Hydro turbine	up to 1400	2 - 10	up to 14	yes	No information
Screw turbine	100 - 800	1 -12	0.25 - 15	yes	yes

Table 12: Characteristics turbines

Four turbines remain, which are the Kaplan bulb turbine, the Ronamic, the Francis turbine and the screw turbine. According to Table 11 the Kaplan turbine shows a 10 % fish mortality rate (which is too high for an additional hydropower facility in the Meuse cascade next to the existing ones at Lith an Linne), while the Francis turbines reaches a rate of 30%. Therefore, the Kaplan- and Francis turbine are eliminated from the list as well.

Two turbines remain. These are the Ronamic and the screw turbine. The discharge capability of the Ronamic is 8 m^3/s. With an available discharge of is 300 m^3/s at Sambeek this would ask for 38 turbines to install. This is considered undesirable within the environment of Sambeek. Furthermore, this device is still is the testing phase. No independent tests on fish mortality are found when gathering information.

This implies the screw turbine remains. According to the company 'Spaans Babcock' screw turbines can process discharges up to 15 m^3/s when equipped with a diameter of 5 meter (Spaans Babcock, 2019). This is confirmed by information from the hydro- and wind company 'Renewables First' which indicates a maximum diameter of 5 meter as well with a flow rate around 14.5 m^3/s (Renewable first, 2019). This makes the installation of multiple screw turbines at Sambeek an interesting option as the device also meets the requirements on fish friendliness.

7.2.1 SELECTED PUMP-TURBINE: ARCHIMEDEAN SCREW

The turbine which is selected after verification is the screw turbine. This turbine is considered to meet the Dutch environmental regulations on fish friendliness for the river Meuse. The device is suitable within the head differences at the weirs in the Meuse and can process a discharge of 15 m^3/s when using a diameter of 5 meter. Last but not least, the Archimedean screw was originally invented for pumping, which is a requirement for the purpose of a PSP-plant.

7.3 CONCLUSIONS CHAPTER SEVEN

Multiple turbines have been analyzed on suitability for low head conditions, turbining- and pumping capabilities, discharge which can be processed and fish friendliness. After verification the Archimedean screw is selected for equipping the conceptual design of the PSP-plant at Sambeek.

The device has been tested positively in studies considering fish friendliness and it therefore expected to meet Dutch environmental regulations for the river Meuse. The device is suitable within the head differences at the weirs in the Meuse cascade. It can process a discharge up to 15 m^3/s when using a 5-meter diameter screw.

8. THEORY ON ARCHIMEDEAN SCREW

In this chapter a theoretical framework related to the Archimedean screw pump- and turbine will be presented which is needed for the development of concepts on screw configurations in chapter 9 and the conceptual design of the Sambeek PSP-plant in chapter 10. The chapter starts with a paragraph on the geometry of the screw.

8.1 GEOMETRY SCREW

The geometry, basic parameters and their abbreviations regarding the Archimedean screw are shown in Figure 36. The abbreviations in the figure are explained as:

- R_i = inner radius (radius shaft)
- R_a = outer radius (screw)
- β = angle of inclination
- S = pitch of the screw
- L_s = length of the shaft
- L_b = length of the screw
- N = number of blades (or flights)

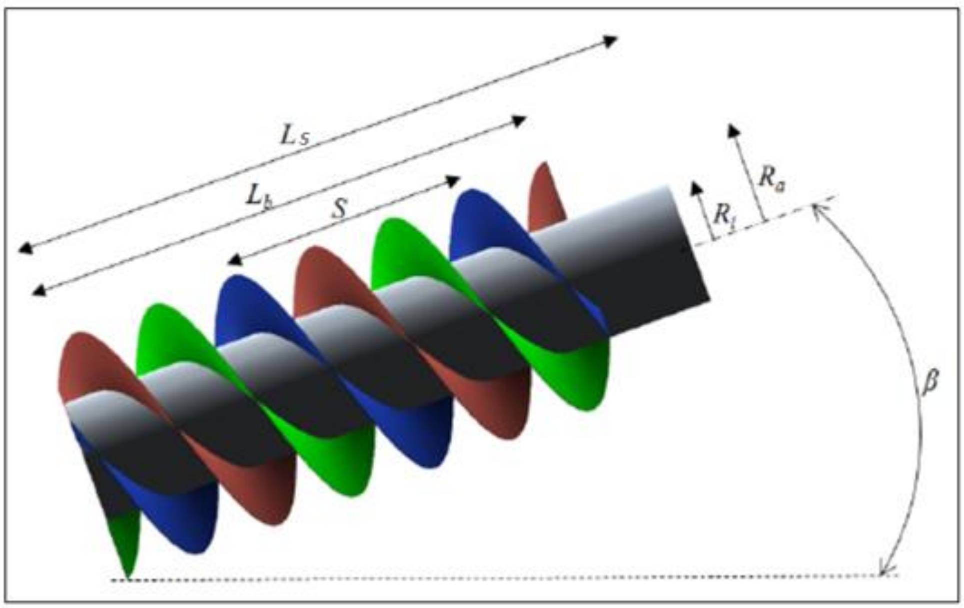


Figure 36: Geometry screw (Dellinger et al,2016).

Most screws have three separate blades welded around the shaft (Charisiadis, 2015). A three-bladed screw is shown in Figure 36. However, four-bladed screws are used as well ("Screw turbine", 2020). The pitch represents the period of one blade (Rorres, 2000).

8.2 THEORY ON SCREW PUMP

This paragraph provides an analysis of the screw pump. It starts with theory on the angle of inclination.

ANGLE OF INCLINATION AT PUMPING

A screw functioning as a pump is shown in Figure 37. The screw can be several meters long and is rotating in an open trough. According to (Blazejewski et al, 2019) the angle of inclination - which is the angle of the screw with the horizontal - lies in the range of 30 ° to 40 °.

Nagel (1968) performed an extensive study on all aspects to consider when using screw pumps. Nagel proposes an angle of 30 degrees as design angle for screw pumps. Furthermore, purely from the amount of material that is needed to construct the screw it is not economical to increase the angle of inclination above 30 °.

Information from KOSOVIT (2020) and Spaans Babcock (2019) confirm the use of an angle of inclination of 30 ° for the use of a screw pump. Higher angles of inclination lead to lower pump capacities. Based on this theory the angle to be used as starting point for the conceptual design will be 30 °.

WATERLEVELS LOWER- AND UPPER END SCREW PUMP

In Figure 37 one can view a screw pump. The abbreviations – of which the explanations are provided by Ritz-Atro (2020) - are marked in red:

- Pump chute point (PCP): the water level at the upstream end of the screw.
- Pump delivery point (PDP): level of water which is leaving the screw. It represents the maximum waterlevel at which no backflow of delivered water occurs.
- Pump filling point (PFP): the water level at the downstream end of the screw.
- Pump touch point (PTP): water level at which delivery will cease.
- K: the distance between PCP and PDP.
- The angle of inclination β.

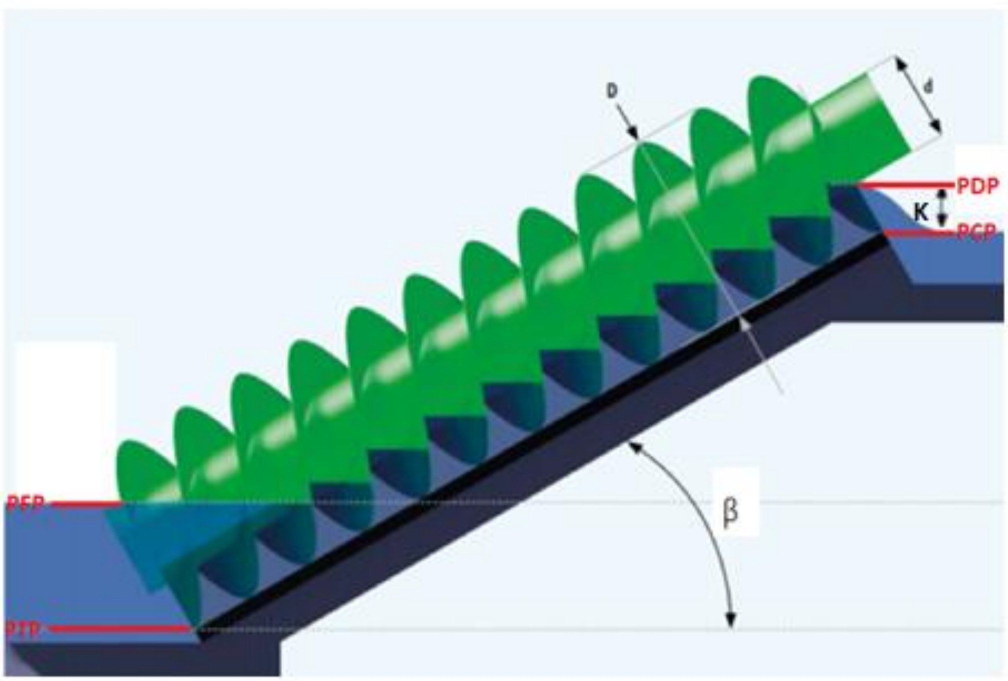


Figure 37: Screw pump, angle of inclination, PCP, PDP, PFP and PTP, adjusted picture (Spaans Babcock, 2019)

As one can observe PFP is located at the waterlevel of the basin at the downstream end just above the shaft of the screw (Spaans Babcock, 2019)(Ritz-Atro, 2020). This position of PFP is confirmed by Nagel (1968, p.39) who states that the optimal position of PFP is reached when the lower waterlevel is located just above the shaft, which can be represented by the following dimensionless formula:

$$\Psi_L = \frac{D+d}{2*D} \qquad \text{formula (4)}$$

In which:

- Ψ_L = optimal position PFP (-)
- D = diameter screw (m)
- d = diameter shaft (m)

A deeper immersion will not result in increased delivery, although a drop in delivery occurs when the waterlevel falls below PFP (Nagel, 1968, p.39).

PTP is the waterlevel at which the supply of water to the screw ceases. Obviously, a screw pump cannot perform at a waterlevel below PTP.

PCP is the waterlevel of the basin at the upstream end of the screw. However, the maximum waterlevel for which no backflow occurs is represented by PDP. The height difference between PCP and PDP is represented by K which is shown in Figure 37. According to Muysken (1932) and Nagel (1968) K is depending on the angle of inclination β and the diameter of the screw D. This is shown in Table 13:

β	K
30 °	0.3 D
33 °	0.26 D
35 °	0.22 D
37 °	0.19 D
40 °	0.15 D

Table 13: Inclination angle β and indication value K (Nagel, 1968, p.42)

EFFICIENCY SCREW PUMP

Nagel (1968, p.45) divides the efficiency losses of a screw pump into four parts, which are:

- Mechanical losses: due to friction in the bearings, speed control and power transmission.
- Hydraulic losses: as a result of the impact of start and end of the screw, friction on the blades and friction on the shaft.
- Leakage losses: due to water which is flowing back and the additional power it takes to lift it up again.
- Discharge losses: due to the kinetic energy present in the water leaving the screw.

According to Spaans Babcock (2020) the average efficiency of a screw pump operating at or above PFP is 75 %. Wijdieks & Bos (1994) indicate the average efficiency of a larger diameter screw pump is 75 %, while this efficiency decreases to 65 % for a smaller diameter screw. For the efficiency of the screw pump in the numerical Meuse model 75 % will be used as default value.

EFFICIENCY AT PARTIAL FILLING

The efficiency curve of a screw pump – shown in Figure 38 – is rather flat. When filled at 40 % of the design capacity the efficiency is still about 75 %. In fact, the efficiency slightly increases when being partially filled at roughly 90 % (Spaans Babcock, 2019). This information is partly confirmed by Ritz-Atro (2020). Between 40 % and 100 % filling the efficiency curve is flat. However, it shows a maximum efficiency at roughly 90 % filling.

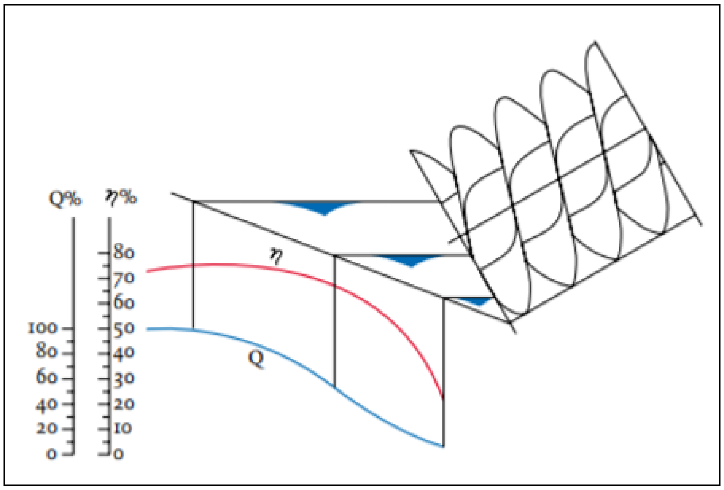


Figure 38: Pump efficiency at partial load conditions (Spaans Babcock, 2019).

SUBMERGENCE OF THE SCREW INLET

A screw pump achieves optimum efficiency when the waterlevel is located at or above PFP (Ritz-Atro, 2020). However, Nagel (1968) indicate this downstream waterlevel should not become higher than $\Psi_L = 1.0$ using formula 4. This implies the waterlevel should not exceed the edge of the screw when being filled to avoid efficiency losses. Additional information on efficiency losses due to submergence is presented in appendix F.

In the Meuse cascade waterlevels are varying. When energy is stored in a section of the cascade by pumping up water at a weir, and when this water is in turn not pumped up at the next weir upstream, the waterlevel in the particular section will rise. This implies the lower end of the screw might become submersed.

PUMP CAPACITY AT INCREASING ANGELS OF INCLINATION

In the paragraph on the angle of inclination it was indicated an angle which is higher than 30° results in a lower pump capacity. For every increase in angle the pump efficiency - with respect to the amount of water displaced - decreases by 3 % (Nagel, 1968, p.36). This is more or less confirmed by information provided by Landustrie (2007) and Spaans Babcock. In appendix F tables are presented with pump capacities at increasing angles of inclination.

ROTATIONAL SPEED SCREW PUMP

For the determination of the rotational speed of a screw pump Nagel (1968, p 36) uses an empirical formula, which reads:

$$n_{pump} = \frac{50}{\sqrt[3]{D^2}} \qquad \text{formula (5)}$$

In which:

- n = rotational speed in round per minute (rpm)
- D = diameter screw (m)

It demonstrates the optimal rotational speed of a screw pump decreases at increasing diameter. This formula is derived by Muysken in 1932 and still in use by manufactures today. It provides satisfactory results when applying at a screw pump in practice (Nuernbergk, 2013).

The rotational speed provided by formula 5 is the largest number of revolutions per minute for which - when the chambers between the blades are filled to an optimal extent - an overflow of water back into the supply side is just avoided. Therefore, the rotational speed should not become higher than the value provided by formula 5 (Nagel, 1968, p.37). This is called the "Muysken limit" by Kozyn et al (2017). In appendix F one can find additional information on work of Muysken.

Using formula 5, Figure 39 is obtained (Nagel, 1968). In chapter 7 a screw with a diameter of 5 meter is proposed. As one can notice the optimum speed of this screw becomes less than 20 rpm.

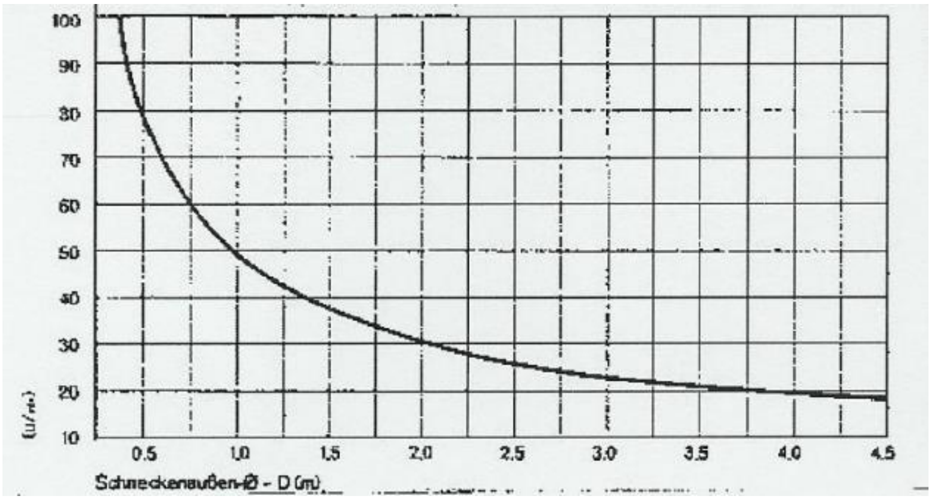


Figure 39: Optimal rotational velocity at increasing diameter screw pump (Nagel, 1968)

8.3 THEORY ON SCREW TURBINE

When the screws in the PSP-plant are used for turbining the angle of inclination and the waterlevels at the down- and upstream end differ compared to the situation at pumping mode.

ANGLE OF INCLINATION AT TURBINING

The angle of inclination is shown in the Figure 40. Usually, a beta symbol is used for turbines as well. This has been adjusted into the alpha symbol, as the beta symbol will be used for the screw pump. In the adjusted Figure 40 one can notice a screw when turbining and abbreviations in red letters:

- Turbine filling point (TFP): located at the water level upstream.
- Turbine exit point (TEP): located at the water level downstream.
- Turbine touch point (TTP): waterlevel at the lower edge of screw downstream.
- The angle of inclination α.

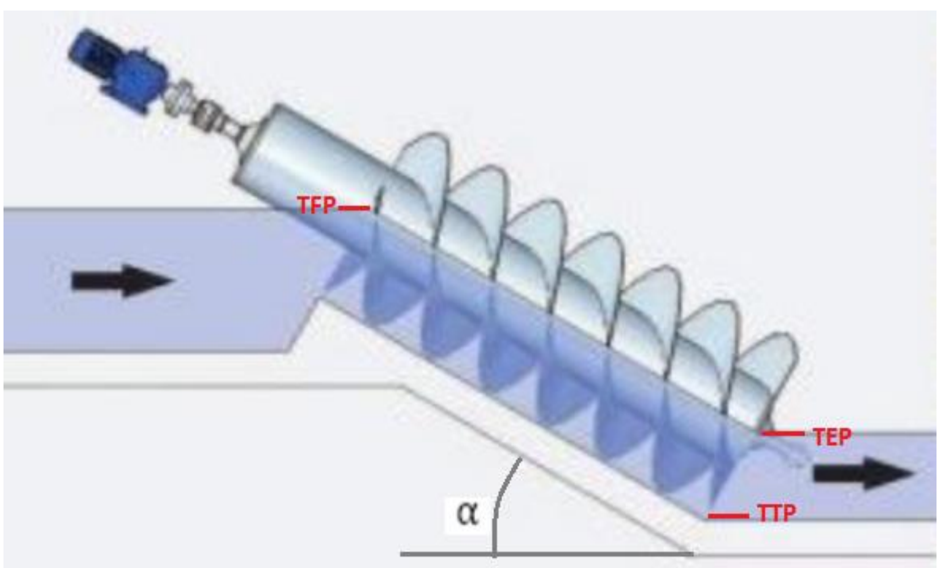


Figure 40: Screw turbine, angle of inclination α, TFP, TEP and TTP ("Archimedean hydrodynamic screw", 2020)

According to information of Renewable First (2019) screw turbines are usually constructed under an angle of 22 °. Akbarzadeh et al (2017) concluded the optimum angle of a screw turbine occurs at an angle of 22 ° as well. This is confirmed in a study on the prospect of micro hydro power plants installed in Nepal by Amgain & Dhakal (2018) in which again an angle of 22 ° is used. However, Saroinsong et al (2015) conclude the optimum angle is 25 °. Dellinger et al (2016) concluded 20 ° scores the best while Dellinger et al (2019) concluded 15 ° is the best turbine angle followed by 25 ° as the almost best angle.

One can conclude a decisive consensus on the turbine angle of inclination is missing in the literature. The range is 15 ° - 25 °. As the majority of the sources indicate an angle 22 ° this value will be used as starting point for the screw configuration and conceptual design of the PSP-plant. As this angle is lower compared to a screw at pumping mode (30 °) a mechanical solution is needed to adjust this inclination angle.

WATERLEVELS LOWER- AN UPPER END SCREW TURBINE

According to Landustrie (2020) the highest efficiency of a screw turbine is reached when TFP is located at the upstream waterlevel halfway the upper end of the screw. This is confirmed by (Saroinsong et al, 2015) who concludes the optimal water inflow head is located at half the outer diameter of the screw, which is at TFP. Using this inflow head a turbine efficiency of 89 % can be achieved.

Landustrie (2020) indicates the efficiency of a screw turbine is further optimized by locating TEP halfway the lower end of the screw at the downstream waterlevel. This is confirmed by a graphical illustration of Nuernbergk (2012). However, a study by (Dellinger et al, 2016) indicate the optimal level of TEP depends on the number of blades and the corresponding pitch. This will be elaborated on in the paragraph on submergence of the lower end of the turbine.

EFFICIENCY SCREW TURBINE

A curve showing the mechanical efficiency of an Archimedean screw compared to the main other types of hydro-turbines is shown Figure 41. According to the information of Booker et al (2020) a screw turbine can reach an efficiency above 80 %. As one can notice a screw turbine has a flat efficiency curve with respect to the discharge processing.

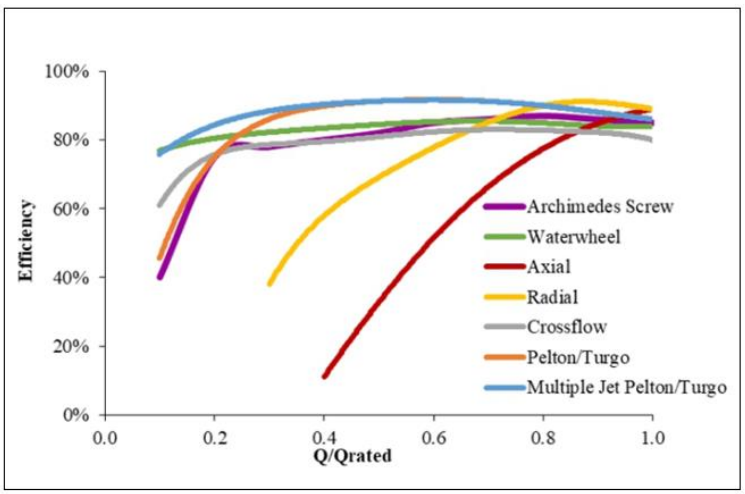


Figure 41: Efficiency curves hydropower turbines (Booker et al, 2020).

According to Renewable First (2019) the turbine efficiency reaches a maximum of 86 %. According to the information of another manufacturer - ANDRITZ (2019) - a screw turbine can reach an efficiency up to 92 %. However, these values do not account for the efficiency losses in components like the generator.

Noortgaete et al (2016) state a screw turbine can reach total efficiencies of 70 to 80 %. Research performed by Amgain & Dhakal (2018) indicate the efficiency of a low head Archimedean screw turbine lies in the range 80 - 85 %. The efficiency of the total system - including generator - is higher than 70 %.

When studying manufacturer information on power output (see Figure 115 in appendix F) from Spaans Babcock (2019) and by using formula 1 reverse engineered it can be concluded the overall efficiency of a 5-meter diameter screw turbine is roughly 75 %. This efficiency will be used as default value for the Meuse model in chapter 11.

EFFICIENCY AT PARTIAL LOAD CONDITIONS

The efficiency curve of a screw turbine at partial load conditions shows the same characteristics as the screw pump. The curve is also characterized by a flat shape. According to Renewable First (2019) it still has an efficiency of about 80 % when the flow is at 40 % of the maximum flow rate. Noortgaete et al (2016) confirm a screw turbine maintains a high efficiency when powered at partial load conditions.

SUBMERGENCE OF LOWER END TURBINE

The downstream waterlevel has a direct impact on the performance of a screw turbine (Lyons & Lubitz, 2013). Submergence of the lower end of the turbine can reduce the efficiency up to 20 %. This is explained by the fact the water is exerting pressure on the submerged last blade(s) of the screw. The pressure increases when the submergence is increasing which leads to efficiency losses as it reduces the torque (Dellinger et al, 2016).

Nuernbergk (2012) studied the optimal waterlevel downstream for a screw under different angles of inclination and a varying number of blades and pitches. Muller & Senior (2009) concluded the efficiency of a screw varies depending on the number of blades, although the effect is minor. This is shown in Figure 116 in appendix F. The optimal waterlevel downstream is described by (Delinger et al, 201, p.11):

$$h_{out,opt} = (R_a + R_i)\sqrt{1 - \left(\frac{\tan(\alpha)S}{2\pi R_i}\right)^2}\cos(\alpha) - \frac{S}{N}\sin(\alpha) + \ h_1 \qquad \text{formula (6)}$$

In which:

- R_i = inner radius (radius shaft) (m)
- R_a = outer radius (screw) (m)
- α = angle of inclination (°)
- S = pitch of the screw (m)
- h_1 = upstream waterlevel (m)
- $h_{out,opt}$ = optimal downstream waterlevel (m)
- N = number of blades (or flights) (-)

Formula 6 is clarified graphically by Figure 42 in which TEP is corresponding to $h_{out,opt}$:

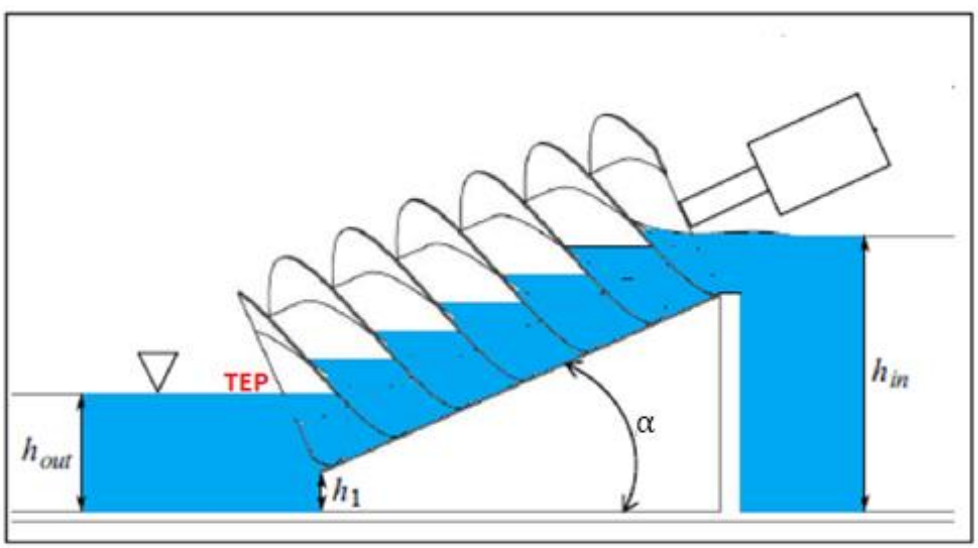


Figure 42: Optimal level of TEP according to Nuernbergk (2013, adjusted picture)

Dellinger et al (2016) performed experimental measurements to be able to determine the influence of submergence on the efficiency of a screw. In order to do so they defined screw submergence I as:

$$I = \frac{h_{out} - h_1}{2R_a \cos(\alpha)} \qquad \text{formula (7)}$$

This is shown graphically in Figure 117 in appendix F. For the situation when I = 0 the water level at lower and of the screw is at TTP. When I = 1 the lower end of the screw is submerged completely. Turbine efficiency is optimal at roughly I = 0.6 – 0.7 which implies 60 to 70 % submergence. This theory will be used for the optimization of the screw configuration selected for the conceptual design of the Sambeek PSP-plant.

ROTATIONAL SPEED SCREW TURBINE

Ghassemi (2017) explains formula 5 - derived for screw pumps - also applies for screw turbines. The rotational speed in rpm should not become larger than de value provided by this formula. It can be considered to be an upper boundary.

When neglecting various leakage losses, the nominal discharge through the screw turbine is equal to the volume of water lifted up in one revolution multiplied by the rotational speed. This volume is dependent on the volume of a bucket - which is the volume between two adjacent blades -and the number of blades leading to the number of starts. The formula reads (Dellinger et al, 2016)(Ahmed et al, 2013)(Saroinsong et al, 2015):

$$Q_{nom} = N * V_b * \frac{n}{60} \qquad \text{formula (8)}$$

In which:

- V_b = volume bucket (m^3)
- Q_{nom} = nominal discharge (m^3/s)
- n= number of revelations (rpm)
- N = number of blades (-)

The number 60 accounts for the fact the number of revolutions (n) is usually provided in rounds per minute (rpm). Rewriting this formula results in the rotational speed of the screw turbine. This formula reads:

$$n_{turbine} = \frac{Q_{nom} * 60}{N * V_b} \qquad \text{formula (9)}$$

This implies the rotational speed of the screw when turbining will vary according to the discharge flowing through the turbine and the volume of water in the buckets. However, as starting point for the design formula 5 of Nagel (1968) can be aplied.

It should be mentioned overflow should be avoided, as this reduces the efficiency of a srew turbine drastically (art 69, p.22). Therefore Q_{nom} should not be exceeded in the numerical Meuse model.

MINIMUM HEAD

According to manufacturing information from SpaansBabcock (2019) the minimum gross head needed for the screw turbine to operate is provided by half its diameter, which can be observed in Figure 115 in appendix F. It is assumed this is a rule of thumb.

At the weirs in the Mesue cascade the gross head is decreasing at increasing river discharge. In the numerical Meuse model the minimum head for a screw to operate is set on 0.4 times its diameter. This is justified be the assumption the turbine will not abruptly stop producing when the gross head becomes less then half the turbine diameter.

8.4 ROUND-TRIP EFFICIENCY PSP-PLANT

According to the theory presented in paragraph 8.2 ‘Efficiency screw pump’ the overall efficiency (including losses due to gearbox and generator) of a screw pump can be considered to be 75 %.

$$\mu_{pump} = 75\ \%$$

Based on the theory presented in paragraph 8.3 ‘Efficiency screw turbine’ the overall efficiency of a screw turbine can be considered to be 75 % as well. Losses due to gearbox and generator are included. (In chapter 10 it will become clear no turbines with variable speed will be used).

$$\mu_{turbine} = 75\ \%$$

Using these efficiencies, the theoretical round-trip efficiency of a PSP-plant in the Meuse cascade can be determined. This reads:

$$\mu_{PSP} = \mu_{pump} * \mu_{turbine} \qquad \text{formula (10)}$$

$$\mu_{PSP} = 75\ \% * 75\ \% = 56.25\ \%$$

8.5 CONCLUSIONS CHAPTER EIGHT

Chapter 8 presents a theoretical framework on the Archimedean screw. The screw pump is commonly installed using an angle of inclination of 30 °. For every angle increase the volume of pumped water decreases for at least 3 %. The optimal waterlevel at the downstream side is located just above the shaft and is called pump filling point.

The maximum waterlevel at which no backflow of pumped water occurs is called pump delivery point. Pump delivery point is depending on the angle of inclination and the outer diameter of the screw.

Both the Archimedean screw pump and- turbine are characterized by a flat efficiency curve. Even at 40 % design capacity both show an efficiency above 80 %. The efficiency of a screw pump slightly decreases when pump filling point becomes submerged. The overall efficiency of a screw pump can be considered to be 75 %.

For the angle of inclination of the screw turbine 22 ° is mainly used. However, angles of 15 ° and 25 ° are also described to be efficient. The optimal efficiency of a screw turbine is reached when the waterlevel at turbine filling point is located halfway the upper end of the screw. This water level avoids overflow which results in considerable efficiency losses.

When the lower end of the screw turbine is completely submerged the overall efficiency is reduced by 20 %. The optimal waterlevel at the downstream end depends amongst other on the number blades wrapped around the shaft and the corresponding pitch. When using three of four blades results in a slightly higher efficiency compared to using two blades. The overall efficiency of a screw turbine can be considered to be 75 %.

The round-trip efficiency of a PSP-plant in the Meuse river – equipped with Archimedean screws – will be 56,25 % by multiplying the overall pump- and turbine efficiency.

The optimal rotational speed is prescribed by the diameter of the screw, either at pumping or turbining. For a screw with a diameter of 5 meter this will be 17.1 rpm. For the screw pump the rotational speed will be fixed.

9. SCREW CONFIGURATIONS

Chapter 9 is a continuation of the developments of concepts using the theoretical framework from the previous chapter on the Archimedean screw. In this second design loop multiple screw configurations will be presented and verified on the requirements.

9.1 DESIGN STARTING POINTS SCREW CONFIGURATION

The information gathered in the previous chapters has resulted in design starting points with respect to the Sambeek weir which are shown in Table 14. These starting points will be used for the assessment of different screw configurations. The calculations on these starting points are presented in appendix H related to the conceptual design (chapter 10).

Description	Value
Outer diameter screw	5 meter
Diameter shaft	2.25 meter
Design level upstream	NAP 11,1 meter
Design level downstream	NAP 7,95 meter
Gross head	3,15 meter
Angle of inclination α screw turbine	22 °
Turbine filling point (TFP)	NAP 11,1 meter
Turbine exit point (TEP)	NAP 7,95 meter
Angle of inclination β screw pump	30 °
Pump filling point (PFP)	Above shaft
Pump chute point (PCP)	NAP 11,1 meter
Pump delivery point (PDP)	NAP 12.6 meter

Table 14: design starting points for screw configurations

EXPLANATIONS ON DESIGN STARTING POINTS

In the paragraph on turbine selection it was explained Archimedean screws with a diameter of 5 meter are available on the market. The main reasons to use this diameter are:

- To minimize the risk of fish mortality.
- To be able to process the available discharge for hydropower purposes.
- To minimize the influence of waterlevels fluctuations on screw efficiency, either at pumping or at powering.

In chapter 8 it was explained the bigger the diameter, the lower the rotational speed. It has been explained this low speed reduces the risk on fish mortality. As the PSP-plant should meet the Dutch environmental regulations this is considered to be important.

The available discharge for hydropower in Sambeek is 300 m^3/s. To be able to process this discharge within a limited amount of space in the environment of the Sambeek weir, screws with the maximum available diameter are considered to be economical. A screw with a diameter of 5 meter is capable of processing 15 m^3/s ("Archimedean screw hydro", 2020).

In the chapter on waterlevels it was concluded the target levels - provided by RWS - will be used as design levels for the conceptual design. As the waterlevels are varying the influence on the efficiency on either the screw pump and - turbine should be minimized. This will be another motivation to use 5-meter diameter screws. The larger the diameter, the smaller the influence of waterlevels variations (fluctuating around the design waterlevels) on the efficiency of the screw, either at pumping or turbining.

The optimal positions of pump filing point (PFP), pump chute point (PCP) and pump delivery point (PDP), as well as turbine filling point (TFP) and turbine exit point (TEP) are based on the theory of chapter 8. These conditions are:

- PFP: just above the shaft downstream.
- PCP: at the waterlevel upstream.
- PDP: at 0.3D above PCP.
- TFP: middlepoint of screw end upstream should be located at the waterlevel.
- TEP: depending on the screw geometry. Starting point: middlepoint of screw end downstream located at downstream waterlevel, needs to be further optimized for selected configuration.

9.2 SCREW CONFIGURATIONS ASSESSED

Using these starting points six configurations have been elaborated on. These are:

1. A screw completely fixed at the angle of inclination for pumping (30 °) equipped with a valve.
2. Screw turbine connected to a hinge with target angle α of 22 °, TFP and TEP as governing starting points for the configuration. PFP, PCP and angle screw pump are restricted by turbine requirements.
3. Screw pump connected to a hinge with PFP, PCP together with target angle β of 30 ° as governing starting points for the configuration. Design on the screw turbine restricted by requirements screw pump.
4. A configuration with the target angles of inclination of both pump- and turbine as starting points.
5. A floating screw configuration.
6. A configuration that can be adjusted to the down- and upstream waterlevels either at pumping or at turbining.

In appendix G one can observe detailed hand-sketches using the starting points of Table 14. The figures in the main chapter are based on these hand-sketches.

CONFIGURATION 1: FIXED AT 30 DEGREES EQUIPPED WITH VALVE

Despite the theory on different optimal angles of inclinations for turbine and pump the first configuration which will be assessed is using a fixed angle. This is motivated by the pump facility located in Hasselt, Belgium. This facility is hosting three screws within a trough of 5 x 5 meter. The angle of inclination is fixed. Switching between turbining- and pumping mode is achieved by using a hydraulically controlled jacket valve. By closing this valve, the chute point of the pump is obtained. When opened the filling point of the turbine is obtained ("Vandezande", 2020).

The facility in Hasselt is primarily designed for the waterlevel regulation in the Albertcanal. This canal is fed by water from the river Meuse. In periods of drought the flow into the canal is too low to account for the loss of locking water at the locking complex of Hasselt. Therefore, the screws are used to pump back locking water in order to optimize navigability ("Vandezande", 2020). Pumping is the main operational process at Hasselt.

A configuration inspired by 'Hasselt' has been compiled. This configuration is using a fixed angle of inclination of 30°. Figure 43 shows this configuration in pumping- and turbining conditions.

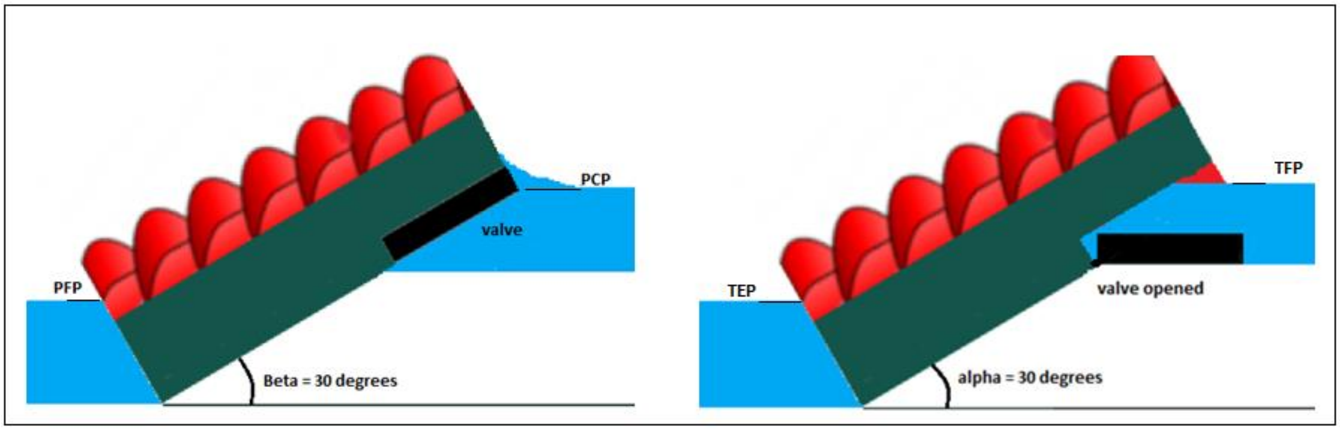


Figure 43: Configuration1. Screw pumping (left) with closed valve and turbining (right)with valve opened

As one can observe obviously the turbine is not operating at the target angle of inclination which is 22 °. The main disadvantage of this configuration is it cannot adapt to the fluctuating waterlevels in the Meuse river. Furthermore, flow over the valve will probably lead to increased turbulence and additional hydraulic loss.

CONFIGURATION 2: SCREW TURBINE GOVERNING

In the second configuration the target conditions on the turbine (angle of 22 °, TFP and TEP) are governing. The length of the trough and screw will be 8.4 meter. The screw is connected to a hinge in order to rotate to pumping mode.

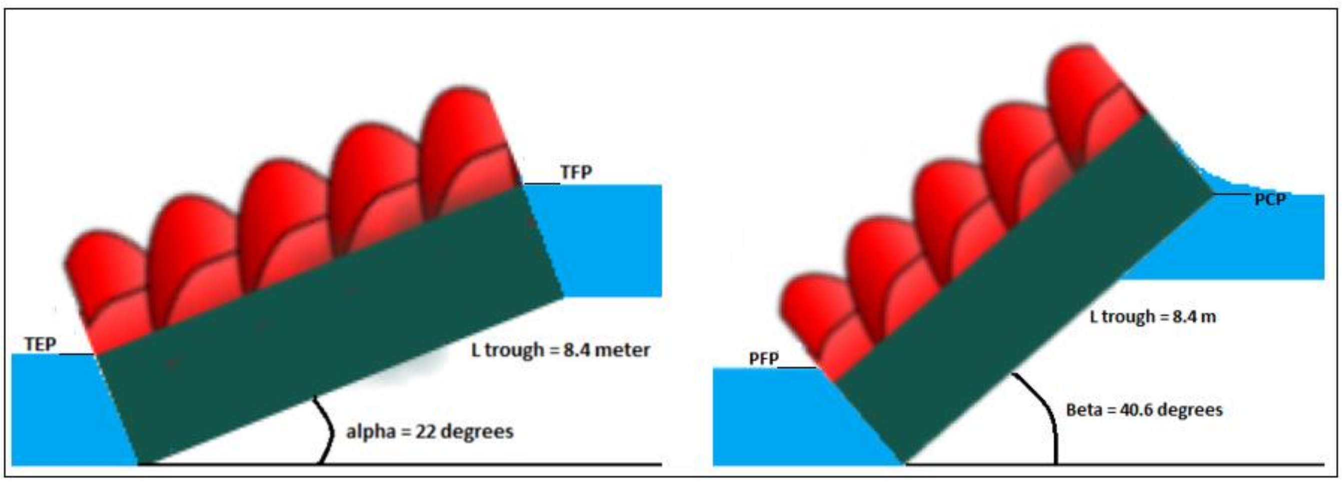


Figure 44: Configuration 2. Screw in turbine mode (left) and pumping mode (wright)

In Figure 44 one can observe the screw in turbine- and pumping mode. The angle of inclination has to be increased in order to position PCP at the waterlevel upstream. One could also choose the lower the pump angle and use pump delivery point. However, as the waterlevel upstream might increase (when pumped water is not pumped up further at the next weir upstream) this would still ask for a rotation in the order of 40 degrees.

With respect to this concept one can observe the angle of the screw at pumping becomes inefficiently high. According to chapter 8 the pumping efficiency of a screw pump decreases with 3 % per angle increase above the target angle of 30 °. Furthermore, PFP is not at the target level just above the shaft. Therefore, this screw configuration is considered to be not suitable.

CONFIGURATION 3: SCREW PUMP GOVERNING

When the screw pump is governing the following sketches are presented. An angle of inclination β of 30 ° together with PFP and PCP are the governing starting points. For this configuration the length of the trough is 12.6 meter. Figure 45 shows the screw in pumping mode and turbining mode.

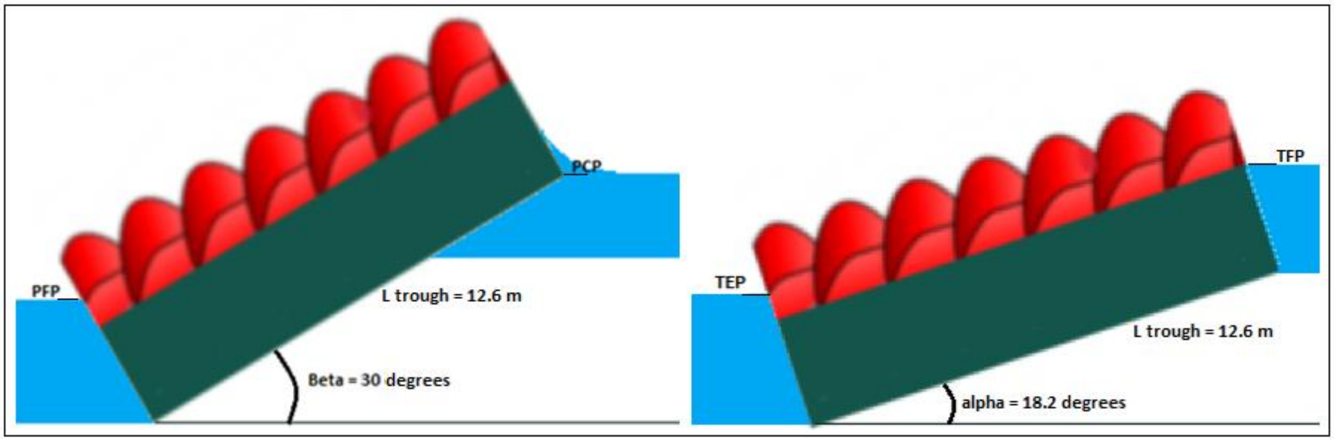


Figure 45: Configuration 3. Screw in pumping mode (left and turbining mode (wright)

As one can view the angle of inclination when powering will be 18.2 °. This is significantly lower than the target level of 22 °. Furthermore, TEP is located not at its target position leading to efficiency losses in the main operational process of turbining.

CONFIGURATION 4: ANGLES SCREW PUMP AND -TURBINE GOVERNING

In this 4th configuration the target angles of inclination of both screw pump (β = 30 °) and screw turbine (α = 22 °) are governing. In order to reach these targets, the trough of the screw has been extended to 18,56 meters. Using this extended through it is possible to obtain the target angles for pumping- and powering. The fourth configuration is shown in the Figure 46.

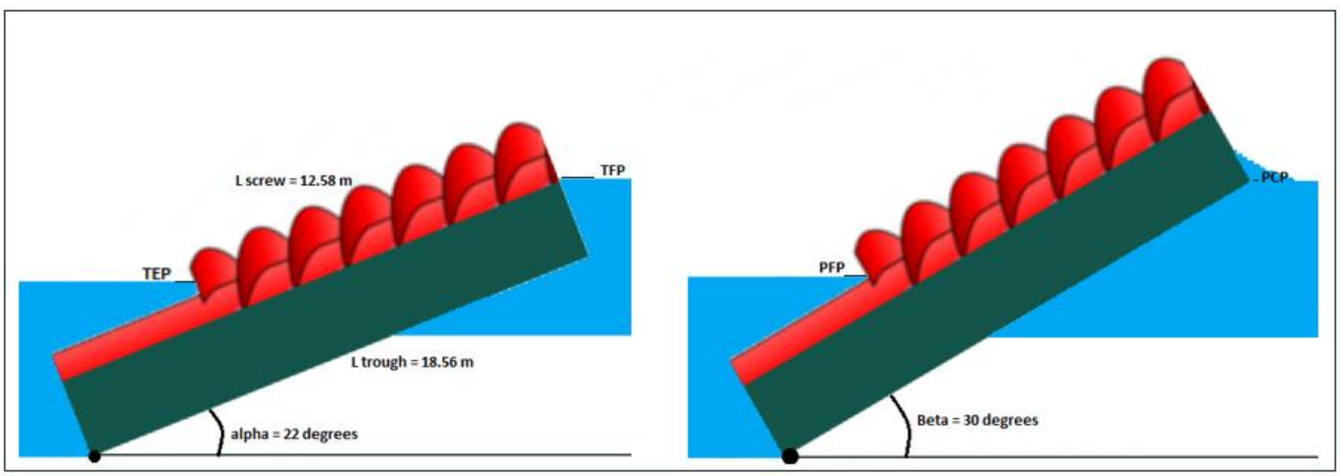


Figure 46: Configuration 4. Turbine mode (left) and pumping mode (wright)

This configuration scores well on angles of inclination, PCP, PFP and TFP. The main disadvantage is TEP which decreases turbine efficiency up to 20 % due to the submergence of the lower screw end. By performing a screw optimization using formula 6 from chapter 8 this decrease in efficiency was not solvable. The mechanical system to adjust the angle of inclination are assumed to be hydraulic pistons.

CONFIGURATION 5: FLOATING SCREW

The fifth configuration is shown in Figure 47. Basically, this is the same configuration as the fourth. The screw can rotate again at the hinge. By connecting air compartments at each side of the trough the angle of inclination can vary. This is done by pumping water in or out the air compartments. This concept is further clarified in appendix G.

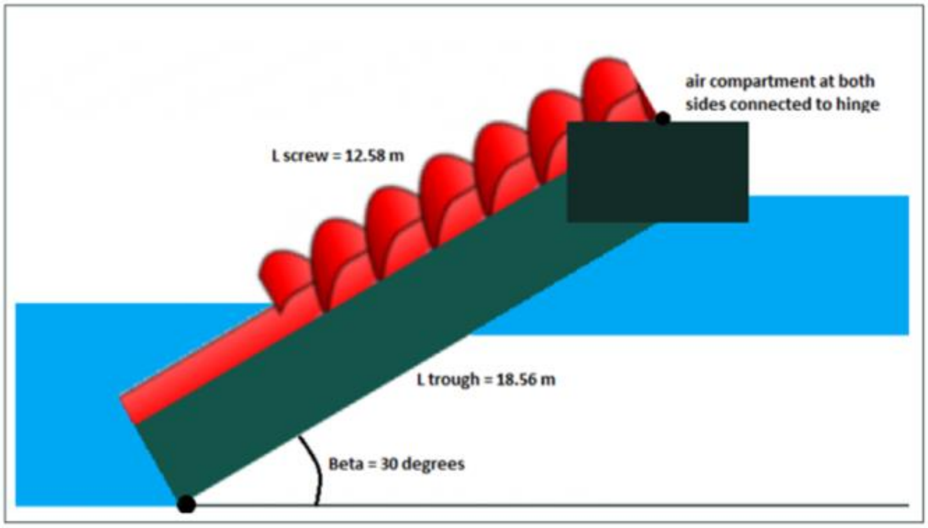


Figure 47: Floating screw with air compartment at each side

Configuration 5 is performing like configuration 4 in terms of achieving optimal angles of inclination and the positions of PFP, PCP's, TEP and TFP. The only difference is the method which is used for adjusting the angle of inclination. Using air compartments to adjust the angle of inclination is asking for a pump within these compartments for water filling and emptying. This might be complex to install and maintain and sensitive to failure.

CONFIGURATION 6: SCREW ADJUSTABLE TO DOWN- AND UPSTREAM WATERLEVELS

The six configuration is shown in Figure 48. This configuration is a further development of configuration four. The main difference is the hinge can be lifted up by a rotational mechanism at the downstream end of the trough. By doing so the screw can adjust to the optimal waterlevels downstream either at pumping or at turbining which eliminates the problem of efficiency losses due to submergence.

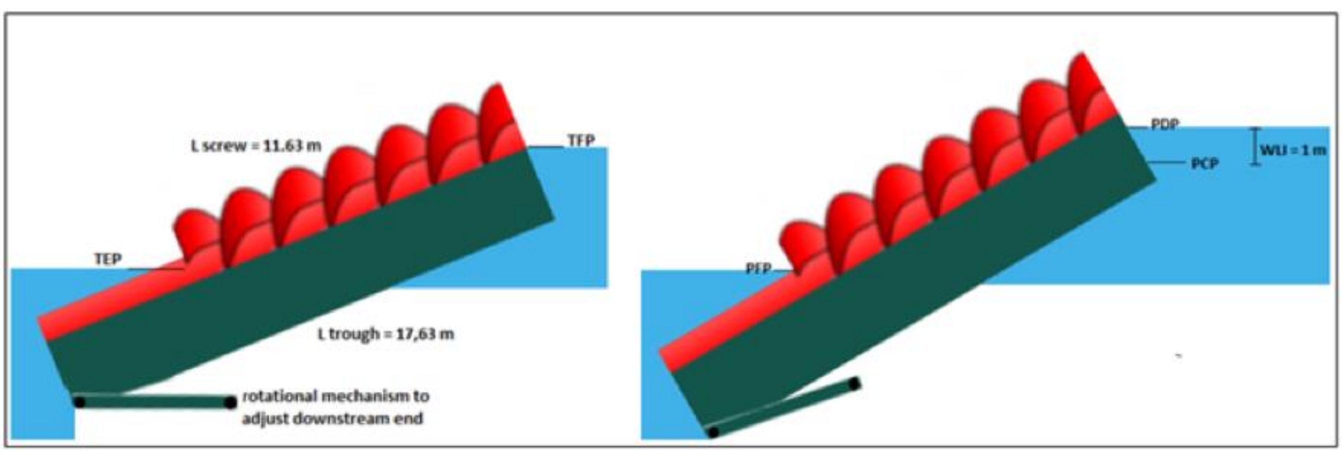


Figure 48: Configuration 6. Screw adjustable at waterlevels up- and downstream. Left: turbining. Right: pumping.

The capability of rotating implies the upstream and of the screw can be adjusted to fluctuating waterlevels in the Meuse, either at turbining or at pumping. In Figure 48 at the left one can observe the screw in turbine mode lifted up at the hinge to perform under the optimal TEP.

At the right in Figure 48 one can observe the screw in pumping mode. The hinge is lowered to obtain the optimal PFP. The screw is rotated to 30 °. Due to pumping the waterlevel upstream has increased (WLI = water level increase) by 1 meter up to PDP.

When turbining the benefit of the rotational mechanism becomes clear when observing Figure 49, which is showing the waterlevels at the Lith weir. The downstream waterlevel in constantly increasing for the days represented in FDC. This already starts at base river mode and would ultimately lead to a submerged lower screw end resulting in efficiency losses. This is avoided by the use of the rotational mechanism.

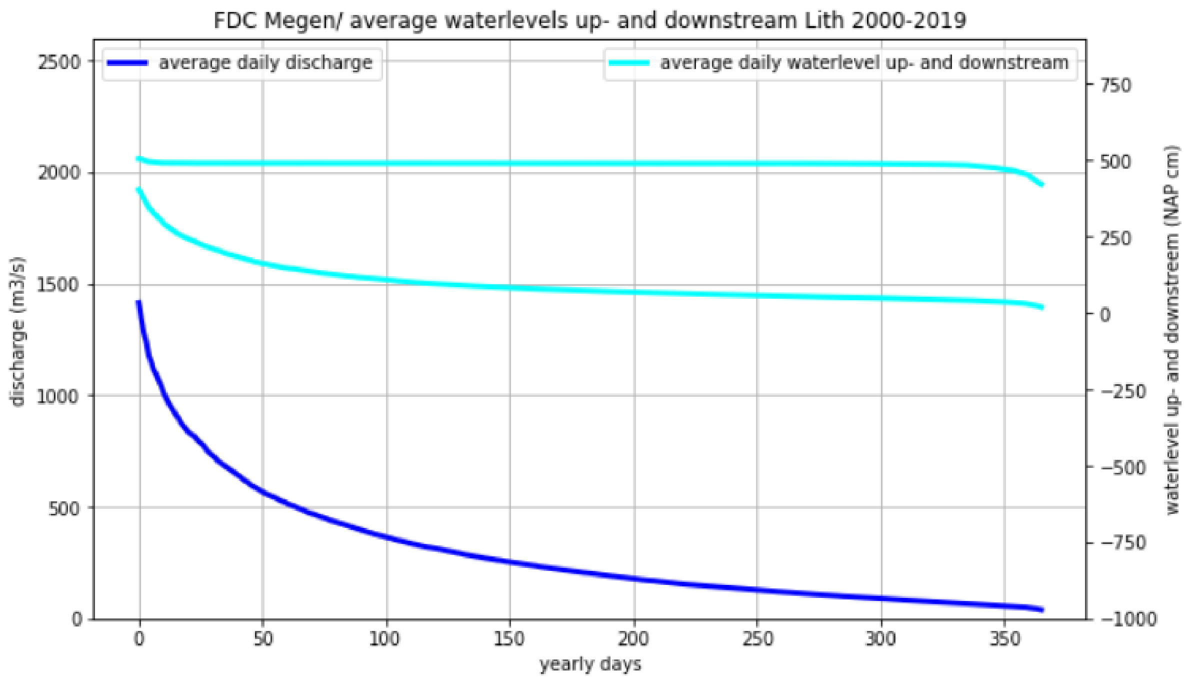


Figure 49: Waterlevels downstream Lith weir increasing throughout the FDC.

The six configuration scores well on PFP, PCP, TFP and TEP. Furthermore, it approaches the target angles of inclination for the pump and turbine.

9.3 VERIFICATION SCREW CONFIGURATIONS

The requirements for the screw configurations are listed in the third chapter. Briefly summarized these are:

- Target angle of inclination β 30 ° when pumping.
- Chute point screw (PCP): located at the upstream water level.
- Pump delivery point: at 0.3 times the outer diameter D above pump chute point.
- Pump filling point (PFP): should be located just above the shaft of the screw at the downstream water level.
- Target angle of inclination α of 22 ° when turbining.
- Middlepoint of the upper side of the screw (TFP) should be located at the upstream water level.
- Middlepoint of the lower side screw (TEP) needs to be optimized by the screw geometry.

In Table 15 the results on these verifications are summarized. Elaboration on the verification on these requirements has taken place at the subparagraph of each configuration.

Configurations:	Target angle at turbining:	Target angle at pumping:	Operating at turbine filling point	Operating at turbine exit point:	Operating at pump filling point:	Operating at pump chute point:
Configuration 1	negative	positive	positive	negative	positive	positive
Configuration 2	positive	negative	positive	positive	negative	positive
Configuration 3	negative	positive	positive	negative	positive	positive
Configuration 4	positive	positive	positive	negative	positive	positive
Configuration 5	positive	positive	positive	negative	positive	positive
Configuration 6	positive	positive	positive	positive	positive	positive

Table 15: Summary results on verification on different screw configurations.

Configuration 6 is the only configuration which scores positive on every requirement. The main advantage of this configuration is it can be adjusted to the waterlevels up- and downstream at either pumping or turbining. By doing so no efficiency losses due to submergence of the screw ends occurs. The hydraulic pistons are expected to use a moderate amount of space within the layout of a screw compartment of the PSP-plant.

The main disadvantage is the extended trough will need additional steel. However, as the six configuration scores positive on every requirement listed in Table 15 it will be selected for the conceptual design of the Sambeek PSP-plant.

9.4 CONCLUSIONS CHAPTER NINE

As the angle of inclination of a screw pump and - turbine differs an assessment of different screw configurations for the conceptual design of the PSP-plant has been carried out. For the verification the requirements and the boundary conditions on the design waterlevels at Sambeek have been used.

The starting points needed for the different screw configurations (and the conceptual design of the PSP-plant) are derived. Using a screw diameter of 5 meter will result in a shaft diameter of 2.25 meter. Furthermore, the target levels provided by RWS are used as design waterlevels up- and downstream.

After verification the most optimal configuration was the one which uses the target angles of inclination of both screw pump and - turbine (configuration 6). By using a rotational mechanism, the lower screw end can be adjusted to the downstream waterlevel either at turbining and at pumping, thereby eliminating efficiency losses due to submergence.

By rotating the complete trough and screw on a hinge, the screw can switch from turbining to pumping mode. The rotational capabilities result in the optimal positioning of TFP, TEP, PFP and PCP.

The main disadvantage of this configuration is it needs additional steel for the construction of the extended trough. Furthermore, the mechanical system needed for the rotations needs additional maintenance.

10. CONCEPTUAL DESIGN PSP-PLANT SAMBEEK

In this chapter the conceptual design of a PSP-plant at the Sambeek weir will be presented. This will be design loop three. The conceptual design will be compiled using the design loops on turbine selection and screw configurations.

The boundary conditions on available discharge, storage volume and waterlevels up- and downstream are taken into account. The available discharge will be used to determine the number of screws.

10.1 STARTING POINTS CONCEPTUAL DESIGN

As this thesis contains a conceptual design, assumptions based on rules of thumbs are used for the thickness of walls and slabs. Furthermore, assumptions have been used for components like gearbox and generator, or the pitch of the screw.

In the previous chapter screw configuration 6 is selected for the conceptual design. Using the theory of chapter 8 an optimization of the screw geometry been carried out in Excel. The main results – in combination with the other starting points - are listed in Table 16.

Description	Value
Outer diameter screw	5 meter
Diameter shaft	2.25 meter
Gross head	3,15 meter
Available discharge	300 m^3/s
Number of screws	20
Number of blades	4
Pitch	5 meter
Length screw	11,63 meter
Length trough	17,63 meter
Length upper side trough extension	10 meter
Angle of inclination α screw turbine	20 °
Turbine capacity	15 m^3/s
Turbine filling point (TFP)	NAP 11,1 meter
Turbine exit point (TEP)	NAP 7,95 meter
Screw submergence	I = 0.61
Rotational speed turbine	target is 17.1 rpm
Angle of inclination β screw pump	30 °
Pump capacity	11.6 m^3/s
Pump filling point (PFP)	above shaft
Pump chute point (PCP)	NAP 11,1 meter
Pump delivery point (PDP)	NAP 12.1 meter
Rotational speed pump	fixed at 17.1 rpm

Table 16: design starting points for conceptual design

By reducing the length of the screw with respect to length used in the configurations, the lower end becomes less submerged thereby positioning TEP at the optimal level, according to the optimization of the screw configuration. This implies the screw will be submerged for 61 % based on formula 7. By increasing the number of blades to 4 the optimal level $H_{out,opt}$ increases. By doing so the target angles for pumping and turbining can be approached.

The turbine angle will become 20 °. According to chapter 8 a decisive consensus on the optimal turbine angle of inclination is missing in the literature. The range varies between 15 ° - 25 ° with the majority of sources indicating an angle 22 °. As a turbine angle of 20 ° falls within the range it is considered to be acceptable to use at the Sambeek weir.

The lower edge of the upper end of the screw end is located 0.5 meter below PCP when pumping. PDP point is located 1 meter above PCP. This implies the screw angle will stay on 30 ° until the waterlevel increases above PDP. In that situation the screw needs to be rotated to a higher angle of inclination.

The calculations and elaborations on starting point and screw optimization are presented in appendix H.

10.2 THREE-DIMENSIONAL IMPRESSIONS CONCEPTUAL DESIGN

Two designs of a screw compartment based on configuration 4 have been compiled. These designs are shown in appendix H. After verification on the requirements one design has been selected and worked out into a PSP-plant. This compartment design and the final PSP-plant will be presented in 3D in this paragraph and the ones to follow.

10.2.1 COMPARTMENT DESIGN IN TURBINE MODE

Figure 50 shows a side profile of the compartment design without the waterlevels up- and downstream for illustration purposes. One can notice hydraulic pistons at the right side, with are needed to change the angle of inclination, which is 20 ° in this figure. At the downstream side one can observe the rotational mechanism needed to lift the lower end of the screw to avoid submergence and efficiency losses.

In Figure 50 the lower screw end is lifted up by 1.2 meter. However, these cylinders can be extended up to 3.6 meter in order to avoid submergence at higher waterlevels downstream, either due to stored water or to river median/peak mode. A graphical illustration of the cylinders in shown in appendix H.

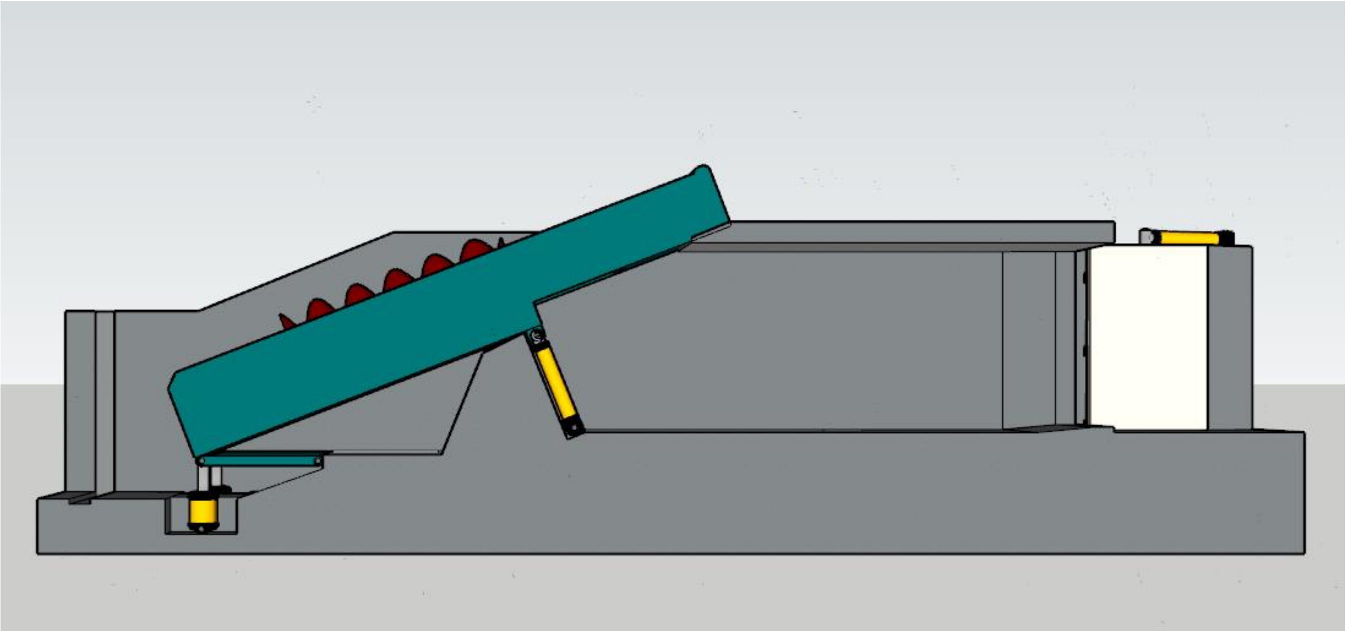


Figure 50: side view compartment design in turbine mode

The length of the design will be 60 meters. The height from bottom to the top of the slab is 15.7 meter. In appendix H an overview of the dimensions is presented.

The hydraulic pistons are placed below the water level. When consulting the company ABS Hydraulic Cylinders Nautical Solutions ("Offshore industrie", 2020) it is learned hydraulic pistons are used in off shore projects. Furthermore, (Wefer et al, 1997) indicates hydraulic cylinders are applied in devices used for deep sea ocean drilling purposes. This implies hydraulic pistons are suitable to apply under the waterlevel. The method to avoid corrosion (cathodic protection) will be elaborated on in appendix H.

Appendix H on the conceptual design contains additional figures on the conceptual design. Amongst others one can observe the hinges and their connection to the concrete wall, or close-up figures of the single leaf door.

EXTENSION TROUGH UPPER SIDE

A picture of the trough is shown in Figure 51. One can view the 5-meter diameter screw, gearbox and generator inside of it.

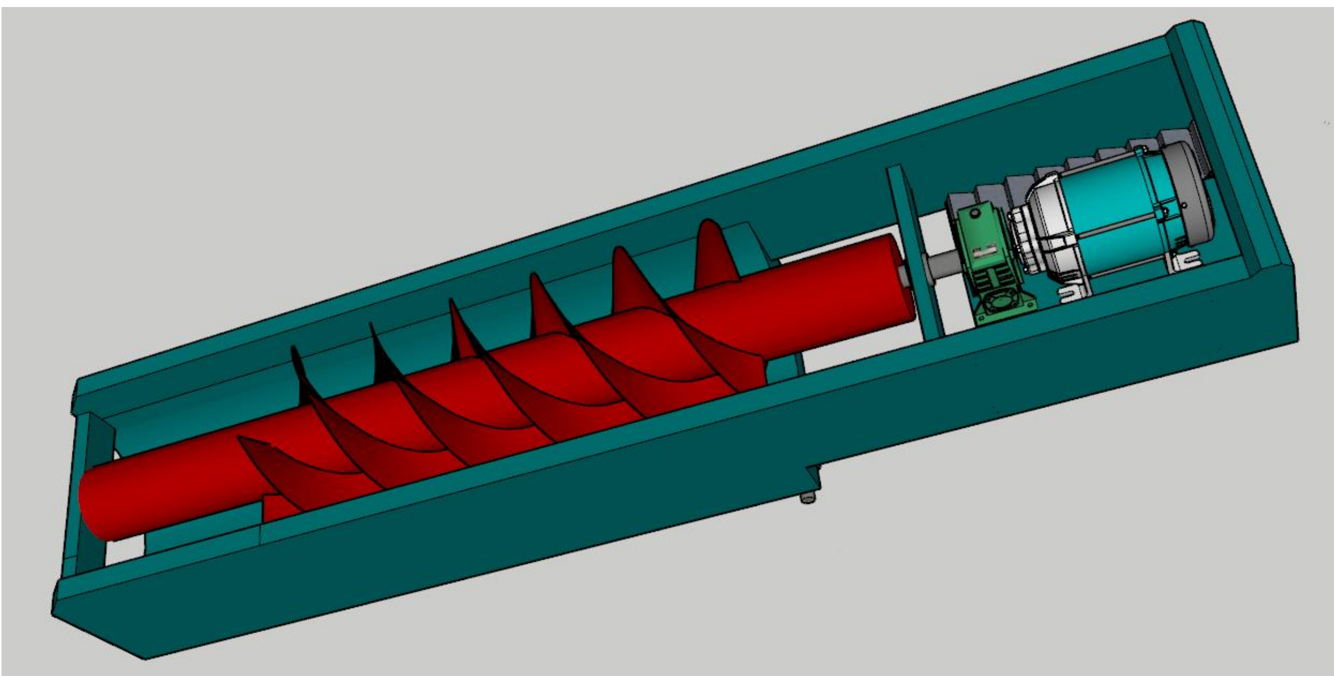


Figure 51: trough, screw, gearbox and generator

The main trough hosting the screw has been extended to 17.63 meter. The total length of the trough will be 27.7 meter, as it is also extended at the upper side in order to host the gearbox and generator. It is needed to host these devices as the complete unit needs to be able to follow the angle of inclination.

A design using a separate unit for gearbox and generator (using a cardan shaft and extensible drive shaft) is presented in appendix H. However, this design has not been selected after verification.

GENERATOR

When using a direct drive generator - which implies no gearbox - the size of the generator is determined by the torque. If it is operating at low rotational speed a larger torque is needed to obtain a certain power. The larger the torque, the larger the volume that is needed for the generator (Zaaijer, 2020).

For this reason, wind towers - which usually operate around 15 rpm - often install a gearbox to step up the rotational speed to 1500 rpm (Zaaijer, 2020). If not using a gearbox the dimensions of the generator can reach a diameter up to a 10 meter.

GEARBOX

The 5 diameter Archimedean screws in the PSP-plant will operate around 17 - 18 rpm. This is the first reason to use a gearbox. By using this gearbox, the amount of volume it will need will be decreased making it fitting in the trough.

The second reason to install a generator is the need for the screw to operate as a pump. The resisting torque (or moment) of the screw needs to be over won by the generator in order to start rotating and as a result pumping. Without going into detail, it is expected a gearbox with several stages (and gears) is needed for this purpose leading to efficiency losses. For the final pump-efficiency (75 %) manufacturing information presented in paragraph 8.2 is used.

Gearbox and generator are shown in Figure 51. As mentioned in the introduction of this chapter assumptions have been used. The gearbox has proportions of roughly 2 x 2 meter. The diameter of the generator is roughly 2.3 meter.

DESIGN IN TURBINE MODE WITH WATERLEVELS

When turbining the regular gross head at Sambeek is 3.15 meter. In Figure 52 one can observe the compartment design with waterlevels included. The waterdepth at the up- and downstream side of the screw is 7.55 meter, in order to obtain comparable flow velocities at each side.

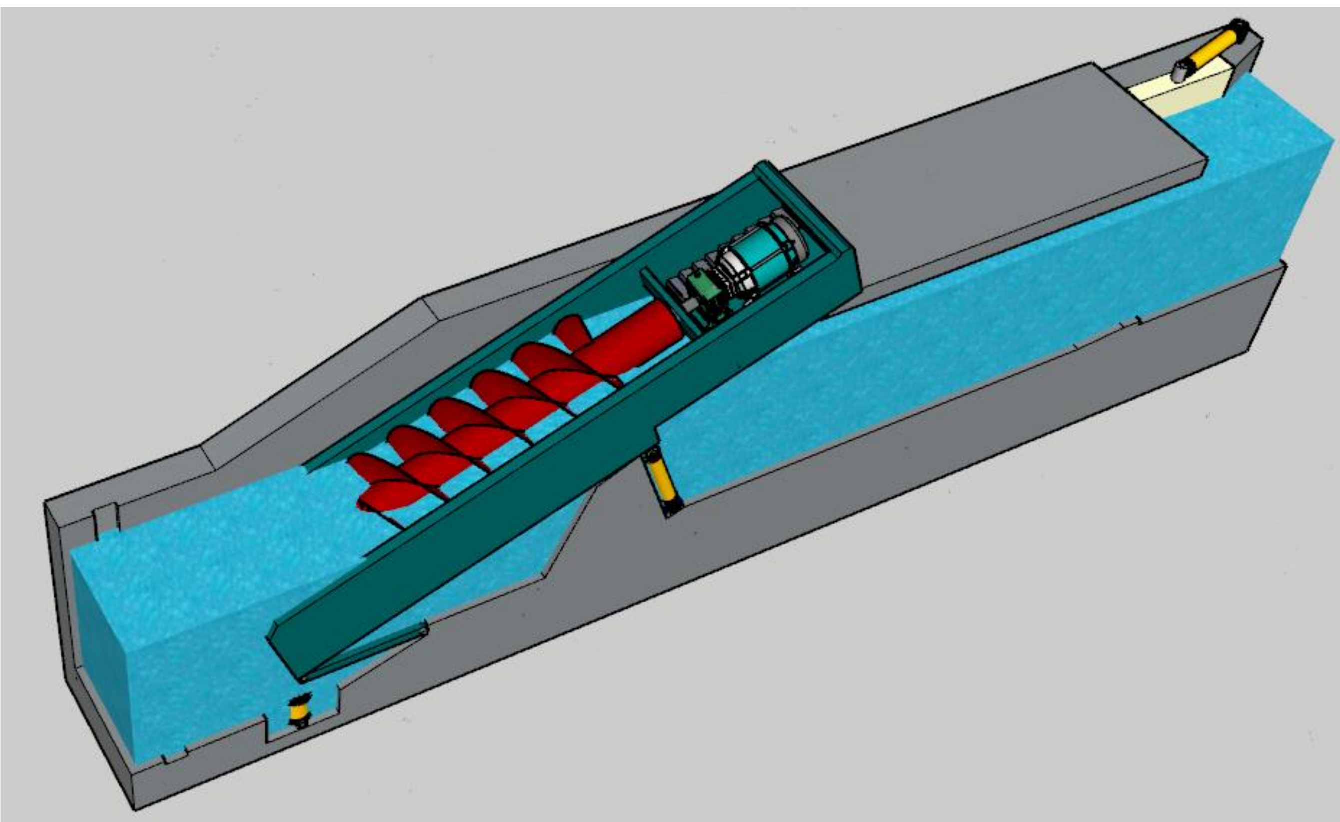


Figure 52: Design when turbining

SINGLE LEAF DOOR AND GATE

The closing measure upstream (the white single leaf door) is needed to close of the compartment in case of a calamity. The upper end of the screw is located halfway the upstream water level. With a diameter of 5 meter this implies almost half of the screw is located below the upstream water level. When the hydraulic pistons fail the trough cannot be rotated to maneuver the upper end of the screw completely above the water level. Water can be lost downstream in this case (although expected to be minor). One reason to design this closing measure is to avoid this scenario.

A second reason to use a closing measure upstream is for maintenance purposes. By closing of the compartment work men are able to perform maintenance on for instance a hydraulic piston. In case maintenance needs to be carried out downstream (on for instance a hinge) this side can be closed off from the water as well by lifting in a temporal closing measure using a mobile crane or a crane vessel. In Figure 53 one can observe the compartment closed at the up- and downstream side for maintenance purposes.

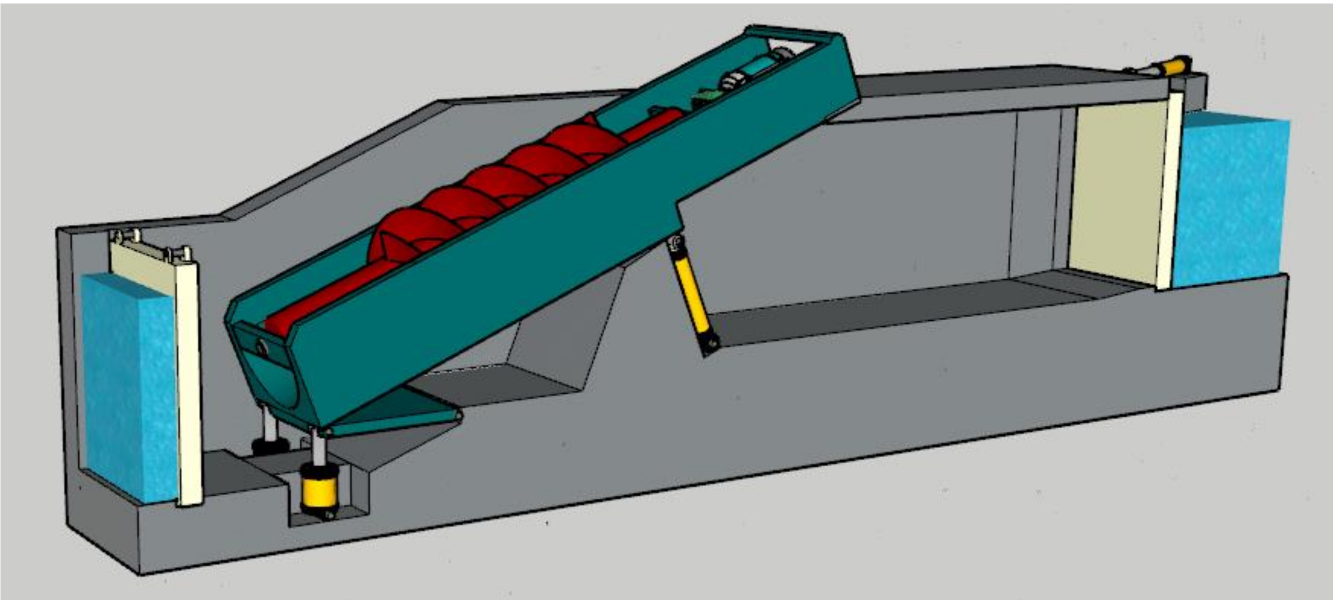


Figure 53: Compartment closed off from the water at down- and upstream side

10.2.2 COMPARTMENT DESIGN IN PUMPING MODE

The design is capable of adjusting the angle of inclination for the screw to be able to function as a pump. By increasing this angle to 30 ° the lower edge of the upper screw end will be located 0.5 meter below PCP.

In Figure 54 one can view the compartment design at pumping mode (without waterlevels for illustration purposes). The hydraulic pistons have been extended and the trough is rotated on its hinge at the downstream end. As one can observe, this downstream end has been lowered to obtain the optimal PFP of the screw.

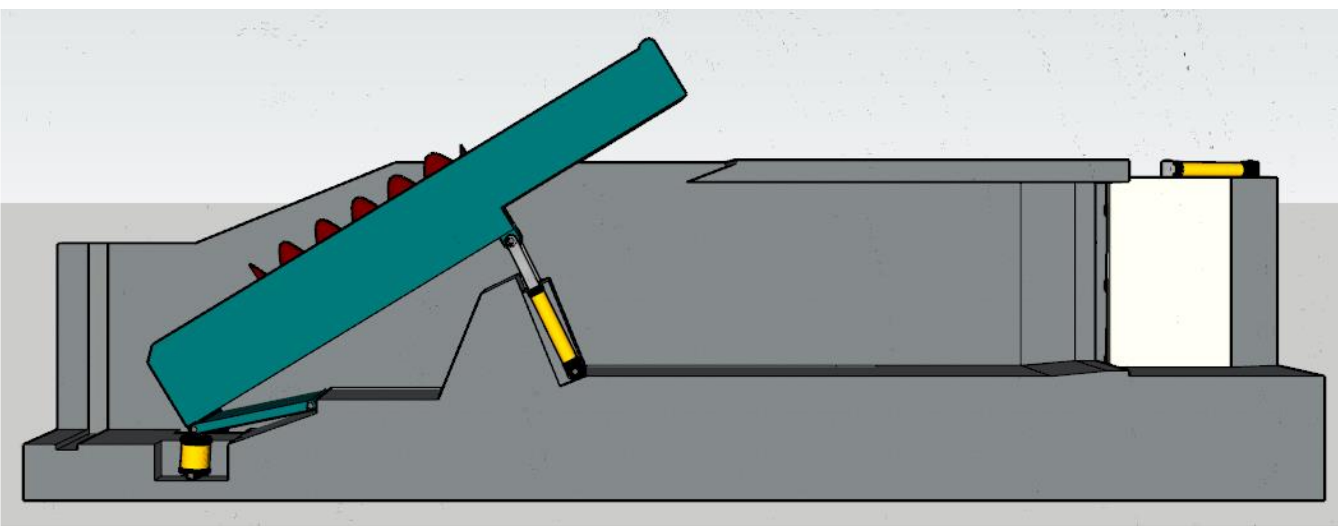


Figure 54: Pump angle increased to 30 degrees, downstream side lowered to obtain PFP.

PUMPING MODE WITH WATERLEVELS

In Figure 55 one can view the design at pumping mode with the waterlevels up- and downstream included. The waterlevel upstream had increased by 1 meter up to PDP.

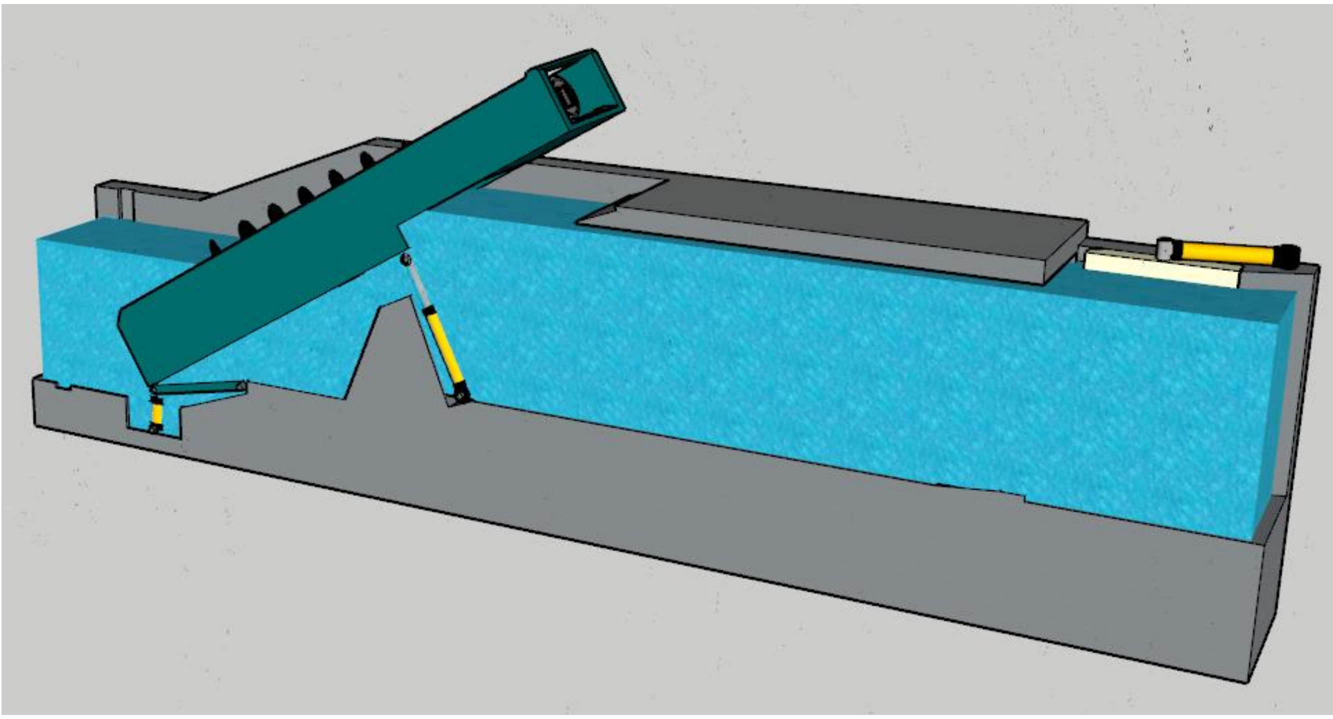


Figure 55: Design in pumping mode, upstream waterlevel at PDP.

When PDP is exceeded the screw needs to be rotated to a higher pump angle. The pistons can be extended to obtain a maximal angle of inclination of 34 °.

The stresses on for instance the hinge are not calculated, as this is a conceptual design as elaborated on in the methodology and not a structural design. The objective of this report is to study if the full hydropower- and energy storage potential of the Meuse cascade can be utilized using the numerical Meuse model for which is assumed conceptual designs like the Sambeek PSP-plant are present at the weirs in the cascade.

10.2.3 DESIGN UNDER PEAK RIVER MODE CONDITIONS

At peak river mode the waterlevels up- and downstream increase. The waterlevel increase happens mainly at the downstream side of a weir complex. However, ultimately the waterlevels down- and upstream will increase. The single highest recorded water level at Sambeek is NAP 1397 cm within the series used in chapter 5.

When increasing the angle of inclination to 34 degrees the gearbox and generator stay above peak flood waterlevel, even at NAP 1397 cm. This will eliminate to need to overhaul or even replace these components after a flood wave. The design under these peak mode conditions is shown in Figure 56.

During river flood waves water is primarily processed by the Stoney weirs which are completely raised, and by the opening of the Poirée weirs which are removed, as explained in chapter 2. As the turbines are rotated such the generator and gearbox stay dry no water will flow through the turbines. The full flood flow will pass the weirs and will flow over the locks, as shown in Figure 18 in chapter 5.

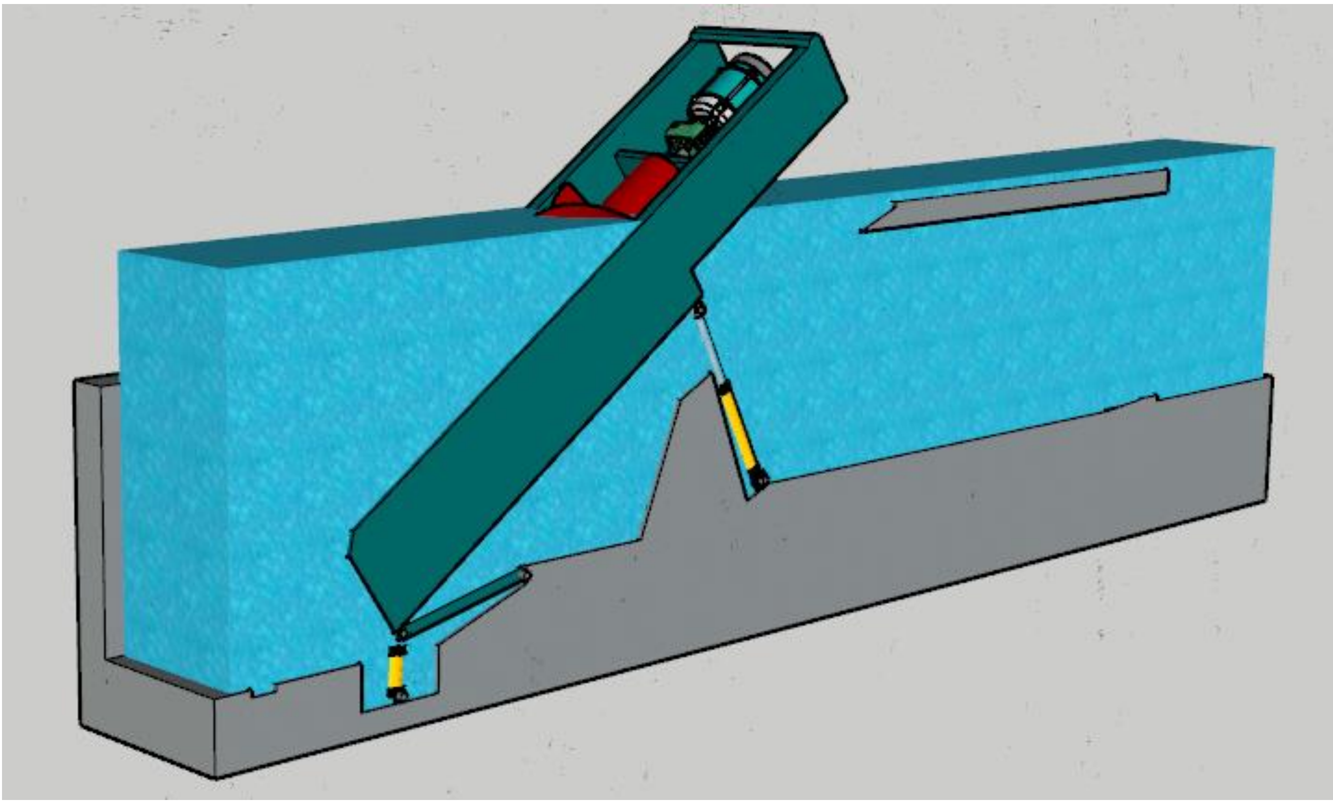


Figure **56: Compartment design under peak river mode conditions at NAP 1388 cm**

10.2.4 PSP-PLANT TURBINING AT FULL CAPACITY

When using 20 compartments parallel to each other finally the three-dimensional design of the Sambeek PSP-plant can be presented. One can view an impression in Figure 57. The concrete wall between each compartment has a thickness of 1.5 meter. The slab at the top of the PSP-plant can function as a platform for a mobile crane needed for maintenance or installation purposes.

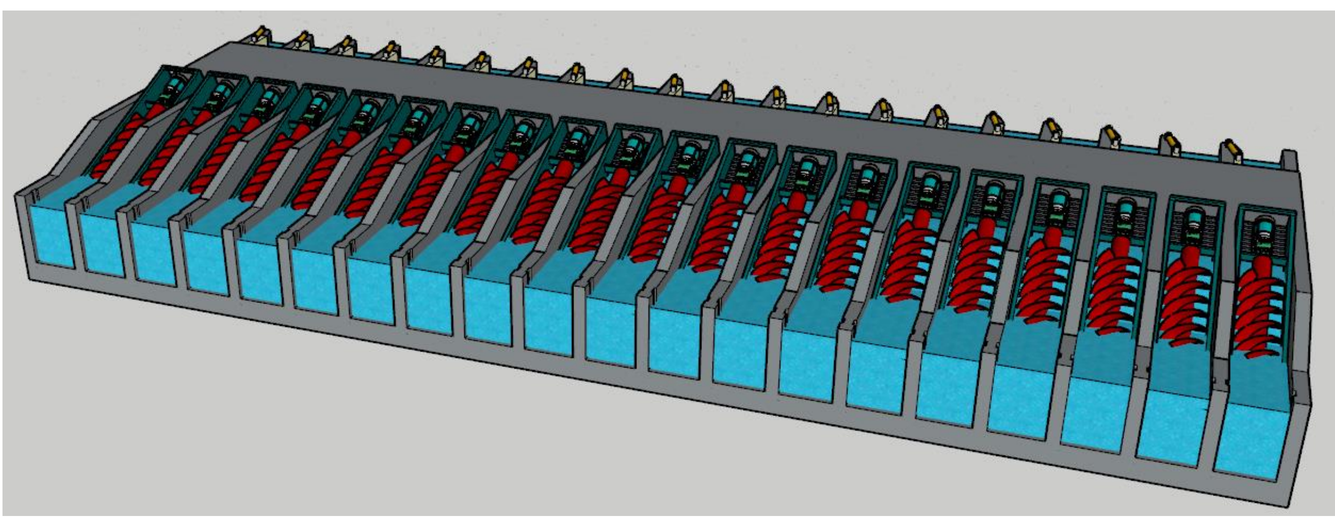


Figure 57: PSP-plant turbining at full capacity using 20 screws

A top view of the plant is shown in appendix H. The total length is 151,5 meters. The total width is 60 meters. What this implies for the implementation of the PSP-plant in the environment of the Sambeek weir will be elaborated on in paragraph 10.3.

10.2.5 PSP-PLANT PUMPING AT FULL CAPACITY

A three-dimensional impression of the PSP-plant in full pumping mode is shown in Figure 58. Notice the rotation of the trough and screw.

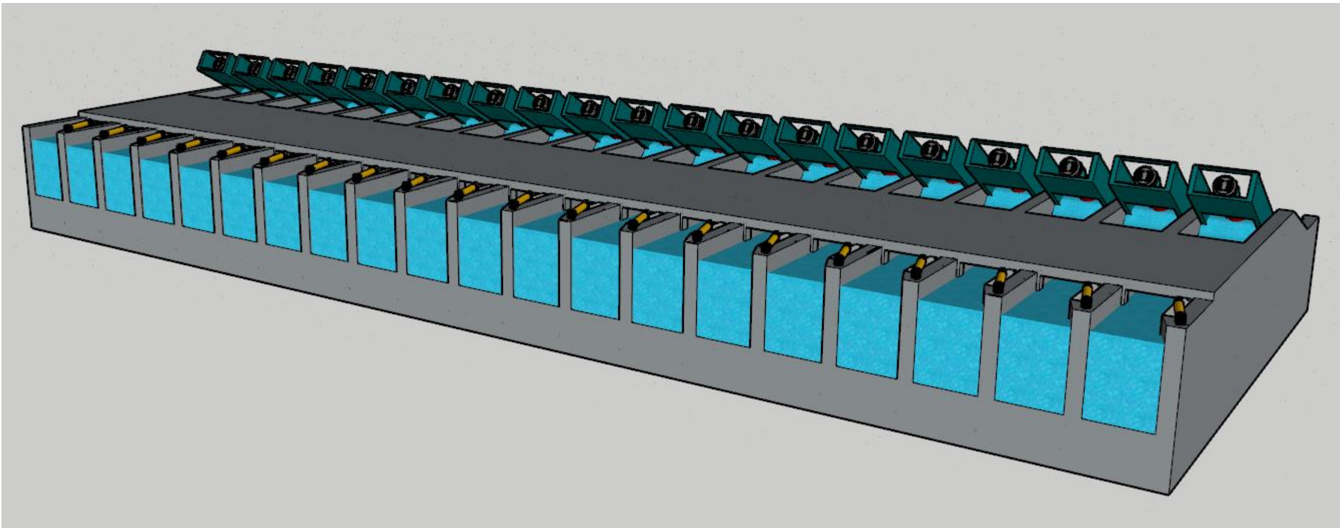


Figure 58: PSP-plant in full pumping mode

ADJUSTING TO DESIGN DISCHARGE

When hydropowering the discharge might be lower than the available design discharge of 300 m^3/s. The PSP-plant can be adjusted to this lower discharge in two ways. The first way is to increase the angle of inclination of several screws, thereby setting them in pumping position without the application of pumping. This is shown in Figure 59 in which 12 units are turbining and eight units are not. With respect to these eight units one can notice the screw trough edge located just above the upstream water level thereby blocking the flow.

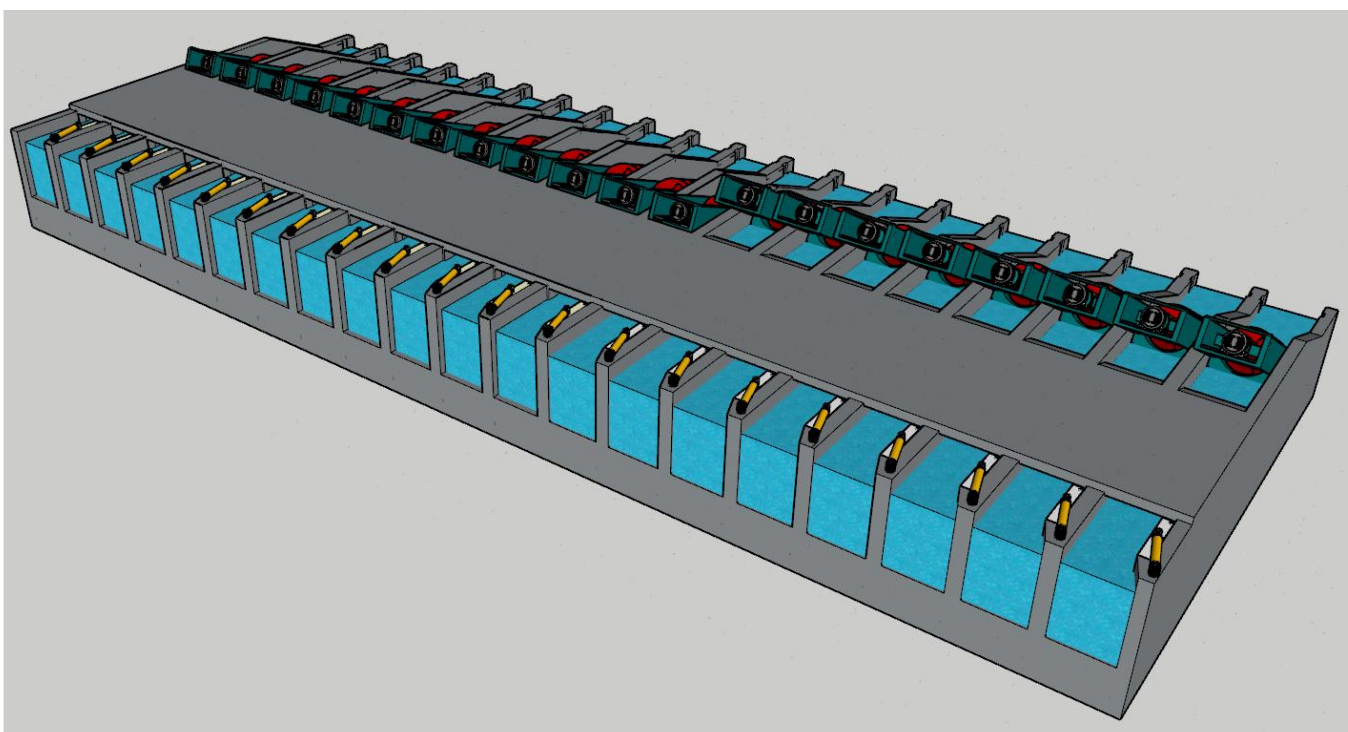


Figure 59: 12 screws powering, 8 screws rotated out of function

Another way to adjust the PSP-plant to the available discharge is by closing one or more single leaf doors. This is shown in appendix Figure 141, in which again 12 screws are actually powering, while 8 screws are closed off from the water flow.

10.3 CURRENT- AND FUTURE OVERVIEW SAMBEEK WEIR COMPLEX

As mentioned before the PSP-plant has a length of 151.5 meter, and a width of 60 meter. This is huge. In this paragraph the implications for constructing the PSP-plant at the weir- and lock complex of Sambeek will be presented. The current- and possible future situation will be compared.

CURRENT OVERVIEW SAMBEEK

The water level at Sambeek is controlled by Poirée- and Stoney weirs, as elaborated on in chapter 2. In this chapter it was mentioned the Poirée-weir consists of 13 gates of 4,85 meter between yokes, which can be removed in periods of peak discharge. The Stoney weir consists of two discharge control gates placed in openings of 17-meter width each. In Figure 60 one can observe an overview of the current Sambeek complex including these Poirée- and Stoney weirs.

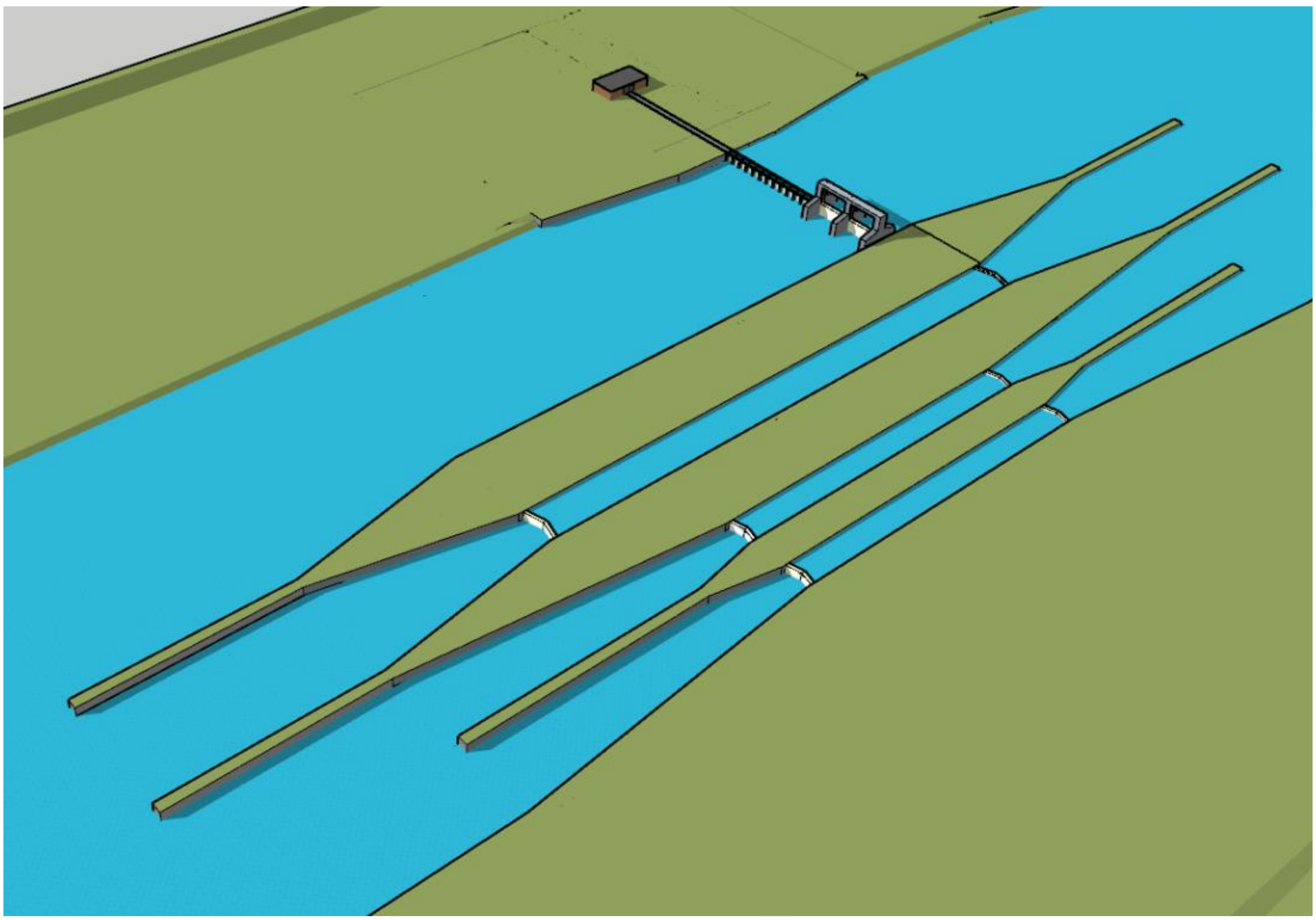


Figure 60: Current overview Sambeek with Poirée- and Stoney weirs.

When the Poirée weirs have to be removed in a flooding event, the gates are lifted up one-by-one using a crane which can roll over the rails laying on top of the Poirée yoke-structure. These rails are finally removed in parts by the crane as well. The rail ends in the building on land. This building is hosting the crane in periods of base- and median river mode. A close-up view of the weir and rail structure is shown in Figure 61.

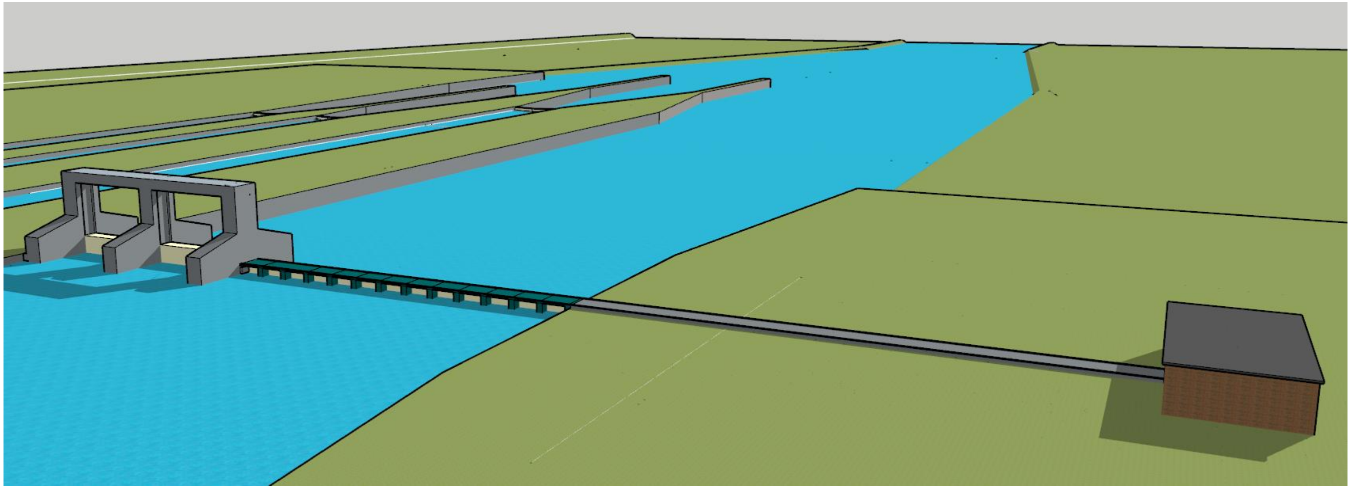


Figure 61: Close up view rail structure needed to remove Poirée weirs

As elaborated on in the chapter on the weir- and lock complexes in the Meuse cascade, the Poirée- and Stoney weirs are reaching the end of their technical life time and have to be replaced in the coming decades. According to Kortlever (interview, 2020 March 2) one option for RWS is to replace the weirs by radial gates, also known as sector gates.

The replacement issue might create an opportunity for a redesign of the Sambeek weir with a PSP-plant included. When the Poirée weirs are replaced the area next to the weirs does not have a function anymore (W.Kortlever, interview, 2020 March 2). This implies it might be excavated and be used for the construction of a PSP-plant.

FUTURE OVERVIEW SAMBEEK: RADIAL GATES AND PSP-PLANT

A future overview of Sambeek is shown in Figure 62. It is hosting a radial gate(s) weir next to the PSP-plant.

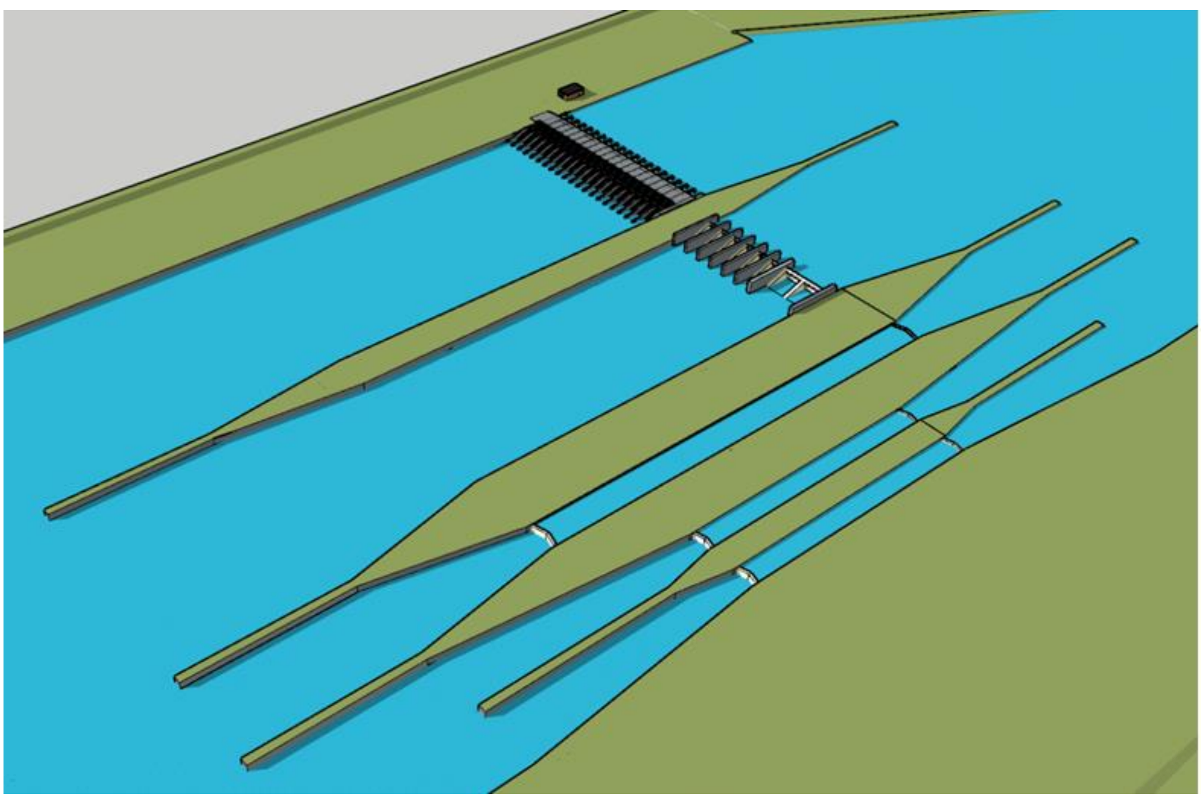


Figure 62: Future overview Sambeek with radial gate weir (right) and PSP-plant (left)

Lock- and weir complex Belfeld is designed in a similar way as lock- and weir complex Sambeek, as explained in chapter 2. Both complexes are hosting Poirée- and Stoney weirs. Frijns (2019) studied the replacement of the weirs at Belfeld. Frijns (2019) proposes to replace the Belfeld weir by an adaptive weir. This weir consists of six radial gates of 10.3 meter. Furthermore, the weir has a 35.4-meter-wide submersible radial gate, which is used for water level regulation and the passage of ships at flooding events.

This weir is incorporated in the future overview of Sambeek shown in Figure 63. In appendix H can find additional figures considering the current- and future overviews.

In the chapter on storage volumes it is described the Meuse river is bounded by summer dikes. At peak river mode the floodplains next to this summer dikes are used to store water. These valleys are bounded by winter dikes. In the Sambeek region these floodplains are approximately more than 300 meter wide. This implies a PSP-plant will not interfere with the winter dikes, as it is 151.5 meter wide.

In Figure 63 one can observe the weir and PSP-plant from a closer point of view. At the upper side one can view a building. This building can host electrical equipment needed to deliver the electricity generated by hydropower to the grid network. Furthermore, some spare parts of the PSP-plant can be stalled in this building.

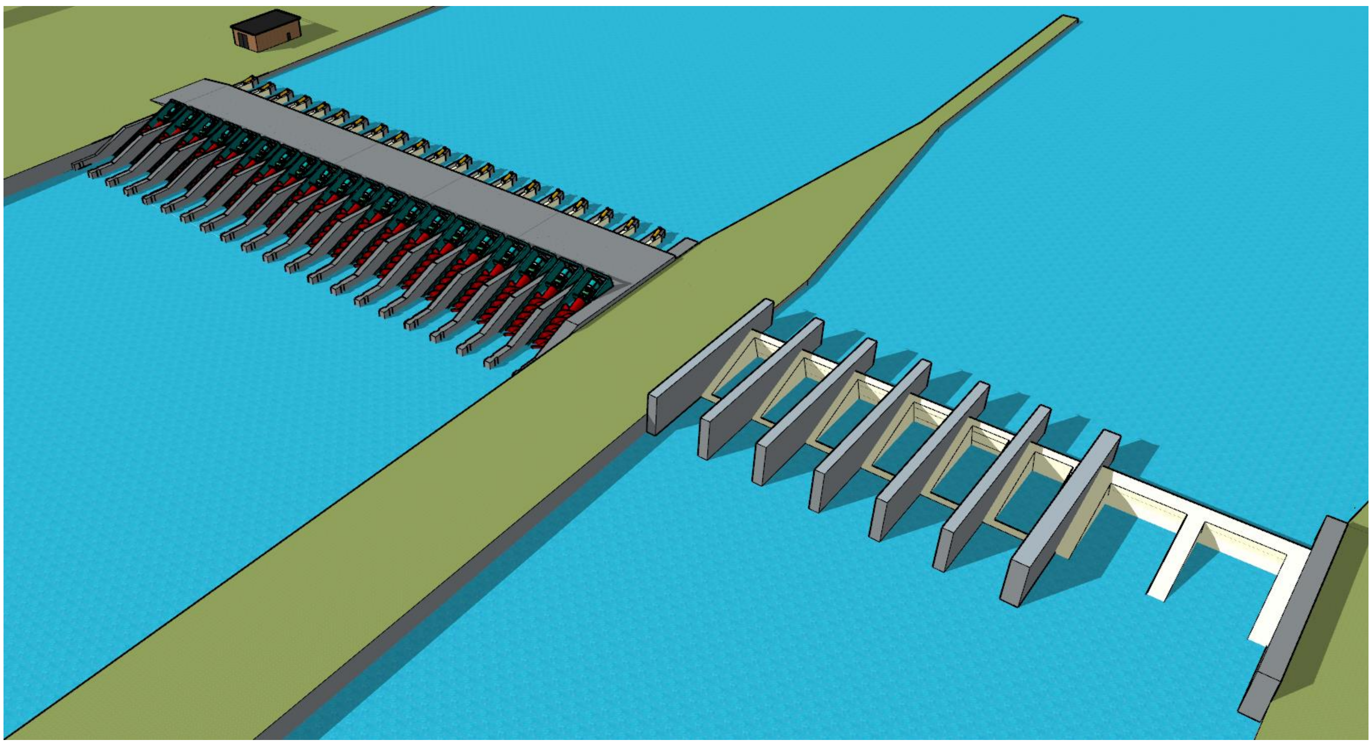


Figure 63: PSP-plant and weir with radial gates from a closer point of view

MAINTENANCE AND INSTALLATION

The PSP-plant is designed in such a way the top slab can be used as a platform for a mobile crane. The width of this slab is 18.2 meter. The slab is connected to the river floodplain by an oblique entrance made of concrete. The mobile crane can be used to install or lift components like the gearbox or generator.

In front of the plant a lifting vessel can be maneuvered to install or replace a screw, possibly in cooperation with the mobile crane. When the downstream side of a compartment needs to be closed of the vessel or crane can lift the temporal gate into position. In Figure 64 one can view a lifting crane on top of the slab and a vessel in front of the PSP-plant.

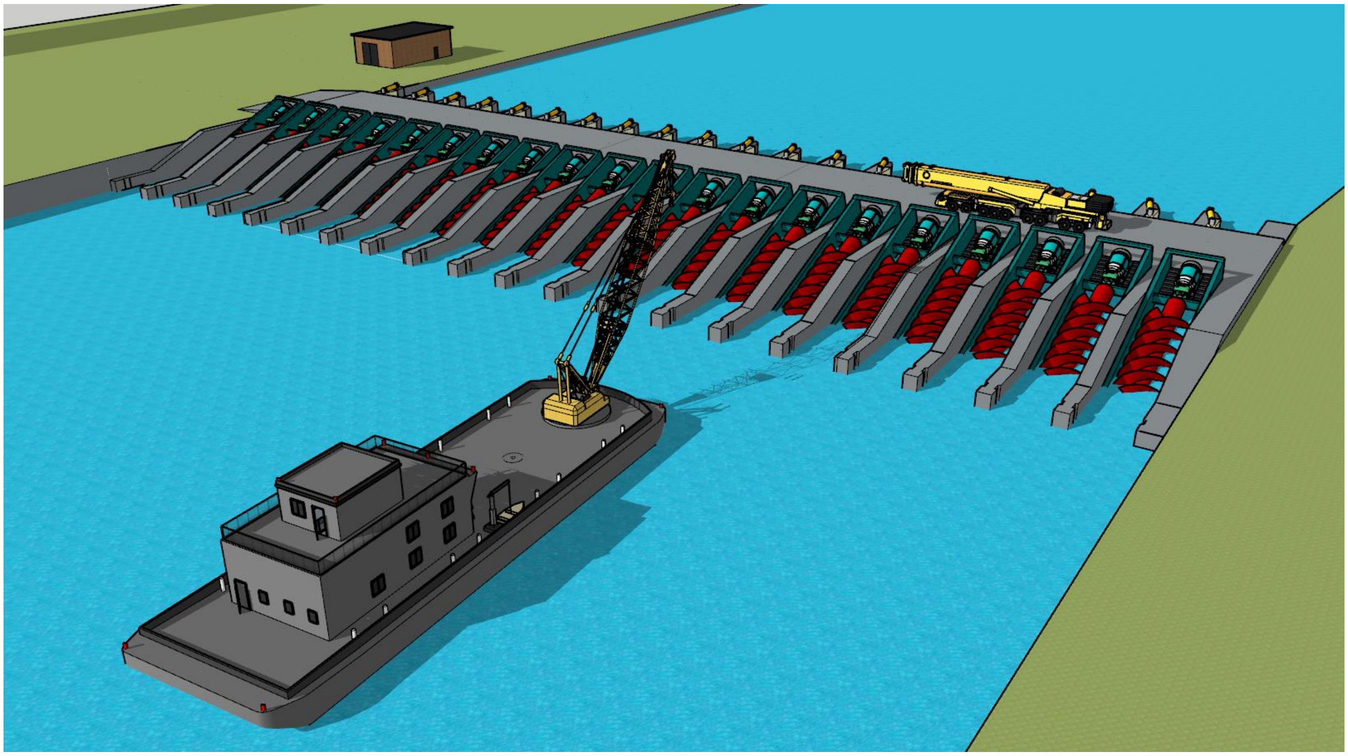


Figure 64: Mobile crane and lifting vessel

10.4 UTILIZING HYDROPOWER- AND STORAGE POTENTIAL MEUSE CASCADE

Based on manufacturer information on screw turbines the minimum head difference needed for the installation of a 5-meter diameter screw is 2.5 meter ("Archimedean screw hydro", 2020).

According to Table 1 the minimum head in the Meuse cascade is 2.5 meter at the Grave weir. As the conceptual design can be scaled by extending of decreasing the main trough the PSP-plant can be constructed at every weir in the Meuse cascade. The scaling results per weir are shown in appendix H in Table 19.

According to the theory presented in chapter 7 the fish mortality using Archimedean screws is expected to be low. Therefore, the cumulative fish mortality when equipping all the weirs in the Meuse with the conceptual PSP-plant design is expected to be less than 10 %.

Based on this information one can assume the hydropower- and energy storage potential of the Meuse cascade can be utilized within Dutch environmental regulations using the conceptual design of the PSP-plant.

However, the number of screws per PSP-plant has been determined using the 100-day design discharge of the FDC. For the Sambeek conceptual design this resulted in 20 screws. In chapter 11 it will become clear more pump-capacity – and therefore more screws – is needed in order to utilize the full energy storage potential of the Meuse cascade. For this purpose at Sambeek 36 screws are needed.

In chapter 11 it will be assumed the cascade is equipped with similar PSP-plants at every weir, in order to be able to assess the Meuse on its hydropower- and energy storage potential as described in the objective of this report.

10.5 VERIFICATION FUNCTIONAL DESIGN

The requirements on the PSP-plant are shown in the third chapter. The main requirements are briefly summarized:

- The PSP-plant should be able to host the number of selected screw turbines.
- The plant should be capable of hydropower generation in the main operational process: energy mode.
- The plant must be capable of pumping in the second operational process: storage mode.
- Components - like generator, hydraulic pistons, singe leaf door, screw, gearbox - must be installable and maintainable.
- Therefore, a mobile crane or crane vessel needs to be maneuverable into position.
- For maintenance purposes - and calamities - closure measures are needed to close of plant compartments.
- In peak river mode no damage to the electrical components - like generator - may occur.
- The PSP-plant should not reduce the current discharge capacity of the weirs by interfering with them.
- The structure should be 'robust' and sustainable and the thickness of slabs and walls needs to be estimated using relevant rules of thumbs.
- The PSP-plant should be constructable at every weir in the Meuse cascade.

Based on the theory presented in this chapter it can be concluded the PSP-plant is verified positively on each point in the list above. (Theory on the rules of thumbs on slabs and wall is presented in appendix H).

10.6 CONCLUSIONS CHAPTER TEN

In chapter 10 the conceptual design of the PSP-plant in Sambeek is presented. The plant consists of 20 screw turbines which are placed in compartments next to each other. By using 20 screws the plant is capable of processing the available design discharge of 300 m^3/s. The wall thickness separating these compartments is 1.5 meter. The whole PSP-plant had dimensions of:

- length: 151.5 meter
- width: 60 meter
- height: 15.7 meter

The angle of inclination of the screw can be adjusted using hydraulic pistons. By doing so the plant is able to operate in turbining- and pumping mode. Furthermore, by using a rotational mechanism at the downstream end of the screw it can be adjusted to the waterlevel thereby eliminating the efficiency loss due to submergence.

By closing of a compartment - either using a single leaf door or by rotating a screw out of position - the hydropower capacity can be adjusted to the discharge conditions in the river Meuse.

The PSP-plant has a concrete slab with a width of 18.2 meter on top. This slab can be used to host a mobile crane in order to install of replace components like a generator. Furthermore, a crane vessel can be manoeuvred into position at the up- and downstream side of the plant.

The PSP-plant might be implementable in the environment of Sambeek when the Poirée weir is replaced, as the area next to the weir - needed to stall the equipment for this weir - will lose it function and becomes available.

The design has been scaled according to the head differences at the other weirs in the Meuse cascade by extending or decreasing the main trough. As the cumulative fish mortality is expected to be lower than 10 % it can be assumed the hydropower- and storage potential of the Meuse cascade can be utilized within Dutch environmental regulations using the conceptual design of the PSP-plant at each weir.

11. NUMERICAL MEUSE MODEL

In chapter 11 all the information from the previous chapters comes together in the construction and application of the numerical Meuse model. This model will be used for an assessment of the Meuse cascade on its energy storage- and hydropower potential in order to meet the objective of this report. It will be assumed similar PSP-plants like the conceptual design for Sambeek are installed at the weirs in the cascade.

11.1 ESSENCE MODEL

The model is constructed in order to compute the hydro- and pumped-stored power production per FDC day per weir. By summing up the results the Annual Energy Yield (AEY) on hydropower and energy storage can be determined. The model is described mathematically by the following volume balance:

$$\Delta V = V_{in} - V_{out} = 0 \qquad \text{formula (11)}$$

During one FDC-day cycle of 24 hours the waterlevel at the end of energy mode should be equal to the waterlevel at the start of storage mode, which implies the change in water volume in the storage section will be zero. Using this principle will result in the possibility of storing energy surplus on a daily repetitive basis.

DEFAULT VALUES MODEL

The model uses 'default values' which are based on the size of the storage volumes and number of screws per facility. As it is a model these values can be adjusted. Storage volumes are assumed to have vertical walls for the calculations on filling and emptying. No specific stage-area relation is used. The duration of storage mode can be adjusted.

The screw diameters result in additional model default values. These diameters can be adjusted as well in the model. As explained in chapter 6, energy storage starts at the section Lith-Grave and ends at the section Roermond-Linne.

Weir:	Default number of screws:	Screw diameter (m):	Width upstream storage volume (m):	Height storage volume (m):	Size storage volume (m^3):
Borgharen	18	5	-	-	-
Linne	18	5	-	-	-
Roermond	30	4	150	1	1,950,000
Belfeld	30	4	150	1	2,550,000
Sambeek	20	5	160	1	7,360,000
Grave	20	5	150	1	4,050,000
Lith	22	5	150	1	3,750,000

Table 17: Default values model

EFFICIENCY AT TURBINING- AND PUMPING

In the model (see appendix I 'model assumption three') the benefit of the selected screw configuration becomes clear. As the screw can adjust to the optimal waterlevels up- and downstream (using the hydraulic pistons) the efficiencies of the turbining processes at the weirs are assumed to be 75 % constantly, based on the (manufacturing) information from chapter 8. Therefore, turbine efficiency will not vary with head in the model.

When the storage height of a section becomes higher than PDP, the pump angle can become higher than 30° thereby reducing the pump-efficiency. It was not possible to program the pump capacity in such a way it decreases at higher pump angles (see appendix I 'shortcoming model'). However, using the default values (max storage height 1 meter) will not result in a waterlevel above PDP. As a result, the pump angle will not exceed 30°. Furthermore, PFP will be at its optimal level constantly due to the hydraulic pistons. Therefore, the pump efficiency is set on 75 % as well.

11.2 STORAGE PROCESS MEUSE CASCADE

Energy is stored in the cascade in two ways, which will be translated into the model:

- Energy storage by river discharge during storage mode.
- Energy storage by the pumping of water at the PSP-plants.

ENERGY STORAGE BY THE RIVER

As indicated chapter 6 a relevant phenomenon in the storage process of the model is 'energy storage by the river'. When storage mode starts the discharge at the weirs is blocked in order to fill the storage volumes of the sections upstream by pumping. At the Linne weir no water will be pumped upstream as explained in chapter 6.

During storage mode discharge will flow downstream from Linne in the storage section Roermond-Linne. This implies the storage volume of this section is partly filled with river discharge from upstream, and with pumped water from the downstream end at the Roermond PSP-plant. The combined inflow is bounded by the size of the storage volume Roermond-Linne, which is 1.950.000 m^3 according to Table 17.

When the discharge becomes larger – depending on the day in the FDC – the complete Roermond-Linne section is stored with river discharge. The surplus discharge will partly fill the storage section Belfeld-Roermond while the remaining volume is filled by pumped water from the Belfeld PSP-plant.

This process is shown graphically in Figure 65. The figure is representative for FDC day 252. The Roermond-Linne section is completely stored by the river. The section Belfeld-Linne is partly stored by the river and partly stored by pumping. FDC day 252 is used in appendix I for a numerical explanation of the model.

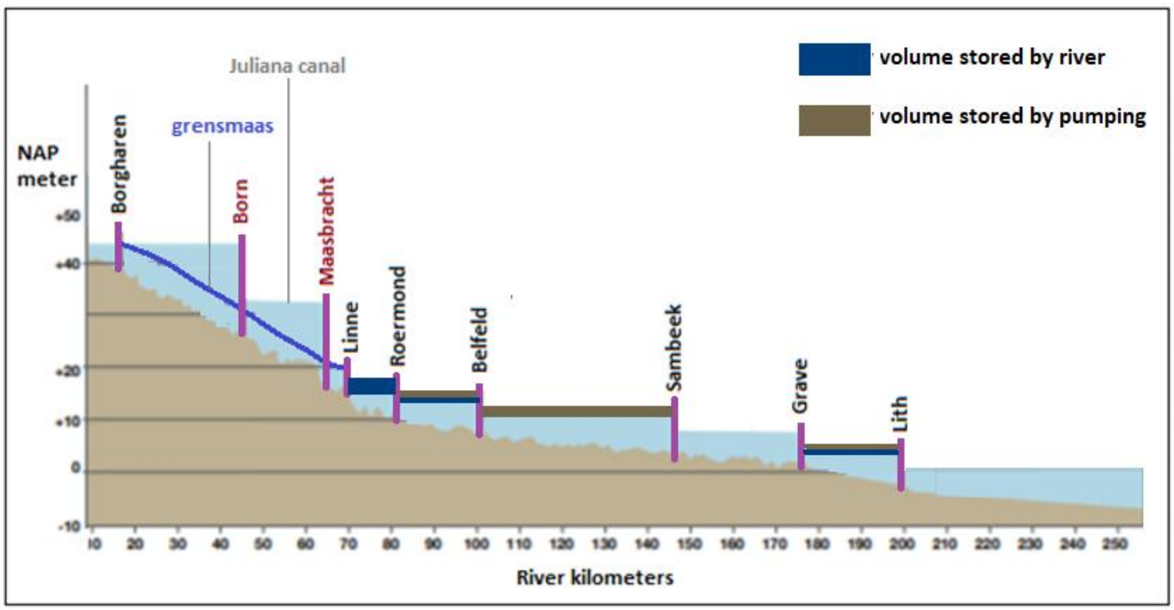


Figure 65: Storage by river and pumping, adjusted picture (Beurskens & van Dongen, 2018)

ENERGY STORAGE BY PUMPING

In the model energy is stored by pumping as well. As one can observe in Figure 65 the waterlevel mainly increases in the upstream storage sections of the cascade. In the section Grave-Sambeek no water is stored at all. All water pumped upstream at the Grave PSP-plant is in turn pumped up further upstream at the Sambeek PSP-plant.

This is explained by the size of the storage volume Sambeek-Belfeld, which is 7,360,000 m^3. This is the largest storage volume of the Meuse cascade. Using the default values, it will never be filled completely. According to the model the maximum stored volume is 5,700,960 m^3 which occurs on FDC 206 showing a river discharge of 122.2 m^3/s.

The storage volume Lith-Grave shows a minor filling by pumping. This is explained by the pump capacity of the Lith PSP-plant (22 screws.) As pump-capacity at Grave is lower (20 screws) the pumped volume of 2 screws will be stored in the section upstream Lith. Furthermore, the river stores water. This is explained more detailed in appendix I, which elaborates on the additional inflow of water as a result of the difference in FDC's used for Lith and Grave.

11.3 VERIFICATION MEUSE MODEL

When verifying the model on its requirements shown in Table 6 it can be concluded the model obeys all. The requirements and verification are discussed more into detail in appendix I related to this chapter which elaborates on the construction the model.

11.4 MODEL RESULTS ON HYDROPOWER AND PUMP-STORED POWER COMPUTATIONS

The main results of the model on computations on pumped-stored power and hydropower are presented in this paragraph. It starts with the results for each weir after which the results for the whole cascade will be presented.

The model shows the results on four types of power, which are:

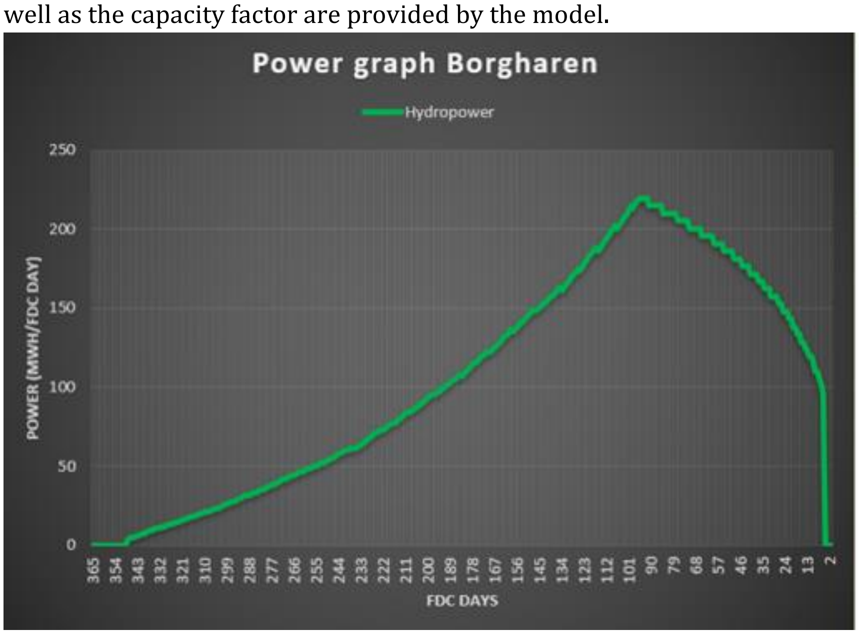
- hydropower
- power stored by the river
- surplus power used
- pumped-stored power

Hydropower is the power produced by the available discharge throughout the year. It does not include pumped-stored power. However, it does include the amount of power stored by the river during storage mode.

The surplus power used is the surplus power available om the grid during hours of low energy demand. The pumped-stored power represents the power which is returned to the grid during hours of high energy demand.

11.4.1 HYDROPOWER PLANT BORGHAREN

As explained in chapter 6: the process of PSP starts at the Roermond weir. Therefore, the power graph of Borgharen only shows the hydropower production based on the FDC. Hydropower production starts at FDC day 348. Above this day the available discharge is too low to power at least one screw partially filled. The annual energy yield (AEY) as well as the capacity factor are provided by the model.

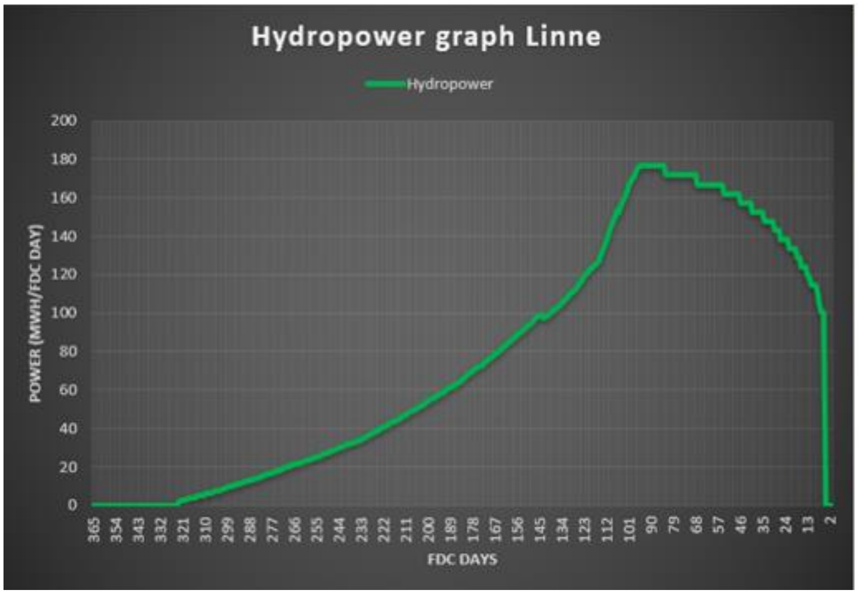


Borgharen per year:		
installed capacity:	10.3	MW
AEY:	37948	MWh
capacity factor:	0.42	

Figure 66: Hydropower graph, AEY and CF of Borgharen facility

11.4.2 HYDROPOWER PLANT LINNE

The hydropower graph for the Linne facility is shown in Figure 67. As the gross head at Linne is lower compared to Borgharen the AEY is lower. However, the capacity factor is increased. This is explained by the pattern of the waterlevels throughout the year at Borgharen shown in Figure 19. From the start of base river mode, the gross head starts to decrease at Borgharen thereby reducing the hydropower production and the capacity factor. At the Linne weir (and the other weirs in the cascade) this decrease in gross head starts roughly in median river mode.

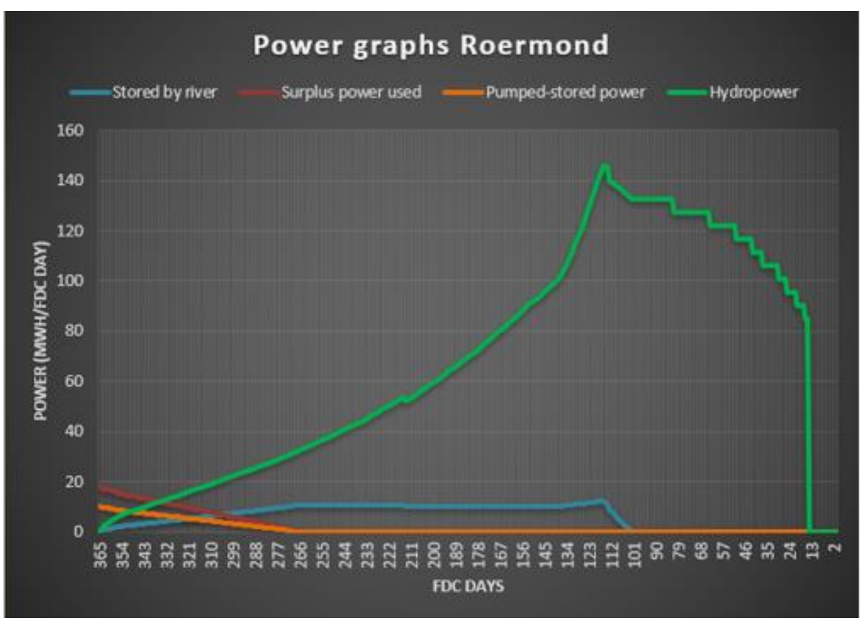


Linne per year:		
installed capacity:	6.6	MW
AEY hydropower:	27524	MWh
capacity factor:	0.47	

Figure 67: Results for hydropower plant Linne

11.4.3 PSP-PLANT ROERMOND

The power graphs of the Roermond PSP-plant as well as the yearly totals – both provided by the model - are shown in Figure 68. As one can observe the hydropower produced increases with increasing river discharge. Production stops at FDC day 15 when the minimum gross head to operate is reached at peak river mode (1.6 meter for the 4-meter diameter screws at Roermond). The hydropower graph shows a stepwise decrease after reaching its peak on FDC day 115. This stepwise pattern is explained in appendix I.



Roermond per year:		
installed capacity:	5.6	MW
AEY hydropower:	24588	MWh
power stored by river:	2256	MWh
hydro capacity factor:	0.50	
AEY pumped-stored power:	488	MWh
surplus power used:	867	MWh
effiency PSP:	56.25	%
storage capacity factor:	0.01	
combined capacity factor:	0.51	
volume pumped:	88554960	m3
volume stored by river:	411562080	m3
stored volume:	500117040	m3

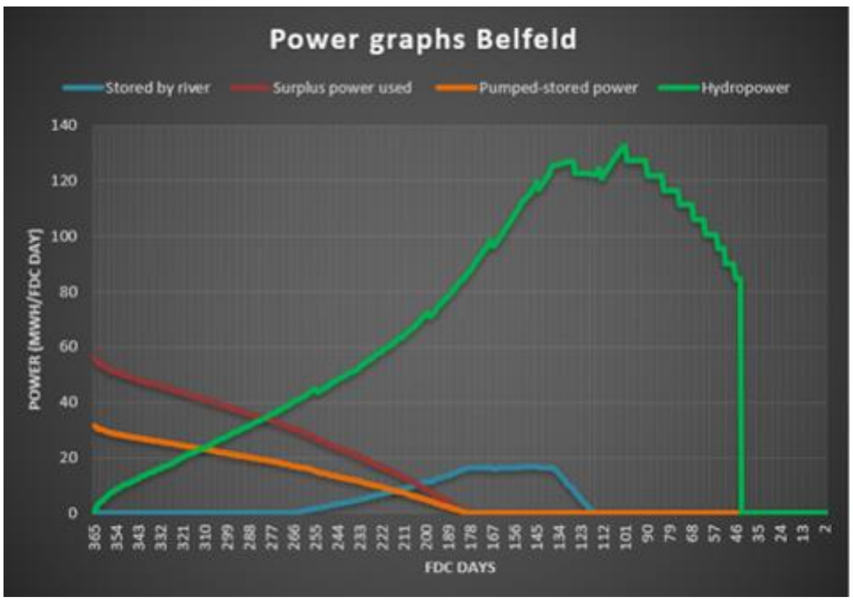
Figure 68: Power graphs Roermond PSP-plant (left) and yearly totals (right)

The power stored by the river is relatively large compared to the power stored by pumping. This is explained by the fact river storage is most dominant in the most upstream storage section. One can observe power stored by the river completely dominates the storage process between FDC days 265 and 105. When this curve becomes flat the river will start to store energy in the section downstream of Roermond.

Amongst others one can observe the hydropower AEY of 24,588 MWh and the capacity factor of 0.5. The results show a round-trip efficiency of 56.25 % using a surplus power of 867 MWh. The combined capacity factor of hydropower and PSP-power increases to 0.51 which is minor because of the relatively large contribution of river storage.

11.4.4 PSP-PLANT BELFELD

At the moment the storage volume of the section Roermond-Linne exceeds its capacity the river will start to store power in the section Belfeld-Roermond. However, this river storage starts not before FDC day 266. Combined with the fact the storage volume upstream of Belfeld is bigger than the volume upstream of Roermond there is more room for pumped-stored power.



Belfeld per year:		
installed capacity:	6.1	MW
AEY hydropower:	22678	MWh
power stored by river:	1504	MWh
hydro capacity factor:	0.43	
AEY pumped-stored power:	3165	MWh
surplus power used:	5626	MWh
effiency PSP:	56.25	%
storage capacity factor:	0.06	
combined capacity factor:	0.49	
volume pumped:	464461920	m3
volume stored by river:	234590400	m3
stored volume:	610497360	m3

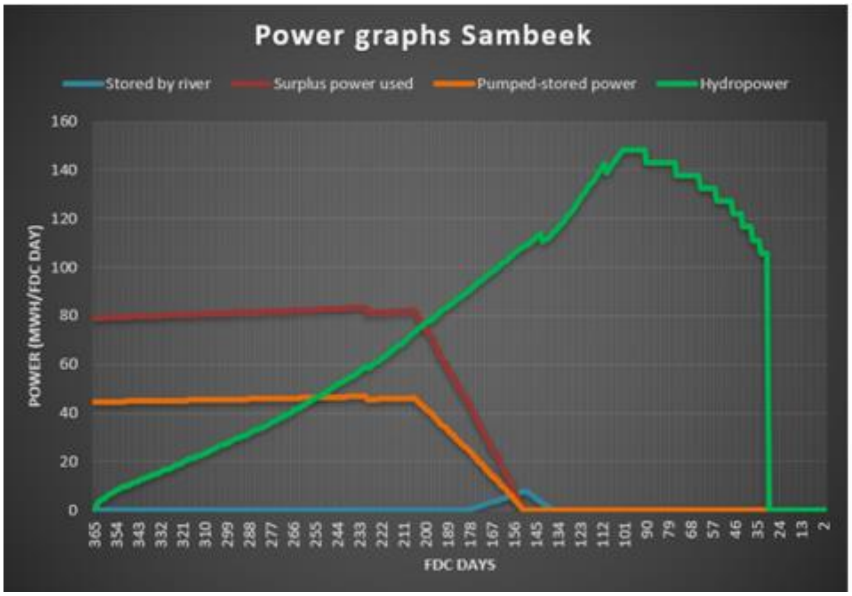
Figure 69: Results on yearly powers and volumes stored for the Belfeld facility

Note: for the sake of the construction of model the horizontal axis (FDC days) is mirrored compared to the graphs showing the FDC's in chapter 4.

11.4.5 PSP-PLANT SAMBEEK

The power graphs for the Sambeek facility are shown in Figure 70. One can observe the reduced contribution of power stored by the river. The majority of river storage occurs in the sections Belfeld–Roermond and Roermond–Linne. As a result, the Sambeek-Belfeld section mainly shows storage by pumping.

Using 20 screws the installed capacity at Sambeek is 6.5 MW. The capacity factor for hydropower is 0.46 and the AEY for on hydropower is 26,297 MWh. When the pumped-stored power is included the combined capacity factor becomes 0.61, indicating a more efficient use of the installed turbine capacity. The yearly surplus power used is 15,301 MWh returning 8,607 MWh to the grid.



Sambeek per year:		
installed capacity:	6.5	MW
AEY hydropower:	26297	MWh
power stored by river:	171	MWh
hydro capacity factor:	0.46	
AEY pumped-stored power:	8607	MWh
surplus power used:	15301	MWh
effiency PSP:	56.25	%
storage capacity factor:	0.15	
combined capacity factor:	0.61	
volume pumped:	1261321920	m3
volume stored by river:	26981280	m3
stored volume:	823841280	m3

Figure 70: Power graphs Sambeek (left) and yearly numbers (right).

River storage starts when the storage volume of Belfeld has reached its capacity. For Belfeld this curve becomes flat at FDC day 178, which marks the start of river storage at Sambeek. At FDC day 205 the discharge of the river becomes so big the maximum capacity the PSP-plant can process at energy mode is reached. After this day the river discharge keeps on growing thereby reducing the room for pumped-storage. For this reason, pumped-storage starts to decline.

In Figure 71 one can observe an additional figure of the Sambeek PSP-plant hosting it default value of 20 screws.

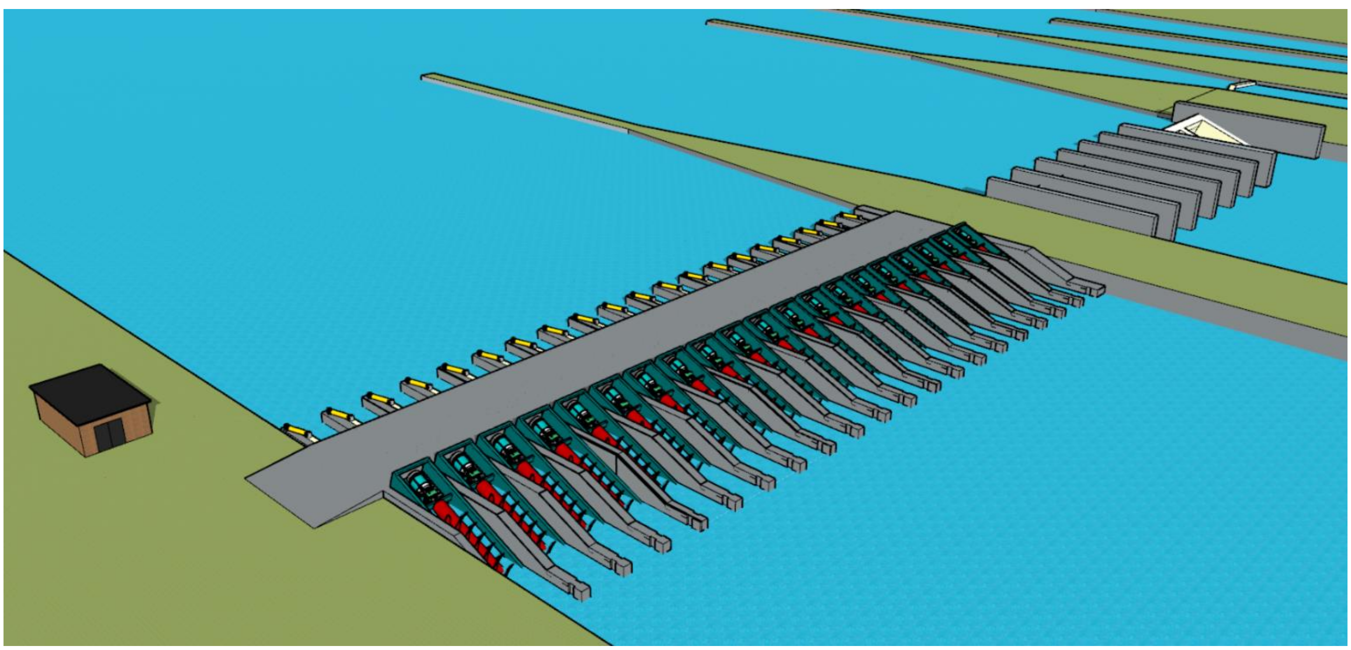
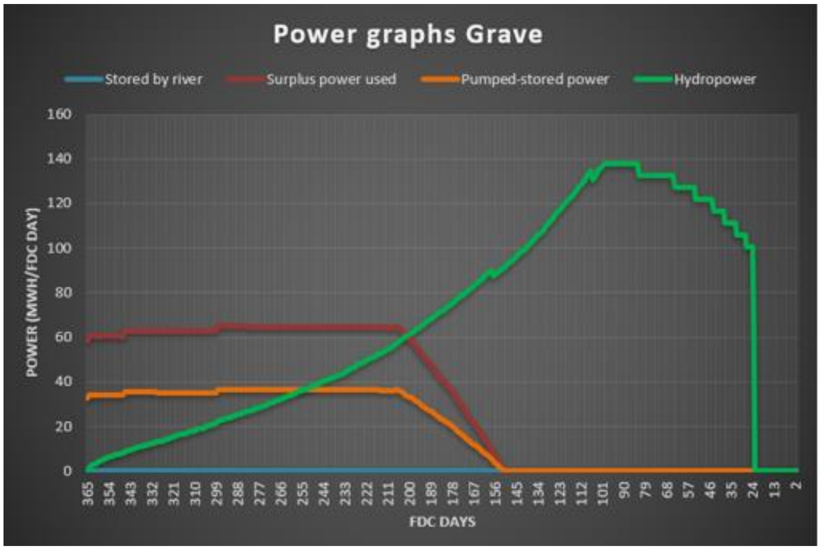


Figure 71: Sambeek PSP-plant hosting it default value of 20 screws

11.4.6 PSP-PLANT GRAVE

The power curves of Grave together with its yearly totals are shown in Figure 72.



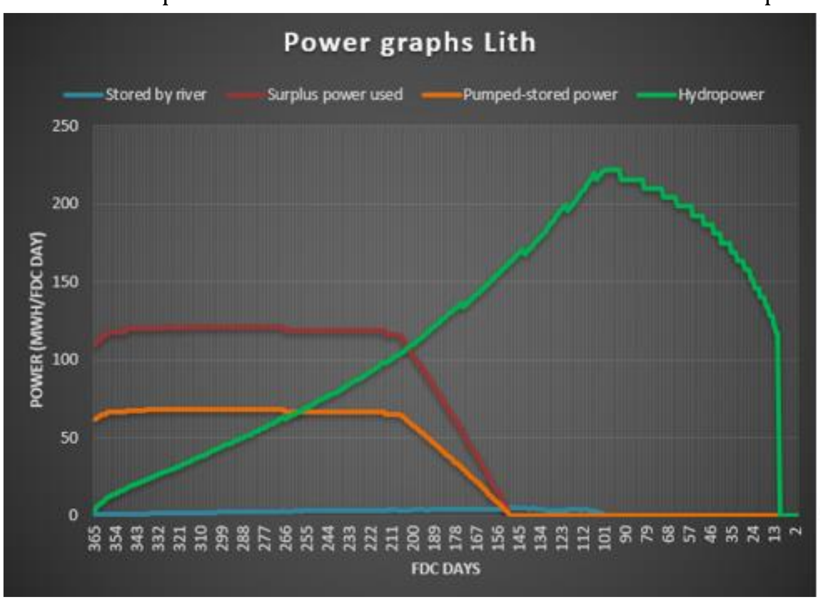
Grave per year:		
installed capacity:	5.5	MW
AEY hydropower:	23891	MWh
power stored by river:	0	MWh
hydro capacity factor:	0.49	
AEY pumped-stored power:	6784	MWh
surplus power used:	12061	MWh
effiency PSP:	56.25	%
storage capacity factor:	0.14	
combined capacity factor:	0.63	
volume pumped:	1261321920	m3
volume stored by river:	0	m3
total stored volume:	0	m3

Figure 72: Grave PSP-plant, power curves and yearly totals

As one can observe no power is stored by the river at Grave. Furthermore, no volume of pumped water is stored as this volume is in turn pumped upstream at the Sambeek facility. These pumped volumes are equal for Grave and Sambeek. The AEY of hydro- and pumped-power is lower compared to Sambeek. This is explained by the gross heads which differ for both PSP-plants.

11.4.7 PSP-PLANT LITH

The final PSP-plant is the one downstream the cascade at Lith. The power graphs are presented in Figure 73.



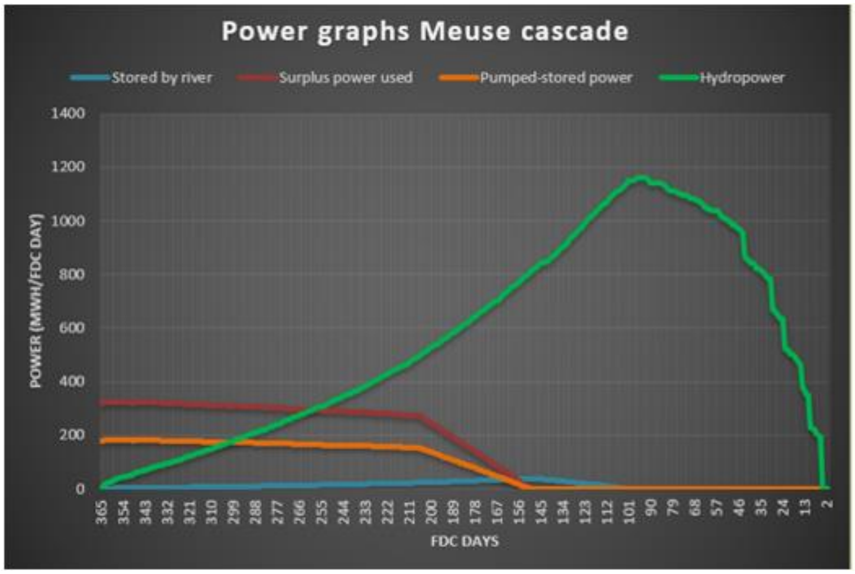
Lith per year:		
installed capacity:	9.7	MW
AEY hydropower:	42088	MWh
power stored by river:	787	MWh
hydro capacity factor:	0.50	
AEY pumped-stored power:	12580	MWh
surplus power used:	22364	MWh
effiency PSP:	56.25	%
storage capacity factor:	0.15	
combined capacity factor:	0.65	
volume pumped:	1387863360	m3
volume stored by river:	89614080	m3
total stored volume:	216155520	m3

Figure 73: Power graphs and yearly totals for Lith PSP-plant

At Lith the FDC of Megen is used which shows a bigger discharge as the FDC of Venlo used for Grave. The additional inflow of water is elaborated on more into detail in the numerical example in appendix I. This additional inflow of water explains why the river is storing energy upstream of Lith. The combined capacity factor increases to 0.65 instead of the 0.5 for hydropower alone. This indicates PSP results in a more efficient use of the installed capacity at Lith (and at the other PSP-plants in the cascade).

11.4.8 YEARLY TOTALS CASCADE

The power graphs and yearly totals for the Meuse cascade are shown in Figure 74. In the model these numbers are obtained by summing up the data used for the individual graphs of each weir.



Cascade totals per year:		
installed capacity:	50.3	MW
AEY hydropower:	205.0	GWh
power stored by river:	4.7	GWh
hydro capacity factor:	0.47	
AEY pumped-stored power:	31.6	GWh
surplus power used:	56.2	GWh
effiency PSP:	56.25	%
storage capacity factor:	0.07	
combined capacity factor:	0.54	
volume pumped:	4463524080	m3
volume stored by river:	762747840	m3
total stored volume:	2150611200	m3

Figure 74: Yearly numbers of hydropower and pumped-stored power Meuse cascade

11.4.9 CAPACITY FACTORS

The cumulative installed turbine capacity throughout the cascade is 50.3 MW. This results in an AEY for the cascade of 205 GWh. The river stores 4.7 GWh a year. As one can observe in Figure 74 the hydropower capacity factor is 0.47. This capacity factor is calculated by dividing the yearly hydropower produced by the installed capacity in the cascade.

The hydro capacity factor of 0.47 is determined by using the weighted installed capacity and hydropower produced for all the facilities in the cascade. This includes the facilities at Linne and Borgharen which only serve the purpose of hydropower.

The AEY of stored power is 31.6 GWh using a yearly surplus power of 56.2 GWh. The capacity factor for pumped-stored power is 0.07. The round-trip efficiency of the PSP-process in the cascade is 56.25 %. The yearly stored volume of water is 2.15 billion m^3.

The combined capacity factor for the cascade becomes 0.54. This implies pump-storage results in more efficient use of the installed turbine capacity along the Meuse cascade. The utilization of the installed capacity is increased by 7 % when applying pumped-storage in the cascade. This is mainly the result of the PSP-plants at Lith, Grave and Sambeek as these plants use their maximum installed pump-capacity, contrary to Belfeld and Roermond at which river storage is present. Because of this Lith, Sambeek and Grave show individual pump-storage capacity factors around 0.15.

NUMBER OF HOUSEHOLDS

According to ("Hoeveel energie", 2020) a 3 MW windmill produces 6.5 GWh a year, enough to power 2,000 households. When scaling this to the AEY's on hydropower and PSP-power around 73,000 households can be powered. According to ("Nuclear energy", 2020) the Borssele nuclear power plant (yearly output of 4,000 GWh) powers 1 million homes. When scaling this to AEY's on hydropower and pumped-stored power it can be concluded up to 59,000 households can be powered. This is a more conservative estimation, which will be governing in this report.

TIME SPAN ENERGY STORAGE CASCADE

As one can observe in Figure 74 energy storage occurs for 265 days a year. However, the bulk of storage occurs during FDC days 365-204. After FDC day 204 the river discharge becomes so big the cumulative process capacity for stored water decreases gradually to zero at FDC day 101. From FDC day 100 the cumulative installed capacity in the cascade is solely used to process the river discharge.

11.4.10 OPTIMAL DURATION STORAGE MODE

The optimal duration of storage mode – using the default values for the number of screws – has been assessed using the model. This is done by comparing storage durations in the range 4 – 14 hours. Obviously, a storage mode of 14 hours is not realistic. However, using this value the optimal storage duration becomes more clearly visible in the graph shown in Figure 75.

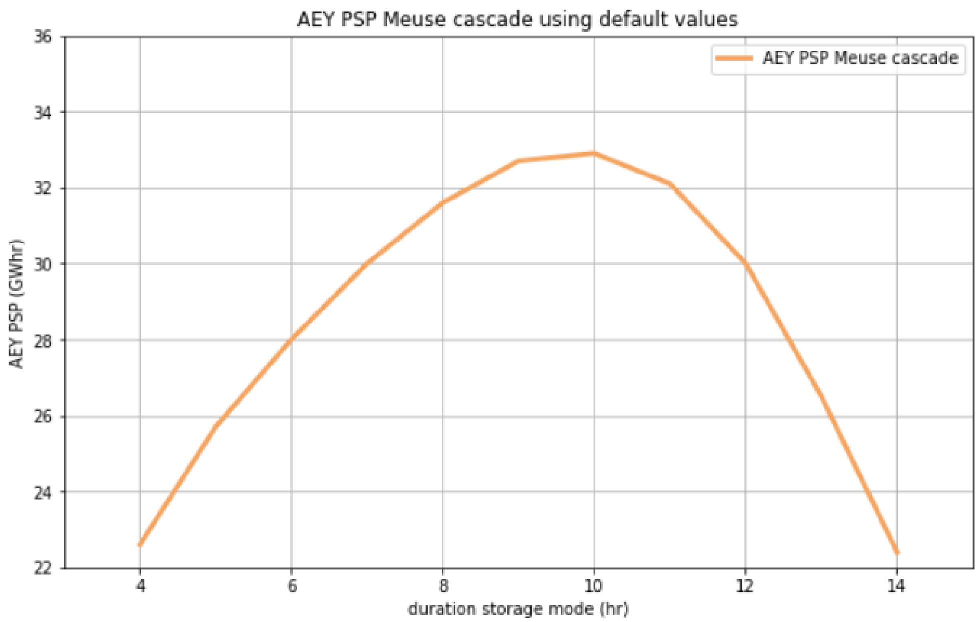


Figure 75: Optimal duration storage mode

As one can observe the pumped-stored power AEY is maximized using a storage duration of 10 hours. It becomes 32.9 GWh. One might argue this is low compared to the AEY for hydropower (205 GWh).

The difference is explained by the size of the storage volumes. Using the default values some volumes are relatively small compared to the capacity of the PSP-plant. For instance, the Belfeld PSP-plant can process a volume of 17,280,000 m^3 during energy mode (using a duration 16 hours). However, the storage volume is only 2,550,000 m^3 using the default values. There is less room for storage compared to the room for powering.

11.4.11 AEY HYDROPOWER UNDER INCREASED TURBINE CAPACITY

The model has been used to calculate the AEY on hydropower when increasing the number of turbines. In Figure 76 one can observe the results. At each step the number of turbines is increased by 2. (For the Roermond and Belfeld PSP-plant this step is 3 as the diameter of the screws is 4 meter. This is not shown on the horizontal axis.)

It might be feasible to increase the number of turbines per facility with 2 or 4. The percentual increase in AEY is 3.9% 3.2% respectively. The levelized cost of electricity should be used to decide on this matter. When increasing the number of turbines with 6 or more the relative increase in AEY decreases more and more.

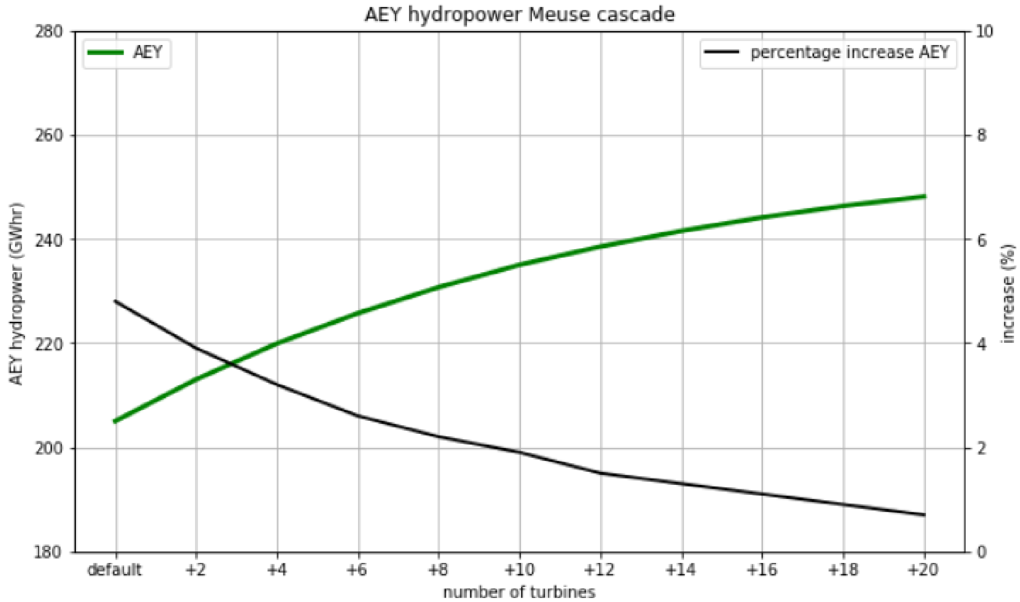


Figure 76: AEY hydropower Meuse cascade with increased number of turbines

11.5 PSP AEY PUT INTO PERSPECTIVE

To put the pumped-stored power AEY from the Meuse cascade in perspective data from a Dutch windfarm are used. The windfarm 'Offshore *Windpark Egmond aan Zee'* (OWEZ) was the first windfarm constructed in the North Sea. It is hosting 36 wind turbines representing an installed capacity of 108 MW ("NoordzeeWind", 2020). This is about twice the installed capacity of the Meuse cascade.

The AEY of the OWEZ windfarm is 315 GWh by applying its capacity factor of 0,33 ("NoordzeeWind", 2020). Using a duration of storage mode of 8 hours the yearly surplus in power for OWEZ is approximated as (assuming the wind blows every night):

$$yeraly\ surplus\ power\ OWEZ = \frac{8}{24} * 315 = 105\ GWh$$

The surplus power used in the cascade – based on the default values of the model – is 56.2 GWh. This implies the cascade can process about 54 % of the surplus power of the OWEZ windfarm. It can be concluded the PSP-capacity of the Meuse cascade is limited as the OWEZ-windfarm is relatively small.

Figure 77: OWEZ windfarm ("Noordzee Windpark", 2020).

11.6 UTILIZING THE FULL ENERGY STORAGE POTENTIAL MEUSE CASCADE

In the methodology of this thesis, it is stated hydropower generation is the main operational process. Energy storage is the second operational process. More specifically, the number of screw turbines per plant – resulting in the default values applied in the model – is determined based on FDC's and the 100-day design discharges. Using the default values for the number of screw turbines per PSP-plant – as shown in Table 17 – has resulted in a hydropower AEY of 205 GWh and a pumped power AEY of 31.6 GWh, as elaborated on into detail in paragraph 11.4.

In paragraph 11.2 it is explained the storage volumes are not fully utilized, illustrated by Figure 65. For instance, all the water pumped upstream at the Grave PSP-plant is in turn pumped up further upstream at Sambeek. Using the model, it becomes clear the full energy storage potential of the Meuse cascade cannot be utilized when the default values for number of screws per PSP-plant are used.

In order to utilize the full energy storage potential more pump capacity is needed throughout the cascade. Therefore, the number of screws per PSP-plant is calculated by dividing the maximum volume to pump by a duration of storage mode of 8 hours and the pump capacity of one screw, which is determined by its screw diameter. This is summarized in Table 18.

PSP-plant	Storage volume Lith-Grave (m3):	Storage volume Grave – Sambeek (m3):	Storage volume Sambeek-Belfeld (m3):	Storage volume Belfeld-Roermond (m3):	Storage volume Roermond-Linne (m3):	Maximum volume to pump (m3):	Number of screw pumps needed:
Lith	3,750,000	4,050,000	7,360,000	2,550,000	1,950,000	**19,660,000**	59 (D = 5 m)
Grave		4,050,000	7,360,000	2,550,000	1,950,000	**15,910,000**	48 (D = 5 m)
Sambeek			7,360,000	2,550,000	1,950,000	**11,860.000**	36 (D = 5 m)
Belfeld				2,550,000	1,950,000	**4,500,000**	30 (D = 4 m)
Roermond					1,950,000	**1,950,000**	30 (D = 4 m)

Table 18: Number of screws needed per PSP-plant in order to fully utilize storage potential cascade

The PSP-plant at Lith will need 59 screws as it has to pump up the total volume of five storage sections. The PSP-plant at Grave will need 48 screws as it has to fill four storage volumes. Sambeek will need 36 screws as it had to fill the storage volumes upstream of Sambeek, Belfeld and Roermond.

The number of screws for Belfeld and Roermond will not change. This is explained by the fact Belfeld can pump up the volumes of the sections Belfeld-Roermond and Roermond-Linne already when using the default number of screws. Furthermore, the PSP-plant at Roermond still only needs to store its own volume so its pump capacity is already sufficient. As a result, the number of screws at Belfeld and Roermond will stay on its default value of 30.

The conceptual design for the Sambeek weir has been adjusted. Using the default value Sambeek is equipped with 20 screws. In chapter 10 it is explained the area next to the weirs might be used for the construction of a PSP-plant. However, when using 36 screws - instead of 20 - the PSP-plant might become too wide. Therefore, the PSP-plant is turned and is located more parallel to the river bank. This is shown in Figure 78.

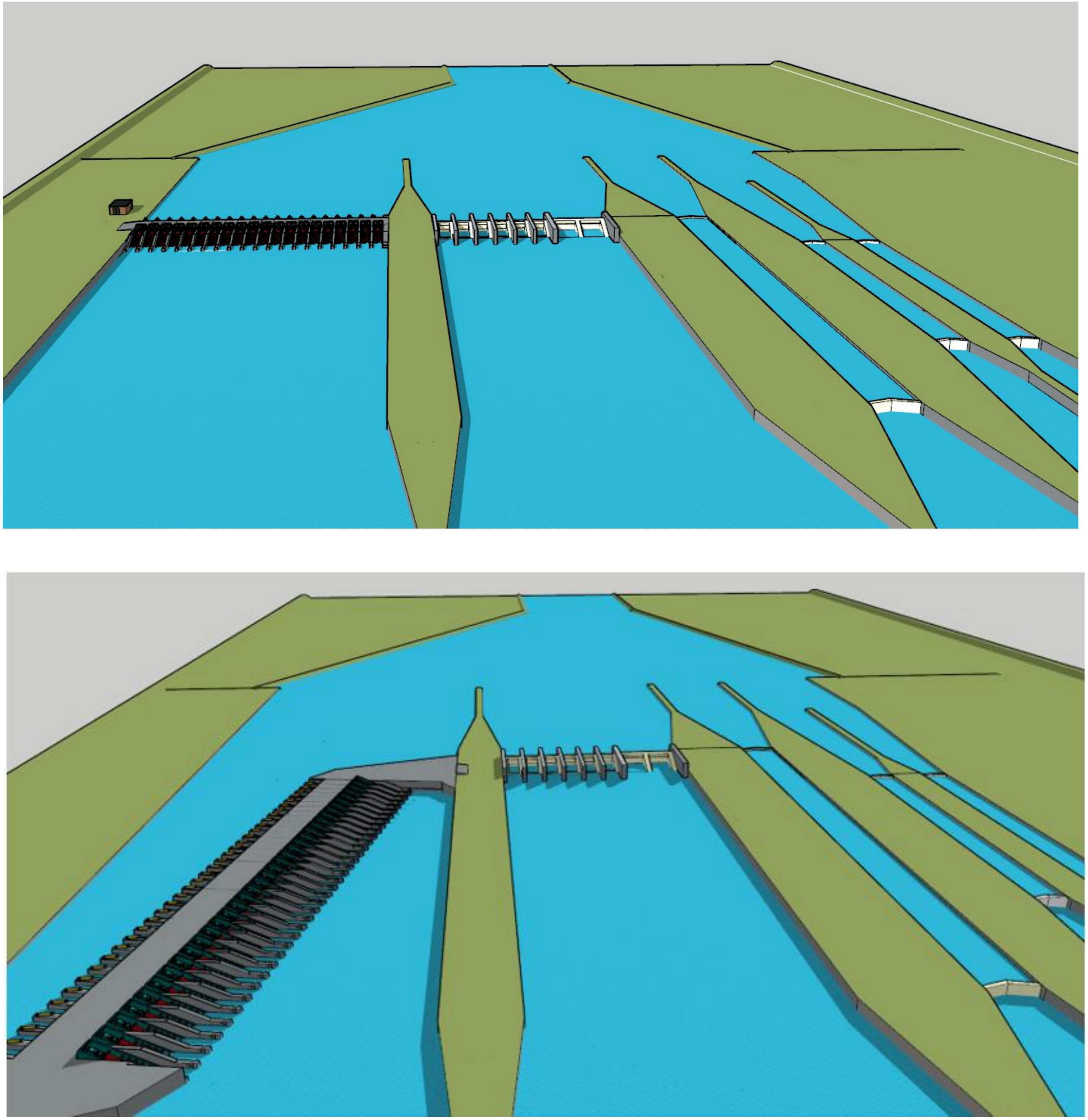


Figure 78: Upper: Sambeek PSP-plant hosting 20 screws. Lower: Sambeek hosting 36 screws

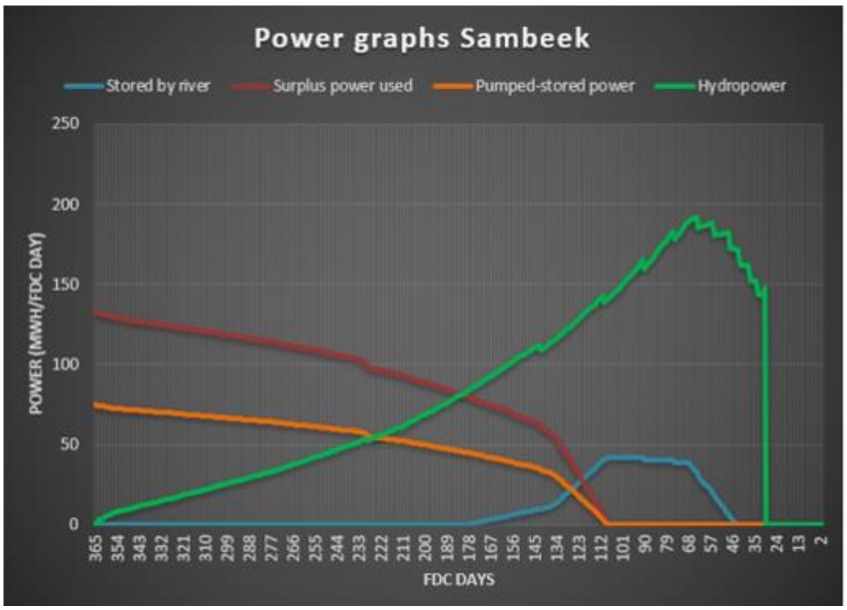
At the Lith PSP-plant 59 screws are needed. It is assumed this plant will have to be constructed completely parallel to the river bank because of space restrictions. The same holds for the Grave PSP-plant hosting 48 screws. The efficiency in turbining- and pumping mode might decrease, as the water is not approaching the PSP-plant in a perpendicular way anymore. This will probably result in increased turbulence and the loss of kinetic energy. However, in the model the overall efficiency at pumping- and turbining is kept on 75 %.

11.6.1 YEARLY TOTALS PSP-PLANTS WHEN UTILIZING FULL STORAGE POTENTIAL

In this subsection the model results per PSP-plant with an increased number of screws are presented. As stated in the previous subsection this holds for the facilities at Lith, Grave and Sambeek. The overall cascade results are presented in subsection 11.6.2.

SAMBEEK EQUIPPED WITH 36 SCREWS

The model results for Sambeek equipped with 36 screws are shown in Figure 79. When using the default values (20 screws) the pump capacity of Sambeek is not sufficient to fill the storage volumes upstream of Sambeek, Belfeld and Roermond. As a result, the storage capacity is not fully utilized. When using 36 screws the storage capacity is fully utilized, resulting in a significant increase of the AEY on pump-stored power, compared to Figure 70. However, the combined capacity factor decreases from 0.61 to 0.44, as the installed capacity at Sambeek has increased to 11 MW.



Sambeek per year:		
installed capacity:	11.0	MW
AEY hydropower:	28187	MWh
power stored by river:	3114	MWh
hydro capacity factor:	0.29	
AEY pumped-stored power:	13694	MWh
surplus power used:	24345	MWh
effiency PSP:	56.25	%
storage capacity factor:	0.14	
combined capacity factor:	0.44	
volume pumped:	2189957120	m3
volume stored by river:	561242080	m3
stored volume:	2286737280	m3

Figure 79: Model results Sambeek weir when utilizing full storage potential

An additional image of Sambeek equipped with 36 screws is shown in Figure 80.

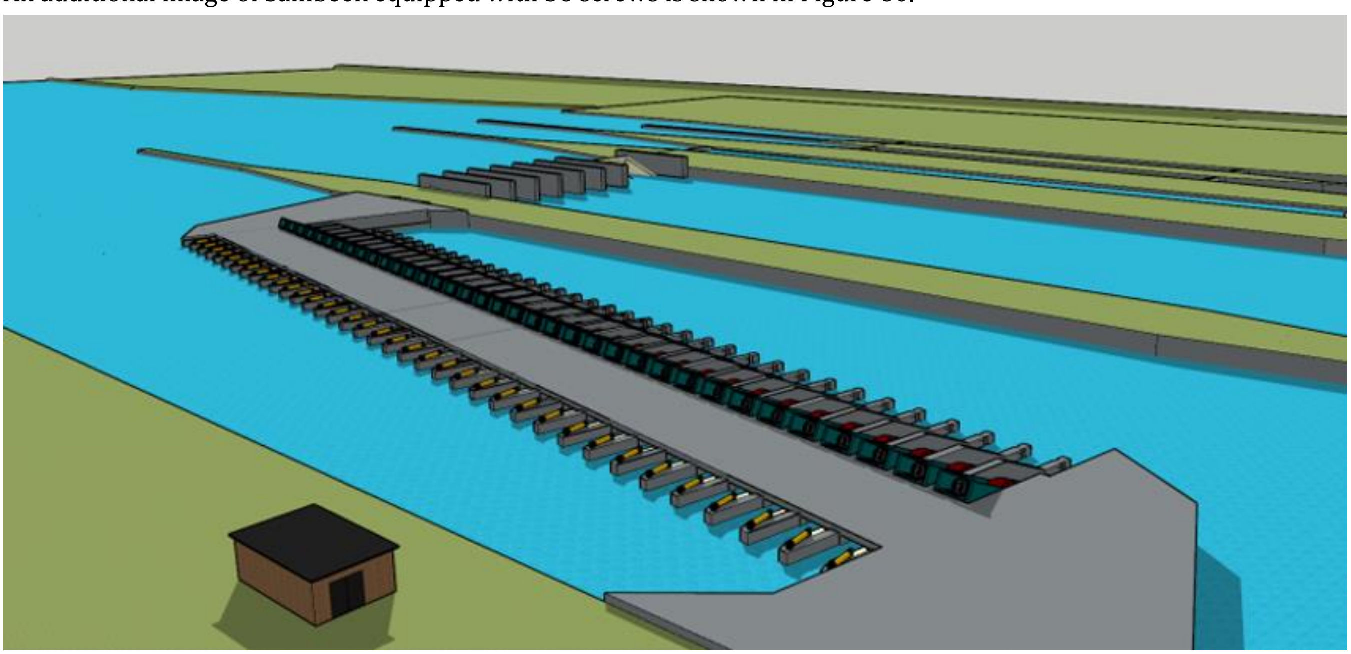
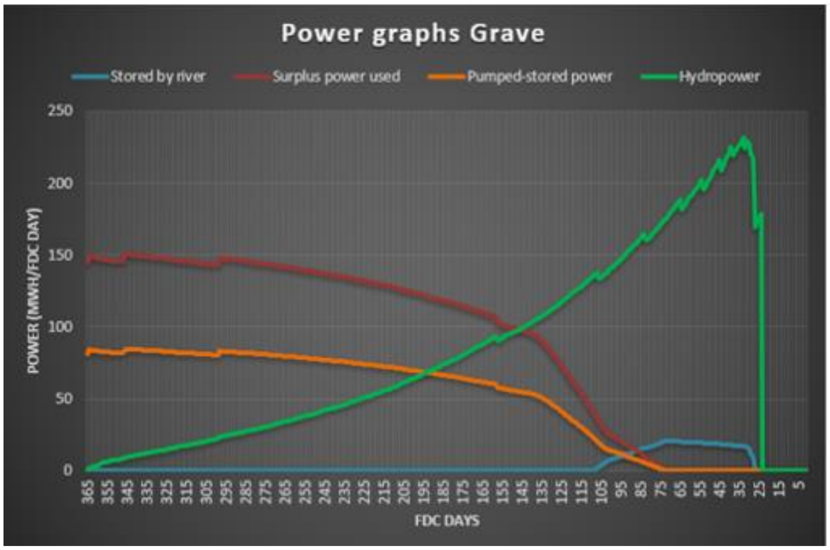


Figure 80: Sambeek hosting 36 screws in order to utilize full energy storage potential

GRAVE PSP-PLANT HOSTING 48 SCREWS

The result for Grave equipped with 48 screws (default number: 20 screws) are shown in Figure 81. The AEY on pumped power has increased from 6,784 to 18,482 MWh when comparing with the results shown in Figure 72.



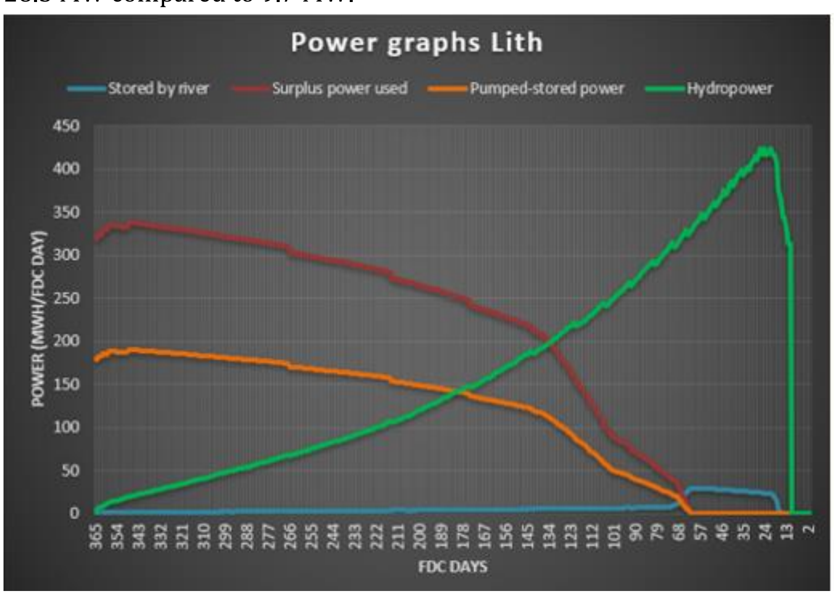
Grave per year:		
installed capacity:	13.6	MW
AEY hydropower:	29030	MWh
power stored by river:	1258	MWh
hydro capacity factor:	0.24	
AEY pumped-stored power:	18482	MWh
surplus power used:	32858	MWh
effiency PSP:	56.25	%
storage capacity factor:	0.16	
combined capacity factor:	0.40	
volume pumped:	3296096720	m3
volume stored by river:	259860960	m3
total stored volume:	1366000560	m3

Figure 81: Results for Grave when number of screws is based on utilizing full storage potential cascade

As the installed capacity has more than doubled the combined capacity factor has dropped from 0.63 to 0.40. It is interesting to notice the installed capacity now allows for river storage as well in the section Grave-Sambeek. This is not the case when the default number of screws is used, as shown in Figure 72.

LITH FACILITY HOSTING 59 SCREWS

In order to fully utilize the storage potential of the cascade the PSP-plant at Lith has to pump up the volume of five storage sections. Besides filling its own volume, the volumes upstream the other PSP-plants needs to be filled. Therefore, 59 screws are needed at Lith, while its default value is 22. As a result, the installed capacity increases to 28.5 MW compared to 9.7 MW.



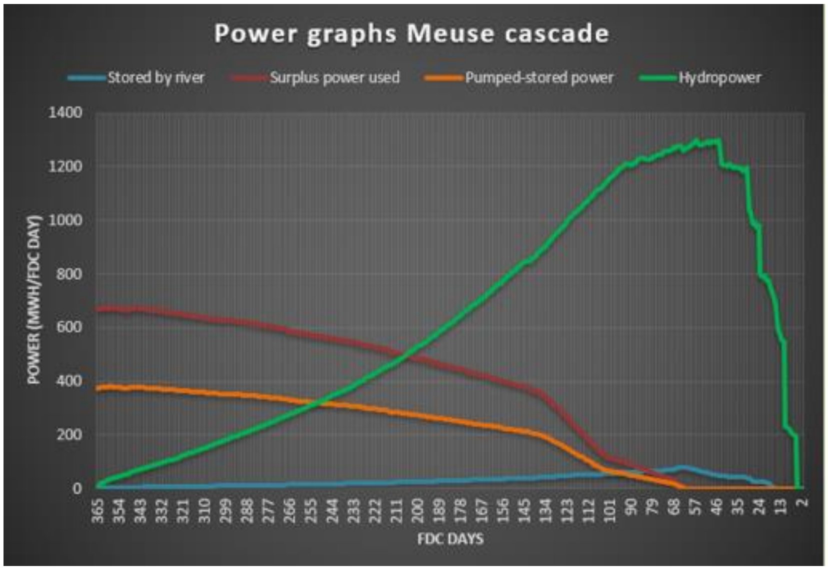
Lith per year:		
installed capacity:	28.5	MW
AEY hydropower:	58218	MWh
power stored by river:	2497	MWh
hydro capacity factor:	0.23	
AEY pumped-stored power:	41590	MWh
surplus power used:	73938	MWh
effiency PSP:	56.25	%
storage capacity factor:	0.17	
combined capacity factor:	0.40	
volume pumped:	4291761600	m3
volume stored by river:	309518960	m3
total stored volume:	1305183840	m3

Figure 82: Model results Lith when utilizing full storage potential Meuse cascade

The consequences for pumped-stored power AEY are the most spectacular for the Lith PSP-plant. It increases from 12,580 MWh to 41,590 MWh at the expense of the combined capacity factor which decreases from 0.65 to 0.40.

11.6.2 CASCADE TOTALS WHEN UTILIZING FULL STORAGE POTENTIAL

The Meuse cascade totals when utilizing the full energy storage potential are shown in Figure 83. As one can observe the AEY on hydropower slightly increases from 205 to 225.1 GWh, when compared to the hydropower AEY shown in Figure 74. The capacity factor on hydropower decreases from 0.47 to 0.32. The installed capacity throughout the cascade increases from 50.3 MW to 81.0 MW when comparing with Figure 74.



Cascade totals per year:		
installed capacity:	81.0	MW
AEY hydropower:	225.1	GWh
power stored by river:	10.5	GWh
hydro capacity factor:	0.32	
AEY pumped-stored power:	77.2	GWh
surplus power used:	137.2	GWh
effiency PSP:	56.25	%
storage capacity factor:	0.11	
combined capacity factor:	0.43	
volume pumped:	10330832320	m3
volume stored by river:	1776774480	m3
total stored volume:	6068536080	m3

Figure 83: Yearly totals cascade when utilizing complete storage potential

The AEY on pump-stored power more than doubles, from 31.6 GWh to 77.2 GWh. However, the combined capacity factor decreases from 0.54 (see Figure 74) to 0.43. This implies the installed turbine capacity is used less efficient.

The capacity factor for a traditional hydropower plant is solely based on its yearly 'internal' power production divided by the installed turbine capacity. The PSP-plants in the Meuse cascade use surplus (or 'excess') energy from 'external' power production sources. This surplus energy is wasted when it is not stored at periods of low energy demand. As a result – although the combined capacity factor decreases – it might still be economically interesting to increase the number of screws in order to utilize the full storage potential of the Meuse cascade.

Ultimately the optimal number of screws with respect to hydropower and pumped-stored power purposes needs to be determined by an economic assessment, which will be a recommendation for further research.

PSP AEY IN PERSPECTIVE WHEN UTILIZING FULL STORAGE POTENTIAL

In paragraph 11.5 the OWEZ-windfarm has been used to put the surplus power used in perspective. This has been done using the default number of screws per PSP-plant. In this subparagraph the surplus power used when utilizing the full energy storage potential of the Meuse cascade is put into perspective, for which more screws are needed.

Assuming the wind is blowing every night in the year the yearly surplus power of the OWEZ-windfarm turned out to be 105 GWh. When utilizing the full energy storage potential of the Meuse cascade 137.2 GWh of surplus power can be processed, which is 131 % of the yearly OWEZ surplus. Using the default number of screws this percentage is 54 %, as explained in subparagraph 11.4.8.

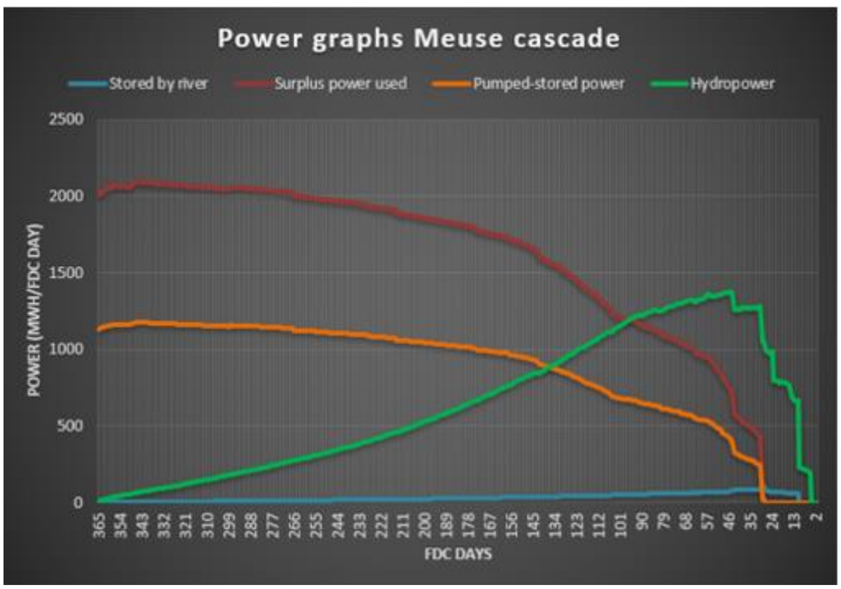
In subparagraph 11.4.9 it was mentioned roughly 59,000 households can be powered using the default values on the number of screws per PSP-plant. By scaling the results on AEY's up to 75,000 households can be powered with hydro- and stored energy by the facilities in the Meuse cascade when the full storage potential is utilized by using more screws at Lith, Grave and Sambeek.

11.7 SIMULATION OF INCREASED STORAGE VOLUMES

The purpose of a model is to simulate a real-life situation. The model uses default values on storage volumes which are related to existing boundary conditions as explained in chapter 6. However, these storage volumes can be increased in the model.

By tripling the width of each storage section an assessment of the AEY on pumped-stored power has been carried out, similar to utilizing the storage potential in paragraph 11.6. The number of screw pumps has been determined based on the storage volumes of each section instead of the design discharge for hydropower purposes.

This implies the PSP-plant at Lith will need 173 screws as it has to pump up the water of five storage sections. The PSP-plant at Grave will need 139 pumps as it has to fill four storage volumes, and so on. The PSP-plant at Roermond will only need to store its volume. As a result, the number of screws will stay on its default value of 30. The results shown in Figure 84 are obtained. As the number of screws throughout the cascade has increased the installed capacity becomes 192.9 MW.



Cascade totals per year:		
installed capacity:	192.9	MW
AEY hydropower:	228.9	GWh
power stored by river:	11.6	GWh
hydro capacity factor:	0.14	
AEY pumped-stored power:	314.9	GWh
surplus power used:	559.9	GWh
effiency PSP:	56.25	%
storage capacity factor:	0.19	
combined capacity factor:	0.32	
volume pumped:	43547405760	m3
volume stored by river:	2187075600	m3
total stored volume:	19373565600	m3

Figure 84: Power graphs cascade when tripling storage volumes and increase number of screws

Obviously, the surplus power used and the pump-stored power AEY are increased. These values become 314.9 GWh and 559.9 GWh respectively. The yearly hydropower production increases to 228.9 GWh which is just 23.9 GWh more compared to using the default numbers of screws. As a result, the combined capacity factor decreases from 0.54 to 0.32. Up to 136,000 households can be powered.

A Meuse cascade redesigned for storage purposes could process the surplus power of five windfarms of the size OWEZ.

As mentioned in subparagraph 11.6.2, surplus power is used which will be lost otherwise. Therefore, despite the reduced combined capacity factor, an increase of the storage volumes throughout the cascade might still be economically beneficial.

However, it is questionable if a Meuse cascade redesigned for the purpose of energy storage is feasible as it will probably ask for huge investments. This question might serve the objective of further research on energy storage and its impact on the environment of the Meuse cascade.

11.8 UTILIZING THE HYDROPOWER – AND STORAGE POTENTIAL JULIANA CANAL

In chapter 4 it is explained just upstream of the Borgharen weir ships are diverted to the Juliana canal because of the steep river bed slope in the Meuse trajectory Borgharen – Linne. The waterlevel in the Meuse river decreases from NAP 44 meter upstream the Borgharen weir to 20 NAP meter upstream the Linne weir, as explained in chapter 6.

In Figure 85 the Meuse cascade and the Juliana canal are shown. One can also observe the locking stations in the canal at Born and Maasbracht. The Grensmaas is the part of the river Meuse which is not navigable for ships.

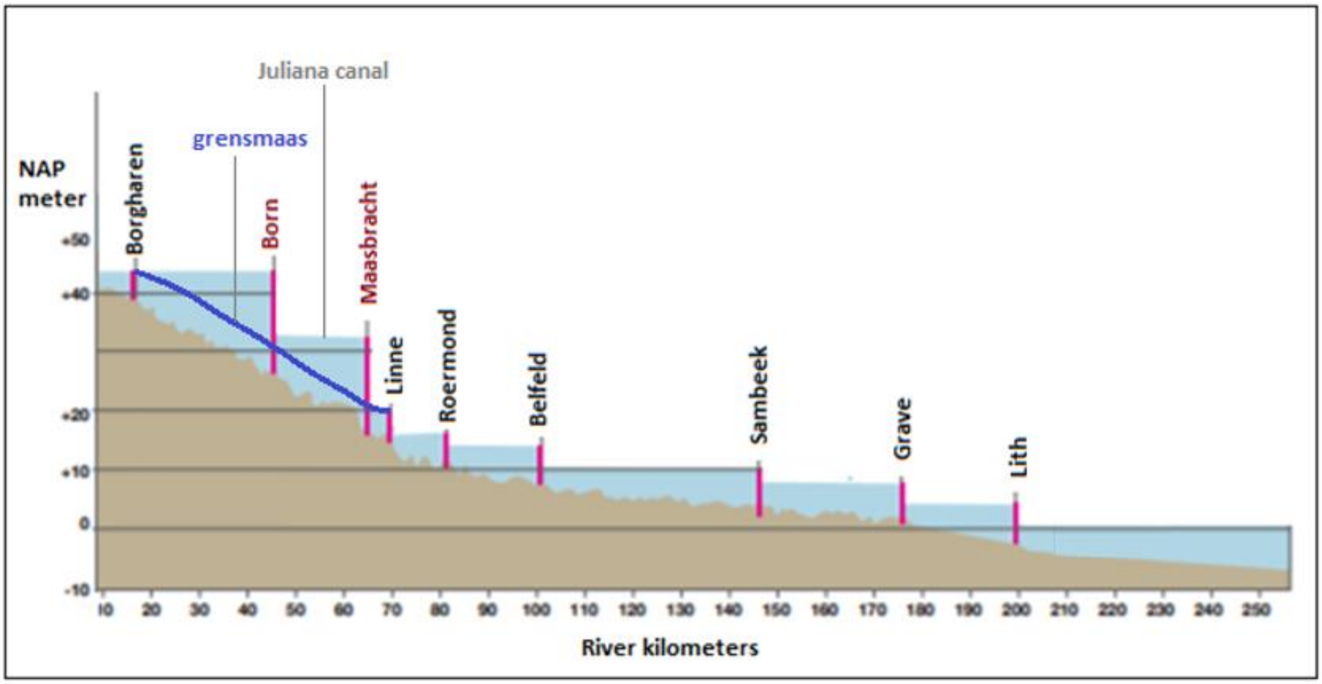


Figure 85: NAP levels Meuse and Juliana canal, adjusted picture (Beurskens & van Dongen, 2018).

The main hydraulic characteristics of the Juliana canal are ("Julianakanaal", 2020)("Sluis Maasbracht", 2020)("Sluis Born", 2020):

- length: 36 km
- width: 60 m
- head difference Born: 11.35 m
- head difference Maasbracht: 11.85 m

Some discharge of the Meuse is bypassed through the Juliana canal. The average discharge in this canal is 15.8 m^3/s with a maximum of 28.8 m^3/s ("Rijkswaterstaat Waterinfo", 2020). As this discharge is low the Juliana canal was excluded from hydropower production in the Meuse model. Furthermore, a canal in general is not designed to process river flood waves with high discharges and fluctuating waterlevels.

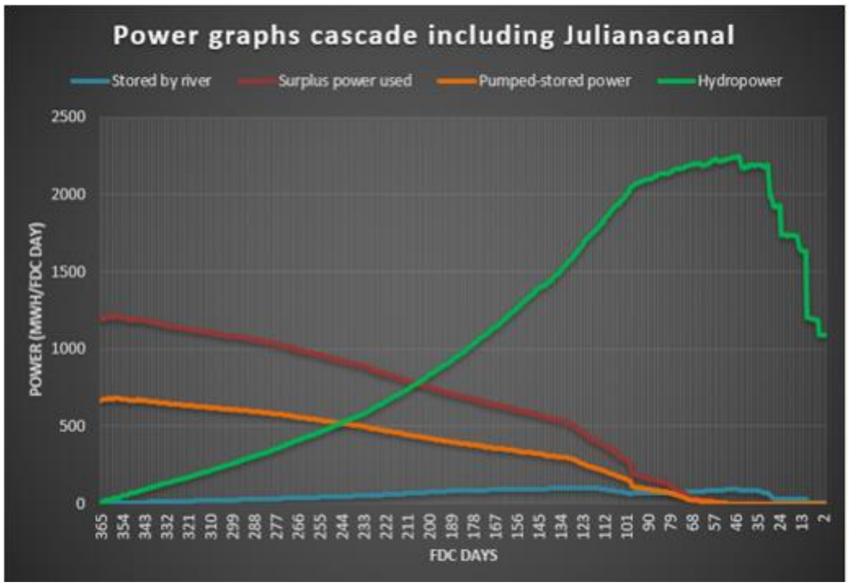
However, the numerical Meuse model has been expanded to assess the theoretical situation the design discharge of the Borgharen weir is bypassed via the Juliana canal. This implies no hydropower generation any more at the Borgharen weir, but instead hydropower generation at the locking complexes of Born and Maasbracht. It is assumed PSP-plants are constructed at these locations. The storage section Linne-Maasbracht is assumed to have a length of 5 km without the presence of a backwater curve.

The model is expanded such that river discharge exceeding the design discharge is processed by the Borgharen weir. Therefore, the maximum discharge in the Juliana canal will be 265 m^3/s. The minimum discharge in the Meuse river downstream Borgharen will be 15 m^3/s (see Table 7 in chapter 4) which will avoid the river from falling dry.

The head differences at Born and Maasbracht are around the upper limits a screw pump and -turbine can process according to manufacturing information presented in appendix F. Therefore, it is assumed Archimedean screws are applicable at Born and Maasbracht.

It is assumed the waterlevels upstream the Maasbracht- and Born PSP-plants can fluctuate without flooding of the surrounding area. The height of the storage volumes is set on 1 meter, similar to the model default values on storage volume heights along the Meuse cascade. As the width of the Juliana canal is 60 meter – instead of 150 meter in the Meuse river – the capacity for energy storage is reduced.

Upstream of Born the waterlevel is equal to the upstream waterlevel of the Borgharen. Cross-border storage will occur, as the next weir upstream Borgharen is located 15 km to the south at the Belgium location of Lixhe (Heijkoop et al, 2008). The results of the assessment including the Juliana canal are shown in Figure 86.



Cascade totals (including Julianacanal) per year:		
installed capacity:	134.2	MW
AEY hydropower:	393.1	GWh
power stored by river:	20.3	GWh
hydro capacity factor:	0.33	
AEY pumped-stored power:	129.3	GWh
surplus power used:	229.8	GWh
effiency PSP:	56.25	%
storage capacity factor:	0.11	
combined capacity factor:	0.44	
volume pumped:	16667875386	m3
volume stored by river:	2036236070	m3
total stored volume:	7581437280	m3

Figure 86: Assessment of Meuse cascade including Juliana canal

In this assessment the number of screws is based on the utilization of the full hydropower- and storage potential, like it has been done in paragraph 11.6 and paragraph 11.7. As one can observe the AEY on hydropower has increased significantly to 393.1 GWh, compared to 225.1 GWh (see Figure 83) when the Juliana canal is not included. This difference is of course explained by the utilization of the relatively large head differences at Born and Maasbracht.

It is interesting to notice hydropower generation at Born and Maasbracht is possible for the majority of the FDC-days. The minimum head difference needed for the screws to operate in turbine mode is always exceeded. This is not the case at the PSP-plants along the Meuse cascade, at which the head differences decrease at periods of peak river mode.

The surplus power used (229.8 GWh) is in the order of two times the yearly surplus of the OWEZ-windfarm. Obviously, including the Juliana canal increases the AEY of hydro- and pumped-stored power. Up to 131,000 households could be powered by hydro- and pumped-stored power. The economic- and environmental feasibility of redesigning the canal for hydropower- and energy storage purposes is a recommendation for further research.

11.9 CONCLUSIONS CHAPTER ELEVEN

In chapter 11 information from the previous chapters has been processed in order to construct the Meuse model. The numerical model describes power storage and -production per weir per FDC day and forms the essence of this report.

In the model it is assumed similar plants like the Sambeek design are installed throughout the cascade. The model uses default values for the storage volumes and number of screws per facility related to boundary conditions and design discharges. When verifying the model on its requirements it has been concluded the model meets all. The model computes the AEY on hydropower and pumped-stored-power of the Meuse cascade in an accurate way, thereby meeting the objective of this report.

The model has been used to compare the hydropower AEY for each weir per screw diameter, in order to decide on the optimal diameter to use. Every weir will be equipped with 5-meter diameter screws with the exception of Roermond and Belfeld. At these facilities a diameter of 4 meter will be used.

Pumping starts at Lith and ends at the Roermond PSP-plant. During storage mode water is discharged downstream from the Linne weir in the storage section Roermond-Linne, which implies the storage volume is partly filled with river discharge from upstream, and with pumped water from the downstream end at the Roermond PSP-plant.

When the river discharge increases the complete Roermond-Linne section is stored by the river and surplus discharge will partly fill the storage section Belfeld-Roermond and so on. When the discharge reaches design values the capacities of the PSP-plants are solely used to process the river discharge for hydropower purposes, either at storage- or at energy mode.

The cumulative installed cascade capacity is 50.3 MW resulting in a hydropower AEY of 205 GWh under a capacity factor of 0.47. The river stores 4.7 GWh per year. The AEY of pumped power is 31.6 GWh processing a yearly surplus power of 56.2 GWh. The round-trip efficiency of the PSP-processes in the cascade is 56.25 %. Including the pumped-stored power AEY results in a combined capacity factor of 0.54 thereby increasing the utilization of the installed capacity by 7 %.

Using the default values for the number of screws the Meuse cascade is capable of processing 54 % of the yearly power surplus of the relatively small OWEZ windfarm. Therefore, the PSP-capacity of the cascade is considered to be limited. Up to 59,000 households can be powered with hydro- and pumped-stored energy.

By using the default values on the number of screws per facility – which are based on the 100-day design discharge related to a FDC – the full storage potential of the Meuse cascade cannot be utilized. More pump capacity is needed at Lith, Grave and Sambeek. The number of screws for these PSP-plants has been calculated by dividing the maximum volume to pump by the duration of storage mode and the pump capacity of one screw. This results in an installed capacity throughout the cascade of 81 MW. However, the combined capacity factor decreases to 0.43. The cascade AEY on hydropower increases to 225.1 GWh and the AEY on pump-stored-power increases to 77.2 GWh. Up to 75,000 households can be powered.

The PSP-plants process surplus energy which is wasted when not stored. Although the combined capacity factor decreases it might still be economically interesting to increase the number of screws in order to utilize the full energy storage potential of the cascade.

Downstream the Borgharen weir ships are diverted from the Meuse river to the Juliana canal. A simulation has been carried out in which the model has been expanded with the Juliana canal which shows a total head difference of 23.2 meter. It is assumed the design discharge for the Borgharen weir is bypassed via this canal. The AEY on hydropower increases to 393.1 GWh. The AEY on pumped-stored power increases to 129.3 GWh. Up to 131,000 households can be powered by hydro- and pumped-stored power when the Juliana canal is included in the assessment.

12. DISCUSSION

The conceptual design of the PSP-plant is capable of adjusting the screw ends to the fluctuating waterlevels up- and downstream, either at turbining or at pumping. By doing so it maximizes the efficiencies of screw pump and – turbine. This is considered to be important for the energy assessment of the Meuse cascade. For this assessment it was possible to scale the conceptual design to the head differences at the other weirs. In the model it is assumed similar PSP-plants like Sambeek are present at the other weirs in the cascade.

However, as there is no lock at Borgharen and because the minimum discharge at every moment in time should be 10 m^3/s due to environmental policies (see chapter 6) no pumping will occur at the Borgharen weir. For Borgharen the screw configuration could be designed less complicated by using a floating support (a kind of pontoon instead of the hydraulic pistons in the conceptual design) at the downstream side.

The conceptual design of the PSP-plant focusses on technical functionality. No attention is paid to stakeholders and costs. Because to this no evaluation phase has been carried out in this report. However, this will be a recommendation for further research in chapter 13.

A shortcoming of the model is it does not account for decreased pump capacity when the height of the storage volume increases above pump delivery point (PDP), and the screw pump has to be rotated in a steeper position. Using the default values of the model on storage sections this shortcoming has no consequences as PDP is not exceeded. However, when using a storage height above PDP the model slightly overestimates the pumped volumes. It is questionable if such a high storage height is reasonable for the Meuse cascade, as the lock- and weir complexes will get submerged and water will flow back downstream.

In the model it is assumed every flow duration curve day - of the four different flow duration curves integrated in the model - occurs on the same day. In reality this is not the case as there will be a time lag. For instance, the peak of a flood wave occurring in January 1981 passed Borgharen on the 7^{th}, while it passed Venlo on the 8^{th}. Because of this the model should use real time data of discharge provided by the measurement stations of RWS.

In the model it is assumed a PSP-plant can switch instantly from turbining to pumping at constant waterlevels up- and downstream at that moment in time. In reality, a wave might develop when storage mode starts as river discharge will accumulate at the upstream side of the PSP-plant, which in turn will roll back upstream. This accumulation of water might increase the waterlevel upstream. However, the inertia of the water – which is an open channel flow phenomenon - is neglected in the model.

The yearly surplus energy of the OWEZ-windfarm has been used to put the cascade AEY on pumped-stored power in perspective, assuming the wind is blowing every night. In reality the wind does not blow every night. However, other sources of surplus power could be processed by the PSP-plants, like surplus power from coal plants (which keep on producing at night as they cannot be switched off instantly) or future dynamic tidal power plants.

Energy assessments have been carried out in two ways: by determining the number of screws per PSP-plant based on the 100-day design discharge, and by determining this number based on the maximum volume to pump. The economic optimal number of screws will probably lay somewhere in between and will be a recommendation for further research.

The model provides reasonable outcomes on the AEY of hydropower and pumped-stored power in the Meuse cascade. By doing so it has been possible to achieve the objective of this report. Although it will need some time to adjust, the model is generally applicable to assess the storage- and hydropower potential of another river cascade. In order to do so the FDC's as well as the gross heads per weir have to be implemented.

13. CONCLUSIONS AND RECOMMENDATIONS

In the last chapter of this report the main conclusions are presented, followed by recommendations for further research.

13.1 CONCLUSIONS

The river Meuse is showing three river modes which are described as base-, median- and peak mode. Roughly at the start of median mode the gross head begins to decrease at increasing discharges. This implies the head difference at the weirs in the cascade is not constant. It is varying throughout the year depending on the discharge. In times of peak mode, the head difference becomes zero implying no production of hydro-electricity.

The storage volumes in the Meuse cascade are bounded by the summer dikes. The distance between these dikes lies in the range 150 – 160 meters. For storage purposes it is assumed the waterlevel can increase one meter. As a result, the storage volumes in the cascade vary in the range 1,950,000 m^3 and 7,360,000 m^3.

The bed slope in the Borgharen – Linne river section causes limitations for energy storage. When the flow at the Borgharen weir is blocked and pumping starts the river might fall dry. Therefore, no storage will occur upstream the Borgharen weir. Upstream the Linne weir a backwater curve will develop when the discharge is blocked. In combination with pumping these might result in overflowing of this weir. For this reason, no water will be stored upstream the Linne weir. This implies energy storage in the Meuse cascade will start at the Lith weir and will end at the Linne weir.

Multiple turbines have been analyzed on suitability for low head conditions, turbining- and pumping capabilities, and fish friendliness. The Archimedean screw has been selected for equipping the conceptual design of the PSP-plant. This turbine has been tested positively in studies considering fish friendliness and it therefore expected to meet Dutch environmental regulations for the river Meuse. The screw is suitable within the head differences at the weirs in the Meuse cascade and can process a discharge up to 15 m^3/s when using a 5-meter diameter screw blade.

As the optimal angle of inclination of a screw pump and - turbine differs an optimisation of different screw configurations has been carried out. A configuration has been selected at which the screw can be adjusted to the fluctuating waterlevels up- and downstream by using hydraulic pistons. By doing so the overall mechanical efficiency for either the screw turbine or -pump will be 75 %. The round-trip efficiency of the PSP-process will be 56.25 %.

The conceptual design of the Sambeek PSP-plant is hosting 20 screws which are placed in compartments next to each other. By lifting a screw out of position, the pump- and turbine capacity can be adjusted to the discharge conditions in the Meuse river or the pump-capacity needed. In case of emergency a compartment can be closed off by using a single leaf door. For the design waterlevels target levels provided by *Rijkswaterstaat* have been used.

The PSP-plant has been scaled according to the head differences at the other weirs in the cascade by extending or decreasing the main trough. As the cumulative fish mortality is expected to be lower than 10 %, it can be assumed the full hydropower potential of the Meuse cascade can be utilized within Dutch environmental regulations using the conceptual design of the PSP-plant. Furthermore, at periods of drought navigability can be served using the pumps thereby eliminating the need of limited locking.

The number of screws per hydropower- and PSP-plant in the Meuse cascade is determined using the 100-day design discharge which is related to a flow duration curve (FDC). The numerical Meuse model computes power production- and storage per FDC-day. It is assumed similar plants like the conceptual design for the Sambeek weir are installed throughout the cascade. The model uses default values for the storage volumes and number of screws per facility related to boundary conditions and design discharges.

During storage mode water is discharged downstream the Linne weir in the storage section Roermond-Linne, which implies this storage volume is partly filled with river discharge from upstream, and with pumped water from the downstream Roermond PSP-plant. Therefore, the river will store energy as well. When the river discharge increases the complete Roermond-Linne section is stored by the river and discharge will partly fill the storage section Belfeld-Roermond and so on. When the discharge reaches the capacities of the PSP-plants these plants are solely used for hydropower production, either at storage- or at energy mode. Under these conditions no energy storage occurs.

The cumulative installed capacity of the Meuse cascade is 50.3 MW resulting in a hydropower AEY of 205 GWh under a capacity factor of 0.47. The river stores 4.7 GWh per year. The AEY of pumped-stored power is 31.6 GWh processing a yearly surplus power of 56.2 GWh. Including the AEY for pumped-stored power results in a combined capacity factor of 0.54 for the cascade, increasing the utilization of the installed capacity by 7 %. The round-trip efficiency of the PSP-processes is 56.25 %. Up to 59,000 households can be powered with hydro- and stored energy.

To put these numbers into perspective: 54 % of the yearly power surplus (assuming the wind is blowing every night) of the Dutch OWEZ-windfarm can be stored in the Meuse cascade. Therefore, the PSP-capacity of the cascade is considered to be limited as OWEZ is representative for a small size windfarm.

By using the number of screws per PSP-plant in relation to the 100-day design discharge the full storage potential of the Meuse cascade cannot be utilized. More pump capacity is needed at the weirs of Lith, Grave and Sambeek in order to do so. Therefore, the number of screws for these PSP-plants has been calculated based on the maximum volume to pump during storage mode. This results in a cumulative installed capacity throughout the cascade of 81 MW. The overall cascade AEY on pumped-stored power increases to 77.2 GWh. When utilizing the full storage potential of the Meuse cascade up to 75,000 households can be powered with hydro- and pumped-stored power. The combined capacity factor decreases to 0.43. Despite this decrease it might still be economically interesting as the PSP-plants use surplus energy which is wasted anyway when not stored.

Downstream the Borgharen weir ships use the Juliana canal as the Meuse river is not navigable between Linne and Borgharen. A model simulation has been carried out in which – besides the Meuse cascade – the Juliana canal is included. This canal shows a total head difference of 23.2 meter. It is assumed the design discharge for the Borgharen weir is bypassed via this canal. The hydropower AEY increases to 393.1 GWh. The AEY on pumped-stored power increases to 129.3 GWh. Up to 131,000 households can be powered by hydropower and pumped-stored power when the Juliana canal is included in the model.

13.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Recommendations for further research are mainly related to the discussion. These recommendations are:

- To perform an evaluation phase for the conceptual design of the PSP-plant including stakeholders and costs.
- To determine the economic optimum number of screws with respect to utilizing the full hydropower- and the full energy storage potential of the Meuse cascade.
- To study the economic, hydraulic- and environmental feasibility of increasing the width of the storage volumes throughout the Meuse cascade thereby increasing the energy storage potential.
- To study the environmental- and economic feasibility of redesigning the Juliana canal for hydropower- and energy storage purposes.
- To improve the model so it can use real time data on discharge provided by the measurement stations of RWS.
- To research the effect of the inertia of the river discharge on the waterlevel upstream a PSP-plant when blocking this discharge.
- The model could serve additional research on the feasibility of hydropower and pumped-stored power in another river cascade as it is generally applicable.

APPENDIX A: GENERAL INFORMATION HYDROPOWER

This appendix contains information on types hydropower plants (as discussed in chapter 1 paragraph 1.3.1 'The river Meuse') in order to classify the concept of a run-of-river plant, which forms the basis for the conceptual design of the PSP-plant at Sambeek. Furthermore, it contains the derivation of hydropower formula (mentioned in chapter 1 paragraph 1.3.2 'Hydropower potential river Meuse').

TYPES OF HYDROPOWER PLANTS

Several types of hydropower plants exist around the globe. The type of plant is determined by the natural boundary conditions like the inclination of the riverbed or the possibility to build a reservoir. The different types are shown in Figure 87.

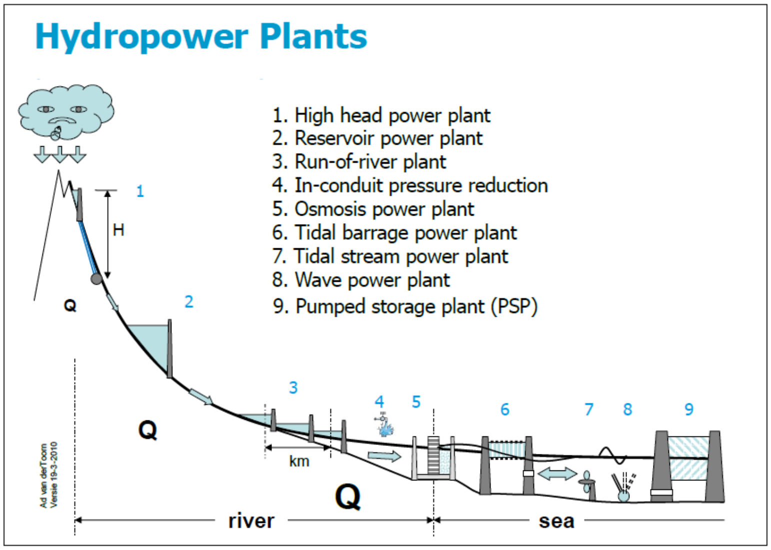


Figure 87: Overview hydropower plants (Bricker, 2018)

Considering the weir at Sambeek the type of hydropower plant which will be researched is a PSP-plant. This plant can be considered to be a run-of-river plant with a low head difference, or low head plant. Inflow equals outflow for a low head plant. Top make such a plant economically viable the discharge should not be too low in order to the low head difference. An example of 106 MW low head plant in at Laufenburg, Germany (utilizing an average discharge of 1,370 m^3/s) is shown is shown in Figure 88.

Figure 88: Run-of-river power plant at Laufenburg, Germany ("Wasserkraftwerk Laufenburg", 2019)

HYDROKINETIC FORMULA

The mass flow rate is the ratio of mass to time at an instant of time. The mass flow rate in equation form reads (Crowe et al, 2010, p.173):

$$\dot{m} = mass\ of\ fluid\ passing\ cross\ sectional\ area\ /\ interval\ of\ time$$

Using Figure 89 and taking the time derivative of the distance L to obtain the velocity, one can derive the mass flow rate:

$$mass = \rho * V = \rho * A * L$$

$$\dot{m} = \rho * A * v \qquad (unit{:}\ {}^{kg}/_{s})$$

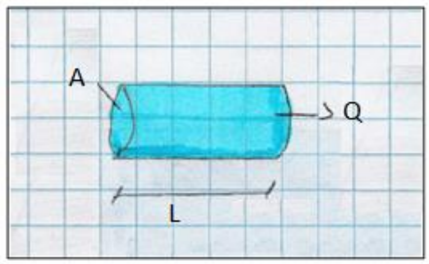


Figure 89: Mass flow rate

Power (P) expresses a rate of work or energy. It is defined as (Crowe et al, 2010, p.254):

$$P = quantity\ of\ energy\ /\ interval\ of\ time$$

Using the definition of kinetic energy to describe the quantity of energy one can derive:

$$P = quantity\ of\ energy\ /\ interval\ of\ time$$

$$P = \frac{1}{2} m v^2 /\ s$$

$$P = \frac{1}{2} v^2\ mass\ /\ second$$

$$P = \frac{1}{2} v^2\ mass\ flow\ rate$$

$$P = \frac{1}{2} v^2 \rho A v$$

$$P = \frac{1}{2} \rho A v^3$$

This formula is the so called hydrokinetic formula which can be used the calculate the power available in flowing water without a head difference. Corrected for efficiency losses the hydrokinetic formula reads:

$$P = \frac{1}{2} * \rho * A * v^3 * \eta \qquad \text{formula (12)}$$

HYDROPOWER FORMULA

The principle of hydropower is based on the conversion of the potential energy of water into kinetic energy. Part of this kinetic energy is converted into rotational energy of a turbine. By rotating this turbine generates electricity which is delivered to the grid. The potential energy that is utilizable is the result of a higher water level upstream a dam compared to a lower water level downstream. This is shown schematically in Figure 90.

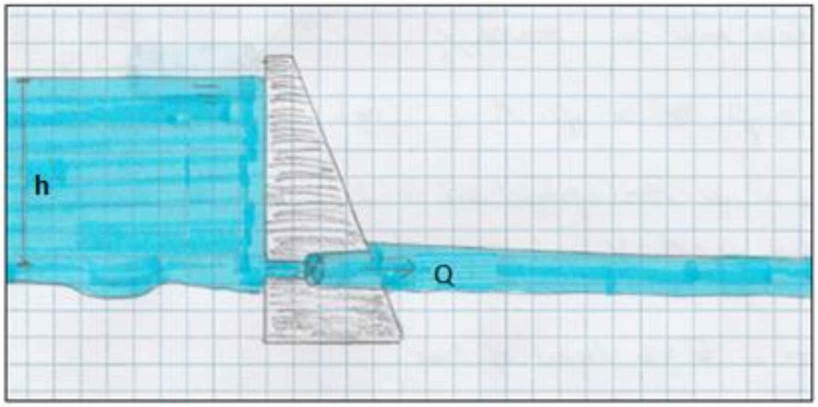


Figure 90: Head difference up- and downstream dam

The principle of conservation of energy in a closed system reads (Crowe et al, 2010, p.255):

$$E_{kinetic} = E_{potential}$$

This results in:

$$\frac{1}{2}mv^2 = mgh$$

$$v = \sqrt{2gh}$$

Using the hydrokinetic formula one can derive:

$$P = \frac{1}{2}\rho A v^3$$

$$P = \frac{1}{2}\rho A v^2 v$$

$$P = \frac{1}{2}\rho A(\sqrt{2gh})^2 v$$

$$P = \rho g A v h$$

$$P = \rho g Q h$$

The latter is the so called hydropower formula. Corrected for efficiency losses it reads:

$$P = \rho * g * Q * h * \eta$$

The hydropower formula is the most essential formula for the design of a hydropower plant. It indicates the amount of energy which can be generated based on a certain discharge and head difference.

APPENDIX B: DISCHARGE ANALYSIS MEUSE

Appendix B contains information on the FDC constructed using peak discharges, fish passages and the diversion of discharge in the Juliana- and Zuid-Willems canal.

FDC USING PEAK VALUES

The FDC showing peak values is constructed by using block maxima and -minima of all the data on discharge in the period 2000-2019. This is shown in Figure 91 and explained on the next page.

upper side arry for extreme **maxima:**			**lower** side array for extreme **minima:**		
array 1-7300:	**discharge**	**FDC day:**			
1	**2288.2**	**1**	7257	25.3	
2	2238		7258	25.2	
3	2142.2		7259	25.2	
4	2122.4		**7260**	**25.1**	**363**
5	2026.4		7261	25.1	
6	2000.0		7262	25	
7	1944.9		7263	24.9	
8	1916		7264	24.9	
9	1868.6		7265	24.8	
10	1856.9		7266	24.8	
11	1856.4		7267	24.7	
12	1823		7268	24.7	
13	1822.2		7269	24.3	
14	1787.4		7270	24.2	
15	1784.8		7271	24.2	
16	1781.4		7272	24.2	
17	1759.8		7273	24.1	
18	1733.5		7274	23.9	
19	1726.4		7275	23.9	
20	1707.8		7276	23.9	
21	**1705.7**	**2**	7277	23.8	
22	1702.8		7278	23.6	
23	1700		7279	23.6	
24	1697.2		**7280**	**23.6**	**364**
25	1663.5		7281	23.3	
26	1646		7282	23.2	
27	1640		7283	22.8	
28	1621		7284	22.7	
29	1607.4		7285	22.6	
30	1601.7		7286	22.2	
31	1599		7287	22.1	
32	1598.5		7288	22.1	
33	1569.6		7289	22	
34	1559.3		7290	22	
35	1559.3		7291	21.9	
36	1551.7		7292	21.7	
37	1543.3		7293	21.6	
38	1536.7		7294	21.6	
39	1527.9		7295	21.4	
40	1523.6		7296	21.3	
41	**1522.9**	**3**	7297	21	
42	1510.1		7298	21	
43	1500		7299	20.9	
44	1483		**7300**	**20.5**	**365**

Figure 91: Array of 7300 data points used for construction of peak discharge FDC

In Figure 91 one can observe the upper side of the array of 7300 discharge measurements for the years 2000-2019. It shows the first 44 data points of this array before it is cut off. For the first half of this 7300 array (1-3660) the maximum value for each block of 20 data points is selected, which is marked by the blue numbers. By doing so 183 FDC days representing the peak maxima on the discharge are obtained. The first three days are shown as FDC day 1, 2 and 3 in Figure 91.

In Figure 91 once can observe the lower side of the array of 7300 data points at the right. For every block of 20 data points (in the range 3661-7300) the peak minima on the discharge are extracted. These numbers are marked in red. The last three days are shown as FDC day 363, 364 and 365.

Using these peak maxima and -minima the flow duration curve is constructed shown in Figure 92. The peak maximum discharge is 2288.2 m^3/s. The peak minimum discharge is 20.5 m^3/s.

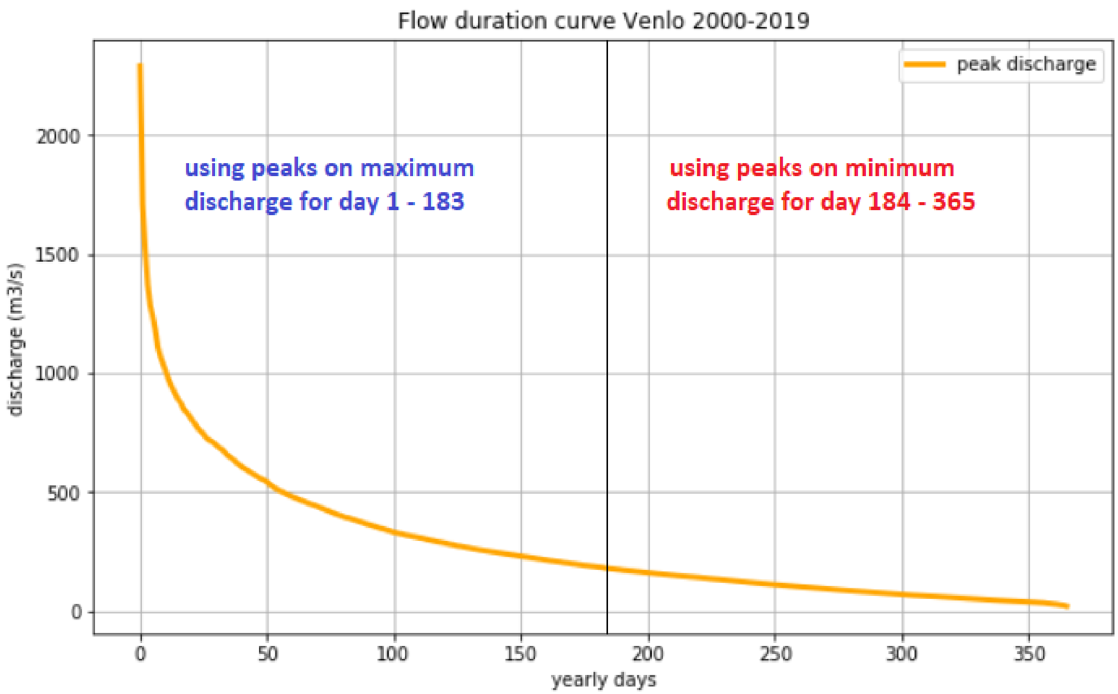


Figure 92: Construction of FDC using peak discharges

FDC AND DESIGN DISCHARGE BORGHAREN

The FDC and design discharge for the measurement location of Borgharen are shown in Figure 93.

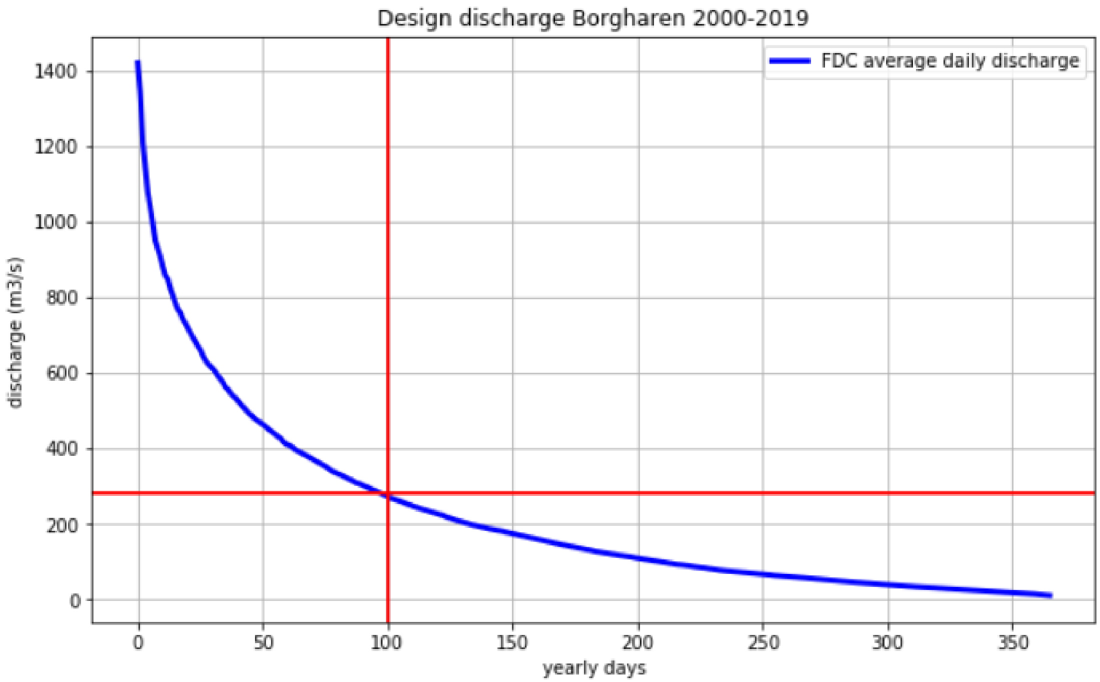


Figure 93: FDC Borgharen, design discharge 280 m³/s

FDC DESIGN DISCHARGE MAASBRACHT

In a similar way the design discharge for Maasbracht has been determined, which will be 300 m³/s. This FDC will be used for the weir at Linne.

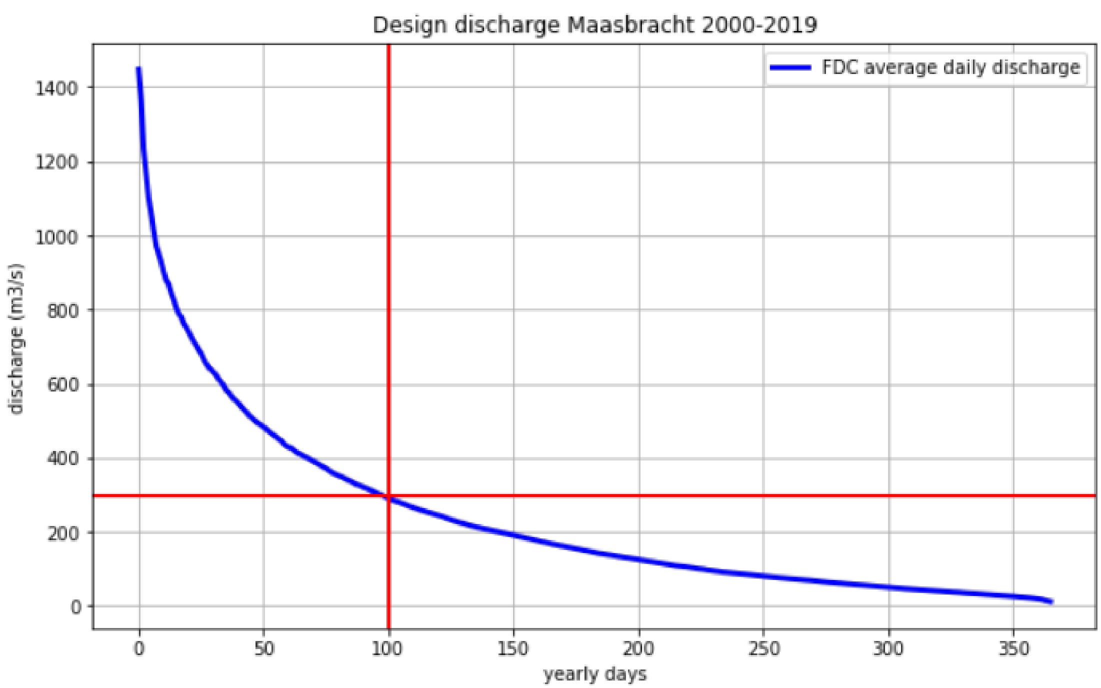


Figure 94: FDC Maasbracht, design discharge 300 m³/s

DESIGN DISCHARGE MEGEN

The FDC for Megen – which will be used for the weir at Lith - and its design discharge (360 m^3/s) are shown in Figure 95.

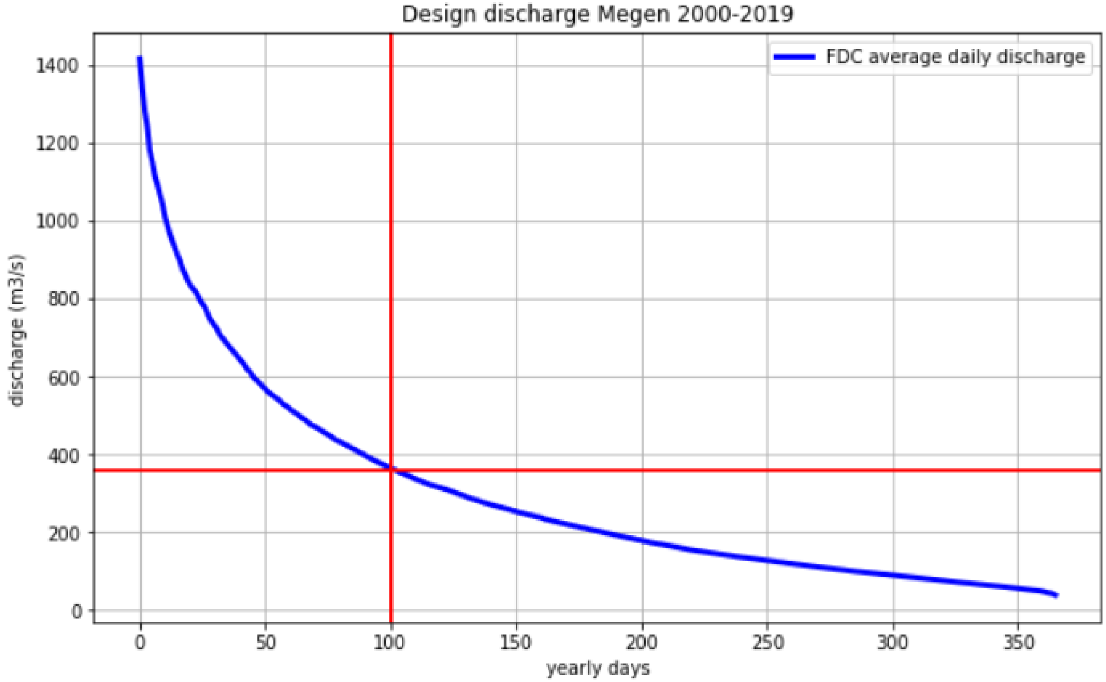


Figure 95: FDC Megen, design discharge 360 m^3/s

COMPARISON OF AVERAGE DISCHARGES

Because of the canals and the presence of tributaries the average daily discharge in the river Meuse differs. For the following measurement locations the average daily discharge in the period 2000 - 2019 is :

- Borgharen: 220.0 m^3/s
- Maasbracht: 235.8 m^3/s
- Venlo: 276.3 m^3/s
- Megen: 295.1 m^3/s

2000-2019	Average discharge (m3/s):
Borgharen dorp	220.0
Maasbracht	235.8
Venlo	276.3
Megen	295.1

Figure 96: Results on data processing Meuse cascade

FISH PASSAGE

Lanters (1995, p.8) evaluated the hydraulic characteristics of the fish passage at the Belfeld weir - which is of the same type as the one at the Sambeek weir - using the graphical illustration shown in Figure 97. Using multiple measurement points to measure the flow velocity, and by measuring the waterdepth the discharge is determined, which is found to be 3 to 4 m^3/s.

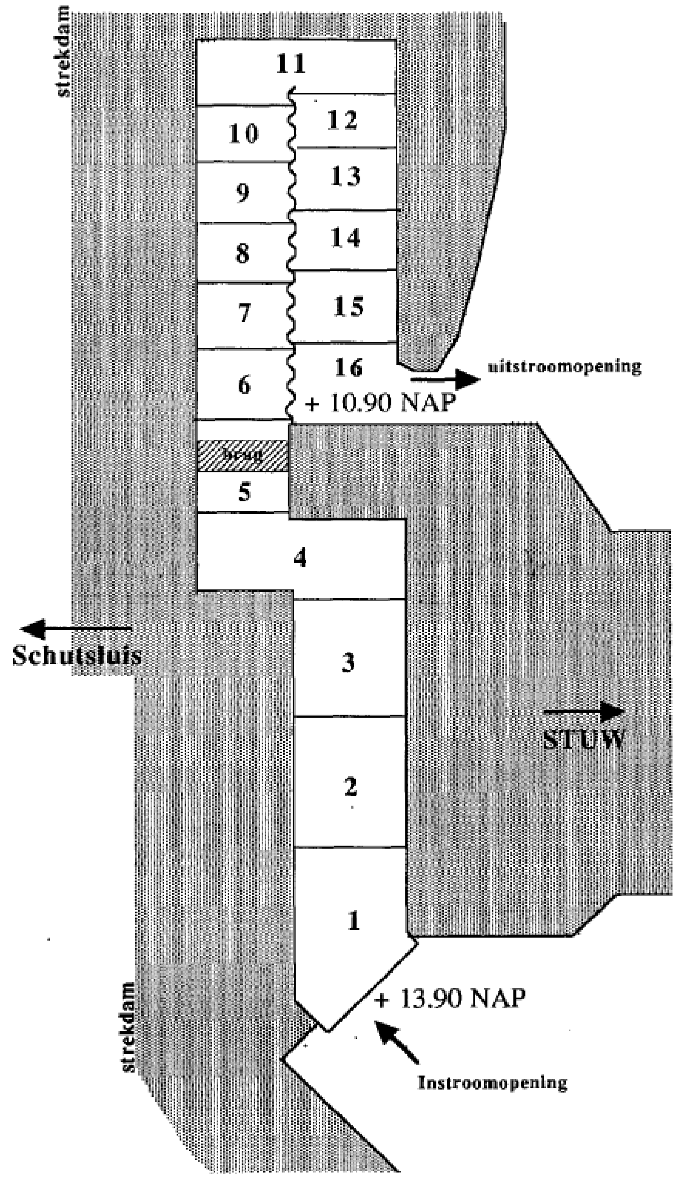


Figure 97: Fish passage at the Belfeld weir used for determination of discharge (Lanters,1995)

CALCULATIONS ON BOUNDARY CONDITIONS FOR SAMBEEK

The available discharge for Sambeek is calculated to be:

$$Q_{available,Sambeek} = 335\, {m^3}/{s} - 20\, {m^3}/{s} - 5\, {m^3}/{s} - 3\, {m^3}/{s} - 7\, {m^3}/{s} = 300\, {m^3}/{s}$$

The minimum discharge to start powering one screw turbine will be:

$$Q_{min} = 20\, {m^3}/{s} + 5\, {m^3}/{s} + 3\, {m^3}/{s} + 7\, {m^3}/{s} + 3\, {m^3}/{s} = 38\, {m^3}/{s}$$

JULIANACANAL AND ZUID-WILLEMSCANAL

Upstream of Borgharen the discharge of the Meuse is divided over the river itself, the Zuid-Willemscanal and the Julianacanal. The measurement locations with respect to this canals - at Smeermaas and Bunde respectively - are shown in Figure 98. Furthermore, the canals itself are marked in the figure.

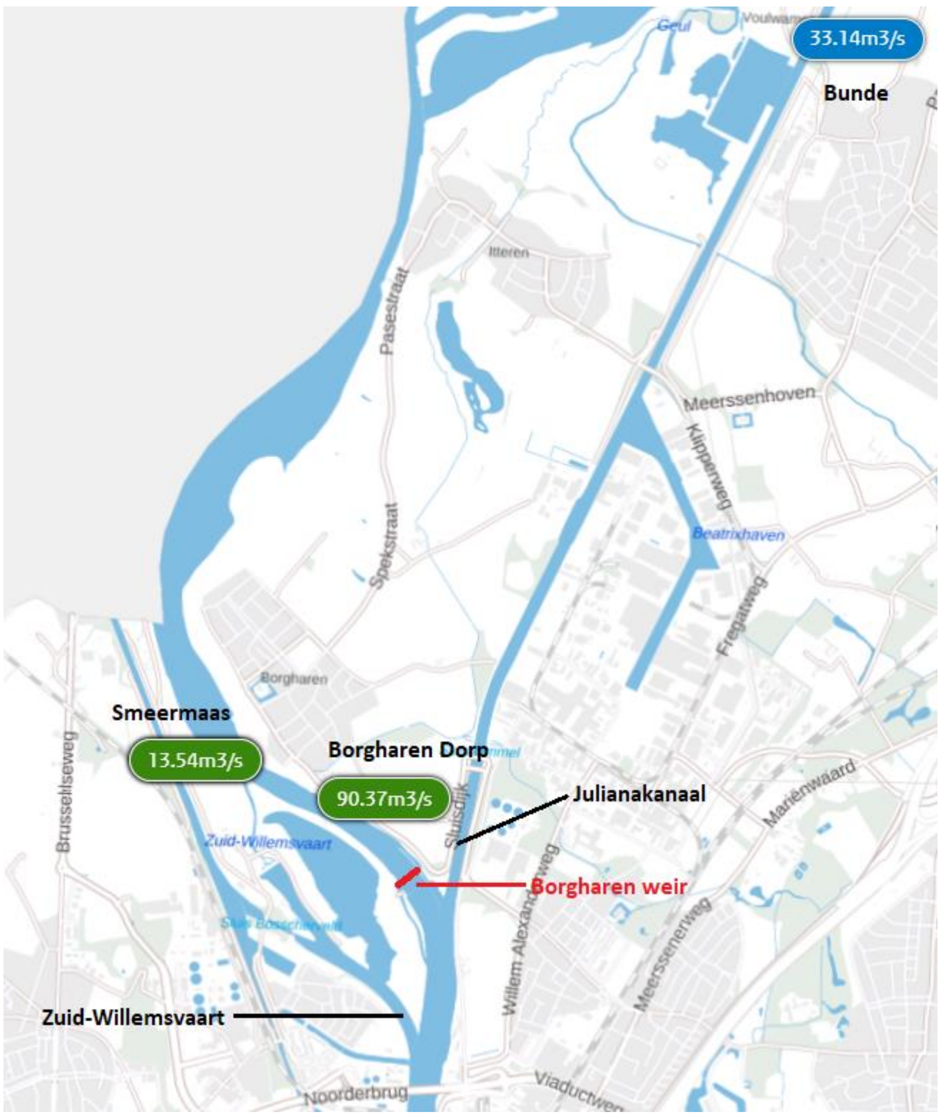


Figure 98: Flow diversion upstream of Borgharen weir ("RWS Waterinfo", 2020)

The Julianacanal is flowing back into the river Meuse at the location of Maasbracht, which is just upstream of lock- and weir complex Linne. This location is shown in Figure 99.

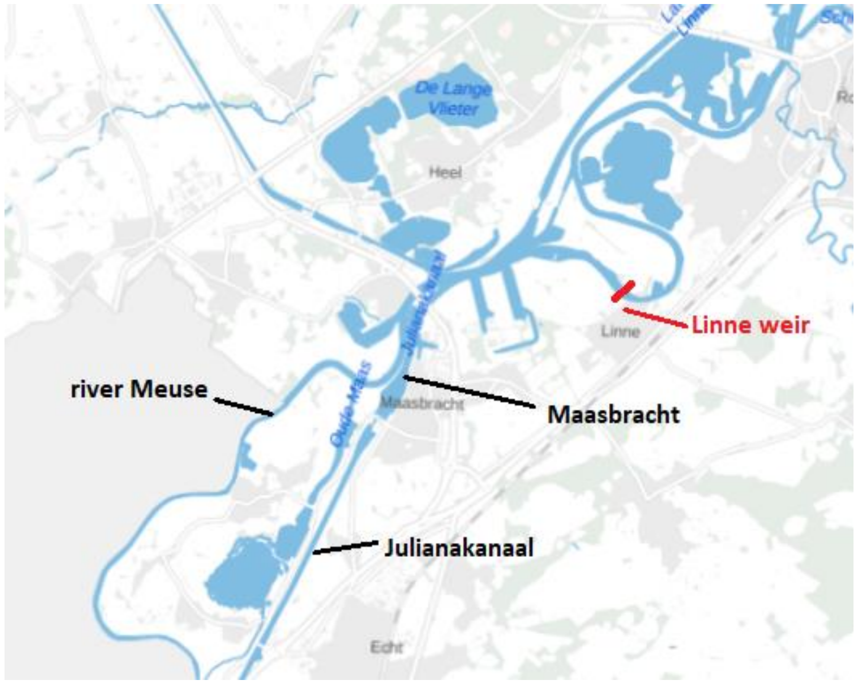


Figure 99: Location of Julianacanal flowing back into river Meuse ("RWS Waterinfo", 2020)

APPENDIX C: WATERLEVELS ANALYSIS WEIRS

Appendix C contains information on peak river mode and waterlevels needed to derive the boundary conditions as discussed in chapter 5.

WATERLEVELS WEIRS CASCADE USING TIME SERIES 2000-2019

In the analysis on waterlevels figures of the Sambeek- and Borgharen weir are shown in the main chapter. Figures for the remaining weirs are shown in this appendix. The exception is the Lith weir, which is shown in chapter 9.

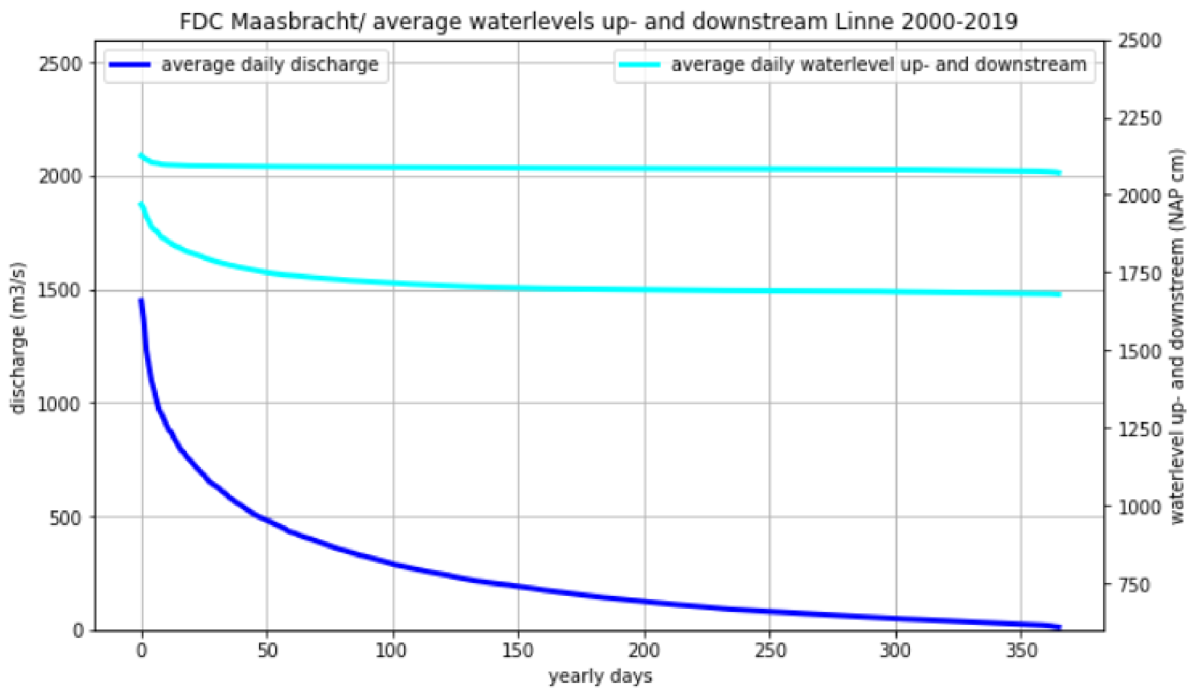


Figure 100: Waterlevels at Linne weir

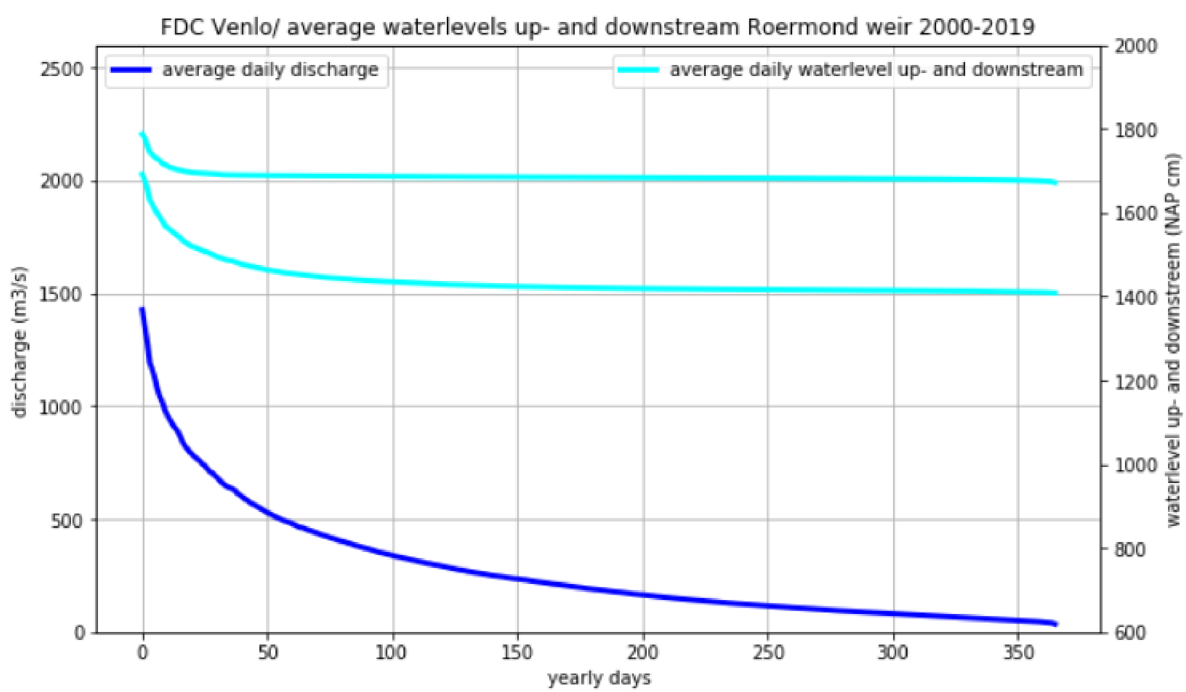


Figure 101: Waterlevels at Roermond weir

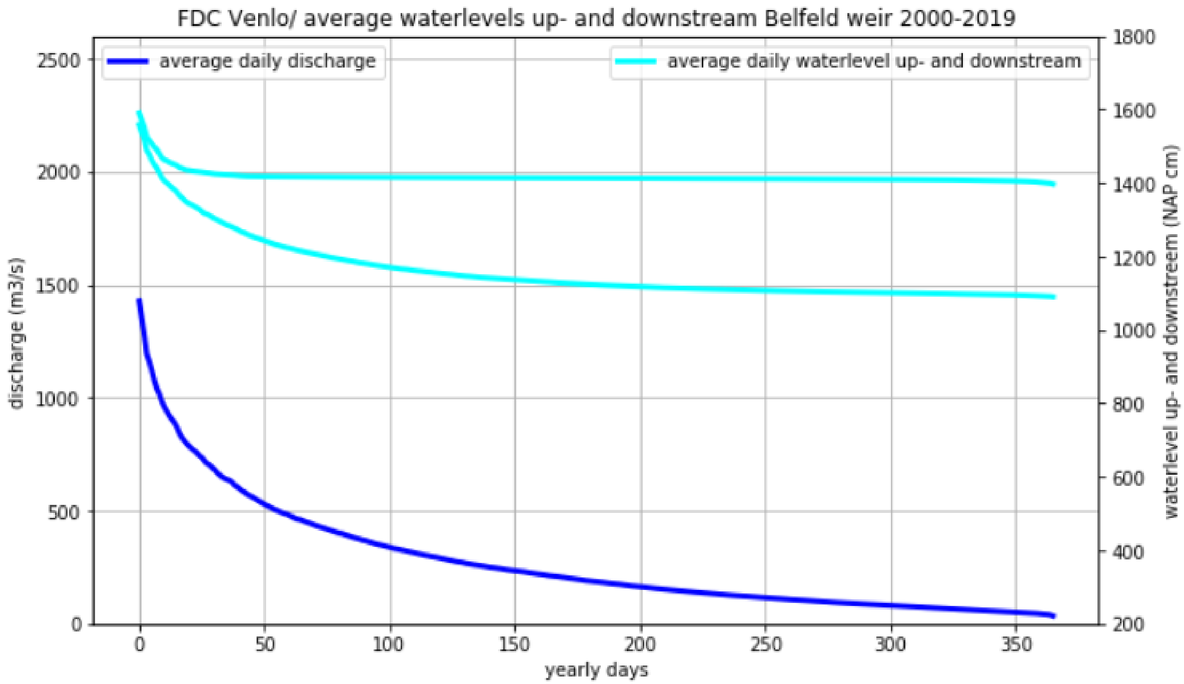


Figure 102: Waterlevels for the Belfeld weir

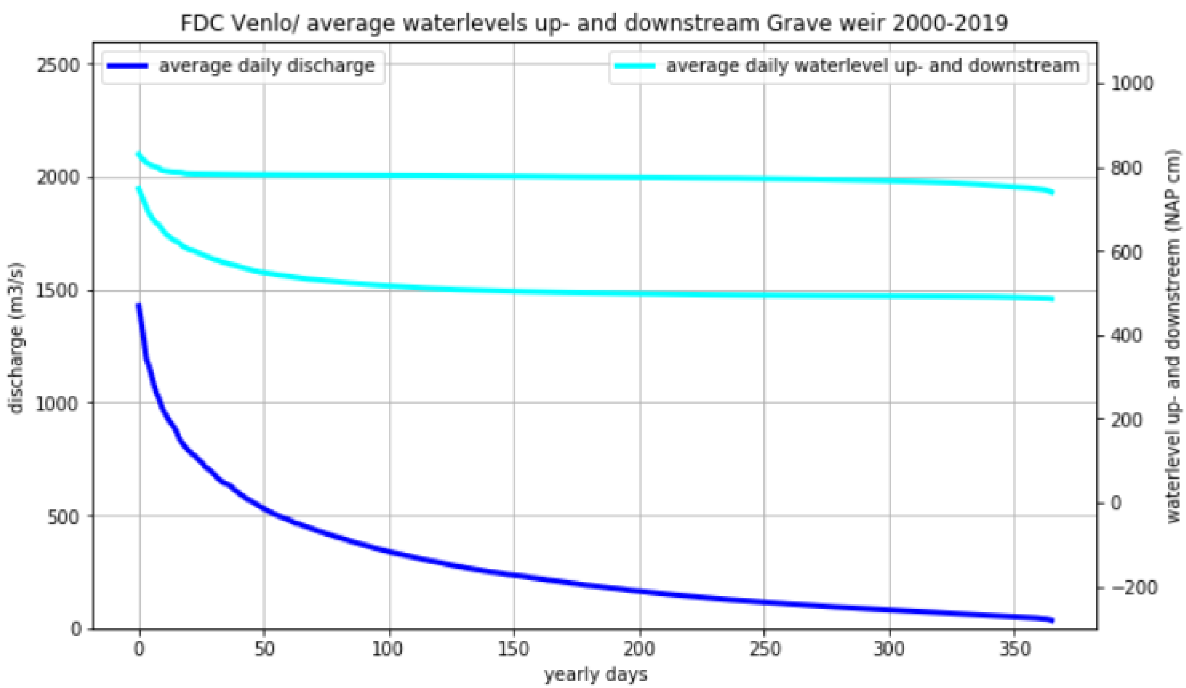


Figure 103: Waterlevels at weir Grave

MARIA VALENTINE

On the 29th of December 2016 the German tanker Maria Valentine collided with the weir upstream at Grave in heavy fog. The lift gates of the weir were ripped of their yokes. A picture of the damaged weir is shown in Figure 104. Due to its inertia the ship sailed completely through the destroyed weir eventually ending below downstream ("Ongeval op Maas", 2020). The Maria Valentine has been repaired and is sailing again despite crashing completely through the weir and falling down 3 meters.

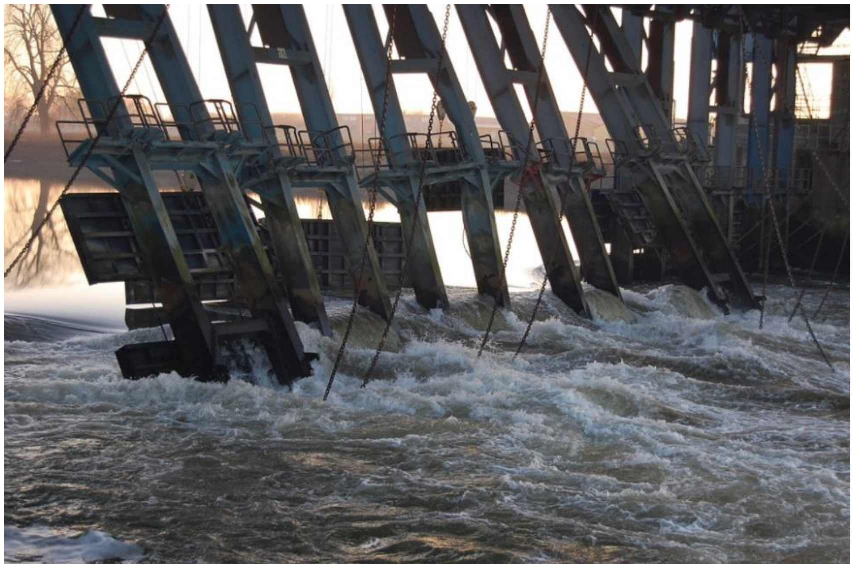


Figure 104: Damaged weir at Grave and emptying of the section upstream ("Bestand: Stuw Grave", 2020)

As a result of the damaged weir the water level in the section upstream of the Grave decreased almost 4 meter, as shown in Figure 105. It lasted for 26 days until a temporary weir was in function at Grave, and the waterlevel could be restored to the usual level upstream (and as a consequence downstream of Sambeek). The waterlevel data of this period have been replaced by a value of 800 NAP cm to make them usable in the analysis of this chapter.

date:	waterlevel NAP cm:
12/26/2016	798.3
12/27/2016	797.2
12/28/2016	795.1
12/29/2016	789
12/30/2016	623
12/31/2016	557
1/1/2017	528.5
1/2/2017	540.3
1/3/2017	540.1
1/4/2017	532.2
1/5/2017	526.5
1/6/2017	527.5
1/7/2017	535.2
1/8/2017	525.9
1/9/2017	537.4
1/10/2017	545.9
1/11/2017	573.5
1/12/2017	589.9
1/13/2017	640
1/14/2017	677.5
1/15/2017	682.5
1/16/2017	675.2
1/17/2017	616.3
1/18/2017	597.3
1/19/2017	602.2
1/20/2017	616.8
1/21/2017	648.7
1/22/2017	685.4
1/23/2017	714.2
1/24/2017	764.2
1/25/2017	795.9
1/26/2017	792.9
1/27/2017	792.9
1/28/2017	794.2

Figure 105: Waterlevels downstream Sambeek weir due to damaged weir at Grave in 2016-2017

DATA FROM RIVER FLOOD WAVES BEFORE 2000

In 1980 two flood waves occurred in the Meuse river. The gross head at Sambeek decreased to 25 cm at the 9th of February with a maximum water level upstream of NAP 1250 cm. This shown in Figure 106.

date:	upstream (NAP cm):	downstream (NAP cm):	difference (cm):
5/2/1980	1130	1100	30
6/2/1980	1192	1168	24
7/2/1980	1231	1205	26
8/2/1980	**1250**	**1225**	**25**
9/2/1980	1247	1223	24
10/2/1980	1228	1203	25
11/2/1980	1198	1173	25

Figure 106: Data on winter flooding event 1980

Remarkably a flood wave occurred during the summer of 1980 as well. During this wave the gross head decreased to 24 cm with a maximum water level upstream of NAP 1260 cm. The data of this flooding event are shown in Figure 107.

date:	upstream (NAP cm):	downstream (NAP cm):	difference (cm):
21/07/1980	1078	1035	43
22/07/1980	1171	1142	29
23/07/1980	1252	1228	24
24/07/1980	**1284**	**1260**	**24**
25/07/1980	1274	1254	20
26/07/1980	1211	1191	20
27/07/1980	1099	1083	16

Figure 107: Data on summer flooding event 1980

The flood wave in 1993 occurred in the month of December (("Rijkswaterstaat Waterinfo", 2019). At the 25th of December the highest water level upstream was measured, which was NAP 1388.1 cm. The difference in head is 18 cm. The data from this flood wave are shown in Figure 108.

date:	upstream (NAP cm):	downstream (NAP cm):	difference (cm):
12/22/1993	1263	1224.2	38.8
12/23/1993	1329.8	1306.8	23
12/24/1993	1375.5	1357.5	18
12/25/1993	**1388.1**	**1370.1**	**18**
12/26/1993	1376.3	1358.3	18
12/27/1993	1353	1335	18
12/28/1993	1320.2	1299.9	20.3

Figure 108: Waterlevels at 1993 flooding Meuse

The Meuse flooding of 1995 occurred in February. The minimum gross head was 8.3 cm. These data are shown in Figure 109.

date:	upstream (NAP cm):	downstream (NAP cm):	difference (cm):
1/29/1995	1356.3	1342.5	13.8
1/30/1995	1378.8	1364.4	14.4
1/31/1995	1387.6	1376.9	10.7
2/1/1995	**1397.2**	**1388.9**	**8.3**
2/2/1995	1394	1383	11
2/3/1995	1365.5	1354.1	11.4
2/4/1995	1333.8	1319.5	14.3

Figure 109: waterlevel up- and downstream at river flood wave Sambeek 1995

APPENDIX D: STORAGE VOLUMES

This appendix clarifies why the Borgharen weir is not suitable for storage purposes, as it will fall dry when the water is pumped upstream.

The Meuse downstream the Borgharen weir contains a relatively steep bed slope. By analyzing data on waterlevels in the period 2014 -2019 the average difference in waterlevel between Borgharen and Lanaken is determined to be 103 cm. In Figure 110 one can view the location of Lanaken and the waterlevel difference at the 24th of June, 2020 (at this date the waterlevel difference is even higher).

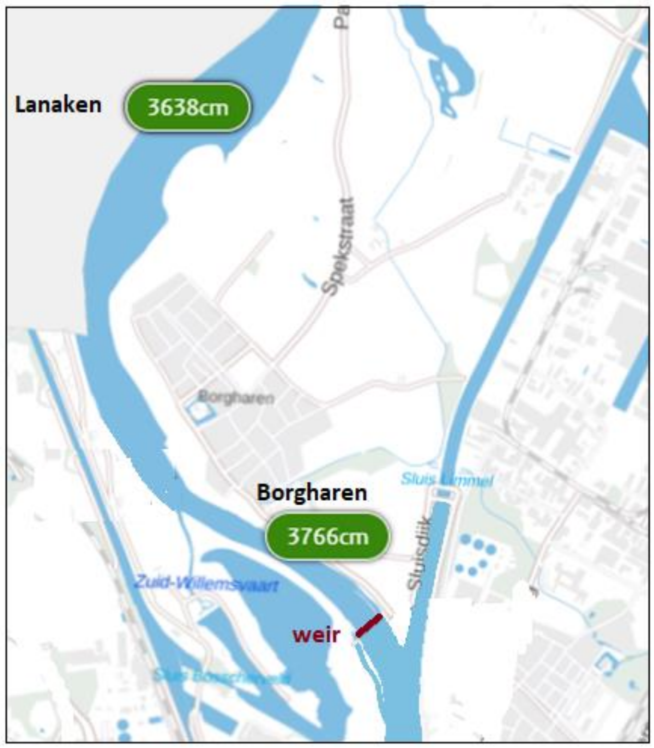


Figure 110: Location of Lanaken and the Borgharen weir ("RWS Waterinfo", 2020)

Lanaken is located 3500 meters downstream of Borgharen. Using the average waterlevel difference the bed slope becomes:

$$i = \frac{1.03}{3500} = 0.000294$$

PSP-plants in the Meuse cascade are be equipped with Archimedean screws, as elaborated on in chapter 10. When using a 5-meter diameter screw under a pump angle of inclination of 30 ° the pump filling point (PFP) is located at a height of 3.25 meter.

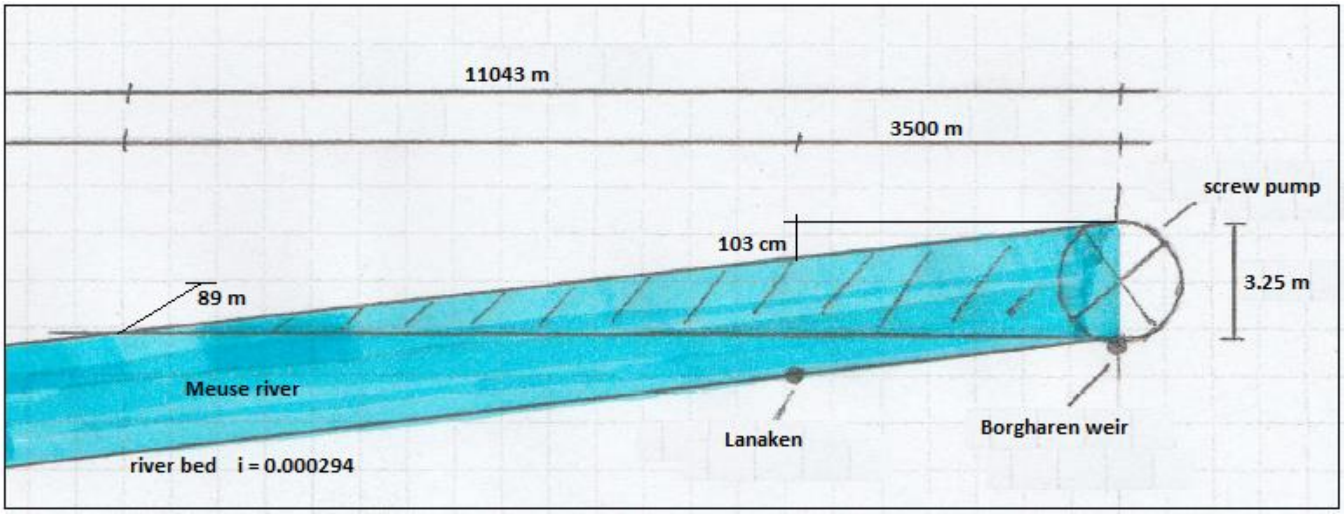


Figure 111: Meuse river downstream of Borgharen weir

The volume in the marked triangle is 3,200,000 m^3 when using a width between the summer dikes of 89 meter (Bodegraven, 2009). When using 18 turbines pumping at 11 m^3/s, the installed pump capacity is 198 m^3/s. This implies the volume will be pumped upstream in 4.5 hrs. (Estimation is not adjusted for decreased pump capacity due to decreasing waterlevel).

The river itself will transport the volume in the blue triangle downstream as it will flow because of the bed slope. By combining the effect of river flow and pumping it can be assumed the river downstream of the Borgharen weir will fall dry within 4 hours after the discharge is blocked and storage pumping starts.

APPENDIX E: TURBINES

In Figure 112 one can observe the results of a study on fish mortality due to the screw turbine performed by Charisiadis (2015).

Species	No. Tested	Length Range (cm)	No. fish Injured	Injuries
Eel	22	36-58	0	
Grayling	3	20-36	0	
Brown trout	31	8-35	0	
Perch	19	14-18	0	
Chub	63	8-43	5	Scale loss, haematoma
Gudgeon	8	12-14	0	
Bullhead	3	11-14	0	
Dace	1	21	0	
Roach	8	16-21	2	Scale loss, haematoma

Figure 112: Result on fish mortality using screw turbine (Charisiadis, 2015)

DUTCH SUPPLIERS

Spaans Babcock is s Dutch supplier with 120 year experience in the construction of waste water treatment plants and more recently the construction of hydropower facilities using Archimedean screws. Their portfolio shows realised hydropower projects in amongst others Albini, Italy and Grünau, Austria (Spaans Babcock, 2020).

Landustrie is another Dutch company active in the field of waste water management. This company extended their range of screw pumps with hydropower screw turbines. Landustrie offers 0.5 m^3/s screw turbines for a head difference of 1 meter up to 15 m^3/s for 10-meter head. Within their international portfolio they show two realised projects in the Netherlands, which are the installation of a screw turbine at Sint-Michielsgestel and the installation of a screw with a length of 20,5 meter in a retrofitted lock chamber in the Wilhelmina canal, Tilburg (Landustrie, 2020).

FishFlow Innovations is a Dutch company which founded in 2006. One of the pillars of this company is the focus on fish friendly innovations to be used at hydropower projects. Amongst other the company offers the horizontal turbine and the screw turbine ("FishFlow Innovations", 2020).

The presence of these companies indicates knowhow on the Archimedean screw is available in the Netherlands, which is considered beneficiary with respect to the Meuse cascade.

APPENDIX F: ARCHIMEDEAN SCREW

Appendix F provides figures and manufacturing information referred to in the main chapter. Furthermore, it presents additional information on the efficiency of the screw pump- and turbine.

EFFICIENCY LOSS DUE TO SUBMERGENCE SCREW PUMP FILLING POINT

According to Fisher et al (2020) in the literature on screw pumps little information is available on the effect on pump efficiency of a submerged lower end of a screw. Fisher et al (2020) present a short overview on research. Muysken (1932) provides some data for a small range of lower end filling points.

Because of the scarcity on information (Fisher et al, 2020) studied the influence of the waterlevel at the lower end on the efficiency of a screw pump. They conclude the efficiency will slightly decrease depending on the rotational velocity of the screw, which is shown in Figure 113. It should be mentioned a screw on a laboratory scale (diameter 0.3 meter) has been tested. The average efficiency of a larger diameter screw is approximately 10 % higher (Wijdieks & Bos, 1994).

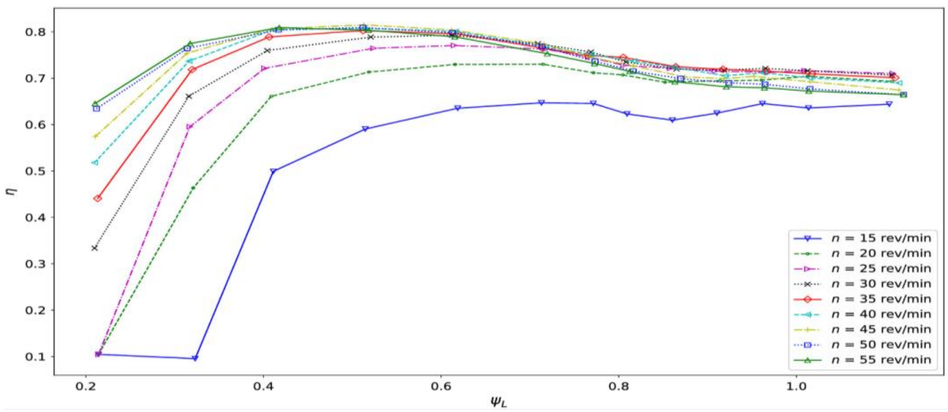


Figure 113: Efficiency loss due to increasing waterlevel at lower end screw (Fisher et al, 2020)

EFFICIENCY SCREW PUMP

As one can notice on the information provided in Figure 114 the maximum pump capacity of a 5000 mm screw decreases from 11.530 m^3/s to 9.260 m^3/s when increasing the angle of inclination from 30 to 35 degrees respectively. This is a 3.9 % average decrease of volume of pumped water per degree increase in inclination angle.

Screw diameter (mm)	Max. speed (r.p.m.)	30°		35°		38°	
		Capacity max (m^3/sec.)	Ho max. (mm)	Capacity max (m^3/sec.)	Ho max. (mm)	Capacity max (m^3/sec.)	Ho max. (mm)
300	118	0,016	2800	0,012	3200	0,011	3500
450	98	0,041	4000	0,033	4600	0,029	5000
600	75	0,082	4700	0,066	5400	0,059	5900
800	62	0,154	5500	0,125	6300	0,0112	6900
1000	53	0,272	6700	0,218	7700	0,196	8400
1250	46	0,430	7700	0,360	8900	0,312	9700
1500	40	0,690	8600	0,556	10000	0,500	10900
1800	36	1,080	9800	0,866	11400	0,777	12500
2100	32	1,500	9200	1,210	10500	1,087	11500
2450	29	2,210	8000	1,770	9100	1,591	10000
2800	26	2,980	10500	2,390	12100	2,150	13300
3200	24	4,070	10600	3,273	12100	2,940	13300
3600	22	5,360	11000	4,306	12600	3,860	13800
4050	21	7,060	11400	5,670	13000	5,090	14200
4500	19	9,000	11700	7,240	13300	6,500	14600
5000	18	11,530	12000	9,260	13600	8,320	14900

Figure 114: Pump capacity at increasing angles of inclination. (Landustrie, 2007)

EFFICIENCY SCREW TURBINE REVERSE ENGINEERED

Figure 115 has been used to reverse engineer the efficiency of a 5-meter diameter screw turbine. It turned out to be 75 %.

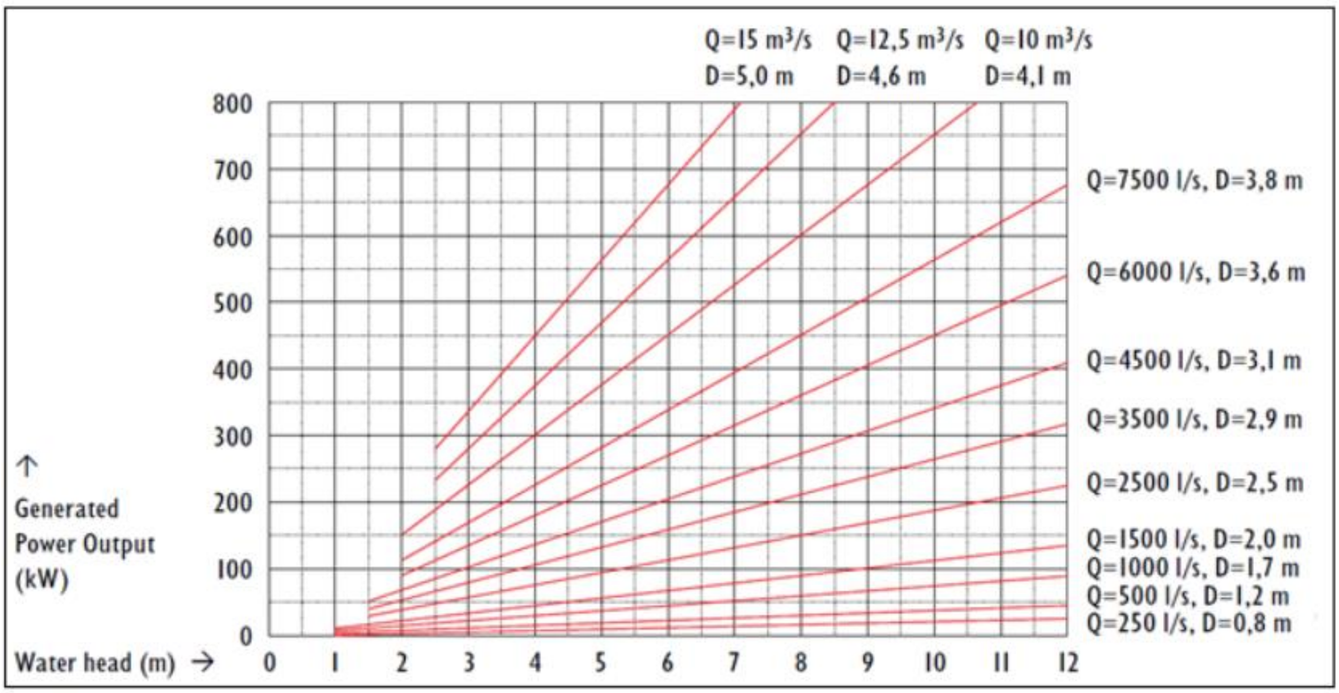


Figure 115: Generated power output screw turbine (Spaans Babcock, 2019)

NUMBER OF BLADES AND EFFICIENCY

Issac et al (2018) performed research on the efficiency of a screw and the number of blades. The influence of the number of blades is minor. This is shown in Figure 116. As one can observe the efficiency using one, three of four blades is slightly higher than using two or five blades.

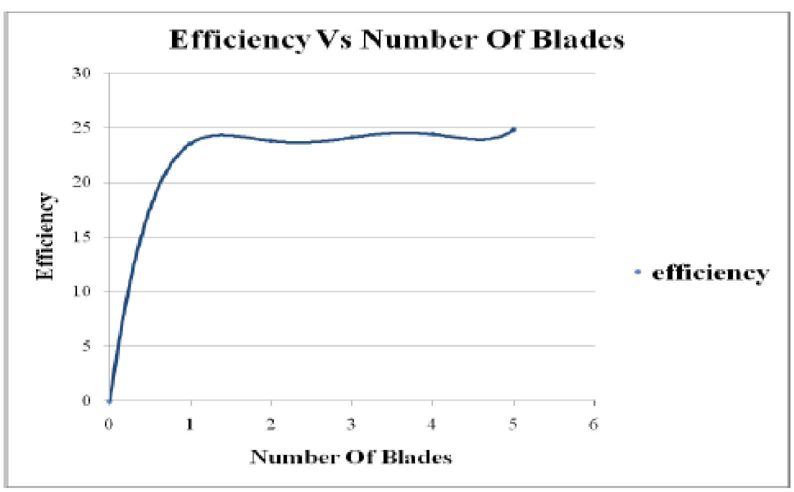


Figure 116: Number of blades and efficiency (Issac et al, 2018).

EFFICIENCY LOSS DUE TO SUBMERGENCE

Figure 117 illustrates formula 7 presented in the main chapter graphically.

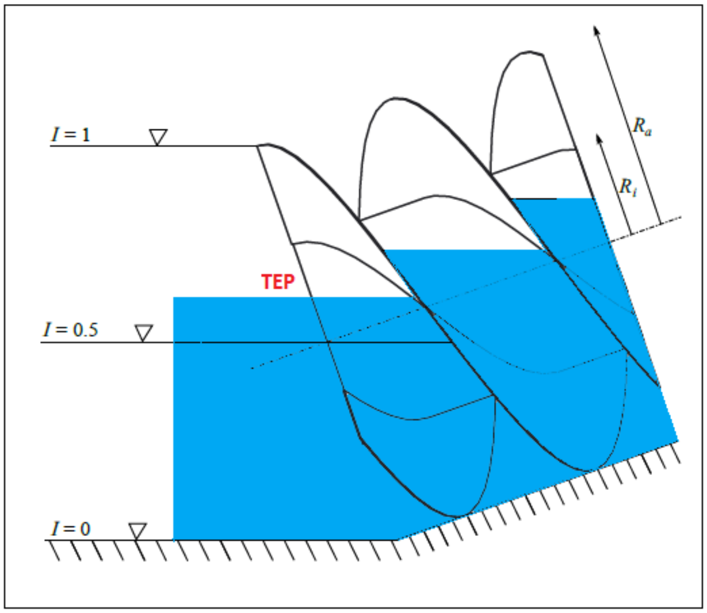


Figure 117: Graphical illustration of formula 7, adjusted picture (Dellinger et al, 2016)

The experiments of Nuernbergk (2012) indicate an efficiency loss up to 20 % can occur due to submergence. The results are shown in Figure 118.

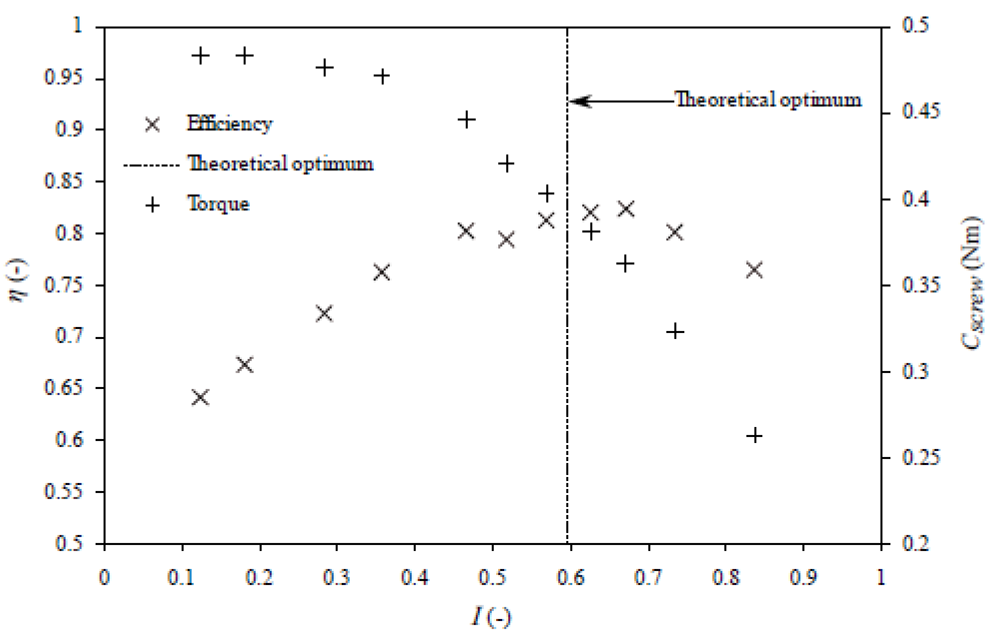


Figure 118: submergence and efficiency (Dellinger et al, 2016).

MUYSKEN LIMIT

The Dutch engineer Muysken published his world-famous article 'Calculation of the efficiency of the screw pump' (In Dutch: 'Berekening van het nuttig effect van de vijzel') on May 20, 1932. The content of the article comprises the derivation of formulas - related to the yield, leakage and efficiency of the screw – using coefficients depending on the geometry of 26 different screw pumps.

The influence on the efficiency and yield of the screw depending on its geometry, length and delivery head are studied in lab experiments. Furthermore, efficiency losses due to friction are studied, as well as the influence on efficiency of the rotational speed of the screw. The results of these lab experiments are compared to the results of the formulas.

For the determination of the rotational speed of a screw pump Muysken advises to use a formula, which reads:

$$n_{pump} = \frac{50}{\sqrt[3]{D^2}}$$

Nowadays this is called the "Muysken limit". This limit is a further development of the work of other engineers on the optimal rotational velocity of a screw (Muysken, 1932, p. W. 88). However, it is an assumptional (In Dutch: 'aanneming') formula, not the result of a mathematical derivation. Muysken states this formula matches data from practice the closest. In Figure 119 one can observe the results of different rules of thumb.

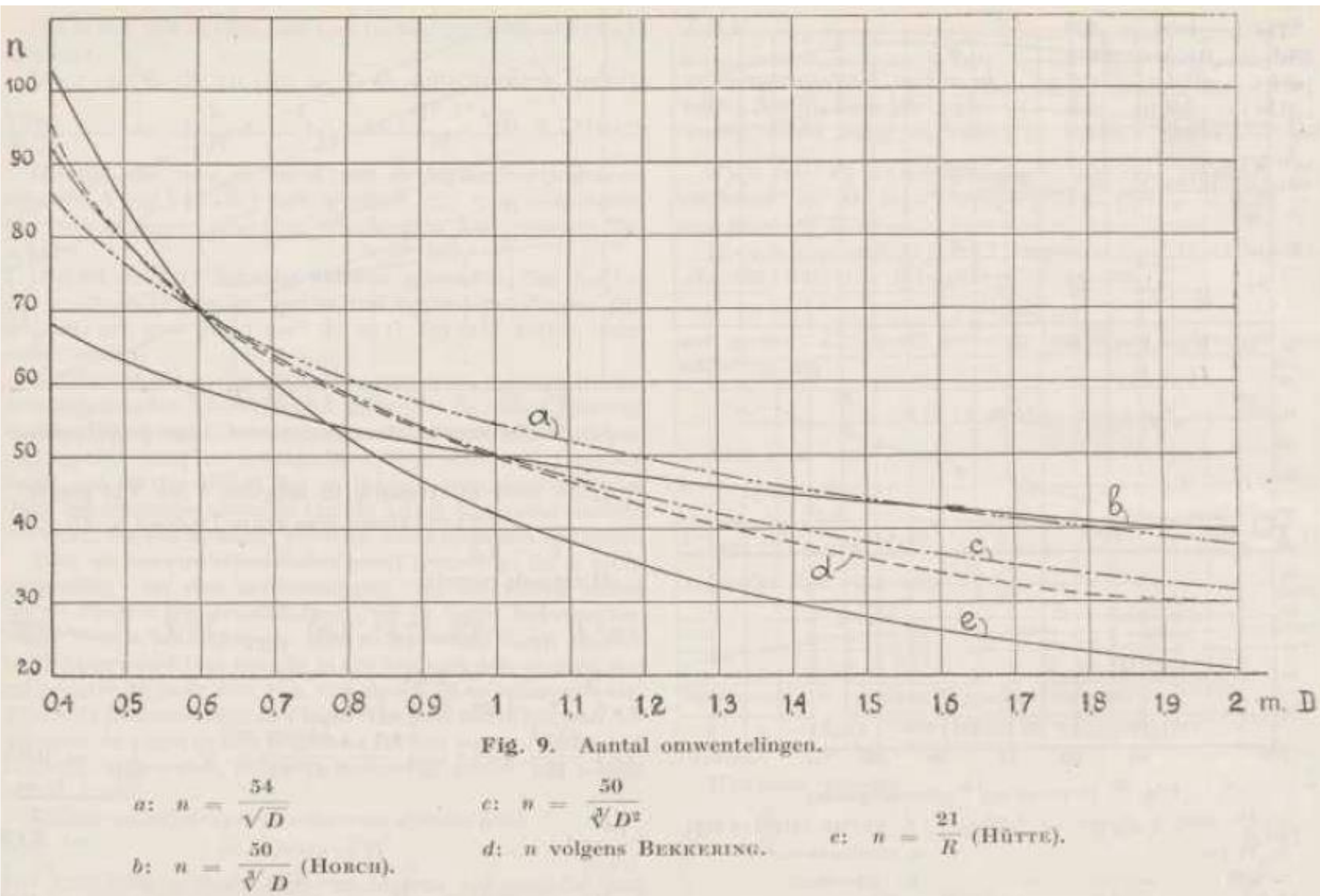


Figure 119: Results of different rules of thumb on optimal rotational velocity screw pump (Muysken, 1932)

In 1932 Muysken advised to use this formula as long as lab experiments did not prove the rotational velocity for a certain diameter screw could be higher (Muysken, 1932, p. W. 88). More than a century further the formula is still in use by manufactures today.

APPENDIX G: SCREW CONFIGURATIONS

Appendix G contains the sketches used for the different screw configurations. These sketches are on scale and include waterlevels up- and downstream and the gross head at Sambeek (3.15 meter).

CONFIGURATION 1: FIXED AT 30 DEGREES EQUIPPED WITH VALVE

The first configuration is equipped with a valve in order to switch between pumping and turbining.

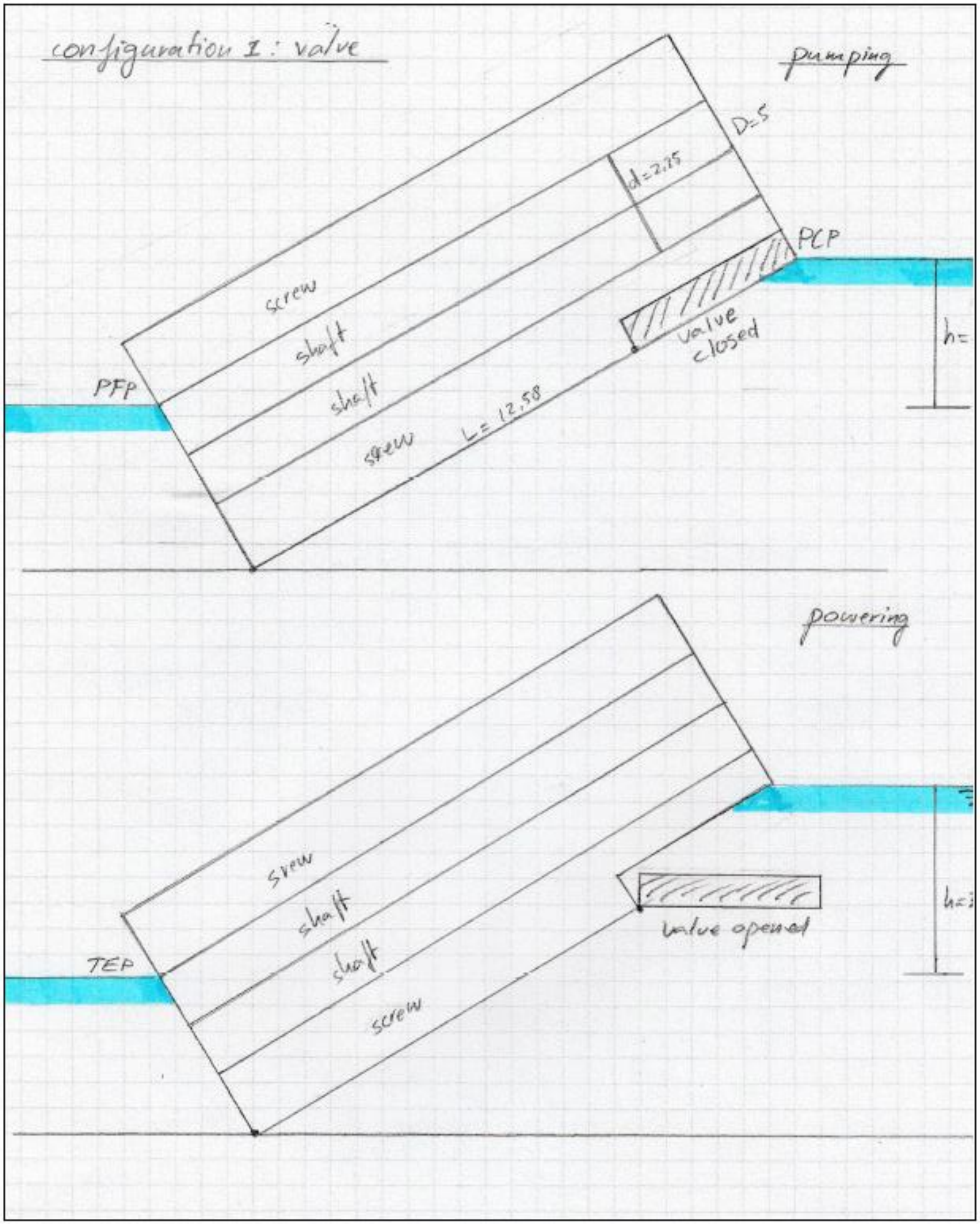


Figure 120: Configuration 1 equipped with valve

CONFIGURATION 2: TURBINE GOVERNING

When the screw turbine and its starting points are governing the following sketches on the turbine when powering and pumping are drawn. The turbine angle of inclination α of 22 °, TEP and TFP are governing. The sketches on the second configuration are shown in Figure 121.

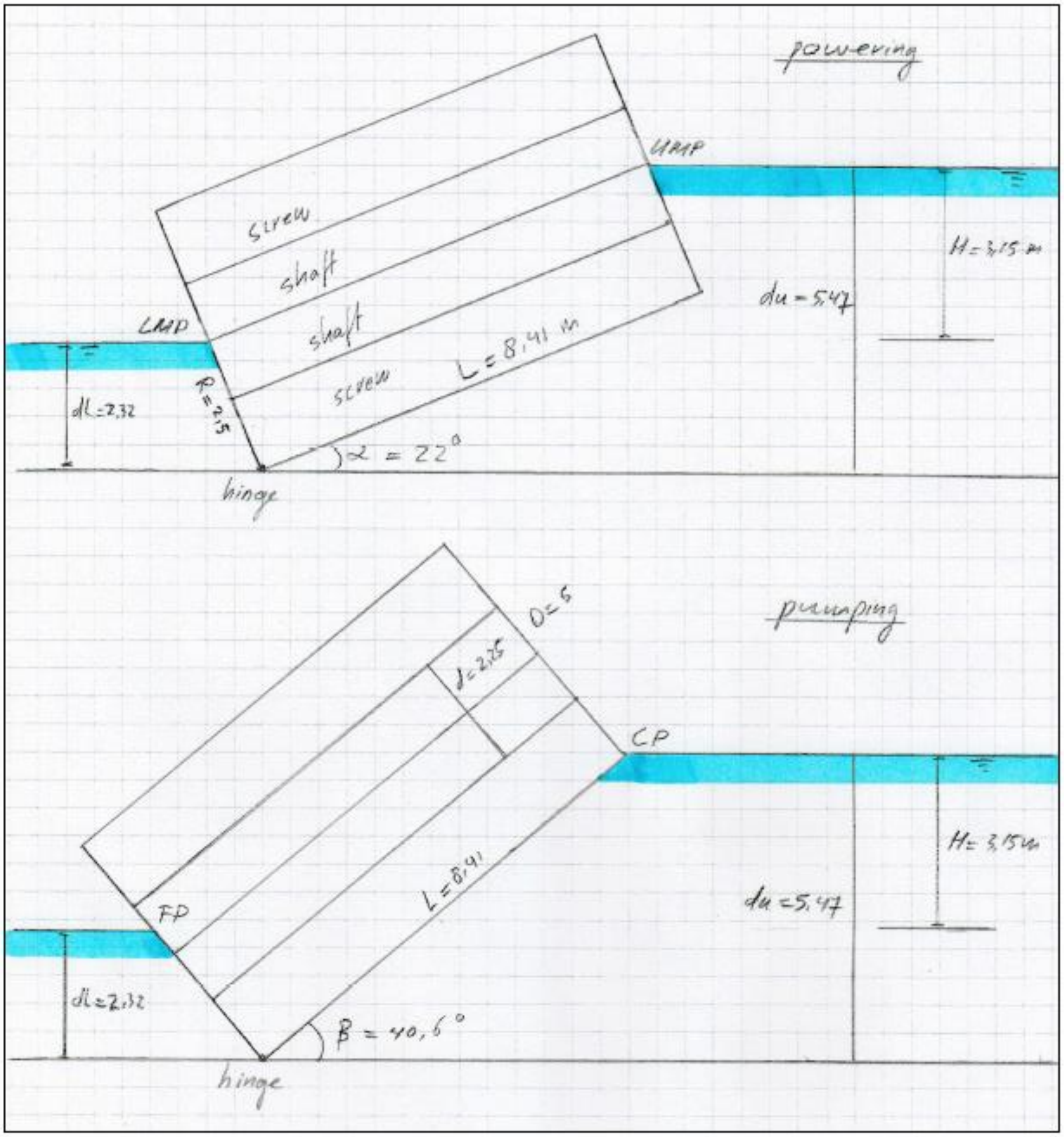


Figure 121: Drawings for second configuration

CONFIGURATION 3: SCREW PUMP GEVERNING

The drawings on this configuration are shown in Figure 122.

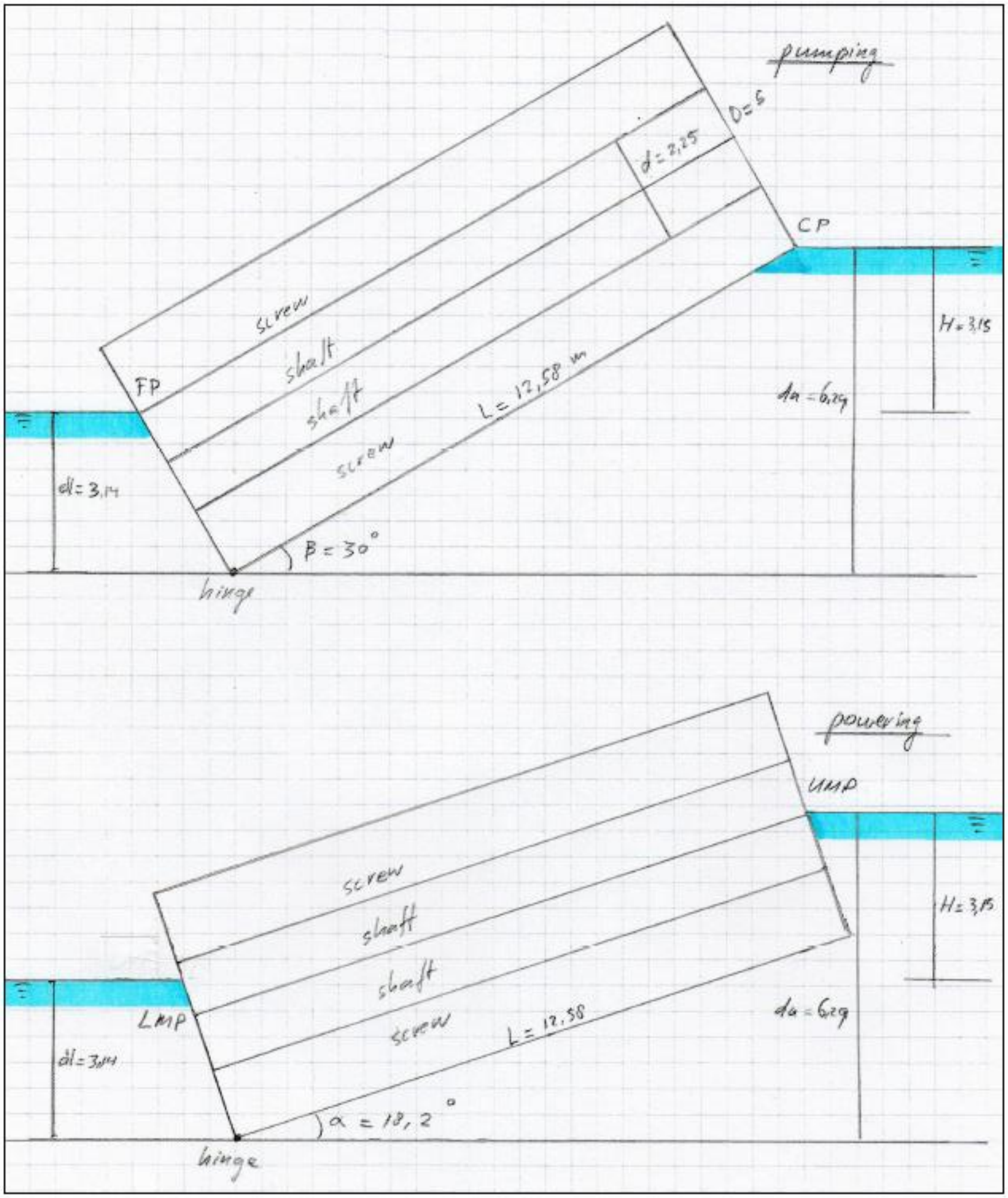


Figure 122: Screw pump governing

CONFIGURATION 4: ANGLES SCREW PUMP AND -TURBINE GOVERNING

The sketch shown in Figure 123 has been used for the fourth configuration.

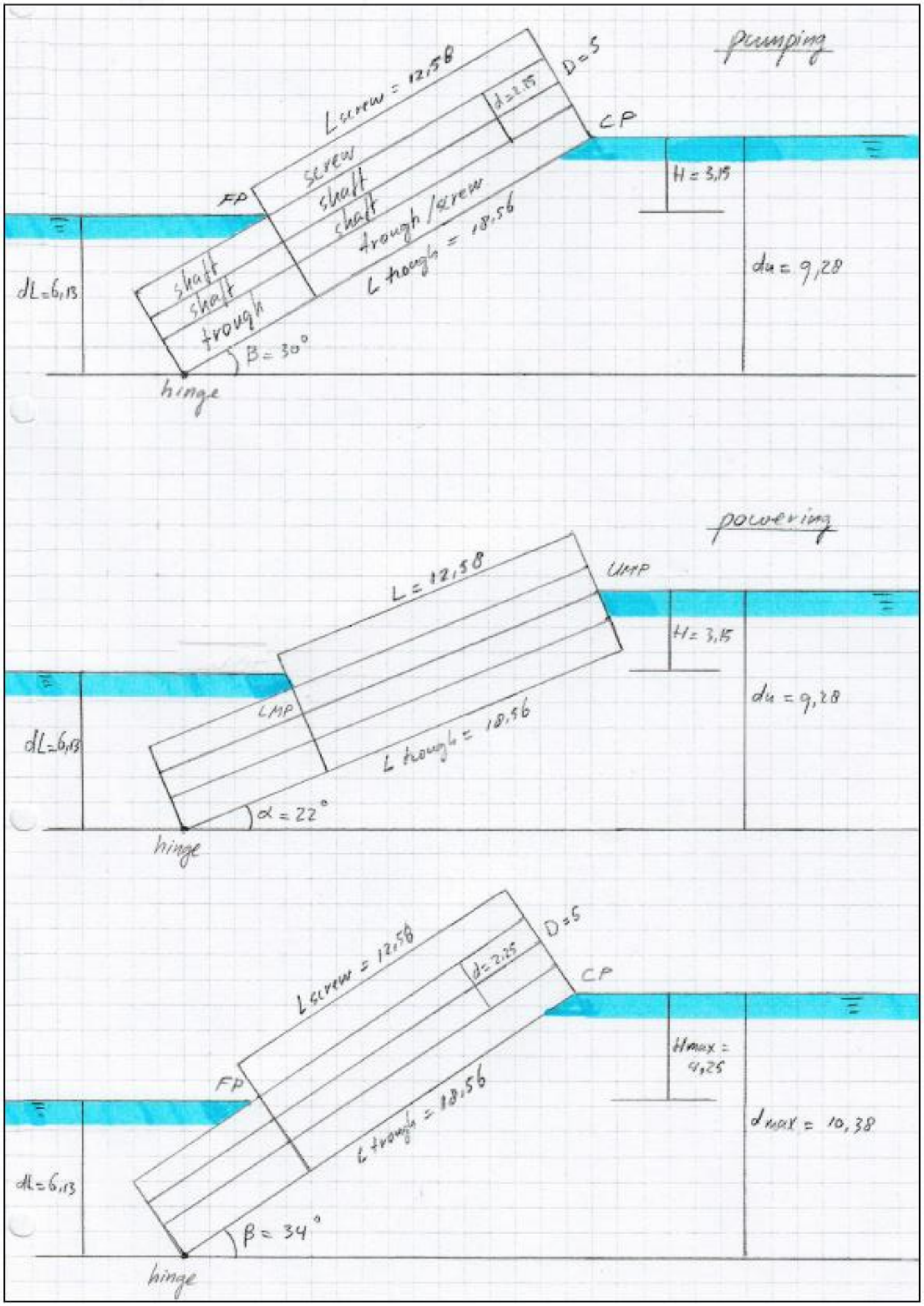


Figure 123: Configuration 4

CONFIGURATION 5: FLOATING SCREW

This configuration is based on configuration 4. It uses air compartments at each side of the trough to float. These air compartments can be filled or emptied with water using pumps inside. By doing so the trough will rotate around the hinges at the downstream side. In Figure 124 a clarification of this principle is shown.

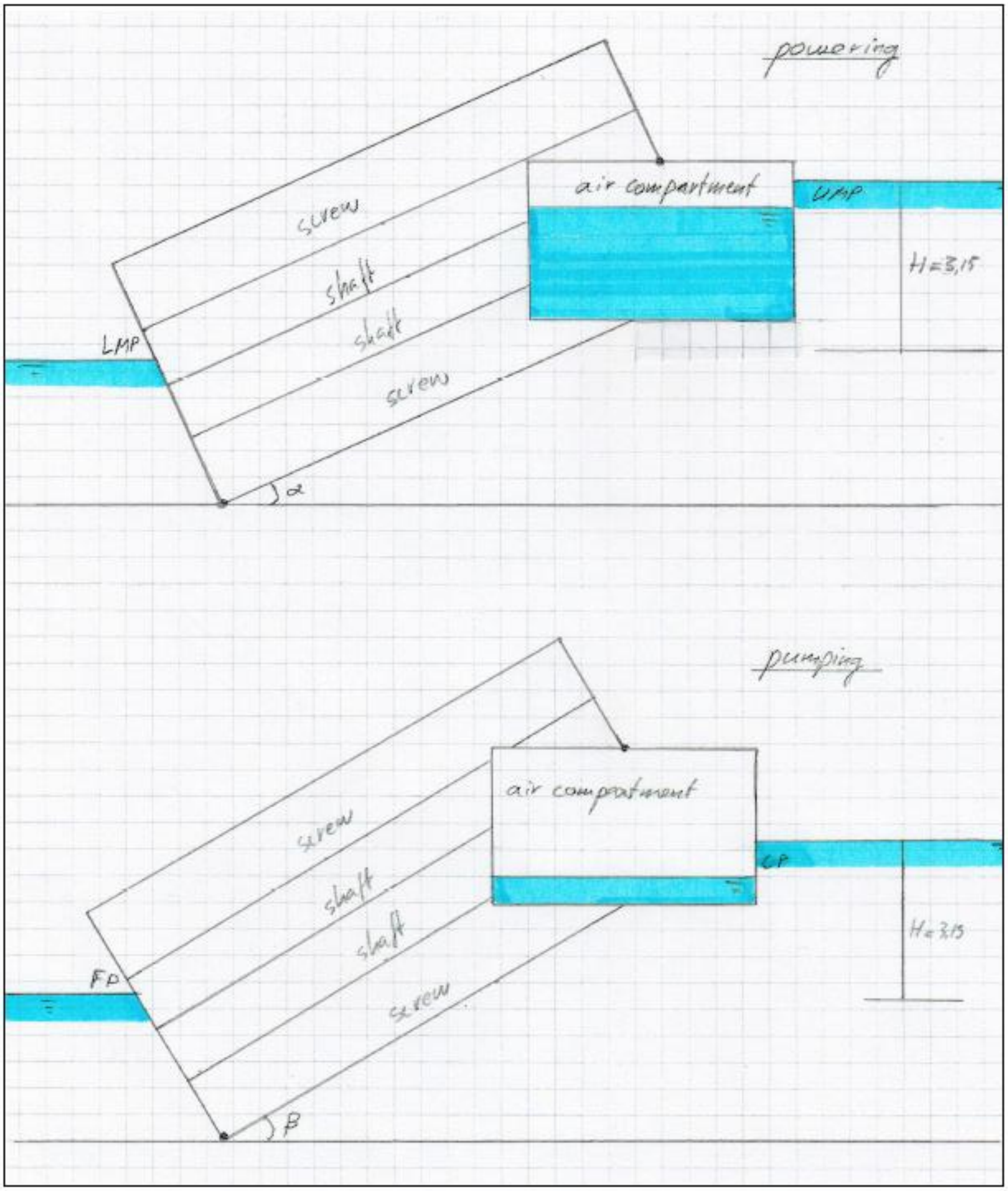


Figure 124: Clarification configuration 5 with air compartments at each side of the screw

CONFIGURATION 6: SCREW ADJUSTABLE TO WATERLEVELS AT LOWER- AND UPPER END

This configuration is based on configuration 4 with the main difference being the hinge which can be lifted up by a rotational mechanism. By doing so the screw can adjust to the optimal waterlevels downstream when turbining or pumping. The lower edge of the upper side of the screw is located 0.5 meter below PCP when pumping.

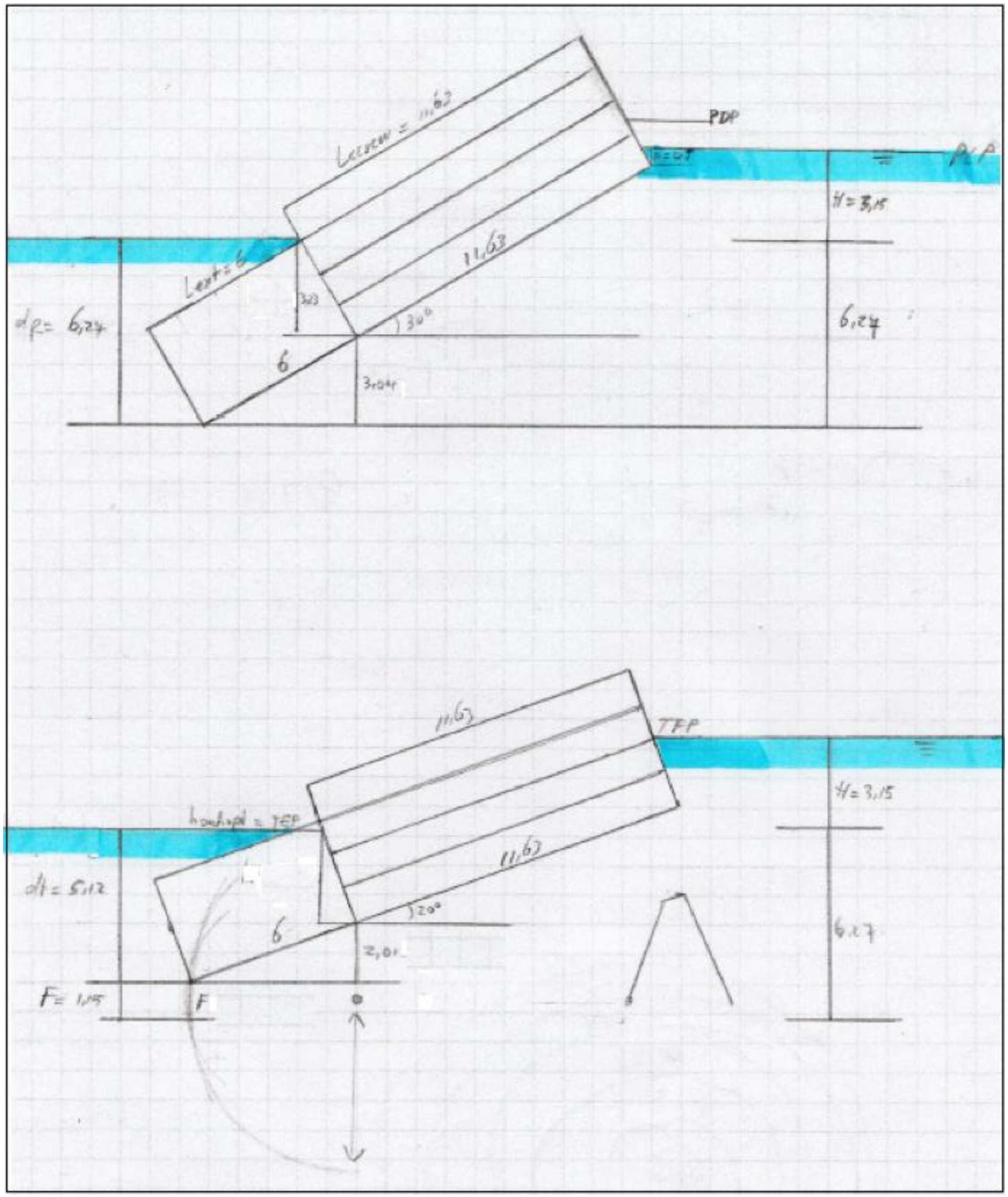


Figure 125: Configuration 6

APPENDIX H: CONCEPTUAL DESIGN PSP-PLANT

Appendix H contains the calculations on several aspects of the screw needed for the configurations and the conceptual design of the PSP-plant. The first design parameter to be analyzed will be the outer diameter of the screw.

OUTER DIAMETER SCREW

The outer diameter (D) will be 5 meters. In chapter 9 the motivations to use this diameter are explained.

$$D = 5\, meter$$

DIAMETER SHAFT

The diameter of the shaft is related to the outer diameter of the screw by the following relationship (Nagel, 1968, p.30):

$$\delta = \frac{d}{D} = \text{ 0,45 to 0,55} \qquad \text{formula (13)}$$

Using this relationship maximum filling and optimum delivery for the screw functioning as a pump are obtained (Nagel, 1968, p.30). In order to process a discharge of 15 m^3/s when turbining the minimum value of 0.45 is used for the calculation of the shaft diameter to create as much space possible for the flow. Using an outer diameter of 5 meter this results in:

$$d = 2{,}25\, meter$$

The shaft diameter is of importance for the optimal filling point (PFP) in relation to the water level at the lower end of the screw when pumping, as explained in chapter 8.

DESIGN WATERLEVELS AT SAMBEEK

RWS uses target levels as a guideline for the waterlevels in the sections of the Meuse cascade. These target levels are shown in chapter 5. The values of these target levels have been used as design waterlevels. The design waterlevels at Sambeek are:

- upstream: NAP 1110 cm
- downstream: NAP 795 cm

ROTATIONAL SPEED

According to Nagel (1968) and Ghassemi (2017 the optimal rotational speed of a screw pump and turbine is solely depending on its outer diameter as described in chapter 8. Using formula 5, the rotational speed will be:

$$n = \frac{50}{\sqrt[3]{5^2}} = 17.1\, rpm$$

GROSS HEAD AT SAMBEEK

The gross head at the Sambeek weir is 3.2 meter according to Table 1. However, for the conceptual design of the PSP-plant the target levels provided by RWS will be used. The gross head follows directly from the difference between these target levels (upstream: NAP 1110 cm, downstream: NAP 795 cm):

$$gross\ head = 1110 - 795 = 315\, cm = 3.15\, m$$

TURBINE CAPACITY AND NUMBER OF SCREWS TO INSTALL AT SAMBEEK

The number of screws to use at the Sambeek PSP-plant results from the available discharge for hydropower purposes. This available discharge is 300 m^3/s as explained in chapter 5. Information from two companies (Renewables First and Spaans Babcock) was used as indication of the maximum discharge a 5-meter diameter screw turbine can process, which is 15 m3/s. Using a 5-meter diameter screw this leads to the installation of 20 screws at Sambeek.

$$number\ of\ screws = {}^{300}/_{15} = 20$$

It would be possible to use a kind of design discharge for pumping and energy storage purposes resulting in another number of screws to install at Sambeek. However, in this report energy mode (when hydropower is generated) is the main process of the PSP-plant. Therefore, the flow duration curve (FDC) is considered to be leading. As a consequence, the number of screws to install will be based on the available discharge for hydropower.

FIXED OR VARIABLE

For the conceptual design of the PSP-plant in Sambeek the optimal rotational speed will serve at target point when turbining. When pumping the rotational speed will be fixed at 17.1 rpm. This is motivated by the following reasons:

- According to Nagel (1968) and Ghassemi (2017) the rotational speed of the screw is solely prescribed by the outer diameter implying a fixed rotational speed.
- The efficiency of a screw pump is mainly influenced by PFP, PDP and the angle of inclination of the pump (Nagel, 1968).
- The efficiency curve of a screw turbine is rather flat. Even at 40 % filling a screw turbine can reach an efficiency of 80 %. As the available design discharge is 300 m^3/s and 20 turbines will be applied, the expectation is the average discharge per screw turbine will be quite constant.
- Furthermore, chapter 10 has shown the distribution of the available flow per screw is controllable by rotating a screw out of position of by using a single leaf door.
- When using screws with variable speed additional efficiency losses occur due to the need of an inverter. The losses due to generator, gearbox and inverter are approximately 15% (Renewable First, 2019). These additional losses on efficiency should be avoided.

FILLING AND EXITPOINT SCREW TURBINE

According to chapter 8 for maximum efficiency of the screw turbine the optimal position of TEP depends on the screw geometry. A screw optimisation has been carried out in Excel. According to Rorres (2000) the boundaries for the pitch of the screw are:

$$0 < S < 2\pi R_{a/}K$$

In which K represents the slope of the screw. As the literature does not supply a rule of thumb considering the pitch an assumption based on Figure 36 has been made, resulting in a pitch of 5 meter equal to the screw outer diameter (R_a).

The number of blades (N) has been set on 4 as it will increase the optimal level $H_{out,opt}$. By doing so it will approach the target angles of inclination. According to formula 7 the screw will be submerged for 61% as I = 0.61.

TFP is positioned halfway the upper end of the screw at the waterlevel according to the theory of chapter 8.

SCREW PUMP CAPACITY

The pump capacity has been set on 11.6 m^3/s. This value is the average of the pump capacity of three different 5-meter diameter screws provided by Spaans Babcock (2020), Landustrie (2007) and KOVOSVIT (2020). This pump capacity will be used for the numerical Meuse model as well.

CHUTE-, DELIVERY- AND FILLING POINT SCREW PUMP

The lower edge of the upper screw end is located 0.5 meter below PCP at pumping mode. For the delivery point the theory of Nagel (1968) presented in Table 13 is used. As the angle of installation will be 30 ° at pumping this results in:

$$PDP = 0.3\ D$$

$$PDP = 0.3 * 5 = 1.5\ m$$

This implies PDP is located 1 meter above PCP which is at NAP 1210 cm at Sambeek.

DESIGN ONE

Two conceptual designs have been compiled for the compartments of the PSP-plant at Sambeek, which are called design one and design two. Design one is differing from design two by the fact the trough of the screw is not extended at the upper side in order to host the gearbox and generator. A separate steel unit is designed for these components. This unit is capable of rotating on a hinge connected to the wall above the middle slab. Gearbox and generator are connected to the screw by a cardan shaft and an extensible drive shaft.

With the waterlevels up- and downstream included this design looks like the one shown in Figure 126.

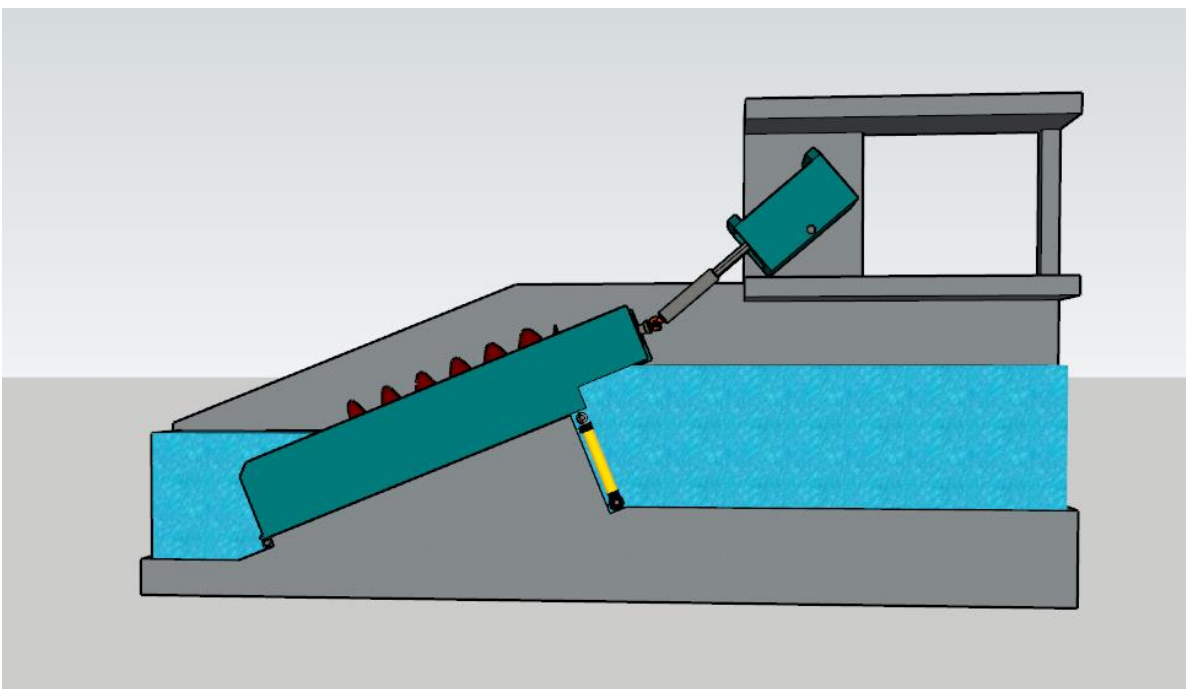


Figure 126: Design one with waterlevels included

The drive shaft has to be extensible as it will decrease or increase in length when the angle of inclination of the main trough is changed by the hydraulic pistons. The unit hosting the gearbox and generator will follow the rotation of the main trough. By doing so the drive shaft needs to be variable in length. Furthermore, this drive shaft must have a certain length (approximately 7 meter) to reduce the maximum angle the cardan shaft has to overcome.

DESIGN TWO

Design two is shown in the main chapter. This design has been used for the conceptual design of the PSP-plant. The main difference with design one is the trough which has been extended at the upper side in order to host gearbox and generator. Because of this extension no separate unit for these components is needed. Furthermore, design two shows a rotational mechanism the adjust the lower screw end to the downstream waterlevels.

VERIFICATION DESIGN ONE AND TWO

The main advantage of design one is it reduces the weight of the main shaft, as this is not extended to 27 meters. However, this design has two additional components that might fail: cardan- and extensible drive shaft. This increases the overall sensitivity to failure.

Furthermore, as a consequence of the extensible drive shaft (which must have a certain length to reduce the maximum angle of the cardan shaft) this design becomes high: 25.7 meter. Another reason not in favor of is the efficiency loss caused by the cardan shaft. Whatever device is used to connect two drive shafts under an angle, it will cost energy. This is inconvenient when optimizing the hydro-electricity production.

Design two has a top slab which is free of walls, which is not the case in design one. This is beneficial for a mobile crane to place into position. With respect to the dimensions in height: design two has a height of 15.7 meter compared to 25.7 meter for design one. This will reduce the amount of concrete needed for construction.

The overall impression after verification is design two will be easier to maintain and will be using less concrete thereby making it economically more attractive. Furthermore, design two has fewer mechanical components making is less vulnerable for failure. Therefore, design two has been selected.

ELABORATION ON SELECTED COMPARTMENT DESIGN

Design two will be elaborated on in many aspects in this paragraph. It will start with the main dimensions, and will be finalized with a paragraph considering corrosion protection. The main dimensions of compartment design two are:

- length: 60 meter
- length top slab: 18.2 meter
- width single compartment: 9 meter
- width compartment integrated in PSP-plant: 7.5 meter (as walls are shared)
- height: 15.7 meter

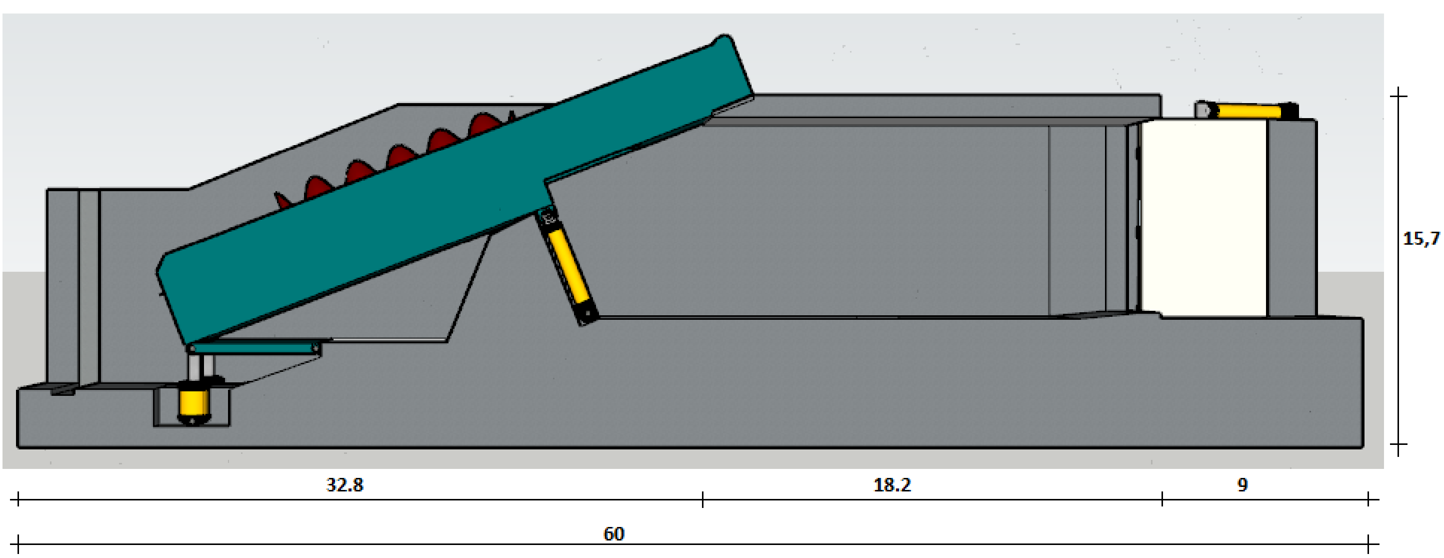


Figure 127: side profile and dimensions (meter)

In Figure 128 one can observe the compartment in from the down- and upstream side. Clearly visible are the concrete walls of 1.5-meter thickness.

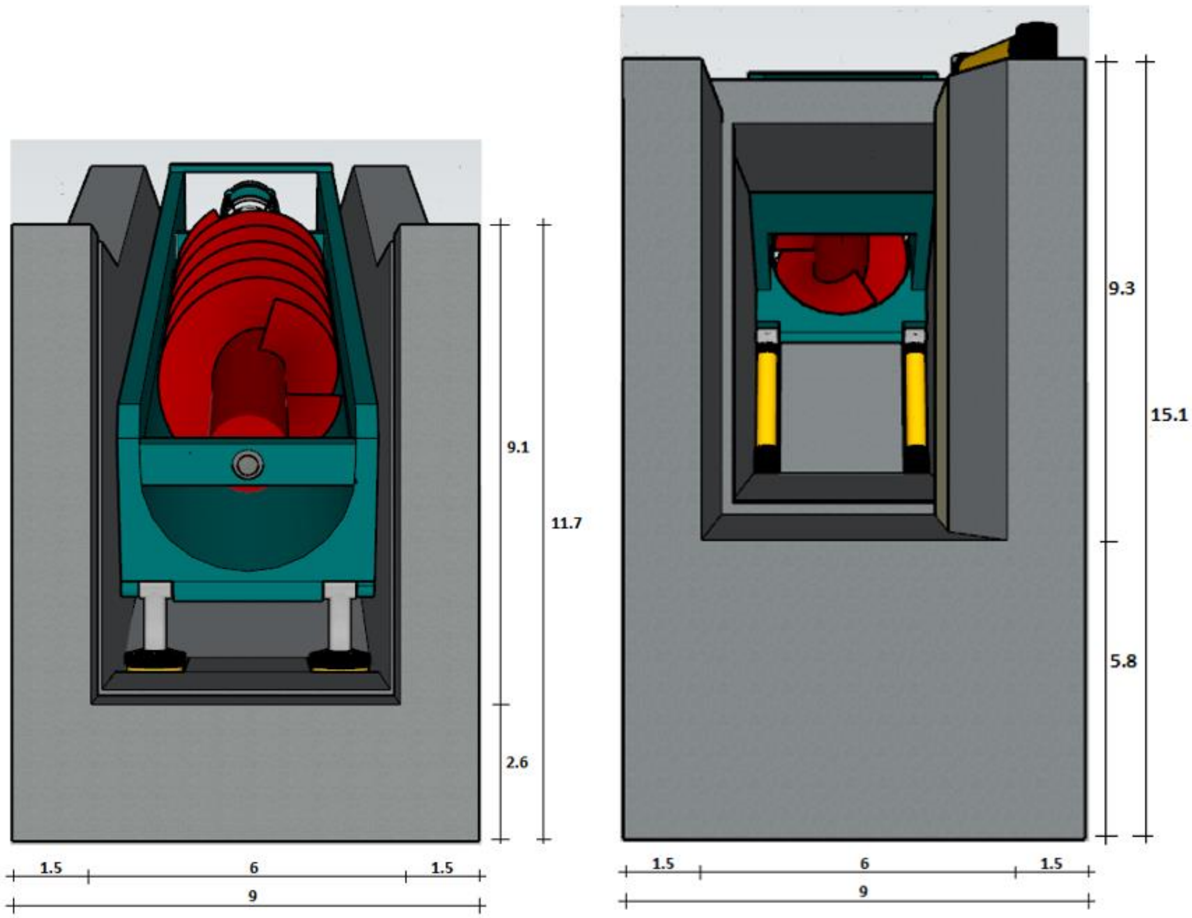


Figure 128: 3D view including measurements (m) from the downstream side (left) and upstream side (right)

DIMENSIONS WALLS AND SLAB

For a detailed design the main dimensions are derived from functional requirements. Dimensions of structural components are forthcoming out of requirements with respect to structural integrity in detailed design loops (Molenaar & Voorendt, 2020, p.64). The thickness of walls and slabs should be verified in ultimate- and serviceability limit states, using for instance the maximum bending moment, the moment of inertia and the strength class of the concrete.

However, for this thesis a conceptual design is compiled, without any force- or moment diagrams. The purpose of this conceptual design is solely to provide a possible solution of a PSP-plant which is hosting screw turbines capable of powering- and pumping, which will in turn be used for the numerical Meuse model.

Therefore, the thickness of walls and slabs has been estimated. A first estimation is based on guidelines provided in the Quick Reference (Pasterkamp, 2015). As a rule of thumb for the dimensions of a concrete slab one can divide the span by 25. As the span is 6 meter this results in a thickness of 24 cm. However, this rule of thumb is designed for buildings. The slab of the PSP-plant should be capable of withstanding the load of a mobile crane shown in Figure 129.

For this reason, the lecture notes on caissons (Molenaar et al, 2016) have been consulted, as a caisson shows similarities with the compartment of the screw turbine. A wall thickness of 0.5 meter and a bottom plate thickness of

1 meter are considered to be reasonable start values (Molenaar et al, 2016, p.36). For the thickness of the roof one can use a first estimate of 1 meter (Molenaar et al, 2016, p.38).

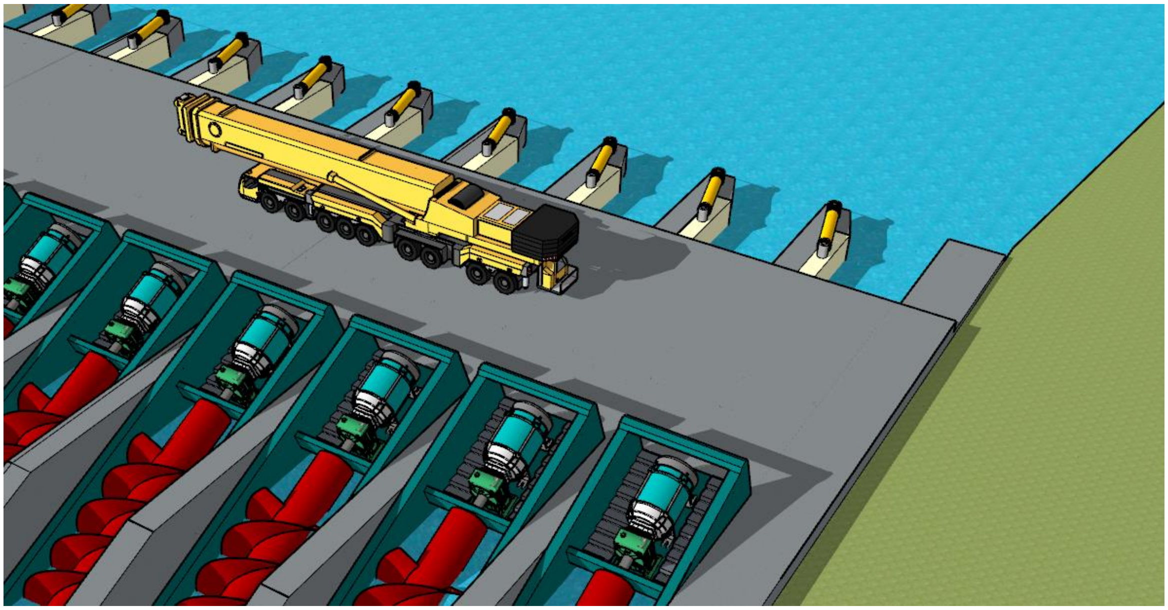


Figure 129: Slab with mobile crane on top

Based on this information the thickness of the top slab ('roof') in design two has been set on 1 meter. For the bottom slab the minimum thickness is 2.6 meter at the downstream side. This is higher than the guidelines for caissons, and is explained by the fact this bottom slab contains a slot for the gate which can close off this downstream side. Furthermore, slots for the hydraulic pistons of the rotational mechanism are present.

For the thickness of the wall originally the caisson value of 0.5 meter was used. However, the walls contain the same slots of 0,25 meter for the gate at the downstream side. Therefore, the wall thickness is increased to 0.75 meter. When combining two compartments this results in a combined wall thickness of 1.5 meter.

DETAILS ON SINGLE LEAF DOOR AND GATE

The gate downstream can be lifted into position by a crane (vessel) and is kept in position by the slots in bottom slab and walls. In this way every compartment of the PSP-plant can be closed off. These slots and lifting of the gate are shown in Figure 130.

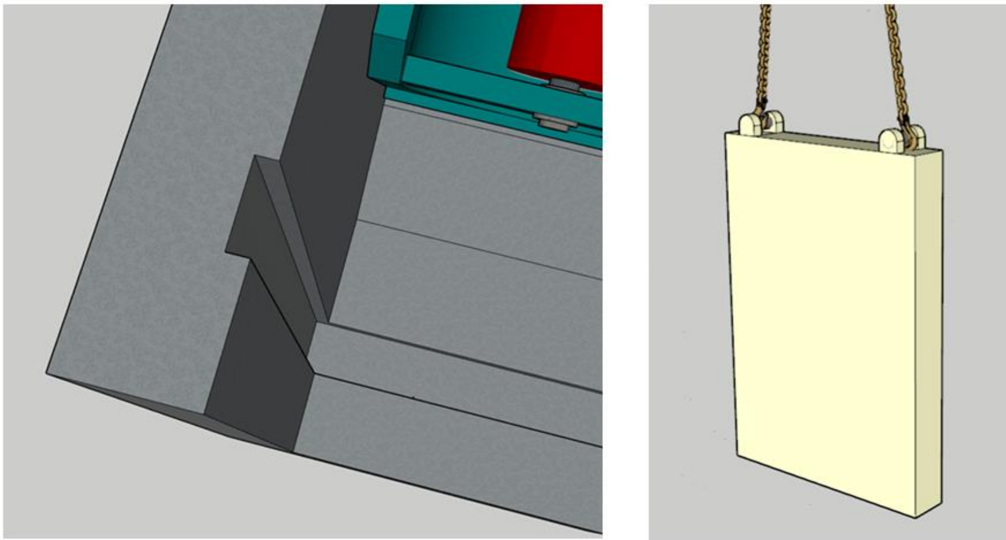


Figure 130: slots in wall and bottom slab downstream (left) and gate lifted in (right)

The single leaf door is present permanently, for the reasons explained in the main chapter. This component is from the rotational gate type which is shown in Figure 131. It is suitable for one sided water retention, and can be installed in a lock chamber with a width of 4 to 10 meter (Voorendt ,2018). As the width of the compartment is 6 meter a single leaf door is considered to be an appropriate solution.

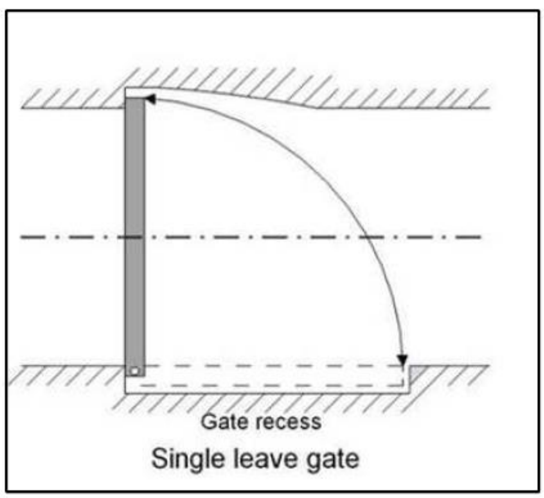


Figure 131: Single leaf door (Molenaar et al, 2016)

In Figure 131 the door is put aside in the gate recess. It is assumed this is done to avoid damage due to a ship collision during the locking process. As the compartment of the PSP-plant obvious is not used for locking processes the gate recess is designed in such away the friction of the flow of water at the upstream side is minimized by an oblique concrete slot. The mechanical device that can close or open the door is a hydraulic piston. This is shown in Figure 132.

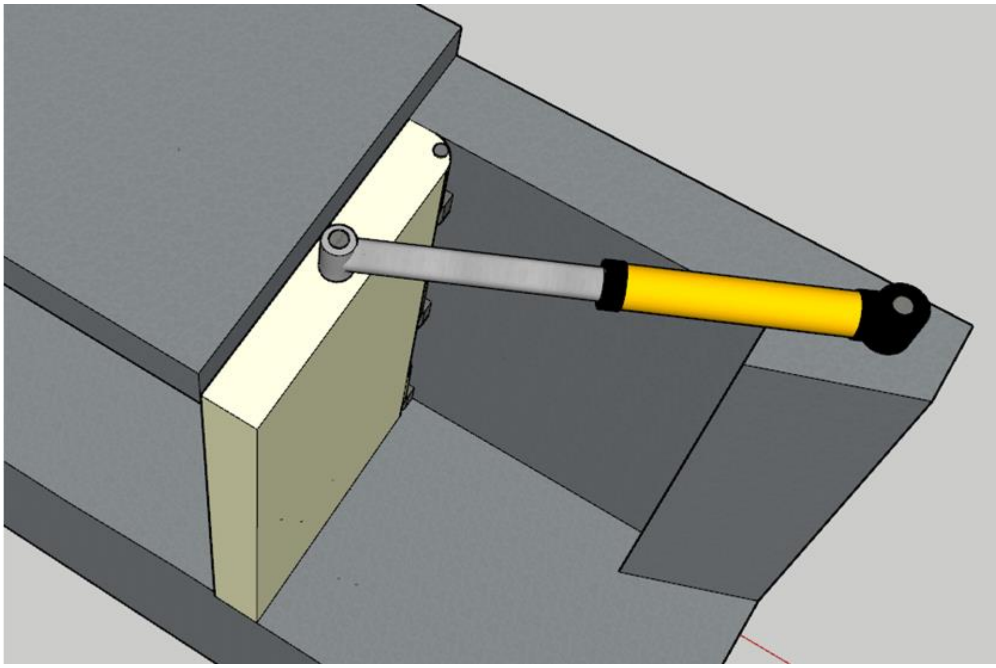


Figure 132: Single leaf door and oblique gate recess

The door will eventually be pushed to the top slab by the hydrostatic water force. In order to be supported on every side the walls and the bottom floor contain oblique supports as well. These supports (with a height of 0.25 meter) are shown in Figure 133.

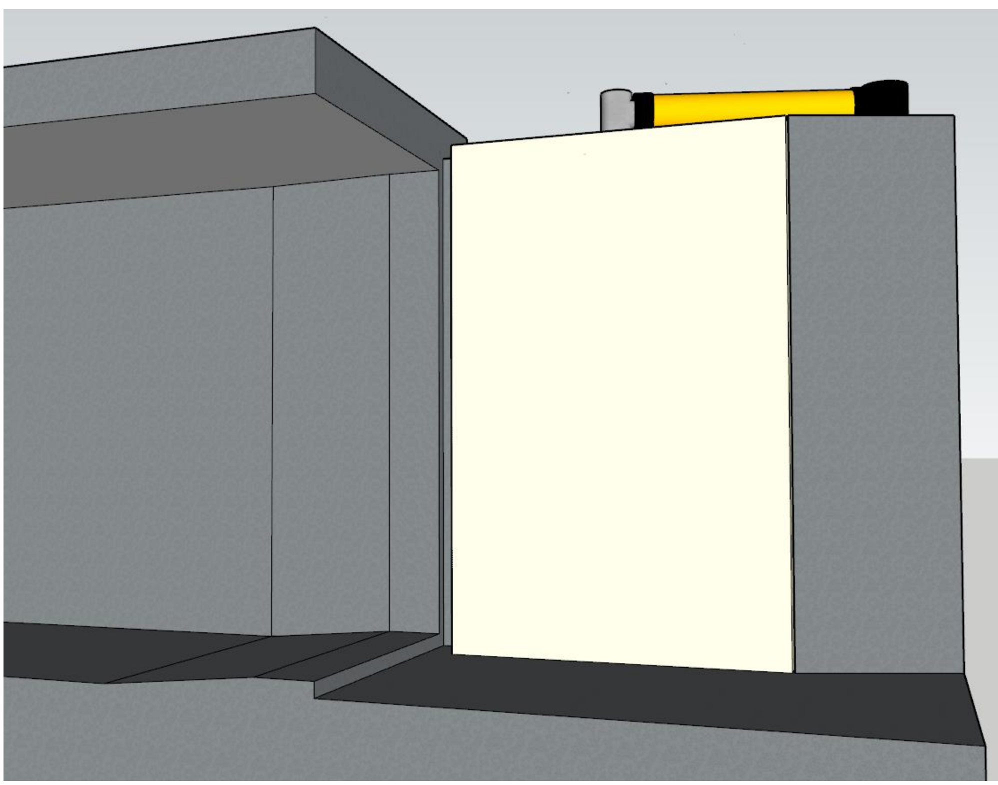


Figure 133: Oblique supports for door in walls and floor

DIMENSIONS TROUGH

In design two the main trough has been extended to host the gearbox and generator. The main dimensions of the trough are:

- height: 4.1 meter
- width trough: 6 meter
- diameter screw: 5 meter
- length main trough: 17.6 meter
- lenght total trough: 27.6 meter

.

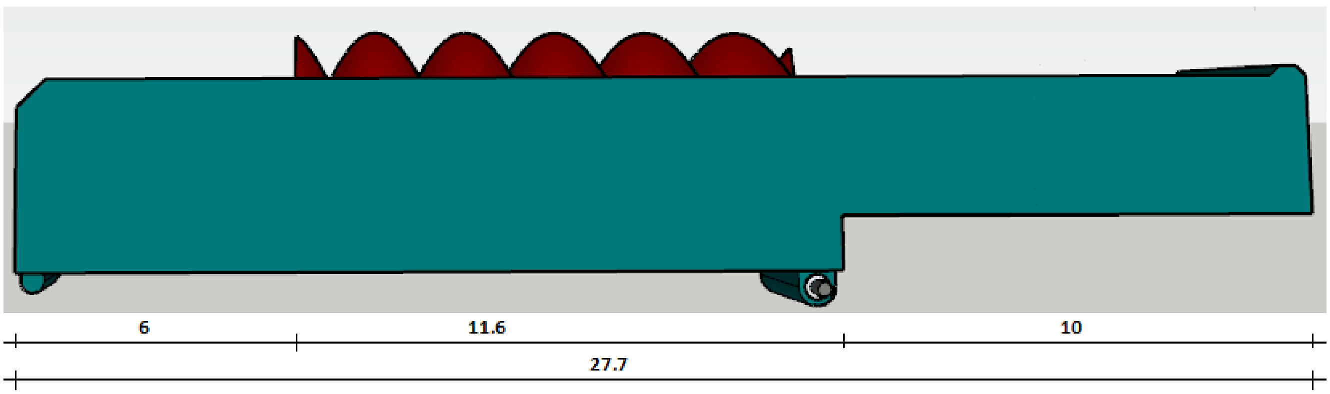


Figure 134: Side view of trough including extension

In Figure 135 one can observe a top view of the trough.

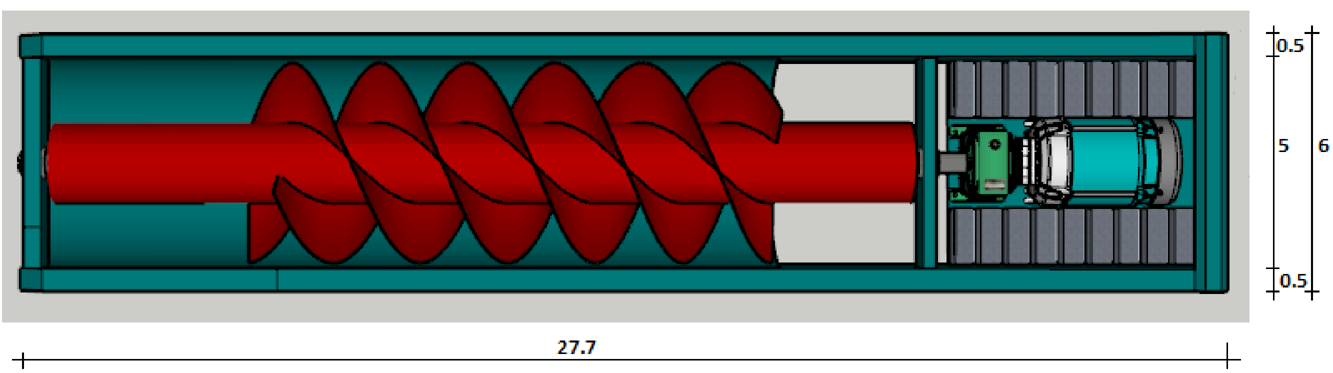


Figure 135: 3D top view of trough and screw

Note: as one can observe this is a 2-bladed screw. The screw optimization resulted in the selection of a 4-bladed screw. It was not possible to import a 4-bladed screw from the 3D-warehouse in Sketchup. However, for illustration purposes the 2-bladed screw is considered to be useful in the main chapter and appendix H.

HYDRAULIC PISTONS

The mechanical system to adjust the angle of inclination consists of two hydraulic pistons. These pistons have a length of 4 meter and a maximum external diameter of 0.7 meter (the yellow part).

The hydraulic pistons needed for the rotational mechanism are shown fully extended in Figure 136. This type of pistons has been selected as there is less room available to host these pistons. Under regular river conditions the pistons are extended by 1.2 meter, as shown in Figure 50. When the waterlevel downstream has increased – either due to storage or due to median/peak river mode – the pistons can be extended up to 3.6 meter.

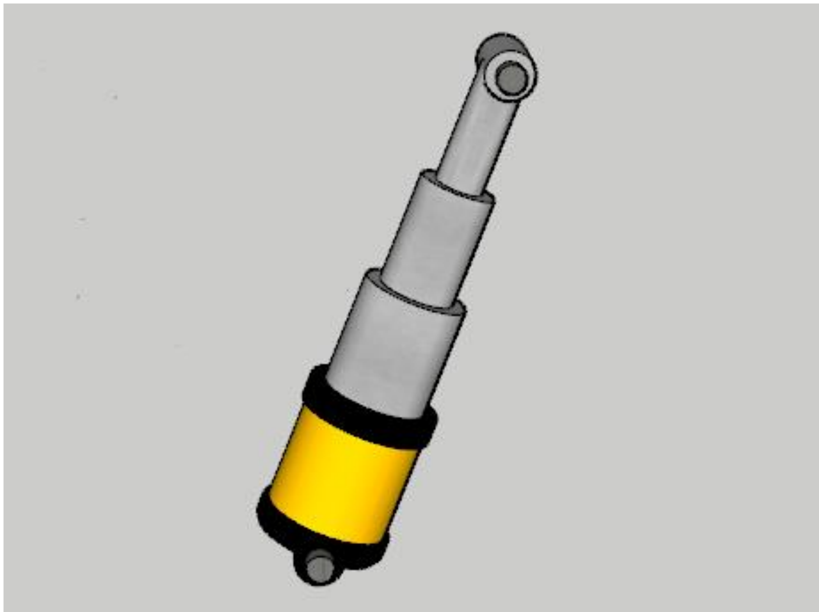


Figure 136: Close up view hydraulic pistons downstream side extended to 3.6 meter

CORROSION PROTECTION

It is expected the PSP-plant can function with hydraulic cylinders placed below water level as the corrosive environment of the Meuse is less aggressive than for instance salt water sea conditions. However, to avoid corrosion the hydraulic pistons - and the trough, screw and single leaf door - will be protected using the principle of cathodic protection.

Two ways of cathodic protection of a structure exist, which are galvanic coupling or using an impressed current (Fontana, 1986, p 295). For the PSP-plant using an impressed current (in Dutch: *'opgedrukte stroom'*) might be a suitable solution. An external dc power supply can be used. The negative terminal of this supply is connected to the components, and the positive to an inert anode such as graphite, usually surrounded by backfill material like bentonite. In Figure 137 is shown how current passes a metallic structure (in this case a tank) thereby suppressing corrosion (Fontana, 1986. p.295).

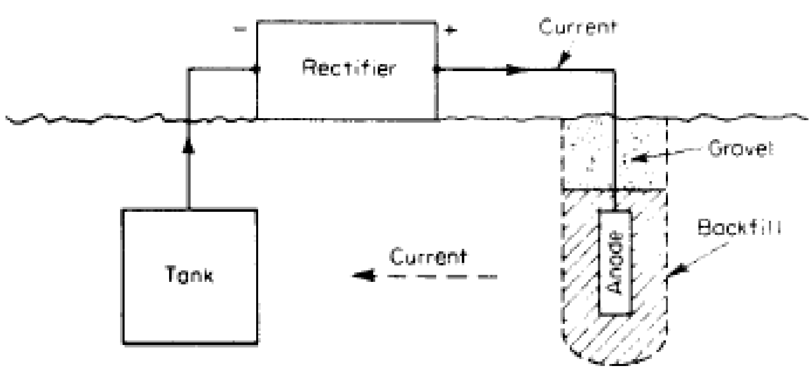


Figure 137: Cathodic protection of a tank by applying impressed current. (Fontana, 1986, p.295)

ANGLES OF INCLINATIONS AND SCREW LENGTH PER WEIR

The PSP-plant is scalable to the other weirs in the Meuse cascade. In chapter 11 it will be assumed every weir is hosting a PSP-plant like Sambeek, although the number of screws will differ.

The results on scaling of the PSP-plant according to the head differences at each weir are shown in Table 19. The design angles of inclination for turbine- and pumping mode will slightly differ.

Furthermore, one can observe the diameter of the screw will become 4 meter at Belfeld and Roermond. The motivation to use this diameter is explained in chapter 11.

As the head per weir varies in the range 2.7 – 5.2 meter obviously the screw length shows considerable differences.

PSP-plant:	Length screw (m):	Diameter (m):	Turbine angle α (°):	Pump angle β (°):
Borgharen	15.9	5	21	30
Linne	13.5	5	20	30
Roermond	9.6	4	20	30
Belfeld	10.3	4	20	30
Sambeek	11.6	5	20	30
Grave	11.4	5	20	30
Lith	13.9	5	20	30

Table 19: Length screw and inclination angels for the PSP-plants cascade

DIMENSIONS OF PSP-PLANT

The main dimensions of the PSP-plant together with additional overview images of the present- and future Sambeek lock- and weir complex will finalize appendix H. The dimensions of the plant dimensions are:

- lenght: 151.5 meter
- width: 60 meter
- height: 15.7 meter

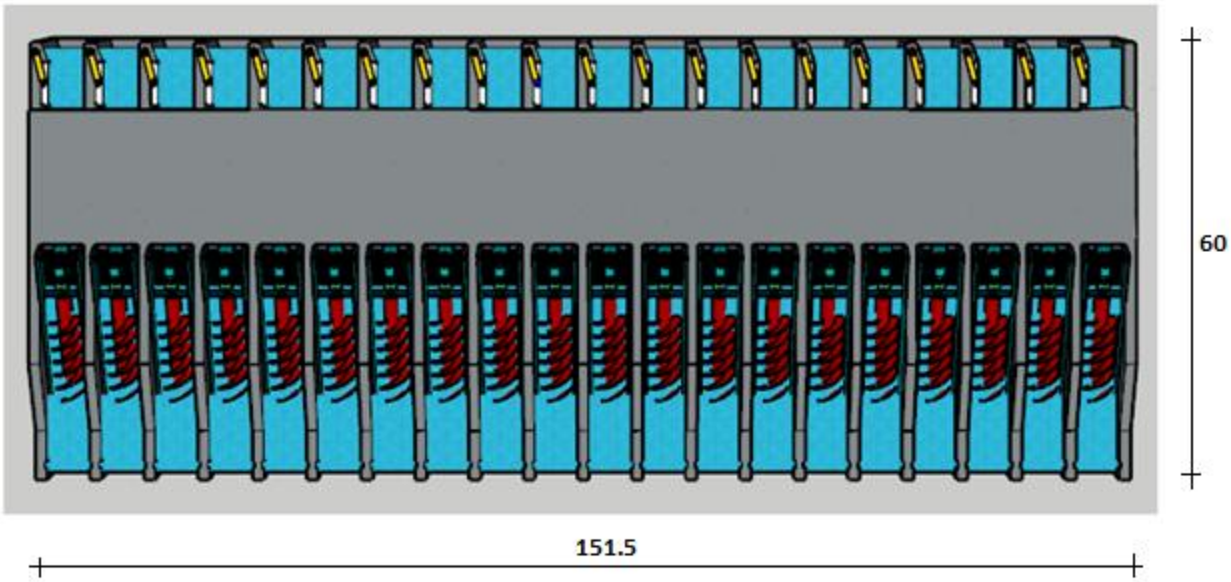


Figure 138: Top view PSP-plant. Length: 151,5 meter. Width: 60 meter

ADJUSTING TO DESIGN DISCHARGE

Another way to adjust the PSP-plant to the available discharge is by closing one or more single leaf doors. This is shown in Figure 139, in which again 12 screws are actually powering, while 8 screws are closed off from the water flow.

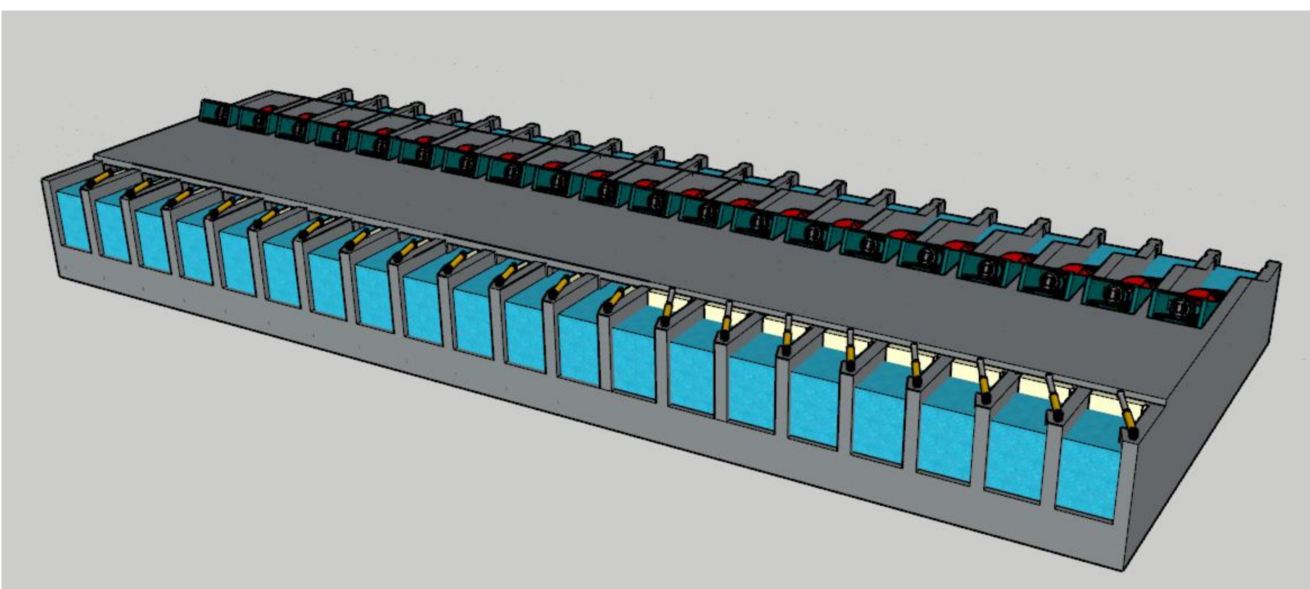


Figure 139: 12 screws powering, 8 units closed off the flow of incoming water by the single leaf doors

CURRENT- EN FUTURE OVERVIEW SAMBEEK

Currently Sambeek is hosting Stoney- and Poirée weirs. When these are replaced by sector gates the area next to the Poirée weirs loses its function. It might be usable for the implementation of the PSP-plant, as explained in the main chapter. Figure 140 shows the current- and future situation of the Sambeek complex from the top.

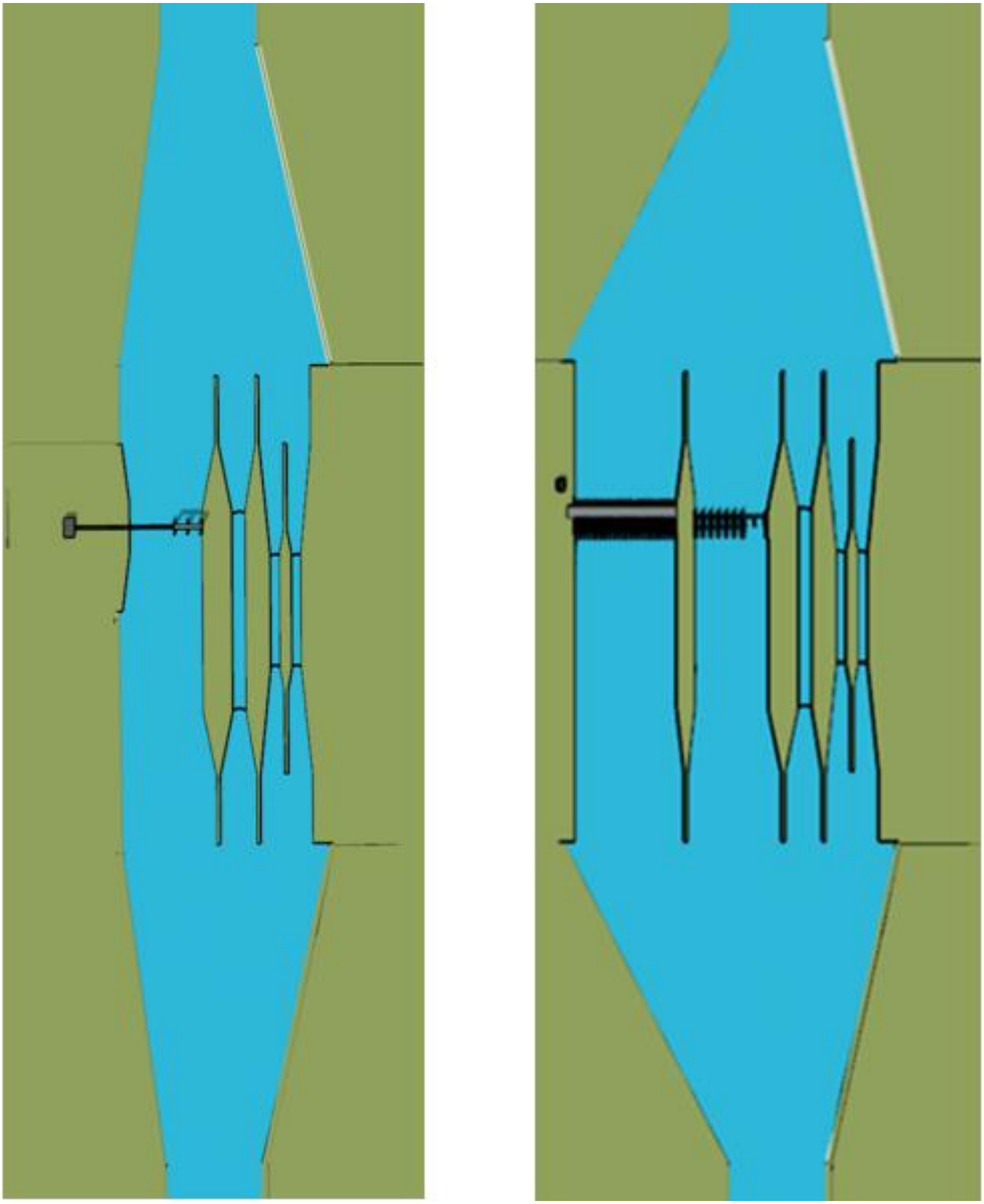


Figure 140: Current situation Sambeek (left) and future situation including PSP-plant (right) observed from top

APPENDIX I: CONSTRUCTION OF AND ELABORATION ON NUMERICAL MEUSE MODEL

In appendix I (related to chapter 11) the construction of the Meuse model will be explained, starting with the interface of the model in the next subsection. The model will be verified on the requirements listed in chapter 3. The model has been constructed in Microsoft Excel.

Note: the theory behind the model is complicated. This appendix tries to clarify the model. However, to get a deeper understanding of the construction of the model one should use it and observe what happens at each column.

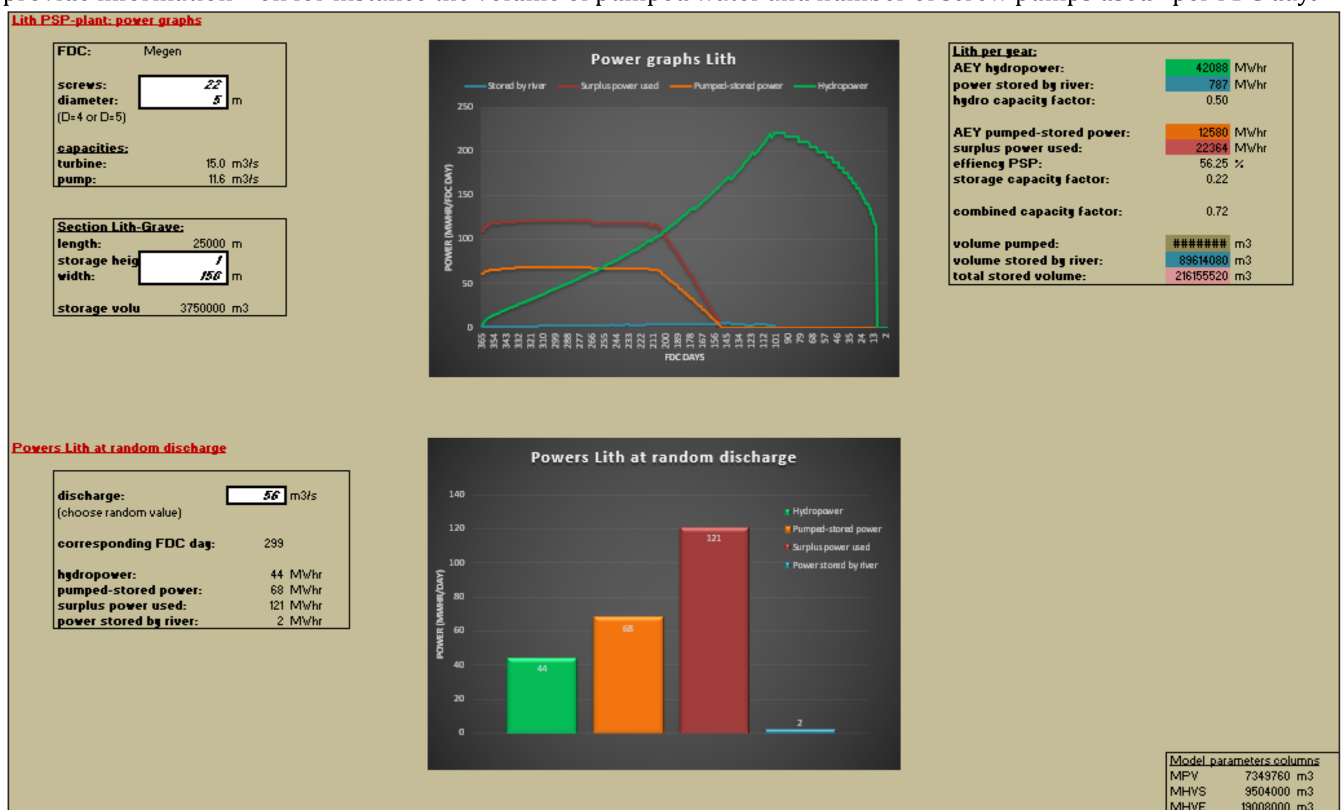
For the assessment of the production of hydropower and pumped-stored power the model is not complicated to use. It provides the main results for the individual weirs and the whole cascade straight away.

INTERFACE MODEL

The interface of the model is shown in Figure 141, related to the Lith PSP-plant. One can observe two graphs. The upper graph shows the PSP- and hydropower production, as well as the surplus power used at each FDC day. At the upper right the yearly totals as well as the capacity factors are shown.

The graph at the bottom shows the power production and consumption at a random discharge. For every weir as well as the cascade these graphs are present in the model.

At the bottom one can observe several columns with abbreviations above. In these columns the programming of the model has been carried out. As a result, the columns are necessary to obtain the results in the graphs. The columns provide information – on for instance the volume of pumped water and number of screw pumps used– per FDC day.



FDC d	QA:	DVS_ups	DVS_ad	DVS_tot	PV:	NSP	NST	SBR:	PSBR	TS:	VLI:	SPU:	TVS:	VVS:	DVE_riv	DVE_ad	TVE:	VVE:	GH:	GHA:	IC:	NSTE:	PSP:	HP:
	(m3/s)	(m3/day)	(m3/day)	(m3/day)	(m3/day)	(-)	(-)	(m3/day)	(MWhr	(m3/day)	(m)	(MWhr)	(m3/day)	(m3/day)	(m3/day)	(m3/day)	(m3/day)	(m3/da	(m)	(m)	(MW	(-)	(MWhr)	(MWhr)
365	3.6	0	103680	103680	7349760	22	0	103680	1	771840	0.2	110	0	0	207360	207360	7660800	0	4.0	4.1	239	9	62	3
364	6.4	0	80640	80640	7349760	22	0	80640	1	748800	0.2	109	0	0	368640	161280	7902720	0	4.0	4.1	239	10	62	5
363	8.5	0	80640	80640	7349760	22	0	80640	1	748800	0.2	112	0	0	489600	161280	8084160	0	4.1	4.2	245	10	63	6
362	9.4	0	83520	83520	7349760	22	0	83520	1	751680	0.2	112	0	0	541440	167040	8161920	0	4.1	4.2	245	10	63	7
361	10.9	0	100800	100800	7349760	22	0	100800	1	768960	0.2	115	0	0	627840	201600	8291520	0	4.2	4.3	251	10	65	8
360	12.5	0	118080	118080	7349760	22	0	118080	1	786240	0.2	115	0	0	720000	236160	8429760	0	4.2	4.3	251	10	65	10
359	14.3	0	120960	120960	7349760	22	0	120960	1	789120	0.2	115	0	0	823680	241920	8585280	0	4.2	4.3	251	10	65	11
358	15.1	0	123840	123840	7349760	22	0	123840	1	792000	0.2	118	0	0	869760	247680	8654400	0	4.3	4.4	257	11	66	12

Figure 141: Interface model for Lith PSP-plant.

ABBREVIATIONS

The model uses several abbreviations. For the sake of the overview these abbreviations are shown on a separate sheet tab. When using the model – for instance when analyzing the results of the Belfeld PSP-plant – one can easily switch to this sheet tab to find the explanation of a certain abbreviation.

The main abbreviations used are:

- FDC day: Flow duration curve day
- QA: Available discharge
- DVS_ups: Discharge volume flowing in a storage section from upstream weir during storage mode
- PV: Volume of pumped water by PSP-plant section
- NSPS: Number of screws pumping during storage mode
- NSTS: Number of screws turbining during storage mode
- SBR: Volume stored by the river
- PSBR: Power stored the river
- TS: Total volume stored
- WLI: Net water level increase due to pumping
- SPU: Surplus power used for pumping
- TVS: Turbine volume at storage mode
- WVS: Weir volume at storage mode
- DVE_river: Discharge volume river at energy mode
- NST: Number of screws turbining
- TVE: Turbine volume at energy mode
- WVE: Weir volume at energy mode
- GH: Gross head
- GHA: Gross head adjusted due to pumping
- NSTE: Number of screws turbining at energy mode
- PSP: Power stored by pumping
- HP: Hydropower produced
- MPV: Maximum pumped volume
- MHVS: Maximum hydropower volume at storage mode
- MHVE: Maximum hydropower volume at energy mode
- IC: Installed capacity
- Q_aver: Average discharge of the four FDC's
- TPSBR: Total power stored by river in cascade
- TSPU: Total surplus power used in cascade
- TPSP: Total power stored by pumping cascade
- THP: Total hydropower produced cascade

Some weirs (Lith, Borgharen and Roermond) contain some additional abbreviations which one can notice when using the model. The abbreviations will be used and explained in appendix I.

MODEL ASSUMPTION ONE: CHANGE OF WATERLEVEL

The first model assumption is related to the change of waterlevel during one cycle of storage- and energy mode. The duration of a cycle will be 24 hrs. The default value for the duration of storage mode is 8 hrs.

In the main chapter it was explained during one cycle of 24 hours the waterlevel at the end of energy mode has to be equal to the waterlevel at the start of storage mode. This implies the change in water volume in the storage section is zero.

MODEL ASSUMPTION TWO: DISCHARGE CASCADE

The second model assumption is related to the FDC's. The model describes power storage and -production per FDC day. It is assumed each FDC day (from the FDC's constructed for Borgharen, Maasbracht, Venlo and Megen) occurs on the same day.

In reality this is not the case as there is a time lag. For instance, the peak of the river flood wave which occurred in January 2001 passed Borgharen on the 7th, while it passed Venlo on the 8th ("Rijkswaterstaat Waterinfo", 2019). However, it is not possible to use real time data from RWS in the model.

ASSUMPTION THREE: OPTIMIZATION ON EFFICIENCY HYDROPOWER AND PSP-PROCESSES

The third model assumption is related to the overall efficiency on hydropower- and PSP production. Considering turbining and pumping the benefit of the selected screw configuration becomes clear. As the screw can adjust to the optimal waterlevels up- and downstream (using the hydraulic pistons) the efficiencies of the pumping- and turbining processes are assumed to be 75 % constantly based on the information from chapter 8.

The volume of water which is pumped upstream in storage mode is not allowed to be larger than the total volume of river discharge and pumped water which will flow downstream through the turbines in energy mode. If more water is pumped up than can be processed by turbining energy is wasted and the overall efficiency of the PSP-process will decrease. This implies the total volume of pumped water stored in the cascade will reach it maximum on day 365 in the FDC, at which the average daily river discharge shows it minimum.

MODEL ASSUMPTION FOUR: PUMP- AND TURBINE CAPACITY MANAGEMENT

Contrary to – for instance a Bulb turbine – the screw turbine cannot process more discharge it is designed for. If the discharge becomes too big it will overflow the screw reducing the efficiently significantly, as explained in chapter 8.

The use of the Archimedean screw has the advantage the processed discharge at turbining of a particular PSP-plant can be controlled by rotating screw(s) in- or out position, which is elaborated on in chapter 10. This advantage also holds for the process of pumping. In the model it is assumed the volume of water pumped or turbined is fully manageable based on this principle of rotating.

Furthermore, it is assumed a PSP-plant can switch instantly from pumping to turbining, with no time lost at constant waterlevels. In reality, a wave might develop when storage mode starts as river discharge will accumulate at the upstream side of the PSP-plant, which in turn will roll back upstream. However, the inertia of the water is neglected.

HYDROPOWER/PSP FACILITIES CASCADE

The conceptual design of the PSP-plant has been designed for the Sambeek weir. In the model it is assumed similar plants will be installed at the locations of the other weirs. The conceptual design is more or less scalable on the gross heads of each weir. As the available discharge differs - depending on the FDC - the number of screws will differ as well.

In chapter 6 it is explained energy storage starts downstream at Lith and ends at the Roermond. This raises the question why to equip the Linne- and Borgharen weir with similar plants like Sambeek. The answer is related to the fish mortality rates. As the cumulative fish mortality in the Meuse cascade may not become higher than 10 % screw turbines will be used for the Linne and Borgharen weir as well, in order to meet the objective of this report.

By using the hydraulic pistons, the upper- and lower side of the screw can follow the up- and downstream waterlevel thereby maximizing turbine efficiency. Furthermore, when rotating some screws in pumping position the facility at Linne can pump back the water which is lost from the nearby lock complex.

However, the facility for Borgharen only serves the purpose of hydropower. This is mentioned in the chapter in the discussion.

DIAMETER SCREW AND AEY

The diameter of a screw is bounding the hydropower production when the gross head becomes low, as explained in chapter 8. In the model two diameters can be used for a PSP-plant, which are:

- D = 4 m: capable of processing 10 m^3/s in turbine mode and 11.6 m^3/s in pumping mode. The minimum gross head to operate as a turbine is 1.6 meter.
- D = 5 m: capable of processing 15 m^3/s at turbining and 7.3 m^3/s at pumping. Minimum gross head: 2 meter.

The model has been used to compare the hydropower Annual Energy Yield (AEY) for each weir per screw diameter, in order to decide on the default values to use. The results are shown in Table 20.

Facility:	Number of screws needed for D = 4 m:	AEY (MWh):	Number of screws needed for D = 5 m:	AEY (MWh):	Relative difference %):
Borgharen	27	38,126	18	37,948	0.5
Linne	27	27,857	18	27,524	1.2
Roermond	30	24,588	20	23,179	6.1
Belfeld	30	21,028	20	22,717	8
Sambeek	30	27,476	20	26,257	4.6
Grave	30	24,809	20	23,495	5.6
Lith	33	42,587	22	42,080	1,2

Table 20: AEY per weir at differing screw diameter

As one can observe the AEY at each weir is higher when using screws with a diameter of 4 meter. The difference is the smallest at the Borgharen weir, which is explained by the fact the head in base mode is the highest within the cascade. This implies it will last longer before the head becomes too small for the turbine to operate during peak river mode.

The AEY at the Belfeld weir is 8 percent higher when using D = 4 m, which might make it feasible to install. However, this diameter results in the construction of a PSP-plant with 30 screws. Furthermore, it needs more generators as well leading to higher operation- and maintenance costs.

Ultimately the levelized cost of electricity should be used as a guide to decide on the screw diameter in combination with an environmental impact assessment. In the model the default values for every weir will be D = 5 meter, with the exception of Roermond and Belfeld at which D = 4 meter will be used as default value.

NUMERICAL EXPLANATION MODEL AT FDC DAY 252

The first model assumption is related to the change of waterlevel during one cycle of storage- and energy mode of 24 hours. During this cycle the waterlevel at the end of energy mode has to be equal to the waterlevel at the start of storage mode. This implies the change in water volume in the storage section will be zero. This is described by the volume balance which is also shown in the main chapter:

$$\Delta V = V_{in} - V_{out} = 0$$

This volume balance will be used to explain the model using FDC day 252. This numerical explanation starts at the Roermond PSP-plant, which is most upstream one in the cascade.

Roermond

The Linne hydropower plant uses the FDC of Maasbracht. For the Roermond PSP-plant the Venlo FDC is used. The Venlo FDC shows higher discharges due to the presence of tributaries, as explained in chapter 4. In order to account for these increased discharges, the Maasbracht FDC has been subtracted from the Venlo FDC. The difference is accounted for as 'discharge from tributaries'. In the model this as mentioned as the discharge from the tributaries at storage mode (DVS_{trib}) and the discharge from the tributaries at energy mode (DVE_{trib}).

The storage volume ($SV_{Roermond}$) upstream Roermond is 1,950,000 m^3. At FDC day 252 the section Roermond-Linne is completely stored by the river from the upstream Linne weir ($DVS_{ups,Linne}$ = 1,270,080 m^3) and the discharge from the tributaries (DVS_{trib} = 999,360 m^3) downstream Linne. Therefore, no volume of water ($PV_{Roermond}$) is pumped by the Roermond PSP-plant as DVS_{total} = 2,269,440 m^3 which is bigger than the storage volume.

$$PV_{Roermond} = 0$$

As the total discharge flowing in at storage mode (DVS_{total} = 2,269,440 m^3) is larger than the storage volume the surplus discharge will power the turbines ($TVS_{Roermond}$) at storage mode:

$$V_{in,storage,Roermond} = DVS_{total,Roermond} - TVS_{Roermond} = 1{,}950{,}000\ m^3$$

$$TS_{Roermond} = 1{,}950{,}000\ m^3$$

$$TVS_{Roermond} = DVS_{total,Roermond} - TS_{Roermond} = 319{,}440\ m^3$$

At energy mode discharge from the river ($DVE_{total,Roermond}$ = 4,538,880 m^3) which includes the discharge from the tributaries (DVE_{trib}= 1,998,720 m^3) flows into the storage section Roermond-Linne. This results in:

$$V_{in,energy,Roermond} = DVE_{total,Roermond} = 4{,}538{,}880\ m^3$$

This results in the volume of water which has to be released during energy mode:

$$V_{out,energy,Roermond} = V_{in,storage,Roermond} + V_{in,energy,Roermond} = 6{,}488{,}880\ m^3$$

As this volume is smaller than the maximum volume that can be processed by the turbines at energy mode ($MHVE_{Roermond}$ = 17,280,000 m^3) the volume of water passing the turbines at energy mode ($TVE_{Roermond}$) is:

$$TVE_{Roermond} = 6{,}488{,}880\ m^3$$

Finally, the volume balance check results in:

$$\Delta V_{Roermond} = V_{in,storage,Roermond} + V_{in,energy,Roermond} - V_{out,energy,Roermond} = 0$$

Belfeld

The storage volume ($SV_{Belfeld}$) upstream the Belfeld weir is 2,550,000 m^3. The storage section Belfeld-Roermond is partly filled by the river from upstream Roermond and partly by pumping from downstream at the Belfeld PSP-plant.

The volume of water flowing in from upstream Roermond at storage mode ($DVS_{upst,Roermond}$) is equal to the volume of water released by the Roermond turbines at storage mode which is 319,440 m^3. This implies the section Roermond-Linne is pumped-stored ($PV_{Belfeld}$) by a volume of 2,230,560 m^3.

$$PV_{Belfeld} = SV_{Belfeld} - TVS_{Roermond} = 2{,}230{,}560\ m^3$$

$$V_{in,storage,Belfeld} = TVS_{Roermond} + PV_{Belfeld} = 2{,}550{,}000\ m^3$$

$$TS_{Belfeld} = 2{,}550{,}000\ m^3$$

At energy mode the volume of water flowing into the section Belfeld-Roermond is equal to the volume of water released by the Roermond PSP-plant:

$$V_{in,energy,Belfeld} = V_{out,energy,Roermond} = 6{,}488{,}880\ m^3$$

The leads to the following volume of water which needs to be released during energy mode at the Belfeld PSP-plant:

$$V_{out,energy,Belfeld} = V_{in,storage,belfeld} + V_{in,energy,Belfeld} = 9{,}038{,}880\ m^3$$

$$TVE_{belfeld} = 9{,}038{,}880\ m^3$$

The volume balance check results in:

$$\Delta V_{Belfeld} = V_{in,storage,Belfeld} + V_{in,energy,Belfeld} - V_{out,energy,Belfeld} = 0$$

Sambeek

As explained in the main chapter, the number of screws per facility is determined by the 100-day design discharge of the governing FDC, resulting in the default values used in the model of which some results are shown in this numerical example. For the Sambeek PSP-plant this results in 20 screw turbines with a diameter of 5 meter. The number of screws per facility are listed in Table 17. Sambeek hosting 20 screws in shown in Figure 71.

The maximum pumped volume ($MPV_{Sambeek}$) of Sambeek is 6,681,600 m^3 using 20 screws with a pump-capacity of 11.6 m^3/s per screw and a duration of storage mode of 8 hours. The storage volume of Sambeek is 7,360.000 m^3 using the default values.

The section Belfeld-Roermond is partly stored by the river and partly by pumping. The Sambeek PSP-plant will pump its maximum pumped volume as this is smaller than the Sambeek storage volume.

$$PV_{Sambeek} = MPV_{Sambeek} = 6{,}681{,}600\ m^3$$

As a part of this volume of water in turn is pumped up at the Belfeld PSP-plant the volume of water stored upstream at Sambeek during storage mode is:

$$V_{in,storage,Sambeek} = PV_{Sambeek} - PV_{Belfeld} = 4{,}451{,}040\ m^3$$

$$TS_{Sambeek} = 4{,}451{,}040\ m^3$$

During energy mode the volume entering the section Sambeek-Belfeld is equal to the volume of water released by the Belfeld PSP-plant:

$$V_{in,energy,Sambeek} = V_{out,energy,Belfeld} = 9{,}038{,}880\ m^3$$

This implies the volume of water which will leave the section Sambeek-Belfeld at energy mode is:

$$V_{out,energy,Sambeek} = V_{in,storage,Sambeek} + V_{in,energy,Sambeek} = 13{,}489{,}920\ m^3$$

$$TVE_{Sambeek} = 13{,}489{,}920\ m^3$$

As this volume is smaller than the maximum volume the turbines at Sambeek can process at energy mode ($MHVE_{Sambeek}$= 17,280,000 m^3) no water needs to be released by the weir.

The Sambeek volume balance reads:

$$\Delta V_{Sambeek} = V_{in,storage,Sambeek} + V_{in,energy,Sambeek} - V_{out,energy,Sambeek} = 0$$

<u>Grave</u>

As Sambeek pumps at its full capacity no water will be stored in the Grave-Sambeek section. The PSP-plant at Grave will pump at its full capacity as well (which is equal to the Sambeek capacity). However, the water will in turn be pumped upstream at Sambeek. This results in:

$$PV_{Grave} = MPV_{Grave} = 6{,}681{,}600\ m^3$$

$$TS_{Grave} = 0$$

$$V_{in,storage,Grave} = PV_{Sambeek} - PV_{Belfeld} = 0$$

During energy mode the volume which will flow in will be equal to the volume of water released at Sambeek:

$$V_{in,energy,Grave} = V_{out,energy,Sambeek} = 13{,}489{,}920\ m^3$$

This results in the following relation for the volume of water which needs to be released at the Grave PSP-plant:

$$V_{out,energy,Grave} = V_{in,storage,Grave} + V_{in,energy,Grave} = 13{,}489{,}920\ m^3$$

$$TVE_{Grave} = 13{,}489{,}920\ m^3$$

The volume balance for Grave results in:

$$\Delta V_{Grave} = V_{in,storage,Grave} + V_{in,energy,Grave} - V_{out,energy,Grave} = 0$$

<u>Lith</u>

At Lith the FDC of Megen is used. As the increased discharge cannot be explained by the existence of tributaries, it is described by 'additional' discharge, assumed to be the result of the catchment area upstream of Megen. In the model this is accounted for by DVS_{addi} and DVE_{addi}. As a result, a volume of water will always be stored by the river caused by this additional inflow.

The PSP-plant at Lith is equipped with 22 screws. Grave is hosting 20 screws. This implies the volume of water pumped by 2 screws will be stored upstream Lith. At FDC day 252 the pumped volume at Lith is:

$$PV_{Lith} = MPV_{Lith} = 7{,}349{,}760\ m^3$$

The volume of water stored is:

$$V_{in,storage,Lith} = PV_{Lith} \text{ - } PV_{Grave} + DVS_{addi} = 1{,}022{,}400\ m^3$$

$$TS_{SLith} = 1{,}022{,}400\ m^3$$

At energy mode the volume of water flowing in from upstream Grave is:

$$V_{in,energy,Lith} = V_{out,energy,Grave} = 13{,}489{,}920\ m^3$$

The total volume of water which will be released at the Lith PSP-plant during energy mode is:

$$V_{out,energy,Lith} = V_{in,storage,Lith} + V_{in,energy,Lith} + DVE_{addi} = 15{,}220{,}800\ m^3$$

$$TVE_{Lith} = 15{,}220{,}800\ m^3$$

As this volume is smaller than the maximum volume the turbines at Lith can process during energy mode ($MHVE_{Lith}$= 19,008,000 m^3) no water needs to be released by the weir.

Finally, the volume balance for Lith reads:

$$\Delta V_{Lith} = V_{in,storage,Lith} + V_{in,energy,Lith} + DVE_{addi} - V_{out,energy,Lith} = 0$$

NUMERICAL EXPLANATION MODEL AT FDC DAY 315

The second numerical explanation will be presented for FDC day 315. At this stage in the FDC curves the room for storage is relatively large as the river discharge is relatively low.

Roermond

The storage volume ($SV_{Roermond}$) upstream Roermond is 1,950,000 m^3. At FDC day 315 the section Roermond-Linne is partly stored by the river from the upstream Linne weir ($DVS_{ups,Linne}$ = 207,360 m^3) and by the discharge from the tributaries (DVS_{trib} = 858,240 m^3) downstream Linne. The volume of water ($PV_{Roermond}$) pumped by the Roermond PSP-plant will be equal to:

$$PV_{Roermond} = SV_{Roermond} - DVS_{total,Roermond} = 884{,}400\ m^3$$

The volume of water stored at storage mode will be:

$$V_{in,storage,Roermond} = DVS_{total,Roermond} + PV_{Roermond} = 1{,}950{,}000\ m^3$$

$$TS_{Roermond} = 1{,}950{,}000\ m^3$$

At energy mode discharge from the river ($DVE_{total,Roermond}$ = 2,131,200 m^3) which includes the discharge from the tributaries (DVE_{trib}= 1,716,480 m^3) flows into the storage section Roermond-Linne. This results in:

$$V_{in,energy,Roermond} = DVE_{total,Roermond} = 2{,}131{,}200\ m^3$$

This results in the following volume of water which has to be released during energy mode:

$$V_{out,energy,Roermond} = V_{in,storage,Roermond} + V_{in,energy,Roermond} = 4{,}081{,}200 \; m^3$$

As this volume is smaller than the maximum volume that can be processed by the turbines at energy mode ($MHVE_{Roermond}$ = 17,280,000 m^3) the volume of water passing the turbines at energy mode ($TVE_{Roermond}$) is:

$$TVE_{Roermond} = 4{,}081{,}200 \; m^3$$

The volume balance check for Roermond results in:

$$\Delta V_{Roermond} = V_{in,storage,Roermond} + V_{in,energy,Roermond} - V_{out,energy,Roermond} = 0$$

Belfeld

The storage volume ($SV_{Belfeld}$) upstream the Belfeld weir is 2,550,000 m^3. The storage section Belfeld-Roermond is only stored by pumping from downstream at the Belfeld PSP-plant.

The volume of water flowing in from upstream Roermond at storage mode ($DVS_{upst,Roermond}$) is equal to the volume of water released by the Roermond turbines at storage mode which is 0 m^3. This implies the pumped volume at Belfeld ($PV_{Belfeld}$) is:

$$PV_{Belfeld} = SV_{Belfeld} + PV_{Roermond} = 3{,}434{,}400 \, m^3$$

$$V_{in,storage,Belfeld} = PV_{Belfeld} - PV_{Roermond} = 2{,}550{,}000 \, m^3$$
$$TS_{Belfeld} = 2{,}550{,}000 \, m^3$$

At energy mode the volume of water flowing into the section Belfeld-Roermond is equal to the volume of water released by the Roermond PSP-plant:

$$V_{in,energy,Belfeld} = V_{out,energy,Roermond} = 4{,}081{,}200 \; m^3$$

The leads to the following volume of water which needs to be released during energy mode at the Belfeld PSP-plant:

$$V_{out,energy,Belfeld} = V_{in,storage,belfeld} + V_{in,energy,Belfeld} = 6{,}631{,}200 \, m^3$$

$$TVE_{belfeld} = 6{,}631{,}200 \, m^3$$

The volume balance check results in:

$$\Delta V_{Belfeld} = V_{in,storage,Belfeld} + V_{in,energy,Belfeld} - V_{out,energy,Belfeld} = 0$$

Sambeek

The maximum pumped volume ($MPV_{Sambeek}$) of Sambeek is 6,681,600 m^3. The section Belfeld-Roermond is completely stored by pumping. The Sambeek PSP-plant will pump its maximum pumped volume as this is smaller than the Sambeek storage volume.

$$PV_{Sambeek} = MPV_{Sambeek} = 6{,}681{,}600 \, m^3$$

As a part of this volume of water in turn is pumped up at the Belfeld PSP-plant the volume of water stored upstream at Sambeek during storage mode is:

$$V_{in,storage,Sambeek} = PV_{Sambeek} \text{ - } PV_{Belfeld} = 3{,}247{,}200\ m^3$$

$$TS_{Sambeek} = 3{,}247{,}200\ m^3$$

During energy mode the volume entering the section Sambeek-Belfeld is equal to the volume of water released by the Belfeld PSP-plant:

$$V_{in,energy,Sambeek} = V_{out,energy,Belfeld} = 6{,}631{,}200\ m^3$$

This implies the volume of water which will leave the section Sambeek-Belfeld at energy mode is:

$$V_{out,energy,Sambeek} = V_{in,storage,Sambeek} + V_{in,energy,Sambeek} = 9{,}878{,}400\ m^3$$

$$TVE_{Sambeek} = 9{,}878{,}400\ m^3$$

As this volume is smaller than the maximum volume the turbines at Sambeek can process at energy mode ($MHVE_{Sambeek}$= 17,280,000 m^3) no water needs to be released by the weir.

The Sambeek volume balance reads:

$$\Delta V_{Sambeek} = V_{in,storage,Sambeek} + V_{in,energy,Sambeek} - V_{out,energy,Sambeek} = 0$$

Grave

As Sambeek pumps at its full capacity no water will be stored in the Grave-Sambeek section. The PSP-plant at Grave will pump at its full capacity as well (which is equal to the Sambeek capacity) and the water will in turn be pumped upstream at Sambeek. This results in:

$$PV_{Grave} = MPV_{Grave} = 6{,}681{,}600\ m^3$$

$$TS_{Grave} = 0$$

$$V_{in,storage,Grave} = PV_{Sambeek} \text{ - } PV_{Belfeld} = 0$$

During energy mode the volume which will flow in will be equal to the volume of water released at Sambeek:

$$V_{in,energy,Grave} = V_{out,energy,Sambeek} = 9{,}878{,}400\ m^3$$

This results in the following relation for the volume of water which needs to be released at the Grave PSP-plant:

$$V_{out,energy,Grave} = V_{in,storage,Grave} + V_{in,energy,Grave} = 9{,}878{,}400\ m^3$$

$$TVE_{Grave} = 9{,}878{,}400\ m^3$$

The volume balance for Grave results in:

$$\Delta V_{Grave} = V_{in,storage,Grave} + V_{in,energy,Grave} - V_{out,energy,Grave} = 0$$

Lith

At FDC day 252 the pumped volume at Lith is:

$$PV_{Lith} = MPV_{Lith} = 7{,}349{,}760\ m^3$$

The volume of water stored is:

$$V_{in,storage,Lith} = PV_{Lith} - PV_{Grave} + DVS_{addi} = 864{,}000\ m^3$$

$$TS_{SLith} = 864{,}000\ m^3$$

At energy mode the volume of water flowing in from upstream Grave is:

$$V_{in,energy,Lith} = V_{out,energy,Grave} = 9{,}878{,}400\ m^3$$

The total volume of water which will be released at the Lith PSP-plant during energy mode is:

$$V_{out,energy,Lith} = V_{in,storage,Lith} + V_{in,energy,Lith} + DVE_{addi} = 11{,}134{,}080\ m^3$$

Finally, the volume balance for Lith reads:

$$\Delta V_{Lith} = V_{in,storage,Lith} + V_{in,energy,Lith} + DVE_{addi} - V_{out,energy,Lith} = 0$$

MODEL AT INCREASED DISCHARGE

For the numerical illustration FDC day 252 was used. However, when using – for instance FDC day 119 – it becomes more complicated as the maximum volumes which the majority of the weirs can process ($MHVE$) has been reached. This implies water has to be released through the turbines at storage mode as well.

The model has been programmed in such a way it cannot pump up more water at a PSP-plant than can be released during energy mode, in order to avoid wasting energy. This is explained using Figure 142 related to the Belfeld PSP-plant.

SBR:	PSBR:	TS:	WLI:	SPU:	TVS:	WVS:	DVE_river:	TVE:
(m3/day)	(MWhr)	(m3/day)	(m)	(MWhr)	(m3/day)	(m3/day)	(m3/day)	(m3/day)
883920	5	883920	0.3	0	4389120	0	14446080	17280000
762960	4	762960	0.3	0	4570560	0	14567040	17280000
624720	3	624720	0.2	0	4777920	0	14705280	17280000
503760	3	503760	0.2	0	4959360	0	14826240	17280000
348240	**2**	**348240**	**0.1**	**0**	**5192640**	**0**	**14981760**	**17280000**
233040	1	233040	0.1	0	5365440	0	15096960	17280000
146640	1	146640	0.1	0	5495040	0	15183360	17280000
0	0	0	0.0	0	5745600	0	15350400	17280000
0	0	0	0.0	0	5883840	0	15442560	17280000
0	0	0	0.0	0	6091200	0	15580800	17280000
0	0	0	0.0	0	6367680	0	15765120	17280000
0	0	0	0.0	0	6531840	0	15874560	17280000

Figure 142: Belfeld weir at FDC day 119.

The blue marked column represents the volume of water stored by the river ($SBR_{Belfeld}$). At this FDC day no water is pumped at all at Belfeld. The total volume stored ($TS_{Belfeld}$ marked in purple) is solely the result from river storage. The volume of water released at energy mode from the Roermond weir is (not visible at Figure 142):

$$V_{out,energy,Roermond} = 16{,}931{,}760\ m^3$$

This implies only 348,240 m^3 can be stored upstream of Belfeld ($TS_{Belfeld}$), as the MHVE and at Belfeld is:

$$MHVE_{Belfeld} = 17{,}280{,}000\ m^3$$

Contrary to the example of the previous paragraph the TVE (marked in green) will be equal to the MHVE:

$$TVE_{Belfeld} = 17{,}280{,}000\ m^3$$

The volume of water processed by the turbines during storage mode at Roermond is (not visible in Figure 142):

$$TVS_{Roermond} = 5{,}540{,}880\ m^3$$

This implies the volume of water processed by the turbines at storage mode at Belfeld (TVS marked in light green) is:

$$TVS_{Belfeld} = TVS_{Roermond} - SBR_{Belfeld} = 5{,}192{,}640\ m^3$$

MODEL AT LARGE RIVER DISCHARGE

When the river discharge increases the weirs are used for discharge purposes as well. This happens when the maximum volume a PSP-plant can process in energy mode (MHVE) as well as in storage mode (MHVS) is exceeded. This is shown in Figure 143, again related to the Belfeld weir.

TVS:	WVS:	DVE_river:	TVE:	WVE:
(m3/day)	(m3/day)	(m3/day)	(m3/day)	(m3/day)
7836480	0	16744320	17280000	0
8035200	0	16876800	17280000	0
8251200	0	17020800	17280000	0
8389440	0	17112960	17280000	0
8640000	0	17280000	17280000	0
8640000	83520	17447040	17280000	167040
8640000	169920	17619840	17280000	339840
8640000	264960	17809920	17280000	529920
8640000	328320	17936640	17280000	656640
8640000	411840	18103680	17280000	823680

Figure 143: Model under large river discharge

As one can observe the model is programmed in such a way the amount of water which is processed during energy mode is maximized. It maximally is equal the $MHVE_{Belfeld}$ (17,280,000 m^3). Ultimately volume is processed by the turbines at storage mode as well when $MHVE_{Belfeld}$ is reached.

This volume at storage mode increases towards the maximum represented by $MHVS_{Belfeld}$ (8,640,000 m^3). At the moment $MHVS_{Belfeld}$ is exceeded either at storage- or energy mode the surplus volumes are released by the weir. This is represented by the weir volume at storage mode ($WVS_{Belfeld}$) and the weir volume at energy mode ($WVE_{Belfeld}$).

As mentioned in the introduction of appendix I the theory behind the model is complicated and hard to explain by the use of an appendix. To get a deeper understanding of the functioning of the model it is advised to use it and to observe what happens at the columns of the weirs.

DURATION STORAGE MODE

The duration of storage mode is set on 8 hours. However, this duration can be adjusted in the model in a value between 4 and 12 hours. A cycle of storage- and energy mode last 24 hours. One can also choose 23 hours for the duration of storage mode, but obviously this is not realistic.

ADJUSTING WIDTH AND HEIGHT STORAGE SECTIONS

One requirement of the model is the volumes of each individual storage section can be adjusted. As explained in appendix I default values are used based on boundary conditions with respect to these volumes. These default values have been made variables in order to assess increased storage sections.

ADJUSTING NUMBER OF SCREWS IN OPERATION

Another requirement is the number of screws in operation can be adjusted for each individual hydropower- or PSP facility. In the model the default value of the number of screws is determined by the available discharges for each weir. However, the number of screws can be de- or increased to assess the characteristics of pumped-stored power and hydropower production thereby satisfying the requirement.

AUTOMATIC ADJUSTMENT TO WATERLEVELS

In the model it is assumed the screw ends will be adjusted to the waterlevels up- and downstream using the measurement locations of RWS. As these locations provide waterlevels for each weir at the up- and downstream side it is assumed the hydraulic pistons will be managed fully automated in turbine- and pumping mode based on these real time RWS measurements.

SHORTCOMING OF THE MODEL

When the storage height of a section is increased above 1 meter, the pump angle might become higher than 30° depending on the increase in waterlevel in the storage section downstream. An increase on angle will reduce the pump capacity.

This effect will not occur using the default value for the storage height. Using this default value will not result in a waterlevel above PDP as this point is located 1.5 meter above the waterlevel using a 5-meter diameter screw. For the PSP-plants at Belfeld and Roermond PDP is located at 1.2 meter above PCP, as the screw diameter is 4 meter, which is also higher than the 1-meter storage height.

However, when the increase in waterlevel becomes more than one meter (using increased storage volume), the pump angle might have to be increased depending on the increase in waterlevel downstream the PSP-plant reducing the pump capacity.

It has been tried to program the pump capacity in such a way it decreases when the pump angle becomes higher than 30°. However, frustratingly this was not possible. Whatever programming solution was thought of, Excel returned the message ‘circular reference’.

AVAILABLE DISCHARGE AND STARTING DISCHARGE

The model uses the available discharge per weir instead of the design discharge. By doing so leakage losses etc. can be neglected in the model. Furthermore, it uses Q_{start} (equal to 3 m³/s) as starting value for turbining, as Q_{min} includes these losses.

NUMBER OF TURBINES

The model provides the number of turbines - used at pumping- or turbining - by dividing the concerning volumes by the pump- or turbine capacity. These numbers are shown in separate columns using the abbreviations $NSPS$, $NSTS$ and $NSTE$.

POWERS PER FACILITY

As one can observe in the figures in the main chapter the model provides information on PSP- and hydropower produced per facility. Furthermore, the power stored by the river is provided. Basically, this is the amount of river discharge which is retained at storage mode and released during energy mode. The surplus power used is provided as well. This surplus power is calculated using:

$$P_{surplus,used} = \rho * g * Q * H / \eta \qquad \text{formula (14)}$$

In formula 14 the head which is used is the GHA. The pump efficiency at each facility is 75 %.

POWERS AT RANDOM RIVER DISCHARGE

The model is capable of providing the daily cumulative powers of the cascade (and each individual PSP-plant). For this purpose, a random value of the average discharge of the 4 FDC's can be selected. An example is shown in Figure 144, at which a discharge of 33 m³/s is chosen.

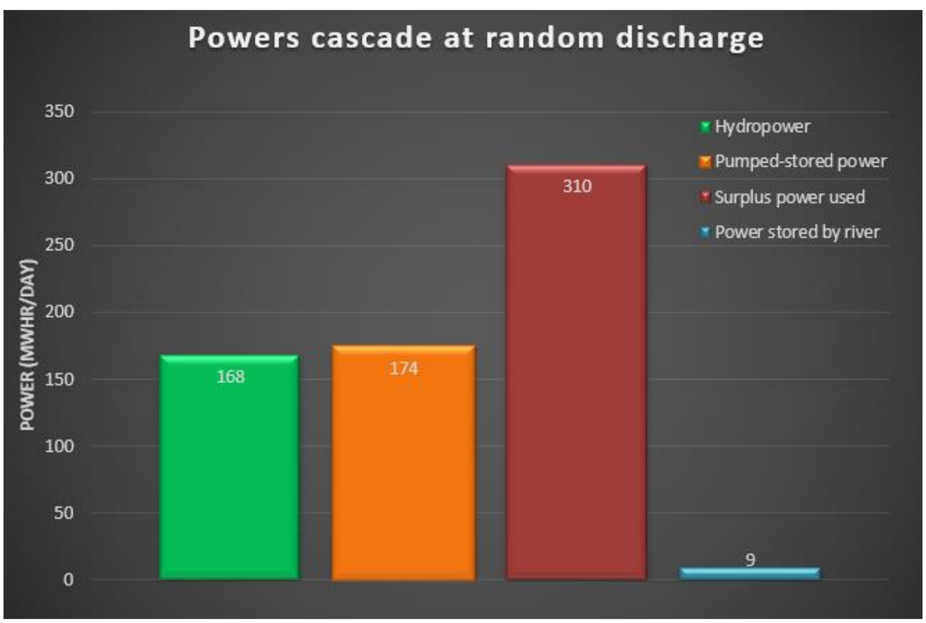


Figure 144: Cumulative powers cascade for a random average discharge of 33 m³/s.

At this FDC day the river discharge is relatively low. As a consequence, the pumped-stored power (174 MWh) in the cascade is larger than the produced hydropower produced (168 MWh).

GROSS HEAD ADJUSTED

The gross head (GH) of each weir can be influenced by storage. For instance, the waterlevel of the section Lith-Grave will rise due to pumping resulting in an increased gross head for the Lith PSP-plant.

In order to account for this rise a short cut has been applied. The model calculates the gross head adjusted (GHA) by adding the average of the water level increase in the storage section (WLI) minus the waterlevel increase in the downstream section to the original gross head. The GHA is used for the calculations of PSP- and hydropower production.

The stepwise pattern in the graphs of the model is explained by the fact the GHA increases/decrease using steps of 0.1 meter.

EFFICIENCY PSP-PROCESS

The efficiency of the PSP-process is calculated by dividing the PSP-power produced by the surplus power used. At each PSP-facility this resulted in an PSP-efficiency of 56,25 %.

This makes sense as one would expect this PSP-efficiency using formula 10 and a pump- and turbine efficiency of 75 %.

$$\mu_{PSP} = \mu_{pump} * \mu_{urbine}$$

$$\mu_{PSP} = 75\ \% * 75\ \% = 56{,}25\ \%$$

CASCADE POWERS

The model provides the total PSP- and hydropower produced in combination with the surplus power used by summing up the individual contributions of each facility in the cascade. By doing so these requirements of the model have been fulfilled.

VERIFICATION OF THE MODEL

The requirements of the model are listed in chapter 3. For the sake of the overview these model requirements are listed below:

- Capable of describing pump-stored power production per weir.
- Capable of describing surplus power used per weir.
- Capable of providing number of turbines in operation depending on river- and stored discharge.
- Capable of describing waterlevel increase due to pumping.
- Capable of providing number of screws in operation while pumping.
- Capable of providing surplus power used – and power produced depending on some random discharge weir.
- Capable of describing pump-stored power cascade.
- Capable of describing hydropower production whole cascade.
- Capable of describing surplus power used cascade.
- Capable of describing efficiency overall PSP-process cascade.
- Capable of providing total surplus power used – and total power produced depending on some random average discharge cascade.
- Obeying boundary conditions on discharge, waterlevels and storage volumes.

As one can observe the model is verified positive on each requirement based on the information presented in appendix I and the main chapter.

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