DELTA21:

Exploration of the possibilities for aquaculture in the Haringvliet area

Final Report 2019

Wageningen University:
Academic Consultancy Training

Course code: YMC60809

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Exploration of the possibilities for aquaculture in the Haringvliet area

Publisher: Animal+1

Date: March 7th 2019

This report is commissioned and financed by DELTA21 as part of the Academic Consultancy Training (ACT) of Wageningen University.

Academic Consultancy Training (ACT)

Wageningen, March 2019

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Executive summary

Animal+1 is a student academic consultancy team founded as of January 2019 in context of Academic Consultancy Training (ACT) at Wageningen University. Animal+1 provides the following: an interdisciplinary investigation of the possibilities for making the transition towards sustainable aquaculture production systems in the Haringvliet, as part of the DELTA21 project using expertise in aquaculture, marine ecology, hydrology and animal production systems.

The current report was based on available reports and academic literature besides semi-structured interviews with experienced people from the relevant aquaculture sectors, and employees of two nature organisations. It was found that water temperature, water depth, water speed, salinity, bottom type, nutrient concentrations (i.e. nitrogen and phosphate) and chlorophyll-α concentration are the most important factors for aquaculture development. The optimal values of these variables for seaweed cultivation and shellfish cultivation are largely in correspondence with the expected band of environmental conditions in the future Haringvliet and tidal basin, except for salinity. However, projected salinity was based on historic data in the Western part of the Haringvliet prior to the construction of the sluices (average discharge of 1210 m3/s at Willemstad), so no claims can be made on the future situation after implementation of DELTA21.

Given the limited environmental data on the impact of DELTA21 plan in the Haringvliet area (salinity, morphology, flow velocity, carrying capacity), Animal+1 urges caution when promising possibilities for new cultivation grounds to aquaculture sectors in the Haringvliet area. Salinity levels are a critical factor for all commercial aquaculture species, and scientific data on expected levels after implementation of DELTA21 are lacking.

Based on our findings, the following recommendations for further research are made:

1. Conduct research on the development of salinity gradients in the Haringvliet and tidal basin for different river discharges (with extremes on the low as well on the high end) by performing a 3D modelling study in which planned constructions of DELTA21 are included.
2. Conduct research on bottom quality and bottom composition on local scale and on different cultivation techniques (near-bottom, off-bottom), a.o. to decrease risks for food safety.
3. Conduct a study on the influence of the constructions of DELTA21 on the morphology and flow velocity in the Haringvliet and tidal basin.
4. Conduct a modelling study to the carrying capacity of the ecological system.
5. Take a cautionary approach by set up a monitoring-and adjusting program which updates the models regularly (in Dutch, this is called “lerend implementeren”)

In addition, changing the upstream water distribution by directing more water to the Nieuwe Waterweg near Rotterdam could be an interesting approach to increase the salinity in the Haringvliet area. This would potentially enable a transition towards sustainable aquaculture production in both the tidal basin as well as the future western part of the Haringvliet, making DELTA21 a valuable contribution to satisfying the demand for new cultivation grounds by the Dutch aquaculture sector.

Nederlandse samenvatting

Animal+1 is een academisch consultancy team opgericht in januari 2019 in de context van het Academic Consultancy Training (ACT) programma van Universiteit Wageningen. Animal+1 biedt het volgende: een interdisciplinair onderzoek naar de mogelijkheden van een transitie richting duurzame aquacultuur in het Haringvliet, als onderdeel van het DELTA21 project vanuit expertise in aquacultuur, mariene ecologie, hydrologie and dierwetenschappen.

Het huidige rapport is gebaseerd op beschikbare rapporten en academische literatuur, aangevuld met diepte interviews met ervaringsdeskundigen uit de aquacultuur sector en medewerkers van twee natuurorganisaties. Uit deze gegevens is naar voren gekomen dat water temperatuur, diepte, stroomsnelheid, zoutgehalte, bodem type, nutriënten concentraties (met name stikstof en fosfaat) en chlorophyll-α concentratie de belangrijkste factoren zijn voor het ontwikkelen van aquacultuur. De optimale waardes voor zowel zeewier- als schelpdierkweek liggen grotendeels binnen de verwachte bandbreedte van deze condities in het toekomstige Haringvliet en getijmeer, met uitzondering van het zoutgehalte.

Gegeven de beperkte hoeveelheid beschikbare data van de effecten van DELTA21 op het Haringvliet (zoutgehalte, morfologie, stroomsnelheid, draagkracht), adviseert Animal+1 dan ook terughoudendheid bij het integreren van de ontwikkeling van duurzame aquacultuur in het toekomstige Haringvliet. Het zoutgehalte blijkt een belangrijke randvoorwaarde te zijn voor zowel zeewier-, mossel- als oesterkweek en zolang wetenschappelijke data over het verwachte zoutgehalte in het gebied na invoering van DELTA21 missen, is het maken van een gedegen inschatting van de mogelijkheden voor kweek onmogelijk.

Om de transitie richting duurzame aquacultuur in het Haringvliet te bespoedigen, formuleert Animal+1 de volgende aanbevelingen voor vervolgonderzoek:

1. Onderzoek de ontwikkeling van het zoutgehalte in het Haringvliet en getijmeer door een 3D model studie van het zoutgehalte onder verschillende debieten (zowel lage als hoge afvoer) waarbij de geplande constructies van het DELTA21 project inbegrepen zijn.
2. Onderzoek de bodemkwaliteit en samenstelling op lokale schaal en onderzoek de mogelijkheid van verschillende kweek technieken (near-bottom, off-bottom), om o.a. de risico's voor voedselveiligheid te verminderen.
3. Onderzoek de geomorphologische effecten en de verandering in stroomsnelheid binnen het Haringvliet en het getijmeer door de geplande constructie van het DELTA21 project.
4. Onderzoek de ecologische draagkracht van het systeem in het gebied alvorens aquacultuur in het plan op te nemen.
5. Pas het lerend implementeren principe toe; dat wil zeggen, creëer een monitoringsprogramma gericht op het verzamelen van data om de gemaakte modellen te updaten. Dit helpt met het voorkomen van grote negatieve gevolgen door implementatie.

Verder is het aan te raden de mogelijkheid van het herdistribueren van de rivier afvoer richting de Nieuwe Waterweg dichtbij Rotterdam nader te onderzoeken. Hierdoor zou het zoutgehalte in het Haringvliet en getijmeer mogelijk aanzienlijk verhoogd kunnen worden, waardoor de potentie voor aquacultuur, en daarmee de bijdrage van DELTA21 aan het bevorderen van de uitbreiding van de beschikbare gebieden voor aquacultuur, sterk zal toenemen.

Chapter 1 – Introduction

1.1 Background information

The current century will seriously pressurize our approach to water safety in delta areas and sea level rise prediction maps illustrate the exceptional vulnerability of the Netherlands (Fig. 1). At the same time, calls for innovative and integrative coastal management are becoming more prevalent. In response to such trends, DELTA21 proposes a coastal protection plan that pursues to integrate solutions for 1) water safety, 2) renewable energy generation & storage and 3) nature restoration in the area of the Haringvliet, a former estuary of the Rhine Meuse Delta (Berke & Lavooij, 2019).

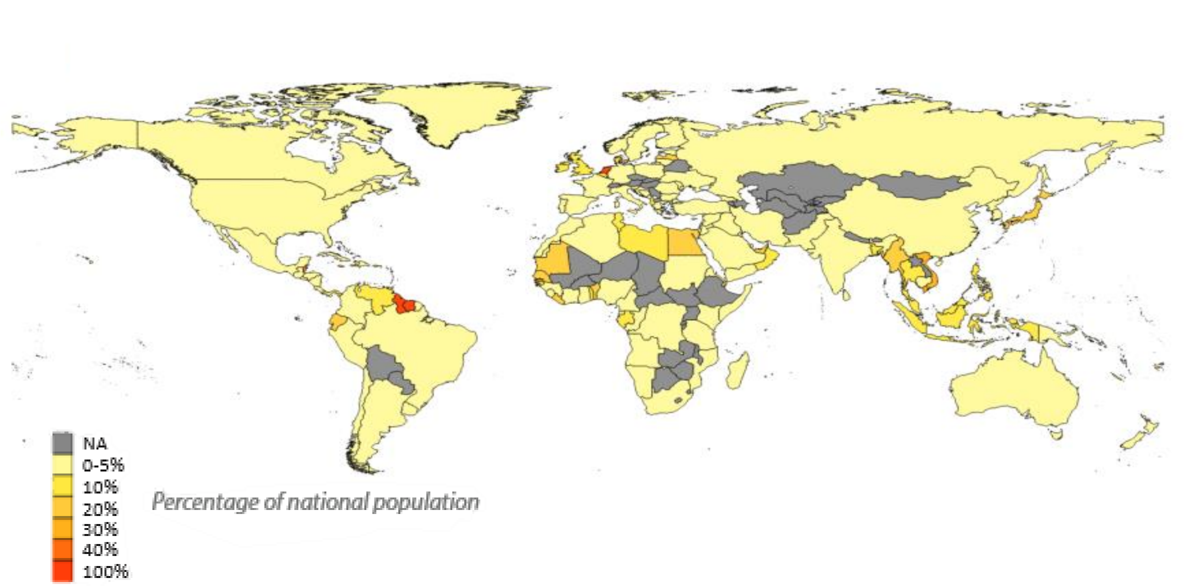

Figure 1: Percentage of total population currently living on land that could be submerged by post-2100 sea level rises (median = 4.7 m) after 2 °C warming (Strauss, Kulp, & Levermann, 2015).

1.1.1 Historical background

After the flooding of 1953, sluices were constructed in the Haringvliet as part of the Delta works to enhance flood protection for the hinterland against storm surges. 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 and bird populations.

1.1.2 Ecological situation before and after the construction of the sluices

In terms of vegetation, the typical *Scirpus* stands and reed (*Phragmiles australis*) vegetation were reduced and transformed into grassland favoured by wintering geese (Smit, van der Velde, Smits, & Coops, 1997). Moreover, ruderal plant species such as the common nettle (*Urtica dioica*) invaded higher zones, some brackish-marsh species (e.g. Parsley water-dropwort (*Oenanthe lachenalii*)) disappeared or decreased (Smit et al., 1997). At many areas pondweed species (e.g. fennel-leaved pondweed (*Potamogeton pectinatus*)) increased due to lower water velocities (Smit et al., 1997). The macroinvertebrate fauna of the area has been reduced in terms of overall abundance and diversity after the construction of the sluices (except for zebra mussel (*Dreissena polymorpha*), the quagga

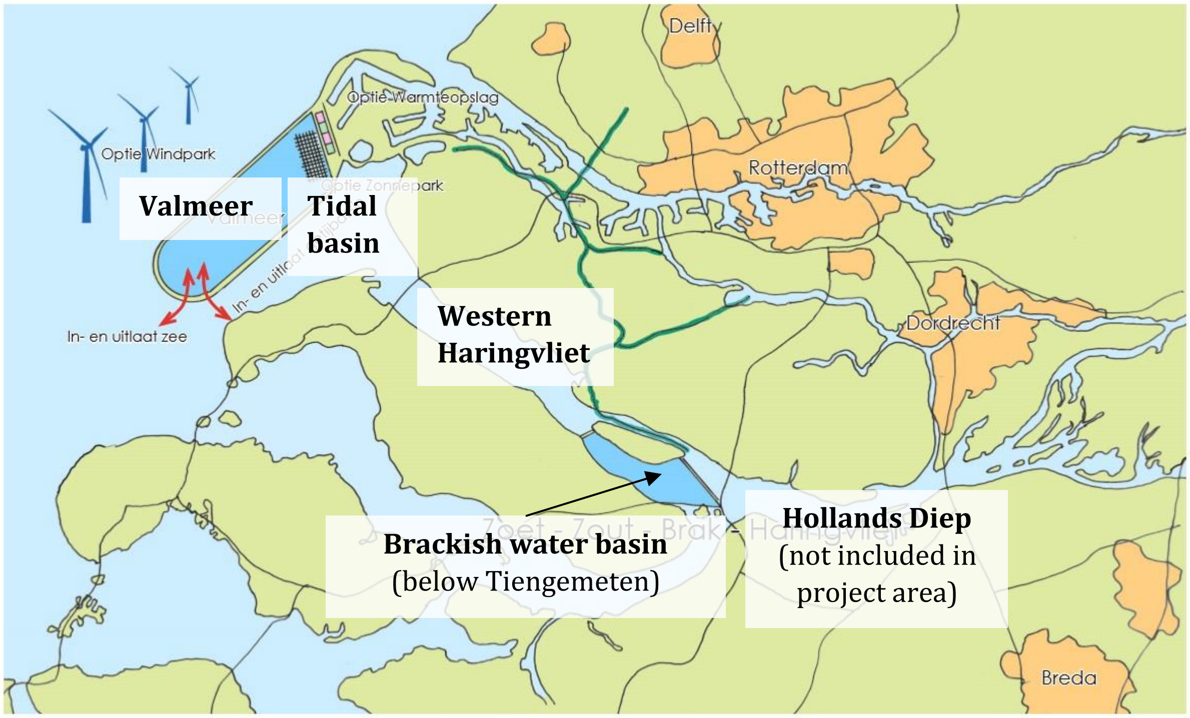

Figure 2: Project area of DELTA21 (Berke & Lavooij, 2019)

mussel (*Dreissena bugensis*), and some tolerant tubificid worm species which feed on organic pollutants that were deposited) (Matthews et al., 2014; Smit et al., 1997). The mussels seem to be an important food source for waterbirds (Smit et al., 1997). Migratory fish species such as the Atlantic salmon (*Salmo salar*) and the twait shad (*Alosa fallax*), and marine species have disappeared, and estuarine residents such as smelt (*Osmerus eperlanus*), flounder (*Platichthys flesus*) and twaite Shad (*Alosa fallax*) cannot build up viable populations in the area (Paalvast & van der Velde, 2014; Van Leeuwen et al. 2004(Paalvast & van der Velde, 2014). Moreover, flounder and European eel (*Anguilla anguilla*) can currently not migrate upstream (Paalvast, 2014). Also the Haringvliet estuary currently does not function as a nursery for plaice (*Pleuronectes platessa*), sole (*Solea solea*), herring (*Clupea harengus*) and allish shad (*Alosa alosa*) anymore (Paalvast, Iedema, Ohm, & Posthoorn, 1998; Paalvast & van der Velde, 2014; Quak, 2016). On the other hand, common fresh water species such as European perch (*Perca fluviatilis*), pike-perch (*Perca fluviatilis*), roach (*Rutilus rutilus*), and bream (*Abramis brama*) increased (Smit et al., 1997). Effects on bird populations have been linked to changes in the amount of particular habitat types (which is related to vegetation changes and erosion), the availability of particular foods (e.g. zebra mussels), and the quality of the surroundings (Smit et al., 1997).

Whether changes to species distributions are desirable is part of a large ethical debate. Yet, as brackish wetlands are counted amongst the most threatened ecosystems of the world, the increase of wetland area and the restoration of the associated wetland communities are therefore generally considered ecologically desirable (Lefeuvre, Laffaille, Feunteun, Bouchard, & Radureau, 2003).

1.1.3 The DELTA21 plan

DELTA21 proposes to open up the Haringvliet sluices, construct an artificial lake in the foreshore (i.e. "Valmeer"), and create a permanent brackish water basin below the island Tiengemeten (Fig. 2).

Such measures would create a tidal basin (from the new 'mouth' of the Haringvliet to the Haringvliet sluices), let salt water enter the Western Haringvliet (which ranges from the Haringvliet sluices to the western boundary of the island Tiengemeten), and separates the brackish water from the fresh water (at the eastern boundary of the brackish water basin). These measures are aimed at increasing storage capacity for flood water, generating electricity in/around the Valmeer, and restoring the estuarine ecology in the Haringvliet area, including facilitating fish migration. DELTA21 is also looking for other opportunities to integrate other, compatible, objectives and/or sectors. One of such potentially compatible sectors is the aquaculture sector, as salt water would be allowed to enter the western Haringvliet. This will be further discussed in the next paragraphs.

1.1.4 Sustainable aquaculture

Defining what sustainable aquaculture is involves the speciation of the cultured species, location and prevalent societal norms (Worldbank, 2014). More generally, such discussions involve what are generally considered three key points of sustainability: People, Planet and Profit (PPP). This means that overall, aquaculture should be socially responsible, it should not disrupt existing ecosystems, pollute the waters or cause a loss in biodiversity and lastly it should be a profitable business with good long-term prospects (Worldbank, 2014). Throughout this report the planet aspect of sustainable aquaculture is only taken into account in the discussion, in terms of recommendations for follow up studies. The profitability and the socially responsible aspects are also not considered in this report. We have, however, chosen to investigate species generally viewed in a 'positive light', namely endemic (and currently cultured) species that are linked to improving water quality (Bcsga, 2019a; Zhang et al., 2018).

1.2 Focus and objective of this report

The project of DELTA21 sparked the interest of the Dutch shellfish breeding sector as this sector is searching for new production grounds (Rijksoverheid, 2014). Similarly, the seaweed cultivation sector shows interest. This aquaculture sector is not yet operating at commercial scale within the Netherlands, but it is a fast growing one. In the future, seaweed cultivation would also need grounds to cultivate. While DELTA21 could offer opportunities for the Dutch aquaculture sector, these opportunities and potential bottlenecks for future development of aquaculture within the context of DELTA21 have not yet been explored. Therefore, the objective of this study is to evaluate opportunities and bottlenecks for the development of aquaculture within the context of DELTA21, as well as to identify knowledge gaps.

To narrow the scope of the project, this report will focus on three shellfish species, namely *Mytulis edulis* (blue mussel), *Crassostrea gigas* (pacific oyster) and the *Ostrea edulis* (flat oyster), and four seaweed species, namely *Laminaria digitate* (finger kelp), *Palmaria palmata* (dulse), *Saccharina latissimi* (sugar kelp) and *Ulva lactuca* (sea lettuce). The shellfish species were selected because they are currently successfully cultivated in the Netherlands (which also means that the required human and physical resources for their production are available). The seaweed species were selected because they are endemic and have been cultivated in the past (although not necessarily in the Netherlands) (Reith, Huijgen, van Hal, & Lenstra, 2009; Van den Burg et al., 2013). Additionally, we will only focus on the tidal basin and the western Haringvliet in this report.

Several questions were developed to satisfy the study its objective. These are:

1. *What are the ranges of environmental conditions required for the cultivation of selected shellfish and seaweed species?*
2. *What are the expected environmental conditions in the future Haringvliet (relevant to aquaculture)?*
3. *At which location(s) is/are the requirements and environmental conditions compatible in the future Haringvliet and tidal basin?*
4. *Based on Q_3, what are environmental bottlenecks and positive aspects associated with (possible) aquaculture in the Haringvliet and the tidal basin?*
5. *What recommendations can be given to stimulate development of aquaculture within the future vision of DELTA21?*

The answers to sub-questions 1 and 2 can be found in chapter 2. Chapter 3 focusses on question 3 and shortly introduces some key topics concerning question 4 and 5. Chapter 4, then, addresses the last two sub-questions in more detail. Chapter 5 includes a brief reflection on the methodology and the results, as well as on ethical concerns. Chapter 6 discusses our final advice on the feasibility of seaweed and bivalve aquaculture integration in the DELTA21 plan.

1.3 Methodology

In order to find answers to the stated questions 1-2 and 4-5, information was gathered from various sources. We conducted semi-structured interviews with experienced people from the relevant Dutch aquaculture sectors (i.e. seaweed and bivalve aquaculture), as well as with employees of two nature organisations (i.e. WWF and Natuurmonumenten). The interview questions can be found in Appendix II. Interviewees were selected based on their knowledge on the area, via the snowball sampling method (in other words, one interviewee or employee in the respective organisation recommends who to talk to). The respondents were also asked for recommended literature. Additionally, two academic experts on aquaculture were asked for relevant academic or grey literature sources concerning our questions. All inputs were examined and used as a starting point for our own literature review study, which looked at additional grey and academic literature. Moreover, publicly available data on environmental conditions in the project area were identified in online databases.

It is unknown what exact environmental conditions will develop in the Haringvliet when the DELTA21 plan is conducted, and to the best of our knowledge no studies are available that exactly simulate this development. Therefore in this study several predictions had to be made based on limited and untailored data. When it comes to reporting estimates of such future conditions, we have tried to find academic sources which discuss similar situations, as the (scientific method and) peer-review process adds to their reliability. Nevertheless, we have not refrained from utilizing non-peer reviewed (scientific) reports and personal communications where no such literature was available, as this still provides valuable information in this early phase of the assessment of the suitability for aquaculture. The limitations of this approach will be discussed in more detail in the discussion (Chapter 5).

Focus of this report

- Investigating possibilities for integrating shellfish cultivation:
  - Pacific oysters
  - Flat oysters
  - Blue mussels
- Investigating possibilities for integrating seaweed cultivation:
  - Sugar kelp
  - Finger kelp
  - Dulse
  - Sea lettuce
- Areas included in this report:
  - tidal basin (in Dutch: getijmeer)
  - the westerm Haringvliet
- Data is gathered through
  - reviewing (grey) literature
  - semi-structured interviews

Structure of this report

Chapter 2	Environmental conditions required for aquaculture Expected environmental conditions in the Haringvliet area
Chapter 3	Suitable locations for aquaculture in the Haringvliet area
Chapter 4	Environmental bottlenecks and opportunities
Chapter 5	Reflection on the methodology
Chapter 6	Final advice

Chapter 2 – Environmental requirements and conditions

2.1 Introduction

In order to determine if the Haringvliet and/or tidal basin would be suitable for cultivation of bivalves and seaweed, data are needed about the biotic and abiotic requirements of these species, as well as on the extent to which these areas are able to meet such requirements. Therefore the aim of this output is to provide an overview of the data required to sketch a potential scenario for aquaculture in the future western Haringvliet and tidal basin in the context of DELTA21.

This output is composed of two parts, namely; 1) requirements for shellfish and seaweed aquaculture, and 2) expected environmental conditions of the future western Haringvliet and tidal basin. This output starts with Table 1, in which a summary of our findings for the two parts can be found. No sources are mentioned in this table, as they are mentioned in the text below Table 1. Furthermore, additional figures, graphs and tables are provided in the text to clarify and visualize some of the things described.

2.2 Requirements for shellfish and seaweed aquaculture

Table 1 Summary of preferred conditions for shellfish and seaweed aquaculture and the future conditions in the Haringvliet and Tidal basin. Extended tables per aquaculture species can be found in appendix I. The sources used to gather this data are referred to in the text below. ME = *Mytulis edulis* , OE = *Ostrea edulis*, CG = *Crassostrea gigas* , LD = *Laminaria digitata*, SL = *Saccharina latissima*, PP = *Palmaria palmata*, UL = *Ulva lactuca*, WH = Western Haringvliet, TB = Tidal basin, N.A.= Not Applicable, N.D. = No Data.

Parameter	Unit	Shellfish			Seaweed				DELTA21 area	
Species/ location	-	ME	OE	CG	LD	SL	PP	UL	WH	TB
Salinity	ppt	30-40	20-25	20-25	30-40	25-31	30-40	20-40	0.2-19	19-35
Temperature	°C	10-25	17-25	11-34	<18	<18	15-17	15-20	0-20	0-20
Water depth	m	0-10	0-10	0-10	>10	>10	>10	>10	0-35	0-10
Water speed	cm/s	20-80	20-50	20-50	<50 - >300	<50 - >300	<50 - 300	-	0-80	0-90
Bottom type	-	Sub-stratum	Sub-stratum	Sub-stratum	N.A.	N.A.	N.A.	N.A.	Sand	Sand
Feed indicator	-	Chloro-phyll α	Chloro-phyll α	Chloro-phyll α	NH_4	NH_4	NH_4.	NH_4.	N.A.	N.A.
Light attenuation	dm	N.A.	N.A.	N.A.	N.D.	N.D.	N.D.	N.D.	25 - 5	< 20

2.2.1 Blue mussel (*Mytulis edulis*)

Blue mussels (*Mytulis edulis*) are commonly cultured in the Netherlands, mainly in the Wadden Sea and the Eastern Scheldt. After literature review and interviews with several people from the mussel sector, the environmental parameters considered most important for mussel cultivation are: Salinity [ppt], water temperature [°C], water depth [m], water speed [cm/s], bottom type and the chlorophyll α concentration [μg/L]. Table 1 also includes light attenuation, but this variable is thought to only indirectly affect mussels, as they affect phytoplankton, a food source of mussels. Each parameter is described below.

Salinity

While the preferred salinity for mussels is 30-40 ppt, mussels can withstand a wide range of salinity (18-40 ppt), depending on the water temperature (Tyler-Walters, 2008). If the temperature is below 10 °C, the metabolism of the mussels decrease, meaning they filter less water and can thus stand lower salinities better (Tyler-Walters, 2008). A salinity of 30-40 ppt is optimal for growing mussels, but a mix of freshwater and saltwater or brackish water has been thought to stimulate spawning and the functioning of nurseries; however, this beneficial effect could also be explained by a higher abundance of food, as a result from the freshwater input (Seed, Suchanek, & Gosling, 1992). Moreover, rapid drops in salinity e.g. as a result from storm run-off may kill large numbers of mussels (Tyler-Walters, 2008).

Water temperature

Water temperature is a very important parameter during all life stages of a blue mussel. Mussels spawn when the water temperature increases (i.e. in spring and summer), and fertilization can occur between 5 °C and 22 °C (Lutz & Kennish, 1992). It was shown that between temperatures of 10 to 20 °C, there was no significant difference in growth, but below 10 °C, the metabolisms of the mussels decrease (Tyler-Walters, 2008). Mussels can withstand extremely cold temperatures up to -10 °C occasionally, but they may die after a couple days of exposure (Seed et al., 1992). The upper temperature limit for survival of adult mussels is 29 °C, however in European waters a limit of 25 °C is more common (Tyler-Walters, 2008).

Water depth

Mussel occur naturally in depth up to 10 m (Zagata, Young, Sountis, & Kuehl, 2008). Mussel Seed Collectors are normally placed at 6 to 13 m depth, according to an interviewee (Padmos, 2019), and bottom cultivation can occur up to 10m (Zagata et al., 2008). Moreover, mussels are also found on subtidal and intertidal beds (Tyler-Walters, 2008; Zagata et al., 2008).

Water speed

According to an interviewee, mussels need water to flow past them in order to get access to food and nutrients, which means there is a lower limit to water speed (Padmos, 2019). This limit was found to be 20 cm/s (Van Broekhoven, 2010). However, mussels can also be swept of the rocks they're attached to, which means there is an upper limit as well. In practice this limit is approximately 80 cm/s (Tyler-Walters, 2008; Van Broekhoven, 2010). Moreover, one of the mussel sector interviewees stated that for successful cultivation of consumption mussels flow rates between 40 to 70 cm/s are preferable (Padmos, 2019).

Bottom type

An important aspect for mussel and oyster bottom cultivation is the composition and quality of the bottom (Van Broekhoven, 2010). When mussels spawn the seed attaches to substrate, where it then stays permanently (Zagata et al., 2008). Substratum preferences include small and large boulders, sandy mud, rockpools, muddy gravel, caves and crevices (Tyler-Walters, 2008). Furthermore, the bottom has to be flat, according to an interviewee (Padmos, 2019), and mussels seem to be unable to attach to very steep or even vertical surfaces (Tyler-Walters, 2008). The composition of the bottom is related to the flow rate in the bottom layers of the water; coarse- grained sand indicates a fast flow, meaning there is a risk the shellfish may be washed away (Steijaert, 1985; Van Broekhoven, 2010).

On the other hand, an abundance of sludge/silt indicates that the flow rate is rather low, which might lead to insufficient washing away of pseudo-faeces, risking suffocation of the mussels (Van Broekhoven, 2010). Additionally, the break-down of organic silt consumes large amounts of oxygen- meaning there is less available for the shellfish (Steijaert, 1985; Van Broekhoven, 2010). Furthermore, mussels need substrate to attach to and protect themselves from washing away in the water or tidal flow (Brinkman et al., 2003).

Feed indicator

Blue mussels are suspensions filter feeders with a varied diet including dissolved organic matter (DOM), bacteria, detritus and phytoplankton (Tyler-Walters, 2008). Chlorophyll-α concentration is an indicator of the food availability for mussels (Widdows, Fieth, & Worrall, 1979). Additionally, flow rate and the concentration of particles are important factors for food availability (Widdows et al., 1979). An estimate of the Chlorophyll-α range in which blue mussels can be cultured, namely 0-20 µg/L Chlorophyll-α, was derived from Rijkswaterstaat's data from the Eastern Scheldt, where several locations in the Eastern Scheldt have been measured for over 15 years (Rijkswaterstaat, 2019). These data were used for our estimate because shellfish (mussels and oysters) are cultivated successfully in this area, which leads us to believe that this range of chlorophyll-α is appropriate to ensure proper food availability. However, note that this is an assumption, and more research is needed to obtain exact estimates of tolerated and maximum ranges. The data derived from Rijkswaterstaat about the chlorophyll-α concentration in the Eastern Scheldt show that during the growing season of shellfish (March-November) chlorophyll-α concentrations ranged from 0,37- 52 µg/L, with an average of 6,35 µg/L. During wintertime the concentrations were usually around 0. As we know that shellfish growth and chlorophyll-α concentration are dependent on the season, we assume that the growing season (here, taken to be March-November) levels are most important. Therefore, we focused on these months instead of taking a year-round average.

Turbidity and sunlight

As suggested earlier, sunlight does not appear to have a direct influence on mussel growth - rather, it affects them indirectly by increasing the water temperature and food availability, since phytoplankton needs sunlight and warmer temperatures to grow (Tyler-Walters, 2008). High turbidity can be both positive and negative for blue mussels, depending on the source of the turbidity. When turbidity is caused by an abundance in algae, it can't hurt since algae are a viable food source for mussels. However, when turbidity is caused by suspended sediment it could cause the mussels to suffocate and decrease primary production, which reduces food availability. The latter is less of a problem since mussels have a varied diet, as mentioned under "Food indicator" (Tyler-Walters, 2008). The suffocation of mussels is most likely caused by prolonged exposure to (or, the volume of) turbid water; Mainwaring *et al.* (2014) hypothesized that filtering larger volumes of turbid water exhaust the mussel, causing it close its shell and die (Mainwaring, Tillin, & Tyler-Walters, 2014).

Tidal flow

Mussels can be found in weak to strong tidal streams, meaning that they are exposed to the air from time to time (Tyler-Walters, 2008). Since mussels can only feed themselves when they are submersed, being exposed alters their ability to feed and consequently their metabolism, resulting in slower growth rates found in mussels higher up the shore (Buschbaum & Saier, 2001). Van Broekhoven (2010) describes that mussels cultivated in the Eastern Scheldt are placed in water depth of -2m NAP to -25m NAP, for practical reasons and tidal exposure (Van Broekhoven, 2010). Tidal exposure poses a risk for mussels; over time (with increasing mussel bed size) the mussels more attached to each other rather than the substratum, as a consequence of the mussel mud layer (faeces, pseudo-faeces and sediment) built by the mussels to which they cannot attach (Mainwaring et al., 2014). The result of the strong attachment to each other instead of the substratum makes them more susceptible to removal by waves (Tyler-Walters, 2008).

2.2.2 Flat and pacific oyster (*Ostrea edulis, Crassostrea gigas*)

Currently, two oyster species are cultivated in Zeeland, the Netherlands. In the beginning of the 20th century only the flat oyster (*Ostrea edulis*) was cultivated, but the combination of the severe winter of 1962, and a disastrous disease nearly decimated the entire stock (Drinkwaard 1998). Therefore a new oyster species, namely the pacific oyster (*Crassostrea gigas*), was introduced. The pacific oyster was released in the delta under the assumption that the pacific oyster would not reproduce in the Netherlands. This assumption proved to be incorrect: uncultivated pacific oysters are now found along the Dutch coastline of the Netherlands (Drinkwaard, 1998). The flat oyster is nowadays ecologically extinct, however recently a local population in the Voordelta area of the Dutch coast was found (Christianen et al., 2018).

Today, the pacific oyster is the most cultured oyster species in Zeeland, due to its fast growth and high resilience, while the flat oyster is a less popular species to cultivate. Yet, significant effort is paid to restore this native oyster species by different organizations, such as the Platte Oester Consortium (POC). To determine if the cultivation of both oyster species is compatible within the DELTA21 plan, it is important to know their ecological requirements, and compare them with expected values in the future Haringvliet. Data on their requirements can be found in Table 1. The most important requirements are further explained below. Some additional information on other relevant parameters, such as diseases, are also mentioned. In the Appendix I, more information gathered from the existing literature can be found.

Salinity

The tolerated salinity levels differ slightly between the two oyster species. The tolerated range is 10-35 ppt for the pacific oyster, while the flat oyster tolerates values between 18-40 ppt (Helm, 2005; Perry, 2017). The salinity for optimal growth is between 20-25 ppt for both species (Helm, 2005). Growth is hampered when the salinity is less than 10 ppt (Mann, 1991). The larvae of the two oyster species reach optimal growth under different salinity levels; the flat oyster prefers salinity levels between 25-35 ppt (Davis & Ansell, 1962), while the pacific oyster larvae reach optimal growth at 25 ppt but values higher than 30 ppt significantly reduce growth (Helm & Millican, 1977). For both species, the salinity tolerance is dependent on the water temperature. Namely, at lower temperatures, the oysters are more resistant to low salinity (Hutchinson & Hawkins, 1992). Oysters can survive a short time as well in freshwater. A study settled *C. gigas* for 18 hours in freshwater to determine the removal of fouling species around *C. gigas* and the mortality of *C. gigas*. During this 18 hours freshwater bath, no *C. gigas* died – unfortunately the temperature of the fresh water was not described in this study) (Haupt, Griffiths, & Robinson, 2012).

Temperature

Water temperature is different for the two oyster species. For the pacific oysters, temperatures between -1.8 – 35 °C are tolerated. For growth, temperatures between 11-34 °C are preferred (Mann, 1991). Juveniles are able to survive at low temperatures but duration of exposure to low temperatures matters: weeks-long exposure to water temperatures of 3 °C will cause significant mortality among juveniles (Child & Laing, 1998). For the flat oyster, temperatures are optimal for growth between 17-25 °C (Hutchinson & Hawkins, 1992), although another study mentioned an optimum temperature around 27.5 °C (Buxton, Newell, & Field, 1981). Above 30 °C, growth is poor for pacific oysters; this could also be explained by the related lack of oxygen (Buxton et al., 1981). Below 10 °C, the flat oyster goes into a winter metabolic state, which makes them able to survive cold temperatures and low salinity levels (Hutchinson & Hawkins, 1992). The pacific oyster spawns at a minimum temperature of 16-18 °C. Optimal temperatures for its spawning are 20-25 °C (Mann, 1991). Moreover, the pacific oyster will not spawn at water temperatures above 34 °C. For the flat oyster, spawning has been found to occur above 15-16 °C, although exact estimates differ per region (Korringa, 1952). Moreover, it has been shown that, in the same estuary, duration and timing of spawning events differ between the species; pacific oysters in the Eastern Scheldt spawn between mid-July and August, while the flat oyster spawns the whole summer but peaks during June and July (Cornelisse, 2019; Korringa, 1952).

Water depth

The pacific oysters is found at depths between 0 and 41 m in the Eastern Scheldt (Kater, 2003). Flat oysters are found even deeper, namely at 80 m (Perry, 2017). Although this range is extremely broad, profitable cultivation is only possible at shallower depths; according to two interviewees, the maximum depth for oyster farms lies between 7-10 meters (Cornelisse, 2019; Nelis, 2019). Oysters that live in deeper waters, will grow slower and have a significantly lower final oyster volume, while oysters in shallower waters have a higher cumulative mortality (Cassis, Pearce, & Maldonado, 2011).

Water speed and exposure time

The required water speed for the pacific and flat oyster is 20 – 50 cm/s. With a (prolonged) low water speed, the oysters do not obtain enough oxygen and food. If the water speed is too high, the oysters are not able to filter the nutrients and food out of the water (Perry, 2017). Note that oysters which live in high water speeds, require a harder substrate, to prevent them from being swept away by the current (Lengkeek et al., 2017).

The exposure time of an oyster is the time an oyster is exposed to the air instead of the water, due to tidal influences. The optimal exposure time for the pacific oyster is 20%, but when the exposure time is 40-50%, a significant decrease in health was observed (Folmer et al.). A lower exposure times causes hydrodynamic stress, but if the exposure time is too high, the Pacific oysters does not have enough time for filter feeding. In general, there is a negative correlation between exposure time and shell or meat growth (Walles et al., 2016). Yet, oysters can survive above the water level for weeks (Yonge, 1960), or 24 days (Korringa, 1952). Note, however, that these duration estimates are based on research on packaged oysters under fridge temperatures. Under natural circumstances, it seems the oyster would not survive long due to suffocation. According to an interviewee, oysters tolerate an exposure time of one week during the winter, but in summer it is approximately one day (Cornelisse, 2019).

Bottom type

Hard substrate such as rocky bottoms are suitable for oysters, as are other oysters, mussel bed or other shells (Reise, 1998). Sandy and sludgy bottoms are also suitable, as long as there are enough shells and stones for the oysters to attach to (Reise, 1998). For natural oyster bed development, availability of settlement substrate is one of the most important conditions (Brumbaugh & Coen, 2009). A solution to cultivate oysters when the bottom not suitable is the bottom-off technique. With this technique the oysters are grown in nets on tables of the bottom. The advantage is the oysters will not be buried in the sediment with this technique (Walton et al., 2012).

Feed indicator

The pacific and flat oysters are dependent of chlorophyll-α, as this is the main indicator of food availability. No data on the exact requirements for oysters in terms of chlorophyll-α availability could be obtained. To obtain a rough estimate of the tolerated range of of chlorophyll-α, data of availability of chlorophyll-α concentration in the Eastern Scheldt were used. For more information on these ranges, see the description about this parameter in the section about the Blue mussel.

Turbidity and sunlight

Sunlight availability does not have a direct effect on oysters, although darker places are preferred by flat oyster larvae looking to settle (Cole & Jones, 1939). Indirectly, it does have an effect, as light levels influence phytoplankton abundance. Turbidity have a positive and negative effect on oysters, dependent on its sourcy: more algae in the water means more food in the water, which is positive for the oysters. Conversely, turbidity can influence the oysters negatively, when the turbidity is caused by suspended sediment particles. This obstructs the gills of the oysters, which means the oysters cannot feed anymore or become less efficient at doing so (Perry, 2017).

2.2.3 Seaweeds

A starting point for the exploration of seaweed aquaculture potential in the DELTA21 context is a focus on currently cultivated species in The North Sea or Eastern Scheldt (The Netherlands). The four endemic species with the most potential for commercial cultivation are the following (Reith et al., 2009; Van den Burg et al., 2013):

- *Laminaria digitata* (finger kelp, brown seaweed)
- *Saccharina latissima* (sugar kelp, brown seaweed)
- *Palmaria palmata* (dulse, red seaweed)
- *Ulva lactuca* (sea lettuce, green seaweed)

For the selection of suitable cultivation areas for these seaweed species, the most defining abiotic requirements are salinity, temperature, water depth and water speed according to interviewees (Leeuwen, 2019; Veen, 2019) (Table 1). Below, these abiotic requirements are further specified for each seaweed species. Additionally, light conditions are briefly discussed.

Salinity

Two aspects of salinity are important for seaweed cultivation, namely optimal salinity and fluctuations in salinity (Leeuwen, 2019; Veen, 2019). The preferred salinity differs per seaweed species. The preferred salinity for *L. digitata* and *P. palmata* is 30-40 ppt , whereas for *S. latissima* (also a kelp species) this ranges between 25-31 ppt (Hill, 2008a; Veen, 2019; White, 2007). Additionally, tolerance for divergence from optimal salinity differs strongly per seaweed species; *L. digitata* and *S. latissima* (kelps), have zero tolerance for fresh water exposure, whereas *U. lactuca* is known to tolerate brackish conditions (Pizzolla, 2008). The red seaweed *P. palmata,* can tolerate minor changes in salinity (Robbins, 1978).

Temperature

The preferred temperature varies strongly between seaweed species; *L. digitata* and *S. latissima* are winter species, whereas *P. palmata* and *U. lactuca* grow in summer period (Van den Burg et al., 2013).

Winter species (kelps) prefer water temperatures between 4 and 17 ℃ (Lee & Brinkhuis, 1988), whereas summer species prefer temperatures between 15 and 20℃ (Keesing, Liu, Shi, & Wang, 2016; Leeuwen, 2019; Van den Burg et al., 2013).

Water depth

Intermediate water depths seem to be the most promising for seaweed cultivation, mostly because of practical reasons related to the cultivation system used. Current seaweed cultivation practices in the sheltered areas of the Eastern Scheldt (Jacobahaven and Schelphoek on Schouwen-Duivenland), use long ropes and buoys anchored to the bottom (SHH, 2019; Zeewaar, 2019). In the North Sea, a wheel based system with a diameter of 5 meters is used, on which seaweed is grown at a depth of around 2 meters (Groenendijk et al., 2016). In both systems, the seaweed is floating in the water column, and not directly influenced by water depth. However, water depth was mentioned by seaweed cultivation sector to be important criteria in site selection by interviewees (Leeuwen, 2019; Veen, 2019). A possible explanation for this is that water depth is indirectly linked to turbidity, and seaweeds prefer minimal turbidity as they require irradiation (light) for photosynthesis. Therefore, minimum 10 meter water depth is preferred for a seaweed cultivation sites (Leeuwen, 2019). An interviewee also emphasized shallow depths are preferred, to minimize the length of (costly) chains to the anchors at the bottom (Veen, 2019).

Water speed

Seaweed cultivation theoretically benefits from both high water speed (because of higher nutrient supply, perpendicular position to incident light), and low water speed (because of a reduced risk of detachment from cultivation system). The importance of these factors for the successful cultivation of seaweed varies strongly between seaweed species. For example, kelp species (*L. digitata* and *S. latissima*) have a flexible morphology, which causes reduced leverage on the line. Thereby, the chance for the seaweed to be turned over by wave movement is reduced (White & Marshall, 2007). Therefore, these species have a solid attachment to the cultivation lines and prefer stronger water speeds. In contrast, *U. lactuca* (sea lettuce) has a small hold-fast and is never found on exposed rocky shores (Pizzolla, 2008). Thus, cultivation of this seaweed species requires more sheltered areas, in order to prevent free floating under harsh conditions. Red seaweed *P. palmata* (dulse) are sensitive to damage by high water speeds (Hill, 2008b).

Feed indicator

Chlorophyll α is measured to indicate the food availability for shellfish, but this indicator is not relevant for seaweed, as they require a variety of nutrients for survival and growth (Harrison & Hurd, 2001). The two main nutrients are Nitrogen (N) and Phosphorus (P) of which the first is the most limiting in saltwater systems (Harrison & Hurd, 2001). The seaweeds studied in this report use all the available nitrogen sources and nitrogen availability it should therefore be ensured that it is sufficiently present (Van den Burg et al., 2013).

Light attenuation

No data was found about the exact light attenuation requirements of the four seaweed species, however it is known that green seaweed (Ulva) grows on the water surface, requiring light for growth, and brown (Laminaria and Saccharina) and red (Palmaria) seaweed species grow deeper in the water column, requiring less light for growth (Branderburg, 2016).

2.3 Environmental conditions of the future Haringvliet and tidal basin

Below, a description is given of environmental conditions that are hypnotized to occur in the western Haringvliet and the tidal basin if DELTA21 is implemented. The focus of this description is mainly put on environmental conditions that are important for realizing aquaculture.

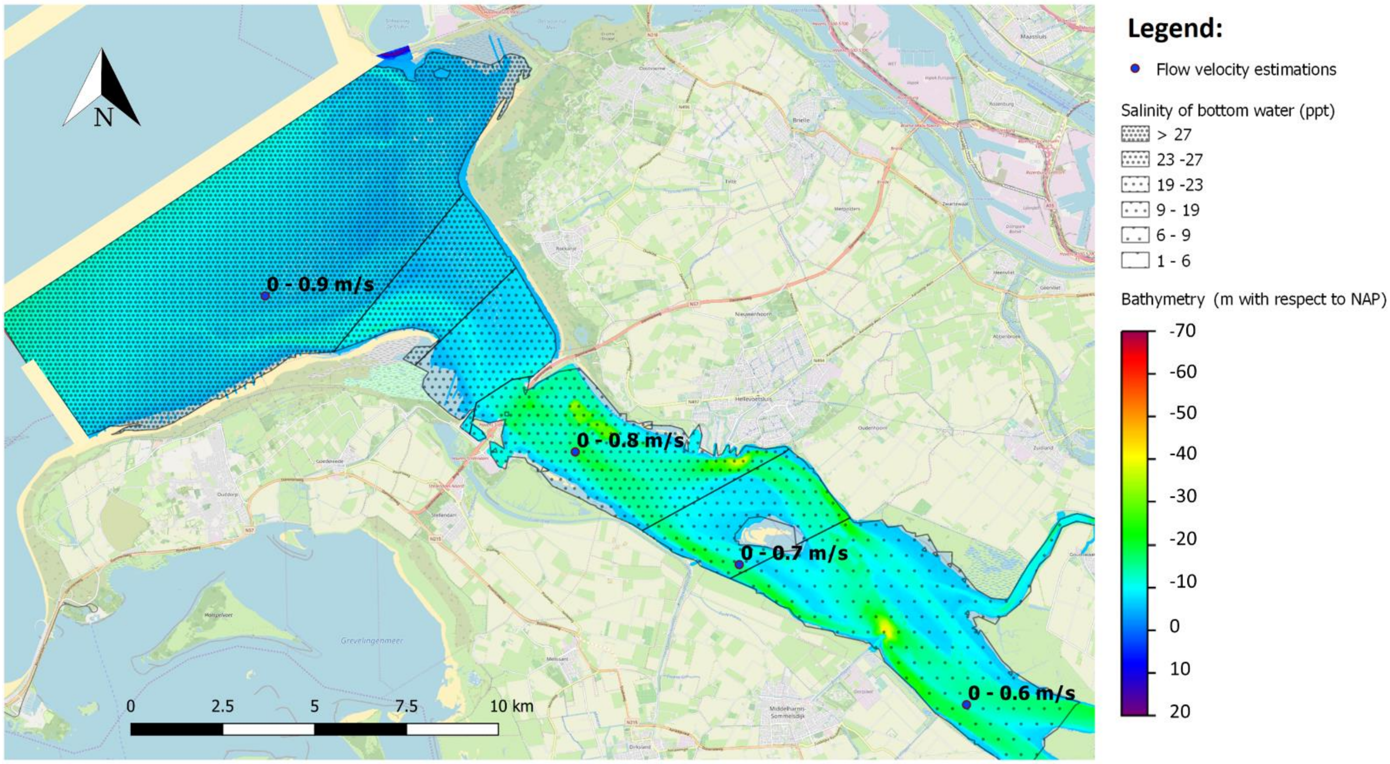

Figure 3 On this map, the water depth and salinity of the western Haringvliet and tidal basin are displayed (Rijkswaterstaat, 2018). The salinity gradient concerns that of the bottom waters (lower water column) during a discharge of 1210 m3/s and high tide based on measurements that date from before the closure of the Haringvliet (Wolff, 1973). Assumed is that the salinity gradient in the DELTA21 scenario could be similar, since it is estimated that the annual average discharge is approximately 1500 m3/s (Berke & Lavooij, 2019). It should however be noted that (1) the discharge and salinity gradients are variable throughout the year (2) the salinity of the upper water column may be lower and (3) the salinity gradient as depicted in this map might deviate from the DELTA21 scenario due to the influence of constructions that have been build or will be build that were not present before the closure of the Haringvliet.

2.3.1. Salinity

Currently, the Haringvliet is disconnected from the North Sea by the Haringvliet sluices. The Haringvliet contains fresh water. After realizing the DELTA21 plan, the western part of the Haringvliet will be reconnected with the North Sea by opening the Haringvliet sluices, and saline water will be reintroduced in the western part of the Haringvliet. A construction southwards from the island of Tiengemeten will separate the fresh water zone from the salt water zone, and a brackish water zone will be created in between (Fig. 4). The salinity in the future Haringvliet is still likely to be influenced by the Rhine river as the water will continue to be discharged to sea via the Haringvliet. Because the river discharge is variable, the salinity is also expected to fluctuate in the Haringvliet during different stages of river discharge (Wolff, 1973). It should be noted that the influx of fresh water could rise significantly. A discharge of 10.000 m3/s, which occurs roughly less than once in ten years, is seen as the capacity of the Haringvliet according to the 'water safety' desk study of DELTA21 (Berke & Lavooij, 2019).

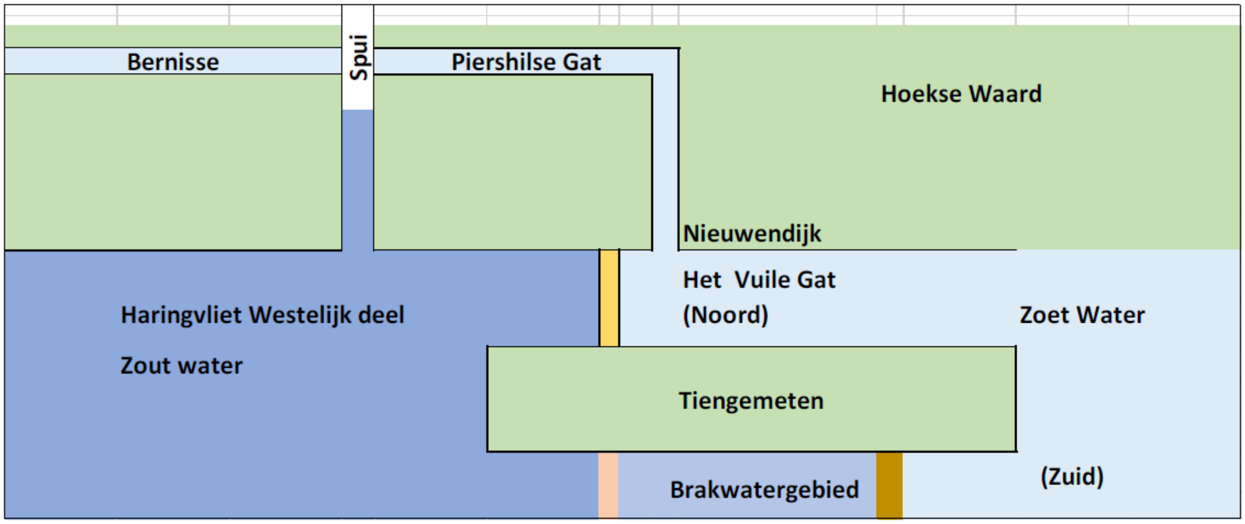

Figure 4 Schematisation of the design of the Haringvliet after completion of the DELTA21 plan. The western part of the Haringvliet will become saline ("Zout water") due to opening of the Haringvliet sluices, and the eastern part will remain fresh ("Zoet water"). The fresh water part will be separated from the salt water part by a spillway in north of the island of Tiengemeten, which will only be used during times of extreme discharge, and a brackish water zone in the south. The brackish water zone ("Brakwatergebied") will bordered by a spillway on the eastern side, from which fresh water inflow occurs, and a dam on the western side through which water exchange with the saline water zone occurs (Berke & Lavooij, 2019).

In the 'water safety' desk study of the DELTA21 plan, it has also been stated that it is expected that the salinity in the Western part of the Haringvliet, up to the eastern dam at the island of Tiengemeten will vary between 30 and 20 ppt, after realization of the spatial interventions (Berke & Lavooij, 2019). It was also stated that the salinity can drop to 15 ppt at discharges larger than 5000 m3/s.

Yet, historic data has shown that the salinity in the Western part of the Haringvliet was lower. Maps of the salinity in the Haringvliet during different discharges are added in Appendix III. The records involve salinity of the lower water column, which is the most saline layer of water. Other data of salinity in the upper water column shows that there was stratification, and that the salinity of the upper water column could be considerably lower (Peelen, 1967). Still, this historical bottom salinity is considered, although we recognize it might provide a somewhat 'optimistic' version of salinity. The border between fresh and brackish water at the bottom (0.5 ppt) was located between the Haringvliet and Hollands Diep during times of average discharge (1210 m3/s at Willemstad) and high tide (Wolff, 1973). At the mouth of the Haringvliet, the salinity was in between 20 and 30 ppt. During times of low discharge (450 m3/s at Willemstad) and high tide, the salinity varied between 14 ppt and approximately 30 ppt in the western part of the Haringvliet. During times of high discharge (4000m3/s at Willemstad) and high tide, the salinity varied between 0.18 and 10 ppt.

Additionally, a recent 2D modelling study also indicates that the salinity in the western part of the Haringvliet might be even lower when reconnected with the North Sea (Kort & Rooij, 2013). The study involved a scenario in which the Haringvliet sluices are opened and a barrier island is constructed in front of the mouth of the Haringvliet. In this scenario, the barrier island attenuates the tides but does not shut off the Haringvliet completely from the North Sea. A discharge of 600 m3/s was taken for the Haringvliet. The location of the barrier island is slightly similar to that of the eastern boundary of the Valmeer in the DELTA21 plan: it is located 3 km westwards from the location of the eastern boundary of the Valmeer. It was found that the barrier island has a considerable influence on the salinity in the western Haringvliet: at the moment that the salinity intrusion was the largest, the barrier island lead to a reduction in salinity of 25% at 10 km from the mouth (near Middelharnis) with respect to the scenario in which there is no barrier island. Even in the scenario in which there was no barrier island, the salinity at Middelharnis was already low (around 3.5 ppt).

Historical data and the modelling study that are mentioned suggest that the salinity in the western Haringvliet may be relatively low compared to the salinity of seawater. Especially since the length of the estuary is increased after constructing the Valmeer and since the tidal influx is expected to be hampered by the construction that will be built between the island of Goeree and the Valmeer (the dam with tidal inlets) (Fig. 3). These changes are likely to decrease the intrusion length of saline water. The construction at the island of Tiengemeten may also influence the salinity gradient in the western Haringvliet in an opposed way however when the inflow of fresh water is hampered, but the effects have not been studied in detail yet. Therefore there is still a large uncertainty.

Other historical data, namely data on aquaculture activity in the Haringvliet area, seems to paint a similar picture. Despite the limited data on the subject, we found an article exploring the economic and social effects of the Delta governance introduced in 1957 (Rijneveld, 1963). This article is directed at employers as well as employees in the oyster- and mussel cultivation sector. None of the companies described in this article were located in the Haringvliet - instead, they were centered in the Eastern Scheldt and the Grevelingenmeer. Also, more recently, mussel and oyster bank restoration efforts were taken at a tidal flat near the mouth of the Haringvliet named the Hinderplaat. In this experiment, the complete oyster population, and almost the entire mussel population did not survive the year (Sas et al., 2018). The authors of this report named freshwater influxes as the most likely culprit. Although not conclusive, the historic evidence (namely, the absence of the aquaculture sectors under comparable river discharge (and predicted salinity)) as well as more recent trials seem to point in the direction that salinity gradients or fluxes in an open Haringvliet would be unfavourable for shellfish cultivation.

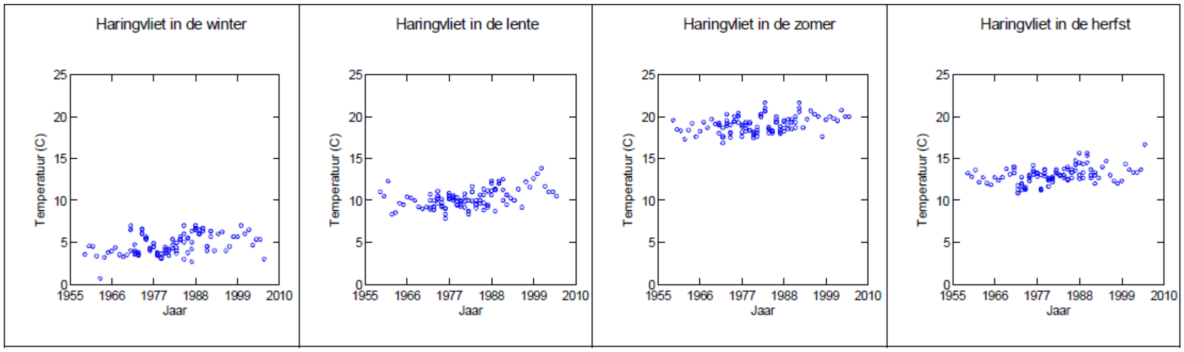

Figure 5 Observed average seasonal temperature in the Haringvliet between 1955 and 2010 (Wijnhoven, 2007). The years are displayed on the horizontal axis and the average water temperature (°C) is displayed on the vertical axis. Seasons from right to left are: winter, spring, summer, autumn.

2.3.2 Temperature

The average seasonal water temperature of the Haringvliet from 1955 up to 2010 is shown in Figure 5. This data shows that during winter, the water temperature fluctuates mainly between 0 and 8 ̊C. During spring, the water temperature rises up to between 8 and 15 ̊C. In summer, a maximum of approximately 20 ̊C is reached and the temperature drops back to around 15 ̊C in autumn. For the tidal basin, it is also assumed that the water temperature varies between 20 and zero degrees celsius during the year, since this is also the case for similar areas located nearby, such as the Western Scheldt (Vroom, Van Gils, & Holzhauer, 2012). In the Western Scheldt, the water temperatures at measured points show similar variations up to a data collection station 20 km offshore from the estuarine mouth.

2.3.3 Water depth

Figure 3 shows maps of the bottom height of the Haringvliet and the foreshore. The depth of the Haringvliet varies approximately up to a maximum of 30 meters, with an average depth of 8 meters. Shallower parts and flats can be distinguished, like the Slijkplaat near Hellevoetsluis, the Tiengemeten island and the Verjagersplaten which are located between Tiengemeten and the Hellengatsdam. The shallower parts are surrounded by deeper channels. Especially in the western part there are some deeper borrows, for example near the mouth of the Spui, near Hellevoetsluis and behind the Haringvliet sluices. The part of the foreshore on which the tidal basin will be constructed is relatively shallow, varying from 1 to 10 meters in depth, with an average depth of 3 to 4 meter (Berke & Lavooij, 2019). In front of the Haringvliet sluices, a tidal flat is located, called the Hinderplaat. The depth of the North Sea bottom increases westwards (Wijsman et al., 2018).

2.3.4 Tidal influence

In a model study that calculated water levels in the Haringvliet in case the Haringvliet sluices only functioned as a storm surge barrier, the average water level was 0.25 meter above NAP (Wijsman et al., 2018). In this scenario, the water level in the western part of the Haringvliet and the tidal basin will vary between -0.65 meter and 1.15 meter with respect to NAP (Wijsman et al., 2018). The model study shows that when climate change is also taken into account, using the 'warm' variant of the KNMI climate scenarios for 2050, average water levels between tides (i.e. mean sea level) are expected to have increased to 0.61 meter above NAP (Wijsman et al., 2018). In the KNMI 14 W scenario a global temperature rise of 2 C to 2050 is taken as an estimate (KNMI, 2015). In the

DELTA21 plan, the water level in the tidal basin and the western part of the Haringvliet will be kept below 1.5 meters NAP (Berke & Lavooij, 2019).

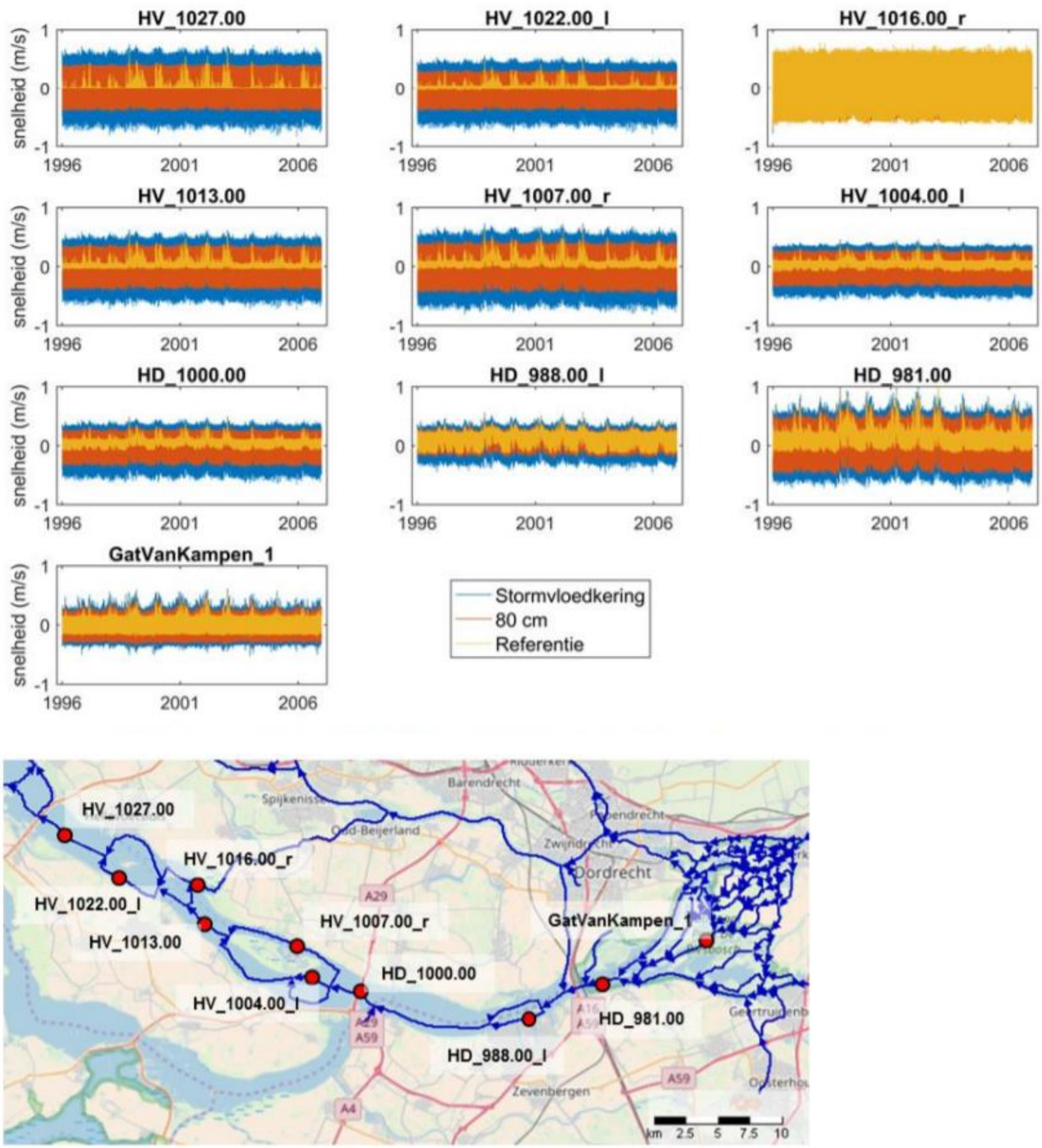

Figure 6 Modelled flow velocities in the Haringvliet between 1996 and 2006 with SOBEK-3 for different scenarios (Wijsman et al., 2018). The velocities are shown in the graphs (vertical axis) and the locations are shown on the map below. Three scenarios are shown: 1) The Haringvliet sluices are fully opened and are only used as storm surge barrier (blue). 2) The Haringvliet sluices are opened that far that a tidal amplitude of 80 cm is maintained in the Haringvliet (red). 3) The Haringvliet sluices are managed as usual and only opened during neap tide for water discharge (orange).

2.3.5 Water speed

The water speed has changed since the Haringvliet was disconnected from the sea. Before the construction of the Haringvliet Sluices, the stream velocity varied between 1.60 and -1.30 m/s at Hellevoetsluis (where a positive velocity is directed seawards). After the construction of the Haringvliet sluices, the velocity reduced to below 1m/s. The water velocity in the Haringvliet was modelled with Sobek-3 (N.B. a hydrological model) for different scenarios (Wijsman et al., 2018). Figure 6 shows an overview of the results of the modelling study, where the storm surge barrier scenario describes the expected situation when the Haringvliet sluices are fully open and only used as storm surge barrier. The model shows that even in this scenario the flow velocity at different locations within the Haringvliet will not reach the original flow velocity, and will remain below 1 m/s. In the future perspective of DELTA21, it is probable that the flow velocities will be even lower than the modelled velocities in the storm surge scenario, due to the construction of another storm surge barrier between the Valmeer and the head of Goerree which could attenuate the tidal currents in the area. For the tidal basin, it is also assumed that the flow velocity will remain below 1 m/s and will be similar to the flow velocities in the Eastern Scheldt estuary since those areas are both separated from the north sea by a storm surge barrier. In the Eastern Scheldt estuary, the average flow velocities generally vary between 0 and 0.6 m/s (Wijsman et al., 2018). A modelling study of the flow velocities in the Eastern Scheldt during spring surge showed that the maximum flow velocity in the Eastern Scheldt was around 0.9 m/s (Rijkswaterstaat, 2012). It should be taken into account that flow velocity varies throughout the cross section of the Haringvliet and the tidal basin: higher velocities are reached in the channels and lower velocities are reached in the shallow areas (Rijkswaterstaat, 2012).

2.3.6 Bottom type

The tidal flats top layers consist predominantly of medium-fine sand (more medium grain size sand at the future tidal basin, and some parts with finer sand more inlands), with varying degrees of humic substances mixed in (DINO; Hagenbeek, 2016). At some locations, in an effort to cover up a contaminated soil, 160.000 m^3 of clayey soil was spread out near the island Tiengemeten in 2003 (Mensink, 2003). Little is known about the roughness (e.g. presence of gravel, covels and boulders) of the riverbed.

2.3.7 Food indicators: ammonium and chlorophyll-α

Table 2: Depicted here are average, minimum and maximum chlorophyll-α (ug/L) content at three different locations in near the Haringvliet between 2004 and 2017 (except for Goeree, where data collection started in 2007). Moreover, a distinction is made between the entire year, and the growing season (March-November) (Rijkswaterstaat, 2019).

Area	Whole year			March-November		
μg/L	Min	Average	Max	Min	Average	Max
Buitensluis	1	6.57	77	2	9.58	77
Haringvlietsluis	1	4.97	40	2	6.20	11
Goeree	0	7.38	56	0	9.39	56

From the time of the closure of the Haringvliet, the concentration of ammonium has been lowered considerably. It has dropped from 4 mg/l from 1970 to around 0 mg/l today (Wijsman et al., 2018).

Chlorophyll α estimates found in Table 2 were based on Rijkswaterstaat its measurements at data collection points Buitensluis, Haringvlietsluis, and Goeree (2 km from the coast). The data at these collection points show the gradient in chlorophyll α from land to sea measured in the period from 2004 (Buitensluis and Haringvlietsluis) or 2007 (Goeree) till 2017. The two extremities of this gradient (i.e. Bovensluis is the most inland point and Goeree the most seaward point) are not expected to change drastically due to the DELTA21 implementation.

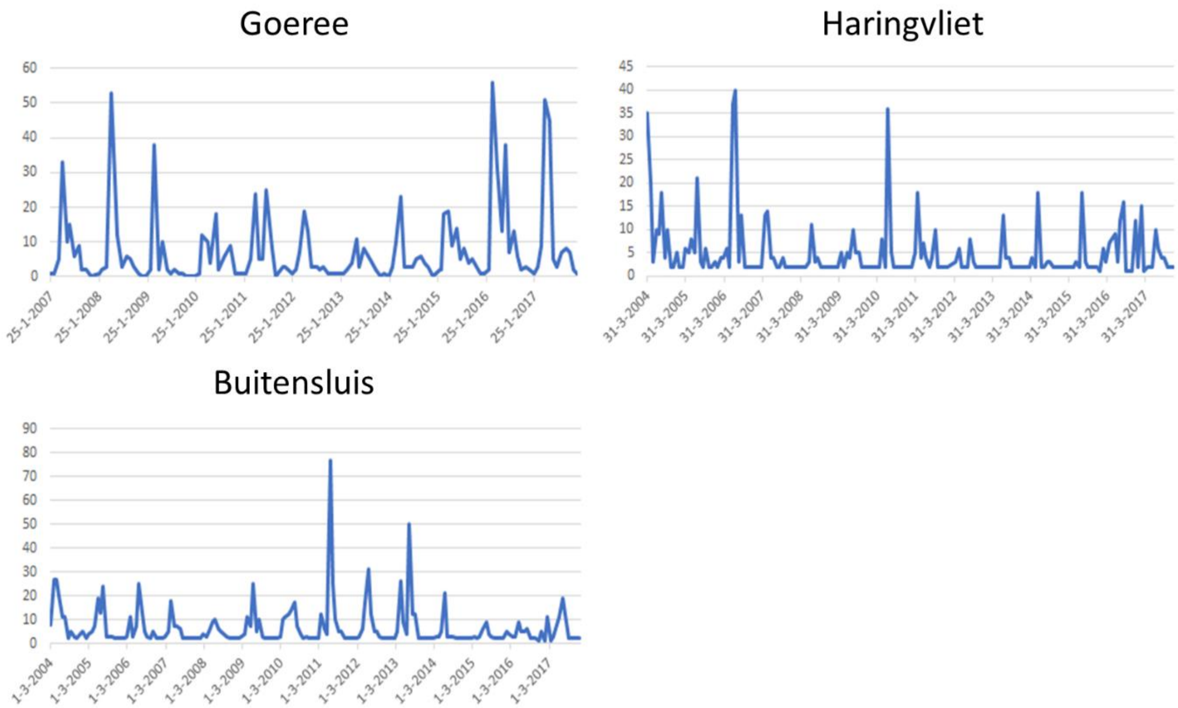

Figure 7 Chlorophyll α (μg/L) concentrations at three Rijkswaterstaat collection points in or near the Haringvliet (Rijkswaterstaat, 2019).

After implementation of the DELTA21 plan, the more in-land section of the Haringvliet is likely to have similar chlorophyll α loads as Buitensluis, and the eastern part of the tidal basin (which starts near the Haringvlietsluis and ends near the western part of Tiengemeten) is likely to have higher values than are observed now, as water near Goeree can flow into the area during high tide. The western part of the tidal basin will likely keep the same levels of chlorophyll α as are observed now, as sea water will continue to have a large impact on the observed levels near Goeree. The range of chlorophyll α is large, and the exact loads vary over time. Figure 7 shows that chlorophyll α loads reach typical peak values around March, after which they decline to the lowest values in their range in winter (NB sometimes there is a second peak in autumn).

2.3.8 Light attenuation

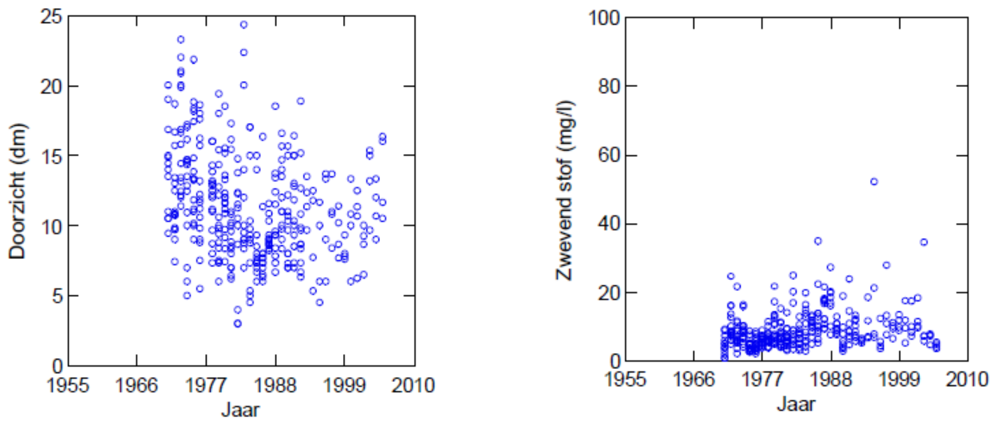

Figure 8 Left: transparency (“doorzicht”) of the Haringvliet in dm. Right: Suspended particles (“zwevend stof”) in the Haringvliet in mg/l. (Wijnhoven, 2007).

The visibility of the Haringvliet has been decreased since the closure of the Haringvliet (Fig. 8). The visibility varied between 5 and 25 dm before closure, but decreased to 15-20 dm throughout the years. The amount of suspended particles in mg/L has varied between 0 and 20. For the tidal basin, it is expected that the visibility will be smaller than 20 dm and the amount of suspended particles for the tidal basin could probably vary between 10 and 100 mg/L, since this is currently also the case for similar areas such as the Western Scheldt estuary (Vroom et al., 2012).

Key points Chapter 2

- Table 1 provides information about the most important environmental requirements for seaweed and shellfish cultivation as well as the expected conditions in the Haringvliet and tidal basin.
- Data is available regarding shellfish and seaweed cultivation, this can be used as a starting point for possible implementation.
- There is large uncertainty regarding some of the expected conditions in the Haringvliet and tidal basin, mainly regarding the salinity.
- Historic data and recent trials point in the direction that salinity gradients in an open Haringvliet would be detrimental for shellfish and seaweed cultivation.

Chapter 3 – Scenario sketch

3.1 Introduction

In this output, a scenario sketch is drafted to spot and illustrate bottlenecks and opportunities for aquaculture in the western Haringvliet and the tidal basin. Attention was paid to the requirements of the seven species described in output 1, namely the blue mussel, flat oyster, pacific oyster, and four seaweed species (finger kelp, sugar kelp, dulse and sea lettuce). These species all have slightly different requirements for growth, which is why different areas within the Haringvliet and tidal basin may be suited for different species, although the data are too rough to make different estimations for the separate shellfish species and seaweed species. The information about the requirements for each species and the predicted environmental conditions were taken from Chapter 2. The requirements of which we had relatively detailed spatial information were salinity, water depth and flow rate, and based on these requirements areas within the Haringvliet and tidal basin were identified which met most requirements.

Often case, only rough estimates about environmental variables are known. This has various reasons. Firstly, there are only limited data available on what the situation was before 1970, when the Haringvliet was still fully connected with the North Sea. Secondly, not all environmental variables have been recorded with great detail or are open to the public. Lastly, no model study has looked into the effect of the spatial interventions planned in DELTA21 and the proposed environmental alterations on environmental conditions. The result of this is, that no hard claims can be made about what exactly the possibilities for integrating aquaculture in the Haringvliet and tidal basin are, especially regarding the expected salinity. In this light we chose to only look at areas in the tidal basin and the westmost part of the Haringvliet (see map below), as data for the eastern Haringvliet were even more uncertain. To be able to sketch a possible scenario for aquaculture despite the prevailing uncertainties we chose to work with the expected salinities as derived from historical data.

In Figure 9, a map is drafted to indicate in which areas follow-up research could be conducted to test the suitability for aquaculture, per aquaculture sector (i.e. shellfish or seaweed cultivation). The hatched areas green and red show the zones which are considered to have the most potential for the shellfish and seaweed cultivation sector respectively. These areas overlap as the data used for the map is not detailed enough, especially since the species prefer almost the same habitat, and can grow and survive in the same habitat. The area in the South-West corner of the Valmeer was marked differently, because of additional uncertainty: according to the DELTA21 plan, this area will be the in- and outlet of water for the tidal basin. Therefore, we expect high flow rates (and navigation) in that area, which could make this location unsuitable for aquaculture. However, since this is still uncertain, this area is marked as a possible location, provided that the flow rate will not exceed critical levels. Below the map a further explanation can be found which discusses the locations of the possible cultivation sites of the different species in more detail.

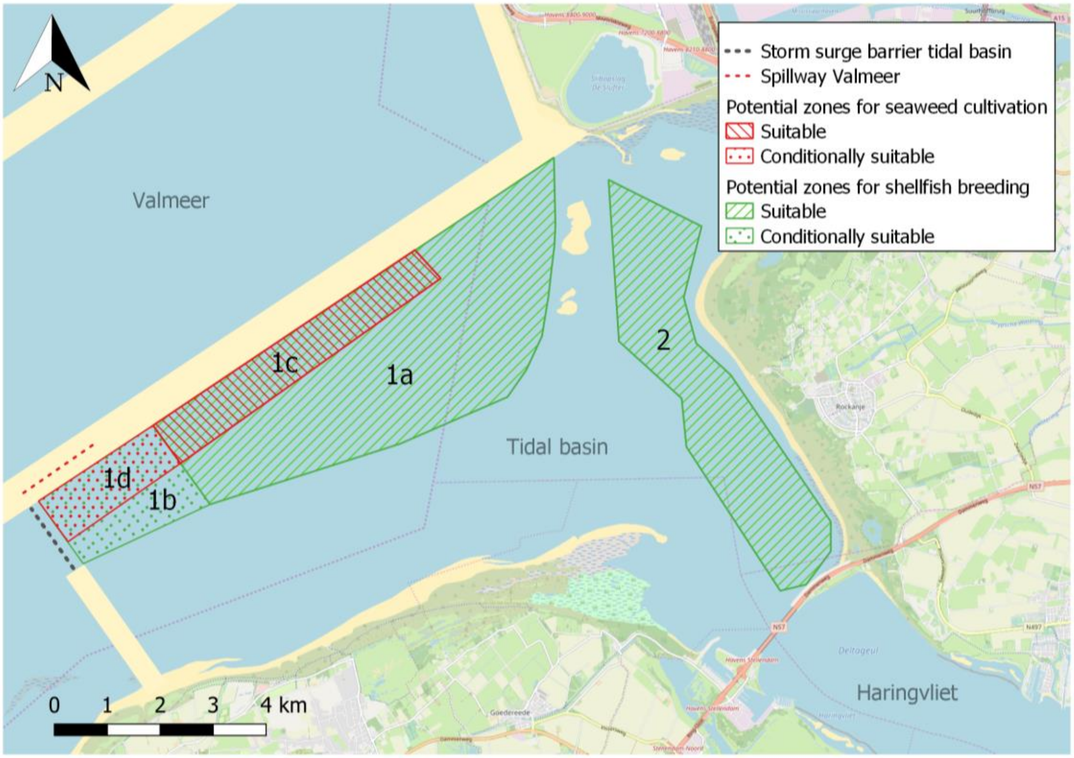

Figure 9 The map shows potential zones for aquaculture. The green areas shows the potential shellfish cultivation (1a, 1b, 2), the red areas are the potential seaweed cultivation zones (1c, 1d). Dashed areas indicate the zones are suitable, while the dotted areas are only suitable under specific circumstances.

3.2 Mussel and oyster placement possibilities

As mentioned in chapter two, under optimal circumstances for the blue mussel, 1) salinity ranges between 30-40 ppt, 2) the water current ranges between 20-80 cm/s and 3) they are cultured at a water depth of 0-10 meter(s). Moreover, the pacific as well as the flat oyster species require: a salinity of 20-25 ppt, a waterflow between 0.2-0.5 m/s and a maximum depth of 10 meters. While temperature is important for shellfish cultivation, the temperature does not seem to differ significantly between areas in the Haringvliet. Furthermore, the temperature in the future Haringvliet will approximately be the same as in the Eastern Scheldt, in which cultivation currently occurs. Therefore, water temperature will be considered generally suitable for mussels in the whole area.

The tidal basin has some areas, which seem potentially suitable for shellfish cultures (Fig. 9). The salinity in these areas are thought to range between 19 ppt west of the Haringvlietsluis and more than 27 ppt near the Valmeer and the opening of the future estuary. Given these assumptions the salinity in the whole tidal basin are relatively well-matched to the shellfish species (although 19 would be too low). Yet, as chapter 4 will point out, tests concerning shellfish bank establishment in the area around 2 in Figure 9 (also referred to as the area around the Hinderplaat), showed extremely high mortality amongst mussels and oysters. This is likely related to sudden fresh water influxes.

Moreover, the water flow rate is assumed to range between 0-0.9 m/s in the tidal basin (See Chapter 2). The stronger currents within this range might be problematic for the shellfish species. This is especially the case for the oyster species, since the stability threshold for the oyster species is 0.5 m/s. As mentioned in Chapter 2, the fastest currents of 0.9 m/s are expected in the deeper parts of the tidal basin, the west part of the tidal basin, nearby the channel. The shallower areas (area 2) and the areas further away from the channel (1a, 1b, 1d) are expected to have a lower flow rate, making these areas potentially suitable for culturing shellfish. Area 1a might be of interest for further studies, as it seems to match salinity, water depth and flow rates (But see above, and Chapter 4). The areas 1b and 1d have a suitable salinity and maximum water depth for cultivating shellfish, but the flow rate might prove to be a problem. As mentioned in the introduction, the in- and outlet of the Valmeer will be constructed in this area, making the area unsuitable because the in- and outlet could cause flow rates that are too high. However, if the in- and outlet of the Valmeer are constructed somewhere else, area 1b and 1d are potentially suitable for cultivating shellfish. Area 2 on the map of the tidal basin has a maximum depth between 5-10 meter, relatively far away from fast currents, which would make this area interesting to explore. Culturing mussels and oysters in this area on the bottom is a possibility, however the quality of the substrate is unknown and should be tested further.

Generally, the highlighted shellfish areas are potentially suitable for oysters as well as mussels, but mussels prefer salinities higher than 30 ppt, while oysters optimally grow between 20-25 ppt. Therefore, if a distinction between culturing grounds needs to be made, it is better to culture the oysters in directly west of the Haringvlietsluis, where the salinity is lower, while the mussel farms have more potential nearby the Valmeer, with salinities higher than 27 ppt and potentially a faster water current.

3.3 Seaweed placement possibilities

While the requirements between the shellfish and seaweed species differ, the four seaweed species included in Chapter 2 have similar requirements for growth, and the data its resolution therefore does not allow for a distinction in zones between the species. The areas marked 1c and 1d in Figure 9 are potentially suitable for seaweed cultivation, meaning the expected conditions meet the requirements of seaweed, although the uncertainties described prior remain. Note that area 1d has additional uncertainty regarding possible cultivation as a consequence of the possible high flow rate.

Area 1c has the best potential for meeting the requirements for seaweed cultivation. These requirements are described in Chapter 2. Considering that one of the interviewees stated that the seaweed needs a water depth of at least 10 meter, the only real possible area for seaweed cultivation is in the Voordelta, right next to the Valmeer. This was also stated by one of our seaweed interviewees, as he thought that the only potentially interesting site was the mouth of the Haringvliet (Leeuwen, 2019). In the DELTA21 plan, this would be referred to as the most western part of the tidal basin, near the Valmeer. However, another interviewee did not express the same concern about the water depth, which is why we chose to expand the possible area for cultivation so that also includes water depths of less than 10 meter (Veen, 2019). Area 1c has a depth of -5 to -10m NAP. Regardless, this is a point for further inquiry and will be elaborated upon in Chapter 4.

Another concern described by an seaweed interviewee (Veen, 2019) was the water flow; A strong flow rate increases the risk that the seaweed may be washed away. According to our literature sources, the water speed seaweed can withstand is moderate to strong (0 m/s to 1.5 m/s) (Hill, 2008a, 2008b; Pizzolla, 2008). A flow rate of 0 to 0.9 m/s is expected in the area South-East of the Valmeer (see Chapter 2), meaning that even though flow rate is a risk factor, it is expected to remain within the survival limits of seaweed.

Furthermore, other important requirements for seaweed cultivation are light attenuation and nutrient (i.e. N & P) availability, since seaweed needs both to grow. Considering that the four seaweed species included in this report were chosen for their ability to grow under North Sea conditions, the expected light attenuation is sufficient. Moreover,it is difficult to predict what the concentration of nutrients will be and what the seaweeds need exactly, as not a lot of data and information are available regarding this topic (Harrison & Hurd, 2001).

Both seaweed interviewees stressed the importance of water temperature to stimulate growth; For two of the four species this temperature was set below 18 °C, for one species 15- 17° C and the last species at 15- 20 °C (see Chapter 2). Expectations for water temperature in the tidal basin fluctuate between 0 and 20 °C (see Chapter 2). Since these temperatures are very similar in the Eastern Scheldt and seaweed is cultivated successfully in that area it is expected that the seaweed may survive in these temperature conditions (MeteoGroup, 2019; Rungis, 2019; SHH, 2019). However, this also remains a point for further inquiry. Another uncertainty is the flow rate caused by pumping water in and out of the Valmeer, i.e. areas 1b and 1d. These points will be further elaborated upon in Chapter 4.

Key points Chapter 3

- Based on historic data on salinity, not a lot of options are available for integrating aquaculture.
- The only area that could of interest to further inspect for possibly integrating seaweed cultivation is next to the Valmeer in the tidal basin, due to depth and salinity requirements.
- The only areas that could be of interest to further inspect for possibly integrating shellfish cultivation are in the shallower sites of the tidal basin, due to depth and salinity requirements.
- A few possible bottlenecks and knowledge gaps were identified and will be discussed in Chapter 4.

Chapter 4 – Bottlenecks and opportunities

4.1 Introduction

During our research a few bottlenecks regarding the integration of aquaculture in the Haringvliet were identified. As seen and discussed in Chapter 3, not a lot of possible cultivation sites could be assigned to mainly seaweed, but also shellfish. The main limiting factor was the low expected salinity. In this chapter, the main bottlenecks and opportunities for the realization of aquaculture are elaborated on and some additional ones are discussed. Bottlenecks and opportunities are divided amongst the following topics: environmental conditions, biodiversity and additional recommendations. These are the sections of this chapter and each section ends with a shortlist of recommendations. These recommendations are gathered and placed into a longlist which can be found in the Appendix IV.

4.2 Environmental conditions

4.2.1 Salinity

Based on the information in Chapter 2, the largest bottleneck for realizing aquaculture in and near the Haringvliet area seem to be the uncertainty regarding the salinity (fluctuations) of the water in the tidal basin and the western Haringvliet after implementing the DELTA21 plan. As was shown in Chapter 2, aquaculture has historically been absent from the area, the historic bottom water salinity levels were too low (also see below) and a recent project near the Hinderplaat showed extremely high mortality attributed to fresh water influxes. Additionally, salinity was deemed a major concern for the aquaculture by interviewees from the mussel, oyster and seaweed sector (Cornelisse, 2019; Leeuwen, 2019; Nelis, 2019; Padmos, 2019; Stee, 2019; Veen, 2019). Furthermore, no model study has yet been performed on the effect of the proposed constructions on the salinity (and geomorphology), and data on salinity and stratification as a result of similar projects were mostly unavailable in the academic and grey literature. Below, a more detailed description of bottlenecks, opportunities and recommendations for further research on salinity in the area is given.

Bottlenecks

According to the 'water safety' desk study of DELTA21, it is estimated that the annual averaged discharge of the Haringvliet would be in the order of 1500m3/s after the implementation of the plan. Historical data show that the salinity in the western part of the Haringvliet during times of a comparable discharge (1210 m3/s, 19 ppt) was below the minimal required salinity level for shellfish breeding and seaweed cultivation (20 ppt). For a visualisation of salinity at the bottom of the Haringvliet area, also see the map in Chapter 2. Additionally, we expect that the construction of the Valmeer and the partly open dam at the southern border at the tidal basin might decrease the intrusion length of saline water into the Haringvliet, as a model study showed that a barrier island in front of the Haringvliet lowered salinity levels (Kort & Rooij, 2013). This might lead to a decrease in salinity of the western part of the Haringvliet and the tidal basin with respect to the historical scenario, and make those locations less suitable for aquaculture development. Besides low salinities overall, fluctuations in salinity might also be important given the function of this former estuary; the Haringvliet will be used to discharge water from rivers upstream in times of high discharges. A discharge of 4000m3/s in the Haringvliet, which has an occurrence chance of roughly one time per year, could lead to a drop in salinity of bottom waters to a value around 10 ppt at the mouth of the Haringvliet (Berke & Lavooij, 2019; Wolff, 1973). Even higher discharges are rare, but could even lead to a further decrease in salinity. In such extreme events, the salinity in the tidal basin is also expected to drop and this might be harmful for aquaculture breeding grounds depending on the duration of the events. The drop of salinity in such a situation has not been assessed.

Opportunities

When considering the historical salinity gradient in the Haringvliet for an annual average discharge of 1210 m3/s, the tidal basin would fulfil the salinity requirements for shellfish and seaweed cultivation (Wolff, 1973). Moreover, the discharge to the western part of the Haringvliet can be regulated with the spillway that will be constructed in the DELTA21 plan southwards from the island of Tiengemeten. This creates the opportunity to direct only a small part of the river water to the Haringvliet , and direct more water to the area of Rotterdam and the Nieuwe Waterweg. This intervention would allow the saline water to intrude further into the western part of the Haringvliet, which would also increase opportunities for aquaculture development in the western part of the Haringvliet.

Recommendations

- It is recommended to conduct further research on salinity gradients for different discharge scenarios in the future Haringvliet as designed in DELTA21. A 3D modelling study is recommended, in which the effect of different discharges on the salinity in the Haringvliet will be explored. In such discharge scenarios, it would be adviced to take into account a version in which more discharge from the upstream river system is directed to the Nieuwe Waterweg, not only because it could create more opportunities for aquaculture, but also because it might potentially help in countering salinization in the area of Rotterdam and Drechtsteden.
- Regulating the discharge of the Haringvliet could potentially be very important in optimising conditions for setting up aquaculture and expanding the potential aquaculture areas to the western part of the Haringvliet, since the salinity, which is a limiting factor for as well shellfish breeding as seaweed cultivation, is strongly related to discharge.

4.2.2 Bottom composition and flow rate

Based on the information gathered in Chapter 2, bottom composition and quality are important factors determining the success of shellfish bottom cultivation. Bottom composition is not relevant for seaweed cultivation, as this will be done off-bottom. A factor that is important for both seaweed and shellfish cultivation is the flow rate (Hill, 2008a; Tyler-Walters, 2008).

Bottlenecks

A bottleneck regarding the bottom composition of the Haringvliet and tidal basin we identified is the lack of information about the current and the expected bottom composition as well as the roughness of the riverbed at a local level. Additionally, large uncertainty prevails on how the geomorphological conditions would be altered by the DELTA21 plan. This remains an issue for the determination of the local flow rates; As can be seen in Chapter 2 and 3, flow rate is an important factor for the success aquaculture and each species has their own limit. How the flow rates may change after the implementation of DELTA21 is uncertain but could be a potential bottleneck for the integration of aquaculture, especially regarding area 1b and 1d in Chapter 3. On the other hand, implementing seaweed and/or shellfish cultivation could alter the flow rates as well (Mork, 1996). Further research is recommended to gather data on what the expected flow rates will look like in various regions in the Haringvliet and tidal basin before implementing seaweed and/or shellfish cultivation.

Data on the bottom composition and substrate availability in the Haringvliet and tidal basin are also needed before a decision on integrating bottom shellfish cultivation can be made.

Another bottleneck that may arise after the implementation relates to food safety. Since mussels are filter feeders they may also filter out contaminants and they have been reported to accumulate viruses and pathogenic bacteria as well as toxins from toxic algal blooms (Shumway, 1992). Not only shellfish are at risk of bioaccumulation; the same is true for seaweeds (Van den Burg et al., 2013). Seaweeds are so-called nutrient strippers and they are sometimes used to store heavy metals, remove an abundance of nutrients and reduce water pollution (Zhang et al., 2018). A study of Van Hoek-Van Nieuwenhuizen (2008) investigated the degree of pollution in the bottom of the Haringvliet, by analyzing the presence of certain pollutants (e.g. organochlorine pesticides and heavy metals) in freshwater shellfish. The pollutants were examined to judge whether there was a risk of poisoning throughout the food chain for predatory animals as well as humans (van Hoek-van Nieuwenhuizen, 2008). In the experiment, organochlorine pesticides (OCP's), organotin compounds, metals and mercury were analyzed (van Hoek-van Nieuwenhuizen, 2008). They concluded that the levels of cadmium (Cd) and lead (Pb) exceeded the norms. PCB levels and organotin compound levels did not exceed any norm (van Hoek-van Nieuwenhuizen, 2008). One of the interviewees suggested that the bottom should also be examined for the presence of dioxins, as these substances are very toxic for humans and the eel industry suffered from a high concentration of dioxins in Dutch eel. This suggestion was confirmed in the academic literature (Hagel, 1990).

Also, up to two meters of sedimentation occurred after the closure of the Haringvliet in 1970 (Sonneveldt & Bovelander, 2002). The metal concentrations present in the surface sediments were lower at the end of 20th century compared to just after closure of the Haringvliet (Sonneveldt & Bovenlander, 2002). Even though sediment quality improved after the Haringvliet sluices were implemented, opening them again will increase the dynamic in the mouth of the Haringvliet (tidal basin) and it is expected that old contaminated sediments could be exposed again, as a consequence of increasing tidal exposure (Sonneveldt & Bovelander, 2002).

Opportunities

To possibly overcome the potential issues with the quality of the substrate in the Haringvliet, it is interesting to explore options that avoid direct exposure to the bottom. Although it should be noted that it is unclear whether avoiding direct exposure to the bottom prevents bioaccumulation altogether. However, utilizing artificial substrate for shellfish cultivation could be an option; one possibility is the use of Mussel Seed Collectors (MSCs).These MSCs are usually made from ropes on which the mussel spat attaches (Commissie, 2012). Note that MSCs require a minimal depth of 5m for proper functioning and as seen in Chapter 2 and 3, not a lot areas in the Haringvliet and tidal basin meet this requirement (Wijsman & Kleissen, 2011). Another way of shellfish cultivation is using a raft system (Bcsga, 2019b). Rafts are used at deepwater sites for suspending cultivation systems for each life stage (Bcsga, 2019b). An example is the use of tray systems, see Figure 10 for a visualization (Pangeashellfish, 2015). Since rafts are used at deepwater sites, they are not suitable for shallower areas in the Haringvliet and tidal basin.

Figure 10a Tray systems used for oyster cultivation; 10b Cage systems used for oyster cultivation; 10c Rack-and-bag systems used for oyster cultivation; 10d Rack-and-bag systems used for oyster cultivation; 10e Rack-and-bag systems used for oyster cultivation (Pangeashellfish, 2015)

Another possibility is the use of a near-bottom intertidal system (Bcsga, 2019a). An intertidal system makes use of the tide and exposes the shellfish to air during the low tide (Bcsga, 2019a). Intertidal grow-out systems in oyster farming include intertidal-longlines, stakes, and racks (Bcsga, 2019a). Note that it is unclear to what extent the tide will return after reopening the Haringvliet and it is thus unclear if intertidal systems can be applied. Other oyster cultivation methods include cage (Figure 10a) culture (Figure 10b), rack-and-bag culture (Figure 10c), floating culture (Figure 10d) and suspended culture (Figure 10e) (Pangeashellfish, 2015). Making an estimation about which of the different culture methods described above are suitable for the Haringvliet and tidal basin is beyond our expertise. It is therefore recommended to research what the requirements are for each cultivation method and if these requirements can be met by the conditions in the DELTA21 project area.

Table 3 Overview of substrates researched for blue mussel attatchment properties (Brenner & Buck, 2010)

No.	Shortcut	Name	Characteristics	Origin
(1)	ASW	Artificial Seaweed	10 mm nylon rope as back bone with 10 cm long pp-leaves attached at both sites	Japan
(2)	LOC	Leaded Christmas Tree	Extruded polypropylene with a straight trim, strands of lead in the center help sinking	New Zealand
(3)	LEC	Looped Christmas Tree	Extruded polypropylene with a looped trim, strands of lead in the center help sinking	New Zealand
(4)	GAR	Galician Rope	Rough surfaced nylon-pe ropes with strands	Spain
(5)	SSC	Self-Sinking Collector	Polyester net formed as a tube, small stones help sinking	Norway
(6)	LAD	Ladder Collector	16 mm parallel running pp-ropes connected every 35 cm by a plastic bar	Norway
(7)	AQU	Aquamats®	Strands of pp fleece material with ballast sleeve	USA
(8)	NFL	Naue® Fleece	pp fleece, cost-saving alternative to AQU	Germany
(9)	COC	Coconut Rope	24 mm rope of coconut fibres	India
(10)	REF	Reference Collector	Bushy tufts of a unravelled 10 mm pp-rope	Germany

As for artificial substrate use in mussel cultivation, a study analysed the attachment properties of the blue mussel on various substrates, both artificial and natural (Brenner & Buck, 2010). Table 3 provides an overview of the researched substrates.

The study found that coconut fibres and commercially applied filamentous substrates provided the best for mussel-attachment. Fleece and felt-like substrates performed second-best (Brenner & Buck, 2010). Number 5, the self-sinking collector performed worst because of the tube-like structure and polyester used to make the tube (Brenner & Buck, 2010). The materials used for the best-scoring substrates were made from natural fibres, nylon-pp or nylon-pe and the materials used for the second-best scoring substrates were made from pp-fibres (Brenner, Buchholz, Heemken, Buck, & Köhler, 2012). A point of interest that should be further investigated is the effect each of these materials has on the surrounding environment. Furthermore, they concluded that substrates utilized for off-shore and exposed areas ought to have a solid core with a fleece-like coat for larval attraction (Brenner et al., 2012). This principle is applied in France, where the use of stakes is primarily used for mussel cultivation (Commissie, 2012). These stakes are made of wood and are pushed into the lower tidal zone and they are wrapped in three to five meters of robe for mussel attraction (Commissie, 2012).

Seaweed cultivation is also done off-bottom, thus possibly limiting the bottlenecks regarding bottom quality (Van den Burg et al., 2013). Note that this does not suppress the issues around bioaccumulation in seaweeds, as they get their nutrients directly from seawater through their entire body (Radulovich et al., 2015). Seaweed farming off-bottom can be done, because like shellfish, seaweed needs to attach to a substrate in order to grow (Radulovich et al., 2015). Examples of such substrates include a buoy and ropes or a drifting log (Radulovich et al., 2015). It is said that any seaweed will grow on robes or nets as long the other environmental requirements as described in Chapter 2 are met (Radulovich et al., 2015). Offshore seaweed farming using net or rope systems have been piloted in the US, Germany and Japan (Van der Burg et al, 2013). Figure X shows a visualization of the concept of offshore seaweed installations (Van den Burg et al., 2013).

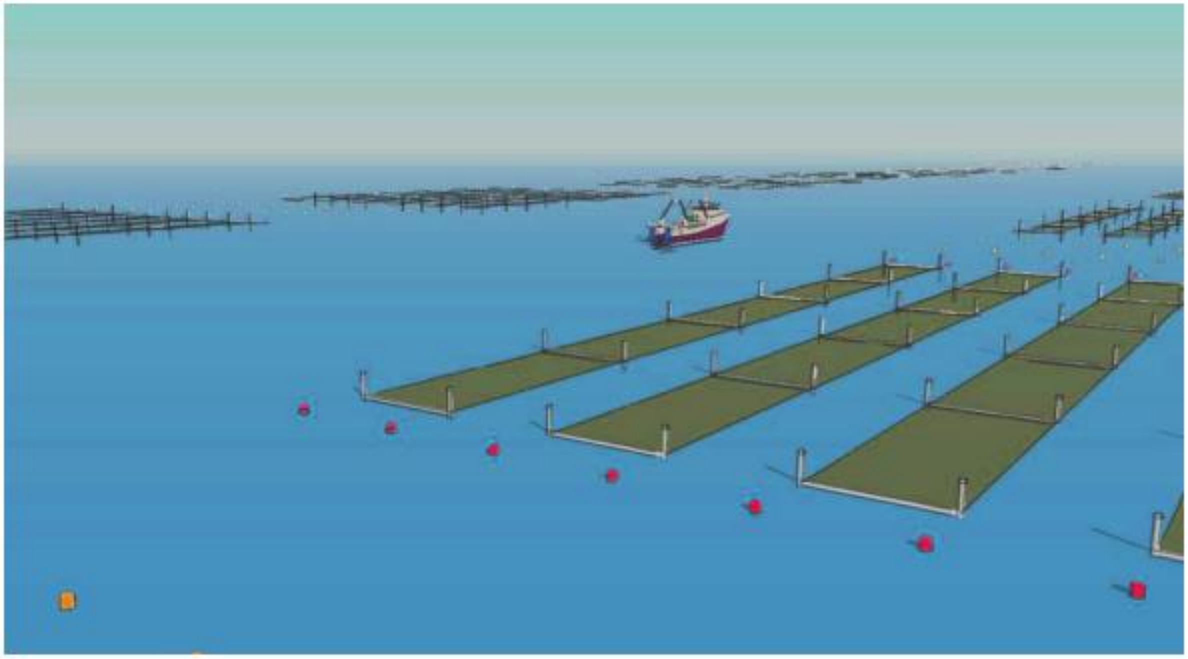

Figure 11. Concept of offshore, off-bottom seaweed installations. These are nets to which the seaweed can attach and grow (Van den Burg et al., 2013)

Another option for tackling the bottlenecks regarding the bottom and substrate quality that could be of interest is covering the current bottom layer with another layer or substrate. A test clean-up of the polluted bottom has already been done in the Haringvliet in 2003 and that was successful in terms of responsibly and cost-effectively covering up the polluted bottom with an unpolluted layer (Waterbodem, 2003). This is based on preventing risks associated with contact with the polluted bottom (Waterbodem, 2003). Another method for tackling the pollution in the bottom could be dredging (Waterbodem, 2003). Further investigation of the options for cleaning up the bottom in the Haringvliet and the tidal basin is recommended.

Recommendations

Follow-up studies are required to gather data on and answer these questions:

- Which bottom will be at a depth appropriate for either bottom or off-bottom cultivation? And what will the flow rate be like at these locations?
- How is the flow rate altered by introducing shellfish or seaweed cultivation?
- What are suitable options for off-bottom shellfish cultivation in the DELTA21 project area?
- To what extent will the waters and the bottom be polluted and is this a risk for aquaculture?
- What are the bioaccumulation risks of off-bottom and near-bottom cultivation for both seaweed and shellfish?
- Would adding clean substrate be a sustainable option to cover up contaminated soil? And will opening the sluices permanently result in significant exposure to old contaminants?
- What, if any, are the effects of certain materials used for artificial substrate on the surrounding environment?

4.2.3. Other environmental conditions

As mentioned in Chapter 3, there is some uncertainty regarding water depth and temperature requirements for seaweed. The uncertainty regarding the water depth requirements for seaweed stems from the different answers given by the two seaweed interviewees. One of them stated they need a depth of at least 10m, while the other explained the chains and construction for seaweed cultivation are expensive, which is why he recommended a depth of 5m. In Chapter 3 we included depths of -5m to -10m NAP.

Another issue that should be further investigated is the expected temperatures in the tidal basin and the Haringvliet and whether or not the seaweed can stand wider fluctuations in temperature than described in Chapter 2. The expected water temperatures range from 0 to 20 °C.

Furthermore, there is uncertainty regarding what the nitrogen and phosphorus availability in the Haringvliet and tidal basin will be after reopening the sluices and how is will be affected by the implementation of the DELTA21 plan. Since seaweed needs both to grow, they're availability is a vital aspect (Radulovich et al., 2015). Nitrogen is often the nutrient that primarily limits growth in seaweed and therefore nitrogen availability should be measured before potentially implementing seaweed farming (Harrison & Hurd, 2001).

Recommendations

Follow- up studies are required to gather data on and answer the following questions:

- To what extent can different seaweed species stand temperature fluctuations and exposure to temperatures above their optimum?
- Is the water temperature is expected to change as a consequence of the implementation of the Valmeer and a reduction of river influxes?
- What is the optimal water depth for seaweed cultivation and what are the maximum and minimum depths seaweed can survive in?
- What are the nitrogen and phosphorus concentrations in the DELTA21 project area and how will this change after reopening the sluices and implementing the DELTA21 plan?

4.3 Biodiversity

It is not only necessary to know the physical suitability of the Haringvliet for aquaculture, but investigating the influences of aquaculture on nature is also necessary, as ecological sustainability is one of the desires of the DELTA21 plan. This part of the report will shortly introduce the bottlenecks, opportunities and recommendations for aquaculture with respect to nature and biodiversity.

Bottlenecks

If there is too much shellfish production in an area, the possibility exists that the system is or becomes overexploited. This concern was brought forth by Angela Duijndam from Natuurmonumenten in personal communication (Duijndam, 2019). Research confirms that overexploitation can be a problem, because not only in the Eastern Scheldt, but also in the Westen-Waddenzee: there are increasing concerns about cultured mussel populations approaching the carrying capacity of the area (Kamermans, Smit, Wijsman, & Smaal, 2014). Exceeding the carrying capacity has consequences for the biodiversity of the system, particularly because of food competition with other species (e.g.

cockles)(Kamermans et al., 2014). Generally, there is a lack of knowledge about the carrying capacity of the Haringvliet.

Seaweeds require the same nutrients as micro-algae, the food source of bivalves. The most important limiting nutrients are nitrogen and phosphate (Xiao et al., 2017). Strong competition for these sources should be avoided, to prevent the system from reaching the carrying capacity. At the moment, detailed predictions on the concentration of nitrogen and phosphate in the future Haringvliet are unavailable,. Additionally, the effects of aquaculture on the ecology of a system may also be location dependent, although the specifics of such differences have not been researched extensively (Smaal, Stralen, & Schuiling, 2001). Another uncertainty with potentially large influences concerns the impact of the constructed water safety works on the morphology of the area. When the tidal basin and the Valmeer are created, currents are likely altered, which could result in geomorphological changes. Concerns were raised by an employee of WWF that the Salt marshes, the area south of the Haringvlietsluizen and the area around the Kop van Goerree could be altered, which, in turn, could negatively impact the biodiversity in the Voordelta (Roels, 2019).

Opportunities

Shellfish reefs filter the water column, and the reefs have the ability to prevent eutrophication via filtration (Kirby & Miller, 2005; Sas, Kamermans, van der Have, Lengkeek, & Smaal, 2016). Not only are the shellfish reefs good for water quality, shellfish reefs are also considered important for the biodiversity of an area, because they provide shelter and food for all different kind of marine species (Sas et al., 2016). According a study, an extensive cultured mussel population increases epibenthic species in the Eastern Scheldt While data between natural reefs and cultured reefs are scarce, a study showed that suspended mussel cultivation, which can create a new habitat, could enhance the abundance and biomass of epifauna and infauna species compared to natural mussel beds (Murray, Newell, & Seed, 2007). Also birds such as Eider ducks profit from cultured mussel areas, as cultured mussels have more meat compared to natural reefs (Capelle, Wijsman, Van Stralen, Herman, & Smaal, 2016; Cervencl et al., 2015). This suggest bottom culture and suspended aquaculture could positively affect nature and biodiversity. Seaweed cultivation also provides opportunities for nature and biodiversity. Seaweed cultivation can inhibit microalgae growth via competition and removing excess nutrients, which are produced by industry and intensive agriculture (Xiao et al., 2017; Zhang et al., 2018). These excess nutrients such as nitrogen, phosphorus and carbon dioxide are used by seaweed for energy and growth (Kim, Yarish, Hwang, Park, & Kim, 2017). Besides filtering the water column and improving water quality, microalgae could serve as a nursery habitat for crustaceans such as the blue crab (*Callinectes sapidus*) (Wilson, Able, & Heck Jr, 1990). Improving the water quality and providing habitat which functions as a nursery are important ecosystem services (Kim et al., 2017).

The co-cultivation of shellfish and seaweed offers another opportunity. A study showed seaweed grows faster in the proximity of blue mussel, which may be related to the excretion of ammonia by mussels (Rößner, Krost, & Schulz, 2014). If there is limited nitrogen or phosphate in the future Haringvliet, co-cultivation is a possible solution for seaweed cultivation, and might increase the carrying capacity of the future Haringvliet. However, this is currently just a hypothesis and not much is known about nutrient uptake in co-cultivation. Therefore more research is needed.

Recommendations

- To prevent future aquaculture from reaching or exceeding the carrying capacity of the system, carrying capacity models should be made to give an indication of the maximum seaweed and shellfish biomass within the ecosystem which could be cultivated (Heral, 1993). The model created for bivalves should look at chlorophyll-ɑ as a limiting resource as a study suggest that mussel conditions and growth are food limited at the ecosystem level (Smaal et al., 2001). Another model could look at nitrogen and phosphate as limiting resource for seaweed. In the models co-cultivation could be included, to investigate if the carrying capacity will increase by co-cultivation.
- Additionally, continuous monitoring of the carrying capacity should be undertaken after aquaculture is implemented, to make the model more accurate and limit damages to the natural system.
- The difference between cultured and natural reef their effects on biodiversity could be researched further.
- Although not directly related to aquaculture, the geomorphological changes caused by the future Valmeer and the tidal basin should be researched further, as this might provide more insight into the project's consequences for the biodiversity in the Voordelta.

4.4 Additional recommendations

Aquaculture opportunities in wind farm

Opportunities of aquaculture (seaweed, mussels and oysters) in the planned wind farms could be further investigated. In the DELTA21 plan, a wind farm is included in plan. According to DELTA21, the location for the wind farm would be located in and around the Valmeer (Berke & Lavooij, 2019). Biologically, technically and economically wind farms could be combined with aquaculture (Bela Buck et al., 2008; B Buck & Langan, 2017). Probably the biggest obstacle to designing a multi-use wind farm is effectively combining the knowledge and experience of aquaculture with the knowledge and experience of windfarm planners (Bela Buck et al., 2008; B. H. Buck, Krause, & Rosenthal, 2004). The experience and knowledge of the aquaculture and wind farm sector could be used to design an integrated framework.

Exploration of alternative cultivation species

Besides the researched species, other species could be investigated. Wakame (*Undaria pinnatifida*) is resident in the Western Scheldt, Eastern Scheldt and Wadden Sea since its introduction in 1999 (Gittenberger, Rensing, Stegenga, & Hoeksema, 2010; Gittenberger, Rensing, & Wesdorp, 2017). The economically interesting invasive species *Undaria pinnatifida* (Wakame) is registered to occupy both marine and estuarien habitats (Gittenberger et al., 2010). However, cultivation of invasive species is currently prohibited in Natura 2000 areas in Europe.

Cautionary approach

It is adviced to take a cautionary approach by set up a monitoring-and adjusting program which updates the models regularly (in Dutch, this is called "lerend implementeren").

Key points Chapter 4

- Bottlenecks and opportunities regarding environmental conditions and biodiversity were elaborated upon.
- Additional recommendations regarding possibly integrating wind farms and aquaculture and using cultivating different species were provided as well.
- The main bottlenecks include uncertainty regarding the future conditions, primarily the salinity, bottom quality and flow rate.
- Temperature, nutrient availability and water depth are possible bottlenecks as well.
- The main opportunities include further research options regarding various river discharges, off-bottom cultivation for both shellfish and seaweed and increase in biodiversity.
- Recommendations for future research were provided and a longlist is included in Appendix IV.

Chapter 5 – Reflection

While the wide range of sources (e.g. academic sources, grey literature, interviews) has helped tremendously to generate this advice, using solely academic works would have been preferred to enhance the reliability of the findings. It was explicitly mentioned in the text whether knowledge was based on communication alone. Additionally, at the end of the report, a reference list is provided. This reference list shows the source of the statement and the kind of source (academic literature, non-academic report or an interview).

DELTA21 has not been executed yet, and to our knowledge no models have yet been constructed to simulate the impacts of this plan. Therefore, we had to rely on data or model study results from similar projects, comparable historical data or data of similar areas such as the Eastern Scheldt. It is inevitable that in an advice (at this stage), such rough assumptions have to be made. We have therefore often recommended to create models for the key concerns, as good model building stimulates explicitness about all assumptions, as well as scientifically acquired data to validate assumptions. Well-made models, then, could make the recommendations more tailored to the researched area, which may make the advice more specific.

Several ethical aspects were considered during our research. One of the aims of integrating aquaculture in the DELTA21 plan is sustainability. Shellfish and seaweed culture are considered by some to be inherently sustainable, since no external food is added into the water. Yet, it is also possible to be unsustainable in other aspects. For example, aquaculture might be in competition for resources with wildlife. To prevent competition of the natural food resources in the Haringvliet, recommendations are given to get an indication of the carrying capacity for aquaculture in the Haringvliet, before aquaculture is implemented. Also, the aim of the report was to investigate the potential aquaculture areas with regard to its environmental suitability. However, no social aspects of resource management were taken into account, such as such as recreation, other types of fisheries and transport. Also, the natural values of the described areas were not explicitly considered. The sketch provided in Chapter 3 which shows potentially interesting areas for aquaculture, but these areas might not be desired by society at large. While such ethical considerations fell outside the scope of this research, they might hold the key for the success of integrative marine resource management, and thus for the future of DELTA21.

Key points Chapter 5

- Scientific literature preferred over interviews and grey literature.
- Data in this report comes from historical data, data or model studies researching similar scenarios and assumptions. This leads to large uncertainty regarding the data used throughout this report and often (model) studies are recommended before hard claims can be made.
- Sustainability side of aquaculture: No extra feed and the water is filtered, however carrying capacity needs to be determined.
- Nature values and social aspects (such as recreation) are not considered.

Chapter 6 – Conclusion and final advice

In this report, possibilities for setting up aquaculture in the future Haringvliet and adjacent foreshore (tidal basin), designed as in DELTA21, have been explored. The focus hereby was on shellfish and seaweed cultivation, and the following species were considered: *Mytulis edulis* (blue mussel), *Crassostrea gigas* (pacific oyster), *Ostrea edulis* (flat oyster), *Laminaria digitata* (finger kelp), *Palmaria palmata* (dulse), *Saccharina latissima* (sugar kelp) and *Ulva lactuca* (sea lettuce). In order to explore and visualize the possibilities, literature research has been conducted in which academic and grey literature were consulted. Besides, semi-structured interviews have been conducted with experts from the aquaculture sector and representatives from two nature organisations to obtain practical knowledge. As mentioned in chapter 5, it should be taken into account that these findings rely on currently available information as no specific studies on the environmental conditions in the future Haringvliet and tidal basin as designed in DELTA21 have been conducted . The environmental conditions considered in this report should therefore be seen as an approximation.

It was found that water temperature, water depth, water speed, salinity, bottom type, nutrient concentrations and chlorophyll-α concentration are the most important factors for aquaculture development. The optimal values of these variables for seaweed cultivation and shellfish cultivation are largely in correspondence with the expected band of environmental conditions in the future Haringvliet and tidal basin, except for salinity.

The main finding is that low expected salinity will be a critical factor for the development of aquaculture in the western part of the Haringvliet. In contrast, the salinity in the tidal basin might be suitable for aquaculture development considering the same scenario. However, it should be noted that the Haringvliet and tidal basin will be used to discharge water in times in which the discharge of the rivers upstream is high. During such events, the salinity in the Haringvliet as well as the tidal basin might drop considerably, and this might be harmful to aquaculture practices depending on the length of the events.

In this report, predictions regarding the salinity are based on historical records prior to the construction of the Haringvliet sluices, when the average discharge in the Haringvliet was around 1210 m3/s (comparable with the expected discharge of the future Haringvliet in DELTA21: 1500m3/s). Therefore, no definitive claims can be made on the future situation after implementation of DELTA21.

Besides, there is still a large uncertainty around the influences of the constructions of DELTA21 on the geomorphology of the tidal basin and Haringvliet and on the changes in flow rate. This information is relevant for choosing locations for aquaculture on a more detailed level. Moreover, the ecological impact of aquaculture development in the future Haringvliet and tidal basin are uncertain, and more insights are required to make concrete statements.

Based on our findings, the following main recommendations for further research are:

- Conduct research on the development of salinity gradients in the Haringvliet and tidal basin for different river discharges (with extremes on the low as well on the high end) by performing a 3D modelling study in which planned constructions of DELTA21 are included.
- Conduct research on bottom quality and bottom composition on local scale and on different cultivation techniques (near-bottom, off-bottom), a.o. to decrease risks for food safety.

- Conduct a study on the influence of the constructions of DELTA21 on the morphology and flow velocity in the Haringvliet and tidal basin.
- Conduct a modelling study to the carrying capacity of the ecological system.
- Take a cautionary approach by set up a monitoring-and adjusting program which updates the models regularly (in Dutch, this is called "lerend implementeren")

In addition, decreasing of the discharge to the Haringvliet might significantly increase the salinity in the Haringvliet area. This could be realised by changing the upstream water distribution by directing more water to the Nieuwe Waterweg near Rotterdam. Alterations in the expected salinity conditions will amplify any potential transition towards sustainable aquaculture production in both the tidal basin as well as the future western part of the Haringvliet. Hereby, implementation of DELTA21 has the potential to make an contribution to satisfying the demand for new cultivation grounds by the Dutch aquaculture sector.

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In-depth interviews per sector

Mussel sector

- Marinus Padmos: Cultivates mussels in Zeeland. Interview took place on 18-02-2019.
- Willy van Stee: Cultivates mussels in Zeeland and at the Wadden Sea. Interview took place on 19-02-2019.

Oyster sector

- Danny Nelis: Cultivates oysters in Zeeland. Interview took place on 19-02-2019.
- Aard Cornelisse: Cultivates oysters in Zeeland. Interview took place on 18-02-2019.

Seaweed sector

- Jasper Veen: Works at the North Sea Farm. Interview took place on 19-02-2019.
- John van Leeuwen: CEO Seaweed Harvest Holland. Interview questions received by mail on 19-02-2019.

Nature organisations

- Angela Duijndam: Projectmanager at Natuurmonumenten. Interview questions received by mail on 21-02-2019.
- Bas Roels: Works at World Wide Fund for Nature (WWF), specializes in nature planning. Interview took place on 18-02-2019.

Appendix I: Extended tables of requirements per aquaculture species

Blue Mussel	Unit	Values	Source
Latin name		*Mytilus edulis*	(Tyler-Walters, 2008)
Salinity	ppt	18-40	(Tyler-Walters, 2008)
Temperature	Degrees (C)	0-25, max. 29	(Tyler-Walters, 2008)
Spawning temperature	Degrees (C)	~10 C	(Tyler-Walters, 2008)
Growth season	Months	April-September	(Tyler-Walters, 2008)
Growing time	Months	18-24	(Tyler-Walters, 2008)
Spawning period		Summer	(Tyler-Walters, 2008)
Exposure to freshwater	Hours	4-5h	Proposal meeting
Water depth	m	0 - 10m; 0-5m; -2 tot -25 m t.o.v. NAP	Proposal meeting (Tyler-Walters, 2008; Van Broekhoven, 2010)
Water speed	cm/s	20-80	(Van Broekhoven, 2010)
Morfology habitat	-	Not too steep or sandy	Interviews (Padmos, 2019; Stee, 2019)
Wave action	cm/s	< 0.3	(Van Broekhoven, 2010)
Food/nutriënt requirements		Bacteria, Detritus, DOM, phytoplankton	(Tyler-Walters, 2008)

Flat oyster	Unit	Values	Sources
Latin name		*Ostrea Edulis*	(Perry, 2017)
Salinity	ppt	18-40 psu	(Perry, 2017)
Temperature	Degrees (C)	17-25	(Perry, 2017)
Spawning temperature	Degrees (C)	15-16	(Perry, 2017)
Growth season	Months	April- Oct	(Perry, 2017)
Growing time	Months	3 years: age at maturity	(Perry, 2017)
Spawning period		Summer	(Perry, 2017)
Water depth	m	0-80	(Perry, 2017)
Current velocity	m/s	0.25-0.8	(Smaal, 2017)
Morfology habitat	-	Shallow waters with subtrate to attach to	Interviews (Cornelisse, 2019; Perry, 2017)
Wave action	-	Preferences for weak waves	(Perry, 2017)
Food, nutrient requirements		Planktotroph; Suspended organic particles	(Perry, 2017)
Oxygen content	mg/L	3.5	(Smaal, 2017)

Pacific oyster	Unit	Values	Source
Latin name		*Crassostrea gigas*	
Salinity	ppt	10 - 35	(Helm, 2005)
Temperature	Degrees (C)	-1.8 - 35	(Helm, 2005)
Spawning temperature	Degrees (C)	16-25	(Helm, 2005)
Exposure time	%	0-50	(Walles et al., 2016)
Growing season	Months	April-October	(Kater, 2003)
Growing time	Months	18-30 (till marketable size)	(Helm, 2005)
Spawning period	Months	June-September	(Helm, 2005)
Clearance rate	L/h/g	0.02-15.7	(Dupuy et al., 2000)
Exposure time fresh water	Hours	24-168	From interview (Cornelisse, 2019)

Water depth	m	0-42	(Kater, 2003)
Oxygen content	mg O2/h	0.05 - 4.13	(Kater, 2003)
Morphology of substrate	-	Hard substrate	(Kater, 2003)
Food and nutrient requirement		Planktotroph; Suspended organic particles	
Parasites		*Ceratostoma inornatum, Pseudostylochus ostreophagus, Mytilicola orientalis*	

Parameter	**Unit**	***Laminaria digitata***	***Saccharina latissima***	***Palmaria palmata***	***Ulva lactuca***
Dutch name	-	Vingerwier	Suikerwier	Dulse	Zeesla
Division	-	*Phaeophyta*	*Phaeophyta*	*Rhodophyta*	*Chlorophyta*
Salinity	ppt	30-40 (Hill, 2008a)	25-30, from Interview (Veen, 2019)	30-40 (Hill, 2008b)	20-40 (Pizzolla, 2008)
Increase in salinity	-	Intermediate tolerance, very high recoverability (Hill, 2008a)	High intolerance, high recoverability (White, 2007)	Intermediate intolerance, high recoverability (Hill, 2008b)	-
Fresh water exposure	Hours	0, from Interview (Leeuwen, 2019)	0, from Interview (Leeuwen, 2019; Veen, 2019)	Intermediate intolerance (Hill, 2008b)	Tolerates brackish conditions (Pizzolla, 2008)
Temperature	Degrees	<18 (Van den Burg et al., 2013)	<18 (Van den Burg et al., 2013); <20, from interview (Veen, 2019)	15-20 (Van den Burg et al., 2013); 5-17, from Interview (Leeuwen, 2019)	15-20 (Keesing et al., 2016)
Dessication resistance	Hours	-	Few hours, from interview (Veen, 2019)	Littoral and sublittoral (Hill, 2008b)	All levels of the intertidal (Pizzolla, 2008)
Growth season	Month	Sept-may (Van den Burg et al., 2013)	Sept-May (Van den Burg et al., 2013); Winter-April (White, 2007)	Presumably summer (Van den Burg et al., 2013)	Summer (Van den Burg et al., 2013)
Water depth	Meter	>10 to minimize turbidity, from Interview (Leeuwen, 2019)	>10 to minimize turbidity, from Interview (Leeuwen, 2019)	>10 to minimize turbidity, form interview (Leeuwen, 2019)	>10 to minimize turbidity, from Interview (Leeuwen, 2019)
Water speed	m/s	-	High intolerance to increase in wave exposure (White, 2007); No sudden changes, from interview (Veen, 2019)	Moderately strong to weak water regimes (Hill, 2008b)	< highly exposed (Pizzolla, 2008)
Wind/wave force	-	Moderately to strongly exposed areas (Hill, 2008a)	Depends on culture installation, but generally moderate, from interview (Veen, 2019)	Sheltered/moderate exposure, free floating under harsh conditions (Hill, 2008b)	< highly exposed (Pizzolla, 2008)
Light attenuation	-	-	Light determines growth (Jasper)	-	Irradiation affects spore release, germination and growth (Sousa, Martins, Lillebø, Flindt, & Pardal, 2007)

Turbidity	SPM mg/l	<100, from interview (Leeuwen, 2019)	< 100, from interview (Leeuwen, 2019)	< 100, from interview (Leeuwen, 2019)	< 100, from interview (Leeuwen, 2019)
Nitrogen-N availability	µg/l	Nitrogen storage in tissue to produce protein in spring	Uses all nitrogen in summer	Uses all nitrogen sources available in warmer water	N-supply limits growth (Teichberg et al., 2010)

Appendix II: Questions interviews

Below are the questions asked to the interviewees. The questions are grouped per sector and the interviews were all held in Dutch, which is why the questions are written in Dutch. For the coherence of this report the questions were also translated to English. The translations are written directly below each question in Italic.

Seaweed sector

1. Hoe ziet u de zeewier kwekerij over 100 jaar?
   What do you think seaweed cultivation will look like in 100 years?

2. Welke dingen vallen u op aan de omgevingseisen tabel?
   Do you notice anything in particular about the table we sent in the attachment?

3. Welke aanvullingen kunt u geven voor de leegstaande vakjes in de tabel?
   Can you add anything to the data still lacking in the table?

4. Welke omgevingseisen in deze tabel denkt u dat het belangrijkste zijn voor het succesvol kweken van uw soort?
   Which environmental parameters described in the table do you consider most important for seaweed cultivation?

5. Welke gebieden denk u dat geschikt zijn voor de kweek in het Haringvliet, wanneer het DELTA21 plan gerealiseerd wordt?
   Which areas within the DELTA21 project area do you think are most suitable for seaweed cultivation?

6. Welke veranderingen verwacht u in het Haringvliet als effect van zeewier kweek?
   What changes do you expect to happen in the Haringvliet as a consequence of local seaweed cultivation?

7. Hoe denkt u dat het kweken van uw soort samen kan gaan met natuurherstel in de Haringvliet, bijvoorbeeld in relatie tot eiland Bliek?
   Do you think seaweed cultivation can occur alongside nature restoration, and if so, how?

8. Welke knelpunten ziet u bij het integreren van aquacultuur in combinatie met natuurherstel in het Haringvliet?
   What bottlenecks do you see with integrating aquaculture in combination with nature restoration?

9. Welke punten zou u ons aanbevelen nog verder uit te zoeken?
   What recommendations regarding our research can you give?

Shellfish sector

1. Hoe ziet u de mossel/oester kwekerij over 100 jaar?
   What do you think mussel/oyster cultivation will look like in 100 years?
2. Welke dingen vallen u op aan de omgevingseisen tabel?
   Do you notice anything in particular about the table we sent in the attachment?
3. Welke aanvullingen kunt u geven voor de leegstaande vakjes in de tabel?
   Can you add anything to the data still lacking in the table?
4. Welke omgevingseisen in deze tabel denkt u dat het belangrijkste zijn voor het succesvol kweken van uw soort?
   Which environmental parameters described in the table do you consider most important for mussel/oyster cultivation?
5. Welke gebieden denk u dat geschikt zijn voor de kweek in het Haringvliet, wanneer het DELTA21 plan gerealiseerd wordt?
   Which areas within the DELTA21 project area do you think are most suitable for mussel/oyster cultivation?
6. Welke veranderingen verwacht u in de haringvliet als effect van mossel/oester kweek?
   What changes do you expect to happen in the Haringvliet as a consequence of local mussel/oyster cultivation?
7. Hoe denkt u dat het kweken van uw soort samen kan gaan met natuurherstel in het Haringvliet, bijvoorbeeld in relatie tot eiland Bliek?
   Do you think mussel/oyster cultivation can occur alongside nature restoration, and if so, how?
8. Welke knelpunten ziet u bij het integreren van aquacultuur in combinatie met natuurherstel in het Haringvliet?
   What bottlenecks do you see with integrating aquaculture in combination with nature restoration?
9. Welke punten zou u ons aanbevelen nog verder uit te zoeken?
   What recommendations regarding our research can you give?

Nature organisations

General

- Kunt u wat vertellen over uw rol binnen de organisatie? Bijvoorbeeld, hoe ziet een werkdag of week er normaal gesproken uit?
  Could you tel lus more about your function within the organization? E.g., what does a regular work day for you look like?

- Kunt u een korte geschiedenis schetsen van uw organisatie? En de rol die u inneemt in het bredere veld van natuurorganisaties?
  Could you paint a picture about the history of your organization? And the role you have compared to other nature organisations?

- Wat zijn dilemma's waar uw organisatie mee kampt? En hoe gaat u hier in de praktijk mee om?
  What are issues your organization is dealing with? And how do you cope with these?

DELTA21

- Kunt u een beeld voor ons schetsen van de ideale Nederlandse delta volgens u en uw organisatie?
  Could you paint a picture for us about what the Dutch delta ideally looks like according to you and your organization?

- Stel, het Haringvliet zou helemaal opengesteld worden (en veranderen in een stormkering). Wat betekenen deze veranderingen voor het behalen van de doelstellingen van uw organisatie? (denk bijvoorbeeld aan soorten, habitats, andere ‘ecosystem services’)
  Suppose the Haringvliet sluices open permanently, causing resalinization of the water, what would this mean for the goals of your organization? (e.g. species, habitats and other ecosystem services)

- Met betrekking tot het DELTA21 Plan (Zie bijlage 1):
  Regarding the DELTA21 plan (Appendix 1):

  - Hoe verwacht u dat dit plan effect heeft op uw doelstellingen? (bijvoorbeeld biodiversiteit, flagship species, habitat diversiteit, duurzaamheid)
    How do you expect this plan to affect your overall goals and mission statement?

  - Wat voor problemen en/of mogelijkheden ziet u in de brakwater constructie voor de vismigratie?
    What kind of bottlenecks and opportunities do you see in brackish water for fish migration?

  - Ziet u mogelijk oplossingen voor de genoemde problemen?
    Do you have possible solutions for these issues?

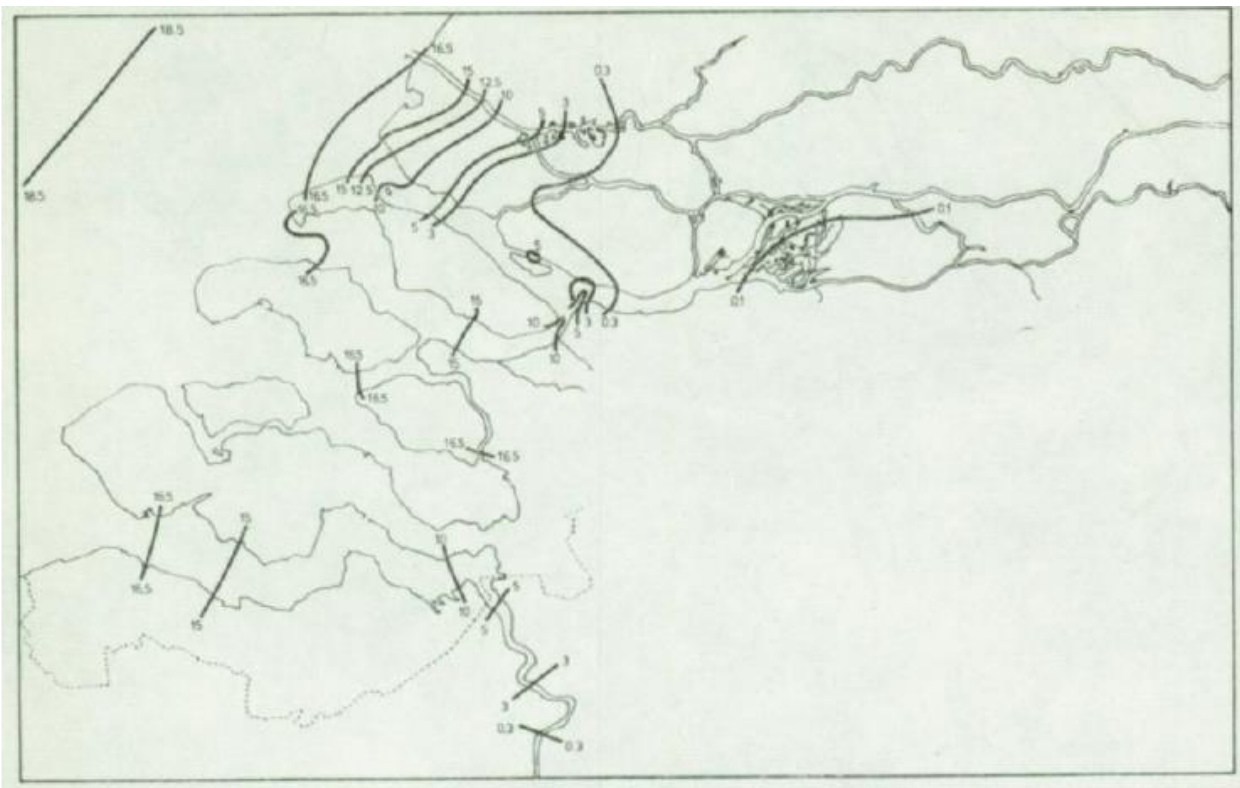
  - Hoe balanceert uw organisatie momenteel de verschillende gebruiken van ecologisch belangrijke gebieden?
    How does your organisation currently balance the various uses of ecologically important areas?

- Wat voor kansen en knelpunten ziet u voor de integratie van schelpdierkweek en zeewiercultivatie in het intergetijdengebied in het Haringvliet met uw doelstellingen?
  What kind of bottlenecks and opportunities do you see for the integration of aquaculture in the Haringvliet and your goals?
- Op welke punten zou u ons aanbevelen vervolgonderzoek te ondernemen wat betreft de integratie van kweek en natuurbehoud/restauratie?
  What recommendations can you give for future research regarding the integration of aquaculture and nature conservation/restoration?

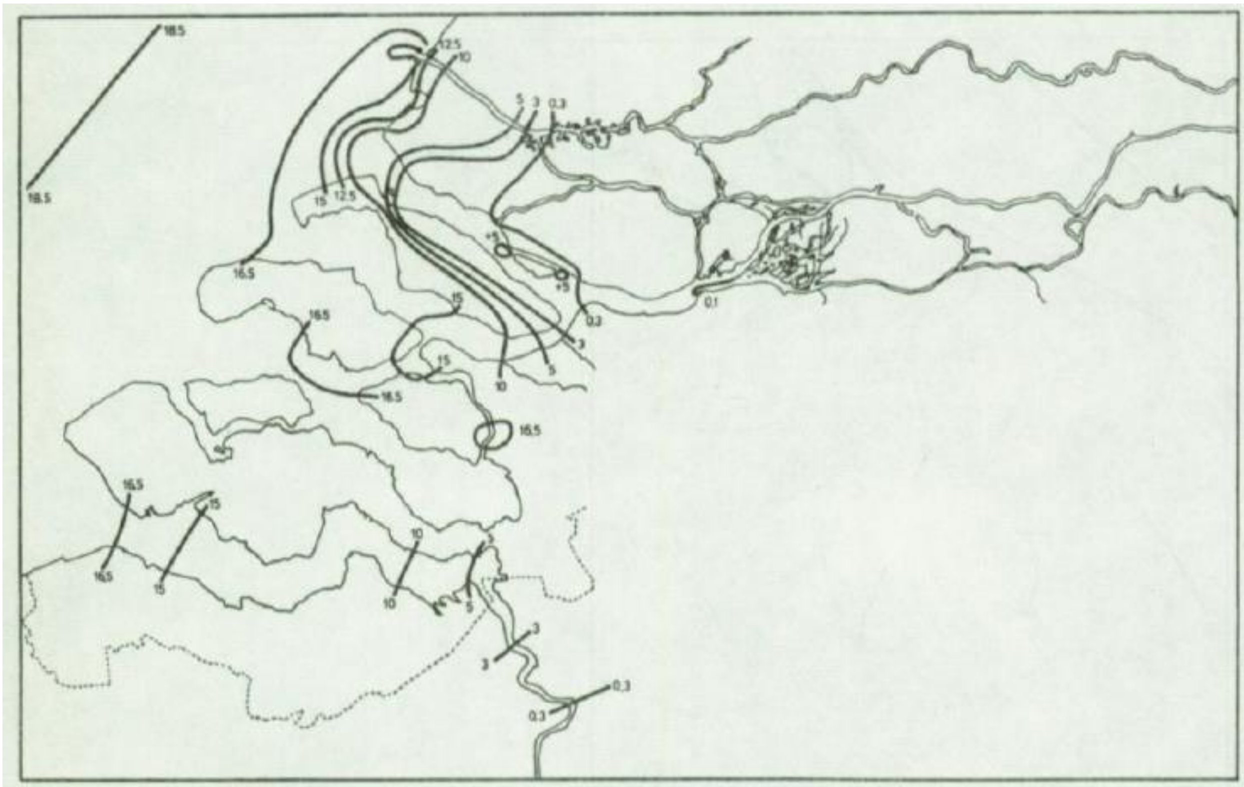
Appendix III: Historical salinity gradients in the Dutch delta during different discharges

Records of the salinity of bottom waters (lower water mass in the water column) of estuaries in the Dutch Delta (Wolff, 1973). Salinity is expressed in ‰ cl'. The following rules can apply: 1 ‰ cl' is equal to 1 g cl'/l and 1,81 ppt

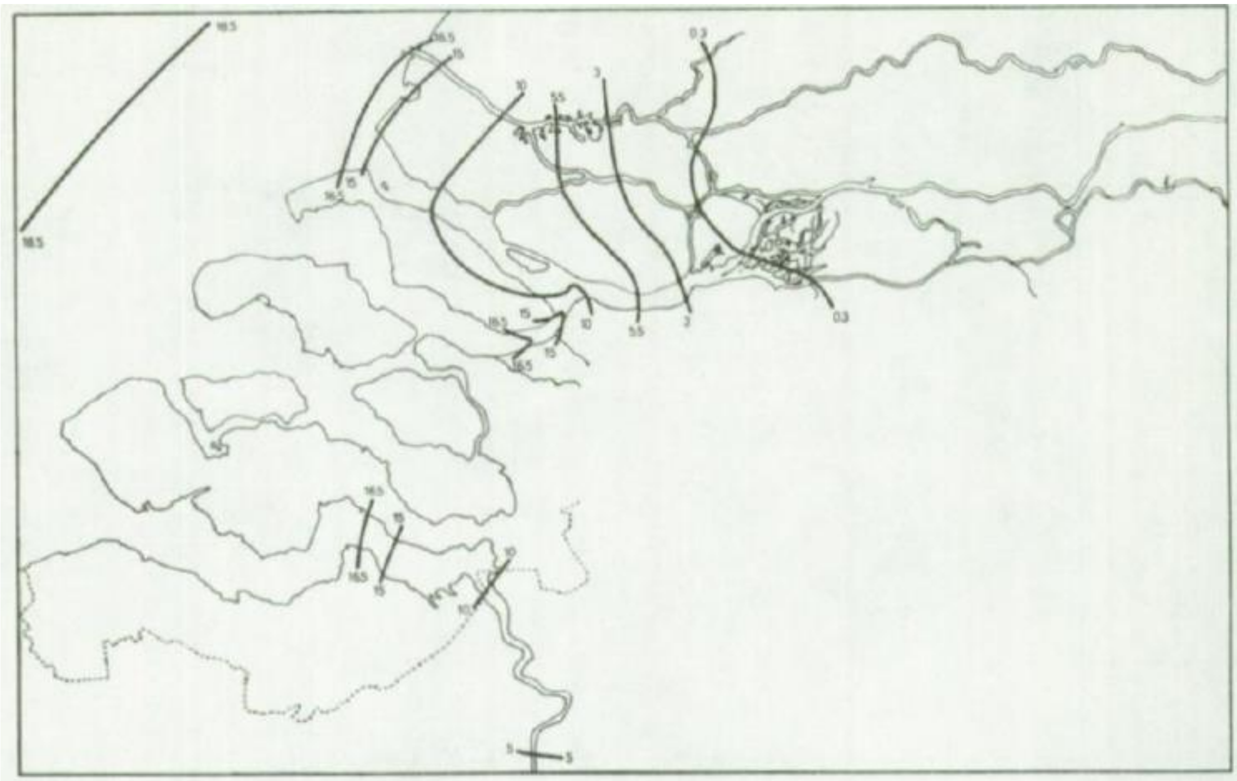
1) Salinity gradients in bottom waters during average discharge (1210 m3/s) and high tide



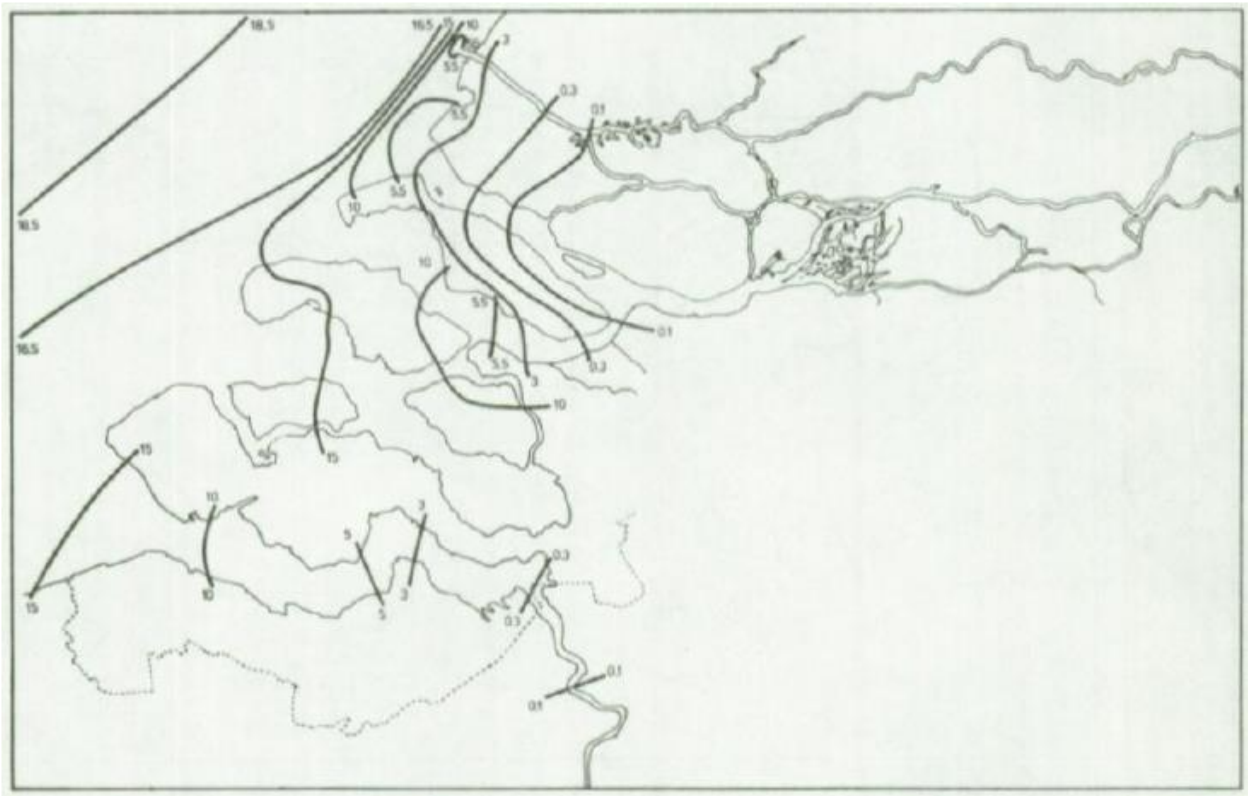
2) Salinity gradients in bottom waters during average discharge (1210 m3/s) and low tide



3) Salinity gradients in bottom waters during low discharge (450 m3/s) and high tide



4) Salinity gradients in bottom waters during high discharge (4000 m3/s) and low tide



Appendix IV: List of Recommendations

Salinity

- It is recommended to conduct further research on salinity gradients for different discharge scenarios in the future Haringvliet as designed in DELTA21. A 3D modelling study is recommended, in which the effect of different discharges on the salinity in the Haringvliet will be explored. In such discharge scenarios, it would be adviced to take into account a version in which more discharge from the upstream river system is directed to the Nieuwe Waterweg, not only because it could create more opportunities for aquaculture, but also because it might potentially help in countering salinization in the area of Rotterdam and Drechtsteden.
- Regulating the discharge of the Haringvliet could potentially be very important in optimising conditions for setting up aquaculture and expanding the potential aquaculture areas to the western part of the Haringvliet, since the salinity, which is a limiting factor for as well shellfish breeding as seaweed cultivation, is strongly related to discharge.

Bottom composition and flow rate

Follow-up studies are required to gather data on and answer these questions:

- Which bottom will be at a depth appropriate for either bottom or off-bottom cultivation? And what will the flow rate be like at these locations?
- How is the flow rate altered by introducing shellfish or seaweed cultivation?
- What are suitable options for off-bottom shellfish cultivation in the DELTA21 project area?
- To what extent will the waters and the bottom be polluted and is this a risk for aquaculture?
- What are the bioaccumulation risks of off-bottom and near-bottom cultivation for both seaweed and shellfish?
- Would adding clean substrate be a sustainable option to cover up contaminated soil? And will opening the sluices permanently result in significant exposure to old contaminants?
- What, if any, are the effects of certain materials used for artificial substrate on the surrounding environment?

Other environmental recommendations

Follow- up studies are required to gather data on and answer the following questions:

- To what extent can different seaweed species stand temperature fluctuations and exposure to temperatures above their optimum?
- Is the water temperature is expected to change as a consequence of the implementation of the Valmeer and a reduction of river influxes?
- What is the optimal water depth for seaweed cultivation and what are the maximum and minimum depths seaweed can survive in?
- What are the nitrogen and phosphorus concentrations in the DELTA21 project area and how will this change after reopening the sluices and implementing the DELTA21 plan?

Biodiversity

- To prevent future aquaculture from reaching or exceeding the carrying capacity of the system, carrying capacity models should be made to give an indication of the maximum seaweed and shellfish biomass within the ecosystem which could be cultivated (Heral, 1993). The model created for bivalves should look at chlorophyll-ɑ as a limiting resource as a study suggest that mussel conditions and growth are food limited at the ecosystem level (Smaal et al., 2001). Another model could look at nitrogen and phosphate as limiting resource for seaweed. In the models co-cultivation could be included, to investigate if the carrying capacity will increase by co-cultivation.
- Additionally, continuous monitoring of the carrying capacity should be undertaken after aquaculture is implemented, to make the model more accurate and limit damages to the natural system.
- The difference between cultured and natural reef their effects on biodiversity could be researched further.
- Although not directly related to aquaculture, the geomorphological changes caused by the future Valmeer and the tidal basin should be researched further, as this might provide more insight into the project's consequences for the biodiversity in the Voordelta.

Additional recommendations

Based on our findings, the following main recommendations for further research are:

- Conduct research on the development of salinity gradients in the Haringvliet and tidal basin for different river discharges (with extremes on the low as well on the high end) by performing a 3D modelling study in which planned constructions of DELTA21 are included.
- Conduct research on bottom quality and bottom composition on local scale and on different cultivation techniques (near-bottom, off-bottom), a.o. to decrease risks for food safety.
- Conduct a study on the influence of the constructions of DELTA21 on the morphology and flow velocity in the Haringvliet and tidal basin.
- Conduct a modelling study to the carrying capacity of the ecological system.
- Take a cautionary approach by set up a monitoring-and adjusting program which updates the models regularly (in Dutch, this is called "lerend implementeren")