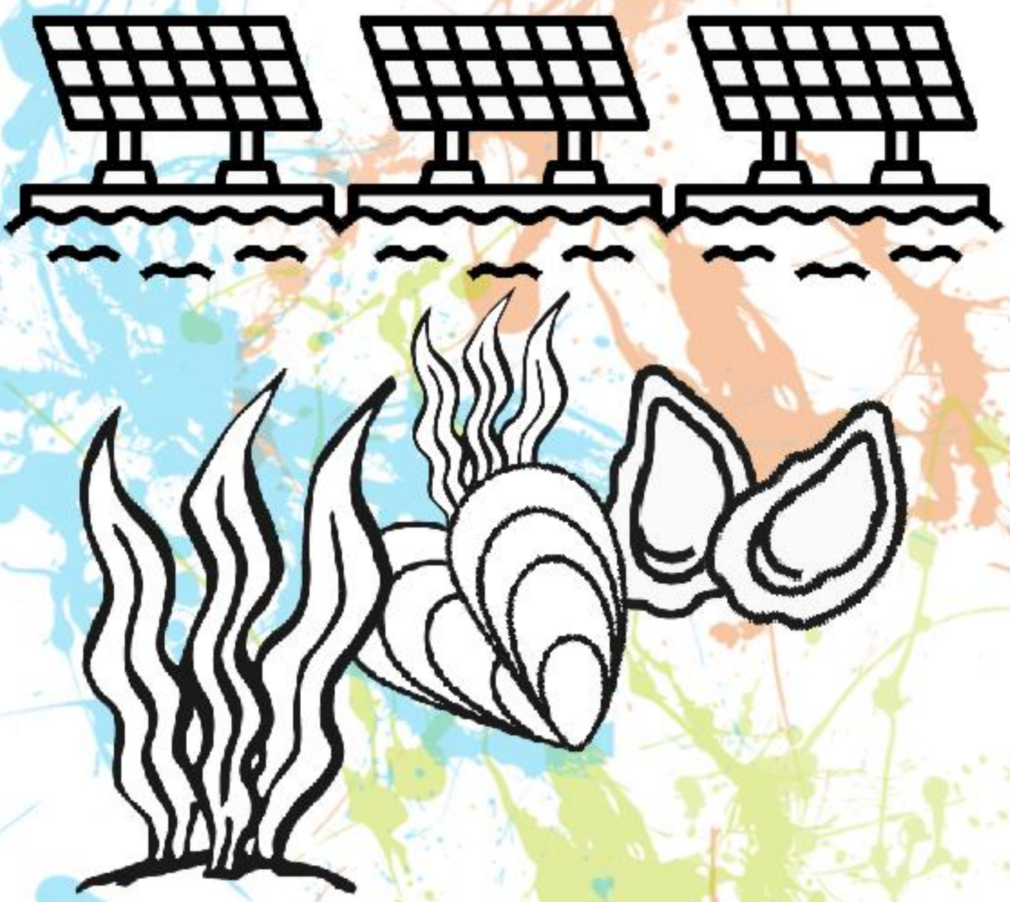
# Aquaculture in the Delta21 Energy Storage Lake



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Final report

DELTA 21

ConsultanSEA

Solar Energy & Aquaculture

# Aquaculture activities in Energy Storage Lake: advice for cultivating shellfish and seaweed in combination with a floating solar park

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# Executive summary

Delta21 aims to create an alternative for flood risk protection through an elaborate plan, which includes the construction of a man-made saltwater lake, called the Energy Storage Lake (ESL). The ESL is 22.5 m deep and has a potential daily water height difference of 17.5 m, with a 5 m deep water layer that will not be emptied. This water flows in during the day, generating 22.3 GWh. During the night, excess energy is used to empty the lake. To make the ESL more economically, ecologically, and politically appealing, Delta21 plans on including several green energy opportunities and aquaculture. In this project, the green energy opportunities that are included in the research are floating solar panels. Aquaculture will be limited to shellfish and seaweed cultivation.

The purpose of this project is to find out the answer to the main research question:

- What is the most viable combination of aquaculture types for shellfish and seaweed, considering suitable sites and positive nature effects in the Energy Storage Lake?

To fulfil this purpose, a literature research was conducted on the different aquaculture practices for shellfish and seaweed cultivation, possibly in combination with a floating solar park. Next to this, interviews with external experts were conducted. These experts were working for Seaweed Harvest Holland, de Nederlandse Oestervereniging, PO Mosselcultuur. Furthermore, a seaweed expert from Wageningen University & Research and a student from Technical University Delft with expertise in floating solar panels have been interviewed.

The following sub questions were answered to be able to make a main conclusion and final advice to the commissioner:

1. What are the expected conditions in the Energy Storage Lake?
2. Which forms of aquaculture require conditions that match the expected conditions at different sites in the Energy Storage Lake?
3. Which requirements does the floating solar park have to meet in order to reach highest production of the species and aquaculture types selected in sub-question 2?
4. Which of these aquaculture types has potential for nature enrichment, regarding water quality and biodiversity?

The most viable combination of aquaculture types in the ESL would incorporate all shellfish species emphasized in this project, as well as sugar and finger kelp. Each provides its own nature enrichment, together increasing the resilience of the ESL system. The shellfish species should be placed close to the pumps, the seaweed species near the middle of the lake, and the solar park opposite of the pumps. These sites and distribution are advised mainly due to the flow rate requirements of the different species.

The most important recommendation for further research is regards the knowledge gap on the fluctuations of resources in the ESL. Knowledge on the fluctuations and depletion of resources when the lake is being emptied is necessary to make sure the lake holds enough resources for aquaculture. No concrete information on fluctuations was found due to time restraints. Information on fluctuations can be obtained by using models like Delft3D or by field measurements in the area of the future ESL-location. Lastly, it is advised to reassess the recommendations of this report after more elaborate modelling of the flow rate and nutrients in the ESL, and after the design of the ESL has been finalised.

# Nederlandse samenvatting

Delta21 streeft ernaar om een alternatief te bieden voor bescherming tegen overstromingsrisico's doormiddel van een uitgebreid plan, omvattende het creëren van een door de mens gemaakt zoutwater meer, het zogenaamde Energy Storage Lake (Energieopslagmeer, ESL). Het ESL zal 22,5 m diep worden en heeft een potentieel verschil in waterniveau van 17,5 m, met op de bodem een 5 m diepe waterkolom die nooit geleegd zal worden. Het water stroomt gedurende de dag het meer in, waarbij 22,3 GWh wordt gegenereerd. Gedurende de nacht wordt overtollige energie gebruikt om het meer leeg te pompen. Om het ESL economisch, ecologisch en politiek aantrekkelijk te maken, is Delta21 van plan om verscheidene kansen voor groene energie en aquacultuur te benutten. In dit project worden drijvende zonnepanelen opgenomen als kans voor groene energie. De aquacultuur is gelimiteerd tot het cultiveren van schelpdieren en zeewier.

Het doel van dit project is het vinden van een antwoord op de volgende onderzoeksvraag:

- Wat is de meest rendabele combinatie van aquacultuur voor schelpdieren en zeewier, in overweging nemend de geschikte locaties en mogelijkheden voor natuurverrijking in het Energy Storage Lake?

Om dit doel te vervullen, werd een literatuuronderzoek over de verschillende vormen van aquacultuur voor schelpdier- en zeewierteelt, wanneer mogelijk in combinatie met een drijvend zonnepark, uitgevoerd. Daarnaast zijn interviews met experts gedaan. Deze experts werken voor Seaweed Harvest Holland, de Nederlandse Oestervereniging, PO Mosselcultuur. Daarnaast zijn een zeewierexpert van Wageningen University & Research en een student van de Technische Universiteit Delft met expertise over drijvende zonnepanelen geïnterviewd.

De volgende deelvragen zijn beantwoord om tot een eindconclusie en een advies voor de opdrachtgever te komen:

1. Wat zijn de te verwachte condities in het Energy Storage Lake?
2. Welke vormen van aquacultuur hebben omstandigheden nodig zoals die die voorkomen op verschillende plekken in het Energy Storage Lake?
3. Aan welke vereisten moet het Energy Storage Lake voldoen om een zo hoog mogelijke productie te krijgen van aquacultuur vormen gekozen in deelvraag 2?
4. Welke vormen van aquacultuur hebben potentie voor natuurverrijking, betreffend waterkwaliteit en biodiversiteit?

De meest rendabele combinatie van aquacultuur typen in het ESL omvat alle schelpdiersoorten benoemd in dit project, evenals suikerwier en vingerwier. Elke soort voegt op zijn eigen manier iets toe aan natuurverrijking en gezamenlijk verhogen de soorten de veerkracht van het ESL-systeem. De schelpdier soorten zullen dicht bij de pompen geplaatst moeten worden, de zeewiersoorten rond het midden van het meer en het zonnepanelenpark tegenover de pompen aan de overzijde van het meer. Deze locaties en verdelingen zijn voornamelijk geadviseerd op grond van de benodigde stroomsnelheden voor de verschillende soorten.

De meest belangrijke aanbeveling voor vervolgonderzoek richt zich op het gebrek aan kennis omtrent de schommelingen van de condities en middelen in het ESL. Kennis over de fluctuaties en het gebruik van de beschikbare condities en middelen wanneer het meer wordt geleegd zijn nodig om er zeker van te zijn dat er genoeg in het meer over blijft voor aquacultuur. Er is geen concrete informatie over fluctuaties gevonden door de beperkte beschikbare tijd. Deze informatie kan echter worden verkregen door het gebruik van modellen zoals Delft3D of door middel van metingen in het gebied van het toekomstige ESL. Tot slot wordt er geadviseerd om de aanbevelingen van dit rapport opnieuw in acht te nemen wanneer uitgebreidere modellering is gebruikt voor de stroomsnelheden en nutriënten in het ESL, en nadat het uiteindelijke ontwerp van het ESL bekend is.

# Chapter 1: Introduction

## 1.1 Background information

For centuries, the Dutch have been working to keep the water out of their land. Quite successfully so far, since roughly one third of the Netherlands is below sea level. Large parts of the Netherlands consist of a delta plain formed by the rivers Rhine, Meuse and Scheldt (Saeijs & Van Kessel, 2005). The Rhine-Meuse-Scheldt delta is of economical, ecological and social importance to the Netherlands (Meyer, 2009).

Living in a delta area below sea level does not come without cost. The flood of 1953 took more than 1800 lives and flooded 165.000 ha of land (Bregt *et al.*, 2014). After this flood, the Dutch government implemented the Delta Works to protect the delta area. The Delta Works separate the Voordelta (Figure 1) from the Rhine-Meuse-Scheldt delta. One of the sluices was built at the entrance of the Haringvliet (Figure 1).

Before the implementation of the Delta Works in 1968 by the Dutch government, the Haringvliet was an intertidal, open estuary with brackish water. With the construction of the Haringvliet sluices, the Haringvliet was cut off from the North Sea and the Haringvliet changed into a freshwater lake. This drastically affected the vegetation composition, marine life via the disappearance of fish migration routes (Braakhekke *et al.*, 2008) and bird populations (Meininger & Graveland, 2002; Tönis *et al.*, 2002; Van Dijk, 2019). An attempt has been made to restore the ecological values: the sluice closing the Haringvliet are opened periodically since 2018. The effects of this opening are not yet understood.

The Voordelta lies West of the Haringvliet and reaches from South of the Maasvlakte to North of the Westerschelde. The Voordelta is classified as a Natura2000 area and seabed protection area in 2008, to compensate for the construction of Maasvlakte 2 and to protect its valuable nature (Rijkswaterstaat, 2016; www.wur.nl/nl/show/Natuurcompensatie-Tweede-Maasvlakte.htm).

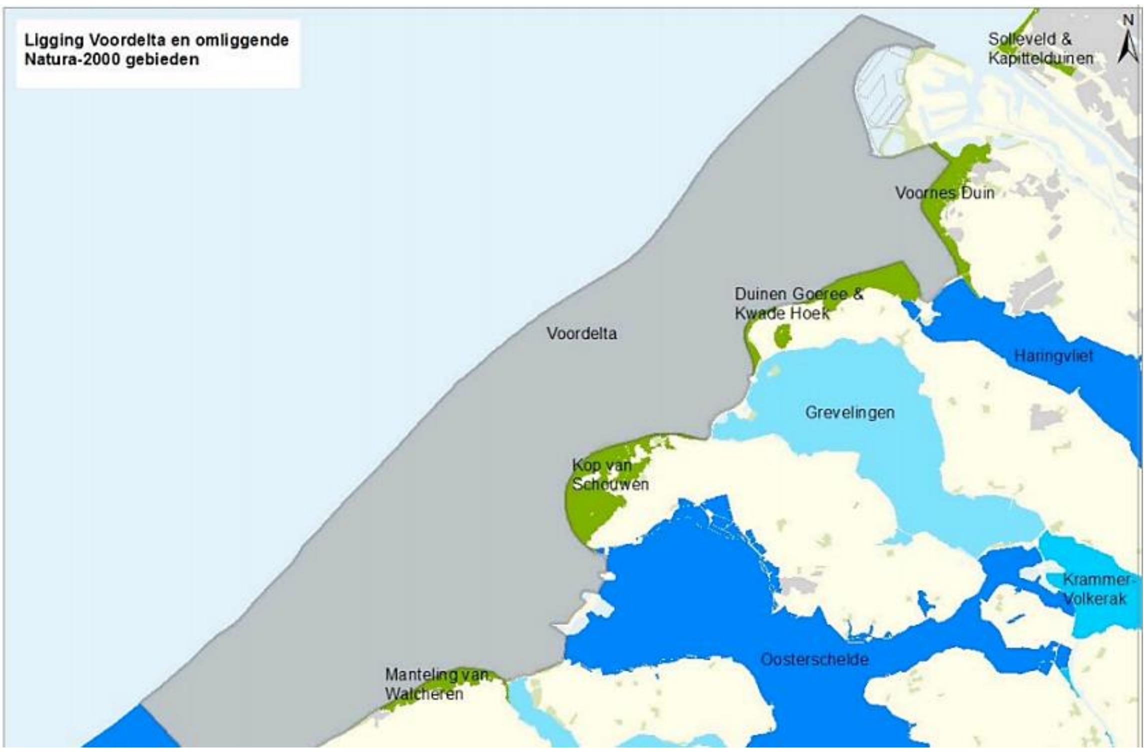


*Figure 1: Location of the Voordelta in grey and location of the Haringvliet indicated by the upper dark blue area. Green areas are Natura2000 areas. (Rijkswaterstaat, 2016).*

The Voordelta is open for recreational activities and even though it is a Natura2000 area, fisheries are allowed as long as the seabed protection areas are respected. The Voordelta is also still used as mussel seed collection area, although the cultivation practices are taking place elsewhere (Rijkswaterstaat, 2016).

In the Netherlands, off-shore shellfish cultivation has been limited to bottom cultures of mussels and oysters, with high risks on diseases and predation resulting in a low yield (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). Regarding off-shore seaweed farming more and more research has been done to investigate the possibilities on marine protein for consumption purposes. To date, off-shore seaweed cultivation is mainly done by start-ups that started in the last 10 years (Seaweed Harvest Holland, personal communication, 2020). Research on off-shore seaweed cultivation increased as well and is mainly executed by Wageningen Marine Research and the Royal Netherlands Institute for Sea Research.

In line with the already existing multi-use approach in the Voordelta and Haringvliet, the commissioner 'Delta21' wants to combine water safety, nature restoration and green energy. As can be read in the policy document 'Delta21 (2019)', Delta21 wants to provide an economically viable alternative to dyke strengthening for water management and safety in the Haringvliet. The intrinsic motivation behind the plan is to lower the water level in the Dutch river network during extreme high water events, by constructing an artificial saltwater lake of 26 km$^2$ with the deepest point at -27.5 m NAP (Normaal Amsterdams Peil or 'Amsterdam Ordnance Datum' in English. A measure for water height in the Netherlands), called the Energy Storage Lake (ESL) (Figure 2).

When storms and high river discharge threaten the Dutch river delta, which is expected to happen once per 10 years, excess river water from the Haringvliet will flow into the ESL via the overflow (Figure

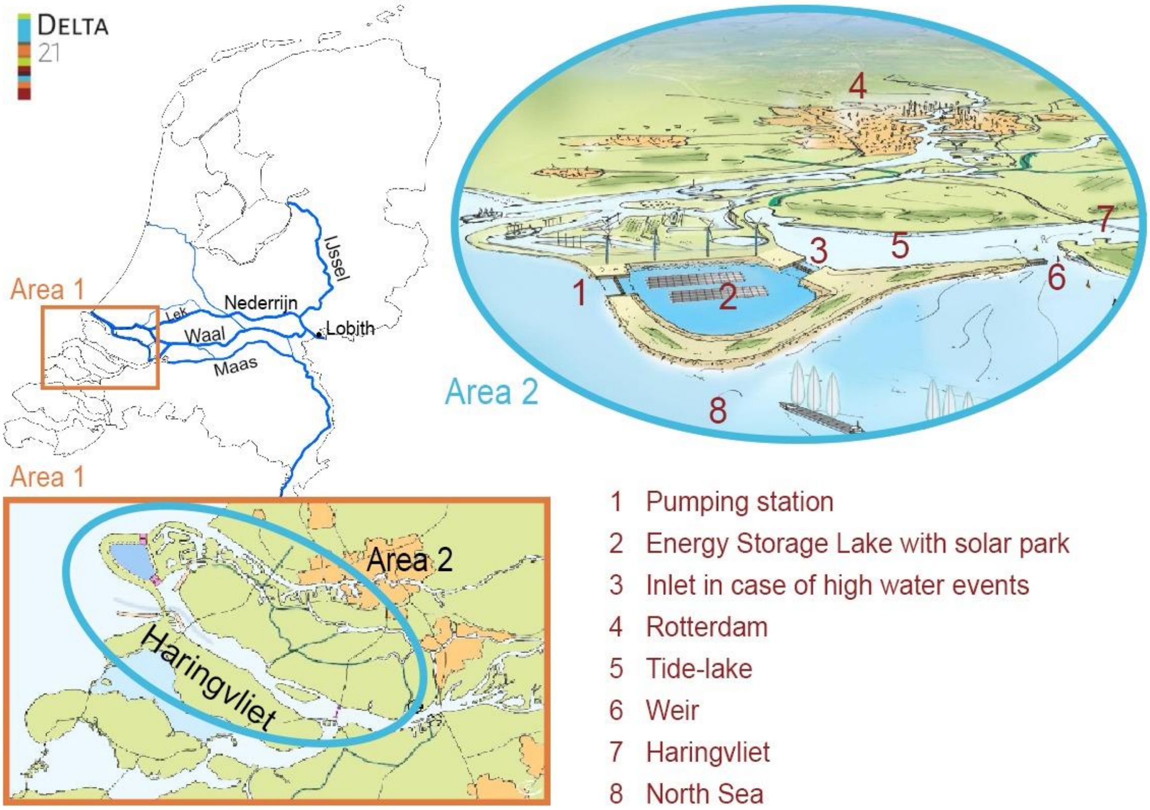


*Figure 2: Geographical representation of the Delta21 project with the Energy Storage Lake in the Haringvliet area, the Netherlands. Notice the Energy Storage Lake (Energieopslagmeer) on the left (west) and the Haringvliet estuarine on right (east), in the Netherlands. Adapted from Delta21 (2019).*

2). The pumps are used to pump this water into the sea, reducing the flood risk of the Haringvliet and the rivers that debouch into the Haringvliet. Part of the Delta21 plan is to fully open the Haringvliet sluices and bring back the salty tide in the former estuary.

When the lake is not needed for water management and water safety, excess solar and wind energy will be used to pump sea water out of the lake. During periods of energy need, the pump-turbines will generate energy through differential water pressure and therewith filling the lake again. The highest water level in the ESL will be 22.5 m, with a height difference of 17.5 m, leading to a depth of 5 m when the lake is on its lowest point. The amount of energy that can be stored in the ESL is estimated to be 22.3 GWh in cycles of 24 hours. In addition to this, the lake will harbour a 1 GW solar park and 1.2 GW Blue Battery by AquaBattery (https://aquabattery.nl/), which generates energy by the ionic potential between fresh and salt water.

The plans of Delta21 are anticipated to realise similar protection against high water as the dyke strengthening plans by the Dutch government, whilst saving up to €6 billion by the year 2100, and providing opportunities for the durable energy transition, nature restoration and aquaculture. The plan will also be adapted into an easily adaptable framework to be exported and used in other locations (Figure 3).

The realisation of the ESL would allow the Haringvliet to open its lock, which may restore the brackish water biotype in the Haringvliet and Hollands Diep, and the fish migration route between the North Sea and the river delta. Next to the ecological benefits of opening the Haringvliet sluices, building the ESL would require a change of a Natura2000 sandy seafloor area, which conflicts with Natura2000 legislations (Rijkswaterstaat, 2016). Besides the expected benefits and issues of the ESL, there are also knowledge gaps regarding the implementation of the plan. This project focuses on the knowledge gap concerning the possibilities of implementing aquaculture in the ESL, continuing on the research of previous ACT groups.

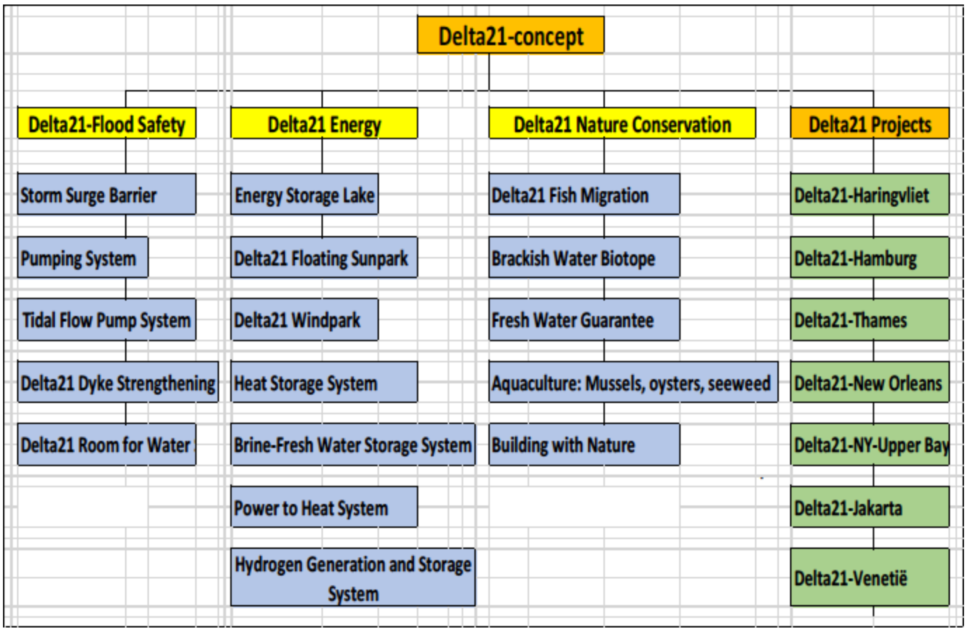


*Figure 3: Delta21 concept and phases (Delta21, 2019).*

## 1.2 Purpose of the project

The purpose of this project is to find out what the most viable combination of aquaculture types are, restricted to shellfish and seaweed cultivation, and suitable sites in the ESL thereby considering accompanying positive nature effects. This will be done by filling in the knowledge gap on shellfish and seaweed cultivation practises in tidal saltwater lakes with a height difference of 17.5 m. The project will be useful in the realisation of the Delta21 project as well as other cases with a high water level difference or aquaculture in a semi-closed embayment like the 'Dubbele Dijk' project from 'EemsDollard2015' (https://eemsdollard2050.nl/dubbele-dijk/). The project will continue on research by previous ACT groups on nature enrichment (De Boer *et al.*, 2019) and aquaculture in the tidal lake (Animal+1, 2019).

## 1.3 Problem definitions and research questions

### 1.3.1 Problem definition

The problem being addressed in our project is the current knowledge gap of how aquaculture, restricted to shellfish and seaweed cultivation, can best be implemented in the Energy Storage Lake. This is essential to know in order to successfully integrate aquaculture activities into the multi-purpose ambitions (flood risk management, energy storage and nature restoration) of Delta21 to create a wide stakeholder support and therewith increase the likelihood of realising the project.

### 1.3.2 Research questions

The main research question of this project, following the above-mentioned purpose, is: What is the most viable combination of aquaculture types for shellfish and seaweed, considering suitable sites and positive nature effects in the Energy Storage Lake?

The sub-questions are:

1. What are the expected conditions in the Energy Storage Lake?
2. Which forms of aquaculture require conditions that match the expected conditions at different sites in the Energy Storage Lake?
3. Which requirements does the floating solar park have to meet in order to reach highest production of the species and aquaculture types selected in sub-question 2?
4. Which of these aquaculture types has potential for nature enrichment, regarding water quality and biodiversity?

### 1.3.3 Scope and limitations

Although the Delta21 project covers a broad spectrum of sectors, we only focus on the aquaculture in the ESL, there where possible in combination with solar panels. In this project, the term 'aquaculture' refers to a combination of cultivation type and marine species. Some terms are used differently than usual to simplify the textual layout and terminology:

- Officially, the term 'shellfish' is used to refer to all aquatic invertebrates with an exoskeleton, like crustaceans (crabs, lobsters, shrimps, etc.), molluscs (mussels, oysters, etc.) and echinoderms (sea urchins, etc.). In this project the term shellfish is used to only refer to species of mussels and oysters. The shellfish species that will be researched in this project are those that are currently used in Dutch aquaculture.
- The term 'seaweed' is used to refer to multi-cellular aquatic plants and the term 'phytoplankton' to refer to microalgae. The seaweed species that will be researched in this project are native to the North Sea and are or have been cultivated.

## 1.4 Multi-disciplinary approach

Our consultancy team consists of maters students from Wageningen University and Research with scientific backgrounds in marine biology, aquaculture, and nature conservation. These backgrounds provide us with the right knowledge in order to contribute towards filling in the knowledge gap that is mentioned in the problem definition. As we all have a bachelor's degree, we have skills and experience in carrying out scientific literature research. Furthermore, individual team members have experience in conducting interviews, tackling society-relevant issues, working for a commissioner, and working in interdisciplinary teams. These team members share their experience and knowledge and take lead where needed to ensure that it benefits the team process and the final product.

## 1.5 Methods

For each sub-question, information was gathered by conducting a literature research, interviewing a floating solar park expert, and interviewing experts from the mussel, oyster, and seaweed sectors.

### 1.5.1 Literature research

The literature research started with an orientation phase and, therefore, multiple key words for each sub-question were identified. The key words, which are mentioned below, were entered into the following search engines: Scopus, WUR Library, Google Scholar, and Web of Knowledge.

- Keywords sub-question 1: North Sea, tidal change, nutrients, flow velocity, light availability.
- Keywords sub-question 2: shellfish, seaweed aquaculture, nutrients, flow velocity, light availability, on-bottom culture, bouchot culture, raft culture, longline culture.
- Keywords sub-question 3: solar farm, floating, light intensity, phytoplankton, zooplankton.
- Keywords sub-question 4: shellfish, nature values, native, sensitivity, resilience, biodiversity.

The main type of literature used to gather information consisted of scientific articles. This was supplemented with information obtained from official reports and datasets from Delta21, STOWA, Deltares, the Water Framework Directive (WFD), and the Food and Agriculture Organization (FAO).

### 1.5.2 Expert interviews

The interviews with the experts were qualitative and semi-structured. Only one person per organisation was interviewed, because the information that was asked for was factual knowledge and input of ideas, instead of multiple views or personal opinions. Before each interview, a thematic analysis was made and a topic list was created, with knowledge and uncertainties from the literature research, that was incorporated in the interview questions (Appendix 1-3). It is important to note that the interviewees are not respondents for this research, but external experts who have knowledge which is valuable for this project. Their knowledge is necessary in order to come to a better understanding of the possibilities and restrictions in the ESL, leading to more complete answers to the sub-questions. Since only the factual knowledge was used, the transcribing and coding of the interviews was not considered necessary.

Three interviews were conducted, and each interview was attended by three or four members from our consultancy team. Before each interview the tasks of chair, secretary, and interviewer(s) were divided and prepared. The first interview was with an expert on seaweeds from the organisation Seaweed Harvest Holland; the second interview was with an expert on mussels and an expert on oyster from the organisations PO Mosselcultuur and Nederlandse Oestervereniging; the third interview was with a floating solar park expert who is working on a MSc thesis for Delta21.

Furthermore, seven nature organisations were contacted for interviews as well, however this came to nothing. Plan B, in case interviews would not be possible due to planning, would be to send the most important questions by email and ask for written answers. Plan B, however, was not possible as we did not manage to get into contact with someone from the organisations that showed interest to help with the project. Plan C was to cover the questions with additional literature research, and this is what we decided to do.

### 1.5.3 Models

Within the literature a model was found that served the literature analysis by providing a tool to vary parameters, which was used in order to roughly simulate the situation in the ESL. This model, the 'Zon op Water' model ('Sun on Water' in English), made by Deltares and STOWA, describes the differences in water temperature that occur with the introduction of a solar park onto a water body (Loos & Wortelboer, 2018). For the implementation of this model the parameters were chosen as such that they matched characteristics of the ESL as good as possible. First, the surface area of the lake was set at 10 $km^2$; second, the maximum depth was set at 25 m; third, the nutrient status was set as eutrophic; and lastly, the bottom type was set as peat-soil. Further assumptions were that the solar park has a surface area of 25% of the surface area of the water body and that the ability for letting light trough is 25%. The outcome of the 'Zon op Water' model is not directly representable for the situation in the ESL, however the outcome does give an indication of possible trends that should be kept in mind when placing solar panels on the ESL. These trends were taken into consideration for the expected temperature and light availability described in Chapter 2.

To obtain the expected flow rates and time of drought exposure of the different parts of the ESL, own calculations were made with a simple flow velocity model (Appendix 4-7). The input for the flow velocity model was provided by Delta21 (Delta21, personal communication, 2020).

## 1.6 Ethics

There are several ethical implications related to the project of our commissioner, Delta21, and our position within this project. Towards Delta21, an independent report is ensured by being honest and reliable in the found information, and the decisions made regarding discussed topics. This means that the report may contain conclusions that contradict the opinions of or may not be in favour of Delta21. As Delta21 indicated, there is no confidentiality within the project, meaning that the findings are allowed to be discussed with those who are interested.

The commissioner has multi-purpose ambitions for the Delta21 project, including flood risk management, energy storage, aquaculture and nature restoration. However, it is not possible to honour such diverse ambitions without having to make trade-offs between the different ambitions. Within our project we researched the possibilities of combining the different ambitions, but we do not give our personal opinions regarding the trade-offs.

Furthermore, the project of Delta21 affects the entirety of the Dutch river delta with many purposes and stakeholders. However, our project only focuses on the development of aquaculture within the boundaries of the ESL. Therefore, we do not concern ourselves with ethical challenges and politics outside of the ESL and/or other topics unrelated to aquaculture.

In this research, several interviews were conducted with experts in different fields of expertise linked to our research questions. Permission was acquired from the interviewees to record their answers to the interview questions, as well as the use of their answers in our report. In dealing with interviewees, it was considered important to provide an honest attitude about our background, the purpose of the interview, as well as what the answers to interview questions are used for. The interviewees have a complete understanding of the position of our consultancy group, the fact that we are students from Wageningen University & Research, conducting research on a specific subject of the project for

Delta21. It was also made clear that our consultancy group does not have any political affection with certain points of view of, or actions by Delta21, and only provides answers to specific research questions in order to fulfil a knowledge gap.

In addition, regarding the privacy of interviewees, information can only be traced back to the organization the person belongs to. By only mentioning the organizations, we try to do justice to everyone who contributed to the research, while ensuring anonymity of the interviewee.

Lastly, in order to remain impartial, it was necessary to ensure that we did not promote the Delta21 project towards the interviewees. Our consultancy group fulfils a neutral position. If there is an interest in the project of Delta21, the interviewees will need to contact Delta21 directly, as we will not answer questions on topics outside of our own research project.

# Chapter 2: Expected conditions in the Energy Storage Lake

## 2.1 Introduction

In this chapter, the first sub-question "What are the expected conditions in the Energy Storage Lake?" will be answered. The answer to this sub-question puts a framework in place that will be used later in the project, by providing a basis of knowledge for the commissioner which is necessary to determine what the most viable combination of aquaculture types for shellfish and seaweed om the Energy Storage Lake (ELS) will be. The chapter is divided into four parts: the physical conditions, the chemical conditions, the risks for aquaculture that might appear in the ESL and lastly, a conclusion with tables summarizing the most important expected conditions.

Since the ESL is not yet established, assumptions are made regarding its conditions. It is difficult to model the phytoplankton, nutrients, oxygen and temperature fluctuation over the day when the lake is being filled and emptied. Next to this, experts in mussel and oyster cultivation say the water body of the ESL is large enough for mussel and oyster cultivation, so it will not run out of phytoplankton, nutrients and oxygen (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). Therefore, regarding the available time there is for this project and the complexity of the required calculations, the fluctuation of resources as a result of the seasons and the daily filling and emptying of the ESL, and the depletion of resources though aquaculture activities are not taken into account. This consideration will be further discussed in Chapter 6.

## 2.2 Physical conditions

In this section the physical conditions of the ESL are described. The main source of data is personal communication with Delta21, that provided the details of the dimensions, slope, pumping system, substrate and sedimentation concerning the ESL, which have been used by the authors to calculate the flow rate and time of drought exposure via a simple flow velocity model. Furthermore, a Deltares model (Loos & Wortelboer, 2018) is used to calculate solar radiation, as well as water temperature in the ESL, and all subjects are supported with scientific literature and expert interviews.

### 2.2.1 General dimension of the ESL

The ESL is located in the Natura2000 Voordelta area, with an average seawater level of –0.25 m NAP. Surface area of the lake of 26 km$^2$ when the water level reaches its highest point, -5.25 m NAP, and a surface area of 19 km$^2$ when the water level reaches its lowest point at –22.75 m NAP (Delta21, personal communication, 2020). The highest water level is expected early in the evening, after a peak in energy demand during daytime, and lowest early in the morning, after the lake has been pumped empty (Delta21, personal communication, 2020). At the lowest water level there will always be 5 vertical meters of water remaining in the ESL. Part of the lake will contain a floating solar park with an area of 5 km$^2$. This floating solar park will change in height based on the current water level in the ESL and will remain at the surface of the water. When the water is at its highest level, this solar park will cover 19 % of the total surface area, while it will cover 26 % when the water level is at its lowest point.

Part of the solar park will have an inlet for salt water, this area contains pumps that will empty the lake when a surplus of energy is generated and will generate energy when there is a peak energy demand. Surrounding the pump area there will be an area of 500 m that will not be used for aquaculture or solar energy generation in order to allow for easy accessibility for maintenance to the pump installation (Delta21, personal communication, 2020).

### 2.2.2 Slope and time of drought exposure

In order to examine possible limitations in sites for aquaculture practices, it is important to have an overview of the slope of the bottom of the ESL, as well as the accompanying time of drought exposure.

In the calculations for the slope and time of drought exposure, the assumption has been made that the ESL is a square shaped lake with sides of 5.1 $km^2$. The slope of the edges around the ESL consists of a 1:20 ratio, which translates to a vertical decline of 0.05 m per 1 horizontal meter (Delta21, personal communication, 2020). Combined with the total change in water level of –17.5 m per cycle in the ESL (Delta21, personal communication, 2020) this results in a time of drought exposure of areas with a certain distance under the highest point of –5.25 m NAP (Appendix 6). Therefore, at –1.5 m under the highest point of –5.25 m NAP in the ESL, there will be no water present for 21.1 hours consecutively, at –9.5 m this will be 10.6 hours, and at –17.5 m this will be 1.4 hours (Appendix 6).

### 2.2.3 Flow rate

The expected water flow rate is needed in order to determine possibilities for aquaculture in the ESL. Water flow rate in the ESL were estimated assuming a cone shape with a constant flow rate in the entire water column, with decreasing flow rate when distance to the pumps increases. Calculations have been made for 18 different layers of 1 m each. Assumed that the flow rate will be consistent across these water layers, the average flow rate has been calculated (Appendix 7). The pump speed used for the calculations is based on the maximum pump speed of 10 000 $m^3/s$. This pump speed is achieved through 93 pumps (Delta21, personal communication, 2020). Natural flow patterns where not considered in the calculations.

The flow rate near the surface of the ESL, when the lake is completely filled, is expected to be between 0.05-0.30 m/s depending on the distance from the pump, while a flow rate of 0.26-1.33 m/s is expected when the lake has been emptied (Appendix 7). The average flow rate is 0.16 m/s. The increased flow rate when the lake has been filled is the result of a large water column, and the total water flow being spread out over a larger area.

### 2.2.4 Substrate

The bottom of the Energy Storage Lake will consist of fine sand with silt layers. This substrate reaches from the current seabed (-10 m NAP) to a depth of -50 m NAP. The bottom of the ESL will be at a maximum depth of -27.75 m NAP, as going any deeper would increase the risk of the groundwater pressure becoming too high and breaking through the bottom of the ESL (Berke & Lavooij, 2018). The slopes on the lakeside of the ESL will exist of the same sandy substrate. However, if the slope does not appear to be stable, a thin layer of gravel might have to be added locally where the wave action is highest (Berke & Lavooij, 2018). Accumulation of silt on the bottom of the ESL is expected due to the large daily inflow of water (Delta21, personal communication, 2020). Also, the floating solar park will be anchored in the lake with metal or wooden constructions, and there will be a net or metal grid in front of the pumps. Furthermore, as the final design of the ESL has not been decided on, it is possible that other substrates (e.g. concrete structures) will be added to enhance nature development. Hard substrates can impact aquaculture, this will be further discussed in Chapter 3. The best substrates for mussel and oyster aquaculture are silt/peat soils due to the ease of harvesting the shellfish. A sandy substrate might limit feeding efficiency of shellfish, thus reducing growth rate (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020).

### 2.2.5 Sedimentation and erosion

Sedimentation (particles deposited), resuspension (particles eroded), and transportation of particles are dependent on flow rate, particle size (Figure 4), and water depth (Miedema, 2010). Sources of sediment are particles flowing in from the North Sea and particles from fluvial origin, as the ESL is surrounded by sand dunes. The sand from these dunes can be blown from the dunes and end up in the ESL (De Boer *et al.*, 2019). The particles that will enter the ESL mainly have a size of 0.22 mm (Prins *et al.*, 2012) (Figure 4).

For the assumption of the amount of transportation and sedimentation, the Hjulström curve is used (Hjulström, 1935). This curve assumes a water depth of 1 m, whereas the water in the ESL is variable between 5 and 22 m. Shields (1936) designed a curve where friction velocity and grain diameter occur in non-dimensional shear stress. The Hjulström curve (Figure 4**Error! Reference source not found.**) is simple and used in this project as a good representation of approximate sedimentation and erosion values, since the flow rates and depths vary over time. For precise prediction of the sedimentation patterns in the ESL complex modelling is needed (De Boer *et al.*, 2019) and falls outside the possibilities of this project.

For the ESL, deposition of particles increases with the distance to the pumps. The average flow rate is 0.16 m/s, meaning there will mostly be transportation. Particles can resuspend and increase the turbidity of the water. Erosion of sediments will occur near the pumps in the ESL, due to the higher flow rate of around 1.3 m/s (Figure 4).

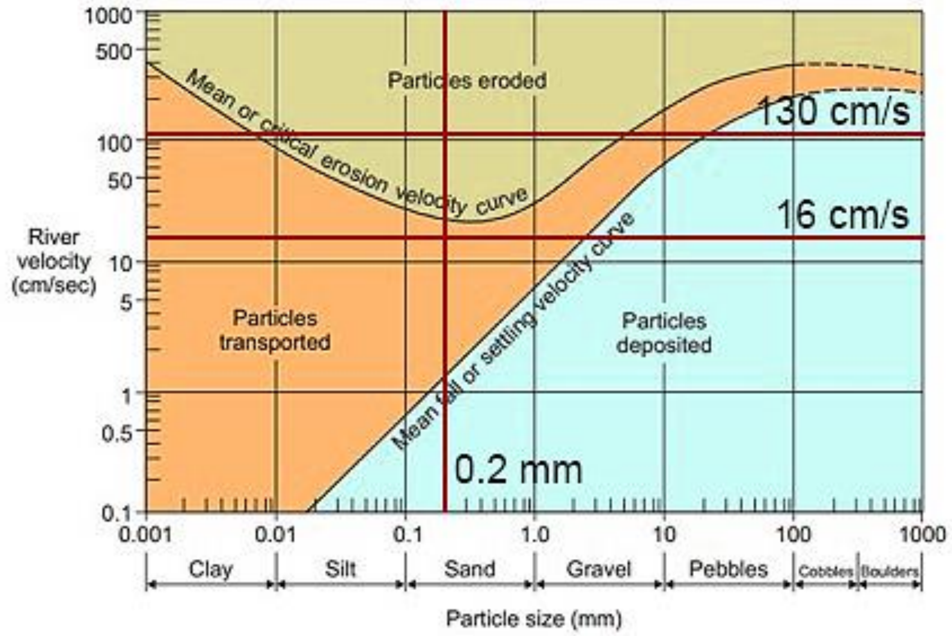


*Figure 4: Hjulström diagram explaining the relation between flow velocity (y-axis) and particle size (x-axis). The upper red line shows the maximum flow rate in the Energy Storage Lake (ESL) (130 cm/s = 1.3 m/s), the lower red line shows the average flow rate in the ESL (16 cm/s = 0.16 m/s), the vertical red line shows the most common particle size in the ESL (0.22 mm).*

### 2.2.6 Solar radiation

Solar radiation drives the primary production of an ecosystem via photosynthesis. The primary production consists of macro algae (which include the seaweeds), phytoplankton (which form the basis of the aquatic food chain), and cyanobacteria.

The amount of solar radiation that falls onto a waterbody depends on the time of the year, the part of the day and the cloudiness of the sky (Wang & Seyed-Yagoobi, 1994). The amount of solar radiation that reaches the water in the ESL will also be limited by the presence of the floating solar park, as the floating solar park will shed a shadow onto the lake. At the edges there will be light that comes in at a diagonal, but the further towards the middle the darker it will become. However, assuming a constant level of solar radiation onto the water, the penetration of solar radiation is mainly the result of the turbidity of the water. The water column that receives light is called the photic zone. Wang & Seyed-Yagoobi (1994) provide a model that describes the relation between solar radiation penetration and turbidity for different water depths, showing that the effect of turbidity on the penetration of solar radiation increases with water depth. Just below the water surface, at –0.15 m, a large increase of turbidity has a relatively small, negative effect on the available solar radiation, and at a depth of –1.22 m a smaller increase of turbidity has a larger negative effect on the available solar radiation (Figure 5). It is however not possible to directly apply this model on the ESL because the composition of particles that causes the turbidity is different for each water body. The turbidity for the North Sea to use as a proxy, was unfortunately not found. Furthermore, the scattering function of particles and the colour of the water also influences the spectral composition of the available light (Eloranta, 1978), which makes comparisons between different water bodies difficult. A seaweed expert from Wageningen University & Research stated that the photic zone in the North Sea does not go much deeper than -5 m, due to high turbidity (Seaweed expert Wageningen University & Research, personal communication, 2020).

Loos & Wortelboer (2018) modelled the light penetration through water for solar panels with light transparency levels from 0 to 25%. Especially in shallow lakes, a higher light transparency increases the ability for light to pass through, increasing bottom surface suitable for water plants. Water bodies deeper than 25 m will have no effect from a higher light transparency. Even though it is assumed that nutrients and phytoplankton will be equally distributed over the lake, it should not be forgotten that seaweeds need direct sunlight for photosynthesis and they can only live in the photic zone, which is between 0 and -5 m in the ESL.

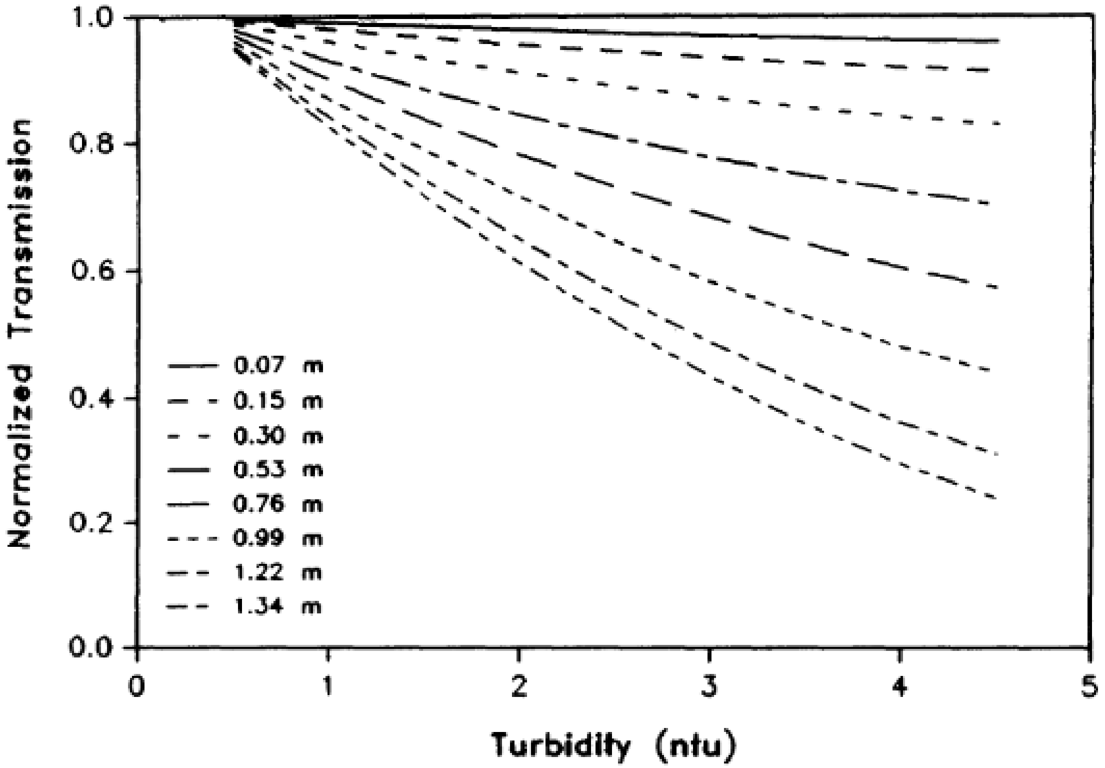


*Figure 5: The normalized transmission (as a proxy for the penetration of solar radiation) as a function of the turbidity of the water at selected water depths (Wang & Seyed-Yagoobi, 1994, p. 435).*

### 2.2.7 Water temperature

The expected water temperature conditions are based on the average temperatures of the Voordelta. With an expected range of 6-17°C depending on the time of year (Jongbloed *et al.*, 2017). Water temperatures are expected to slightly increase over the coming years, as a yearly increase in water temperature of 0.025°C has been estimated by Tulp *et al.*, 2018 (Figure 6). The temperatures in the ESL are expected to be similar to temperatures measured in the Voordelta due to the large water exchange rate between them.

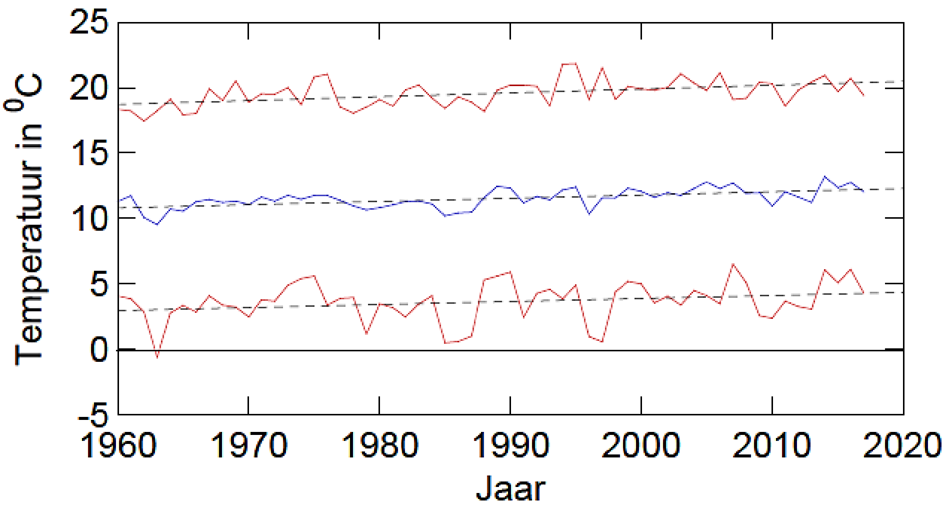


*Figure 6: Average annual sea water temperatures (Blue line), and 5- and 95- percentile water temperatures (red lines) near the Voordelta. Showing a linear increase over the years. Adapted from Tulp et al. (2018).*

Temperatures in the water layer after the lake has been drained to its lowest level are not expected to increase significantly from the expected temperature, because the water level is lowest early during the day (Delta21, personal communication, 2020).

Implementation of a floating solar park has been shown to impact water temperatures beneath the solar park. The solar panels will decrease the impact of solar radiation on the water column beneath them, thus reducing the increase in temperature during daytime. A trend of lower temperatures in the different water layers during the summer months can be seen (Figure 7). Other factors, such as wind velocity and wind direction might also impact the temperature of the upper water layer (Loos & Wortelboer, 2018). However, impact of wind speed and direction are difficult to predict, thus the impact of the solar park, wind speed, and wind direction on the water temperature of the ESL are not considered in this project.

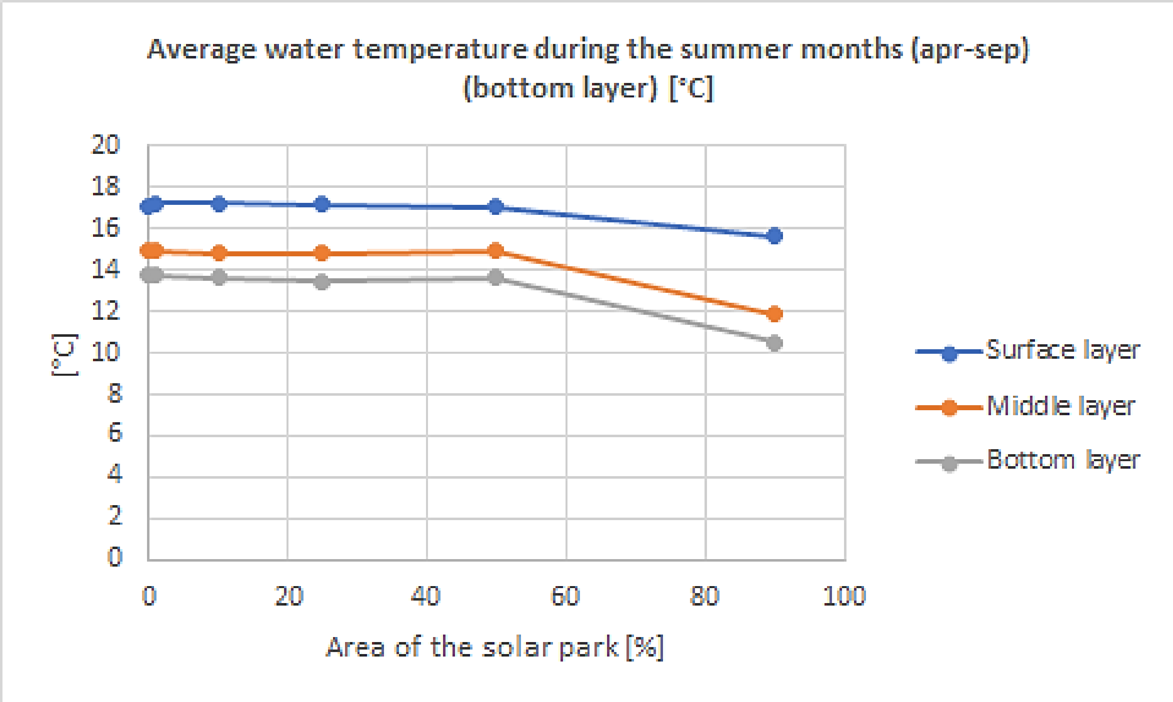


*Figure 7: Average water temperature during the summer months based on solar park coverage of a lake with a surface area of 10 km2 and a depth of 25 m. Adapted from Loos & Wortelboer (2018).*

## 2.3 Chemical conditions

In this subsection, the chemical conditions are described. For some variables, the website from the DWA 'Waterinfo.rws.nl' is used to collect data on locations nearby the future location for the Delta21 project. Not all chemicals had the same sample location and the used sample locations were all located as close to the future Delta21 location as possible (Figure 8). The second and last main source of information is the report from STOWA (2018). This report describes the frame of reference used to check if water bodies are in line with the regulations set by the Water Framework Directive (WFD).

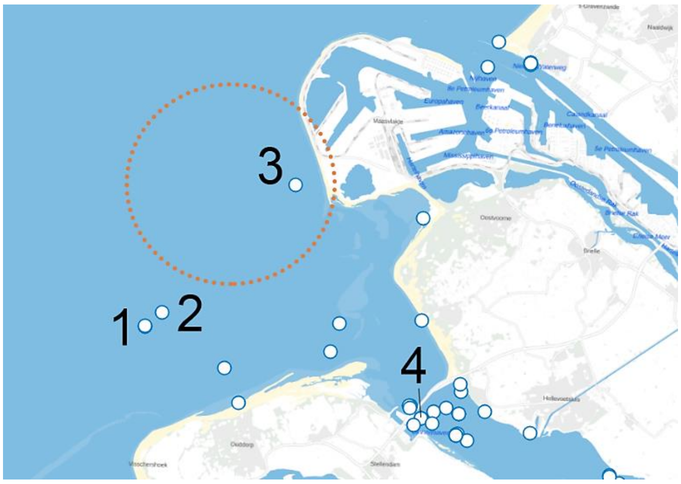


*Figure 8: The website 'Waterinfo.rws.nl' with the four chosen locations: 1) Haringvliet (b), 2) Goeree, 3) Maasvlakte, and 4) Haringvlietsluis. The orange circle is the future location for the Delta21 project.*

### 2.3.1 Salinity

The largest part of the Voordelta has a salinity higher than 30 psu, due to the instream of salt water from the North-Atlantic drift. Because the Delta21 project is located near the river delta, the salinity varies with the tide and can sometimes drop even under 5 psu, meaning the water can be mostly fresh at times. These drops to low salinity are the result of changes in outflow of the Haringvliet depending on the tides, and occur for short durations daily (DWA, n.d.). This variety in salinity is caused by the tidal outflow of salt water, resulting in an outflow of freshwater. Between the years 2015 and 2020, the mean salinity in the area of the Delta21 was 31.03 psu with a median of 31.305 psu, which is, according to the DWA, 'strong brackish to salt water'. When looking at the classification of the Water Framework Directive, the mean salinity in combination with the tidal character of the area suggests the Delta21 area will be a so-called ‘K2’ area. A ‘K2’ area is characterised by a salinity between 18 and 30 psu. Other examples of ‘K2’ areas are the Wadden Sea and the Eastern Scheldt (STOWA, 2018). The ‘K2’ classification from the WFD will be used later in this chapter, when actual values for abiotic variables are not found in literature. The WFD uses four classifications to explain the state of a nature area, these are ‘bad-insufficient’, ‘insufficient-mediocre’, ‘mediocre-good’, ‘good-excellent’.

### 2.3.2 Oxygen

In this project, dissolved oxygen is described in µM. It was possible to retrieve the dissolved oxygen concentrations of the location ‘Goeree’ (Figure 8) from 2015 to 2020. The mean oxygen concentration between these years was 251.6 µM and the median was 246.9 µM (DWA, n.d.). The WFD describes the dissolved oxygen as percentage saturation of optimal saturation. This optimal saturation is dependent on other variables, such as pressure and temperature. According to the WFD, the oxygen saturation should be higher than 60% for a ‘K2’-area to be classified as ‘good’. It was found that the mean saturation at the location of the Delta21 project was on average 91.34% (DWA, n.d.). This means, that the oxygen saturation for the Delta21 area is within the WFD aim and thus shall most likely not change in the future. In the ESL, there will be higher mixing of the water due to the pumping station. This will increase the oxygen concentration in places where the water flow is higher around the pumps (Potter *et al.*, 1982). Oxygen production shows a strong dial pattern, with lower oxygen concentrations during night time. This is due to the change in primary production during the night time when less light is available (Howarth *et al.*, 2014). Thus, oxygen depletion during the night when the water level is lowest in the ESL might become a risk.

### 2.3.3 Acidity

The acidity in the North Sea is slowly declining. In 1990, the pH was around 8.15, whereas the pH in 2010 was 8.05 (Beare *et al.*, 2013). For the location where the Delta21 project will be built, the pH between 2015 and 2018 was on average 7.98, whereas the median is 8.05 (DWA, n.d.). This is still a basic pH, which is aimed for at the WFD. However, with the increasing $CO_2$ level in the atmosphere, the pH will also decrease. This will lead to an expected decrease of 0.4 unit pH by the end of 2100 for sea water (Birchenough *et al.*, 2015).

### 2.3.4 Nitrogen

Nitrogen is an essential nutrient in aquaculture systems, playing an important role in the food chain, but also in environmental pollution (Luo *et al.*, 2018). The mean nitrogen concentration measured between 1990 and 2014 in the southern part of the North Sea was found to be exceeding 60 µmol N/L (=0.84 mg N/L) along the Dutch coast (OSPAR Commission, 2017a). The exact numbers were not found. This is quite high, as the WFD suggests aiming for a concentration of less than 33 µmol N/L (=0.46 mg N/L) for a ‘K2’ area to receive the status of ‘mediocre-good’ (STOWA, 2018). In general, a declining trend was found, however, the years between 2006 and 2014 showed an increasing trend (OSPAR Commission, 2017a).

### 2.3.5 Phosphorous

As with nitrogen, phosphorous is an important nutrient in the food chain of aquaculture systems. However, too much phosphorous can contribute to eutrophication, having a negative alteration on aquatic ecosystems (Sugiura, 2018). The phosphorous concentration along the Dutch coast is high: in winter on average 1.2 µM. There is a declining trend seen from 1990-2014, but between 2006 and 2014, there was no significant difference (OSPAR Commission, 2017a). The WFD does not make statements about phosphorous as a physical-chemical quality element in any ‘K’-area (STOWA, 2018).

### 2.3.6 Chlorophyll-α

Chlorophyll-α is measured as a proxy for the biomass of phytoplankton. Phytoplankton is used as food source for shellfish (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020), but is competing with seaweed over nutrients (Smith & Horne, 1988). The DWA provides regular measurements on chlorophyll-α. In this project, data from January 1991 to December 2019 was used to calculate the mean and the median. In summer, the mean value is 13.42 µg/L and the median is 9.78 µg/L, while in winter the mean value is 4.34 µg/L and the median is 2.5 µg/L. Overall, the mean value is 8.9 µg/L and the median is 4.8 µg/L (DWA, n.d.).

### 2.3.7 Heavy metals

Heavy metals that are commonly found in nature are mercury, lead, cadmium. These are considered most harmful for living organisms, and specifically for proper functioning of the human body (OSPAR Commission, 2017b). Therefore, the OSPAR Coordinated Environmental Monitoring Programme defined these three as priority heavy metals in monitoring (OSPAR Commission, 2017b). Furthermore, arsenic can be accumulated up to high concentrations in seaweeds through the process of bioaccumulation, posing a threat for food safety (Monagle & Morrison, 2019), which will be elaborated on in the next section.

The heavy metal concentration measurements for surface water, sediment and floating particles are presented in Table 1 for the four available measurement points in Figure 8. It must be stated that the sediment data consisted of only three data points up to 2012, showing a downward trend between 2006 and 2012 (DWA, n.d.). Furthermore, the measurement was before the Maasvlakte had been completed, and therefore, this data may not provide an accurate representation of the current heavy metal concentrations in the sediment in the planned project area. Lastly, it is important to note that when the Delta21 project proceeds, the currently closed Haringvlietsluit will open, and the floating particles, as well as accumulated heavy metals in old sediments will erode and enter the Delta21 project area, with a possibility of ending up in the ESL. However, the impact of these eroded contaminated sediments of the Haringvliet delta mouth on the Dutch coastal zones are expected to be small (Animal+1, 2019).

*Table 1: Average heavy metal concentrations over the last 15 years, unless otherwise stated, in surface water, sediment and floating particles from available measurement point in the Delta21 project area. (Source: DWA, n.d.)*

| **SURFACE WATER** | | |
|---|---|---|
| | **Goeree** (6 km offshore) | **Haringvlietsluis** |
| *Mercury (µg/l)* | 0.002 | 0.008 |
| *Cadmium (µg/l)* | 0.021 | 0.024 |
| *Lead (µg/l)* | 1.038 | 0.484 |
| *Arsenic (µg/l)* | 1.572 | 1.254 |
| **SEDIMENT** | | |
| | **Maasvlakte** | **Haringvliet** (4 km offshore) |
| *Mercury (mg/kg)* | 0.205* | 0.304* |
| *Cadmium (mg/kg)* | 0.4* | 0.689* |
| *Lead (mg/kg)* | 39.7* | 138* |
| *Arsenic (mg/kg)* | 18.3* | 20.8* |
| **FLOATING PARTICLES** | | |
| | **Haringvlietsluis** | |
| *Mercury (mg/kg)* | 0.647 | |
| *Cadmium (mg/kg)* | 2.543 | |
| *Lead (mg/kg)* | 99.410 | |
| *Arsenic (mg/kg)* | 15.98 | |

*= Measurement point in 2012, before completion of Maasvlakte.

## 2.4 Risks

The physical and chemical conditions described above can only be estimated to a certain extent. Beyond this extent, fluctuations of these conditions are not considered within this project. There are, however, events that can drastically alter the conditions in the ESL and potentially form a risk for the aquaculture. These events are stratification, freshwater influx during high water, harmful algal blooms, and a higher secondary release of pollutants than expected.

Stratification occurs when there are different layers in a lake that do not mix. It is not very likely that stratification will be an issue in the ESL due to a large amount of water that is replaced daily; due to the pumping installations that stimulate the mixing of the water (Bermúdez *et al.*, 2018); and due to the presence of the floating solar park (Loos & Wortelboer, 2018). The water below the surface area of the floating solar park will warm up slower due to the obstruction of direct solar radiation onto the water. This results in less temperature difference between the top and bottom water layers, reducing the chance that the lake becomes stratified (Loos & Wortelboer, 2018). Wind also plays a role in the mixing or stratifying of the water column (Appt *et al.*, 2004). The grip and impact of wind on the surface of the ESL will, however, be limited by the presence of the floating solar park. If stratification does occur, it will have large effects as the limited mixing between layers can cause a reduced concentration of oxygen and an accumulation of waste products and organic matter in the bottom layer of the lake. Dependent on the precise shape and design of the ESL, there might be some small areas where the water does not mix as well as in other areas in the lake.

Freshwater influx into the ESL during high water events will drastically affect the salinity, changing the saltwater system into a freshwater or brackish system. The freshwater from the Haringvliet is also very nutrient rich which can affect the concentrations of nitrogen and phosphor in the ESL, perhaps even provoking an algal bloom. The likelihood of events that result in an influx of freshwater into the ESL is estimated to be once every ten years (Delta21, personal communication, 2020), but due to the many climate change scenarios it is not possible to provide certain numbers regarding this matter. In general, it is expected that extreme weather events with high amounts of rainfall in short periods of time, leading to high water in the Dutch rivers, are becoming more frequent (Tol *et al.*, 2003).

Harmful algal blooms (HABs) are associated with climate change stressors such as high temperatures, low pH and deoxygenation of the oceans (Griffith & Gobler, 2020). At present, with climate change being an unresolved issue, HABs pose a threat to freshwater and marine ecosystems, including aquaculture. Especially, in coastal areas the risk of HABs has increased. (Griffith & Gobler, 2020). There are several HAB species that produce biotoxins that can accumulate in filter feeding shellfish, such as mussels and oysters. These biotoxins can cause poisoning, or even death, to humans if consumed (Griffith & Gobler, 2020) and, thus, HABs can make the harvests from aquaculture useless for consumption. Furthermore, algal blooms use a lot of the available oxygen and intercept solar radiation, changing these conditions within the waterbody and therewith altering the growth conditions for other organisms. After an algal bloom, when the algae die and sink to the bottom, the rotting process causes deoxygenation of the water and this has a negative effect on aquaculture, especially on on-bottom aquaculture (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020).

Furthermore, the digging activities to construct the ESL will lead to the displacement of sediment, which comes with the risk of the exposure of accumulated pollutants. It is often assumed that the North Sea is a never-ending sink that dissolves pollutants, but pollutants accumulate in the sediments at the bottom of the sea (Kersten, 1993). These accumulated pollutants can be released again, possibly causing secondary pollution. There is a knowledge gap regarding how to prevent secondary pollution resulting from polluted sediments (Peng *et al.*, 2009). Nevertheless, it is important to mention this risk, as aquaculture practices in the ESL might be exposed to this risk. This poses a threat to food safety through the accumulation of pollutants, such as heavy metals, in this case in aquaculture species. Measurements since 2009 by the OSPAR Commission for concentrations of mercury, cadmium, and lead in mussels and oysters in Europe (OSPAR, 2017b) are all below European Commission safety limits for foodstuffs (Table 2: European food law norms for heavy metals in shellfish and seaweed (European Commission, No 1881/2006, 2006).). However, due to the uncertainty of the consequences of opening the Haringvlietsluis, and sea bottom modifications of the establishment of the Delta21 project, and the gap in DWA data of pollution measurements after the creation of the Maasvlakte, it is necessary to collect pollution data when the project is realized. Especially, in order to stay within the European Commission (2006) food safety limits (Table 2: European food law norms for heavy metals in shellfish and seaweed (European Commission, No 1881/2006, 2006).) for shellfish and seaweed produced in the Energy Storage Lake (OSPAR Commission, 2017b).

This project does not investigate the chances that the above-mentioned risks occur and neither the effects that they would have, as it is not possible to make predictions about this within the project. These risks are purely mentioned to create awareness of their existence, but they are left out of consideration for the remaining's of the project, including the advice for the commissioner for aquaculture (Chapter 8.1).

*Table 2: European food law norms for heavy metals in shellfish and seaweed (European Commission, No 1881/2006, 2006).*

| | *Heavy metals* | | | |
|---|---|---|---|---|
| *Food types* | Mercury | Cadmium | Lead | Arsenic |
| Shellfish | 0.5 mg/kg | 0.5 mg/kg | 0.5 mg/kg | No regulation |
| Seaweed | No regulation | 0.05 mg/kg | 0.1 mg/kg | No regulation |

## 2.5 Conclusion

To answer the sub-question "What are the conditions in the Energy Storage Lake?", summarizing tables are presented describing the expected physical conditions (Table 3Table 3: Summary of the physical conditions in the Energy Storage Lake. The calculations for the flow rate and time of drought exposure are described in Appendix 4-7.) and the expected chemical condition (Table 4). The expected conditions in the ESL are subject to uncertainties and are dependent on the assumptions that have been made, which is inevitable as the ESL does not yet exist. To gain precise information on the actual conditions it is essential that regular measurements are taken once the ESL is established. The risks' section purely has an advisory purpose and, thus, the risks mentioned in this section will only return as recommendations for further research.

*Table 3: Summary of the physical conditions in the Energy Storage Lake. The calculations for the flow rate and time of drought exposure are described in Appendix 4-7.*

| Variable | Value | Unit | Reference |
|---|---|---|---|
| Surface area of ESL at highest point | 26 | $km^2$ | (Delta21, personal communication, 2020) |
| Surface area of ESL at lowest point | 19 | $km^2$ | Authors, through Delta21, personal communication, 2020 |
| Surface area of solar park | 5 | $km^2$ | (Delta21, personal communication, 2020) |
| Slope | 0.05 | m/m | (Delta21, personal communication, 2020) |
| Tidal change in ESL per cycle | 17.5 | m | (Delta21, personal communication, 2020) |
| Pumping cycle | 12 | h | (Delta21, personal communication, 2020) |
| Pump speed | 10 000 | $m^3/s$ | Authors, through Delta21, personal communication, 2020 |
| Water temperature summer months | 17 | °C | (Jongbloed *et al.*, 2017) |
| Water temperature winter months | 6 | °C | (Jongbloed *et al.*, 2017) |
| Substrate | Fine sand with silt layers | | |
| Flow rate top layer (-0.5) | 0.05 - 0.30 | m/s | Authors, through Delta21, personal communication, 2020 |
| Flow rate middle layer (-8.5) | 0.09 - 0.48 | m/s | Authors, through Delta21, personal communication, 2020 |
| Flow rate bottom layer (-17.5) | 0.26 - 1.33 | m/s | Authors, through Delta21, personal communication, 2020 |
| Drought exposure time (-1.5m) | 21.1 | h | Authors, through Delta21, personal communication, 2020 |
| Drought exposure time(-5.5m) | 15.7 | h | Authors, through Delta21, personal communication, 2020 |
| Drought exposure time (-9.5m) | 10.6 | h | Authors, through Delta21, personal communication, 2020 |
| Drought exposure time (-13.5m) | 5.8 | h | Authors, through Delta21, personal communication, 2020 |
| Drought exposure time (-17.5m) | 1.4 | h | Authors, through Delta21, personal communication, 2020 |

*Table 4: Summary of the chemical conditions in the Energy Storage Lake.*

| | | | | | | **Likely to change in the next 20 years?** | | |
|---|---|---|---|---|---|---|---|---|
| **Variable** | **Season** | **Mean** | **Median** | **Unit** | **Variability** | Increase/ decrease | Amount | **Reference** |
| **Salinity** | Whole year | 31.030 | 31.305 | psu | 0-35 psu | *Unknown* | | DWA, n.d. |
| **Oxygen** | Whole year | 251.6 | 246.9 | µm/L | *Unknown* | No | | DWA, n.d. |
| **pH** | Whole year | 7.89 | 8.05 | DIMSLS | *Unknown* | Decrease | 0.4 /year | DWA, n.d.; Birchenough *et al.*, 2015 |
| **Nitrogen** | Whole year | 0.84 | | mg/L | *Unknown* | Increase | *Unknown* | OSPAR commission, 2017 |
| | Whole year | 60 | | µm/L | *Unknown* | *Unknown* | | |
| **Phosphorous** | Winter | 0.037 | | mg/L | *NA* | Decrease | *Unknown* | OSPAR commission, 2017 |
| | Winter | 1.2 | | µm/L | *NA* | *Unknown* | | |
| **Chlorophyll-α** | Winter | 13.42 | 9.78 | µg/L | *NA* | *Unknown* | | DWA, n.d. |
| | Summer | 4.34 | 2.5 | µg/L | *NA* | *Unknown* | | |
| **Heavy metals** | No risk for growth only for food safety | | | | | *Unknown* | | OSPAR, 2017 |

# Chapter 3: Possibilities for aquaculture in the Energy Storage Lake

## 3.1 Introduction

In this chapter, the second sub-question "Which forms of aquaculture require conditions that match the expected conditions at different sites in the Energy Storage Lake?" is answered. The in Chapter 2 established framework will be used in this chapter in order to provide the commissioner with necessary knowledge about what the most viable combination of aquaculture types for shellfish and seaweed in the Energy Storage Lake (ESL) will be. The chapter is divided into five parts: mussels, oysters, seaweed, combinations of species and lastly, a conclusion with a table summarizing which aquaculture types are possible in the ESL. The information provided in this chapter is obtained from literature research and several interviews with experts on shellfish and seaweed cultivation in the Netherlands.

In the literature research, not only Dutch aquaculture practices were considered, but also practices from other European countries (mostly France, Spain and Norway), East Asia and South America. In this chapter, the origin country of the information is only mentioned when the aquaculture conditions in the country of origin were expected to be significantly different to that of Dutch aquaculture. An example would be the crystal-clear seawaters from Norway and the tropics, compared to the turbid and green Dutch seawaters. All other information can be assumed to be directly relevant for Dutch aquaculture practices and is discussed within this chapter.

## 3.2 Mussels

The blue mussel (*Mytilus edulis*) is the most common mussel in cultivation and natural harvest. It is spread worldwide and cultivated in many forms (Figure 9, **Error! Reference source not found.**). The most frequently used cultivation methods are on-bottom culture, table culture, bouchot culture and longline culture (Figure 10) ("Cultured Aquatic Species Information Programme *Mytilus edulis* (Linnaeus, 1758)", 2020; Smaal *et al*., 2018). Before going into detail on every cultivation type some of the general characteristics of the blue mussel are described.

*Figure 9: The blue mussel (Mytilus edulis), left a sketch right pictures of three different appearances ("Cultured Aquatic Species Information Programme Mytilus edulis (Linnaeus, 1758)", 2020)*

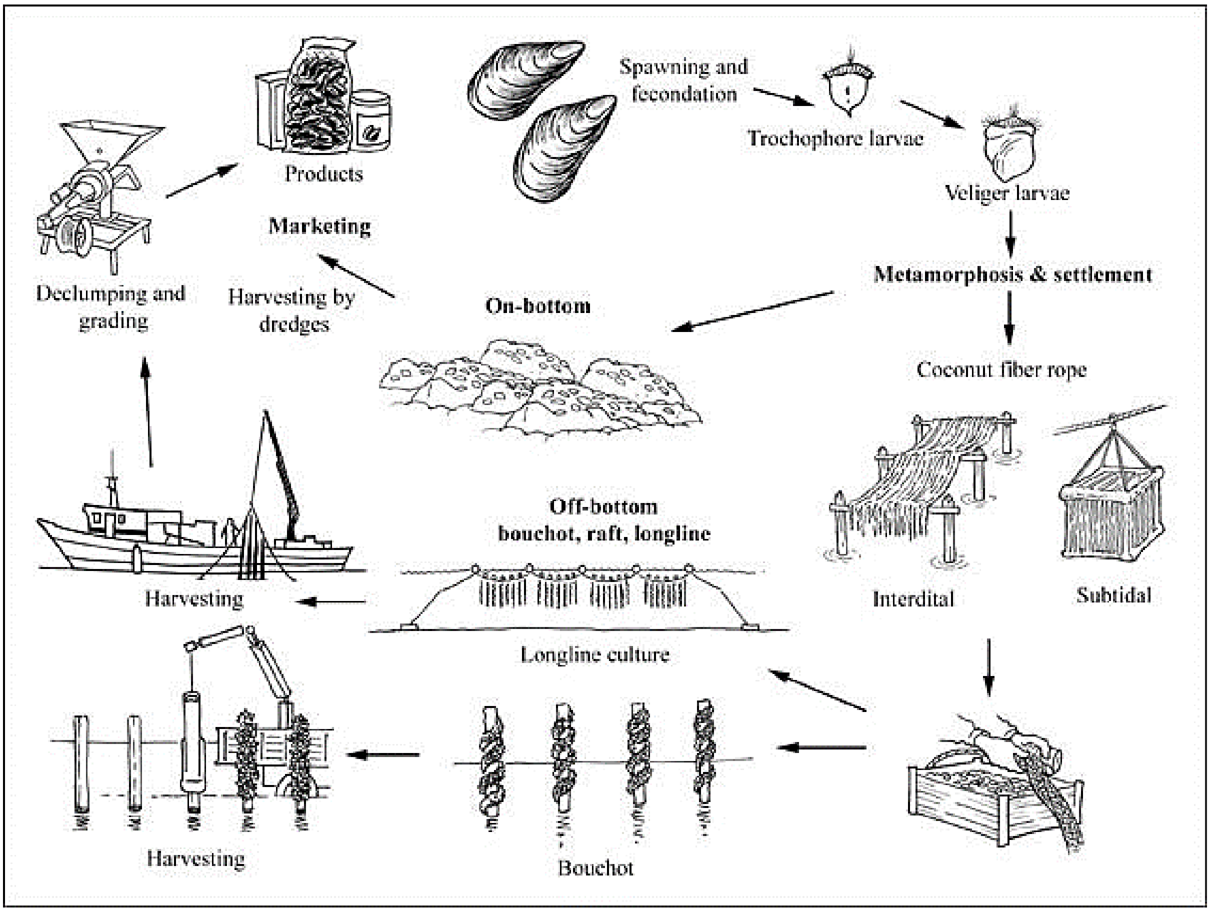


*Figure 10: Different mussel culture techniques and their cycle of cultivation. ("Cultured Aquatic Species Information Programme Mytilus edulis (Linnaeus, 1758)", 2020)*

### 3.2.1 Survival and growth conditions

Generally, the blue mussel has a wide depth tolerance ranging from 0-20 m. However, its optimum is at -15 m (Gallardia *et al.*, 2017). Within this optimum it can withstand temperatures ranging between 0-20 °C with an optimum at 20 °C (Animal+1, 2019; Handå *et al.*, 2013; Stevens *et al.*, 2018). Salinity tolerance ranges from 18-40 psu. However, if the salinity exceeds 25 psu there will be a decrease in spawning behaviour (Zitoun *et al.*, 2019). Furthermore, it can cope with water speeds from 0.2-0.8 m/s (Animal+1, 2019). Although it can generally cope with rough conditions, wave height is limited to 0.3 m. Exceeding this wave height can result in mussels being knocked off the substrate. Thus, to have bottom culture, either waves must be reduced/limited to 0.3 m, or the bottom should be deep (>5 m). If the conditions are around the optimum and oxygen levels are sufficient (5 mg/L) the oxygen uptake is 7.5-12.2 µmol/g/h (Barrento *et al.*, 2013).

The blue mussel is a filter feeder with a filtering capacity of 350 L/day if fully grown, filtering out detritus, bacteria, dead organic matter, and phytoplankton (Inglis *et al.*, 2000). However, the turnover per day, and the amount of food that it can filter, depends mainly on water current velocity and chlorophyll content of the water. With a water flow rate of at least 0.15 m/s there is little depletion going on. If the flow rate is lower than 0.15 m/s depletion starts to become a limiting factor on growth. When it comes to the chlorophyll concentration, the ideal concentration would be 4-8 µM. However, these conditions are rare, and cannot be assumed. Above this concentration the time required for the mussel to process the food, may reduce mussel growth. Below 4 µM growth rate starts to decline until the critical concentration of 0.5 µM is met. Lower conditions may result in a decreased growth rate, and if the conditions remain low for a prolonged period, it may lead to a severe increase in death rate within the culture (Inglis *et al.*, 2000).

### 3.2.2 Feedback mechanisms

Another important factor to consider is the concentrated organic matter in, and adjacent to, the intensive mussel cultivation. About a third of the ingested organic material is deposited as faeces on the benthic floor. Furthermore, the mussel deposited pseudofaeces, consisting out of non-organic material, that accumulates as well (Folke, 1989). They can change the nutrient distribution within the system. This can have serious consequences for important natural feedback loops (Inglis *et al.*, 2000). An example of such an important feedback loop is the nutrient cycle of nitrogen. Dissolved nitrogen is taken up by phytoplankton which is consumed by mussels. The particulate nitrogen is then processed and released as ammonia into the system, which in turn is taken up by phytoplankton again. With intensive mussel culture the nutrients accumulate in large amounts. Depending on the stocking density, method, and culture depth, this sedimentation of nutrients in the form of (pseudo)faeces can lead up to 170 g/m$^3$/d (Dahlbäck & Gunnarsson 1981; Hatcher *et al.*, 1994). Whenever there is good water movement or mixing of the water column, there is enough oxygen for the benthic microorganisms to consume the nutrients released by the mussels. However, if this is not the case this leads to anoxic conditions where sulphur bacteria take over producing toxic sulphide (Grant *et al.*, 1995). Furthermore, the accumulation of mussel shells, due to storms or rough harvesting, can influence the surrounding area by providing shelter, nurseries and feeding areas for some organisms (Grant *et al., 1995)*

Nutrient deposition is not the only factor that can inhibit growth. Stratification of water columns also plays an important part in this. The best situation would be a well-mixed system. If these circumstances are met, the mussels can filter at their maximum capacity, resulting in a higher growth rate. Similarly, the opposite happens when the systems is stratified seasonally or continuously. Additionally, sunlight also plays a role within stratification and mussel growth. Although, sunlight itself does not have a direct effect on mussel growth, it does on phytoplankton since it needs sunlight, and by raising the water temperature (Animal+1, 2019; Tyler-Walters, 2008). In combination with low stratification there are two scenarios that can occur, both with a different effect on mussel growth. Firstly, turbid water that is caused by an abundance phytoplankton due to a large input of sunlight. This stimulates the mussel growth since there is a higher food availability. Furthermore, sunlight can cause algal blooms that create a toxic environment. Secondly, turbidity caused by sediment particles (Animal+1, 2019; Tyler-Walters, 2008). This can suffocate the mussels since they filter and separate the sediment particles from food particles leading to potential loss of shell or even death (Tillin & Mainwaring, 2016). It can also lower the growth of phytoplankton due to the shading effect (Tyler-Walters, 2008). Both decrease the overall production of the mussel culture.

### 3.2.3 Predation

Predation can have a large impact on the mussel population (and cultivation) if not naturally or anthropologically regulated. Crabs (*Carcinus maenas*) and starfish (*Asterias rubens*) are the most common natural enemies of the blue mussel (Kamermans *et al.*, 2009). Without them, populations can reach an extreme population size, damaging the natural environment. However, in culture populations, the mussels are regulated by humans and often kept within a certain area or site. If to speak of shallow on-bottom culture shore crab (*e.g. Cancer pagarus and Carcinus maenas*), starfish, snails (e.g. *Ocenebra inornata, Rapana venosa*, *Nucella lapillus*), and shore birds (e.g. oystercatchers *Haematopus ostralegus*) are very likely to threaten the culture (Capelle, 2017; Seed, 1969; Smaal *et al.*, 2018; Wijsman, 2020). On-bottom culture mussels can be predated on by birds when the water level is low within the intertidal zone (Capelle, 2017).

However, there are techniques to counteract this threat (Saier*,* 2001). Catching of sea stars or other kind of actions are taken to prevent great loss of the population. Although humans can reduce predation, mussels are also capable of defending themselves. The blue mussel grows thicker shells which are better attached to the substrate if predation pressure is high (Leonard *et al.*, 1999).

### 3.2.4 Legal restrictions

Mussel cultivation is restricted to areas that are not marine protected areas, or habitats that are of ecological importance (Inglis *et al.*, 2000). Because they have the capacity to damage the ecosystem by dominating the benthic floor causing a cascade of effects negatively effecting the natural ecosystem.

### 3.2.5 Cultivation types

*On-bottom cultivation*

On-bottom cultivation works best on shallow mudflats where naturally mussel beds are found as well (Figure 11) (Capelle, 2017; Smaal *et al.*, 2018). On-bottom culture will not be successful on sand since it interferes with their filtration. Sand is moving slightly with the current and is filtered out by the mussels. Filtering sand costs energy which cannot be used for digestion or growth. Energy wasted on the sand cannot be used to filter food particles (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). Within on-bottom culture, the focus and challenges lay in getting the best seedlings, predator control, and optimizing culture practices such as harvest time, substrate, and harvesting techniques (Smaal *et al.* 2018). As explained above, the spat of on-bottom culture comes from wild populations and is spread out on the benthic floor to give opportunity for growth. The bottom used for the mussel culture is prepared before the spat spread out (Smaal *et al.*, 2018). 1 ton of marketable mussels are collected out of 1 ton initial laid spat ("Cultured Aquatic Species Information Programme *Mytilus edulis* (Linnaeus, 1758)", 2020). For this culture technique it takes the mussels about 14-24 month to reach maturity after which most of them are harvested. Using this technique brings some challenges with it. Active predator removal is necessary for prevention of severe culture loss (Capelle, 2017). Furthermore, bottom layer water current is of great importance to prevent (nutrient) sedimentation and reach the minimum supply of nutrient, food and oxygen. Looking at tidal challenges, laying dry for a prolonged period can cause severe death rates, especially during high summer season (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). Harvesting on-bottom culture is done with trawls dragging on the benthic floor collecting the mussels.

*Figure 11: On-bottom culture in the Netherlands. Notice how the mussel beds lay on the intertidal seafloor (Smaal et al., 2018, p. 32.)*

*Table culture*

The table culture is characterized by horizontal culture just above the benthic floor, often build out of steel plates or nets. It has the same properties of on-bottom culture, but this steel construction is to prevent predation mainly done by snails (*Nucella lapillus*), crabs (*Carcinus meanas, Maja brachydactyla), and* starfish (Smaal *et al.*, 2018). Furthermore, the sedimentation process describes by the 'on-bottom culture' is also reduced. Due to the elevation, the sediment, both produced by the mussel itself and accumulating form the water, can fall to the benthic floor instead of accumulation on the mussels suffocating them. Besides those two mechanisms the culture and its characteristics are almost identical to on-bottom culture.

*Bouchot cultivation*


*Figure 12: Bouchot culture in France with collectors wraped around the bouchots (poles). (Smaal et al., 2018, p. 32.)*

Although 'the bouchot' (pole) cultivation has not dramatically changed for centuries, the mechanical methods for bouchot culture are still under development to make it more efficient ("Cultured Aquatic Species Information Programme *Mytilus edulis* (Linnaeus, 1758)", 2020; Smaal *et al.* 2018). This kind of culture is mostly done in intertidal zones such as mudflats or beaches (Capelle, 2017). Within the bouchot culture as explained before, spat is put directly on the poles or on collectors to attach themselves to (Figure 12). Each pole is generally around 4-7 m long and 15-25 cm in diameter. If mussels are given enough space for filtering out the sufficient nutrients, a minimum of 25 m apart should be maintained ("Cultured Aquatic Species Information Programme *Mytilus edulis* (Linnaeus, 1758)", 2020). Harvest efficiency is limited due to technical restriction: amphibious vehicles or small boats are the only two options to harvest this culture type. A cylinder, which is lowered on the bouchots, is used to scrape of the mussels (Prou & Goulletquer, 2002). Collector preparations are mostly done around spring and replaced on the poles around summer for further growth of the mussels. The collectors are initially attached at the bottom ends to give room for further dispersal to the higher ends. Eventually the entire pole is colonized and gives around 60 kg of mussels (live weight) ("Cultured Aquatic Species Information Programme *Mytilus edulis* (Linnaeus, 1758)", 2020).

*Longline cultivation*

Longline cultivation is developing at high speed and is widely used. Long polymer lines are attached to buoys or rafts and generally reach depths of 2-12 m (Smaal *et al.*, 2018) (Figure 13 a-b). Harvesting is done by hand, venturi pump or scarpers with general yield numbers of 18-20 tonnes/ha/yr ("Cultured Aquatic Species Information Programme *Mytilus edulis* (Linnaeus, 1758)", 2020; Smaal *et al.*, 2018). Being exposed in this way requires protection against hydrodynamic forces and buoyancy control (Capelle, 2017; "Cultured Aquatic Species Information Programme *Mytilus edulis* (Linnaeus, 1758)", 2020). Although protection mechanisms cost money, the general production is higher than on-bottom culture and more efficient. Also, the harvest techniques are less costly and easier. Seed is normally collected from wild populations and put on collectors. After settlement, thinning and reseeding onto the polymer ropes is done to reach marketable harvest size ("Cultured Aquatic Species Information Programme *Mytilus edulis* (Linnaeus, 1758)", 2020). Within longline culture stock densities plays an important factor (Smaal *et al.*, 2018). Too high densities of seed on the ropes causes insufficient mussel sizes and an overall loss of production. Reaching optimum stock densities can deliver around 4-12 kg harvest from 1 kg seed (Ferreira *et al.*, 2009). However, within the Netherlands production is very low (marginal 1% of spat) due to infrastructure of the culture and market structure (Smaal *et al.*, 2018).

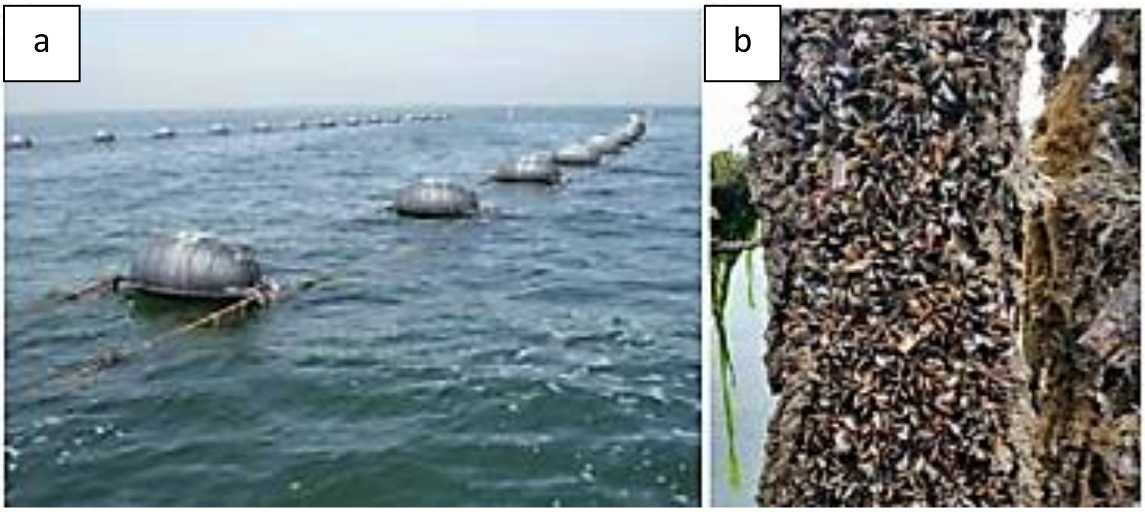


*Figure 13 a-b: Images of a) longlines attached to buoys reaching a length of several km and b) a picture of a longline with mussel culture attached. Adapted from Capelle (2017), p. 54.*

*Raft cultivation*

Raft cultivation has only recently been developed efficiently. Although rafts and longlines are very similar they are discussed separately since there are small differences and harvest techniques do differ highly. They are generally smaller in scale than longlines and less productive per unit substrate than nets or tubes (Capelle, 2017). General production is much higher due to much higher densities. On the rafts, longline ropes are hung from buoys or directly attached to the raft (Figure 14 a-b). Commonly, rafts are combined with longline culture making them the most common method for mussel culture worldwide (Capelle, 2017). However, this is different for Dutch aquaculture where bottom culture is the most common ("Cultured Aquatic Species Information Programme *Mytilus edulis* (Linnaeus, 1758)"). Regarding seed collecting and growing techniques this correspond identically with longline techniques. The main challenge within this culture lies within optimizing the stock density, farm infrastructure, and investing in the best spat.

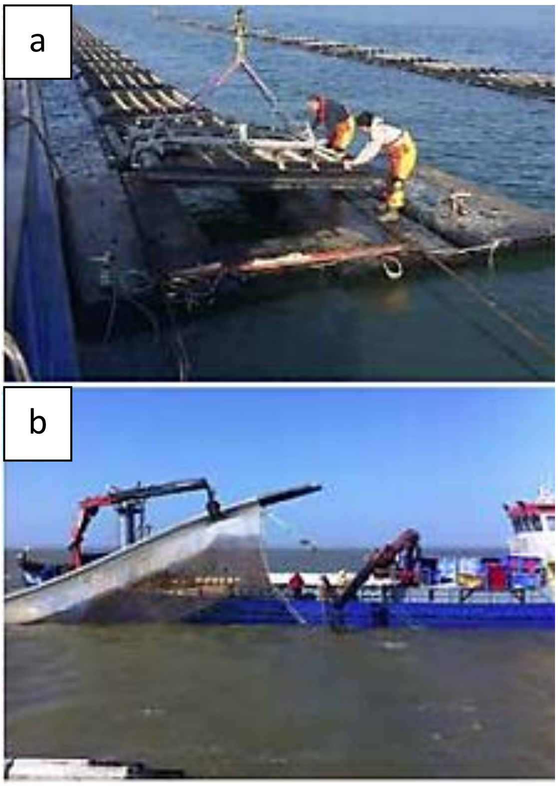


*Figure 14 a-b: Images of a) directly to raft attached polymer line and b) nets and line attached to rafts Adapted from Capelle (2017), p. 54.*

## 3.3 Oysters

In the Dutch aquaculture sector, two species of oysters are used. The Pacific oyster and the European flat oyster ("National Aquaculture Sector Overview Netherlands", 2020). As both species have similar characteristics and growth conditions (Animal+1, 2020), both species are discussed together and not in separate sections.

The Pacific oyster (Figure 15), *Magallana gigas* (Thunberg, 1973), often also called the Japanese oyster, and previously called *Crassostrea gigas*, is an oyster species native to the Pacific ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020). In the twentieth century, the Pacific oyster was introduced to the North Atlantic to replace the depleted flat oyster cultivation stocks (see next paragraph below) (Héral & Deslous-Paoli, 1991; "National Aquaculture Sector Overview Netherlands", 2020). The Pacific oyster lives in the intertidal zone up to 40 m depth, where it anchors itself on hard substrates, like rocks and shells ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020; Héral & Deslous-Paoli, 1991). As a sessile filter feeder ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020), it feeds itself on algae, plankton and organic matter in the water (Animal+1, 2019). To reach a marketable size of 70-100 g, the Pacific oyster should grow for 18 to 30 months, dependent on the growth conditions (Animal+1, 2019; "Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020). The growth happens primarily in the growing season from April to October (Animal+1, 2019; Kater, 2003).

The European flat oyster (Figure 16), *Ostrea edulis* (Linnaeus, 1758), is an oyster species native to the

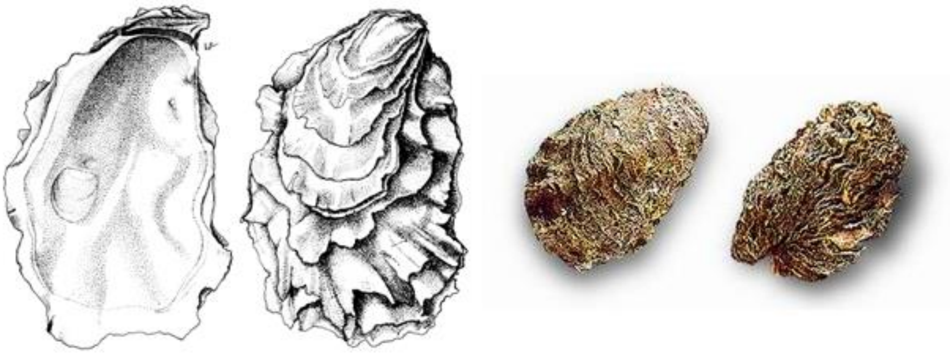

*Figure 15: Drawings (left) and pictures (right) of the Pacific oyster. ("Cultured Aquatic Species Information Programme Crassostrea gigas (Thunberg, 1973)", 2020)*

European coast ("Cultured Aquatic Species Information Programme *Ostrea edulis* (Linnaeus, 1758)", 2020). After several mass mortality events in the 1920s, 1970s and 1980s, the natural and aquaculture production of the European flat oyster has been greatly reduced and replaced by Pacific oysters ("Cultured Aquatic Species Information Programme *Ostrea edulis* (Linnaeus, 1758)", 2020). Identical

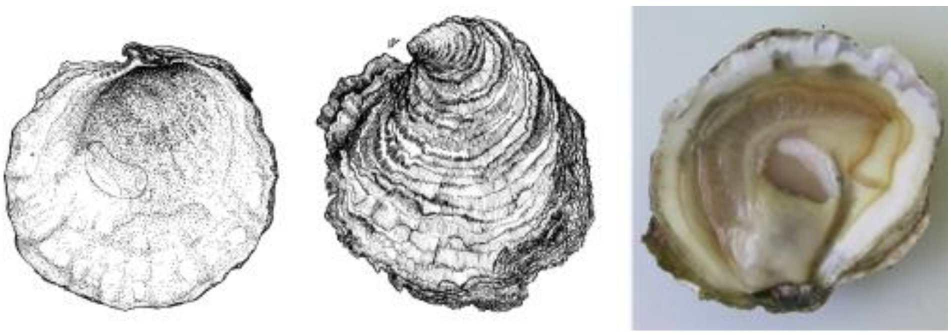

*Figure 16: Drawings (left & middle) and anatomical picture (right) of the European flat oyster. ("Cultured Aquatic Species Programme Ostrea edulis (Linnaeus, 1758)", 2020)*

to the Pacific oyster, the European flat oyster is a sessile filter feeder, filtering the water for plankton and organic matter, while being attached to a hard substrate, like rocks and shells (Animal+1, 2019).

### 3.3.1 Survival and growth conditions

Both oysters are able to survive under wide temperature and salinity ranges. Juvenile and adult Pacific oysters survive water temperatures of 3-35°C (Animal+1, 2019; "Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020), while European flat oysters survive under a narrower range of 7-25°C (Smaal *et al.*, 2017). Still, both species have a similar optimal growth temperature of roughly 16-25°C (Animal+1, 2019; "Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020).

The tolerable water salinity for the Pacific oyster ranges from 10-35 psu (Animal+1, 2019) and for the European flat oyster ranges from 20-40 psu (Héral & Deslous-Paoli, 1991; Smaal *et al.*, 2017). The salinity for optimal growth conditions for both species is between 25-35 psu ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020; Héral & Deslous-Paoli, 1991; Kater, 2003; Smaal *et al.*, 2017).

The main limiting factor in oyster cultivation is food availability (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). In order for the oysters to get the optimal amount of food and oxygen, a current of 0.2-0.5 m/s is required (Animal+1, 2019). Too slow currents will limit the food availability, while too fast currents cause sediment to resuspend in the water and consequently damage the gills (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020).

As both oysters live in the intertidal zone, the oysters do tolerate air exposure. It is found that for the Pacific oyster an air-water exposure ratio of 20% is optimal for growth (Animal+1, 2019), with a maximum survivable exposure for both oyster species of 1 day in the summer (Animal+1, 2019). Air exposure data on the European flat oyster could not be found.

### 3.3.2 Predation

There are several predators that prey on oysters in the Netherlands. The species that came up multiple times in literature and interviews were the green shore crab (*Carcinus maenas*) (Fey *et al.*, 2010; Mascaro & Seed, 2000), the predatory sea snail Japanese oyster drill (*Ocenebra inornata*) (Gercken & Schmidt, 2014; Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020) and several species of birds (Gercken & Schmidt, 2014), like the herring gulls (*Larus argentatus*) and the oystercatcher (*Haematopsus ostralegus*) (Cadée, 2001; Cadée, 2008). In the interview with the Nederlandse Oestervereniging & PO Mosselcultuur (personal communication, 2020), only the predatory snail the Japanese oyster drill was named as a threat to oyster aquaculture. It has to be noted that Gercken & Schmidt (2014) report, besides the Japanese oyster drill, the presence of a second predatory snail that predates on oysters in the Oosterschelde, the Atlantic oyster drill (*Urosalpinx cinerea*). Which adaptations are taken to prevent predation in oyster aquacultures are described below for each cultivation type individually.

### 3.3.3 Cultivation types

For both oyster species similar cultivation types were found. Of the different cultivation types, four categories can be distinguished: on-bottom cultivation, table cultivation, longline cultivation and raft cultivation. Of these cultures, only on-bottom and table cultivations are used in the Netherlands ("National Aquaculture Sector Overview Netherlands", 2020). However, due to predation by the predatory snails on the Pacific oyster, a shift to off-bottom cultivation, like table cultivation, is being made (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). Also, different cultivation types can be used at different life stages of the oysters ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020).

*On-bottom cultivation*

*Figure 17: Oyster farmers harvesting on-bottom cultures of oysters during low tide. (http://www.photolib.noaa.gov/htmls/fish0744.htm by Bob*

In on-bottom cultivations, oysters are grown on the seafloor of the intertidal zone (Figure 17). During low tide, the oysters are harvested manually, using oyster forks and baskets or float boats ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020; Héral & Deslous-Paoli, 1991). At high tide, the oysters are dredged up from the bottom floor ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020; Héral & Deslous-Paoli, 1991). To protect the oysters from predators, fences and netting can be used to cover the oysters ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020; "Cultured Aquatic Species Information Programme *Ostrea edulis* (Linnaeus, 1758)", 2020).

A variation of the on-bottom cultivation takes place in the deeper sub-intertidal zone, between 3-10 m deep (Héral & Deslous-Paoli, 1991). The deep cultivation is only harvested by dredging (Héral & Deslous-Paoli, 1991).

*Table cultivation*

*Figure 18: Image of table cultivation at low tide in Georges River, Australia. (http://www.scienceimage.csiro.au/image/2901, by Robert Kerton, CSIRO)*

For table cultivations, the oysters are cultivated on trays or in mesh bags that are attached to tables, frames or trestles ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020; "Cultured Aquatic Species Information Programme *Ostrea edulis* (Linnaeus, 1758)", 2020; Héral & Deslous-Paoli, 1991; Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). The tables, frames and trestles are placed in the intertidal zone (Delta21, personal communication, 2020) and prevent the oysters of touching the seafloor. When harvesting, the trays or mesh begs are collected, while the tables, frames or trestles remain on the seafloor ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020).

*Longline culture*

In longline cultures, ropes or chains that can reach 10 m deep are seeded with oyster spat ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020; Héral & Deslous-Paoli, 1991). With this cultivation type, the oysters are suspended to a depth where fouling organisms occur less, while preventing the oysters of reaching the seafloor ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020). Although not specified in the source literature, fouling organisms may decrease oyster growth rate by competing for food or forcing oysters to allocate energy to maintenance, and preventing the oysters of reaching the seafloor may prevent predation of oysters by benthic predators like certain species of crabs and snails.

*Raft culture*

For oyster cultivation, the raft culture is a less common variety of longline culture (Figure 19). Instead of using ropes or chains, the oysters are grown in or on mesh bags, trays or nets that are suspended in the water underneath rafts or buoys ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020). Similarly to the table cultures, the oysters are thinned out and relocated to bigger mesh bags, trays and nets as the oysters grow ("Cultured Aquatic Species Information Programme *Ostrea edulis* (Linnaeus, 1758)", 2020). As a variation of longline cultivation, similar advantages hold true for raft cultures as it does for longline cultures. Still, they are mentioned separately because the raft or buoy structures requirement.

*Figure 19: Raft oyster cultivation using baskets in Halong Bay, Vietnam. Notice how the wooden frame by which the baskets are suspended, are kept afloat using buoys. (https://www.publicdomainpictures.net)*

## 3.4 Seaweed

In this project three different phylogenetic groups of seaweed are discussed: Phaeophyceae, Rhodophyceae and Chlorophyceae (brown, red, and green algae respectively). They differ on many aspects such as growing season and morphology, but generally for all three groups 4-5 m is the minimum depth of water column to cultivate (Barbier *et al.*, 2019). Furthermore, the most important limitations for seaweeds are nutrients, light and water flow. Seaweeds have the capacity to filter out the chemical components at a high rate (Animal+1, 2019). Normally, this is very effective and growth stimulating for the plant, however if there are contaminants (e.g. heavy metals, bacteria, viruses) in the water it can lead to accumulation. Severe accumulation can lead to toxic concentrations for both the algae and/or for humans if used as (raw) consumption (Animal+1, 2019).

In the Netherlands, seaweed cultivation is still at an early stage of development (Seaweed expert Wageningen University & Research, personal communication, 2020). This results in a lot of knowledge from other countries where different growth conditions apply. The general information therefore comes from other countries. When information specifically applies to the Netherlands, this is explicitly stated.

The focus is on native North Sea seaweed species with potential which include the brown seaweeds *Laminaria digitata* and *Saccharina latissima* (formerly known as *Laminaria saccharina*), the green seaweed *Ulva lactuca,* and the red seaweed *Palmaria palmata* (Van den Burg *et al.*, 2013) (Figure 20). *Palmaria palmata* is the only species that is not yet cultivated in the Netherlands (Van den Burg *et al.*, 2013). There is also an ongoing discussion whether this species is native to the Netherlands, this will be further discussed in the discussion (Seaweed expert Wageningen University & Research, personal communication, 2020). Although, there are more species that can be cultivated these four seem the easiest and most profitable to cultivate.

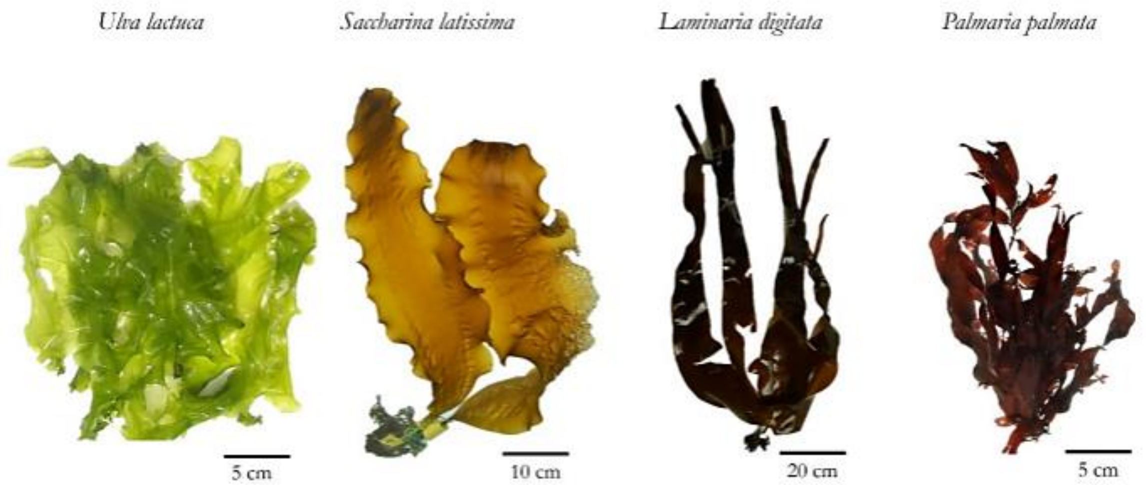


*Figure 20: The four seaweed species under investigation Ulva lacutca (sea lettuce), Saccharina latissima (sugar kelp), Laminaria digitata (finger kelp), and Palmaria palmata (dulse) (Lubsch, 2019, p. 8)*

### 3.4.1 Finger kelp (*Laminaria digitata*)

*Laminaria digitata* is a brown seaweed commonly referred to as finger kelp due to its finger-shaped leaves (Figure 20), as well as its ability as a 'kelp forest' to harbour other marine flora and fauna (Groenendijk *et al.*, 2016). Under optimal conditions, the seaweed can grow up to 4 m in length, but more often it grows to 2-3 m, since the length of the plant is related to the growth conditions (Groenendijk *et al.*, 2016). Van den Burg *et al.* (2013) observed in 2011 at the Wiederij the Netherlands that finger kelp grew from 44 mm seedling to 2 m long and 20 cm wide kelp (Lubsch, 2019).

The natural habitat of finger kelp consists of rocky grounds to a maximum depth of 20 m, most often occurring at depths of approximately 5 m (Van den Bogaart *et al.*, 2019). McHugh (2003) describes the habitat more in detail as the upper sublittoral zone where the plant is exposed to waves. Finger kelp is adapted to this by its flexible stem and divided finger-shaped leaves (McHugh, 2003). Finger kelp is assumed to be the most robust of the four species (Van den Burg *et al.*, 2013), although no exact values for the flow rate range for finger kelp could be found. In response to a flow rate suitability of 0.11-0.55 m/s for Norwegian sugar kelp (Matsson *et al.*, 2019), finger kelp can be assumed to tolerate at least this and perhaps even higher flow rates. In sheltered areas, the number and the length of leaves is reduced (Groenendijk *et al.*, 2016). With higher flow rates the number of leaves increases with 10-12 per plant (Groenendijk *et al.*, 2016).

The optimum temperature for finger kelp ranges from 10°C to 15°C and it can withstand 5°C to 23°C, it dies at temperatures above or below this range (Kerrison *et al.*, 2015; Wald, 2010). The optimal conditions for salinity range from 25-35 psu, reduced growth is experienced at 15-25 psu levels (Kerrison *et al.*, 2015). Finger kelp has an annual light requirement of 45-50 mol/m$^2$yr$^1$ and can absorb blue-green and green light through chlorophyll-α and chlorophyll c (Wald, 2010). The minimum nutrient requirement for kelp is 0.014 mg nitrogen/L (Wald, 2010). Nitrate ($NO_3^-$) is optimally absorbed at values between 10-40 µM (Kerrison *et al.*, 2015). Under optimal conditions for phosphate, nitrogen and carbon the growth rate of finger kelp is 30 cm/day (Wald, 2010).

The cultivation cycle of finger kelp starts with the production of spore-filled sori, depending on the specific location. Then they are raised in a hatchery under red light for about 20 weeks in the summer, after which the settlement is sprayed 25 cm apart onto culture strings which are coiled on spools. This means that on a line of 1 m there will be 12 to 15 plants. Before deployment at sea, the string must be twisted onto a thicker rope. These ropes are deployed on preinstalled horizontal carrier lines in the sea for the growing at sea from September to March-May after which the kelp is harvested in May and June (Animal+1, 2019; Forbord *et al.*, 2018; Rolin *et al.*, 2016; Wald, 2010; Van de Burg *et al.*, 2013). Finger kelp is a perennial species and could be harvested several times (Wald, 2010). It is believed that this will not be the case in the Netherlands due to, among other things, higher temperatures in the summer and therefore will have to be cultivated every year. Sea urchins are the predators of finger kelp (Wald, 2010).

### 3.4.2 Sugar kelp (*Saccharina latissima*, formerly *Laminaria saccharina*)

*Saccharina latissima*, formerly known as *Laminaria saccharina*, is commonly referred to as sugar kelp because it contains a high content of a sweet chemical called mannitol, giving it a sweet taste (Duran-Frontera, 2017) (Figure 20). This species of seaweed is favoured in the North Atlantic region and Norway due to its grow rate and simple life cycle: sugar kelp can easily be seeded and grown (Matsson *et al.*, 2019). Sugar kelp can grow on rocks as well as on wooden or metal structures (Groenendijk *et al.*, 2016).

Like finger kelp, the habitat of sugar kelp is the upper sublittoral, until a depth of -20 m in clear water, but the species prefers a more sheltered spot due to its fragile blades (McHugh, 2003). The kelp can reach 2.5 m in length (Van den Burg *et al.*, 2013) with a width of 10 cm (Lubsch, 2019). In the interview with the seaweed expert (Wageningen University & Research, personal communication, 2020) was said that this species only grows to 1.5 m in the Netherlands. The growing season is like finger kelp from September to March or May (Van den Burg *et al.*, 2013).

Sugar kelp has a wide range of temperature ranging from 5-17 °C (White & Marshal, 2007). Despite its wide range the optimum lays between 10-15 °C (Andersen, Pedersen & Nielsen, 2013). The salinity ranges from 15-35 psu with an optimum salinity of 24-35 psu (Kerrison *et al.*, 2015). A salinity below 10 psu results in mortality for sugar kelp (Seaweed expert Wageningen University & Research, personal communication, 2020). Kelp has an annual light requirement of 45-50 mol/m$^2$/yr and can absorb blue-green and green light through chlorophyll-α and chlorophyll-c (Wald, 2010). The minimum nutrient requirement for kelp is 0.014 mg N/L (Wald, 2010). Nitrate ($NO_3^-$) is optimally absorbed at values of 10 µM (Kerrison *et al.*, 2015). If the general condition describes above are within reasonable range its growth rate will be around 1.1 cm/day (White & Marshal, 2007).

Matsson *et al.* (2019) determined effects on kelp biomass and biofouling (the accumulation of small organisms on wetted surfaces) at three different culture sites for sugar kelp in Norway. The sporophytes were attached to two sets of 2 m ropes that were hung horizontally on a PVC-frame at -3 m and -8 m. Biofouling mainly took place due to the colonial bryozoan species sea mat *Membranipora membranacea* also known as the sea-mat or lacy crust bryozoan. Biofouling caused loss of kelp biomass through mechanical damage, decreasing flexibility and increased drag. All this can lead to bad kelp tissue, making it no longer suitable for human consumption. To prevent this, the kelp is harvested in May before colonization of the epibionts takes place in mid-July, shortening the growing season in Norway as there are favourable light conditions in June till August. Biofouling is highly influenced by temperature, an increase of 1 °C leads to an increase of coverage by *M. membranacea* of factor 9 and 2 °C leads to factor 64. Biofouling occurred less on 8 m than on 3 m, thereby suggesting that it is decreasing with depth. The study found a positive correlation between kelp biomass and elevated water temperature, shallower depth and increased salinity. Currents and nitrate did not show a correlation, which might be explained by the fact that both the semi-offshore, fjord, and inshore location are within the suitable ranges. This suitable range of water currents would then be 0.11-0.55 m/s (Matsson *et al.*, 2019).

### 3.4.3 Sea lettuce *(Ulva lactuca)*

*Ulva lactuca*, also known as sea lettuce because of its morphological resemblance with lettuce, is an edible green alga which occurs almost worldwide (Figure 20). Sea lettuce is a fast-growing species, with a daily increase of 50% in DM (dry matter) under optimal conditions (Van den Burg *et al.*, 2013). This makes that under eutrophicated, and warm circumstances sea lettuce can form a 'bloom' (Wald, 2010).

Sea lettuce is especially influenced by light, temperature and nutrient availability. Therefore, sea lettuce can be cultivated in water depth from 1-15 m, depending on the turbidity of the water, as they need sunny conditions (Wald, 2010). The seaweed contains the pigment chlorophyll-α and chlorophyll b absorbing blue-green and yellow-green light (Wald, 2010). Wald (2010) found a temperature range for sea lettuce between 10-25°C. Van den Burg *et al.* (2013), however, found that sea lettuce needs higher temperatures ranging from 15-20 °C.

The growth is most often N limited as requirements for N uptake are much higher than P uptake. Wald (2010) describes an absorption of 1.4-14 mg $NO_3$-N/L and 0.84-1.4 mg $NH_4$-N/L. This high nutrient uptake is due to the morphology of the seaweed. The thallus of sea lettuce consists of only two cell layers resulting in a large surface area per unit of volume. Therefore, it absorbs 4-6 times as many nutrients than other seaweeds (Wald, 2010). This makes that sea lettuce can overgrow slow-growing kelps. Furthermore, sea lettuce is lacking an internal transport system, requiring it to react quickly to osmotic change, making it an osmotic stress tolerant species. The salinity can range from 5-40 psu, idealistic 30 psu (Wald, 2010; Groenendijk *et al.*, 2016; Seaweed expert Wageningen University & Research, personal communication, 2020).

An adverse effect of the thallus being only two cell layers thick is the vulnerability to mechanical stress of sea lettuce. No flow rates could be found, but a maximum flow rate of 0.05 m/s was assumed (Seaweed expert Wageningen University & Research, personal communication, 2020). However, the species was successfully cultivated in 2011 in the Wiederij, Oosterschelde, the Netherlands (Van den Burg *et al.*, 2013).

The spore formation of sea lettuce is stimulated in laboratories and the seedlings are in the summer sprayed 20 cm apart onto lines or nets (Wald, 2010; Breure, 2014). In addition, sea lettuce can also be propagated vegetatively and applied directly to the culture string (Van den Burg *et al.*, 2013). The rapid growth of sea lettuce during the summer months must be considered as in May-August it can be necessary to harvest it every three weeks (Van den Burg *et al.*, 2013). The seaweed will grow to 30 cm until harvested and can be predated by small crustaceans such as isopods and amphipods (Wald, 2010).

### 3.4.4 Dulse (*Palmaria palmata*)

*Palmaria palmata* or dulse is a red seaweed with a high protein content (Van den Burg *et al.*, 2013) (Figure 20). As already mentioned in the introduction of seaweeds, dulse in native to the North Sea but does not grow naturally in the Netherlands. However, dulse is still discussed, since it can have future potential for culture within the Netherlands and thus for the ESL.

Dulse is a perennial weed with a complicated reproduction cycle which is only known since the 1980s (Wald, 2010). The growing season of dulse is like sea lettuce presumably in summer and under optimal conditions dulse can increase daily with 35% of the DM (Van den Burg *et al.*, 2013).

The seaweed grows in the lower intertidal and shallow subtidal zone on rocks until a depth of -20 m (Werner & Dring, 2011). However, it is usually found at a depth of -5 m (Van den Bogaart *et al.*, 2019). Dulse is also found as an epiphyte on finger kelp (Van den Bogaart *et al.*, 2019). Sheltered or semi-exposed sites are preferable for dulse with a water current of 0.05-0.10 m/s (Werner & Dring, 2011).

The optimal water temperature for dulse ranges from 15-20°C (Wald, 2010). The seaweed is very tolerant as it can survive in salinities ranging from 3-30 psu (Wald, 2010). However, the optimal salinity ranges from 21-34 psu (Bak, 2014). Dulse absorbs large amounts of nitrogen as can be seen in the requirements of minimum 0.042 mg N/L with an optimum of 0.42 mg N/L (Wald, 2010). The seaweed consists of multiple pigments including chlorophyll-α and chlorophyll d (Wald, 2010).

Dulse is difficult to cultivate and has long been harvested from the wild shores of Europe, Canada and America for centuries. However, nowadays a trial of kuralon string cultivation is in place in Norway for later upscaling if successful. Small seedlings are placed on nets/strings, before put into open sea. The seedlings should have a minimum size of 0.5 mm before putting it on nets/strings (Edwards & Dring, 2011). Despite the new insights in cultivation of dulse, it remains difficult to upscale production since raw materials comes from wild populations, resulting in more pressure on the wild population when upscaling this species as an industry (Grote, 2019). In addition to this pressure on the population, the genetic variation decreases, which can have consequences for susceptibility to diseases. The harvest of dulse happens when they have reached 30-40 cm in length, as with the laminaria, it is important to monitor the last growth stages at sea to detect biofouling in time (Werner & Dring, 2011).

The biofiltration capacity of dulse makes it a good candidate for an integrated multi-trophic aquaculture system (IMTA) (Lüning, 2001). Since it takes $NO_3^-$ out of the water which boosts growth and $NH_4^+$ is used to make proteins it is ideal to use since both these components are used in fish feed (Corey *et al.*, 2013).

### 3.4.5 Seaweed cultivation types

In the Netherlands seaweed cultivation is operating on a small scale. In 2016 there were only three initiatives known and described where seaweed harvesting happens manually and the technology to harvest otherwise was not yet completely invented. These initiatives were the seaweed farming test location of the WUR: 'de Wierderij, Schelphoek' in the Oosterschelde (2011), the NoordzeeBoerderij 10 km offshore Texel (2015) and the commercial seaweed farm ZeeWaar in a sheltered location in the Oosterschelde (Groenendijk *et al.*, 2016). Nowadays 'de Wierderij, Schelphoek' is a location of Seaweed Harvest Holland (Seaweed Harvest Holland, n.d.) and the NoordzeeBoerderij offshore Texel is no longer is use, instead the location 12 km offshore Scheveningen (Stichting Noordzeeboerderij, n.d.). Some of these companies will be discussed later in the text.

*Horizontal longline culture*

The traditional longline culture is characterized by horizontal ropes up to 50 m, anchored at each end, and with floats every 10 m to keep the support the longline (Figure 21) (De San, 2012). For optimal growth, the seaweed should be 1-3.5 m below the water surface (Barbier *et al.*, 2019). Horizontal longline culture is often employed in water depths ranging between 6 and 10 m, therefore a boat is needed to reach the culture site (De San, 2012). They can easily be commercialized by putting enough space between the lines so that large commercial vessels can sail through, collecting the culture vast and efficiently.

In 2015, the commercial seaweed cultivation company ZeeWaar used a system of several km of lines, connected with buoys to wooden posts to let the entire system move with the water level (Figure 22). There is 1 m space between the lines to allow a small boat in between and harvest is happening manually. The seaweed grows 1 m below the water surface (Pors-Schot, 2016).

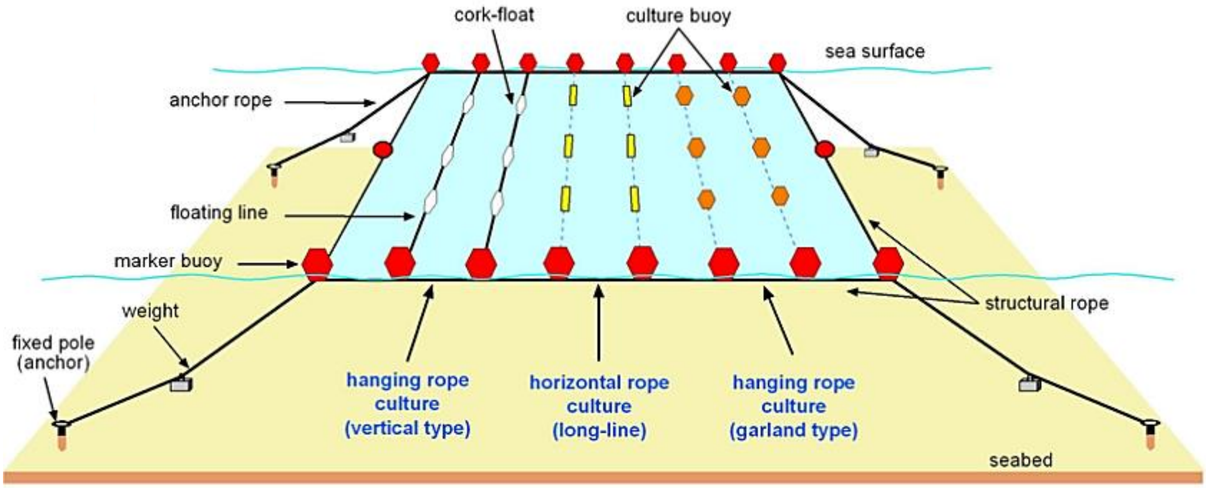


*Figure 21: Schematic drawings of an overview of the longline systems of vertical, horizontal and garland types. Adapted from Peteiro et al. (2016), p. 11.*

*Figure 22: Seaweed cultivation set up by company ZeeWaar. (Pors-Schot, 2016).*

*Vertical longline culture*

Vertical longlines are ropes that are attached to constructions made from combinations of floating objects such as buoys and bamboo, anchored to the shore or benthic floor. Although they are very similar, a distinction has been made due to the difference in harvests.

To get a better understanding of a vertical longline cultivation structure an example from China will be discussed (Figure 23). The system consists of three floating lines with a length of 100 m with every 0.4 m distance a hanging rope, resulting in 120 kelp ropes in between two of the floating lines. Each kelp rope is planted with 40 pieces of kelp (Zhang *et al.*, 2017). The structure is thus more complex than that of a longline due to the many connections. Furthermore, vertical longlines are more compact and therefore difficult to harvest by bigger harvest vessels making it more labour intensive. The harvest is often done by hand with smaller boats. The hanging buckle is highlighted because the study focused on inventing a machine in order to more efficiently harvest a raft (Zhang *et al.*, 2017). It was suggested that an automatically opening hanging buckle is needed for mechanical harvesting (Zhang *et al.*, 2017).

Both longline culture types are very exposed to hydrological forces such as waves and currents making its application limited to their location (Barbier *et al.*, 2019). Although all four species discussed above can be applied on longline, but mostly this is used for kelp (Barbier *et al.*, 2019).

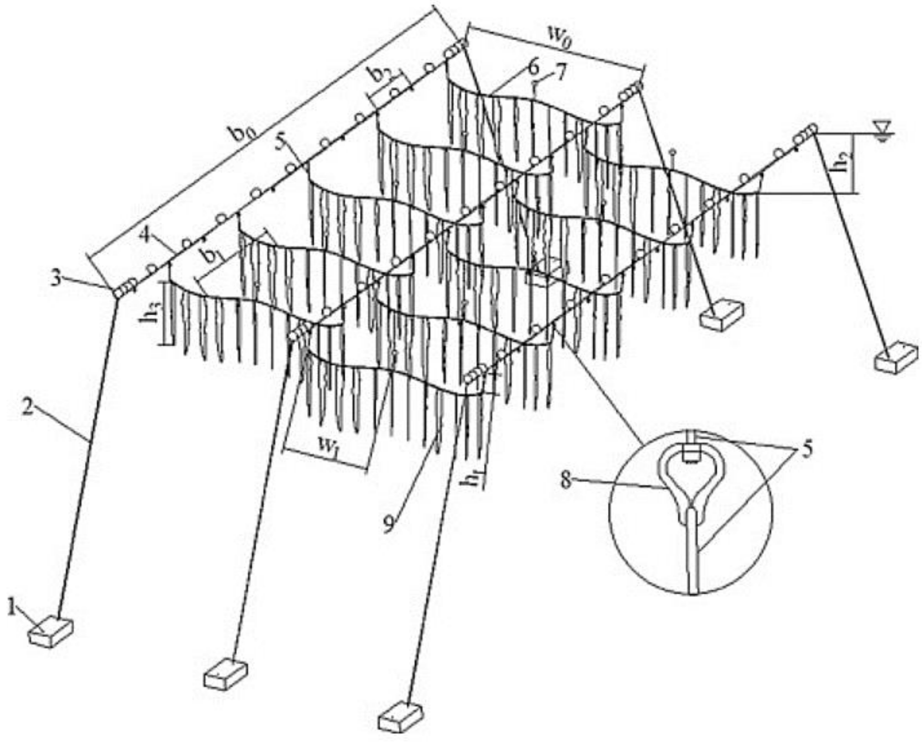


*Figure 23: Schematic drawing of a floating raft structure for kelp cultivation in China. 1) Heavyweight anchor; 2) Anchor rope; 3) Floating device; 4) Floating raft rope; 5) Hanging rope; 6) Kelp rope; 7) Smaller floating device; 8) Hanging buckle; 9) Kelp (Zhang et al., 2017, p. 174).*

## 3.5 Combination of species

Several variants of cultivation combinations exist in the North Sea (Peteiro *et al.*, 2016; Reith *et al.*, 2005). Although this is offshore, it can inspire cultivation in the ESL.

The Dutch aquaculture is looking for ways to combine mussel and oyster cultivation with the seaweed cultivation. They do however compete for substrate, so combination cultures would require separate lines for seaweed and mussels (Seaweed Harvest Holland, personal communication, 2020).

### 3.5.1 Cultivation of seaweeds in layers

The seaweed species used in this combination are different from each other regarding their light requirements, which provides opportunities for cultivation in layers. This would imply that sea lettuce is grown in the top meter below the water surface and dulse at a depth between 1 and 2 m (Reith *et al.*, 2005). Sea lettuce is a green seaweed and therefore it makes optimal use of the red and blue part of the sunlight spectrum that falls onto the water surface. The red seaweed dulse that is cultivated deeper in the water, can capture the green light (Reith *et al.*, 2005). This layered system does require a certain minimum depth but is more effective in space.

Furthermore, the risk of culture failure is reduced since there are two different species cultivated at the same time. If one crop fails, due to for instance predation or disease, the other one remains, increasing harvest security for the farmer.

### 3.5.2 Cultivation of seaweed and mussels

Seaweed longline culture in combination with mussel cultivation also works with layers. The first layer can be provided with 2 m long lines of mussels in hanging culture and the second line at 2 m depth is used for the cultivation of kelp (Reith *et al.*, 2005). Whenever nitrogen turns out to be limiting, co-cultivation of blue mussels with seaweed potentially offers a solution. Seaweed grows faster in the proximity of blue mussels, which may be related to the excretion of ammonia by mussels (Rößner *et al.*, 2014). However, this can also help under light-limited conditions as ammonium excreted by mussels can be assimilated easier than the naturally more abundant ammonia in seawater, thereby still enhancing nitrogen uptake and growth of the seaweed (Jansen *et al.*, 2019).

Jansen *et al.* (2019) report a disadvantage of this combination as it requires harvesting the seaweed before the mussel spat falls, as mussel spat can lead to fouling damage on the seaweed. In addition, the weight of the mussels can damage the culture structure of the seaweed or make it difficult to harvest. From data on the Oosterschelde and the Waddenzee it can be concluded that mussel spat is taking place in May and June, usually earlier in the Oosterschelde compared to the Waddenzee. Therefore, it is suggested to harvest the seaweed before the end of May to ensure the quality of the seaweed by avoiding damage of spat fall.

There are more disadvantages of growing mussels and seaweed together. First, the mussels provide shade which is detrimental to the seaweed (Rößner *et al.*, 2014). Second, no evidence was found to support the theory that the enhanced growth of seaweed in the proximity of mussels is due to the excretion of ammonium, as the seaweed in the study did not have a higher nitrogen content (Rößner *et al.*, 2014). As the mechanisms behind the potential benefit have not been proven and the drawback of shade is known, it is not recommended to grow mussels and seaweed close together. This is supported by Jansen *et al. (2019)* who also found no difference between growth of seaweeds in monoculture and in combination with mussels.

### 3.5.3 Seasonal cultivation of seaweed

Besides, cultivating seaweed in combination with other seaweeds or mussels, seasonal variety can also make cultivation much more efficient and productive. A well-known Dutch example is that of ZeeWaar. They cultivate sugar kelp during the winter and sea lettuce during summer (Pors-Schot, 2016). Sugar kelp is still productive within the winter months where other seaweed grows much less. In this way, the high growth rate performance state of the cultivation continues which results in much more yield.

Although this combination is the most common other combination are possible as well. These combinations can be modelled, looking at how the different species distribute naturally within the Dutch ecosystem.

## 3.6 Conclusion

The sub-question addressed in this chapter was: “Which forms of aquaculture require conditions that match the expected conditions at different sites in the Energy Storage Lake?". A brief explanation of whether a cultivation type suits the ESL can be found in the table below (Table 5). In many cases, the inventory of the conditions required for aquaculture matched the expected conditions in the lake and are discussed per species below.

### 3.6.1 Mussels

Generally, the blue mussel matches with the conditions of the ESL making it an excellent candidate for culture in the ESL and can be applied in different culture types. For the blue mussel, flow rate is the most important (potentially) limiting factor for growth, since it provides food and oxygen. Water velocity below 0.15 m/s causes food depletion, which reduces growth. The flow rate close to the pumps, when the ESL is completely filled, is 0.26 m/s, while the flow rate declines down to 0.05 m/s at the furthest sites from the pumps. Concluding, blue mussel culture is only possible relatively close to the pumps.

The main source of food for the blue mussel is phytoplankton. Within the ESL the mean chlorophyll-α content during summer is 13.42 µg/L, while during winter it is 4.34 µg/L. The ideal range for the blue mussel lays at 4-8 µg/L, matching within the ESL. Thus, food availability is not a problem for implementation of blue mussel cultivation.

The mean salinity of 31.030 psu in the ESL is within the range of tolerance of the blue mussel. The water temperature tolerance ranges from 0-20°C, which fits well within the range of 6-17°C of the ESL. The optimum water temperature for blue mussels is 20°C, which occurs around summertime. Although, the optimum is during the summer months, the blue mussel grows year-round according to literature. Nutrient availability within the ESL will not inhibit growth.

For heavy metals no values were found. However, it can be concluded, looking at the North Sea, that they do not inhibit growth nor safety regarding consumption of the blue mussels.

On-bottom culture has its own challenges regarding nutrient and sedimentation. Sedimentation and pseudofaeces can cause severe inhibition of growth. Furthermore, predation can cause severe loss of culture if not counteracted. Predation found within the literature and interviews is mostly done by shore crab (*e.g. Cancer pagarus and Carcinus maenas*), starfish (e.g. *Asterias rubens)*, snails (e.g. *Ocenebra inornata, Rapana venosa*, *Nucella lapillus*), and shore birds (e.g. oystercatchers (*Haematopus ostralegus*)). However, sedimentation and predation problems can be solved by using table cultivation. With this culture type, predators such as crabs and snails cannot reach the mussels and sedimentation cannot suffocate the mussels since it falls to the lake floor. The ESL is relatively shallow making table culture easy to reach and harvest. Although, this culture type could solve the predation issue it is not commonly used in literature. Other anti-predation measures are taken (e.g. active predator removal).

Bouchot culture has a great potential for the ESL. Large open beaches with different tidal zones makes it the perfect place for bouchot culture. The most important thing to consider when implementing this culture type is desiccation. The blue mussel can withstand some drought. However, during summertime, when temperature rise above 20°C, desiccation can occur after hours.

Although, longline and raft culture in this chapter has been discussed separately, for implementation of mussel culture in the ESL only the harvest technique is different. Both are well fit for use in the ESL.

### 3.6.2 Oysters

The requirements for oysters to survive match the conditions in the ESL. The expected year-round temperature range of 6-17°C meets the needed 3-35°C for Pacific oysters, and almost the needed 7-25°C for European flat oysters. It is important to note that these are growth temperatures, meaning lower temperatures are survivable. Still, the optimal growth temperature for both species lays at 16-25°C, which may only be reached in the highest temperature season of the year. The expected salinity of 31 psu matches the required salinity ranges of 10-35 psu and 20-40 psu for Pacific oyster and European flat oyster respectively. Although food availability often is the main limiting factor in oyster growth, for the ESL it is not expected to be overall limiting, as long as the water flow rate conditions are met.

At some sites in the ESL, dependent on the water depth, tide and distance to the water pump, the flow rate requirements are not met. The slowest expected flow rate occurs during high tide in the upper water layer and is estimated at 0.05-0.30 m/s, dependent on distance from the pumps. The slower expected flow rates are lower than the required 0.2-0.5 m/s required for oyster growth. This may lower the overall growth rate of the oysters. The fastest flow rate occurs in the bottom layer at low tide and is estimated at 0.26-1.3 m/s. The 1.3 m/s reached close to the pumps is too high and may resuspend sediment in the water. Too high sediment concentrations in the water may damage the oyster gills.

All cultivation types for oyster cultivation found can be applied to the ELS, but some factors may hinder the implementation. The on-bottom cultivation and table cultivation are already in use in the Dutch oyster aquaculture sector. The issue that arises for implementation in the ELS, is the requirement for an intertidal area. In order to harvest the oysters, the harvesters need to access the oysters during low tide. Dredging the cultures during high tide instead of manual harvesting during low tide would require soft sediment on the bottom, which is not preferred due to resuspension of the sediment. Hanging cultures, like raft cultivation and longline cultivation, for oyster cultivation are currently not done in the Netherlands. Implementing these cultures would require foreign expertise and pioneering. It would, however, be possible, as long as the cultures are suspended high enough not to reach the lake's floor during low tide scenarios.

### 3.6.3 Seaweed

The mean salinity of 31.030 psu in the ESL is around the optimum for all seaweed species. The variability in salinity could result in reduced growth or even death. Based on the literature found, sea lettuce is the most resilient for this variability in salinity since it is lacking an internal transport system. The water temperature range of 6-17 °C is optimal for the kelp. The mean water temperature of 17 °C in summer makes it suitable for sea lettuce and dulse which prefer higher temperatures of 15-20 °C. The mean nitrogen content is also interesting to look at, as the estimated value of 0.84 mg/L is the minimum amount for sea lettuce and thus indicates not ideal growth conditions. However, the nitrogen content is expected to increase in the coming years, so this might not be an issue in the future.

The horizontal and vertical cultivation types can both be implemented in the ESL, but consideration must be given to the flow rate. In the top layer, the flow rate starts at 0.05 m/s which is assumed to be too fast for the fragile sea lettuce. A flow rate of 0.05-0.10 m/s for dulse can also form a problem close to the pumps or in a deeper water layer. The flow rate requirement may be easiest to meet for the robust species sugar kelp and finger kelp which handle a flow rate of 0.11-0.55 m/s. An ideal location would be at a site where the flow rate is not too low or high and where the seaweed would not touch the lake floor. Either by cultivating less deep under the water surface or by choosing a species with another length.

The implementation of these cultivation types must be carefully considered and may require some adjustments to growing and harvesting. The kelp species are cultivated during the winter whereas sea lettuce and dulse are cultivated in the summer. This could lead to cultivation at more sites in the ESL during the winter compared to summer due to the higher flow rate acceptance of kelp. In addition, it should also be considered that the harvest of certain species, such as sea lettuce, is more complicated because it must be harvested every three weeks because of its fast growth.

### 3.6.4 Combinations

The cultivation of two seaweed species simultaneously or polyculture seaweed in layers is not feasible in the ESL as only the growing seasons of sea lettuce and dulse match in summer. In polyculture, one seaweed is cultivated under the other. Sea lettuce should be harvested every 3 weeks in the summer when it grows fast and this could do damage to the cultivation of dulse. Therefore, it is not recommended to implement this in the ESL.

The vertical cultivation of seaweed in combination with mussels is also not feasible within the ESL. First, the mussels will shade the seaweed which negatively effects the growth of the seaweed. Second, there is no concrete evidence of the supposed benefits of this combination.

Seasonal cultivation of seaweed could be implemented if the requirements mentioned by the cultivation types are met. Seasonal cultivation is already happening in the Netherlands with sea lettuce and kelp. This offers the advantage that income can be generated all year round and risks of sudden market drop or loss of culture due to diseases can be lowered.

Overall, cultivation of seaweed, mussels, and oyster, should be done separately within the ESL. Only the seasonal cultivation of seaweed can be considered viable in terms of combining culture. Growing two seaweed species or seaweed species and mussels side by side is possible in the ESL, if the other required conditions are met as well. However, it is not likely that the spatial orientation of the different species provides additional benefits, thus this is not considered a combination, but just the result of multiple single cultures next to each other. This is in contrast to vertical combinations whereby the extra benefit lies within the efficiency of the use of space due to the differences in light absorption or hypothesised enhanced nutrient exchange.

*Table 5: Summary of the suitability of the different cultivation types for the ESL with conditions that have to be met at the site in the ESL.*

| Aquaculture systems | Fit for ESL | Conditions |
|---|---|---|
| **Blue mussel** | | |
| a. On-bottom culture | Yes | • Active predation removal<br>• Close to pumps for sufficient flow rate<br>• Removal of sedimentation |
| b. Table culture | Maybe | • Not common for mussels |
| c. Bouchot culture | Yes | • Close to pumps for sufficient flow rate<br>• Desiccation, if laid to long dry |
| d. Longline culture | Maybe | • Longlines too long for ELS<br>• Culture may not touch lake floor<br>• Often large boats needed for harvest |
| e. Raft culture | Yes | • All conditions met |
| **Oysters** | | |
| a. On-bottom culture | Yes | • Intertidal area needed or soft bottom substrate for harvesting<br>• Flow rate close to pumps too fast |
| b. Table culture | Yes | • Intertidal area needed for harvesting<br>• Flow rate close to pumps too fast |
| c. Longline culture | Yes | • Culture may not touch lake floor<br>• Flow rate further away from pumps too slow |
| d. Raft culture | Yes | • Culture may not touch lake floor<br>• Flow rate further away from pumps too slow |
| **Seaweeds** | | |
| a. Horizontal longline culture | Yes | • Flow rate close to the pumps and in the bottom layer too fast for some species |
| b. Vertical longline culture | Maybe | • Culture may not touch lake floor<br>• Flow rate close to the pumps and in the bottom layer too fast for some species |
| **Combinations** | | |
| a. Seaweed in layers | No | • Harvesting sea lettuce too often |
| b. Seaweed species seasonal | Yes | • Meets the cultivation requirements |
| c. Seaweed and mussels close together | No | • Benefits not proven, serious drawbacks |

# Chapter 4: Requirements for the floating solar park

## 4.1 Introduction

In this chapter, the third sub-question "Which requirements does the floating solar park have to meet in order to reach highest production of the species and aquaculture types selected in sub-question 2?" will be answered. The answer to this sub-question provides the commissioner with insights on the possible combinations of aquaculture with the floating solar park in the Energy Storage Lake (ESL) (Figure 24). This chapter is divided into three parts. Suitable locations for aquaculture in the ESL will be discussed first. Followed by interactions between the floating solar park and aquaculture in the lake. Lastly, a conclusion will be given on the most suitable forms of aquaculture within the ESL.

*Figure 24: Image of a floating solar park. ("Floating solar, a solution to increasing scarcity of land", 2019)*

In order to determine suitable locations for aquaculture in the ESL, comparisons have been made between the expected conditions of the lake described in Chapter 2, and the requirements for shellfish and seaweed aquaculture described in Chapter 3. Species and cultivation types not suitable for cultivation in the ESL are not taken into consideration in this chapter. The requirements for the water flow rate are assumed to be the same for the different cultivation methods. The differences between the species of shellfish and seaweed are taken into consideration.

Several assumptions have been made in this chapter in consultation with the solar panel specialist (Delta21, personal communication, 2020). Firstly, the mooring system that is necessary to keep the floating solar panels in place in the ESL is not taken into account. This has been decided due to uncertainty of the type of mooring system that will be implemented by Delta21, and the necessary information for this construction not yet being available. The floating solar park is assumed to be a single large island of 5 $km^2$ with a certain light transparency as it would not be economically viable to split the solar park into smaller sections. Splitting the solar park into smaller islands would either require a large number of cables connecting the islands together which would make it impossible for boats to pass between them, or require a separate mooring system for each island which would significantly increase the costs. It would also require a separate energy cable going over the bottom of the lake for each island (Delta21, personal communication, 2020).

Furthermore, due to safety reasons and the need to access the area around the pumping system for maintenance, the possibilities for aquaculture practices in the range of 0-500 m distance from the pumps are left out of this chapter. Aquaculture activities will not be allowed within this range (Delta21, personal communication, 2020).

## 4.2 Suitable locations for aquaculture in the ESL, preparing for a floating solar park

In this section the suitable locations in the ESL for different aquaculture species will be discussed. This section is divided in bottom cultivation types and hanging cultivation types, considering the different species discussed in Chapter 3. Requirements for temperature will not be discussed in this section as all the species mentioned are able to survive within the expected temperature range of the ESL. When calculating the flow rates in Chapter 2, a large amount of assumptions where made. Because of these assumptions, a small error around the flow rates will be assumed when determining suitable locations for aquaculture. This section provides the necessary knowledge on the different cultivation possibilities, in order to be able to implement the floating solar park in the ESL, harmonizing the aquaculture practices with green energy production.

### 4.2.1 Bottom culture

Different aquaculture species have different optimal conditions and are therefore bound to different locations for bottom culture within the ESL. The ESL can be roughly divided into two parts. On the one hand, the edges of the ESL with a slope of 1:20, a certain inundation time due to daily water level change and a flow rate depending on the location. On the other hand, the bottom that is a flat surface with a depth of 5 m that will always be filled with water.

Considering the edges around the ESL, the possibilities for bottom culture are limited, due to the expected sediment composition in the ESL of fine sand soil with silt layers and its implications for aquaculture. As explained in Chapter 3, direct on-bottom cultivation of shellfish is inefficient, since predation is an issue and the sandy substrate on the edges damages the shellfish' gills. Table cultivation is the most suitable form of bottom culture in the ESL and considering the inundation time and flow rate this is possible for oysters in specific locations. Based on the interview with the Nederlandse Oestervereniging & PO Mosselcultuur (personal communication, 2020), it is assumed that that oysters can withstand 5 hours of drought. Therefore, on the lower part of the edges of the ESL that are no longer than 5 hours a day above the water level, table culture for both oyster species is possible. Considering the necessary flow rate of 0.2-0.5 m/s at the particular water depths in the ESL that have a sufficient inundation time, gives four different ranges at four different heights that are suitable for oyster table cultivation (Table 6). According to the calculations that have been made in this project, the total area that could be used for table cultivation of oysters is approximately 119 ha (Appendix 8).

Another bottom cultivation method that has been considered as a possibility in Chapter 3 is bouchot cultivation of blue mussels. However, the maximum time a day that blue mussels can survive above water is unknown. If bouchot culture would be implemented on the edges of the ESL, a certain duration of drought exposure is unavoidable. Furthermore, the Nederlandse Oestervereniging & PO Mosselcultuur (personal communication, 2020) have mentioned that for the Dutch mussel cultivation sector this type of cultivation is not of interest. Therefore, bouchot culture is from here onwards left out of the possibilities for bottom cultivation in the ESL.

*Table 6: Possible geographical locations for oyster bottom cultivation in the ESL, considering inundation time and flow rate*

| **European flat & Japanese oyster (Table culture)** | | |
|---|---|---|
| **Water depth with inundation time <5 h** | Possible range for cultivation, measured in distance from pump (m) | |
| **-14.5** | 1000 | 3750 |
| **-15.5** | 1500 | 4500 |
| **-16.5** | 1500 | 5000 |
| **-17.5** | 2000 | 5000 |

### 4.2.2 Hanging culture

Within the ESL there are possibilities for longline and raft aquaculture for shellfish and seaweeds. There are two important limiting factors for these culture types as discussed in Chapter 3; the flow rate of the water (Animal+1, 2019; Matsson *et al.*, 2019), and the required depth of the longline cultures (Smaal *et al.*, 2018; "Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020; De San, 2012). The ESL will have a depth of 5 m when the lake has been completely emptied and some forms of longline aquaculture require greater depths in order to be efficient. It is also important that the cultures do not touch the bottom of the lake, as this might damage the cultures (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). The types of shellfish discussed in this section are the blue mussel (*Mytilus edulis*), Pacific oyster (*Maggallana gigas*), and the European flat oyster (*Ostrea edulis*). The seaweed species discussed are finger kelp (*Laminaria digitata*), sugar kelp (*Saccharina latissima*), sea lettuce (*Ulva lactuca*), and dulse (*Palmaria palmata*).

*Blue mussel*

The blue mussel has an optimum flow rate of 0.20-0.80 m/s in order to meet its food demand (Animal+1, 2019). However, little depletion occurs when the flow rate is above 0.15 m/s (Inglis *et al.*, 2000). The 500-1000 m from the pump area matches these requirements most closely (Appendix 9). The flow rate of the water in the 5 m layer at the bottom of the ESL will be larger than the optimum flow rate for mussel cultivation. However, it is assumed that mussels will be able to survive slightly higher flow rates for a short duration. Depletion might start to occur in the area 1500 m away from the pumps due to the lower expected flow rate in the top layers. There is a knowledge gap regarding the impact of lower flow rates for short durations. However, mussels have been known to survive short draughts, e.g. when using a bouchot culture. Thus, it is likely that the lower flow rate for a few hours each day will not negatively impact mussel aquaculture in the 1500 m area.

Longline and raft cultures typically reach depths of 2-12 m (Smaal *et al.*, 2018). Due to depth of 5 m when the ESL is empty (Delta21, personal communication, 2020), longline cultures of 2-4.5 m are possible within the lake. The total possible area for hanging mussel cultivation in the ESL is 275 ha (Appendix 9).

*Pacific and European flat oyster*

The flow rate conditions for the Pacific and European flat oyster are assumed to be the same. Optimum flow rates for oyster cultivation are between 0.20-0.50 m/s (Animal+1, 2019). Larger flow rates limit oyster growth, mostly due to damage to the gills resulting from sediment particles suspended in the water. Lower flow rates reduce food availability for the oyster (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). The most likely location for oyster cultivation in the ESL would be between 1000-1500 m from the pumps. However, based on the expected flow rate in this area, cultivation would not be possible. The flow rate near the bottom of the lake would exceed the maximum flow rate (Appendix 10), and resuspension of sediment could occur in this area, possibly damaging the gills of the oysters. The flow rate 1500 m away from the pumps would be too low for cultivation, and the oysters would remain in the low flow rate area for 12 hours at a time (Appendix 6). Thus, the food supply would be limiting to growth, assuming that oysters are only able to survive 5 hours outside of the water, without food available as explained in 4.2.1 (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020).

Vertical longline cultures will pose some problems when implemented in the ESL. These cultures can typically reach a depth of 10 m below the surface, while the ESL only has a depth of 5 m when the lake has been emptied ("Cultured Aquatic Species Programme *Crassostrea gigas* (Thunberg, 1973)", 2020;

Héral & Deslous-Paoli, 1991). These types of cultures will likely be damaged when implemented as a result of them colliding with the bottom of the lake. Horizontal longline, and raft cultures are assumed to require a lower depth, thus can be implemented within the permanently water covered area of the ESL. The possible area for hanging oyster cultivation is estimated at 122 ha (Appendix 10).

*Seaweed*

Options for hanging cultivation of seaweed in the ESL mainly exist for sugar kelp and finger kelp as for sea lettuce the minimum flow rate of 0.05 m/s in the ESL was assumed to be too fast. Dulse is also impossible to cultivate in the ESL as it is believed that dulse can handle flow rates of 0.05-0.10 m/s and these are located only in the top layer where dulse has a low probability of surviving since it falls dry more than half of the time.

Measurements show that sugar kelp grows in areas with a flow rate of 0.11-0.55 m/s, however, they are likely to be able to survive slightly lower, or larger flow rates for short durations (Matsson *et al.*, 2019). It is possible that finger kelp can survive even larger flow rates as it is the most robust species of seaweed studied in this project (Van den Burg *et al.*, 2018).

Flow rates within the ESL match these requirements in the area between 1500-3000 m from the pumps. The flow rate will become too low if these species are grown further away, possibly limiting their growth rate (Appendix 11). The total area estimated to be suitable for seaweed aquaculture in the ESL is 647 ha (Appendix 8).

There are possibilities for horizontal and vertical long line cultures in the ESL. Important to take into consideration regarding seaweed cultivation is the size of the cultivated species. Sugar kelp can reach a size of 1.5 m in the Netherlands, while finger kelp can reach a size of 2 m (Lubsch, 2019; Wageningen University & Research, personal communication, 2020). Taking their length into account is important as seaweed is cultivated at 1-3.5 m below the surface of the water (Barbier *et al.*, 2019). Horizontal longline cultivation is preferred in the ESL because vertical long lines might be limited due to the 5 m depth of the water column when the lake has been emptied.

## 4.3 Solar park aspects and implementation in ESL

In this section the possibilities and limitations of implementing the floating solar park together with aquaculture in the ESL are elaborated on. The suitable locations for the floating solar park are explained, as well as the combination of the floating solar park with aquaculture. Furthermore, the impact of reduced light from the floating solar park on the ecosystem, as well as the importance of a certain light transparency between the panels is discussed, and lastly, the risks of combining aquaculture with the floating solar park. In this project, a potential set up for the floating solar panels was discussed with Delta21 and a solar panel specialist (Delta21, personal communication, 2020). The outcome of this conversation led to a set up where the solar panels are gliding over a central pole (mooring pole) with changes in water height. The electricity cables are guided to the bottom using a float and will lie on the bottom going to shore (Figure 25).

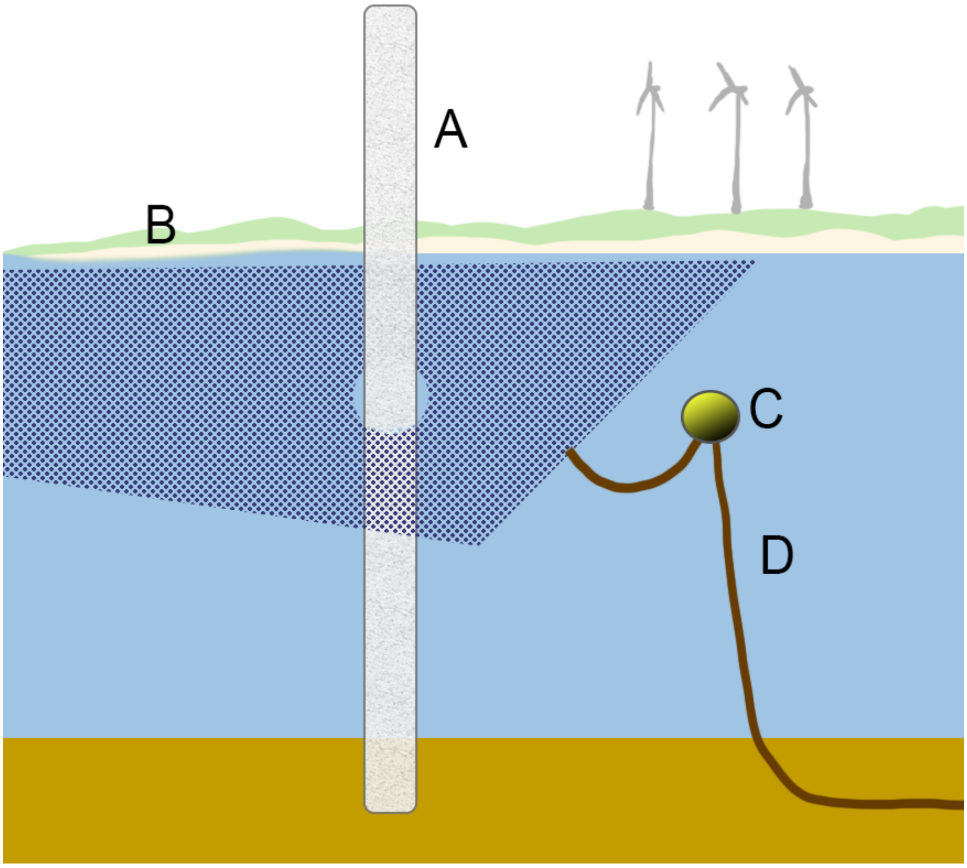


*Figure 25: The set up for the floating solar panel island that is assumed in this project. A) Mooring pole over which the solar panels glide with water changes, B) Solar panels with light transparency, C) Float, D) Electricity cable going on-bottom to shore.*

### 4.3.1 Suitable locations for the floating solar park

There are a few considerations to take into account when determining the most suitable site for the floating solar park in the ESL. Firstly, the area close to the pumps needs to remain free of obstructions in order to allow access to the pumps when maintenance is required (Delta21, personal communication, 2020). Secondly, overlap with suitable locations for aquaculture should be kept in mind. Finally, the sloped areas near the edges of the ESL that will not be permanently covered by water will not be suitable for the floating solar park.

The total area suitable for shellfish aquaculture near the pumps is 275, and the total area suitable for seaweed is 647 ha. Thus, a total area of 922 ha (9.44 km$^2$) (Appendix 8). This would leave a large enough area further away from the pumps for the 5 km$^2$ floating solar park, where aquaculture is not possible due to the flow rate becoming too little for shellfish and seaweed species. This would mean a separation between aquaculture and the floating solar park.

Placing the floating solar park closer to the pumps might limit the total available area for aquaculture, however, some options for combining aquaculture and the floating solar park do exist.

### 4.3.2 Floating solar park in combination with aquaculture

Combining aquaculture and the solar park is an option when the solar park is located closer to the pumps where the conditions are more suitable for aquaculture. One of the possibilities for integrating aquaculture with the solar park could be to use the structure of the floating solar park as rafts for hanging cultures. The potential set up for the floating solar panel island is assumed to be strong enough for carrying hanging cultures (Delta21, personal communication, 2020).

Shellfish or seaweed hanging cultures could be attached to the outer edge of the solar park (Figure 26). However, combining seaweed aquaculture with the solar park could limit the growth of the seaweed cultures due to the light requirements (Wald, 2010). This is expected to be less of an issue for shellfish as they do not require light for growth. The reduction in primary production below the solar panels, which is described more in depth in Chapter 4.3.3, could limit food and oxygen availability for the shellfish.

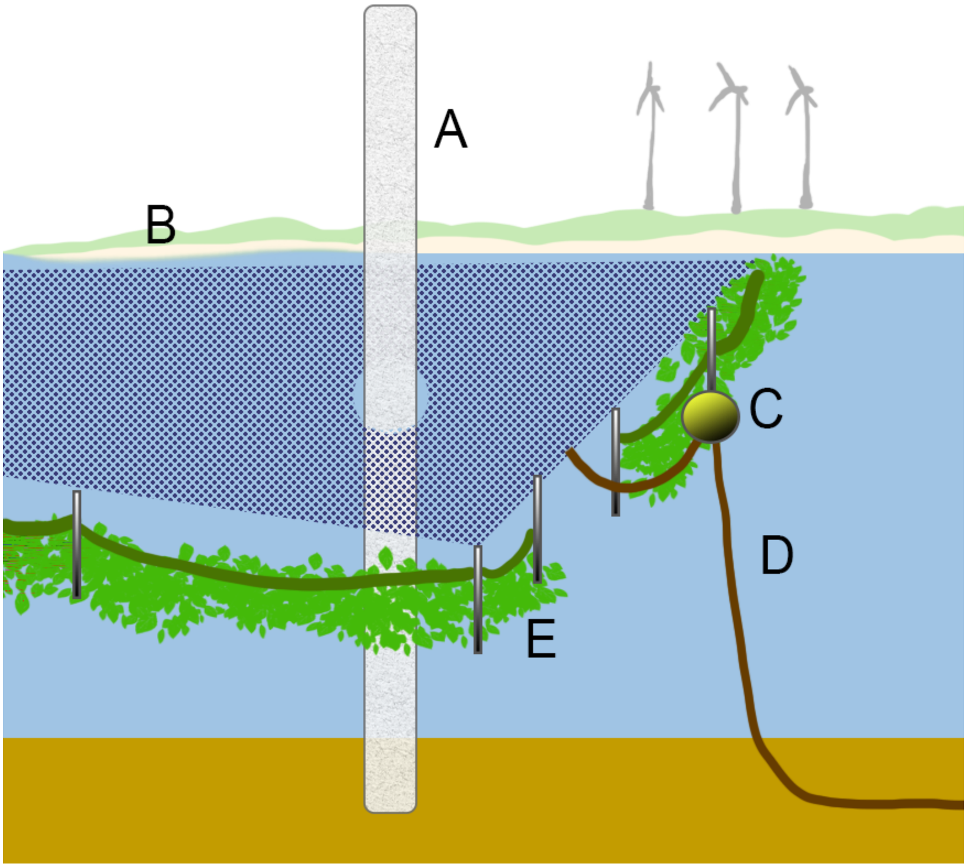


*Figure 26: Hanging cultures attached under the floating solar park. A) Mooring pole over which the solar panels glide with water changes, B) Solar panels with light transparency, C) Float, D) Electricity cable going on-bottom to shore, E) Hanging cultures on the sides of the solar panel island.*

### 4.3.3 Impact of reduced light

Light is an important variable for production of phytoplankton as feed for shellfish and as energy source for seaweed. Since it is assumed that the phytoplankton concentrations will be equal over the lake and over time, this paragraph is focussed on the light necessary for seaweed cultivation. The only possible method of seaweed cultivation is a hanging culture, as is shown in Table 5. These hanging cultures should not touch the bottom when the lake is almost empty, so the hanging cultures will not be deeper than -5 m.

As stated in paragraph 2.2.6, turbidity is generally a determining factor in light penetration through the water (Wang & Seyes-Yagoobi, 1994). According to the seaweed expert of Wageningen University & Research (personal communication, 2020), the photic zone will not be deeper than -5 m. This means that light penetrates deep enough to use the full length under the solar panels for hanging cultures.

However, the effect of the solar park on the light penetration will have a larger impact than the effect of turbidity on light penetration.

The solar panels will shed a shadow on the water, blocking light. When looking at the direction of sunlight, the north-side of the solar panels would not allow sunlight to reach hanging cultures attached to the floating solar park and is thus unusable for seaweed cultivation. The other sides will receive sunlight, although the east and west will have sunlight for only half of the time. Only the south side would be fully usable, with less light due to a lower scatter from other angles. A higher light transparency percentage will also increase the light scatter and thus, increase the possibilities of hanging cultures on all cardinal directions.

Loos & Wortelboer (2018) found that not only the coverage of the solar panels is determining for the ecology in the water body, but also the specifications of the water body itself. When a water body is around 25 m deep, the effect of a high coverage will be less than for a water body of around 4 m. The light transparency of the solar park can flatten the effects of a high coverage. The optimal combination between the specifications of the water body, coverage and light transparency can be found using the 'Zon op Water' model. When this model is applied for the ESL, several conclusions can be drawn. Firstly, it turns out that when the lake is full, the effect of a solar park with 25% coverage and 25% light transparency is very small on the bottom of the lake (Figure 27 and Figure 28 top). According to the 'Zon op Water' model, there is almost no light on the bottom of the ESL once the lake is filled (Figure 27), this might be problematic for benthic species that need photosynthesis. Secondly, when the lake is almost empty and the water is 5 m high, there are larger differences between the percentages of light transparency (Figure 27). A light transparency of at least 25% results in the highest light intensity, the percentage coverage does not make a large difference (Figure 28 top and bottom).

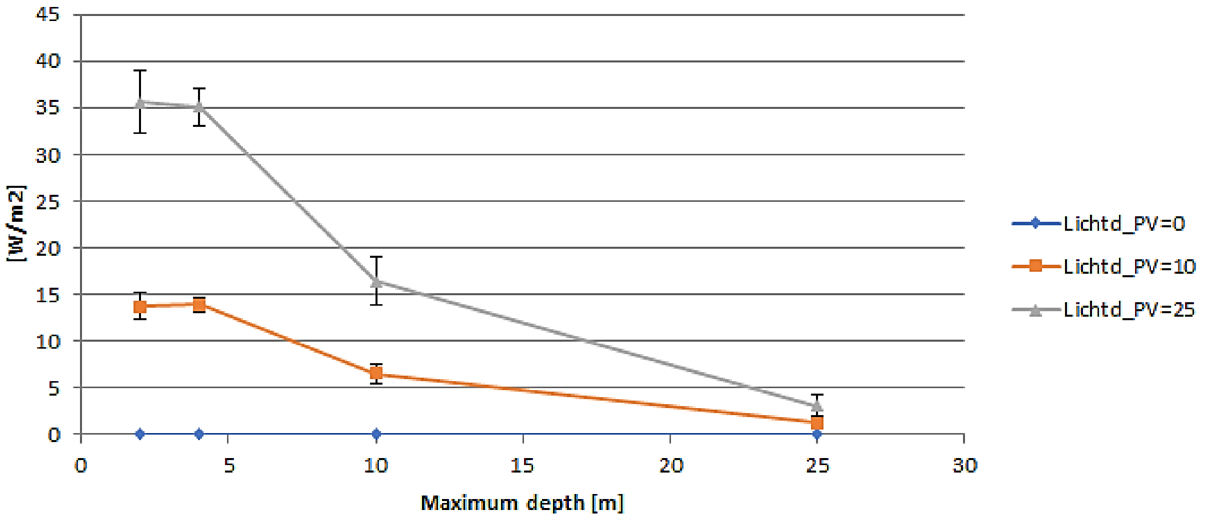


*Figure 27: Mean light intensity under the solar panels W/m² (y-axis) for different depths (m) (x-axis) of a water body with a surface of 10 km² and a solar panel coverage of 25%. The lines represent a light transparency of 0%, 10%, and 25% for the blue, orange and grey line respectively.*

Karpouzoglou *et al.* (2020) describes that for large water bodies, the coverage of the solar park should not exceed 20%. Within the 20%, the changes in primary production were less than 10%, whereas for higher coverages, the changes in primary production decreased substantially.

In paragraph 2.2.6 it was stated that the photic zone in the ESL will not be deeper than -5 m. Because the solar panels will be used as rafts and the hanging cultures will not go deeper than 5 m below these rafts, there will be no issue with the light penetration for hanging cultures. However, the light entering from the side and scattering in the direction of hanging cultures should be increased by using a light transparency of at least 25 %.

At night, the absence of light will lead to an uptake of oxygen by seaweed and other photosynthesizing organisms. This will deplete the oxygen resources, as is also described in paragraph 2.3.2.

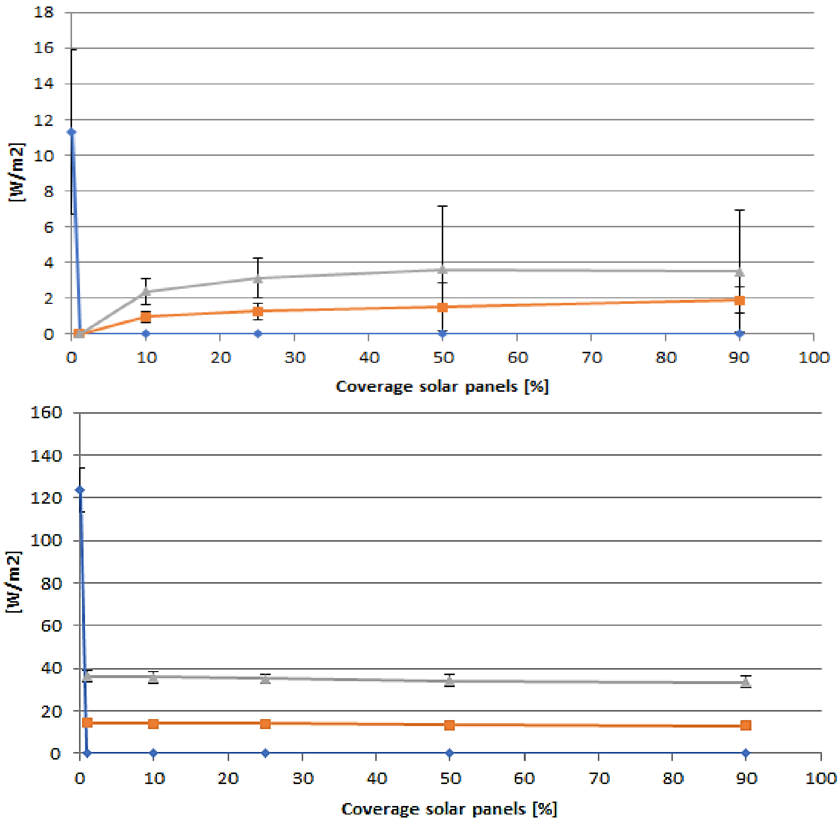


*Figure 28: Mean light intensity under the solar panels W/m² (y-axis) for different solar panel coverages (%) (x-axis) of a water body with a surface of 10 km² and (top) a depth of 25 m, and (bottom) a depth of 4 m. The lines represent a light transparency of 0%, 10%, and 25% for the blue, orange and grey line respectively.*

### 4.3.4 Risks associated with combining the floating solar park and aquaculture

Integrating aquaculture into a floating solar park introduces additional risks. The floating solar park increases the number of obstacles on the water surface, including the mooring lines, energy cables, and the solar panels themselves. This increases the chance of collisions when harvesting the shellfish and seaweed cultures. Collisions can result in harm to persons harvesting the cultures due to them falling from the vessels, and due to the risks involved with working near the power lines connected to the floating solar park. These collisions with the solar park might also add unexpected costs due to the damage caused to the vessel and solar park. The chance of collisions could be reduced by increasing the distance between the solar park, including mooring and power lines, and aquaculture.

The floating solar park also poses some ecological risks. The ecological risks also pose a risk to aquaculture in the lake, as damage to the ecosystem will also result in damage to organisms used for aquaculture. Damage to the solar panels can release pollutants into the water column. This damage can occur due to the weathering of the protective coating on the panels, handling during installation, and within the ESL due to collisions with vessels harvesting the cultures (Espinosa *et al.*, 2016). Damage to the panels can also result in spills of chemicals used in the cooling system of some panels (Lovich &

Ennen, 2011). However, this depends on the cooling system used, and as the solar panels are possibly cooled due to being situated in a lake, this might not be a large risk in the ESL. Some types of solar panels also pose a risk of leaching heavy metals into the environment, which might impact the ecosystem that develops in the ESL (Espinosa *et al.*, 2016). Light depletion can impact the ecosystem due to a change in primary production and by impacting benthic organisms. The impact of light depletion is discussed in more detail in Chapter 4.3.3.

For now, it turns out that a combination of aquaculture and the floating solar park does not turn out to be the best combination. However, when calculations that are made in this project are not correct and conditions are different, this might be of interest.

## 4.4 Conclusion

Different forms of aquaculture can be combined in the ESL. An area of 1041 ha is expected to have conditions suitable for aquaculture (Table 7). Most of this area can be used for hanging cultures, with possibilities for table cultures of Pacific and European flat oysters. The largest area is most suitable for sugar and finger kelp hanging cultures. The area closest to the pumps is most suitable for mussel and oyster cultures, while the area in the middle of the lake is most suited for seaweed cultures. The area suitable for oyster hanging cultures overlaps with the suitable area for mussel cultures, thus a decision needs to be made if the entire area is used for mussel cultivation, or if the area is split in 122 ha oyster cultivation, and 153 ha of mussel cultivation. The available areas are the maximum that reflects an ideal situation. Also, it must be noted that the calculated areas are dependent on the dimensions and conditions that were assumed within this project.

If the floating solar park is combined with aquaculture, it should cover less than 20% of the total surface area of the water body and should allow for 25% of light to pass between the panels. If the solar panels occupy a larger area, or block more of the light, a negative impact on the growth of benthic organisms that rely on photosynthesis, including seaweed, can be expected. The 20% coverage should not be exceeded even if aquaculture is not performed in the ESL, because a larger coverage area will negatively impact primary production in the lake, resulting in a decrease of the oxygen concentration.

The most suitable location for the floating solar park in the ESL is furthest away from the pumps. This allows for the largest area of shellfish and seaweed aquaculture. There are also possibilities of integrating aquaculture in the floating solar park. The solar panels can be used as rafts for aquaculture. Where hanging cultures are attached to the structure of the floating solar park. However, this might result in lower yields for aquaculture because only the edges of the solar park can be used, and light availability might impact growth of seaweed if it is placed too close to the solar panels.

Integrating the floating solar park with aquaculture increases the risk of collisions on the water, resulting in an increased risk for human health, increased costs due to damage, and ecological damage due to leaching or spills of pollutants.

*Table 7: Area available for aquaculture in the ESL.*

| Species | Culture type | Available area (ha) |
|---|---|---|
| *Pacific and European flat oyster* | Table culture | 119 |
| *Pacific and European flat oyster* | Hanging culture | 122 |
| *Blue mussel* | Hanging culture | 275 |
| *Blue mussel combined with oyster* | Hanging culture | 153 |
| *Sugar and finger kelp* | Hanging culture | 647 |
| ***Total available area for aquaculture*** | **Table and hanging culture** | **1041** |

# Chapter 5: Aquaculture and Nature enrichment

## 5.1 Introduction

In this chapter, the fourth sub-question "Which of these aquaculture types has potential for nature enrichment, regarding water quality and biodiversity?" will be answered. The suitable aquaculture types of Chapters 3 and 4 are elaborated on within this chapter to provide the commissioner with knowledge on the nature values associated with aquaculture. The chapter is divided into five parts. First the mussels, oysters and seaweed are discussed in their respective parts, for their nature value enriching properties and how different cultivation types may enhance or limit these properties. Then the part on the capacities of the system will access the production capacity and ecological capacity of the Energy Storage Lake (ESL), as well as, the importance of the balanced system. Finally, a conclusion part is written in which the main findings of this chapter are summarised, and the research question is answered. The information provided in this chapter is obtained from literature research and several interviews with experts on shellfish and seaweed cultivation in the Netherlands.

## 5.2 Mussels

The blue mussel (*Mytilus edulis*) is native to the North Sea area making it an excellent candidate for environmental enrichment. Native mussel beds can facilitate substratum for many infauna species, increasing local biodiversity with the increase of age of the mussel beds (Holt, 1998; Koivisto *et al.*, 2010). Looking at mudflats mussel beds generally have a higher biodiversity (Holt, 1998; Hild & Günther, 1999; Koivisto *et al.*, 2010). Mussel beds can transform into reefs once other organisms have settled on the beds. Next to this, mussel beds stabilize the substratum increasing the stability of the system (Hilt, 1998).

In the study of Borthagaray (2007) significant increase in species richness was found in plots with mussels in contrast to plots without bare sand without mussels. Therefore, blue mussel is considered an ecosystem engineer due to its capacity to significantly modify, maintain or destroy (local) habitats (Arribas *et al.*, 2014; Hild & Günther, 1999; Borthagary, 2007). Mussel beds can protect coastal areas against hydrological forces due to sedimentation trapping. Trapping of sedimentation stabilizes the substratum, forming banks that reduce hydrological forces such as waves and currents (Borsje *et al.*, 2011). These mussel beds produce significant amounts of larvae, being an essential food source for herring larvae and carnivorous zooplankton (Seed & Suchanek, 1992). Contributing to the food chain both in larval- and adult life stage. The adult mussels, if present in dense beds, can increase primary production turnover into secondary production, boosting the benthic biomass. This contributes to biodiversity as this biomass serves as food and substrata for other organisms (Dame, 1996; Holt, 1998). Furthermore, this adult biomass enhanced the biodiversity of the system (Borthagary *et al.*, 2007).

Besides contributing to (local) biodiversity and being a bioengineering species, the blue mussel also contributes to the water quality. Blue mussels have exceptional filtering capacity reaching maximum of 350 L/day in adult life stage (Inglis *et al.*, 2000). By doing so, detritus, bacteria, organic matter, phytoplankton, heavy metals and other pollutants are filtered out. Partially, these are converted to secondary products, while the remaining part is deposited on the benthic floor as faeces and pseudofaeces. If water velocity or other hydrologic forces (e.g. waves) are low, these faeces and pseudofaeces with pollutants and pathogens, are 'locked' out of the system and thereby cleans the water of pollutants (Lindahl & Kollberg, 2008; Lindahl *et al.*, 2005; Shumway, 1992). Additionally, mussels are described as nitrogen removers and consequently reduce the frequency and severity of algal blooms (Carmichael *et al.*, 2012). Having this filtering capacity, blue mussel culture can be used as bioindicator for water quality (Beyer *et al.*, 2017; Walker & MacAskill, 2014). With having blue mussel beds in the ecosystem system, water quality can be maintained and monitored, thereby contributing to nature enrichment. However, this filtering capacity can only take place when water velocity is high enough. If this is not the case, local phytoplankton levels can decrease significantly, effecting other organisms that feed on this (e.g. zooplankton) (Holt *et al.*, 1998; McKay & Fowler, 1997).

### 5.2.1 Food web

As mentioned in Chapter 3, mussels are predated on by many benthic species contributing to the food web within the Dutch Wadden Sea, which are expected to be similar to that of the ESL. Within the Dutch marine ecosystem, mussels are an important diet for many bird species (e.g. oystercatchers (*Haematopus ostralegus*) and ducks) (Nehls & Thiel, 1993; Raffaelli *et al.*, 1990). The Dutch Wadden Sea is considered a UNESCO World Heritage site among the fact of its large intertidal ecosystem (UNESCO, 2020), offering crucial feeding grounds for migrating birds such as the oystercatcher. Mussels play a crucial role within this intertidal ecosystem since, they provide the food for the oystercatchers. A severe decline of the mussel population in the Dutch Wadden Sea in 1990, resulted in an increased migration and mortality of many oystercatchers (Nehls & Thiel, 1993). Furthermore, mussel seed is eaten by wading birds and herring gulls (*Larus argentatus*), which is important to maintain the current food web and thus contributes to local biodiversity (Capelle *et al.*, 2017).

### 5.2.2 Cultivation types

*On-bottom cultivation*

As described above, mussel beds can protect coastal area due to its sedimentation trapping capacity. Implementing on-bottom culture can simulate this effect by creating artificial mussel beds, forming reefs (Figure 10 in Chapter 3). The filtering capacity also reduces pollutants in the water, stimulating nature enrichment. For on-bottom culture the challenge lies within balancing predation levels. Mussel predation, as discussed above, stimulates biodiversity, yet causes a decline in mussel culture. Normally, mussel farmers would actively take measures to prevent or counteract predation (Capelle *et al.*, 2017; Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020; Saier, 2001). Still, on-bottom culture is expected to contribute to nature value. Although on-bottom culture can bring several positive effects for nature enrichment, harvesting the culture will erase most of the established effects (Capelle *et al.*, 2017). Reefs generally take years to develop, while mussel culture is harvested after several months.

*Bouchot cultivation*

As bouchot culture is placed in the intertidal zone, the structure changes the natural water flow. Around the bouchots, the water flow rate increases, which affects the habitat heterogeneity. This heterogeneity contributes to biodiversity enhancement of the system (Pickett *et al.*, 1997). Further away from the bouchots, the overall flow rate of the water decreases, reducing the impact of hydrodynamic forces on the coast (Grant *et al.*, 2012). As previously mentioned in this chapter, mussel cultivation increases the supply of food for other organisms in the benthic environment (Callier *et al.*, 2007; Cranford *et al.*, 2009; Haven *et al.*, 1966). However, this deposition of organic material is limited by hydrodynamic forces. Strong hydrodynamic forces can replace these depositions, reducing the nutrient deposition on the benthic floor (Grant *et al.*, 2012).

*Longline & raft cultivation*

The most important contribution to nature enrichment for these two cultivation types is the facilitation of hard substrate and shelter (McKindsey *et al.*, 2011). The anchoring of the longlines and rafts provide shelter for benthic organisms, increasing the heterogeneity of the benthic floor and thereby increasing the biodiversity (McKindsey *et al.*, 2011; Pickett *et al.*, 1997). Furthermore, the longlines and rafts themselves also provide refuge and shelter for many small organisms, further increasing the local biodiversity (McKindsey *et al.*, 2011; Pickett *et al.*, 1997; Ysebaert *et al.*, 2009).

## 5.3 Oysters

The cultivation of both the Pacific oyster (*Magallana gigas*) and European flat oyster (*Ostrea edulis*) have the potential to contribute to nature enrichment. As oysters filter feed on organic matter and algae (Animal +1, 2019), oysters may reduce the effects of algal blooms (Kellogg *et al.*, 2014; Newel *et al.*, 2007). This is done through two different pathways (Figure 29). Firstly, by eating the algae and therefore directly reducing the algae biomass that may build up, and secondly, by reducing nutrient availability for algae to grow on (Carmichael *et al.*, 2012; Kellogg *et al.*, 2014). When eating the algae, nitrogen, an important nutrient for algal blooms, is taken up by the oysters. A part of this nitrogen is expelled into the environment as nutrients for algae and seaweed, but the remaining part is assimilated in oyster tissue and shells (Carmichael *et al.*, 2012; Kellogg *et al.*, 2014). In wild populations, the shells may act as a long-lasting sink of nutrients, as the shells remain after the oyster dies and consequently reduces the amount of nutrients available for algae (Carmichael *et al.*, 2012; Kellogg *et al.,* 2014). In aquaculture, the oysters are regularly harvested, which also removes the accumulated nutrients, resulting in a similar nutrient sink effect (Kellogg *et al.,* 2014). An additional effect of the filtration by oysters, is the reduction in turbidity (Grabowski & Peterson, 2007; Kellogg *et al.*, 2014; Newell *et al.*, 2007), which enhances the light availability for seaweed. This light availability allows seaweed to grow and provide their own nature values, as further described in section 5.4.

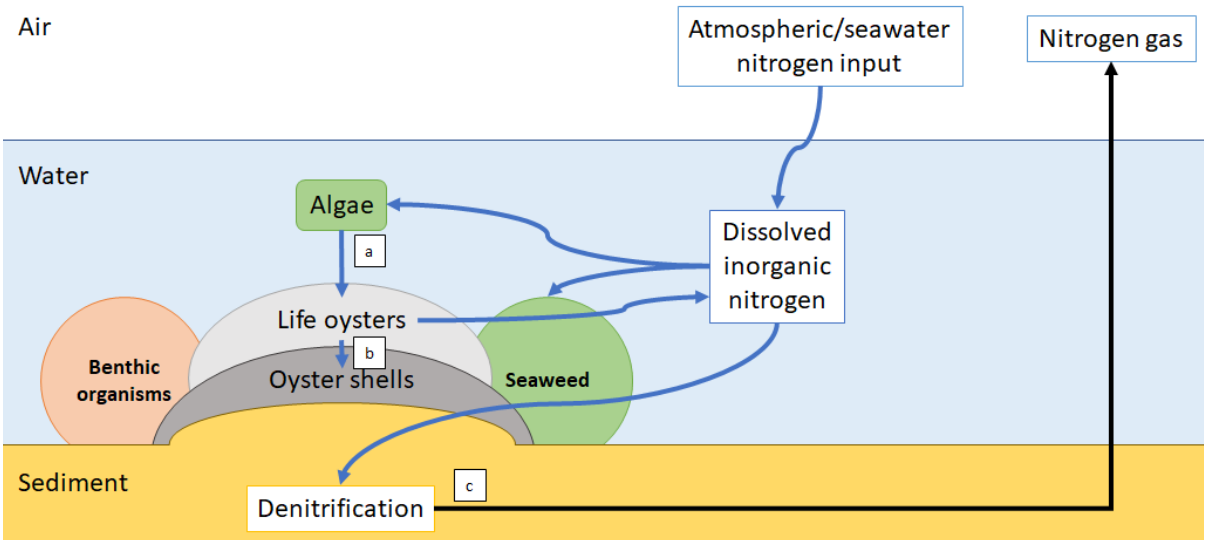


*Figure 29: Simplified schematic drawing of nitrogen fluxes (arrows) around oyster reefs. Notice that oysters consume algae (a) and shells form a permanent nitrogen sink (b), and that denitrification (c) removes nitrogen from the water and is facilitated by oyster reefs. Based on Figure 1 in Kellogg et al. (2014), p. 157.*

Besides filtering the water, oysters are also reef builders, especially the Pacific oyster (Gercken & Schmidt, 2014). Their shells form hard substrate for sessile organisms to grow on, like plants and shellfish, including other oysters (Gercken & Schmidt, 2014; Grabowski & Peterson, 2007; Smaal *et al.*, 2015). As shell layer upon shell layer grows, oyster reefs form complex three-dimensional (3D) structures with holes and cavities. These cavities are used by benthic organisms to hide from predators (Gercken & Schmidt, 2014; Grabowski & Peterson, 2007; Smaal *et al.*, 2015). As oysters filter the water column, they excrete waste products. These waste products provide food for the benthic life on the reefs (Gercken & Schmidt, 2014; Grabowski & Peterson, 2007; Smaal *et al.*, 2015). This transfer from nutrients from the water column to the benthos is called benthic-pelagic coupling and is an important ecological feature of filter feeders (Dame *et al.*, 1980). The benthic life that comes to the reefs due to the benthic-pelagic coupling attracts pelagic predators, like fish, that predate on the benthic life. The oyster reef also locally stabilises the sea bottom, preventing sediment of washing away with the currents or rocks to be eroded by wave action (Gercken & Schmidt, 2014; Grabowski & Peterson, 2007). Due to this stabilisation of the sediment and the formation of 3D-structures, the oyster reef also changes the oxygen content of underlying sediment, which facilitates denitrification (Figure 29) (Grabowski & Peterson, 2007; Kellogg *et al.*, 2014). Denitrification is a series of reactions performed by bacteria, in which nitrogen from ammonia is eventually converted to nitrogen gas. Explaining how these oxygen gradients form and how nitrogen gets converted is beyond the scope of this paragraph, but denitrification by oyster reefs lowers the nitrogen availability for algae, and may consequently result in a decrease in algal blooms and seaweed growth (Grabowski & Peterson, 2007; Kellogg *et al.*, 2014). However, due to the daily refreshment of water in the ESL, it is assumed that denitrification will have little effect on the nitrogen availability for algae and seaweed.

### 5.3.1 Cultivation types

The advantages of oysters to nature values, as described above, require certain conditions to be met. The different cultivation types suitable for the ESL, as identified in Chapter 3, each have their own characteristics, which may or may not meet the requirements for the oyster cultivation advantages. Note that not all nature value increasing properties are desired in commercialised oyster aquaculture. An example is competition for space and food with other sessile organisms that may settle on and between the oysters.

*On-bottom cultivation:*

What differentiates on-bottom cultivation from the other cultivation types, is its direct connection to the sea floor. This allows the potential for reef building (Forrest *et al.*, 2009) and denitrification (Kellogg *et al.*, 2014). The reef may attract other organisms through benthic-pelagic coupling and increase the biodiversity of the ESL (Forrest *et al.*, 2009). However, due to the cultures laying on the floor, the risk of benthic predators, like the crabs and snails mentioned in Chapter 3, may threaten the cultivation (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). Additionally, as the culture is placed in the intertidal zone, predation by seabirds during low tide may also threaten the cultivation (Cadeé, 2001; Cadeé, 2008), while simultaneously increasing the biodiversity around the ESL by attracting birds. Protective nets and fences over the oyster beds are assumed to reduce the ability of other organisms to settle on the reef and hide in the cavities, reducing the biodiversity advantages of cultivation without protection. Additionally, due to the lack of light during high water, plants are assumed not to grow on the reef, as described in Chapter 2. The harvest of oysters may also disrupt the oyster reef as part of the reef is destroyed (Forrest *et al.*, 2007). This may especially be true for trawling harvest (Gercken & Schmidt, 2014; Smaal *et al.*, 2015), as trawling pulls chains through the reef, damaging oysters.

*Table cultivation:*

Unlike on-bottom cultivation, table cultures are suspended above the sea floor. This takes away some of the reef forming advantages, like denitrification (Kellogg *et al.*, 2014), but may reduce the risks of benthic predators (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020). Still, reef formation will take place and this reef will attract other sessile organisms that need a hard substrate to attach themselves to (Forrest *et al.*, 2007). However, harvesting the tables does completely remove the reefs, meaning it has to reform from sketch after every harvest (Chapter 3). As the table cultivations do not move with rising water levels, plants are not likely to be able to settle on the oyster due to the lower light availability in the depths of the lake (Chapter 2). Additionally, just like on-bottom cultivation, the table cultures will be exposed to and attract bird predation (Cadeé, 2001; Cadeé, 2008), lowering the oyster production, but raising the biodiversity around the lake.

*Longline & raft cultivation:*

Longline and raft cultures are unique in that they move with the water level. This allows the oysters to always be close to the algae producing upper layers of the lake. Although no specific literature was found to confirm or deny this statement, it is assumed that as the oysters are closer to the algae producing layers, more algae are available for filtration. This may increase food availability for the oysters and reduce the effects of algae blooms more so than in cultivation near the bottom. The rafts, buoys and line anchors on the bottom may present structures for organisms to hide or attach themselves to (Forrest *et al.*, 2007). However, the rafts and buoys in raft cultures do cause shading, which reduces seaweed and algal growth (Forrest *et al.*, 2007). This will lower the primary production, as described in Chapter 2, but will also have negative consequences for seaweed cultivation near the rafts. The advantages of reef formation and the potential to form reefs is assumed to be lower for longline and raft culture, compared to the other cultivation types. Besides the reduced plant growth due to shading, the accessibility of the reef for benthic life is assumed to be an issue, as the oysters are suspended above the sea floor, where benthic animals may not be able to reach them.

### 5.3.2 Special mention European flat oyster

As described in Chapter 3, the European flat oyster is native to the North Sea and the Dutch coast (Gercken & Schmidt, 2014; Smaal *et al.*, 2015). Increasing fishing efforts in the 19$^{th}$ century lead to overexploitation, which resulted in a massive decline of wild stocks throughout Europe (Gercken & Schmidt, 2014; Smaal *et al.*, 2015). The following century, the European flat oyster was plagued by mass extinction events, like cold winters (Gercken & Schmidt, 2014; Smaal *et al.*, 2015) and diseases caused by the parasitic protozoans *Matreilla regringens* (Berthe *et al.*, 2014 in Smaal *et al.*, 2015) and *Bonamia ostrea* (Engelsma *et al.*, 2014).

As a response to the near extinction of the European flat oyster in the North Sea, several European governments, including the Dutch (Smaal *et al.*, 2015) and German (Gercken & Schmidt, 2014) governments, and nature organisations like the World Wildlife Fund (WWF) and ARK Natuurontwikkeling (Didderen *et al.*, 2019; Sas *et al.*, 2019) have set out to restore European flat oyster reefs. One of these restoration sites in the Netherlands is in the Voordelta (Sas *et al.*, 2019).

There are European flat oyster populations in the Grevelingen, and in smaller numbers also in the Oosterschelde and Westerschelde (Smaal *et al.*, 2015). However, restoration in the North Sea is a slow process due to the lack of available undisturbed hard substrates (Gercken & Schmidt, 2014; Smaal *et al.*, 2015) and the small dispersion distance of the oyster larvae (Jackson, 2007 in Smaal *et al.*, 2015).

With the location of the ESL in-between the restoration site of the Voordelta and the established population in the Dutch delta, nature value might be created by furnishing the ESL to facilitate European flat oyster reefs. The lake might form a bridge for genetic exchange and larvae settling between the delta populations and the North Sea restoration sites, and a small-scale non-destructive harvest might be realised.

## 5.4 Seaweed

Seaweeds provide habitat and are a food source for many small aquatic organisms, such as isopods, that are important for ecosystem functioning due to their position at the base of the food-web (Wernberg *et al.*, 2013). Isopod densities differ for different types of seaweed habitats, Wernberg *et al.* (2013) found that isopod densities per seaweed biomass are highest for seaweeds that have a simple structure, like *Ulva* species. Looking at biodiversity in a broader sense, especially kelp is known to support high numbers of other species. Kelp is an ecosystem engineer that creates a structure for other plants and animals to grow on, and it creates an own microclimate that adds to the diversity of habitats in an area (Morris *et al.*, 2020; Rolin *et al.*, 2016; Teagle *et al.*, 2017). One of the seaweed species that can grow onto the structure provided by finger kelp (*Laminaria digitata*) is dulse (*Palmira palmata)* (Van den Bogaart *et al.*, 2019).

Seaweeds produce oxygen during the day, and remove ammonia and nitrate from seawater, thereby increasing the water quality (Brito *et al.*, 2014; Gao *et al.,* 2018; Neori *et al.,* 1996). The removal of nitrogen compounds limits eutrophication and, thereby, also reduces the chance of harmful algal blooms (HABs). The presence of seaweeds also increases the competition for light, which restricts the abundance of phytoplankton (Campbell *et al.*, 2019). Furthermore, seaweeds remove heavy metals from the water, which is beneficial for the water quality. This can, however, be an issue for human health, depending on the production purpose of the seaweeds (Van den Burg *et al.*, 2018; OSPAR Commission, 2017b). Oxygenation of the water is a result of carbon dioxide assimilation. Especially *Ulva* species capture high levels of carbon dioxide due to their high growth rates and relatively long turnover time. On the short term, a combination of higher temperatures, lower pH, and more nutrients results in more *Ulva* biomass production and thus more carbon capture, which is interesting in light of mitigating climate change. It is, however, uncertain how the growth rate of *Ulva* species is affected by continued climate change (Gao *et al.,* 2018).

### 5.4.1 Nature values of cultivation

A general benefit of seaweed cultivation is that it can aid in reducing the pressure of (over)-harvesting on wild seaweed populations (Grote, 2019; Rolin *et al.*, 2016). According to Mac Monagail *et al.* (2017), annually, over 800.000 tons of seaweed is harvested from wild populations worldwide. In order to make seaweed cultivation more sustainable and enhance the nature values that are associated with the cultivation, there is a need for ecological intensification (Grote, 2019). Ecological intensification means that external inputs are reduced, nutrients and water are recycled, and biological interactions are strengthened (Grote, 2019).

A nature related risk of aquaculture is the loss of genetic diversity (Van den Burg *et al.*, 2018; Cottier-Cook *et al.*, 2016). Using seaweeds from populations in other countries or regions, which could be done for the higher productivity of those genetic variants, can be at the expense of local genetic diversity (Campbell *et al.*, 2019; Seaweed expert Wageningen University & Research, personal communication, 2020; Van den Burg *et al.*, 2018). A loss of local genetic diversity can cause the seaweeds to become more susceptible to diseases, which can be a major issue in seaweed cultivation with large ecological impacts (Campbell *et al.*, 2019).

*Longline cultivation*

Longline cultivation, in particular with horizontal longlines, is the most feasible cultivation type for finger kelp, sugar kelp *(Saccharina latissima),* sea lettuce (*Ulva lactuca*) and dulse. The cultivation of finger kelp and sugar kelp contributes towards the biodiversity of the ecosystem in the ESL, because it creates habitat for other species to grow. Kelp cultures in the ESL will probably have to be harvested yearly due to the summer temperatures in the Netherlands and this will cause a huge disturbance within the ecosystem of the ESL. Cultivation of sea lettuce is beneficial due to its carbon storage capacity. In Australia and multiple countries across Asia, the capture of carbon dioxide by commercial seaweed aquaculture is seen as a potential for mitigating the levels of carbon dioxide (Sondak *et al.*, 2017). Furthermore, as mentioned above, sea lettuce enhances biodiversity through the high density of isopods that are generally associated with *Ulva* species. As mentioned in Chapter 3, dulse is a good candidate for integrated multi-trophic aquaculture (IMTA). IMTA systems aim for sustainability and are a method for ecological intensification (Grote, 2019).

*Combination cultivation: seasonal*

As concluded in Chapter 3, the best combination cultivation in the ESL is the seasonal cultivation of seaweeds. A benefit of year-round seaweed cultivation (e.g. sugar kelp during the winter and sea lettuce during summer (Pors-Schot, 2016)) is that positive effects of seaweeds on the water quality and the carbon storage also continue year-round.

*Special mention on-bottom cultivation*

Real on-bottom cultivation of seaweeds does not exist, because these practices only include the harvesting of wild populations and not the actual cultivation, and therefore it was also not included in Chapter 3. Still, on-bottom seaweed attracts many other organisms and, therefore, has a value in enhancing the biodiversity of an area (Barbier *et al.*, 2019). A species that can grow on-bottom is finger kelp. If the conditions are right (enough light and hard-substrate to grow on) finger kelp could grow on-bottom in the ESL. However, this is unlikely, because temperature and light availability are expected to be limiting at the bottom of the ESL.

## 5.5 Carrying capacity of the system

The ecological definition of the carrying capacity of a system can be explained as the ability of an ecosystem to sustain a population of organisms or to produce a certain number of products (e.g. shellfish) (Van Duren, 2011). Gibbs (2009) defined this distinction as the effects on production and ecological capacity. Production capacity examines the cultivation employing quantitative and qualitative measurements to the yields of the cultivated product. Ecological capacity discusses the significant effects aquaculture has on the entire ecosystem, looking at, among others, processes and species. Finally, the balancing of the whole system in the form of a food web is discussed.

### 5.5.1 Production capacity

Policymakers typically focus on the higher trophic levels when setting standards for carrying capacity (van Duren, 2011). Therefore, the ecological capacity focuses on birds because they are higher in the food chain. This choice is made because the carrying capacity of one species can be at the expense of another species (Kamermans *et al.*, 2014).

The ESL located in the Voordelta is designated as a Natura2000-area, which means that it is mandatory to maintain the qualifying habitat types and associated bird species in the area (Smit *et al.*, 2011). The ESL will consist of the habitat types H1110, Permanently flooded sandbanks, and H1140, Silt and sandbanks (Swinkels *et al.*, 2020). These silt and sandbanks on the edges of the ESL can function as foraging and resting spots for birds depending on the species.

An example of an ecological capacity effect was discussed in Kamermans *et al.* (2014), where a decreasing amount of phytoplankton results in less food for certain bird species as the shellfish they feed on have fewer growth opportunities. Offering more food, on the contrary, could attract birds such as the scaup (*Aythya marila*), common eider (*Somateria mollissima*), black sea duck (*Melanitta americana*), and common goldeneye (*Bucephala clangula*) because they forage on mussels (Ministerie van Infrastructuur en Milieu & Rijkswaterstaat, 2016). In the intertidal area this can also be interesting for various waders, such as the oystercatcher (Ministerie van Infrastructuur en Milieu & Rijkswaterstaat, 2016). According to Ministerie van Infrastructuur en Milieu & Rijkswaterstaat (2016) both food availability and rest are insufficient. The ESL offers a solution in this respect because the ESL can contribute to a higher food availability. However, rest may not be guaranteed due to ships near the ESL. Plant-eating birds may also forage on the seaweed.

The distribution of fish-eating birds between 2009-2011 showed that many divers and grebes have their foraging site located close to the future Energy storage lake (Ministerie van Infrastructuur en Milieu & Rijkswaterstaat, 2016). Habitat quality for fish-eating birds is determined by the amount of fish to prey on, suitable foraging conditions in terms of sight, and resting areas. Rest is not guaranteed in the fish-rich areas at the mouth of the Haringvliet in the Voordelta (Ministerie van Infrastructuur en Milieu & Rijkswaterstaat, 2016). The red-throated diver (*Gavia stellata*) is particularly sensitive to disturbance by recreationist or ships (Ministerie van Infrastructuur en Milieu & Rijkswaterstaat, 2016). This bird has a conservation objective and therefore it might be interesting to allow fish to the ESL to attract the birds as the ESL can at times serve as a resting area due to the absence of recreation.

### 5.5.2 The system in balance

In order to successfully cultivate seaweed and shellfish, the system and the food web must be in balance. As described earlier, seaweed and shellfish are prey for a certain number of predators. In the Netherlands, the blue mussel is mainly targeted by the green shore crab (*Carcinus maenas)* and the common starfish (*Asterias rubens*). Oysters are the prey species for the green shore crab *(Carcinus maenas*), a sea snail named the Japanese oyster drill (*Ocenebra inornata*), and previously mentioned bird species. Without the natural enemies of these predators, they can grow to large numbers, making it very labour-intensive for mussel and oyster farmers to keep the predators away from their plots (Kleis, 2017). A solution could be to introduce the natural enemies of these species. The natural enemies of the green shore crab include herring gulls, European sea bass (*Dicentrarchus labrax*), and the common shrimp *(Crangon crangon*) *(*CAB International, 2008). The natural enemy of the common starfish is cod *(Gadus morhua)* (Kleis, 2017). For the Japanese oyster drill no natural enemy could be found in literature.

As described in Chapter 3, depending on the species of seaweed it is predated by small crustaceans like Isopoda (sea lettuce), predated by sea urchins (kelp) or grazed by fish (dulse) (Reith *et al.*, 2005). In the Netherlands kelp is mainly predated by the green sea urchin (*Psammechinus miliaris*) (Stichting Anemoon, 2020). According to Cook *et al.* (1998) the green sea urchin predates on sugar kelp although the softer green algae sea lettuce can be an important nutrient source when small. The sea urchin can be predated by, among others, starfish, crabs and birds such as herring gulls and oystercatchers (Jackson, 2008). The nutrients that these grazers release can be absorbed by the seaweed, forming a food circle (Reith *et al.*, 2005).

By looking at the entire food web an idea is formed of which species predates on which. Adding these species to the system creates a more complex food web, which makes the system more resilient. A resilient system means that when one species dies from disease or predation, another species can take over the niche. In ecological terms, niche refers to the functional role an organism fulfils within a community.

## 5.6 Conclusion

The sub-question addressed in this chapter was: “Which of these aquaculture types has potential for nature enrichment, regarding water quality and biodiversity?”. This is discussed per species followed by the elaboration on the capacity of the system.

Mussels largely contribute to nature enrichment through their filtering capacity and habitat facilitation on the benthic floor. Filtering detritus, dead organic material, sediments, pollutants, and pathogens out of the system increases the water quality. Furthermore, as mussels filter components out of the water, a part of the filtered components will be deposited as faeces or pseudofaeces. This process stimulates the sedimentation of nutrients and increases the amount of nutrients on the benthic floor. This is expected to have a positive effect on the biodiversity. However, if too much is deposited, opportunistic species may grow faster than other species and start to dominate the benthic, counteracting the mediation of biodiversity.

All mussel cultivation types facilitate habitat by providing shelter and hard substrate for other organisms. On-bottom and bouchot culture in specific stabilize the substrate due to sedimentation trapping, providing coastal and seafloor protection. Furthermore, mussels are an important organism within the food web, providing food for many organisms in both larval and adult life stages. As development from mussel beds into reef takes years, harvesting yearly has devastating consequences for the local environment.

Oyster aquaculture has the potential to create nature value in the ESL by filtering water and forming oyster reefs. By filtering the water for food, they may reduce the effects of algae blooms and reduce turbidity. While reef forming provides hard substrates for sessile organisms to attach themselves to and provides cavities for benthic organisms to hide in.

Each of the different cultivation types has its advantages and disadvantages in terms of aquaculture production and nature value. On-bottom culture is expected to enhance nature by having the largest potential to form a lasting reef that is accessible for all benthic life. The disadvantage of on-bottom aquaculture regarding production is the relatively high risk of predation. The alternatives, table culture and especially longline or raft cultures, are expected to reduce the predation risk, but coincidentally also reduce the biodiversity on the reef.

Regardless of cultivation type, harvesting the oysters will result in damage to the reef. In this, on-bottom cultures may sustain the least damage of harvesting, as the oysters are removed by hand and substrate like shells might be left behind. In the other cultivation types, the entire reef is removed during harvest, as the oysters grow directly on the harvested tables and ropes.

The nature values of seaweeds lie within the biodiversity that they support by creating habitat for many other marine organisms. Especially kelp supports high numbers of other species. Furthermore, seaweeds contribute to water quality through oxygenation and by removing nitrogen compounds. Also, they have an environmental value due to their potential for carbon storage. Especially sea lettuce stores high levels of carbon. Longline cultivation is the most feasible cultivation type for seaweeds in the ESL and the general nature values mentioned above are also valid under this cultivation type. On-bottom cultivation in the ESL does not provide perspective for production purposes, due to the absence of real on-bottom cultivation practices in general and the lack of suitable habitat in the ESL. However, the potential nature values of on-bottom seaweed are high as it enhances the biodiversity of an area.

From the capacity of the system, it is important to see whether the introduction of aquaculture has no influence on the surrounding environment by extracting too many nutrients. The system is assumed to be sufficient based on the chlorophyll- α content and water current for mussels. In addition, the relationship between picoplankton and mesoplankton, as well as the meat weight of the mussel, can be used to monitor the carrying capacity during a later stadium. There are still too many uncertainties regarding seaweed to make a good statement about the maximum carrying capacity expressed in available space.

The ESL can offer a solution to many birds that are important to the Voordelta by offering food. In addition, an overview of the whole food web could help in getting insight in the predator-prey relationships in the ESL. This could be used in preventing predation on the culture. It is also interesting to apply many forms of aquaculture to increase the resilience of the system.

# Chapter 6: Reflection on methods

In this chapter, a reflection will be given on the methods used throughout the project putting it in a broader perspective. Assumptions and constraints influencing the entire project will also be discussed. Furthermore, some recommendations for future research are given throughout this chapter.

In this project, mostly scientific literature research has been used to gather answers for all research sub-questions, complemented with expert interviews and information obtained from official reports and datasets from Delta21, Deltares, Dutch Water Authorities (DWA), Food and Agriculture Organization (FAO), STOWA, and the Water Framework Directive (WFD). The ethical principles according to interviews and scientific research raised in the introduction of this project have been adhered to, and the perception of the researchers towards these ethical principles have not changed during this project.

Literature research has proven to be effective in providing a solid scientific base for the team in order to critically assess the different sub-questions. However, there have been several gaps in knowledge and limitations in the scientific literature that made it hard to provide exact answers to questions raised during this project. This was specifically the case for literature according to the Dutch part of the North Sea since not many reports have recently been published that proved to be useful for this project. Additionally, measurement data of DWA proved to be outdated for several chemical conditions in the project area, as well as the geographical locations of the DWA measurement points not being ideally located near the Delta21 project area. Therefore, gaps in knowledge on specific expected conditions in the Energy Storage Lake (ESL) emphasized in Chapter 2, were sometimes unable to be overcome.

Furthermore, there have been several situations during this project where literature research was inadequate, and where modelling could have generated results that would be more accurate than calculations that have been made by the authors. This has been especially the case for the flow rates in the ESL impacted by the pumping activity, wind conditions, and other factors affecting the flow rate. As well as for the time of drought exposure, stratification, turbidity, the impact of the solar park on the ecology in the ESL through a decrease of sunlight in the water, and in general the placement of different cultivation types for different species and the floating solar park in the ESL. The calculations that have been made by the authors without modelling capacity, are made under rough assumptions. Additionally, the assumption has been made that the pumps in the ESL always work at full power. If this assumption is incorrect, the calculations should be made again. The calculations that have been made influence the outcomes of Chapter 2 and therefore influence the outcomes of the other chapters as well. To conclude, due to time restrictions for this project, it was not possible to model the important variables mentioned, which led to broader assumptions and more uncertainty throughout the project.

- It is recommended to invest time in modelling capacity to be able to get a better understanding of the exact conditions in the ESL and reduce uncertainty according to the implementation of aquaculture.

Furthermore, in Chapter 2 certain risks are described that require research methods that are beyond the available resources for this project, and therefore it was not possible to set accurate predictions for these risks within this project. However, the effects of these risks could have a large impact on the conditions in the ESL, and thereby alter the success of aquaculture in the ESL.

- It is recommended to investigate the precise impact on the ESL of the risks of stratification, freshwater influx during high water, harmful algal blooms, and a higher secondary release of pollutants, such as heavy metals.

Another research method that has been used in this project is expert interviews to gather in-depth practical and technical knowledge on several important topics, such as cultivation of the different species and the floating solar park. Firstly, it is important to note that in the methodology suggested in the proposal of this project, there was the intention to have expert interviews with nature organisations. However, due to time restrictions and hindrance in accessibility resulting from the coronavirus, no expert interviews with nature organisations have taken place during this project, despite widespread attempts of arranging appointments.

- It is recommended to gather in-depth information from nature organisations according to the nature values that can be generated from the ESL, since the Delta21 project location is within Natura2000 area.

Furthermore, in this project, only a small number of interviews have been conducted. It was not necessary to conduct many interviews since the interviewees were people that have a certain expertise in the topics that this project touches upon, and the answers, and therefore data, rely not solely on the opinion of the interviewees. However, for this project, only one interviewee per cultivation sector has been interviewed, which could in the end give this project a deficient scope of the total situation and could lead to relying on a base of short-sighted argumentation. In addition, the commissioner has been present at several interviews, which could have influenced the interviewees to a certain extent and lead to socially desirable answers to the questions asked. To conclude, it must be taken in to account that answers to the interview questions are never objective and are influenced by the background and possible interests of the interviewees. For instance, the interview with Seaweed Harvest Holland, one of the few companies in the pioneering stage of seaweed cultivation in the Netherlands, which could possibly experience this project as competitive to its interests. Consequently, this could possibly have led to the adoption of information that is biased or incomplete, influencing the outcomes of this project.

- It is recommended to conduct interviews with several interviewees per sector to gather data that is as unbiased as possible.

Since seaweed cultivation is currently in a pioneering phase in the Netherlands, data and literature on seaweed cultivation in the Netherlands were lacking during this project, interviews with different experts resulted in contradicting answers. Therefore, broader scientific literature and data acquired in other European countries, with sometimes different physical and chemical conditions in the growth area, have been used in order to develop a hypothesis on the possible seaweed species and cultivation types that can be used in the ESL.

This project was based on an already outdated layout for the ESL. In the new layout, presented during the timespan of this project, the pumps will be closer to the outlet of Haringvliet, so more fresh and nutrient-rich water will enter the lake. The numbers named in the conclusion of Chapter 4 regarding the hectares of possible aquaculture, might change due to new dimensions of the lake. It is also written that these surfaces represent ideal situations. This should be researched further to give a more realistic view of the possible cultivation areas.

- It is recommended to perform calculations regarding physical and chemical conditions are revised to check the feasibility of aquaculture in the new ESL layout, and include a more realistic view on the hectares that can be used for aquaculture by, for example, finding a balance between resource depletion and aquaculture production.

The best way to make predictions about the resource availability is to monitor the most important physical and chemical conditions closely when the ESL is constructed, whilst modelling future situations, before instating aquaculture grounds or a floating solar park.

- It is recommended to have a period of intensive monitoring of physical and chemical conditions when the ESL is finished, to check if the calculated conditions match expected conditions, before building aquaculture structures or a floating solar park.

# Chapter 7: Challenges and chances

In this chapter, the results of the previous chapters will be critically discussed in order to outline possible challenges and chances for aquaculture and nature enhancement in combination with a floating solar park, within the Energy Storage Lake (ESL). This will provide the commissioner with an overview of the significance of the findings gathered in this project, as well as advance the commissioner's understanding of the research problem addressed in this project. This chapter will first discuss the challenges and changes regarding the resources and technical matters within the ESL, followed by a discussion on the implementation of aquaculture, and ends with the challenges and chances for nature values. Some recommendations for future research are also included in this chapter.

## 7.1 Resources and technical matters

One of the challenges regarding the technical aspects is the difficulty to find a value for the fluctuations in the ESL. This is apparent from a report by Wageningen Marine Research (WMR) describing the origin of nutrients in the North Sea, together with the limiting nutrients. From this WMR report, it turns out that the ratio between the chemical elements carbon, nitrogen, and phosphorous is more important than the exact amounts. It is also written that the preferred nutrient ratios are depending on the (cultivated) species, the location, and other environmental factors such as mechanical load (Van den Bogaart *et al.*, 2020). The exact ratio that might occur in the ESL is dependent on the water that flows in via the pumps. In this project, the used values come from the area around the location of the future ESL. It is difficult to calculate the depletion of resources especially within the restricted time for the project, making it impossible to get a realistic view of the future resource fluctuations in the ESL.

The nutrient content of the ESL also offers a chance. In interviews with the Nederlandse Oestervereniging, PO Mosselcultuur, and Seaweed Harvest Holland (personal communication, 2020), it became apparent that the ESL is most likely large enough to not run out of nutrients for shellfish and seaweed culture.

- It is recommended to check this assumption, which was based on information from the Nederlandse Oestervereniging, PO Mosselcultuur, and Seaweed Harvest Holland (personal communication, 2020), and calculate the fluctuations in resources. This can be done by modelling the expected change in nutrients based on the amount of cultures present in the lake.

Freshwater influx into the ESL poses another challenge for the ESL. It was found that, since the pumps are pumping for 12 hours straight and are not pumping with the tide, it could happen that a large part of these 12 hours, relatively fresh water will be pumped in the lake. This fresh water arrives with ebb tide, when fresh water reaches further in the North Sea see paragraph 2.3.1. The effects of pumping fresh water of sometimes only 5 psu in the ESL will have consequences for the aquaculture practices in the lake. It is shown that shellfish generally require a salinity of 10-40 psu (Animal+1, 2019; Héral & Deslous-Paoli, 1991; Smaal *et al.*, 2017; Zitoun *et al.*, 2019), and sugar kelp (*Saccharina latissima*) and finger kelp (*Laminaria digitata*) require a salinity of 15-35 psu (Kerrison *et al.*, 2015). It has also been shown that a salinity content between 15-25 psu will reduce the growth of finger kelp, and a salinity below 10 psu will result in sugar kelp mortality (Kerrison *et al.*, 2015; Seaweed expert Wageningen University & Research, personal communication, 2020). This, together with the above information on pumping in fresh water, will most likely have a decreasing effect on aquaculture production.

Fresh water influx also provides a chance for shellfish cultivation. Temporary reducing the salinity can help reduce the predation risk from starfish. One of the techniques currently used in order to reduce predation by starfish is by temporarily flooding the culture with freshwater. Thus, temporary lower salinity levels will likely prevent starfish from predating on the cultures in the ESL.

As mentioned before, changes to the layout of the ESL have been made during this project. The location of the pumps has been moved closer to the mouth of the Haringvliet. This could increase the total amount of freshwater intake, but also the nutrients available within the ESL (Seaweed Harvest Holland, personal communication, 2020). This is likely to impact aquaculture within the lake.

- It is recommended to research the possible change in nutrient content and freshwater intake due to the changed location of the pumps in the ESL in order to determine the conditions when the lake has been completed.

Regarding the physical conditions, it was decided that the slopes of the lake will have sand, and the bottom of the lake will have fine sand with silt/peat soil. The challenge here lies in the movement of sediment: both types of ground cover will resuspend around the pumps where the flow rate is around 1.3 m/s and will only be deposited in the back of the lake. This means that the silt/peat soil with fine sand must be replenished or dredged after a while, to make sure the ground cover remains optimal for natural bottom cultures.

- It is recommended that research is done regarding movements of the sediment and the frequency of dredging, which should be kept to a minimum for nature development.

The resuspension of particles influences the turbidity and thus the amount of light in the water. Resuspension can occur with higher flow rates, but also with wave action. Van Emmerink (2019) describes a chance for this project: the dampening effect of a solar park on the wave activity, resulting in less resuspension and clearer water with a deeper light penetration. However, a challenge is that lower wave action might result in a higher risk for stratification, because there is less mixing. Due to time constraints, it was decided to not further research this.

- It is recommended to research the chances of the solar park lowering the wave action, which might result in clearer water with more light. Next to this, it is important to research the challenge of a higher risk of stratification.

The estimated flow rates within the lake are used largely in order to determine suitable locations for aquaculture within the lake. However, it is possible that the solar park and hanging cultures will influence the flow rate because they form obstructions within the water column. This impact on flow rates was not taken into account due to the time constraints.

- It is recommended to research the impact of obstructions caused by aquaculture and the floating solar park on the flow rates in the ESL. Suitable locations for aquaculture can be determined more accurately when all the parameters of the lake are fully understood and mapped out.

It is not likely that the ESL will finish construction within the next few years, but innovation within the aquaculture and solar energy sector will continue. As a result, new methods and techniques could have been developed that might work better than methods and techniques studied in this project. Implementing new methods could also have different constraints than current methods.

- It is recommended that research is done regarding new methods of aquaculture and innovation within the solar energy sector. This could provide insights in new possibilities and limitations.

Lastly, using rafts for aquaculture is common practice, however, using a floating solar park for hanging cultures has not been done yet. This project provides some insights into possible combinations of aquaculture and a floating solar park. The insights, however, are based on expectations and calculations with assumptions.

- Once the ESL is in place, there are chances for further research that can reveal how to master the combination of aquaculture and the floating solar park, which also provides opportunities for similar projects in other countries in the future.

## 7.2 Aquaculture

The realization of this solar park poses challenges. The floating solar park includes electricity cables that can make it challenging to harvest table cultures. Table cultures for the Pacific and European oysters are harvested by hand and if there is an electricity cable nearby this could pose a threat.

- It is recommended that while making the design of the lake it should be kept in mind that the electricity cables must not interfere with the harvest of the cultures.

Implementation of the floating solar park without combination with aquaculture is also a viable option. To give the aquaculture enough space and water velocity, the solar park should be placed further away from the pumps. The area suitable for oyster hanging cultures overlaps with the suitable area for mussel cultures, thus a decision needs to be made if the entire area is used for mussel cultivation, or if the area is split in e.g. 122 ha oyster cultivation and 153 ha of mussel cultivation.

- It is recommended that this decision is based on the commissioners needs and market value, for which more research on economic value and potential yield is necessary.

This project focuses only on whether the implementation of aquaculture is biologically possible. In the Netherlands, the aquaculture sector is still young but has many potentials. However, due to the variable production in oyster and mussels (Nederlandse Oestervereniging & PO Mosselcultuur, personal communication, 2020) no concrete statements can be made about the expected production. Nor can any concrete statement be made about the expected production of seaweed. Based on the calculations, statements have been made about the suitable cultivation area for aquaculture in ha. The sales values were not discussed due to uncertainties about expected production and therefore the turnover. These uncertainties and start-up costs can make it difficult to start an aquaculture company because it is not known whether it will pay for itself and how long it will take.

- It is recommended to not only look at the rental or selling prices per hectare, but to also make an estimation of the yield for aquaculture companies. When this yield is more certain, for example due to low predation or high nutrients, the companies are more likely to work in the ESL.

In the cultivation of various edible organisms, both in water and on land, it is possible to use triploid organisms (Nell, 2002; Piferrer *et al.*, 2009). Normal organisms (diploid) have a set of two chromosomes, while in triploid organisms, a third of each chromosome is added (Nell, 2002; Piferrer *et al.*, 2009). Triploidisation can be induced through a variety of methods, of which some are chemical exposure, genetic manipulation or specific breeding (Nell, 2002; Piferrer *et al.*, 2009). For the Pacific oyster, triploid variants are available (Nell, 2002; Piferrer *et al.*, 2009). By 2009, the European production of Pacific oyster consists for 20% of triploid variants and in the United States of America this was 50% (Piferrer *et al.*, 2009).

The advantages of triploid Pacific oyster (*Magallana gigas*) are that they are theoretically sterile and therefore do not 'waste' energy on reproduction. Instead, this energy is used to produce more body mass or grow faster (Nell, 2002; Piferrer *et al.*, 2009). This means that triploid Pacific oysters spat must be obtained from specific hatcheries (Piferrer *et al.*, 2009), but the chances for the ESL are that these triploid oysters are less likely to crossbreed with wild populations (Piferrer *et al.*, 2009). Some of the challenges are an increased mortality among juveniles (Nell, 2002; Piferrer *et al.*, 2009) and more abnormalities in shape (Nell, 2002; Piferrer *et al.*, 2009). Also, the acceptance of triploid organisms as food is, especially in Europe, limited due to its genetically altered nature (Nell, 2002; Piferrer *et al.*, 2009). Also, it is assumed that there are specific Dutch legislations that limit the use of triploid organisms in Dutch aquaculture for human food production. Triploidy has also been observed in the European flat oyster (*Ostrea edulis*) (Nell, 2002) and blue mussel (*Mytilus edulis*)(Piferrer *et al.*, 2009), but no commercial markets have been established for these species.

- ➢ It is recommended that it is researched whether a market for Dutch triploid Pacific oyster exists or can be created, as well as the state of Dutch legislation on the aquaculture of triploid species for human consumption.

Chapter 3 briefly mentioned that there is discussion about whether dulse (*Palmaria palmata*) is native to the Netherlands. The legal status of dulse is 1b, which means that it occurs periodically in the Netherlands with less than 10 years of successive reproduction (Naturalis, 2018). Although dulse is native to the North Sea it is not native to the Netherlands (Seaweed expert Wageningen University & Research, personal communication, 2020).

Seaweed cultivation in the Netherlands is still new, which means that the regulations are not yet clear and, moreover, are developing (Seaweed expert Wageningen University & Research, personal communication, 2020). There is still no concrete statement on the definition of exotic species. The general rules state that exotic species may not be cultivated (Seaweed expert Wageningen University & Research, personal communication, 2020). Cultivation of dulse is therefore permitted until the regulations change or dulse is seen as an exotic species and therefore banned.

- ➢ It is recommended to follow developments regarding the regulations on cultivating dulse.

Dulse is discussed here even though Chapters 3 and 4 showed that dulse and sea lettuce (*Ulva* lactuca) cannot be cultivated in the ESL due to their flow rate range. It is very difficult to find flow rates for seaweed and therefore flow rates are based on limited sources. Especially the flow rates of dulse and sea lettuce are questionable. The maximum flow rate for sea lettuce, for example, was assumed to be 0.05 m/s (Seaweed expert Wageningen University & Research, personal communication, 2020), however, it is cultivated in the Jacobahaven in the Oosterschelde, the Netherlands (Pors-Schot, 2016). The flow rate here is assumed to be higher than the 0.05 m/s used as a safe value in this project.

- ➢ It is recommended to further investigate the suitable flow rates for dulse and sea lettuce if these species are of interest.

For mussels and oysters, no exact times for exposure to drought could be found. The drought exposure tolerance for oysters was assumed to be five hours, however, spring tide in combination with wind regularly ensures longer periods of drying than five hours (Seaweed expert Wageningen University & Research, personal communication, 2020). If this were the case, bottom or table culture could occur in more places in the ESL because the oysters could lie dry longer than the safe value that has now been assumed.

- It is recommended to investigate the drought exposure tolerance of mussels and oysters to potentially cultivate in a larger area of the ESL.

## 7.3 Nature values

### 7.3.1 Mussels

Mussels have a great potential to enrich nature due to its filtering capacity as discussed in chapter 5. However, in the study of Rodhouse and Rodon (1987), they predicted that a decrease in production yield and significant modifications of the local environment are the result of mussels capturing more than 50% of the primary production out of the system. The influence of this feedback depends on water velocity, filtering capacity of the population, the size of the water column, and the influx of new oceanic water. The depletion of primary production due to mussel filtration becomes especially important at low proportions of primary production. Mussels can survive a prolonged period of low food availability whereas this is not always the case for other benthic organisms. Thus, at low food availability mussels dominate the benthic food chain reducing biodiversity. Furthermore, having this filtering capacity causes nutrient deposition on the benthic floor. The effects this has on the environment are still debated on. In the study of Grant *et al.* (1995), they showed that ammonium efflux of the sediment, often associated with toxic algal blooms, is higher near dense mussel cultures. However, this efflux seems rather small when looking at the nutrient cycle over a lager spatial area (Inglis *et al.,* 2000).

In addition, the filtering capacity of oysters for algae and organic matter in both natural and anthropogenic environments, is a hotly debated topic with supporters and opponents (Carmichael *et al.*, 2012; Kellogg *et al.*, 2014; Newell *et al.*, 2007). Although the implementation of filters is debated, the support that they take up nitrogen en filter organic particles is substantial, and the main argument of opposition is that the studies are too inconsistent in experimental approach and study areas are too small and local (Carmichael *et al.*, 2012).

- Because of the limited size of the ESL, the effects of filtering are expected to be substantial, there are chances for further research on these effects.

Besides the filtration effects, mussels and oysters can also have an additional- or inhibiting effect on biodiversity depending on e.g. harvest techniques, water velocity, culture type, etc. When looking at on-bottom culture mussels can facilitate and/or boost the local biodiversity. However, harvesting these mussel beds can destroy the positive effects that have been build-up. This also applies for oyster on-bottom culture. On land agriculture techniques have been developed to (partly) prevent this catastrophic harvesting. Scherr & McNeely (2008) describes how to implement an eco-agriculture on land, which is an agricultural land with many different niches and where harvest for each plot is done at different times to boost biodiversity.

- Creating different niches and harvesting small plots at different times could be a chance to boost local biodiversity within the ESL. However, it has not yet been tested for aquaculture and should be done in future research.

### 7.3.2 European flat oyster

As mentioned in Chapter 5, there are European flat oyster populations in the Grevelingen, and in smaller numbers also in the Oosterschelde and Westerschelde (Smaal *et al.*, 2015), but the restoration efforts are slow. The two main challenges in European flat oyster restoration are the availability of undisturbed hard substrate (Gercken & Schmidt, 2014; Smaal *et al.*, 2015) and the small dispersion distance of the oyster larvae (Jackson, 2007 in Smaal *et al.*, 2015). The amount of hard substrate for oyster larvae to settle on is scarce in the North Sea and a part of the hard substrate that is available gets occasionally trawled by fishing ships, which destroys the early reefs (Gercken & Schmidt, 2014; Smaal *et al.*, 2015). This, combined with the short distance of 1 km that the larvae swim (Jackson, 2007 in Smaal *et al.*, 2015), greatly reduces restoration success chances (Smaal *et al.*, 2015).

The location of the ESL between the North Sea and the Dutch delta might make it ideal for restoration efforts. A successful restoration site in the ESL might create a bridge between populations in the North Sea and the Dutch delta. However, it is unclear whether this would be restoration or reintroduction of the European flat oyster, for which different legislations apply (Smaal *et al.*, 2015). Furthermore, the survivability of the larvae as they pass through the pumps should be accessed, or alternative paths in and out of the lake should be thought of. Still, as the lake is not constructed yet and furnishing of the lake is still flexible, the construction plans can still be adapted to meet restoration requirements to maximise the success chance for European flat oyster restoration (Sas *et al.*, 2019; Smaal *et al.*, 2015).

- ➢ It is recommended to investigate whether turning the ESL into a restoration site for the European flat oyster is possible or not. This could be done by investigating legislation, survivability and construction possibilities.

### 7.3.3 Heterogeneity of aquaculture species

For the general nature enrichment of the ESL it is attractive to apply as many different forms of aquaculture within the ESL. As described earlier, increasing heterogeneity of the area increases and facilitates biodiversity, thereby contributing to the resilience of the system. Creating heterogeneity within aquaculture counteracts devastating effects on diseases and predators as not all the culture is lost at once which is often observed in monocultures. However, smaller plots with different cultures decreases harvesting efficiency and increases labour intensity making it more costly.

### 7.3.4 Birds

Aquaculture in the ESL can contribute to higher food availability in the area, which poses chances to attract more birds, such as oystercatchers (*Haematopus ostralegus*) and eiders (*Somateria mollesimal*). To ensure a year-round food availability for birds it can be considered to sacrifice part of the production, instead of harvesting all cultivated mussels, oysters, or seaweed. Another option to ensure a more stable food availability would be the option suggested above, to harvest small plots at different times, as is done in eco-agriculture.

- ➢ It is recommended that for further research, increasing food availability by harvesting less should be investigated as a chance for attracting birds.

### 7.3.5 Fish as part of the ecosystem in the ESL

Regarding the ecological capacity of the ESL, it is important to consider the role of fish. This project has only slightly touched upon the topic of fish as the commissioner had indicated their preference for no fish in the ESL (Delta21, personal communication, 2020). Nevertheless, it is unlikely that fish larvae will not get into the lake by themselves. Fish larvae are small and could be transported from the Voordelta into the ESL when it is filled with seawater. This also poses a threat, as the fish are at risk of being caught in the pumps when they are bigger (Ventikos *et al.*, 1999). According to the current design of the ESL there will be a barrier at the seaside of the pumps, to prevent fish from getting in (Delta21, personal communication, 2020). However, it was not clear for us if there will also be a barrier on the lakeside of the pumps. Additionally, (exotic) fish introduction by humans has been observed in many cases in the past (Gherardi *et al.*, 2009; Lintermans, 2014; Mills *et al.*, 1994) and this could also happen in the ESL.

- It is recommended that in the design of the pumps, barriers are placed on both sides to protect fish populations on either side.

If the fish can only get in, but not out of the ESL, a challenge may occur that populations might become too large, causing a potential unbalance in the food web. If this poses a problem, it can be considered to reduce the size of the fish populations in the ESL. Nevertheless, having fish in the ESL is likely beneficial for the aquaculture, because fish, such as cod (*Gadus morhua*) and the European eel (*Anguilla anguilla*) predate on crabs and starfish (Kleis, 2017). Having this predator control contributes to the resilience of the system. Furthermore, herbivorous fish can help to control algae.

- It is recommended that if fish can only get in, but not out, research is done on the fish populations in the ESL regarding their numbers, growth, the carrying capacity of the ESL, and possible methods of removing the fish from the ESL if needed.

### 7.3.6 European eel

The European eel is a species of migrating fish that spawn in the Sargasso Sea, swim as larvae across the Atlantic Ocean, swim as juveniles up the European rivers, to eventually swim back to the Sargasso Sea to reproduce (Van Ginneken & Maes, 2006; Klein Breteleer, 2005). In the Dutch rivers, the European eel stock has declined to 10% since 1980 (Dekker, 2003), resulting in effort by the government, nature organisations and the European Commission to protect the European eel (Klein Breteler, 2005).

Considering the interest of Delta21 to open-up migratory routes for migratory fish, like the European eel, up the Dutch rivers (Delta21, personal communication, 2020), it might also be of interest to invest in possibilities to house wild European eel populations in the ESL. Especially, measurements like creating soft substrates for eel to dig in, and vegetation for eels to hide in, and a path for the eel to migrate out or into the ESL could be considered (Klein Breteleer, 2005).

- More measurements can be implemented, but a more elaborate research would be needed to access which and how these measurements can be implemented in the ESL. This can be drawn wider to other migratory fish.

# Chapter 8: Conclusion & advice

In this chapter the main research question "What is the most viable combination of aquaculture types for shellfish and seaweed, considering suitable sites and positive nature effects in the Energy Storage Lake?" will be answered. This will be done by combining the answers to the different sub-questions, followed by the final advice towards the commissioner.

Several cultivation types for mussels, oysters, seaweeds and combinations of species were first identified and then analysed for requirements necessary to implement the cultivation type in the Energy Storage Lake (ESL) (Table 5). Most of the found cultivation types met the requirements for implementation if certain cultivation type or species-specific conditions were met at the site in the ESL. These cultivation types for blue mussels were: on-bottom culture, bouchot culture and raft culture; for Pacific and European flat oysters: on-bottom culture, table culture, longline culture and raft culture; for seaweeds the horizontal longline culture; and finally, for the combinations of species: the seasonal different seaweeds.

These approved cultivation types were then used to assess the requirements of the floating solar park, and suitable locations within the ESL. The sloped edges of the lake allow for table cultures of Pacific and European flat oysters, while hanging cultures of oysters and blue mussel are able near the pumps, and sugar and finger kelp cultures are able to grow in the middle of the lake. The optimum location for the floating solar park would be opposite of the pumps, due to the lower flow speed not allowing for aquaculture in this area. This would allow for the largest area suitable for aquaculture in the lake, thus allowing for the largest production. Mussels, oyster, sugar kelp, and finger kelp can be cultivated in the ESL due to the expected conditions regarding flow rate, temperature, salinity, and nutrient content, matching the requirements for these species (Table 3, Table 4, Table 5)

The floating solar park needs to cover less than 20% of the total surface area of the ESL, and should allow for at least 25% of the light to pass between the panels in order to reduce the impact of light depletion on the area beneath the solar panels. Primary production could decrease if these requirements are not met, resulting in a decrease in available oxygen in the ESL.

The previously discussed approved cultivation types were also analysed for their nature enriching characteristics regarding water quality and biodiversity. Both for mussels and oysters the filtering capacity contributes to nature enrichment trough cleaning of the water. Since they filter detritus, dead organic material, sediments, pollutants, and pathogens out of the system they increase the water quality. Furthermore, for both mussels and oysters, on-bottom culture is the best type to facilitate biodiversity. These on-bottom cultures provide substrate for other organisms to attach on, forming a reef with a high biodiversity. Important to notice is that harvesting can have devastating effects on the established biodiversity. Solving this problem could be done by plot harvesting, giving reef formation some extra time to facilitate biodiversity. However, this must be tested in future research. The downside of on-bottom culture type is that the culture is exposed to predation. This can be solved by active predator removal or a healthy food web.

The nature enrichment of seaweeds lies within the facilitation of biodiversity due to creation of new habitats for other marine organisms. Furthermore, seaweeds contribute to water quality through oxygenation and by removing nitrogen compounds. Additionally, it has been found that they have a high potential for carbon storage which can have a positive environmental value. For seaweed culture within the ESL, horizontal longline culture is the most feasible whereas on-bottom (wild) seaweed does not provide perspective for the ESL due to lack of suitable habitat. However, it is important to mention that on-bottom seaweed can have large nature enriching capacities by facilitating habitat for other organisms and thereby increasing the biodiversity.

Based on the chlorophyll- α content and water current, the carrying capacity for mussel populations is assumed to be sufficient. In addition, the relationship between picoplankton and mesoplankton, as well as the meat weight of the mussel, can be used to monitor the carrying capacity during a later stadium. There are still too many uncertainties regarding seaweed to make a good statement about the maximum carrying capacity expressed in available space.

Assumptions and estimations have been made regarding the conditions within the ESL. This is specifically the case with the calculations for the expected flow rate and nutrients. Modelling the flow rate and nutrients, and possible impact of obstructions like hanging cultures or the floating solar park is recommended. Possible species of seaweed where largely limited due to the flow rate of the water. However, if the flow rate is lower than calculated or the flow rate suitability of the species is in reality higher than assumed, cultures of other seaweed species could also be possible within the ESL.

## 8.1 Advice for commissioner

The most viable combination of aquaculture types in the Energy Storage lake, would be to use all approved species; blue mussels, Pacific oyster, European flat oyster, sugar kelp and finger kelp. Each provide their own nature enrichment. Combining these nature enriching characteristics will increase the resilience of the ESL system.

The shellfish should be placed close to the pumps, the seaweed near the middle of the lake, and the solar park opposite the pumps. These sites and distribution are advised mainly due to the flow rate requirements of the different species.

It is recommended to reassess the above mentioned advise after more research and modelling has been conducted on the expected flow rates and resource availability for the ESL, considering the final design. The recommendations for further research were given in Chapter 7, indicated by the arrows.

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# Appendix

*Appendix 1: Interview questions of interview with seaweed expert.*

**Interview seaweed expert**

- Hoe ziet de zeewier cultivatie er op dit moment uit in Nederland, en hoe ziet u dit in de komende 20 jaar ontwikkelen? Types, soorten, economisch, politiek? Waarom ziet de zeewier cultivatie er op dit moment zo uit/bevindt zich op dit punt? Zijn er hekel punten?
- Worden specifieke cultivatie methodes toegepast op bepaalde soorten? Op het moment hebben wij de indruk dat er meer naar mogelijkheid op locatie wordt gekeken dan naar soort specifieke methodes. (Is er een lijst met bekende cultivatie methodes?)
- Wat is de economische (markt) waarde van de verschillende zeewiersoorten? Hoe hoog moet de minimale productie (totaal of per oppervlak) zijn voor jullie om een rendabele kwekerij te hebben?
- Wat zouden voor het energieoplagmeer problemen kunnen zijn voor zeewier aquacultuur? Denk aan predatoren, ziektes, voedingslimieten, diepte van meer, blootstelling lucht?
- Zijn er gevallen bekend waar de zeewierkweek werd “verpest” door mossel/oesterzaad? We hebben hier een nieuwsartikel (m.b.t. mosselzaad) over gelezen.
- Zien jullie de samenwerking met de mossel/oesterboeren zitten, en of doen jullie dit al?
- Zijn er mogelijke voordelen/nadelen om zeewier cultivatie te integreren met het drijvend zonnepark? Denk aan bijvoorbeeld hangplekken voor culturen.
- Wat zouden positieve/negatieve effecten kunnen zijn van zeewier cultivatie op de natuurwaarden van het gebied?
- Welk type cultuur (en soorten) zou u aanbevelen aan het energieopslagmeer?
- Is er nog literatuur en of mensen die u ons aanraadt om te lezen of contact mee op te nemen?

*Appendix 2: Interview question of interview with mussel and oyster experts.*

**Interview with mussel and oyster experts**

- Welke soorten mossels en oesters worden er gebruikt in Nederland?
- Welke abiotische variabelen zijn kenmerkend voor de locaties waar de soorten goed groeien?
- Wat is het effect van de tijd dat die mossels/oesters boven water zitten op de productie?
- Wat zijn de gevaren van predatie door krabben/kreeften of door vogels?
- Zijn er ziektes en hoe worden die voorkomen?
- Hoeveel oogst verliezen jullie aan predatie en ziektes
- Hoeveel voedsel hebben mosselen en oesters nodig?
- Wanneer wordt het oppervlak van een cultuur té groot en wordt de groei verminderd door intraspecifieke competitie?
- Hoe wordt er normaal gesproken geteeld in bijvoorbeeld de Oosterschelde?
- Waar komt het zaad vandaan en hoe wordt dit opgekweekt?
- Hoe oogst je een bodemcultuur en een hangcultuur normaal gesproken?
- Wat is er bekend over een optimale verhouding van mosselen en oesters in een gebied; denk daarbij aan concurrentie?
- Heeft de schaduw van het zonnepanelenpark invloed op de productie? En zo ja, wat verwachten jullie dat deze invloed is?
- Hoe zouden jullie oogsten als de culturen onder de zonnepanelen hangen?
- Oestercultuur in Nederland is voornamelijk legcultuur, maar het meer wordt dieper dan 3-10 meter, dus zien jullie dan potentie in hangculturen voor oesters?
- Welke mogelijkheden zien jullie in een samenwerking met zeewierboeren, of doen jullie dit al?
- Wat is de economische waarde voor de mossel/oesterboeren van mossels/oesters per kilo/biomassa én per oppervlak?
- Hoe hoog moet de productie (totale kg opbrengst of opbrengst per oppervlak) zijn voor jullie sector om een rendabele kwekerij te hebben op een “normale” plek?
- Zijn er nog nieuwe ontwikkelingen op het gebied van cultuurtypes en welke cultuur types hebben jullie de meeste interesse in.

*Appendix 3: Interview question of interview with solar park expert.*

**Interview floating solar park expert**

- Hoeveel kennis heb je op dit moment over het onderzoek (heb je al voor onderzoek gedaan, achtergrond in zonnepanelen, etc.)
- Zijn er vergelijkbare (zout water) systemen?
- Hoeveel stroomsnelheid kunnen de solar panels aan?
- Wat voor bekabeling hangt onder de zonnepanelen?
- Hoeveel drijfvermogen heeft het solar park? (hangcultuur kan redelijk veel gewicht toevoegen)
- Hoe zitten ze aan de bodem vast?
- Is het een mogelijkheid om de zonnepanelen met de zon mee te laten draaien?
- Is er een maximum afstand tussen zonnepanelen op een eiland? We gaan nu uit van 50% bedekking.
- Wat zijn de mogelijkheden om een solar park op te splitsen in kleinere gebieden/eilandjes? Dit komt de ecologie ten goede (licht), en zorgt voor een grotere omtrek, dus meer gebieden voor aquacultuur (zeewier) en bereikbaarheid (oogsten)
- Zijn er nog specifieke stoffen die vrijkomen door leaching van de zonnepanelen/het onderstel waar ze op zitten?

*Appendix 4: Calculations for the general dimensions of the ESL*

The calculations are based on the parameters of the Energy Storage Lake provided by Delta21, personal communication (2020) (Appendix 5).

Calculations performed to estimate the length of the sides of ESL at depth 0.

$$Sides_0 = \sqrt{Surface\ area\ when\ filled}$$

The length of the sides is based on the surface area of 26 km$^2$ when the lake has been completely filled. This results in the length of the sides (m) of the upper water layer.

$Sides_0 \approx 5100$ m

The sides are offset by 0.5 m because this gives the average length of the sides within a 1 m water layer. Thus, the length of $Sides_{0.5}$ is used as the basis for calculations.

$$Sides_{0.5} = Sides_0 - 20$$

The length of the sides decreases by about 40 m for a 1 m water level decline. Thus, the length of the sides with decreasing depths is calculated.

$$Sides_{n-1} = Sides_n - 40$$

The total surface area of the different water layers is based on the length of the sides of the water layer. Resulting in the surface area of water layer n.

$$Surface\ area_n = Sides_n^2$$

The expected pump speed (m$^3$/h) at full pump capacity has been calculated.

$$Pump\ speed = \frac{Volume}{12}$$

*Appendix 5: Parameters used in the calculations, retrieved from Delta21, personal communication (2020).*

| Parameter | Value | Unit |
|---|---|---|
| **Surface area when filled** | 26000000 | m2 |
| **Depth** | 22.5 | m |
| **Depth change** | 17.5 | m |
| **Volume** | 430000000 | m3 |
| **Slope** | 0.05 | m/m |
| **Time to fill** | 12 | h |
| **Pump speed** | 10000 | m3/s |

The pump speed (m$^3$/h) is used to calculate the expected time of drought exposure. Performing this calculation for the different 1 m water layers results in Appendix 6.

$$Time\ of\ drought\ exposure_n = 2 * \frac{Surface\ area_n}{Pump\ speed} + Time\ of\ drought\ exposure_{n+1}$$

*Appendix 6: Time of drought exposure in the ESL.*

| Water level (m) | Time of drought exposure (h) |
|---|---|
| **-0.5** | 22.6 |
| **-1.5** | 21.1 |
| **-2.5** | 19.7 |
| **-3.5** | 18.4 |
| **-4.5** | 17.0 |
| **-5.5** | 15.7 |
| **-6.5** | 14.4 |
| **-7.5** | 13.1 |
| **-8.5** | 11.8 |
| **-9.5** | 10.6 |
| **-10.5** | 9.4 |
| **-11.5** | 8.2 |
| **-12.5** | 7.0 |
| **-13.5** | 5.8 |
| **-14.5** | 4.7 |
| **-15.5** | 3.6 |
| **-16.5** | 2.5 |
| **-17.5** | 1.4 |

The expected flow rate in the lake is based on the water level, and ranges from 5-22 m. There will always be a 5 m water layer at the bottom of the lake. The lake is assumed to have a cone shape, with a width of 1500 m at the pumps, and width of 9000 m at a distance of 6000 m from the pumps. Calculations are made in steps of 500 m away from the pumps.

Width (m) of the lake at distance (m) m:

$$Width_m = 1500 + Distance_m * 1.25$$

Flow $rate_{mn}$ (m/s) at $width_m$ and water $layer_n$, based on pump speed (m/s) (Appendix 7):

$$Flow\ rate_{mn} = \frac{Pump\ speed}{Width_m * Water\ layer_n}$$

*Appendix 7: Calculated flow rate within the ESL.*

| | | Distance from pumps (m) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 |
| | | Width (m) | | | | | | | | | | | | |
| | Water level (m) | 1500 | 2125 | 2750 | 3375 | 4000 | 4625 | 5250 | 5875 | 6500 | 7125 | 7750 | 8375 | 9000 |
| **Area -0.5** | 22 | 0.30 | 0.21 | 0.17 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 |
| **Area -1.5** | 21 | 0.32 | 0.22 | 0.17 | 0.14 | 0.12 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.05 |
| **Area -2.5** | 20 | 0.33 | 0.24 | 0.18 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.06 | 0.06 | 0.06 |
| **Area -3.5** | 19 | 0.35 | 0.25 | 0.19 | 0.16 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | |
| **Area -4.5** | 18 | 0.37 | 0.26 | 0.20 | 0.16 | 0.14 | 0.12 | 0.11 | 0.09 | 0.09 | 0.08 | 0.07 | 0.07 | |
| **Area -5.5** | 17 | 0.39 | 0.28 | 0.21 | 0.17 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.08 | 0.07 | |
| **Area -6.5** | 16 | 0.42 | 0.29 | 0.23 | 0.19 | 0.16 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | |
| **Area -7.5** | 15 | 0.44 | 0.31 | 0.24 | 0.20 | 0.17 | 0.14 | 0.13 | 0.11 | 0.10 | 0.09 | 0.09 | 0.08 | |
| **Area -8.5** | 14 | 0.48 | 0.34 | 0.26 | 0.21 | 0.18 | 0.15 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.09 | |
| **Area -9.5** | 13 | 0.51 | 0.36 | 0.28 | 0.23 | 0.19 | 0.17 | 0.15 | 0.13 | 0.12 | 0.11 | 0.10 | 0.09 | |
| **Area -10.5** | 12 | 0.56 | 0.39 | 0.30 | 0.25 | 0.21 | 0.18 | 0.16 | 0.14 | 0.13 | 0.12 | 0.11 | 0.10 | |
| **Area -11.5** | 11 | 0.61 | 0.43 | 0.33 | 0.27 | 0.23 | 0.20 | 0.17 | 0.15 | 0.14 | 0.13 | 0.12 | 0.11 | |
| **Area -12.5** | 10 | 0.67 | 0.47 | 0.36 | 0.30 | 0.25 | 0.22 | 0.19 | 0.17 | 0.15 | 0.14 | 0.13 | 0.12 | |
| **Area -13.5** | 9 | 0.74 | 0.52 | 0.40 | 0.33 | 0.28 | 0.24 | 0.21 | 0.19 | 0.17 | 0.16 | 0.14 | | |
| **Area -14.5** | 8 | 0.83 | 0.59 | 0.45 | 0.37 | 0.31 | 0.27 | 0.24 | 0.21 | 0.19 | 0.18 | 0.16 | | |
| **Area -15.5** | 7 | 0.95 | 0.67 | 0.52 | 0.42 | 0.36 | 0.31 | 0.27 | 0.24 | 0.22 | 0.20 | 0.18 | | |
| **Area -16.5** | 6 | 1.11 | 0.78 | 0.61 | 0.49 | 0.42 | 0.36 | 0.32 | 0.28 | 0.26 | 0.23 | 0.22 | | |
| **Area -17.5** | 5 | 1.33 | 0.94 | 0.73 | 0.59 | 0.50 | 0.43 | 0.38 | 0.34 | 0.31 | 0.28 | 0.26 | | |

The suitable locations for aquaculture in the Energy Storage Lake is based on the flow rate requirements described in Chapter 3, and the calculations described in Appendix 4-7. The suitable area for off-bottom culture ($m^2$) in water layer n is based on the equations below.

Sloped area in water layer n:

$$Sloped\ area_n = Surface\ area_n - Surface\ area_{n-1}$$

Fraction suitable for off bottom culture in water layer n, based on the suitable distance from the pumps:

$$Fraction\ suitable_n = 1 - \frac{Distance\ from\ pumps_{suitable,n}}{Distance\ from\ pumps_{no\ longer\ suitable,n}}$$

Total area suitable for (off-)bottom culture (ha) in water layer n:

$$Area\ for\ bottom\ culture_n = \frac{Sloped\ area_n * Fraction\ suitable_n}{10000}$$

Suitable locations for hanging cultures are based on the flow rate requirements for the species and the calculated flow rates in the ESL. The suitable areas for different species are described in flow rate tables (Appendix 9-11)

The surface area of the suitable locations has been calculated using the equation below. Suitable area (ha) for species I, based on the distance from the pumps where aquaculture is suitable ($Distance_s$ (m)), the distance where it is no longer suitable ($Distance_{us}$ (m)), Width of the area ($Width_s$ (m) and $Width_{us}$ (m)).

$$Suitable\ area_i = \frac{(Distance_s - Distance_{us}) * (Width_s + Width_{us})}{10000}$$

*Appendix 9: Possible locations for blue mussel cultivation. The red cells show the flow rate in the area 0-500 m from the pumps, aquaculture within this area is not recommended as an area of 500 m around the pumps is required to access the pumps when maintenance needs to be performed. The green cells show the areas and depths at which optimal flow rate conditions for blue mussel cultivation are met. The orange cells indicate the areas with flow rates that are survivable for the blue mussel but are outside of the optimum range.*

| Blue mussel | | Distance from pumps (m) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 |
| | | Width (m) | | | | | | | | | | | | |
| | Water level (m) | 1500 | 2125 | 2750 | 3375 | 4000 | 4625 | 5250 | 5875 | 6500 | 7125 | 7750 | 8375 | 9000 |
| Area -0.5 | 22 | 0.30 | 0.21 | 0.17 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 |
| Area -1.5 | 21 | 0.32 | 0.22 | 0.17 | 0.14 | 0.12 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.05 |
| Area -2.5 | 20 | 0.33 | 0.24 | 0.18 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.06 | 0.06 | 0.06 |
| Area -3.5 | 19 | 0.35 | 0.25 | 0.19 | 0.16 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | |
| Area -4.5 | 18 | 0.37 | 0.26 | 0.20 | 0.16 | 0.14 | 0.12 | 0.11 | 0.09 | 0.09 | 0.08 | 0.07 | 0.07 | |
| Area -5.5 | 17 | 0.39 | 0.28 | 0.21 | 0.17 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.08 | 0.07 | |
| Area -6.5 | 16 | 0.42 | 0.29 | 0.23 | 0.19 | 0.16 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | |
| Area -7.5 | 15 | 0.44 | 0.31 | 0.24 | 0.20 | 0.17 | 0.14 | 0.13 | 0.11 | 0.10 | 0.09 | 0.09 | 0.08 | |
| Area -8.5 | 14 | 0.48 | 0.34 | 0.26 | 0.21 | 0.18 | 0.15 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.09 | |
| Area -9.5 | 13 | 0.51 | 0.36 | 0.28 | 0.23 | 0.19 | 0.17 | 0.15 | 0.13 | 0.12 | 0.11 | 0.10 | 0.09 | |
| Area -10.5 | 12 | 0.56 | 0.39 | 0.30 | 0.25 | 0.21 | 0.18 | 0.16 | 0.14 | 0.13 | 0.12 | 0.11 | 0.10 | |
| Area -11.5 | 11 | 0.61 | 0.43 | 0.33 | 0.27 | 0.23 | 0.20 | 0.17 | 0.15 | 0.14 | 0.13 | 0.12 | 0.11 | |
| Area -12.5 | 10 | 0.67 | 0.47 | 0.36 | 0.30 | 0.25 | 0.22 | 0.19 | 0.17 | 0.15 | 0.14 | 0.13 | 0.12 | |
| Area -13.5 | 9 | 0.74 | 0.52 | 0.40 | 0.33 | 0.28 | 0.24 | 0.21 | 0.19 | 0.17 | 0.16 | 0.14 | | |
| Area -14.5 | 8 | 0.83 | 0.59 | 0.45 | 0.37 | 0.31 | 0.27 | 0.24 | 0.21 | 0.19 | 0.18 | 0.16 | | |
| Area -15.5 | 7 | 0.95 | 0.67 | 0.52 | 0.42 | 0.36 | 0.31 | 0.27 | 0.24 | 0.22 | 0.20 | 0.18 | | |
| Area -16.5 | 6 | 1.11 | 0.78 | 0.61 | 0.49 | 0.42 | 0.36 | 0.32 | 0.28 | 0.26 | 0.23 | 0.22 | | |
| Area -17.5 | 5 | 1.33 | 0.94 | 0.73 | 0.59 | 0.50 | 0.43 | 0.38 | 0.34 | 0.31 | 0.28 | 0.26 | | |

*Appendix 10: Possible locations for oyster cultivation. The red cells show the flow rate in the area 0-500 m from the pumps, aquaculture within this area is not recommended as an area of 500 m around the pumps is required to access the pumps when maintenance needs to be performed. The green cells show the areas and depths at which optimal flow rate conditions for oyster cultivation are met.*

| Oyster | | Distance from pumps (m) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 |
| | | Width (m) | | | | | | | | | | | | |
| | Water level (m) | 1500 | 2125 | 2750 | 3375 | 4000 | 4625 | 5250 | 5875 | 6500 | 7125 | 7750 | 8375 | 9000 |
| Area -0.5 | 22 | 0.30 | 0.21 | 0.17 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 |
| Area -1.5 | 21 | 0.32 | 0.22 | 0.17 | 0.14 | 0.12 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.05 |
| Area -2.5 | 20 | 0.33 | 0.24 | 0.18 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.06 | 0.06 | 0.06 |
| Area -3.5 | 19 | 0.35 | 0.25 | 0.19 | 0.16 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | |
| Area -4.5 | 18 | 0.37 | 0.26 | 0.20 | 0.16 | 0.14 | 0.12 | 0.11 | 0.09 | 0.09 | 0.08 | 0.07 | 0.07 | |
| Area -5.5 | 17 | 0.39 | 0.28 | 0.21 | 0.17 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.08 | 0.07 | |
| Area -6.5 | 16 | 0.42 | 0.29 | 0.23 | 0.19 | 0.16 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | |
| Area -7.5 | 15 | 0.44 | 0.31 | 0.24 | 0.20 | 0.17 | 0.14 | 0.13 | 0.11 | 0.10 | 0.09 | 0.09 | 0.08 | |
| Area -8.5 | 14 | 0.48 | 0.34 | 0.26 | 0.21 | 0.18 | 0.15 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.09 | |
| Area -9.5 | 13 | 0.51 | 0.36 | 0.28 | 0.23 | 0.19 | 0.17 | 0.15 | 0.13 | 0.12 | 0.11 | 0.10 | 0.09 | |
| Area -10.5 | 12 | 0.56 | 0.39 | 0.30 | 0.25 | 0.21 | 0.18 | 0.16 | 0.14 | 0.13 | 0.12 | 0.11 | 0.10 | |
| Area -11.5 | 11 | 0.61 | 0.43 | 0.33 | 0.27 | 0.23 | 0.20 | 0.17 | 0.15 | 0.14 | 0.13 | 0.12 | 0.11 | |
| Area -12.5 | 10 | 0.67 | 0.47 | 0.36 | 0.30 | 0.25 | 0.22 | 0.19 | 0.17 | 0.15 | 0.14 | 0.13 | 0.12 | |
| Area -13.5 | 9 | 0.74 | 0.52 | 0.40 | 0.33 | 0.28 | 0.24 | 0.21 | 0.19 | 0.17 | 0.16 | 0.14 | | |
| Area -14.5 | 8 | 0.83 | 0.59 | 0.45 | 0.37 | 0.31 | 0.27 | 0.24 | 0.21 | 0.19 | 0.18 | 0.16 | | |
| Area -15.5 | 7 | 0.95 | 0.67 | 0.52 | 0.42 | 0.36 | 0.31 | 0.27 | 0.24 | 0.22 | 0.20 | 0.18 | | |
| Area -16.5 | 6 | 1.11 | 0.78 | 0.61 | 0.49 | 0.42 | 0.36 | 0.32 | 0.28 | 0.26 | 0.23 | 0.22 | | |
| Area -17.5 | 5 | 1.33 | 0.94 | 0.73 | 0.59 | 0.50 | 0.43 | 0.38 | 0.34 | 0.31 | 0.28 | 0.26 | | |

*Appendix 11: Possible locations for sugar and finger kelp cultivation. The red cells show the flow rate in the area 0-500 m from the pumps, aquaculture within this area is not recommended as an area of 500 m around the pumps is required to access the pumps when maintenance needs to be performed. The green cells show the areas and depths at which optimal flow rate conditions for seaweed cultivation are met.*

| Seaweed | | Distance from pumps (m) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 |
| | | Width (m) | | | | | | | | | | | | |
| | Water level (m) | 1500 | 2125 | 2750 | 3375 | 4000 | 4625 | 5250 | 5875 | 6500 | 7125 | 7750 | 8375 | 9000 |
| Area -0.5 | 22 | 0.30 | 0.21 | 0.17 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 |
| Area -1.5 | 21 | 0.32 | 0.22 | 0.17 | 0.14 | 0.12 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.05 |
| Area -2.5 | 20 | 0.33 | 0.24 | 0.18 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.06 | 0.06 | 0.06 |
| Area -3.5 | 19 | 0.35 | 0.25 | 0.19 | 0.16 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | |
| Area -4.5 | 18 | 0.37 | 0.26 | 0.20 | 0.16 | 0.14 | 0.12 | 0.11 | 0.09 | 0.09 | 0.08 | 0.07 | 0.07 | |
| Area -5.5 | 17 | 0.39 | 0.28 | 0.21 | 0.17 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.08 | 0.07 | |
| Area -6.5 | 16 | 0.42 | 0.29 | 0.23 | 0.19 | 0.16 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | |
| Area -7.5 | 15 | 0.44 | 0.31 | 0.24 | 0.20 | 0.17 | 0.14 | 0.13 | 0.11 | 0.10 | 0.09 | 0.09 | 0.08 | |
| Area -8.5 | 14 | 0.48 | 0.34 | 0.26 | 0.21 | 0.18 | 0.15 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.09 | |
| Area -9.5 | 13 | 0.51 | 0.36 | 0.28 | 0.23 | 0.19 | 0.17 | 0.15 | 0.13 | 0.12 | 0.11 | 0.10 | 0.09 | |
| Area -10.5 | 12 | 0.56 | 0.39 | 0.30 | 0.25 | 0.21 | 0.18 | 0.16 | 0.14 | 0.13 | 0.12 | 0.11 | 0.10 | |
| Area -11.5 | 11 | 0.61 | 0.43 | 0.33 | 0.27 | 0.23 | 0.20 | 0.17 | 0.15 | 0.14 | 0.13 | 0.12 | 0.11 | |
| Area -12.5 | 10 | 0.67 | 0.47 | 0.36 | 0.30 | 0.25 | 0.22 | 0.19 | 0.17 | 0.15 | 0.14 | 0.13 | 0.12 | |
| Area -13.5 | 9 | 0.74 | 0.52 | 0.40 | 0.33 | 0.28 | 0.24 | 0.21 | 0.19 | 0.17 | 0.16 | 0.14 | | |
| Area -14.5 | 8 | 0.83 | 0.59 | 0.45 | 0.37 | 0.31 | 0.27 | 0.24 | 0.21 | 0.19 | 0.18 | 0.16 | | |
| Area -15.5 | 7 | 0.95 | 0.67 | 0.52 | 0.42 | 0.36 | 0.31 | 0.27 | 0.24 | 0.22 | 0.20 | 0.18 | | |
| Area -16.5 | 6 | 1.11 | 0.78 | 0.61 | 0.49 | 0.42 | 0.36 | 0.32 | 0.28 | 0.26 | 0.23 | 0.22 | | |
| Area -17.5 | 5 | 1.33 | 0.94 | 0.73 | 0.59 | 0.50 | 0.43 | 0.38 | 0.34 | 0.31 | 0.28 | 0.26 | | |