



ACT-group 2780 “Arti Mare”

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Picture from: <https://www.foodunfolded.com/article/cleaning-the-seas-with-mussel-and-oyster-farms>

Aquaculture systems inside of the energy storage lake, special interest in integrated multitrophic aquaculture

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Glossary

Carbon sequestration: is the process of storing and capturing atmospheric/aquatic carbon dioxide.

Ecotopes: are the smallest ecologically distinct landscape features.

Fitness: the ability of an organism to adapt and overcome challenges often resulting in increased reproduction.

Halophytes: a class of plants that tolerate salty environments.

Genetic diversity: diversity in genetic profiles.

IMTA: (Integrated Multi-Trophic Aquaculture) a model for aquaculture practices that consists of the combination of more than two groups of organisms with the ability to benefit each other. The main purpose of IMTAs is to reduce production losses by maximizing the intake given to the system.

Phytoremediation: direct mitigation of nutrients and pollutants by assimilation in photosynthetic organisms, usually plants in inland cultures. It is usually used to remove toxic pollutants from ecosystems, can also be used to remove radiation and microplastics for example. The yield is then discarded (incinerated) to avoid the returning of these comp

SeaStairs: The SeaStairs technique consists of a series of levels (Steps/corridors/channels/streams) that are set concentrically around the lake and on top of each other. Although their sizes, heights and wideness per levels can vary, they all have the same objective, retain water and therefore, marine organisms. The different styles of SeaSteps are designed to host different organisms and accomplish different tasks. For example, top SeaSteps are shallower and meant to retain sediments from dunes and macroinvertebrates that can attract birds that prey on them.

Seaweed: Although seaweed is referred to extensively in this report, the use of this term in this document is not entirely accurate, as we are referring to macroalgae that can be grown for human consumption. Traditionally, seaweeds are macroalgae with a "lettuce-like" structure, some of the species we talk about cannot be considered seaweed due to their consistency and morphology. Nevertheless, we use this term as it is more practical to be understood.

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Summary

Anthropogenic climate change is expected to lead to higher sea levels and increased water stress events in the future. To prevent such water stress events and guarantee the safety of the Dutch coasts, reinforcement of the coast is necessary. The most conventional method to achieve this is through dyke reinforcement. As an alternative, the Delta21 project has been set up, in which an Energy Storage Lake (ESL) would be constructed near De Voordelta. In case of water stress events where there is insufficient river capacity to drain the water fast enough, the lake can be used to temporarily store the excess freshwater and prevent nearby areas from flooding. During the time the lake is not used for flood prevention, the lake will act as an energy battery. Excess renewable energy can be used to drain the lake while filling the lake will generate energy in times of scarcity. Lastly, the lake will be an opportunity for nature restoration and conservation in the area according to Natura 2000 regulations.

To promote the multifunctionality of the lake, the initiators of the Delta21 project have shown interest in the possible application of aquaculture within the lake. This report analysed the options and feasibility of implementing an Integrated Multitrophic Aquaculture (IMTA) system within the ESL while improving, or at least not negatively impacting, nature conservation and Natura 2000 regulations within the area. Within this report, the plan for the ESL made by Esmée van Eeden has been taken as starting point. Several aquaculture systems have been described and compared, and possible synergies between aquaculture and other components in the lake such as floating solar parks have been analysed. Interviews have been held with representatives of the mussel, oyster and seaweed industry to gain their insights and perspective on the project.

Based on the most important parameters related to aquaculture and sustainability, which are productivity, profit, nature restoration and carbon sequestration, various IMTA systems have been developed. IMTA systems that emphasize fish production are very productive and profitable, but the excess production of faeces and the use of feed can lead to potential environmental problems when not properly balanced with the capacity of filter and deposit feeders. However, the use of fish in the system can prevent nutrient deficiencies if nutrient availability is shown to be problematic. Another point that should be taken into consideration is the negative image of the public on aquaculture, even in the case of more sustainable IMTA systems. The use of aquaculture to replenish wild fish stocks could alleviate part of this negative image. However, one of the largest problems with the implementation of fish cages in the lake is the large fluctuations in the water level, as cages will not have enough space when the water level will be lowered to 5 m. Constructing the lake in such a way that fish aquaculture takes place in separate ponds connected to the main lake, but which can be closed off when the water level drops, could prove a solution in this situation.

Systems that do not focus on fish production, but instead focus on seaweeds, bivalves and deposit feeders have more positive effects on the environment. Since these organisms improve the water quality and help recirculate nutrients by filtrating the water column, their introduction into the system can help improve the environmental quality of the area.

The combination of aquaculture with floating solar parks was found to be difficult to implement and could only effectively be done using bivalves. However, it does efficiently make use of the available space.

This latter point, efficient use of available space, is a particularly important part of our design since we assumed that the conditions in the lower part of the ESL were unfitted to grow consumable seafood such

as shellfish, seaweeds, or fish due to the sediment accumulation at the bottom. For this reason, we decided to design an alternative that would use the slope instead of the center part of the lake. This idea, called *SeaStairs*, consists of building a step-over-step structure on the slope of the lake. Since each step is hollow inside, they will be filled with water. By holding the water, they would create a set of multiple long open-air tanks that would be interconnected. These long tanks can be used to grow shellfish such as cockles, mussels, or even oysters. Moreover, if the incoming sea water travels through the tanks, the outgoing water will be filtered first. This biofilter option has as an added value, as the water will be clearer and more transparent. This might be crucial to the survival of photosynthetic organisms like seagrasses and seaweeds. Other aspects such as holding sediments from outside and the aesthetical component can also be especially important for the entire system.

The volume capacity of the lake will not be decreased by the stairs. The first step will be created by the material that is dug out for the second step. By doing this, the volume that is needed for energy production will not be compromised. Nevertheless, the *SeaStairs* will need maintenance at some point, mostly because of inorganic sediments from the sand banks and filtered material. We then suggest that maintenance is done at the same time of product harvesting, as it is easy and practical.

Besides implementing an IMTA system in the lake, various components could be included in the IMTA but are optional. These components include the addition of buffer zones in the lake, the addition of seagrass, the cultivation of amphipods, the use of aquaculture organisms for medicine and the collection of spat for restoration or additional aquaculture production. The combination of IMTA with the restoration of the permanently flooded sandbanks habitat type in the ESL did not seem feasible, so it is recommended to compensate for the loss of this habitat type elsewhere.

In our report we have assessed the suitability of different species for the development of an IMTA within the ESL. Taking into account the main goal of having no harmful effects on nature, we do not advise the addition of fish to the ESL as it is currently a too detrimental practice. On the other hand, the cultivation of different species of shellfish and seaweed could be possible. We have estimated the maximum productivity of different species of seaweed and shellfish that could be cultured. We have also developed the idea of: *SeaStairs* on which both ecological restoration and aquaculture could be performed within distinct areas for specific cultivations. The ecological restoration is also partly taken into account by the tidal landscape created by Esmee. The retention of water tanks to the steps could benefit the cultivated benthic species, salt farms and seagrasses and would allow for a better biofiltration from shellfish. This filtration will affect the water column creating more clarity which can improve seaweed growth in the lake itself. The seaweed will be attached to floating lines in the deeper parts. Next to their economic profitability, their fast growth and cultivation would be a positive carbon sequestration tool.

Nederlandse samenvatting

Antropogene klimaatverandering zal in de toekomst leiden tot hogere zee-niveaus en hogere frequenties van waterstress evenementen. Om dit te voorkomen en de veiligheid van de Nederlandse kust te garanderen zal kust versterkt moeten worden. De meest conventionele methode om dit te bereiken is het verhogen van de dijken. Als alternatief voor deze methode heeft Delta21 een plan opgezet waarbij een Energie Opslag Meer (EOM) wordt gebouwd rond De Voordelta. In het geval dat de rivieren niet de capaciteit hebben om het inkomende water af te voeren zal het EOM gebruikt worden om overtollig zoet water op te slaan, om zo het overstromen van nagelegen gebieden te voorkomen. Gedurende de tijd dat het meer niet gebruikt wordt voor dit doel zal het meer dienen als energieopslagbatterij. Hierbij slaat het meer overtollige energie van hernieuwbare bronnen op door het meer te legen in tijden van overtollige energieopwekking, en weer te vullen in tijden van energieschaarste. Tot slot zal het meer ook een mogelijkheid bieden voor natuurherstel in het gebied conform Natura 2000 regulaties.

Om de multifunctionaliteit van het meer verder te versterken zijn de initiatiefnemers van het Delta21 project geïnteresseerd in de mogelijkheid van het toevoegen van aquacultuur in het meer. In dit rapport is geanalyseerd of het EOM gebruikt kan worden voor aquacultuur door het toepassen voor een "Integrated Multitrophic Aquaculture system" (IMTA), zonder dat dit negatieve consequenties heeft voor natuurbeheer en Natura 2000 wetgeving en wellicht de kwaliteit van het gebied kan verhogen. Hierbij is uitgegaan van de planning van het meer die is uitgewerkt door Esmée van Eeden. In dit rapport zijn verscheidene aquacultuursystemen beschreven en vergeleken. Mogelijke synergiën met andere systemen op het meer zoals drijvende zonneparken zijn ook onderzocht. Daarnaast zijn interviews gehouden met vertegenwoordigers van de mossel, oester en zeewierindustrie om hun inzichten en perspectief op het project te krijgen.

Gebaseerd op de meest belangrijke factoren gerelateerd aan aquacultuur en duurzaamheid, namelijk productiviteit, winst, natuurherstel en koolstofopslag, zijn verschillende IMTA systemen ontwikkeld. IMTA systemen waarbij de nadruk lag op visproductie waren zeer productief en winstgevend, maar de overtollige uitstoot van faeces en het gebruik van toegevoegde voeding kan leiden tot potentiële milieuproblemen wanneer er geen correcte afstemming is met de capaciteit van filtrerende organismen. Echter kan het gebruiken van vissen in het systeem wel eventuele nutriëntlimitaties voorkomen. Ook moet rekening gehouden worden met het algemeen negatieve beeld van het publiek op aquacultuur, zelfs in het geval van IMTA systemen. Het gebruik van aquacultuur om natuurlijke vispopulaties aan te vullen zou dit negatieve beeld deels kunnen verlichten. Een groot probleem rond het implementeren van vishokken in het meer is de grootte fluctuatie in het waterniveau, waarbij de hokken vaak niet genoeg ruimte zullen hebben wanneer het meer gelegeerd is. De vis aquacultuur verplaatsen naar specifieke secties van het meer die in verbinding staan met de rest van het meer maar afgesloten kunnen worden bij laagwater zou een oplossing kunnen bieden.

Systemen die de nadruk leggen op het produceren van zeewier, schelpdieren en bodemvoeders hebben gunstigere effecten op de omliggende omgeving. Gezien het feit dat deze dieren de water- en bodemkwaliteit verbeteren en het van circuleren van nutriënten bevorderen zal het toevoegen van deze organismen in de vorm van IMTA's leiden tot een hogere milieukwaliteit van het gebied.

Het combineren van aquacultuur met drijvende zonnepanelen is moeilijk te implementeren, en alleen effectief wanneer dit gedaan wordt met schelpdieren. Daarbij kan het combineren van zonneparken met schelpdieren wel leiden tot een efficiënt ruimtegebruik in vergelijking met een losgekoppeld systeem.

Het efficiënte gebruik maken van ruimte is dus belangrijk binnen dit project. Hierbij wordt ervanuit gegaan dat het lagere deel van het EOM niet optimaal is voor het groeien van schelpdieren, zeeieren of vissen doordat er veel sediment aggregeert op de bodem. Ook moet er een deel zijn wat zowel ondiep is als altijd onderwater. Dit is moeilijk te realiseren in het EOM. Om dit probleem aan te pakken hebben wij *SeaStairs* ontwikkeld. Dit is een stapsgewijze constructie op de helling van het meer. Elke trede is uitgehold en gevuld met water, en al deze treden zijn met elkaar verbonden. Dit creëert lange tanks die kunnen worden gebruikt om schelpdieren te groeien, zoals kokkels, mosselen en oesters. Verder kan dit systeem ook gebruik maken van zeewater dat bij de bovenste trede naar binnen gepompt wordt. Dit kan als een extra worden gezien, aangezien de *SeaStairs* ook het water zuiveren met behulp van de schelpdieren. Zuiver en helderder water is beter voor fotosynthetische organismen zoals zeegras en zeeieren.

Het totale volume van het meer neemt niet af door de *SeaStairs*. De eerste gevormde trede is opgebouwd uit de materialen die vrijkomen bij het graven van de trede eronder. Dit zorgt ervoor dat het totale volume niet afneemt en zo dus ook de energieproductie capaciteit niet wordt verlaagd. Desondanks moeten deze tredes wel onderhouden worden, aangezien er een laag met bezinsel van inorganische sedimenten kan ontstaan. Wij suggereren om het weghalen van deze lagen tegelijk te doen met het oogsten van de organismen. Hierdoor is het makkelijker en praktischer uit te voeren.

Buiten het implementeren van een IMTA systeem in het meer zijn er ook verscheidene componenten onderzocht die kunnen worden toegevoegd aan het aquacultuursysteem, maar die alleen een toevoegende waarde hebben en niet vereist zijn voor het functioneren van het systeem. Hieronder vallen het toevoegen van bufferstroken, het herstellen van zeegras, het cultiveren van amfipoden, het kweken van organismen voor medicijnen en het verzamelen van schelpdierzaad voor gebruik in restoratie of aquacultuur. Het combineren van een IMTA met het herstellen of creëren van permanent overstroomde zandbanken is niet aannemen gebleken. In plaats hiervan wordt aangeraden om dit habitattype te compenseren door het elders te herstellen.

In ons report hebben we gekeken welke soorten het meest geschikt zijn binnen de ontwikkeling van een IMTA systeem passend voor het EOM. Aangezien een van de hoofddoelen van dit project natuurherstel is adviseren we geen visteelt toe te voegen aan het meer omdat de huidige methodes te veel negatieve aspecten hebben en niet passen binnen het natuurbeleid. Wij raden aan om bentische organismen te gebruiken in het meer vanwege de voordelige effecten die zij hebben op abiotische factoren. Ons advies is om specifieke gebieden in het meer te hebben voor de toegewezen aquacultuur systemen. In het *SeaStairs* idee is al rekening gehouden met de verschillende hoogtes waarin bentische organismen worden geplaatst. Ook is zilte teelt samen met zeegras mogelijk in het systeem. Het meer zelf zal gebruikt worden voor zeewierteelt welke aan drijvende lijnen bevestigd worden. Naast de economische waarden van zeewier dragen ze door de snelle groei ook bij aan koolstofvastlegging binnen het meer. Het ontwerp van Esmee bevat naast het meer ook een groot stuk toegewezen aan natuurherstel door het creëren van een getijden-landschap en helpt hiermee ook met de opgelegde onderzoeksvragen.

Introduction

The Delta21 project focuses on creating an Energy Storage Lake (ESL), which will mainly serve for water management/safety and as an energy battery by storing water that can be used for hydroelectric energy. The lake also provides opportunities to focus on nature restoration and preservation within the area. The commissioners want to make the concept of the lake design as well-rounded as possible to make the plan for the ESL attractive to as many different stakeholders as possible and accelerate the implementation phase. We use information from literature research and expert interviews to conclude the most suitable aquaculture systems for the ESL. This conclusion is mostly influenced by the impact that the system will have on the environment. We also took into account societal benefits and economic profit, but these parameters had a lower priority.

Purpose of the project

The purpose of this ACT project is to investigate the possibility of including innovative options with varying intensities and complexities of Integrated Multitrophic Aquaculture systems, and options that combine aquaculture with renewable energy or other systems present in the lake ecosystem. We will investigate ways to compensate for the loss of habitat type H1110 and comply with the Natura 2000 legislations. With this in mind, we will analyse whether aquaculture systems could be included in the ESL or if it is possible to combine the habitat type characteristic species with an aquaculture system. In this case we attempt to design an IMTA system to achieve aquaculture production and H1110 habitat restoration in the same area. If this not possible we will look at the best alternatives for the lake.

Problem definition and research questions

Definition

In this project, the addressed knowledge gap is the implementation of a future proof aquaculture system, for example a (restorative) Integrated Multi-trophic Aquaculture (IMTA) system, in the Energy Storage Lake. The future proof aspects are in line with the Netherlands 2120 plan, which looks into more green energy, greener cities and more local production. At the same time, the implementation of this IMTA should keep the area in line with Natura 2000 legislation, resulting in a beneficial impact on the environment. The new system would have to increase the ecological value of the area. The problem with creating systems such as an IMTA in the ESL is that there are various stakeholders in the area with different goals. To satisfy the needs of these different stakeholders, the main focus, which is the environmental aspect of the project, should be taken into consideration. Therefore, our team will look at possibilities to implement an IMTA system in the energy storage lake in such a way that Natura 2000 regulations will be met or even reinforced.

Research questions

Main questions: What is the optimal aquaculture system for the Energy Storage Lake in terms of economic profit, societal benefit and nature improvement? The following sub questions will be explored:

1. Which different aquaculture systems exist nowadays and what are their advantages and disadvantages?
2. Are synergies between aquaculture and other uses of the lake such as renewable energy, possible? If so, to which extent?
3. What type of aquaculture features to suit the conditions within the lake, also from an ecological standpoint?

Multidisciplinary approach

The Arti Mare team consists of six members, all of whom have different backgrounds and specialities. This allowed for a multidisciplinary approach to the problem, resulting in input in discussions from many different angles. It makes for good discussions about how to tackle problems and how to find fitting solutions. We had two members who are in their second year of Msc Biology, both with a specialization in Marine Ecology. We also had two members that are in their second year of the Msc Aquaculture and Marine Resource Management, both focusing on Ecology. Another member is in the second year of the Msc Plant Sciences, with a specialization in Natural Resource Management. The last member is in the second year of the Msc Animal Sciences, specialization in Behaviour, Adaptation and Health and the first year of the Msc Organic Agriculture with a specialization in Agroecology. Although our courses and studies differ quite a lot, we still share roughly the same views for the future, which allows for discussion with a lot of information and creative solutions. The multidisciplinary surely adds many benefits to our final result.

Methods

Literature research

We conducted literature research on various aquaculture systems and culturing methods. Based on the results from this study, several options for IMTA systems were established considering abiotic and biotic parameters as well as social, economic, and environmental factors.

Expert interviews

Besides our literature analysis, interviews have been conducted with stakeholders in the area and experts to gain more information about the specific views and needs of different parties. Interviews have been conducted with representatives of the mussel, oyster and seaweed industry. The meetings with the experts were mainly done via Microsoft teams due to covid regulations.

During the meetings, there were always at least two members of Arti Mare present. One of them took the role of interviewer, whilst the other member took on the role of secretary. However, these roles were not fixed, as both members could ask questions, but the secretary was assigned to take notes for each question. We conducted four interviews, of which the interview with Addy Risseeuw from PO Mossel was the only one that took place in person. We did this after having given a short progress presentation in Yerseke, Zeeland. The other interviews were with (in chronological order), Bertram de Rooij from Wageningen Environmental Research, Job Schipper, expert in seaweed cultivation export from Seawiser, and Jaap de Rooij from the Dutch Oyster Association (Nederlandse Oestervereniging). Lastly, we interviewed Marnix Poelman from Wageningen University, Marine Research about the calculation of our maximum productivities in the ESL. The information that was gathered for the interviews was implemented in the text and referenced accordingly.

Ethics

Our advice is meant to give an overview of objective and unbiased information. As a group, we made sure that the information in our advice is of a sound and reliable nature. Additionally, the formation of our advice is designed to be both practical and solution driven. The advice, solutions and conclusions that have been produced are objective and therefore might contradict with views of Delta21. In this report, multiple solutions are presented, each with a different focus. The decision to implement any of the mentioned aquaculture systems will remain with the commissioner. Since this project is non-confidential, the different views of parties on the project could always be up for discussion.

The Delta 21 project has multiple aspects, including water management, energy production, aquaculture and nature restoration. There are of course certain conflicts when optimizing a project for these different goals since each solution will have different kinds of consequences for different stakeholders. In this project, we aimed to create the most fitting advice(s) focused on nature restoration and the possibilities of aquaculture. This does not mean that we have ignored the other aspects. However, they will not be discussed in detail within this report.

As aforementioned, the implementation of this project can have impacts on a diverse fan of stakeholders. This project will not touch upon the arguments of promoting the implementation or rejecting it. In the advice, we have made sure that the opinions of each member have not been linked to the Wageningen University and Research or to the Delta 21 project but should be seen as their own opinions. By distancing the opinions of our group from the stakeholder, We have ensured our independence without criticizing

anyone's opinion. During our interview activities, we made sure to request permission to use the name of the interviewee in the report.

Background

1. The lake: what is it; what is our starting point

a. Energy storage lake plan

Ever since the floods of 1953, flood protection has been a priority of the Dutch government (Dammers *et al.*, 2014). This has led to an extensive network of dykes and projects, including the famous Deltaworks protecting the Dutch coast. However, due to climate change, sea levels are rising (Rahmstorf, 2010), which means there is a need for further coastal protection. One way to achieve this is through raising the currently established dikes for them to be able to cope with the increasing sea levels. The Delta21 project has been created as an alternative to the idea of raising dykes. Instead, a lake of 30 km² will be constructed between the Tweede Maasvlakte and the island Goeree Overflakkee to hold and release water during water stress events (Delta21, 2018). The lake will have a water depth of 22.5 m, with a maximum potential daily water height difference of 17.5 m (ConsultanSEA, 2020). By allowing excess water to be pumped into the lake at a rate of 10000 m³/s during events with heavy water discharge from rivers, the flooding of neighbouring areas can be prevented. It is estimated that such an event would occur approximately once every ten years, although this is variable and depends on the effects of climate change (ConsultanSEA, 2020).

Besides serving for coastal protection, the lake will be used for energy storage (Delta21, 2017). At present, there is an imbalance in the energy supply of renewable energy sources. Depending on the weather conditions, the energy supply might be too low or high compared to the demands. If there is a surplus supply of renewable energy from solar panels and wind turbines, this surplus energy is lost (curtailment) (Delta21, 2017). A shortage of energy at other times would have to be met with energy production from conventional energy sources. The introduction of the energy storage lake allows excess renewable energy to be used to power the turbines to empty the ESL. The ESL can then be filled at a later point in time when there is an energy demand to generate energy (Delta21, 2017). Hence, the ESL will increase the efficiency of green energy sources by storing excess energy for later use. Since the proportion of energy derived from renewable sources is expected to increase in the future, the ESL will become more essential over time to effectively use and distribute the generated energy (Delta21, 2017).

b. Project design by Esmee

For this project, a landscape design was made by Esmee van Eeden. This design has been proposed to form our starting point for the general layout and includes the ESL, a dynamic tidal lake and a creek landscape based on the following technical requirements:

- The pumping station and spillway need to stay clear from sediments
- The ESL has a minimum surface area of 24km²
- The depth of the ESL is -25 meters
- Water fluctuations in the ESL can be up to 20m
- The entire area can be closed off by a storm surge barrier
- The slopes of the energy lake and beaches will not be too steep (1:10 or gentler)

- The separation between the energy lake and the tidal lake must be at least 5m + NAP
- The tidal lake will be a natural area
- The new layout must be in harmony with the natural processes

Ecological parameters

- The salinity can change due to freshwater inflow
- Temperature can vary a lot due to the inflow of freshwater/seawater
- Current speeds vary when the lake is emptied and filled

Figure 1 shows the general masterplan for the design for the ESL and surrounding area made by Esmee van Eeden. It shows the ESL on the left with the pumping station, spillway and storm surge barrier numbered 1,2,3 respectively. On the right side of the ESL, a broad area will be developed into a creek and marshland landscape, made in a way that after implementation the natural processes of erosion and sedimentation will continue developing the creek landscape.

Figure 2 shows the aquatic ecotopes that will exist with the implementation of the design. In this case, the ESL can be considered saltwater, whereas the tidal area and marshlands will be more of a brackish nature. A fish migration river will be present to act as a continuous gateway from the sea to inland, even when the storm surge barrier is closed.



Figure 1. Masterplan of the design by Esmee van Eeden. Retrieved from: 'A new dynamic landscape for the Haringvliet' (Esmee van Eeden 2021)

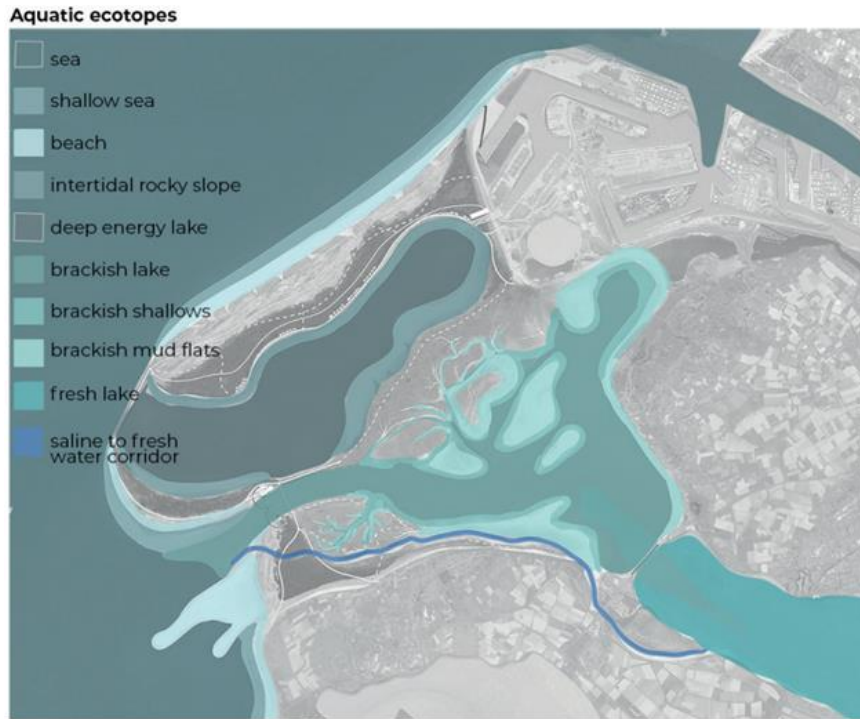


Figure 2. Aquatic ecotopes in the design. Retrieved from: ‘A new dynamic landscape for the Haringvliet’ (Esmee van Eeden 2021)

Looking at the design, the aquatic landscapes can be roughly divided into two parts: the more functional storage lake and the restorative tidal area. The tidal area is meant to be created and developed into a nature and bird reserve. The main focus of the area lies on nature restoration, allowing nature to take back the reigns of the landscape and provide valuable habitats for vulnerable species in the area. The contents of the ESL are still open to suggestions and will be the main focal point for our project.

Esmee’s design contained the following drawing concerning the ESL with possible aquaculture options, showing the situation for the lake with both low- and high-water levels (figure 3). In this design, the species reared for aquaculture will be submerged during the day when the lake is filled and out in the open air when the lake is drained during the night. The suggestion is made that the farmers use the nights to work and harvest their shellfish and crops when the water retrieves. As this might not be completely feasible or preferred by the farmers themselves, we will look further into the aquaculture options within the ESL specifically. In optimal situations, the lake will be filled

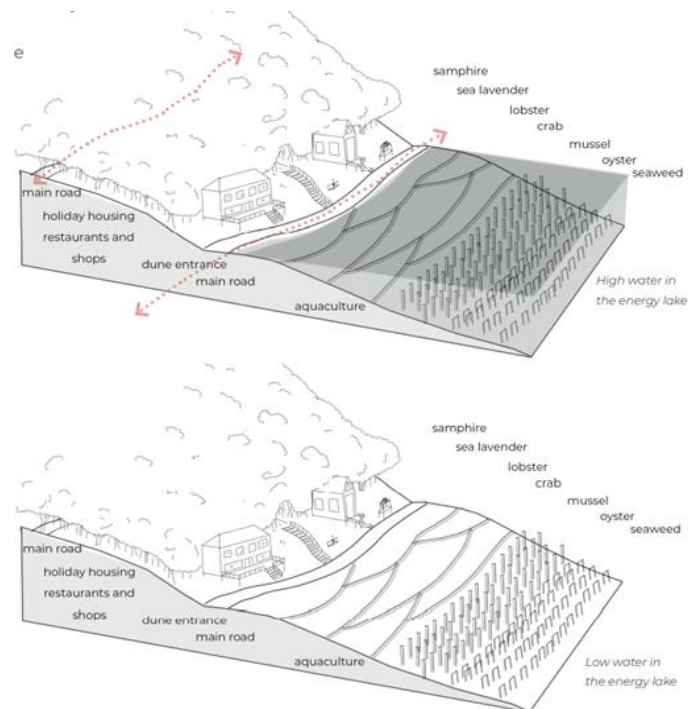


Figure 3. Slope of the Energy Storage Lake; a place for aquaculture. Retrieved from: A new dynamic landscape for the Haringvliet (Esmee van Eeden, 2021)

most of the time, and the freshwater inflow will be limited. This allows for stable conditions for the organisms to grow.

If we take the design from Esmee as our starting point, the most important parts to take notice of for our project are:

- 1) The ESL can have a water level difference of ~20m.
- 2) The north side of the lake has a steep slope that shows the rising/falling water levels, the south side's slope is barely noticeable.
- 3) The pumping station and spillway need to stay clear from sediments.

We will make different suggestions and options that are feasible for the ESL and focus on ways that we can create stable systems that can handle the ever-changing environment.

Analysis of the various aquaculture systems






c. Parameters

Within this report, the effects of introducing an IMTA system into the ESL has been analysed. An Integrated Multi-Trophic Aquaculture system or IMTA is a food production system that utilises species from different trophic levels simultaneously by cultivating them in proximity to each other. An IMTA combines fed species (e.g. shrimps, fish) with extractive species (e.g. seaweeds, shellfish and other invertebrates). By doing so you take advantage of the synergies between these species by recycling nutrients and waste produced from top trophic level species which is then used by lower trophic levels. The lower levels could potentially be used to feed the top levels again or for other purposes (e.g. biofuels, human consumption). This creates a circular system where waste is reduced and revalued and diversifies the sources of revenues for farmers. Nowadays, other benefits of IMTA have been found through the multiple ecosystem services that they provide, such as providing nursery and refuge habitats, bio-remediation, coastal protection and others.

There is the only existent criterium for the aquaculture system; it cannot hamper the existing water management system in any way. Instead, the inclusion of the IMTA should improve the ecological value of the area, or at least not affect it negatively (1st commissioner's meeting, personal communication). In this manner, the IMTA system is seen as an addition to the system. For this analysis, each potential aquaculture has been analysed based on three parameters: economic profit, societal benefit and nature improvement. When talking about the societal benefit, looks into the impact that the lake can have on local employment and development, and therefore on public opinion. Nature improvement will focus on the losses that occur when the ESL is constructed and how to revive the ecosystem or improve it.

The scoring will be summarized shortly beneath every piece, the pros and cons will be summed up. After this, we state if the option, based on our opinion, would be suitable for the ESL. After this, a score will be given on a scale from one to five. An explanation of this scoring system can be found below.

Table 1. Scoring system of the different aquaculture systems. The amount of mussels represents the number of parameters included in the system and how beneficial the system overall would be for the ESL.

Scoring	Explanation
	None of the three parameters is developed thoroughly, it could be a potential option but needs further research before being implemented.
	One of the three parameters is included. The cons of the option outweigh the pros.
	Two of the three parameters are included. The pros and cons equalise each other.
	All parameters are included, and the pros outweigh the cons. There are still some drawbacks.
	All parameters are included, the option has been shown to work and can be implemented practically.

It has also been analysed whether saltwater agriculture could be added to the ESL system.

d. Boundaries

i. Focus of our design

To specify the focus of our design, we all gave a top three priorities for the design. The resulting focus points of our design were innovation, synergies and nature inclusivity. These aspects will be a priority throughout the design of the IMTA system.

We also thought of how our systems aligned with the goals of Netherlands 2120. These goals were created by Wageningen University as a set of guidelines for how to build a more sustainable future. The five guiding principles that form the backbone of the Netherlands 2120 report are using the natural system as a starting point, optimal use of water, creating a nature-inclusive society, establishing a circular economy and fostering adaptive spatial planning (Baptist *et al.*, 2019). In the future, there will be a further need to sustainably combine development with nature conservation. For this reason, this report will highlight how the Delta21 project combined with the introduction of an aquaculture system could help achieve and strengthen the Netherlands 2120 goals.

ii. Species type

With the view of creating an IMTA system in the lake, several groups of organisms have been considered for implementation into aquaculture systems. These groups include seaweeds, bivalves, fish, and deposit feeders. These species have been and are native to the Dutch waters. Each group and the organisms associated is further described below.

Seaweeds and bivalves

A previous ACT group has already identified the environmental requirements for the cultivation of various species of seaweed and shellfish. Their findings are summarised in table 2. Regarding the cultivation of seaweed species, *Palmaria palmata* has still many challenges when cultivated and is also not yet grown in the Netherlands. However, research on its cultivation is ongoing. *Ulva lactuca*, *Laminaria digitata* and *Saccharina latissima* are currently cultivated in the Netherlands.

Mussel and oyster cultivation is widespread in the Netherlands. The main cultivation locations of the mussels are the Eastern Scheldt and the Wadden Sea. Oyster cultivation occurs mostly in the province of Zeeland (Animal+1, 2019). Another bivalve that is included in our design is the Cockle (*Cerastoderma edule*). Cockles are fished in the Netherlands.

Fish

Atlantic Salmon (Salmo salar)

The Atlantic Salmon used to be common in the Netherlands, but increasing barriers between the rivers and the sea have left the species in decline (Breukelaar *et al.*, 1998). The species is anadromous, meaning the salmon migrate into riverine systems for reproduction but spend their adult life at sea. Salmon are carnivores and feed on fish and crustaceans in the wild (Aas *et al.*, 2010).

Parameter	Unit	Shellfish				Seaweed			DELTA21 area	
		ME	OE	CG	LD	SL	PP	UL	WH	TB
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

Table 2. Environmental requirements for shellfish and seaweed species. For each species, the requirements in terms of the salinity, temperature, water depth, water velocity, bottom substrate type, feed type, indicators for feed presence and the light attenuation are given. ME = *Mytilus 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 (source: animal+1, 2019).

Brown trout (*Salmo trutta*)

The brown trout is a European species part of the salmonid. The species is facultatively migratory, which allows it to adapt to many different environments (Baglinière, 1999). Aquaculture of Brown trout in Europe is already common as the species is often reproduced in hatcheries for sport fishing purposes (Quillet *et al.*, 1992). Brown trout are resistant to high salinities and temperatures. They show higher growth rates in salt water than in fresh water, with growth rates similar to Atlantic Salmon (Quillet *et al.*, 1992).

Sea bass (*Dicentrarchus labrax*)

The European Sea bass was one of the first species to be commercially farmed, excluding salmonid species. The species can tolerate a wide range of temperatures (5-28 degrees) and salinities (from 3‰ to seawater) levels. Most of the aquaculture production comes in the form of sea cage farming, although production of sea bass in seawater ponds and lagoons is also occurring (FAO, 2005-2021).

Gilthead sea bream (*Sparus aurata*)

The Gilthead sea bream lives and feeds near the bottom of sea or coastal ecosystems. Similar to Sea Bass, they can withstand a large range of temperature and salinity levels. They are found in marine and brackish water bodies, such as lagoons and estuaries (Pavlidis *et al.*, 2011).

Deposit feeders

Polychaete worms

Polychaete worms can be found in virtually every marine system. Within these systems, they feed on marine detritus and act as deposit feeders (Fauchald & Jumars, 1979).

2. Restrictions for the lake; what to keep in mind

a. Natura 2000

The ESL will be constructed in De Voordelta, which is marked as a Natura 2000 area that falls under both Bird and Habitat protection. Natura 2000 is a European network consisting of many nature conservation areas that aim to supply and maintain habitats for threatened and valuable species. In the Netherlands, Natura 2000 areas are leading for other plans being executed in the same area (Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2021). Consequently, only projects that fit within the regulations of Natura 2000 are allowed. However, if a new plan in a Natura 2000 area does affect the Natura 2000 area or management, Article 6.3 of the Habitats Directive states that the effects of the new plan will be investigated, and it will be evaluated if it is in line with the conservation objectives of the area (Council Directive 92/43/EEC).

A previous ACT report concluded that Delta21 will have negative effects on parts of De Voordelta (ACT DELTADO CONSULTING, 2020). The areas which will be most affected by the construction of the ESL are the Hinderplaat and the Permanently flooded sandbank habitat (type H1110) that is found at the location where the ESL will be constructed. Due to these negative effects, their advice is to follow the ADC-test when the project needs approval. The ACD-test states that the losses of habitat type and/or species should be minimised and compensated for/ This could for example be accomplished by providing that habitat type elsewhere. The habitat of the Hinderplaat will be compensated by the tidal lake. However, the loss of the permanently flooded sandbanks will be difficult to compensate for in the current plan for the ESL, which will likely result in heavy critique from nature organizations (ACT DELTADO CONSULTING, 2020).

For the ESL to support nature restoration according to Natura 2000 regulations, various principles should be taken into account. Natura 2000 has set several guidelines to consider when working towards nature restoration in an area. Firstly, the area considered for restoration should have a similar diversity and community structure when compared to reference sites. Secondly, when restoring an area, only indigenous species should be selected for inclusion in the system. The introduction of non-native species in natural systems has led to several cases of species becoming invasive, which resulted in a loss of biodiversity and degradation of the ecosystem (Sakai *et al.*, 2001). Therefore, non-indigenous species should be excluded as much as possible from any nature restoration effort. Thirdly, the presence of functional groups is necessary for long-term stability. These functional groups include, amongst others, autotrophs, planktivores, herbivores, detritivores, omnivores and consumers (Micheli *et al.*, 2005). Lastly, the physical environment should be able to support reproducing populations. This entails that all environmental requirements for organisms are met, which includes both biotic and abiotic factors. Import abiotic factors include the temperature, salinity, pH, turbidity, currents and nutrient concentrations present in the water. Biotic factors include the availability of food and predation pressure.

As De Voordelta is a Natura 2000 area, any construction project should take these nature restoration principles into account in their design. As such, this research on IMTA or other aquaculture systems in the ESL will consider these guidelines when designing the system. For this reason, the aforementioned principles of nature restoration according to Natura 2000 standards have been used in analysing possible aquaculture systems within the ESL.

i. Habitat 1110

The habitat type that is lost due to the construction of the ESL is named permanently flooded sandbanks, otherwise referred to as habitat type H1110. The information about this habitat was described by Natura 2000 in their profile report of 2014. This habitat is formed by currents and geological morphology. These sandbanks are in shallower parts of the seas and are, as the name suggests, permanently flooded. The layer of water on top of the sandbanks is rarely deeper than 20 meters, and often there are hard substrates on the sandbanks such as shell banks, stones and clay. Additionally, there are some biogenic structures, which are structures that are built up by living or dead organisms, for example, mussel banks.

The definition of a habitat type is very broad. The trenches (in between sandbanks), water column and the different ground layers are all included in the H1110 habitat type. The quality of the habitat is greatly influenced by criteria such as water clarity and hydrodynamic force. Clear water allows photosynthesis to occur on the bottom. However, the deeper waters are often very cloudy, which limits light from reaching the bottom. Due to this, the shallower areas usually have more algae growth and algae diversity. One example of a permanently flooded sandbank that has algae growth is the Doggersbank, which is a marine protected area (MPA) with a large variety of microphytobenthos due to the clear seawater.

The most important characteristic to maintain a habitat H1110 type is current dynamics (hydrodynamics). The most important characteristic to maintain a habitat H1110 type is current dynamics (hydrodynamics). When there is low hydrodynamics, especially in trench areas, sludge will form sediment on the bottom. This sludge then forms a layer with limited photosynthesis and biodiversity. Habitat maintenance is also dependent on nutrient availability. There is medium to high nutrient richness since they are replenished by inflow via rivers and inflow from the Channel and nutrient turn-over by the system itself. Combined with salinity and temperature these abiotic factors are determining the biodiversity and the organisms that are present for the H1110 habitat type. Due to the natural dynamics of the tides and waves interactions the community is resilient and is characterized by rapid recolonization after bigger disturbances. When the circumstances are highly dynamic the community tends to be relatively short-living, fast-growing and reproducing at a young age, species such as worms and smaller crustaceans. Areas with low dynamics usually have higher biodiversity and a higher density of long-living, slow-growing organisms. These communities are hit harder after a disturbance and take longer to recover, often these areas are nurseries for juveniles disturbing the population.

There are also different subtypes of the H1110 habitat type, which will not be discussed in detail. Subtype B is the one represented in the area where the ESL will be built. These subtypes are close to unnatural salt-fresh water separations, where occasionally large freshwater inflows happen. So, the species that inhabit these habitats are suited to survive big salinity fluctuations. The species richness is therefore not that high in these habitats compared to more stable environments. The species that are present in H1110B can be found below. If these species reappear in the energy storage lake, the loss of biodiversity will be contained.

Table 3. * = Cab= constant species indicative of good abiotic factors, K= characteristic species. (Natura 2000, 2014)

Dutch name	Scientific name	Species	Category*
Dwergtong	<i>Buglossidium luteum</i>	Fish	Cab
Haring	<i>Clupea harengus</i>	Fish	Cab
Kleine pieterman	<i>Echiichthys vipera</i>	Fish	K + Cab
Kleine zandspiering	<i>Ammodytes tobianus</i>	Fish	Cab
Noorse zandspiering	<i>Ammodytes marinus</i>	Fish	Cab
Pitvis	<i>Callionymus lyra</i>	Fish	Cab
Schol	<i>Pleuronectes platessa</i>	Fish	Cab
Tong	<i>Solea vulgaris</i>	Fish	K + Cab
Wijting	<i>Merlangius merlangus</i>	Fish	Cab
Schelpkokerworm	<i>Lanice conchilega</i>	Bristle worms	Cab
Zandkokerworm	<i>Spiophanes bombyx</i>	Bristle worms	Cab
	<i>Nephtys cirrose</i>	Bristle worms	Cab
	<i>Ophelia borealis</i>	Bristle worms	Cab
Kniksprietkreeftje	<i>Bathyporeia elegans</i>	Crustacean	Cab
	<i>Urothoe poseidonis</i>	Crustacean	Cab
Hartegel	<i>Echinocardium cordatum</i>	Echinoderms	Cab
Glanzende tepelhoorn	<i>Lunatia alderi</i>	Mollusca	Cab
Halfgeknotte strandschelp	<i>Spisula subtruncata</i>	Mollusca	K + Cab
Nonnetje	<i>Macoma balthica</i>	Mollusca	K + Cab
Rechtgestreepte platschelp	<i>Tellina fabula</i>	Mollusca	Cab

ii. Freshwater input

As mentioned before, the lake is created primarily for water safety. This means that the ESL will be (partly) filled with freshwater due to the opening of the sluice of the lake connected to the Haringvliet when waters from the river are high (see Figure 4). In reality, this will mean that the ESL will have a freshwater inflow once every ten years. Climate may change these rates, but it will not happen often. Nevertheless, if aquaculture will be done in the ESL, the rare inflow of freshwater will affect the aquaculture. For this reason, the effects of different salinity levels are estimated for different aquaculture species will be estimated in the following part.

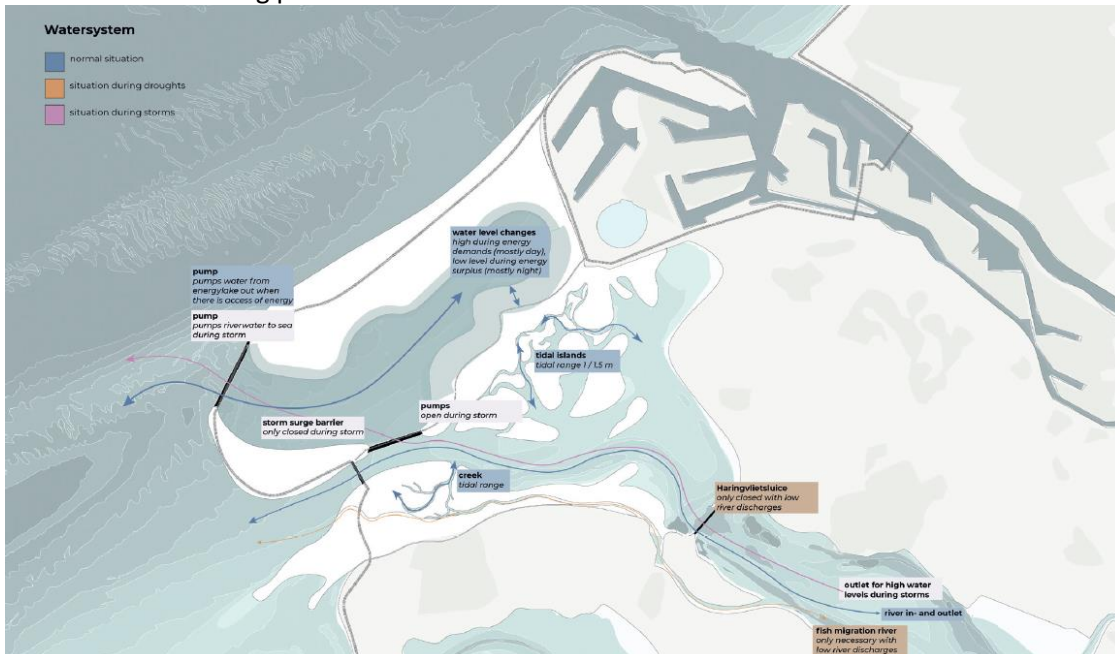


Figure 4. The water system of the lake was described by Esmée van Eeden (2021). In blue how the water will flow in normal situations, in orange how the water will flow in situations during drought and in pink how the water will flow in storm situations.

It is impossible to know when the freshwater inflow of the Haringvliet will happen, how many litres there will be pumped into the lake and how often this will happen in the future. Therefore, to estimate the effects of the different salinity levels on different aquacultural species, it is calculated if an x percentage of the lake is freshwater. Besides, it will be estimated how this amount corresponds to the amount of freshwater inflow and what the salinity levels are. These salinity levels can be compared to optimal salinity levels of aquaculture species. The results are summarised in Table 4.

Percentage of the lake freshwater (%)	Freshwater inflow (litres)	Salinity level (psu)	Blue mussel	Flat oyster	Pacific oyster	Laminaria digitata	Saccharina latissima	Palmaria palmata	Ulva lactuca
0.00	0	31.0	Green	Green	Green	Green	Green	Green	Green
5.00	21500000	29.5	Orange	Orange	Green	Orange	Green	Green	Green
10.00	43000000	27.9	Orange	Orange	Green	Orange	Green	Green	Green
15.00	64500000	26.4	Orange	Orange	Green	Orange	Green	Green	Green
20.00	86000000	24.9	Orange	Orange	Green	Orange	Green	Green	Green
25.00	107500000	23.3	Orange	Orange	Green	Orange	Green	Green	Green
50.00	215000000	15.6	Orange	White	Orange	Orange	Green	Green	Green
75.00	322500000	7.9	White	White	Orange	Red	Red Germlings injured and death after 4 days	White	White
100.00	430000000	0.2	Red death after >2 days			Red	Red Germlings injured and death after 4 days	White	White

Table 4. Salinity levels per percentage of freshwater with the corresponding growth of bivalve and seaweed species. The colours in the table indicate the growth of the species: (Green) optimal growth, (orange) reduced growth, (red) death, and (white) unknown.

The estimated mean salinity level of the ESL without freshwater is around 31.03 psu. This can however vary due to the freshwater inflow of the Haringvliet with low tides. This salinity level is comparable to the Eastern Scheldt and the Wadden Sea. The estimated salinity level of the freshwater inflow is based on the lowest level measured in the Haringvliet, which is 0.2 psu. This number is chosen because when there will be freshwater inflow in the ESL, it will be mainly river water because of high water levels. The freshwater inflow in the lake is based on the fraction of freshwater in the lake times the total volume of 430 million litres of water. The salinity levels are calculated by the fraction of freshwater times 0.2 + the fraction of saltwater times 31.03.

As can be seen in Table 4, blue mussels (*Mytilus edulis*) grow best when there is no inflow of freshwater. This is because their optimal growth happens when the salinity is between 30-40 psu (Tyler-Walters, 2008). They have reduced growth when there is more freshwater inflow. According to Tyler-Walters (2008), mussels have reduced growth between 18-30 psu. However, in the study of Line & Pleissner (2012), mussels still grow at a salinity level of 15 psu. Mussels have a high tolerance for salinity changes because they close their siphons when salinity is changed. Unfortunately, when mussels are exposed to freshwater for more than two days, some will die (personal communication Jaap de Rooij).

The flat oyster (*Ostrea edulis*) also has its optimal growth between 30 and 40 psu and when there is no freshwater inflow. They can grow at lower salinities (18-30). However, this will be reduced growth (Perry, 2017). The pacific oyster (*Crassostrea gigas*) has on the other hand its optimal growth between 20 and 25 psu (Helm, 2005). It can therefore tolerate more than 25% of fresh water in the lake. According to Helm, they can occur at salinities below 10 psu and survive a salinity level higher than 35 psu. However, this is

not optimal. Fuhrmann *et al.* (2016), found similar relations between growth and salinity. However, they have not found significant changes between 25 psu and 35 psu. Both oyster species die when they are exposed for more than two days in freshwater (personal communication Jaap de Rooij).

For oarweed (*Laminaria digitata*), the salinity level should be between 30 and 40 psu. Therefore, it grows optimally if no/hardly any freshwater is in the ESL. However, in nature, for example on the Norwegian coast, oarweeds can be found at salinity levels ranging between 15-25 psu. However, this is not optimal and thus results in less growth (Hill, 2008a). Although oarweed is also a kelp species, sugar kelp (*Saccharina latissima*) can tolerate lower salinities better. This was found by ACT group Animal+1 by interviewing Jasper Veen from North Sea Farm. Sugar kelp grows optimal between 25 and 30 psu. Peteiro & Sánchez (2012) found that germlings of sugar kelp grow well until salinity levels become lower than 16 psu. At 11 and 6 psu, more germlings got injured and eventually died after more than 4 days of exposure. Besides, ACT group Animal+1 found that both kelps have a zero tolerance of freshwater exposure.

Dulse (*Palmaria palmata*) and sea lettuce (*Ulva lactuca*) have a higher tolerance for brackish environments than sugar kelp and oarweed. Dulse was found to prefer salinity levels between 30 and 40 psu (Hill, 2008b). However, research done by Schmedes *et al.* (2019) found seedlings cultivated at a low salinity level of 15 psu were growing even better than at higher salinity levels. Sea lettuce was found by ACT group Animal+1 to be growing well at 20-40 psu. Bews *et al.* (2021) found that the metabolism of sea lettuce was negatively affected by a salinity of 15 psu. However, it could have a higher tolerance for brackish environments than sugar kelp and oarweed grow well under these low salinity levels when there are high nutrient levels. So, both dulse and sea lettuce can tolerate 50% of freshwater in the ESL.

3. Aquaculture; what are the different options

Throughout the world, many different techniques have been applied for culturing aquatic animals. Each of these systems has its advantages and disadvantages and could either focus on creating the most product, gaining the highest profit, being sustainable or focus for instance on being future-proof. For this report, we wanted to find a system that would be most suitable for the ESL specifically. To conclude, we have analysed many different conventional aquaculture systems. After looking at systems that include a focus on either a) productivity and profitability, b) nature restoration and biodiversity, c) carbon sequestration d) IMTA's. We will summarise the pros and cons of each IMTA system. These IMTA systems will be scored on the parameters which were mentioned early, they will also be given a score from one to five indicating how fitting they are. In the conclusion, we combine the best parts and come up with the best solution tailor-made to fit the ESL. With this in mind, we have analysed possible systems which maximise nature restoration, and which are future proof taking into consideration the Netherlands 2120 goals to be future proof.

a. Traditional aquacultures

i. Productivity and profit

One of the most common and traditional ways of aquaculture are culture systems that focus on high productivity and-or high profit.

Highly productive aquaculture systems show a trend of focusing on high fish production. Antibiotics are commonly found in high productivity systems to reduce the risks of disease outbreaks and ensure a high growth rate. Consequently, the more productive systems, the higher rates of pollution due to the residuals of antibiotics and surplus fish feed remaining in the water (Tovar *et al.*, 2000). It adds extra pressure and disturbances to the local ecosystem and hence would generally not be considered to be very nature friendly.

Although many fish species can be sold at high market prices, their production also requires higher investments in the form of feed than organisms at lower trophic levels such as shellfish and seaweeds. Because the production costs of shellfish and seaweeds are low, these organisms can be more profitable to produce on a bigger scale, compared to expensive fish species. Although only if market demands are high enough, therefore, the price per kilo can increase (Knowler *et al.*, 2020). At the same time these kinds of shellfish focussed aquaculture that are not based on fish production, also require fewer capital risks.

In the case of having a bivalve or seaweed system, however, production is limited by the number of nutrients or particulate organic matter in the water. Seaweed can grow very rapidly (Chung *et al.*, 2013), yet large scale seaweed cultivation remains difficult. Bivalve production such as in the Eastern Scheldt is quite productive as well without fish, creating less pollution than fish culture. However, intensive mussel cultures do produce high amounts of pseudo-faeces, which can lead to anoxia when the additional organic material is being decomposed.

When the focus lies mainly on profit, having high-quality species or species with a high market value is an important factor. A species that has become an increasingly big market in Asia are sea cucumbers. They have a high-profit value as they are mostly deposit feeders that will also clean the waters and hence cause less pollution. Other less conventional options include for instance the farming of oysters for pearls which

is an ancient practice in the North Sea shores as well as other parts of Europe and Scandinavia (Jan Asplund FGA DGA, 2018).

To help combat problems often occurring when having large scale monocultures, Integrated Multitrophic Aquaculture systems can be used. It combined fed-species with extractive species: Nutrients released by the cultured (fed) fish are taken up by filter feeders and seaweeds, while the deposit feeders reduce pseudo-faeces concentrations near the sediment (Ren *et al.*, 2012). In this sense, IMTA systems can increase overall biomass production by combining multiple species which use each other's waste products as nutrients for growth. Although overall biomass production is higher, it is also spread across multiple species and production lines (Park *et al.*, 2018). The main factor that influences the profitability of an aquaculture system is the ratio between income and expenses. For IMTA systems, having to invest in multiple production lines and sell products on different markets can lead to high initial market costs and thus lower profits. At the same time, IMTA systems allow farmers to diversify their product range, which can help mitigate financial losses when the market for one specific product is not doing well or harvests are low due to disease outbreaks (Chopin, 2010; Chopin *et al.*, 2010).

Creating a highly productive IMTA would involve incorporating as many trophic levels as possible to maximize the flow of energy through the system and minimize energy loss. Feed addition would be a requirement to stimulate the growth of the fish species cultured, which requires a good balance between the fish density used and the number of organisms present at the lower trophic levels which are needed to prevent pollution caused by excessive food.

An important argument for the use of IMTA's is sustainability: More sustainably produced products are also receiving more attention on the market, with consumer awareness about environmental sustainability increasing. Eco-labelling IMTA products as environmentally friendly compared to monocultures or polycultures can help increase profit by charging premiums on these more sustainable products (Knowler *et al.*, 2020). Similarly, governments could help make IMTA systems more attractive and profitable by providing subsidies or compensation based on the amount of pollution prevented in comparison with more conventional aquaculture systems (Knowler *et al.*, 2020).

Overall, highly profitable aquaculture systems could either focus on producing high cost, high-value market products, or low cost along with limited maintenance production of organisms at simpler trophic levels. Eco-labelling of IMTA products will help in creating more environmental awareness among consumers, which can also lead to higher profits in the form of premium prices. Yet high profit-and or production systems will always have a risk of increased pollution, disease outbreak or creating excess nutrients.

b. Nature restorative and biodiversity

Aquaculture is currently being used for nature restoration in the form of restorative aquaculture (Froehlich *et al.*, 2017). This type of aquaculture mainly involves shellfish and seaweed cultivation. One of the ways in which restorative aquaculture aids in nature conservation is through the improvement of the water quality. By filtering phytoplankton and other material out of the water column, shellfish such as mussels and oysters can improve the passage of light in the water column, which helps support aquatic vegetation. At the same time, the consumption of phytoplankton helps prevent algae blooms, which together with the increased light penetration promote nature restoration.

Shellfish and seaweed help restore natural systems by creating habitat for fish and other species. In this manner, the systems can provide refuge, foraging areas and stress reduction for wild species (The Nature Conservancy, 2021; Grabowski & Peterson, 2007). However, the type of gear used can influence the nature restoration potential (Theuerkauf *et al.*, 2021). Elevated and suspended bivalve gear was found to lead to larger increases in the abundance and richness of species compared to bottom and longline gear (Theuerkauf *et al.*, 2021).

One of the major advantages of using restorative aquaculture for nature restoration is that it combines economic benefits and nature conservation. Traditional nature restoration methods can be expensive, so restorative aquaculture is seen as a more affordable alternative method of nature restoration. For restorative aquaculture to have these effects, only indigenous species should be considered for inclusion in the aquaculture system. By including species which have locally disappeared, aquaculture systems could help natural populations recover. However, introducing new organisms for cultivation can also bring diseases into the ecosystem as well as introduce exotic species which hitchhike alongside the introduced species (Theuerkauf *et al.*, 2021) so caution should be taken.

Restorative aquaculture can also have negative influences on the ecosystem if not properly implemented. Large scale aquaculture can lead to increased disease transmission between aquaculture and wild populations (Theuerkauf *et al.*, 2021). Highly intense aquaculture systems with frequent maintenance or harvesting operations can also damage the species that use aquaculture areas as habitat for shelter or as foraging areas by forming ecological traps. This occurs when organisms are lured to the aquaculture system due to its high habitat quality, after which maintenance and harvesting operations lead to high-stress levels or even mortality. Restorative aquaculture can also inhibit the well-being of the ecosystem if its introduction to the area causes the carrying capacity to be exceeded (Theuerkauf *et al.*, 2021).

In general restorative aquaculture has great potential for places where the local environment has been disturbed or destroyed, yet the specifics should be tailor made to fit the local area.

c. Carbon sequestration

Carbon sequestration is gaining increasing popularity as a method of decreasing the rate of climate change (Ussiri *et al.*, 2017). As the oceans hold much higher carbon concentrations than the atmosphere, the idea of using marine vegetation as a sink for carbon dioxide has received great attention. This has resulted in the concept of Blue Carbon, where coastal ecosystems absorb carbon from the atmosphere, thus helping mitigate climate change (Radiarta, 2015).

One of the most promising candidates for carbon mitigation is seaweed. Although seaweeds do not directly contribute to carbon mitigation by trapping carbon in the sediment as is the case with mangrove forests, seagrass meadows and salt marshes, their biomass can be used as a substitute for fossil hydrocarbons (Chung *et al.*, 2013; Ahmed *et al.*, 2012), although this would be seen as carbon mitigation as opposed to sequestration. However, seaweed can aid in carbon sequestration through transportation to sites where carbon sequestration into the sediment does occur (Ahmed *et al.*, 2012). Annual biomass production values of seaweeds can go up to three kg carbon per m² (Chung *et al.*, 2013). However, the rate of carbon accumulation by seaweeds can vary by the species of seaweed used and the environmental conditions in which it is grown (Radiarta *et al.*, 2015).

Besides seaweeds, there has also been an interest in using bivalves for carbon sequestration. Carbon sequestration using bivalves can be achieved through the harvesting of shells. However, it has also been noted that bivalves show CO₂ production in the form of respiration, biocalcification and (pseudo)faeces production and mineralization. Therefore, the carbon sequestration of bivalves can vary depending on the calculation chosen. Mussels can show a net uptake or net release of carbon depending on the method used (Jansen *et al.*, 2020). However, since the main goal of IMTA systems is food production, the CO₂ sequestration of carbon by bivalves into their shells could be seen as separate from the CO₂ production of bivalves during growth and meat production. If this were the case, bivalves would be able to aid in carbon sequestration (Filgueira *et al.*, 2015).

IMTA systems that focus on carbon sequestration should prioritize seaweed production, as they show the highest rate of carbon sequestration. However, since the seaweeds have to be stored in the sediment for carbon sequestration, they cannot be cultured and harvested for consumption or other uses. Therefore, a financial setup would have to be made in which the culturing of seaweed for carbon sequestration would be financially beneficial for the seaweed farmers. Although the carbon sequestration of bivalves into their calcified shells is lower than the carbon sequestration of seaweeds, capturing and storing bivalve shells can still be a beneficial addition to carbon mitigation. Fish production would not be beneficial for carbon sequestration apart from the fact that they can supply additional nutrients into the system. However, seaweeds have been shown to show the highest growth in more nutrient-poor water, as too much nutrient addition can lead to epiphyte growth on the seaweeds, resulting in reduced photosynthesis (Job Schipper, personal communication).

d. IMTA's

i. IMTA with a focus on fish production

IMTA systems utilising fish in open systems are currently not being implemented in the Netherlands. This is due in part to the water temperature of the North Sea: it is either too cold or too warm depending on the season to fully grow one species of fish during the full year (Personal communication). However, it is possible that in the future the temperature of the sea will increase, perhaps making it possible to grow some species for which it is too cold for now. Indeed, there are several species native to the Netherlands which could be candidates for implementation in an IMTA system. These include the Atlantic Salmon (*Salmo Salar*), Brown Trout (*Salmo trutta*), Sea Bass (*Dicentrarchus labrax*) and the Gilthead Sea Bream (*Sparus aurata*). The Feed Conversion Ratio (FCR) of each species is given in table 5. The FCR indicates the amount of feed required for the production of a certain amount of fish biomass. For instance, an FCR of 2 would indicate that for every 2 kg of feed the fish would produce 1 kg of biomass. However, when analysing the FCR of a species it should be taken into consideration that the FCR can vary with environmental factors and the type of feed used (e.g. Arzel *et al.*, 1994; Belghit *et al.*, 2018).

Table 5. Feed conversion ratios for various aquaculture species.

Species	Feed Conversion Ratio (FCR)	Source
Atlantic Salmon (<i>Salmo Salar</i>)	0.76-1.13	Carter <i>et al.</i> , 1994; Belghit <i>et al.</i> , 2018
Brown Trout (<i>Salmo trutta</i>)	1.13-1.33	Arzel <i>et al.</i> , 1994 Dosdat <i>et al.</i> , 1997
Sea bass (<i>Dicentrarchus labrax</i>)	1.36-1.64	Ballestrazzi <i>et al.</i> , 1998
Gilthead sea bream (<i>Sparus aurata</i>)	1.14-1.79	Lupatsch <i>et al.</i> , 1998

Within the ESL, fish could be included in aquaculture systems in various ways. Open systems cannot be considered, since the ESL will be connected to the North Sea, and passage of fish between the North Sea and the lake is possible in both directions. This means that the ESL will not be a closed system by itself, so free-swimming fish would be able to leave the lake at any time, making aquaculture impossible. Out of the other most traditionally used methods (raceways, tanks and cages), cage systems would be the most viable way of culturing fish in the ESL. These cage systems can be placed in existing water bodies, allowing water from the lake to flow through the cage system, while the cage itself contains the fish to a specific area of the lake (Masser, 2004). In this manner, the aquaculture of fish species would have a limited impact on the rest of the lake, since the fish themselves are confined to a predetermined area. Additionally, observing, sampling and harvesting fish would be simplified compared to more open aquaculture systems (Masser, 2004), which decreases the operations needed in the lake and keeps disruption of the ecosystem to a minimum. The use of fish in IMTA systems also can lead to increased biomass of filter feeders, for

instance, mussels (Handå *et al.*, 2012). Combined with the biomass production of fish themselves, this would lead to the IMTA system being much more productive than systems without fish.

Known disadvantages of including a cage aquaculture system with fish are the requirement of nutritionally complete feed and the increased risk of disease outbreaks (Masser, 2004). The use of feed-in open aquaculture systems can lead to increased nutrient concentration in the surrounding water through uneaten feed, while fish excretion also adds nutrients to the system. Therefore, when including fish in the IMTA design, it is critical to determine what ratio of fish, filter feeders and deposit feeders should be included in the IMTA system to prevent excess nutrients from polluting the rest of the lake. However, if nutrients are a limiting factor in the lake, an imbalance of fish and filter and deposit feeders can be allowed to increase nutrient concentrations in the lake.

Another disadvantage of including fish in the IMTA system is the general perspective of the public on aquaculture. In general, the public opinion on aquaculture tends to be negative (Osmundsen *et al.*, 2017). Even though IMTA systems are more environmentally friendly than traditional aquaculture, they might still suffer from the same bad image of aquaculture in general. As one of the main purposes of the ESL lake is on nature conservation, having an aquaculture system with fish in place might damage the image of the project, even if the net effects of the IMTA on the environment are minimal or absent. This might then also decrease the willingness of other stakeholders with environmental concerns to cooperate and join the ESL project.

However, since the ESL lake will be constructed in a Natura 2000 area that prioritises nature conservation and restoration, the aquaculture of fish could also be used for restocking purposes to help support this purpose. The produced fish would then not be used for consumption, but instead would be released into the wild to help replenish existing populations. If implemented, it would be important to consider the genetic diversity of the fish population, since it will influence the genetic composition of the wild population and its fitness (Gil *et al.*, 2014). An additional point of interest would be how to financially set up the system regarding fish aquaculture. As the fish are not produced for consumption, the producers will not be able to sell their fish to the consumption market, which is their normal source of profit. Therefore, a different financial agreement should be set up, in which the producers gain financial backing for their restocking aquaculture activities.

The main restriction to the implementation of an IMTA using fish is the varying water depth. In the current plans of the ESL presented by Esmée van Eeden, the lowest water level in the lake will be 5 m. If this is the case, then the implementation of a cage system would be difficult, as either the cage cannot be higher than 5 m, or the density of fish will increase substantially as the water level goes below the cage height. Additionally, the cage system would disturb the benthic layer underneath each time the water level is dropped to the lowest level, leading to negative consequences for the benthic community as well. To overcome this problem, a separate lake could be created from the main lake, where the water level does not drop. Water exchange between this lake and the main ESL during high water levels would then allow the filter and deposit feeders to clean the water coming from the fish aquaculture area, leading to a lower environmental impact.

To summarise, the usage of fish in an IMTA system in the ESL can lead to more production and food provisioning. Nutrient addition to the system can be prevented by using filters and deposit feeders. If nutrients are limiting in the ecosystem, it can also be decided to create an imbalance between fish waste production and filter and deposit feeder filtration capabilities and allow some excess nutrients to diffuse into the rest of the lake. Aquaculture enterprises producing fish face the problem of negative perception by the general public, which can undermine the goal of the project, even if IMTA aquaculture is more environmentally friendly than traditional aquaculture systems. Producing fish for restocking purposes could help overcome this disadvantage and improve public perception, but this would require a financial setup that ensures that the system remains profitable for the fish farmers. The main restriction to implementing an IMTA in the lake is the lack of water depth when the lake is emptied, which severely limits the size of the cage systems that can be included in the lake. The addition of a smaller lake that has water exchange with the full ESL but does not get drained could help overcome this problem. However, it would require additional space and planning within the project.

IMTA focus on fish

Pros

- High profit
- Less harmful than traditional fish farming
- Improve mussel yield
- Solves nutrient deficiencies
- Nursery for wild populations

Cons

- Negative environmental impact
- Negative public opinion
- Difficult to implement
- Disease occurrence
- Not viable in the Netherlands due to temperature

Suitable for the ESL? No



ii. IMTA focused on seaweeds, bivalve and deposit feeders

The previous chapter dived deeper into the option of having an IMTA with a focus on fish production. Adding extra layers to the traditional ways of aquaculture allows for many benefits and can greatly decrease the environmental impact of the system (Jansen 2020). However, as one of the goals of the ESL is to focus on being in balance with nature and helping with nature restoration, a production-focused system might not be most preferable.

One of the downsides of fish culture is the excess of nutrients and waste that can occur due to fish feed and faeces (Jansen 2020). It was also mentioned that the general view on cage-aquaculture can negatively affect the view the public might have on the ELS. A more sustainable and perhaps 'eco-friendly' option would hence be to create a system that might still contain fish, but one that is not focused on fish production. Instead, now the focus lies on the lower trophic organisms and how the system would be able to act as a biofilter, remove nutrients from the water and help capture carbon (Jansen 2020).

Inorganic waste dilutes in the water, whereas organic waste settles on the bottom (Jansen 2020). To remove the diluted waste mussels can be used. The blue mussel (*M. edulis*) is a generalist that can feed on organic food from non-organic phytoplankton sources (Lander *et al.* 2013). Bivalves such as mussels help clean the water, decrease turbidity, capture nutrients and remove carbon from the system (Verdegem 2020). It has also been shown that co-culturing blue mussels or oysters (*C. gigas*) with fish can help increase the growth rate of the bivalves as well (Lander *et al.* 2013).

However, although mussels might have a positive effect on the water quality, they also create waste that settles on the bottom. To combat this production of waste, the addition of benthic species such as polychaetes might be interesting, as they are capable of removing excess waste created by other organisms and uneaten fish feed. Sea cucumbers can feed on faeces and pseudofaeces created by mussels (Verdegem 2020). Research has shown that sea cucumbers can reduce the load of the particulate organic carbon parts reaching the bottom below finfish culture up to 86% and up to 99% for shellfish culture. At the same time, the production for the deposit feeders was enhanced by 600% below finfish- and 150% below shellfish cultures (Cubillo *et al.* 2016). Hence, deposit feeders could be a valuable addition to the system. However, since sea cucumbers are not endemic, it is recommended to add polychaete worms to the system instead to fulfil the role of deposit feeders.

Finally, seaweed can help with the inorganic nutrients. They can take up nitrogen and phosphorus, help with carbon sequestration and the removal of heavy metals (Janssen 2020). For the optimal performance of seaweeds, sufficient nutrients should be available ($>/ 4\text{g ammonia -N m}^{-2}\text{ d}^{-1}$ and $>-0.5\text{g phosphate-P m}^{-2}\text{ d}^{-1}$ (Jansen 2020)). Within this system, this could mean that the added nitrogen by the fish can help improve seaweed (such as kelp) production (Cubillo *et al.* 2016). At the same time, seaweed can improve the ecological value of the area by providing shelter and creating a better habitat for the native fish and invertebrates (Janssen 2020).

Something to keep in mind is that for the best efficiency of this system, the mussels should be placed as close to the enrichment place (i.e. the fish and their feed) as possible, to be able to capture most of the nutrient cloud (Lander *et al.* 2013). It should also be checked whether the size of the fishes' waste particles is suitable for the mussels to feed on (Lander *et al.* 2013). When tested in combination with salmon, 90%

of the particles turned out to be appropriately sized (Verdegem 2020). In turn, the sea cumpers should be placed below the mussels, and perform best at a density of 2.5 individuals per m² (Verdegem 2020).

Creating a system that focuses not on profit but on being circular and using the fish as a means to benefit the bivalves' – and seaweeds' growth, might be an interesting option for the ESL. It would also be a good opportunity for education purposes, as even on a small scale the alternatives to traditional aquaculture can be explained. If implemented properly the system can enhance the local environment and help deal with possible water issues such as an excess of inorganic- or organic nutrients.

However, the final implementation may need some tweaking to suit the ESL properly. As the ESL does deal with fluctuating water levels, this should be held into account. Having a layer of fish- mussels - then polychaete worms and seaweed might look good on paper but is perhaps not feasible when water levels are low. Further options should explore the placement of the bivalves and benthic species in a more horizontal fashion. Additionally, the changing current in the lake can affect the efficiency of the system. If the current drives the nutrients in the opposite direction of the lower trophic species, they will not enter the circle and the beneficial effects will be lost. As the most limiting nutrient determines the level of (primary) productivity tests should be done to make sure nutrients are present in the right proportion (Jansen 2020).

In general, this system would generate lower profits and is more complex than some others. However, ecological and social benefits are higher (Jansen 2020).

IMTA focused on benthic species and seaweeds

Pros

- Environmentally friendly
- Positive feedbacks within the system
- Create habitats
- System acts as a biofilter

Cons

- Height of the system
- Currents should be optimal

Suitable for the ESL? Yes



iii. IMTA focused on saltfarming

Saltwater agricultural systems are gaining more interest and could be an important service the ESL could deliver. The reason for this is that there is trouble in finding enough freshwater and land to feed the whole world. Normal on-land seawater agriculture has two requirements that must be fulfilled to have an economically and ecologically sustainable farm. Firstly, the crops must be of high value to compensate for the costs of pumping seawater on land. Secondly, the agricultural system must not damage the surrounding environment. To prevent this, agronomic techniques must and have been developed (Glenn *et al.*, 1998). Since the ESL already pumps seawater into the lake and the environment is already salt-tolerant, both of these requirements are already met. Besides, the products can be of value for restaurants for possible tourists. Therefore, the ESL has the potential to create a saltwater agriculture system.

Several species could be included in a saltwater agriculture system. The species could be separated into two categories: conventional crops with a bred salt tolerance and domesticated wild halophytes (Glenn *et al.*, 1998). Conventional crops that can tolerate some salt are sea kale and potato. They are currently cultivated in the Northern part of Texel and are the dominant agricultural product in salt-tolerant agriculture. Besides, in Texel, there is a salt farm that is experimenting with different conventional crops on different salinity levels to test which species are salt tolerant. The experiments are designed in such a way that each crop is tested with mixtures of freshwater and seawater to check for growth under different salt concentrations. The water is irrigated by drip irrigation and monitored. The species that grow well on these tests and are thus salt-tolerant can be selected for breeding. Besides sea kale and potato, they found that strawberries also grow well on higher salt concentrations (Duan, 2016).

Domesticated wild crop species that are currently grown are species of the genus *Salicornia*. They are being cultivated for nutrition, medicine, feed and oilseed production (Gunning *et al.*, 2016; Glenn *et al.*, 1998). Other known cultivated species are sea aster (*Aster tripolium*) and ice plant (*Mesembryanthemum crystallinum*). Both are interesting for consumption. The advantage of using domesticated halophytes is that there is no need for breeding as these species naturally like high salinity levels. Besides, since these species are part of the surrounding ecosystem, they could have an interaction with nature.

Besides nutrition, medicine, feed and oilseed production, halophytes or salt-tolerant species have also shown potential for biofuel production and could be used as phytoremediation to improve environmental conditions. For the production of biofuel, it is important that the species that are cultivated for this exclude salt instead of simply tolerating high salinity concentrations. This is because salt within the plant can be problematic in the processing of the material. *Suaeda maritima* is a species that is interesting for biofuel production (Sharma *et al.*, 2016b). For the use as phytoremediation to improve environmental conditions, nothing special is needed. In this way, they can be seen as part of the IMTA system and thus another trophic level that helps in the circulation of nutrients.

The disadvantages of saltwater agriculture are that saltwater agriculture could be labour intensive. *Salicornia* is for example hard to harvest because the plants can lie flat in the field in times of harvest. Moreover, seed harvesting is hard because the seeds can spread easily before harvest (Glenn *et al.*, 1998). Additionally, there could be competition for space with nature and recreation in the area, especially when conventional crops are cultivated. These crops need prepared land such as ploughed land, which could harm nature. Therefore, it is not recommended to cultivate conventional crops if land preparation is needed. However, crops such as *Salicornia* have fewer of these problems and thus still have the potential to be cultivated in the area.

IMTA focused on saltfarming

Pros

- Production of products for human use
- Could act as phytoremediation to recreation improve environmental conditions of the area
- In line with Netherlands 2120 sustainability goals of producing more sustainable agricultural products

Cons

- Labour intensive
- Competition with nature and in the area

Suitable for the ESL? Yes



iv. Solar panels

Floating solar panels have been made more and more durable over the years and can even function in the rough North Sea (Oceans of Energy, 2020). The combination of aquaculture with solar energy, specifically the combination of mussels, seaweed and solar panels, could be interesting for the ESL and will be explored further in this section. One of the ways to combine mussels with solar panels would be by adding hanging rope cultures below the panels (see figure 5) (SVP, 2018).

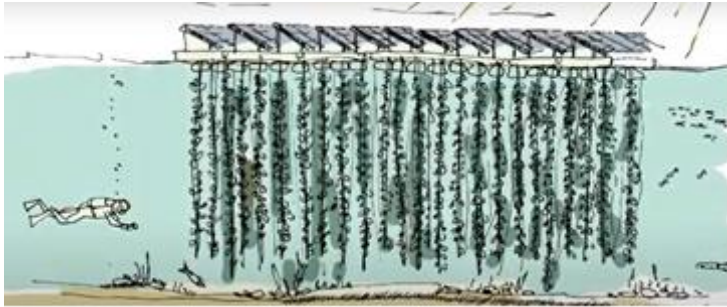


Figure 5. mussel culture attached to floating solar panels (SVP, 2018)

For seaweeds, the preferred cultivation method depends strongly on the water velocity (Peteiro *et al.*, 2016). As the lake experiences different velocities in different parts due to the pump, this will affect the optimal placement of the seaweeds (ConsultanSEA, 2020). A previous ACT group (ConsultanSEA) already worked out the possibilities of combining a floating solar park with aquaculture. At the time of writing, Delta21's idea for the park was to create a single island of 5 km², as having multiple smaller sections would not be economically viable.

ConsultanSEA analysed the best placement for shellfish- seaweed cultivation and the solar park based on the flow rate requirements of the species. Blue mussels need a water velocity above 0.15m/s to avoid food depletion. As the velocity is expected to be around 0.05m/s in the parts of the lake furthest from the pumps, the advice was to have shellfish near the pumps, the solar panels opposite of the pumps and seaweed close to the middle of the lake (ConsultanSEA, 2020). This would already make a direct synergy between the mussels, seaweed and solar panels more difficult, as combining them might result in either of them not experiencing optimal conditions. Adding the competition for substrate between the seaweed and shellfish, the combination of both mussels and seaweed close together was not advised (ConsultanSEA, 2020). Another important aspect to keep in mind is that for the cultivation of seaweed, non-uniform light levels can be a disadvantage (Peteiro *et al.*, 2016). Adding solar panels will have different effects on the water below; 1) it reduces the available light (to combat these effects the use of translucent solar panels can be interesting (Solar Constructions, n.d.)), 2) it reduces the increase of temperature of the water beneath the solar park during the day, 3) it reduces primary production below the panels, which can affect oxygen and food availability for the shellfish (ConsultanSEA, 2020).

The reduction of available light could affect the growth of seaweed when attached near the solar park (Wald, 2010). Since shellfish don't have these light requirements, this effect would not be an issue. In general, according to ConsultanSEA, the solar park should not block more than 75% of the light and should cover less than 20% of the total water surface of the lake. Overstepping these boundaries will

result in negative effects on oxygen concentrations and the growth of benthic species, including seaweed (ConsultanSEA, 2020).

In conclusion, the combination of seaweed, solar panels and mussels in one system that is directly linked with one another most likely is not very suitable for the ESL. A combination of solar panels with seaweed would not be optimal due to the light requirements of the species. Combining mussels with solar panels could work, but the placement of the system within the lake should be kept in mind to make sure the water velocity needs of the shellfish are met. When the goal of the lake is nature restoration, the possible negative effects of the solar panel-island on the aquatic environment should be considered as it might not be the most suitable solution for the goal.

Solar panels

Pros

- Use of synergies
- Efficient use of space
- More green energies

Cons

- Hard to incorporate
- Only bivalves
- Could have negative effects on primary production of the lake if too large an area is used



Suitable for the ESL? No

e. Additives

i. Buffer zones

Buffer zones in general allow for a softer transition between areas. They are widely used in landscape architecture. For example, trees next to a busy highway reduce noise air and water pollution, while also functioning as a space for organisms to thrive. In agriculture, the buffer zones are often referred to as riparian areas or riparian buffers. These buffers are used for multiple purposes: to reduce the number of pollutants in subsurface flows and on land, filter polluted air, improve the microclimate of adjacent fields, create new habitats and many more (Mander *et al.*, 1997). Usually, buffers are mostly focused on reducing the amount of phosphorus (P) that enters groundwater (Stutter *et al.*, 2012). For our project, we focus mainly on the filtering of pollutants, creation of new habitats and improving the microclimate of adjacent fields.

In the ESL, the use of these barriers could prove to be beneficial, as there are parts of the ESL that will mainly focus on nature conservation or part which will not be used for aquaculture purposes. By adding buffer zones next to the aquaculture areas, the adjacent areas can have improved water quality and limited pollution from the aquaculture zone. The limiting of pollution would also safeguard the waters from eutrophication and the consequences of it. Although this all sounds promising, there has not yet been research in creating riparian buffer zones in aquaculture systems. Moreover, there are big differences between a more open aquaculture system, where pollution can easily spread through the system, and adding new plant species that will pose as a buffer in agricultural areas. Therefore, the ESL can be the first in implementing buffers in aquaculture. This could have far-reaching consequences on how aquaculture systems influence the surrounding environment.

ii. Reefs outside the energy storage lake

Another idea of how to use the output from our lake for different purposes than human consumption. We expect to at least have mussels, oysters or other bivalves in the ESL. These bivalves, or at least their remaining shells, can potentially be used to create biogenic reefs. If these biogenic reefs would be placed outside of the lake, this can yield numerous benefits for the local ecosystem, but also fisheries in the area. The 3D structure of these reefs has a lot of interaction with the local hydrodynamics and influences the surrounding habitats (Ysebaert *et al.*, 2019). As mentioned earlier in this report, mussels and oysters are filter feeders and will therefore clean the waters rapidly, increasing the clarity and quality of the water. They also produce faeces and pseudo-faeces, which accumulate in the areas behind these reefs, creating nutrition for fauna there.

There are also differences between the mussel reefs and oyster reefs, having to do with the way that these species attach themselves to substrates. Mussels attach themselves by using byssal threads, silky threads that the mussels create from protein. Oysters use calcification to create a stronger attachment to each other. The result of these two different techniques allows mussels to be more flexible, which also affects the longevity of the mussel reefs. Oyster reefs are fixed and therefore remain long after the last oyster has died (Ysebaert *et al.*, 2019).

A bonus to the biogenic reefs is that they grow vertically, which allows them to follow the global sea-level rise and to be used to mitigate some of the effects the higher sea level and the associated wave interactions can have. This characteristic gives them an advantage over traditional man-made structures. Moreover, the reefs also provide two important other coastal protection aspects. As can be seen in the figure below, the biogenic mussel or oyster reefs can mitigate waves, which will benefit erosion control of the coast (Ysebaert *et al.*, 2019). This wave attenuation, as it is also called, has been a topic of major interest over the last year. In the Eastern Scheldt, three oyster reefs have been constructed to protect tidal flat erosion. Within this area, it was concluded that there was a 51 – 29% decrease in erosion of the tidal flats (Walles *et al.*, 2016a; Walles *et al.*, 2016c). The other aspect will be increased shoreline stabilisation which arises from less disturbance of the sediment.

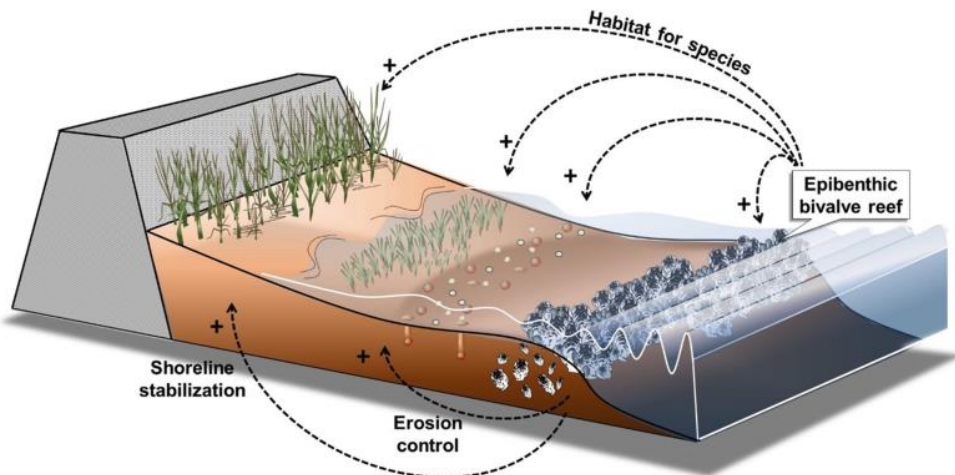


Figure 6. Some benefits of adding an (artificial) reef before the coast (Ysebaert *et al.*, 2019)

As mentioned earlier, the reefs also have benefits for the local ecosystem, improving water quality and clarity and acting as a physical barrier to create calmer waters that are ideal areas for flora and fauna nurseries (Sheehan *et al.*, 2015). A study that was done on a mussel reef inside of a marine protected area (MPA) near the coast of the United Kingdom showed that these reefs can also provide another benefit for humans. The combination of having a mussel reef, which provides the aforementioned ecosystem services, and the protected status that MPA's have allows organisms in these areas to thrive. These biodiversity hotspots can create a spill-over effect into surrounding areas, increasing the overall species richness, which can give an incentive for fisheries to support the idea of placing these reefs near the coast (Kent *et al.*, 2017). The additional biogenic reef as an output of our system will provide a future proof solution for a sea-level rise while also contributing to the local ecosystem.

iii. Seagrass

Historically, seagrass has been present in the south of the Netherlands in the Grevelingenmeer, Eastern Scheldt, Western Scheldt and Veerse meer (De Mesel *et al.*, 2009; Wielakker *et al.*, 2011). However, a 'wasting disease' and changes in the dynamics of these systems, such as changes in freshwater inflow, higher turbidity, have led to declines in seagrass coverage in almost all these areas (Lindeboom *et al.*, 2002; De Mesel *et al.*, 2009; Hanssen *et al.*, 2010). Competition of seagrass with lugworms is also seen as a possible driver of seagrass decline (De Mesel *et al.*, 2009).

Before the construction of the Stormvloedkering in 1986, Zeeland held around 1200 ha of seagrass field. In 2010, the amount of seagrass still present was estimated at 75 ha (Giesen *et al.*, 2010). For the Eastern Scheldt, seagrass has declined from around 800-1000 ha in 1976-1980 to around 21 ha in 2011. In the Western Scheldt, the seagrass density has stayed at the same level of ~3 ha in the same reference period, where most of the seagrass is present in the mouth of the Sloehaven (Wielakker *et al.*, 2011; Wijsman *et al.*, 2007).

The importance of discussing seagrasses within our project is that through proper management of shellfish aquaculture methods it is possible to reduce the negative impacts of the activity on them and that it is possible for some of the species cultivated within the IMTA to have a positive effect, perhaps in assisting future restoration projects. Water turbidity is one of the most limiting factors for seagrasses since it prevents them from performing photosynthesis. Bivalves, through their filtration and binding of particulate matter, reduce water turbidity, therefore increasing light penetration and enhancing habitat suitability for the seagrasses (Barañano *et al.* 2018). Indeed, Newell and his team, through their model of the effects of oyster beds on seagrasses, predict that the restoration of eastern oysters could facilitate seagrass restoration projects through the reduction of water turbidity in shallow estuaries (Newell *et al.*, 2004). Furthermore, in a study conducted by Sharma and his team, a "shadow" effect has been observed: an increase in seagrass cover in all experimental areas after the construction of oyster reefs. This seagrass cover was still higher 5 years after the deployment of the reefs and was not seen in nearby areas (Sharma *et al.*, 2016a).

The types of oyster culture have different impacts on seagrasses. In a study conducted on eelgrasses, it was observed that their density was the same in areas where longline oyster cultivation was practised, compared to areas with no cultivation. On the other hand, the eelgrass had a lower production per area and was smaller. Different outcomes were observed for hand-picked and dredged methods. For both methods, a slight increase in growth rate was observed, while density, production and plant size decreased. The worst outcomes were observed for the dredged method. It is therefore important to assess the pros and cons of the different methods when thinking about seagrass well-being (Tallis *et al.* 2009)

One problem between the seagrasses and shellfish cultivation is the competition for space with bottom shellfish cages. Under normal circumstances, with no large tides, this would not be an issue for floating cultivation techniques, as they don't touch the bottom. However, given the tidal nature of the lake, we believe that it could be in this case. One solution that could be investigated is putting a protective structure on the bottom under the shellfish ropes and cages. By doing this the shellfish cultures can rest on the structure during low tides. This would stop them from touching the bottom, where seagrasses might be growing, preventing the disturbance of the sediments, their resuspension and the pulling out of seagrasses when the tides go up again.

Although not much research has been done on the response of seagrass species under hypo-salinity conditions or temporal events, it has been shown that some species of Indo-Pacific seagrasses, such as *Zostera muelleri* react by increasing their shoot density (Collier *et al.* 2014). Although this pre-mortality signal of stress has not been studied in Dutch seagrass species, in the case in which this response does exist, the occasional flooding events due to high rain could be beneficial for the development of a meadow. However, this would only be the case provided that the incoming water velocities do not tear out the plants from the sediment and that the high turbidity often following such events does not stay for too many days, just like for the hypo-salinity conditions. For the hypo-salinity conditions, the duration that seagrasses can withstand these conditions is a few weeks at most (Collier *et al.* 2014). Interestingly, salinity only becomes an issue for *Zostera marina* below 10‰. Indeed, through their experiment on optimal salinity and temperature for the species, Nejrup *et al.*, 2008 suggested that the optimal salinity for the species would be between 10 and 25‰, while the optimal temperature would be between 10 and 20°C.

iv. Amphipod cultivation

Amphipods, small benthic crustaceans, could also be cultivated within the ESL. They could then be used or sold as feed for fish, given their high nutritional value and richness in n-3 PUFA (Fernández-Gonzalez *et al.* 2018, Guerra-García *et al.* 2016). This exploitable resource is commonly found in fouling communities, both on aquaculture structures, and algae, which are fast-growing and present in the Netherlands (Fernández-Gonzalez *et al.* 2011). Indeed, it has been shown that they are present in high population densities around fish-farming activities, which could be leveraged for commercial use (Fernández-Gonzalez *et al.* 2017). Amphipods, most notably Caprellids, are detritus feeders, capable of feeding on fish faeces and uneaten fish pellets. As such, they could be used as a supplementary biofilter for finfish aquaculture. Adding them to the IMTA, could potentially reduce waste and provide an additional economic source for the farmers (Guerra-García *et al.* 2016). Additionally, they would represent another intermediate trophic level between fish and primary producers, allowing for a more complete production system (Baeza-Rojano *et al.* 2013).

The feasibility of adding this innovative species to an IMTA is still under research, but in their pilot experiment, Fernández-Gonzalez and his team used net bags with a volume of 51 litres. Two types were made: one containing plastic raffia; while the second was filled with dried mussel shells, which is considered a waste product of the mussel industry. Their freshwater extraction method showed an extraction of 80% of the total biomass present within the collector. Hence, both the extraction method and the collectors could be used within the lake for the harvesting of amphipods. Adding value to dried mussel shells which were seen as a waste product before. The collectors were set at different depths up to 15m, and no difference was observed between these depths, indicating that there it is possible to use the entire water column within the lake for their setting. Drop ropes could be used to couple these collectors to fish cages, as suggested by Fernández *et al.*, 2018. The optimal time for harvesting has not been researched yet, but 12 weeks seems to be ideal, since at that moment the presence of other species is low (at 2%), and the amphipod biomass per collector was around 30g or more in the pilot experiment (Fernández-Gonzalez *et al.* 2018). In their study, the production of amphipods was around 10g per month (Fernández-Gonzalez *et al.* 2018)

v. Medicine

The IMTA system can also be used to cultivate seaweeds, bivalves or other organisms for medicinal purposes. For example, seaweeds have been used for medicinal purposes for a long time. For instance, brown seaweed (*Sargassum*) has already been used in traditional Chinese medicine for nearly 2000 years. It is used for goitres, elimination of phlegm and the reduction of swellings. The therapeutic effects are scientifically plausible, however, they have not been proven. The effects are attributed to biologically active metabolites. They seem mainly to play a role as immunomodulators in treating thyroid metabolic diseases. However, since the evidence is not plentiful, it would not be a focal point to cultivate this particular seaweed for this purpose (Liu *et al.*, 2012).

Other organisms that have shown a lot of potential therapeutic benefits are sea cucumbers. To name a few properties of sea cucumbers, they can be neuroprotective, antitumor, antimicrobial and be used for wound healing (Pangestuti & Arifin, 2018). These properties have also been validated by science, and there is still a lot that we can learn and use from sea creatures (Pangestuti & Arifin, 2018). Due to a lack of time and specific literature, we decided not to continue on one IMTA system specifically designed for medicinal yield.

vi. Spat collection

Just like the creation of reefs outside of the lake our products can also be used for other purposes. For example the capturing of the mussel or oyster offspring or spat. The collection of spat can be of importance for the wild populations of mussels and oysters in the Netherlands. These populations have been declined by approximately one third already (personal communication Addy Risseeuw). By catching spat in the ESL natural areas can be replenished, hopefully, this will help the wild population to increase and thrive again. During the interview with Addy Risseeuw, he also shared some images that show the growth of young mussels on the nets that are used for spat collection (figure 7). The idea of spat catching inside the ESL was not further investigated due to time constraints but it could be considered for future research of aquaculture systems inside the ESL.



Figure 7. The net with spat at the start of the collection (left), net with young mussels (right).

Our idea

Preferred basis system

As seen throughout the report, every aquaculture system has its advantages and disadvantages. The traditional systems are generally more harmful to the ecosystem, and a focus on high fish production leads to an excess of nutrients in the water and has an aggravated risk of diseases or need for antibiotics or hormones. This dampens the value chain of the other organisms and causes accumulation of sediments below the cage systems and/or fishponds. This in combination with limited knowledge of fish farming in the Netherlands leads to an overall problematic system. Following these disadvantages, we advise not to include fish in aquaculture systems inside the ESL. As one of the goals for the ESL is to help improve the ecological value of the area and if possible, help with nature restoration, we chose the 'Nature Restorative + Biodiversity' in combination with the 'IMTA focused on seaweeds, shellfish, and deposit feeders as the basis for our advice.

We believe the IMTA can have great educational values to inform the public on more sustainable ways in which aquaculture can be implemented, At the same time, we chose to not focus on high production or profit of any kind, as this usually adds more pressure to the ecosystem. We want to create a system high in ecological and educational value that can help increase the water quality and create a good local environment for the lake's residents and their surroundings. We also believe that the creek and marshland landscape as seen in Esmee's design is already a powerful addition for the nature restorative goal, and hence will focus mostly on the IMTA design specifically within the lake. On top of this, we see the implementation of a structure like the *SeaStairs* (figure 8) as a solution that can incorporate all that is mentioned above.

Our advice for the use of SeaStairs is a triple-goal approach regarding organism production (bio-inclusivity, bio reef restoration, and seafood production) and a triple-goal approach as well for the abiotic goals (sediment fixation in the steps, therefore, avoiding solid matter flow into the centre of the lake, filtration of the turbid waters that come from the sea, and avoidance of unaesthetic components such as an empty slope full of mud, leading to unattractive smells).

The SeaStairs system will be implemented on the western side of the lake (figure 9). This site was chosen because the slope that is already planned for this side is steeper. It does not conflict with the natural restorative tidal area, as is the case if the project would be executed on the eastern side. In the initial plans by Esmee, there will be a small fishing village near the western side, which allows for convenient maintenance of the SeaStairs.

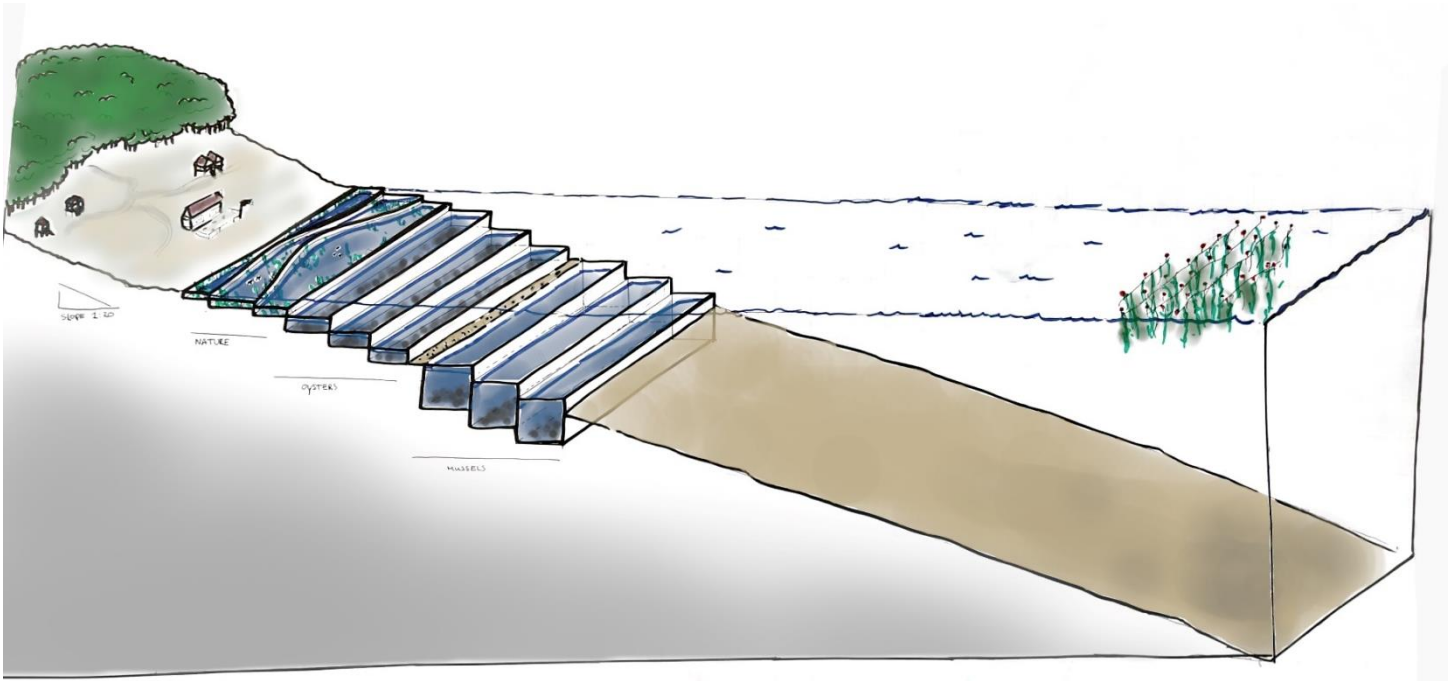


Figure 8. SeaStairs, rough idea of how the SeaStairs could look. Creating space for nature as well as aquaculture in the stairs by giving different purposes to different steps. In this case; the most shallow layers are ‘given back’ to nature, creating habitats for wading birds, the layers below could be used for oysters and mussels respectively.



Figure 9. The layout of the lake by Esmee adapted to our advice. The number 1 represents the location of the SeaStairs where for example, seagrass meadows or the permanently flooded sandbanks can be restored.

In terms of species distribution on the SeaStairs, the species in the top layers will create sediment stability while partly being used for farming. They also have nature restorative functions such as available food for migratory birds or safe stocking of seagrass in case the tidal lake needs replanting. The lower layers will be for higher production organisms, which will be bivalves (e.g. *Crassostrea gigas*, *Mytilus edulis* and *Cerastoderma edule*), which feed on the water particles and microalgae by filtering the ESL. Other species which can be used in the stairs system are tube worms, sandworms and seagrass. Other parts of the system will have seaweed cultivation blocks. In these areas, there is the option of implementing the floating

structures with hanging ropes covered by seaweeds in the middle of the lake. Seaweeds from the families *Ocrophyta* and *Chlorophyta* could be included in these structures. The fact that shellfish can filter the water body helps seaweed photosynthesis, since the water becomes clearer, and light can penetrate deeper.

Within the stair system, the harvesting will of species take place from the lower to the middle steps. The farmed species will be cockles, oysters, and mussels. The other system will provide only seaweeds, which are harvested by a seaweed company. As previously mentioned, IMTA has spatial issues where the changing water level of the lake will lead to the slope falling dry for long periods. These issues of IMTA's can be solved by implementing the SeaStairs concept. In the next chapter, we will go further into detail about the SeaStairs concept.

Additions

a. Maximum productivity of the system

The carrying capacity of the ESL is the maximum population the ESL can sustain without negatively affecting the environment and the population itself. The carrying capacity depends on the physical, chemical, biological and social conditions in the area. Since the carrying capacity is difficult to measure, this report tries to calculate the maximum productivity of solely seaweeds or solely bivalves. From this maximum productivity, the carrying capacity could be estimated by getting a percentage of the maximum productivity. The exact percentage can't be known but it will probably be around 25% (Personal communication Marnix Poelman). Since this report only calculates the maximum productivity of seaweeds and bivalves, it is important to keep in mind that every form of IMTA will affect the carrying capacity.

I. Maximum productivity seaweeds

The maximum productivity of the seaweeds is based on the amount of dissolved inorganic nitrogen (DIN) and phosphorous (P) that will flow into the ESL in the growing season of the seaweeds. To calculate the amount of DIN and P the seaweeds need, the fraction of nitrogen (N) and P is determined by the Redfield ratio and the moisture content of the seaweeds. To know what will be the total area that is needed to mitigate all these nutrients, the number of seaweeds needed should be divided by the biomass production per year.

For these calculations, some assumptions needed to be made. The first assumption made is that seaweeds take up the same amount of N and P every day. However, in reality, the seaweeds take up less N and P at the start of the growing season because they are not full grown. The second assumption is that the amount of N and P influx is based on the number of nutrients that are currently in that area and that this amount will flow into the lake every day. The inflow of nutrients is also assumed to go directly to the seaweeds. This however can change during the growing season and change every day. The third assumption made is that the growing seasons are calculated by taking the days of the months given in articles. In reality, the growing season is varying per year because of factors such as temperature change. The last assumption made is that for calculating the amount of *Ulva lactuca* needed to mitigate all P, the amount of P available in winter is taken. However, *Ulva lactuca* is a species cultivated in summer. The P concentration may therefore be lower in reality.

The total amount of DIN and P in the ESL per day is calculated by taking the DIN and P concentration of the Voordelta, which is seen in table 6, 0.84 mg N/L and 0.037 mg P/L (ACT Aquaculture), times the total amount of throughput per day, which is 430 million m³ (personal communication commissioners).

Table 6. Chemical conditions ESL from ACT report Aquaculture

Variable	Season	Mean (mg/L)	Variability	Likely to change in the next 20 years?	
				Increase/decrease	Amount
Nitrogen	Whole year	0.84	Unknown	Increase	Unknown
Phosphorous	Winter	0.037	NA	Decrease	Unknown

The C, N and P content of the seaweeds is calculated by the Redfield ratio and the moisture content of all species. The Redfield ratio is the ratio between C:N:P, which is 550:30:1 (Atkinson *et al.*, 1983). This is the mean Redfield ratio of all seaweeds where the content is known of. The Redfield ratio means that 94.66 % of the dry weight (DW) is C, 5.16% N and 0.17% is P. The fraction of the moisture content for *Saccharina latissima* and *Laminaria digitata* is 0.83. The moisture content of *Palmaria palmata* is 0.84 and for *Ulva lactuca* 0.79 (Holdt & Kraan, 2011). In table 7 the calculated N, P and C content are seen in kg per tonne freshweight (FW).

Table 7. Moisture and nutrient content on four seaweeds species.

Species	Moisture content (Holdt and Kraan, 2011)	N content (kg/tonne FW)	P content (kg/tonne FW)	C content (kg/tonne FW)
<i>S. latissima</i> <i>L. digitata</i>	0.83	8.78	0.29	160.93
<i>P. palmata</i>	0.84	8.26	0.28	151.46
<i>U. lactuca</i>	0.79	10.84	0.36	198.80

With these fractions of N and P in the seaweeds and the total amount of DIN and P in the ESL per day, the total amount of tonne FW of the seaweeds is needed to mitigate all N or P. The amount of kg DIN and P seen in Janstable 8 influx in the ESL is calculated by calculating the days in the growing season per seaweed times the total amount of DIN and P in the ESL per day. The growing season for *Saccharina latissima*, *Laminaria digitata* and *Palmaria palmata* is between October and April, so \pm 212 days (Dring *et al.*, 2013; Werner & Dring, 2011). The growing season of *Ulva lactuca* is between April and October, \pm 214 days (Groenendijk *et al.*, 2016). The total kg DIN influx is therefore 76574400 kg for *Saccharina latissima*, *Laminaria digitata* and *Palmaria palmata*, and 77296800 kg for *Ulva lactuca*. The total kg P influx is 3372920 kg for *Saccharina latissima*, *Laminaria digitata* and *Palmaria palmata*, and 3404740 kg for *Ulva lactuca*. The amount of tonne FW to mitigate all N or P is calculated by dividing the kg DIN/P influx by the N/P content of the seaweeds. The results can be seen in table 8.

Table 8. Tonnes FW to mitigate all N and P calculated by the growing season and the DIN and P influx.

Species	Growing season	Days per growth season	kg DIN influx during growth season	kg P influx during growth season	tonne FW to mitigate all N	tonne FW to mitigate all P
<i>S. latissima</i> <i>L. digitata</i>	October - April (Dring <i>et al.</i> , 2013)	212	76574400	3372920	8723475.76	11527450.12
<i>P. palmata</i>	October - April (Werner and Dring, 2011)	212	76574400	3372920	9268693.00	12247915.75
<i>U. lactuca</i>	April - October (Groenendijk <i>et al.</i> , 2016)	214	77296800	3404740	7128482.67	9419780.67

The amount of ha/year needed to grow all these seaweeds is calculated by dividing the total tonnes of FW needed to mitigate N/P by the biomass production in tonne FW/ha/year. The biomass production for

Saccharina latissima and *Laminaria digitata* is 41 tonnes FW/ha/year (Dring *et al.*, 2013), for *Palmaria palmata* 7.5 tonnes FW/ha/year (Dring *et al.*, 2013), and *Ulva lactuca* tonnes FW/ha/year (Nikolaisen *et al.* 2011). As can be seen in Table 9, the tonnes of FW needed to mitigate all P is bigger than needed to mitigate all N. Therefore, N is the limiting nutrient, so the amount of ha/year per seaweed is based on the DIN influx. The results can be seen in Table 9. In figure 10, the maximum productivity in ha/year for each seaweed species can be seen.

Table 9. Maximum productivity per year calculated by the tonne FW to mitigate all N and the biomass production.

Species	Biomass production (tonne FW/ha/year)	tonne FW to mitigate all N	tonne FW to mitigate all P	ha/year	% of the lake
<i>S. latissima, L. digitata</i>	41	8723475.76	11527450.12	212767.70	8865.32
<i>P. palmata</i>	7,5	9268693.00	12247915.75	1235825.73	51492.74
<i>U. lactuca</i>	214	7128482.67	9419780.67	33310.67	1387.94

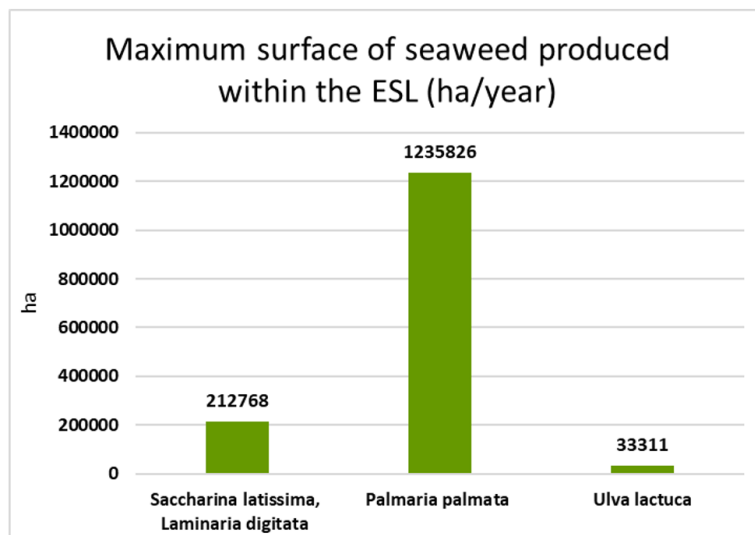


Figure 10. Maximum productivity of different seaweeds.

II. Maximum productivity bivalves

As it is known, bivalves and seaweeds can both live and grow in a system without any exterior input of nutrients, unlike fish and other invertebrates. Seaweeds use sunlight radiation and nutrients that are dissolved in the water column to grow. On the other hand, bivalves benefit from filtering and grazing autotrophic microorganisms such as phytoplankton and inorganic matter from the water. Phytoplankton and seaweeds can compete for these dissolved nutrients (Smith *et al.* 1988), and therefore shellfish could benefit indirectly from this competition since phytoplankton is one of its foods. It is interesting to note that in mesocosm experiments, differential enrichment of Nitrogen (N) and Phosphorous (P) can be modulated to benefit phytoplankton or seaweed, depending on what is the most preferable outcome. Although more research must be done on the subject, in their study, Zhang and his team have shown that enriching the mesocosm with both N and P is more favourable for phytoplankton in competition with

seaweed compared to the enrichment of either N or P alone (Zhang *et al.* 2015). Regardless of this negative interaction towards the bivalves, these filtering organisms can help boost seaweed production, as they can clear the water column. The cleaner the water is, the easier it is for sunlight rays to penetrate it. This means that more sunlight will reach the seaweeds, which is positive for their growth.

For this reason, and because we want the calculations to be as precise as possible, we are separating both cultures as much as possible, since seaweed can dampen the growth of microplankton, which is the food of bivalves. Even with their physical separation, many factors can be included in this equation, and many distinct aspects and specific studies need to be done to understand and calculate the number of microalgae available for mussels to feed and grow. Even though many approaches were tried, none of them gave the team clear conclusions and certainties. There was only one aspect that we could agree on and confirm, which was the filtration ratio of the three species of shellfish. This together with anatomy and physiology knowledge of the different bivalves (mussels, oysters, and cockles) gave us a better perspective of what to expect of them in the lake.

Table 10. Filtration data and population density for three bivalve species

Species	Mean FR (l/h/ind)	Proportion eaten	CR (l/h/ind)	Ind/m ²
<i>Cerastoderma edule</i>	3	0.2	0.6	100
<i>Mytilus edulis</i>	4	0.2	0.8	100
<i>Crassostrea gigas</i>	7	0.2	1.4	100

To calculate the number of bivalves that can feed on the lake as it gets full, we used the individual filtering rate. With this number we know how many litres of water are filtered *per hour*. Since the organisms will not be able to filter 100% of the particles due to a high presence of sediments and other inorganic materials in the water column, a percentage of particle ingestion should be determined. As lab conditions can proportionate an environment where a 100% filtration rate can take place, literature could not provide help with these calculations. Because there will be a lot of turbidity due to the dynamics of the water entering the lake and revolving all the deposited sediments in its shallow area, we assumed that an average clearance rate of 20% (CR-proportion of particles retained) was adequate. Therefore, for every 10L filtered, only 2L would be cleared (entirely filtered). In addition, we assumed a density of 100 animals per square meter for all species, as it seemed the most reasonable number for a production-oriented culture.

For the calculation of the maximum productivity of bivalves, some additional assumptions needed to be made. Because the average amount of chlorophyll- α varies within seasons, we based our calculations on the total amount of water that will enter the lake, which is around 430 million m³ every time for periods of 12h, because our focus was to reach maximum filtration. We were then able to calculate the number of individuals needed for this purpose for every species. The main reason behind this simplification was the difficulty to assess the number of microalgae that would enter the lake and the biomass of microorganisms that would be produced inside the ESL.

One other assumption was that there is a constant water intake for a period of 12h. This was done to have a precise number of litres *per hour*, because filtration rates are measured also as litres *per hour*. By doing this, we were able to understand how many mussels are needed by knowing how much water every bivalve filters from the system (figure 11).

By knowing how much can a single animal filter, and by knowing the total volume of the lake, it was possible to calculate the number of bivalves for every species. This gives us a good perspective on what would happen if we preferred only one type of farm (monoculture). The results are summarised in table 11. The number of cockles would double the number of oysters.

Table 11. Demonstrates the area possible to grow on the volume

Species	Ind needed/12h	m2	ha
Cockles	59722222222	597222222	59722
Blue mussel	44791666667	447916667	44792
Pacific oyster	25595238095	255952381	25595

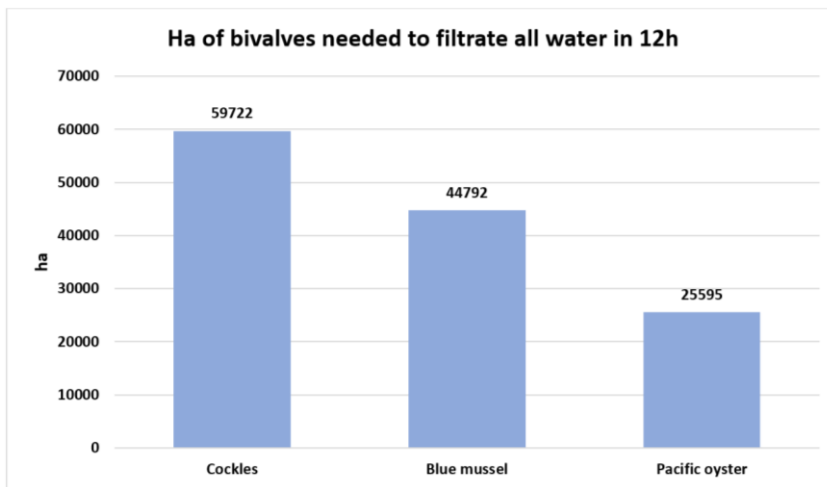


Figure 11. Hectares of bivalves needed to filtrate all the water in 12h for three bivalve species

b. SeaStairs

The Energy Storage Lake will essentially be a dug-up structure that will be surrounded by either sandbanks, dunes or cement peers as exterior borders. A gently sloped ramp will surround the majority of its perimeter, in which the water will be stored. According to the current planning of this energy storage lake, the slope will drop 1 m every 20 m of distance (Eastern side). The fact that the drop-angle of this slope is 5% in its majority allows the incorporation of structures that can retain water. In this case, our best advice is to choose a steeper slope (like the one in the Western side of the ESL). This aspect, combined with the relative proximity to the turbine, can be useful to directly transport a portion of the incoming water through the SeaStairs. This can be done while filling the lake, or as a permanent stream while the lake is empty. By doing this, a continuous supply of food to the bivalves can be assured.

Species

Different species have different preferences and different demands from the water column. Bivalves, for example, need proximity to the surface to not be overwhelmed by dense concentrations of sediments and algae. At the same time, they can remove most of the suspended particles in the water column. In the case of seaweeds, they can use this filtering of the water by bivalves to their benefit, as they profit from the low turbidity levels that allow photosynthesis to occur efficiently. For this reason, it would be optimal if both families of organisms could work together, where one would filter the water (bivalves) and the other would remove the dissolved nutrients (seaweeds). If this is carried out sequentially in the step rivers, there is the possibility of cleaning the water system while producing seafood at the same time.

Structure

The existing slope can be adapted to be a waterfall of long interconnected tanks. This cascade effect will work as one fragmented system due to the connections between tanks. Once the water reaches the higher tanks, it will push the remaining water to the ones downstream. There are three ways this can work (see figure 12):

- *Waterfall stairs:*

The Sea Steps would be on top of each other symmetrically. The water transfer would be done either by small escapes in the lower part of the tanks, or from the surface allowing the water to give the stairs an esthetical value when the lake is drained. This technique would work in areas with a steeper slope as the tanks do not require a large space.

- *Pamukkale inspired stairs*

The Sea Steps in this case would be larger and broader, but shallow at the same time. These types of Sea Steps would work efficiently in the slow sloped parts of the lake, where the rising angle of the slope would be exceptionally low (around 5%).

- *Douro inspired stairs*

This type of stairs is a reedition of the classic original shape of the Sea Steps (as in the *Waterfall stairs*), the main difference for this system is the increased interconnectivity between “tank channels”. This allows an easier flow of water on the slope. Furthermore, this type of design can be applied to both the “waterfall” system and the “Pamukkale” system.



Figure 12 (in order) – Waterfall model (1st), Pamukkale model (2nd) and detail of an aerial view of Douro interconnection model (3rd), which were part of the inspiration of the SeaStairs.

Function

Production oriented: this type of culture would allow the ESL to produce organisms on a scale great enough to reach market goals.

Filtration: this solution centres itself around the ability of bivalves to filter the water system where they are inserted. Because the channels are connected and relatively narrow, the water will be filtrated by multiple bivalves along its way. This means that the Sea Steps can be used as a “filtering highway” when water is entering the ESL system.

Bio-reefing development and role in future-proof solutions: although organisms as bivalves are mainly known for their filtration properties, they are also known for their reef-building abilities. Oysters for example can be used to build artificial reefs that can work as hard substrates for other organisms to grow or use as protection or feeding ground. Oysters are reef builders, and because of this, blocks of oysters can be grown in the step-rivers of the Sea Steps. By doing this, these blocks can be transferred to the sea afterwards and therefore create an offshore reef system that will grow continuously. This is seen as a future-proof project for coastal protection, which is very relevant for the Netherlands 2120 agenda.

Special Products: Oysters are not known only for their filtration properties, they can also produce high-value products, such as pearls. One other vision for these steps is to create a pearl industry inside the lake. This high-labour high-reward system can bring jobs for the neighbouring population, but also economic benefits for the ESL.

Other alternatives: Other types of structures were considered, like having small to medium fishponds (as seen in Figure 14) where fish could not escape and where contaminated water could be stored for later filtration in the steps below. Other options included inland production facilities for microalgae production or special types of aquacultures that need more effort to produce.

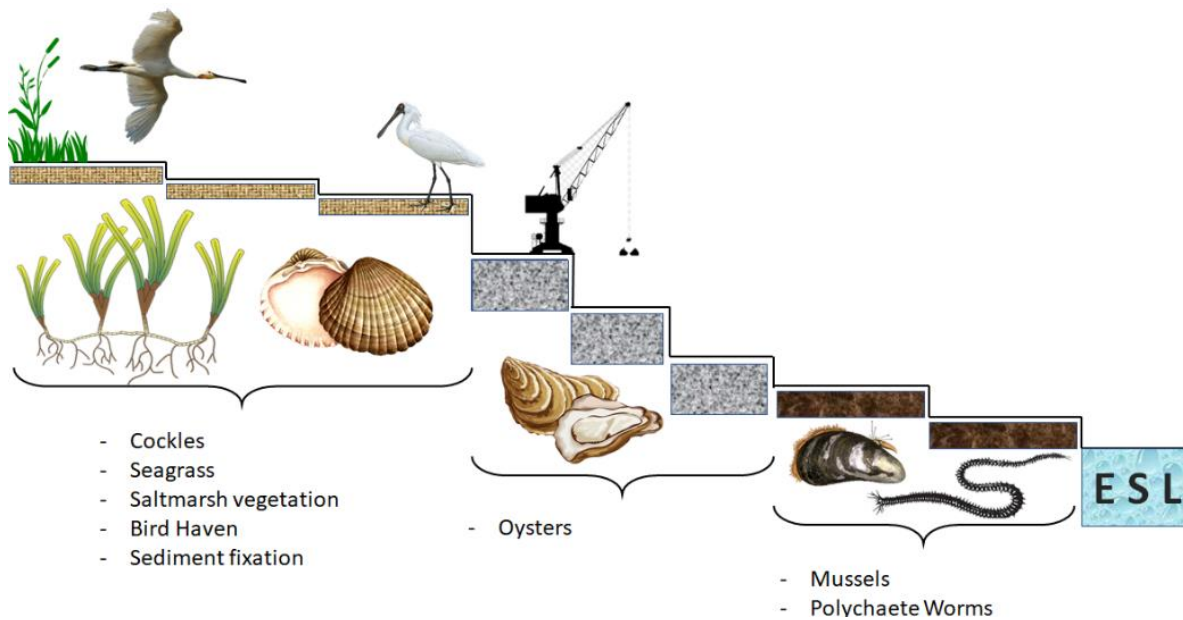


Figure 13. Design of the SeaStairs, with the multiple levels and species.

On top of this, the SeaStairs model allows the mixture of various species in the same slope. As well as several types of steps (figure 12). The approached model we preferred was a hybrid one, where interconnection and different shapes of steps are combined. This combination of different interconnected steps and species allows the lake to have a broad set of marketable products (different shellfish) and different goals (such as conservation efforts in the top layers). This is relevant due to the various characteristics of the species. The design can be found in Figure 13.

This model was designed to unite all the positive aspects that the SeaStairs will bring to the lake. The ability to retain water is seen as an added value to the lake because having water all the time might help boost the productivity of organisms. Even if the organisms do not show additional growth because they are submerged, they can still withstand climate pressure better by simply being underwater. By doing this, not only will there be a better use of the already available water space (because shellfish will not have to be in the middle area of the lake), but also new space can be used. In the case of the SeaStairs, this would be the nude slope that was initially designed in the early project stages. Holes and trenches can be dug in this slope, allowing the existence of the water channels that will run in an open circuit to provide fresh oxygenated water with food to all steps. The existence of a wet platform 24 hours a day allows organisms to grow non-stop and gives them a better resilience against unpredictable weather as high wind levels or prolonged direct sunlight may dry bivalves at a fast rate. Having an added growing platform can bring a lot of benefits without compromising the water space or the functioning of the energy storage lake machinery. In addition, the lake maintenance would be simpler, since it can be performed at the same time the organisms are collected. For instance, when a corridor of oysters or mussels is removed for adult shellfish extraction and there is re-settlement of spat oysters, there is the opportunity of dredging the sediments and removing waste products produced in the bivalve corridor.



Figure 14. Fish tank as an example of other structures that can be done alongside Sea Steps (Vietnam Travel Guide)

Sea Stairs

Pros

- System acts as biofilter
- Educational purposes
- Enhances production of bivalves
- Reduces possible 'swamp' smell as steps will continuously be submerged
- Production, of any kind (production for food, as hatchery, research, nature restoration etc) can be performed without interruption
- Retention of sediments that exist in sand banks and other dynamic structures
- Can help with nature restoration

Cons

- Added maintenance
- Will take in some space

Suitable for the ESL? Yes



c. Permanently flooded sandbanks

One of the main problems of implementing the ESL in the Voordelta area was the loss of nature, especially the loss of a specific habitat type, the permanently flooded sandbanks. The characteristics of this habitat type were already discussed in detail before. This habitat should be recreated or compensated for by the ESL, which is one of the main goals of the aquaculture systems. However, the actual recreation of this habitat type will be challenging, since it requires specific conditions. Moreover, the habitat cannot be efficiently combined with an IMTA system, making it even harder to implement. Therefore, we focus on the nature restoring capabilities of the IMTA.

Although the implementation of the SeaStairs system will not directly contribute to the restoration of permanently flooded sandbanks, it does provide nature restoration when considering other systems. For example, the first steps of the stairs system are designed to be used for the restoration of saltwater vegetation and seagrass. Combined with the presence of cockles in the area, this would help create a suitable feeding area for many species of birds (Figure 13). Additionally, restorative aquaculture could also help replenish natural populations of shellfish in the area, and the creation of shellfish reefs outside the ESL using aquacultured organisms would help improve the biodiversity outside of the ESL as well (Figure 6). Although this system would diverge from the conditions seen in the area before the construction of the ESL, the resulting ecosystem could promote a higher biodiversity compared to the current situation.

Future predictions; how will the system look in the next 100 years

In light of the challenges that climate change will bring to the Netherlands, it is important to think of how resilient our IMTA would be to these challenges, and how it would cope with the climate in the next 100 years. In the future, it is expected that the climate in the Netherlands will be dryer, with higher temperatures compared to today. Here, we discuss some of the challenges that we expect could influence the production system in the future, and how they could be solved, but also how the IMTA could be used to assist the lake against climate change.

Due to climate change, the temperature will increase. This could have multiple effects on the species cultured. One main concern would be the exposition to thermal stress conditions. When this happens, they become more vulnerable to diseases, which would inevitably result in economic losses (Gubbins *et al* 2013; Maulu 2021). Furthermore, some of the species discussed in our report, and especially shellfish, are extremely sensitive to heat waves. This becomes more of a problem in small bodies of water such as the SeaStairs, where insulation and high air temperature can quickly decrease the water levels, especially if the water is stagnant. On the other hand, we believe the SeaStairs could be designed in such a way that the water can circulate between ponds, therefore greatly enhancing the resilience of the IMTA to heatwaves. Furthermore, the lake's large daily influx of water from the sea already makes it much more resilient compared to a normal lake used for aquaculture. Higher temperatures could also provide more opportunities for fish aquaculture. Currently, fish aquaculture is not executed in the Netherlands in outside ponds and lakes because the temperatures are not optimal (Marnix Poelman, personal communication). However, as temperatures are currently increasing, fish species will also migrate to other areas with more favourable temperature ranges (William & Rota, 2011). Therefore, in the future, the Dutch waters might reach more acceptable temperature levels for fish aquaculture, which could open up new options for expanding the aquaculture systems in the ESL. Lastly, higher water temperature reduces water mixing, which increases the risk of harmful algal blooms. These algal blooms can be extremely detrimental to some cultured species, especially shellfish. On the other hand, the tidal regime of the lake should assist in doing the opposite.

Another consequence of climate change will be that overall, the Netherlands will have more frequent periods of drought, alternated with more weather extremes, such as periods with extreme precipitation. These extreme precipitation events will increase the risk of flooding events in the future. The influx of freshwater due to river discharge would be different from today, either in the amount of freshwater influx or the frequency of such events. Accordingly, the types of species could be chosen in a way that the most appropriate combination of them is used to reduce the risk of their loss. For this purpose, Table 4 could be used as guidance for choosing which species to cultivate with regard to expected salinity. Furthermore, it is expected that during these events, there will be stratification between fresh and saltwater, with the saltwater (present at all times in the system) occupying the lower strata.

Conclusion and advice

In our report we have assessed the suitability of different species for the development of an IMTA within the ESL. Taking into account the main goal of having no harmful effects on nature, we do not advise the addition of fish to the ESL, as it is currently a too detrimental practice. On the other hand, the cultivation of different species of shellfish and seaweed could be possible. We have estimated the maximum productivity of different species of seaweed and shellfish that could be cultured. We have also developed the idea of SeaStairs, on which both ecological restoration and aquaculture could be performed within distinct areas for specific cultivations. The ecological restoration is also partly taken into account by the tidal landscape created by Esmee. The retention of water tanks to the steps could benefit the cultivated benthic species, salt farms and seagrasses and would allow for a better biofiltration from shellfish. This filtration will affect the water column creating more clarity which can improve seaweed growth in the lake itself. The seaweed will be attached to floating lines in the deeper parts. Next to their economic profitability, their fast growth and cultivation would be a positive carbon sequestration tool.

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