On combining coastal defence and aquaculture

Opportunities in the Southwest Delta of the Netherlands

Christiaan van Sluis and Tom Ysebaert

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IMARES Wageningen UR

(IMARES - Institute for Marine Resources & Ecosystem Studies)

Client: Ecoshape

Ecoshape
Burgemeester de Raadtsingel 69
3311 JG Dordrecht

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P.O. Box 68
1970 AB IJmuiden
Phone: +31 (0)317 48 09 00
Fax: +31 (0)317 48 73 26
E-Mail: imares@wur.nl
www.imares.wur.nl

P.O. Box 77
4400 AB Yerseke
Phone: +31 (0)317 48 09 00
Fax: +31 (0)317 48 73 59
E-Mail: imares@wur.nl
www.imares.wur.nl

P.O. Box 57
1780 AB Den Helder
Phone: +31 (0)317 48 09 00
Fax: +31 (0)223 63 06 87
E-Mail: imares@wur.nl
www.imares.wur.nl

P.O. Box 167
1790 AD Den Burg Texel
Phone: +31 (0)317 48 09 00
Fax: +31 (0)317 48 73 62
E-Mail: imares@wur.nl
www.imares.wur.nl

Contents

Summary

In reaction to an extreme flooding event in 1953 in the south-western part of the Netherlands, the Dutch shortened and strengthened their estuarine coastline with dams, dikes and land reclamation. In retrospect, the construction of these large scale artificial coastal defence structures and the closure of several sea inlets have come with several adverse effects. Hard substrate (i.e. dikes, dams) reduced the area with natural habitats like saltmarshes, mudflats and sandy intertidal areas and their associated ecosystem services. In case of the Oosterschelde, adverse effects occur as tidal flats are eroding and slowly disappearing into the gullies which are too large for the strongly reduced tidal exchange and water currents. At the same time, climate change and increased human exploitation pose. new threats to the area. The sea level will rise and river runoffs will change while the use Southwest delta increases. This calls for a new approach in protecting the land from floods while ensuring proper ecosystem functioning, in the exploitation of natural resources and in maintaining a healthy distribution of flora and fauna. In this way management of the Southwest Delta is oriented to a more sustainable and robust approach in which ecosystem services of estuarine ecosystems are more fully integrated.

The innovation program 'Building with Nature' aims to use the forces (dynamics) of nature to construct hydraulic engineering infrastructure while creating opportunities for nature. To further explore the possibilities of this approach and more importantly to use the Southwest Delta more efficiently, we explored possibilities to combine coastal defence with the profits of aquaculture. Coastal defence might offer possibilities for shellfish culturing by creating interesting infrastructure or better growing conditions. On the other hand, structures for shellfish aquaculture such as shellfish long lines, shellfish tables, beds and reefs, have the potential to reduce wave energy and therefore contribute to lowland coastal protection.

This report, based on literature and a stakeholder analysis, reveals that a combination between aquaculture and costal defence can benefit both sectors. A combination between aquaculture and coastal defence is not straightforward or easily implemented. Coastal defence is mainly used on more exposed sites while aquaculture asks for more sheltered ones. Although this contradiction complicates combined applications, the more detailed exploration of coastal defence and aquaculture techniques in this study, shows multiple opportunities for beneficial combinations. The combinations where coastal defence facilitates aquaculture will probably be the easiest applicable and most profitable. However, at locations that are more sheltered aquaculture may reduce maintenance costs of coastal defence structures by reducing currents and dissipating wave attenuation under average weather conditions. All combinations do however require a special design, but can benefit both coastal defence and aquaculture while partly restoring or protecting habitats like saltmarshes, mudflats and sandy intertidal areas. Local delicacies, recreation and tourism are opportunities to make combinations more profitable. For the success of such combinations the collaboration between policy makers, researchers, and especially the experience of the aquaculture sector is essential.

1. Introduction

Coastal defence is crucial in safeguarding the life of people living near the sea. Low lying coasts and deltas are highly populated, despite a higher risk to flooding. In the future, even more people will inhabit coastal areas. Bulleri *et al*. (2009) expect that around 2050, the human population will have grown by 50%. Before 2025 75% of the people will live within 100 km of the coasts (EEA 2006). This is a trend of concern, as sea level rise and climate change make coastal areas and deltas more likely to be flooded (Michener, Blood et al. 1997; Thompson, Crowe et al. 2002). According to the Royal Dutch Meteorological Institute, sea level in the Netherlands will rise with a minimum of 35 cm and a maximum of 85 cm by 2100 (KNMI 2011).

To ensure safety, people increasingly modify coastal habitats. In the past, natural habitats such as large intertidal areas, shellfish beds, saltmarshes and dunes formed extended barriers in coastal zones that naturally protected inhabited lands from flooding. Nowadays, well developed areas with high economic value are increasingly protected by land reclamation and a range of Artificial Coastal Defence Structures (ACDS) (FAO document #1) (EEA 2006; Unknown 2012). Examples of ACDS include groynes, seawalls, sills, dikes, etc. In some places ACDS are or will become the most dominant intertidal and shallow subtidal habitats (EEA 2006; Bulleri and Chapman 2010). Between 1990 and 2000 artificial surfaces increased by 190 square kilometre per year along European coasts (EEA 2006). The coast of the North Sea is most drastically modified, with 17% of its coasts inhabited and 16% armoured (EEA 2006). In the quest to ensure the safety, ACDS have strongly reduced the gradual transition zone between the land and sea.

Although an effective solution on the short term, the longer-term effectiveness of ACDC often can be unsatisfactory (Smits, Nienhuis et al. 2006). Nowadays, it is clear that armouring of coasts comes with diverse adverse effects like: disturbed sediment balances, coastal erosion, eutrophication, a decline of natural coastal habitats and biodiversity loss (Boers, van Geer et al. 2011; Borsje, van Wesenbeeck et al. 2011; Chapman and Underwood 2011; Unknown 2012). These changes are reflected in the goods and services that estuarine and vegetated near shore habitats naturally provide. It is estimated that coastal habitats represent 23.7% of the total global ecosystem services (Scyphers, Powers et al. 2011). Examples of these are e.g. fisheries, recreation, protection from natural hazards, and general environmental resilience (Fletcher, Saunders et al. 2011). The adverse effects of ACDS on the one hand and the benefits of ecosystem services that natural coastal habitats provide on the other hand, show that adequate governance and management of coastal and estuarine systems cannot be achieved by solely making infrastructural adjustments (Unknown 2012).

Changing the current practice of armouring coasts will require a change in the coastal management framework. Decision makers must appreciate the cost and benefits of potential solutions to coastal erosion. This, while including potential cumulative impacts on shoreline features, habitats, and other amenities. We must look for strategies that maintain safety standards in coastal defence in a sustainable way. This also includes being beneficial or, at least, not negative, for natural assets such as natural dynamics and habitat quality. Creating transition zones or restoring natural transition zones, may help to achieve such a new coastal management framework.

This study is part of the Building with Nature programme. The concept of Building with Nature is compatible with the new insights on coastal defence. Building with Nature aims to use the forces of nature (i.e. natural processes) to produce hydraulic engineering infrastructure and to create new opportunities for nature (ecosystem services) at the same time (www.ecoshape.nl). This approach must balance coastal protection and the need to maintain the integrity of natural ecosystems (Bendell 2006; Scyphers, Powers et al. 2011). The difficulty with more natural coastal defence techniques is that they have a high demand for space. Consequently, more natural ways of coastal defence may conflict with other uses of the area like transport and fishing. This problem could be solved when a more natural coastal defence can be combined with other uses of the area (Unknown 2012). For example, a combination of coastal defence with aquaculture.

1.1 Motive

In reaction to the adverse effects of ACDS the Dutch management perspectives have changed over the last decades. Rather than solely making infrastructural adjustments for safety, a more integrated approach is adopted in which safety for the region should be in balance with an economically vital and ecological resilient Delta (Fiselier, Jaarsma et al. 2011; Scyphers, Powers et al. 2011) (Figure 1). The aim is to restore natural processes like estuarine dynamics, sedimentation processes and the existence of transition zones, while the region remains economically vital. This could include restoring natural defences such as dunes, salt marshes, mudflats and oyster reefs. However, the new management approach is challenged by the expected sea level rise, asking for reinforcement of the Dutch coastal defence systems. These reinforcements must therefore be carried out meeting the following:

- Some adverse effects of ACDS are avoided
- Building and maintenance costs are low
- Nature and/or economy benefits

The combination of coastal defence and aquaculture may be an example of an integrated water management where multiple use of delta functions benefits safety, ecology and profits. Yet, it is unknown whether such a combination is compatible and profitable.

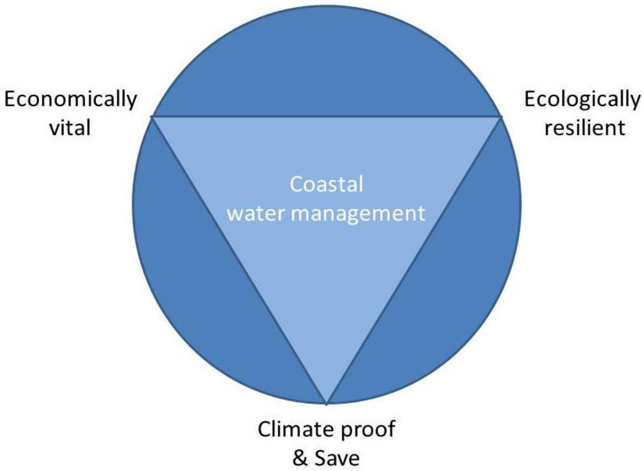


Figure 1) Schematic overview of the newly adopted Dutch water management approach. The measures must be cost effective and support natural dynamic estuarine processes of sedimentation and erosion, nutrient fluxes and gradients of fresh to marine waters in the Dutch Delta waters (Delta 2011; Unknown 2012). The Southwest Delta must be: 1) Economically vital, 2) Ecologically resilient and 3) Save and Climate proof. For more information see www.zwdelta.nl.

1.2 Objective

There is a great potential for natural ecosystems and human intervention to reinforce each other. The Building with Nature approach lay emphasis on the opportunities an ecosystem offers, yet obviously without ignoring infrastructural and economic conditions. Starting from the natural system and making use of nature's forces, Building with Nature attempts to meet society's needs for infrastructural functionality, and to create room for new nature and other services at the same time.

Sustainable and cost-effective coastal defence and flood protection is vital to low-lying coastal and estuarine areas. Recently, the demand for multifunctional approaches increases. This study aims to find how coastal defence infrastructure can be combined with shellfish aquaculture, and if coastal defence can be supported by structures and organisms associated with shellfish aquaculture.

1.3 Method

In search of feasible combinations of aquaculture and coastal defence, literature is used to explore the properties of both: natural coastal defence environments and associated ecosystem services, and existing artificial coastal defence structures. We also explored literature for different aquaculture techniques. The most suitable combinations between coastal defence and aquaculture in the Southwest Delta were further explored through a stakeholder analysis. Through oral interviews we confronted stakeholders and experts with the idea of combining coastal defence and aquaculture and looked for ways for its implementation. Interviewed stakeholders include: the local aquaculture sector, governmental departments and professionals (ecological and morphological experts) (appendix 1). The same questions were asked to all respondents (appendix 2). The results of the interviews were used in four examples of coastal defence and aquaculture. The first two examples relate to aquaculture techniques: Rafts, long lines and floating cages and poles and tables respectively. The third and fourth example show how aquaculture can be combined with coastal defence on relatively small and very large scales. All examples include an overview of Strengths, Weaknesses, Opportunities and Threats (SWOT analysis) and an artist impression.

1.4 Demarcation

In search of feasible combinations of aquaculture and coastal defence, literature is used to explore the properties of both: natural coastal defence environments and associated ecosystem services, and existing artificial coastal defence structures. We also explored literature for different aquaculture techniques. The most suitable combinations between coastal defence and aquaculture in the Southwest Delta were further explored through a stakeholder analysis. Through oral interviews we confronted stakeholders and experts with the idea of combining coastal defence and aquaculture and looked for ways for its implementation. Interviewed stakeholders include: the local aquaculture sector, governmental departments and professionals (ecological and morphological experts) (appendix 1). The same questions were asked to all respondents (appendix 2). The results of the interviews were used in four examples of coastal defence and aquaculture. The first two examples relate to aquaculture techniques: Rafts, long lines and floating cages and poles and tables respectively. The third and fourth example show how aquaculture can be combined with coastal defence on relatively small and very large scales. All examples include an overview of Strengths, Weaknesses, Opportunities and Threats (SWOT analysis) and an artist impression.

1.5 Bookmark

Chapter 1 and 2 give a brief impression on the Southwest Delta and the concept of combining aquaculture with coastal defence. Chapter 3 foccusses in natural habitats that function as coastal defence and their associated ecosystem processes and services. In chapter 4 and 5 we respectively focus on the applicability of artificial coastal defence techniques and different techniques for aquaculture. Chapter 6 integrates the previous chapters by summarizing the conditions for combinations between coastal defence and aquaculture. At the end of chapter 6 four example combinations are reviewed by listing their Strengths, Weaknesses, Opportunities and Threats (SWOT analysis). This includes a comparison to natural coastal defence and associated ecosystem processes and services. Conditions for combining aquaculture and coastal defence are discussed in chapter 7 and the main conclusions for applications are drawn in chapter 8.

1.6 The Southwest Delta

The Delta in the Southwest of the Netherlands (hereafter Southwest Delta), is an estuarine region where dikes and dams protect the land reclaimed from the sea. The area has undergone drastic changes after the severe flooding of 1953, which initiated the Delta Plan. This plan resulted in a shortening of the coastline with dams, sluices and storm surge barriers. Building and strengthening this shortened coastline was significantly cheaper than adjusting all coastal defence of the Southwest Delta (for more information see www.deltawerken.com). These measures resulted in large scale changes in the estuarine ecosystem and loss of intertidal area. The waters of the Southwest Delta are productive and the shellfish industry is of great importance to the area (Delta 2011). Besides shellfish culture, the area is mainly used for shipping, agriculture, harbour industry, and recreation. The natural value of the area is high, as reflected in the conservation status of many water bodies (N2000 areas).

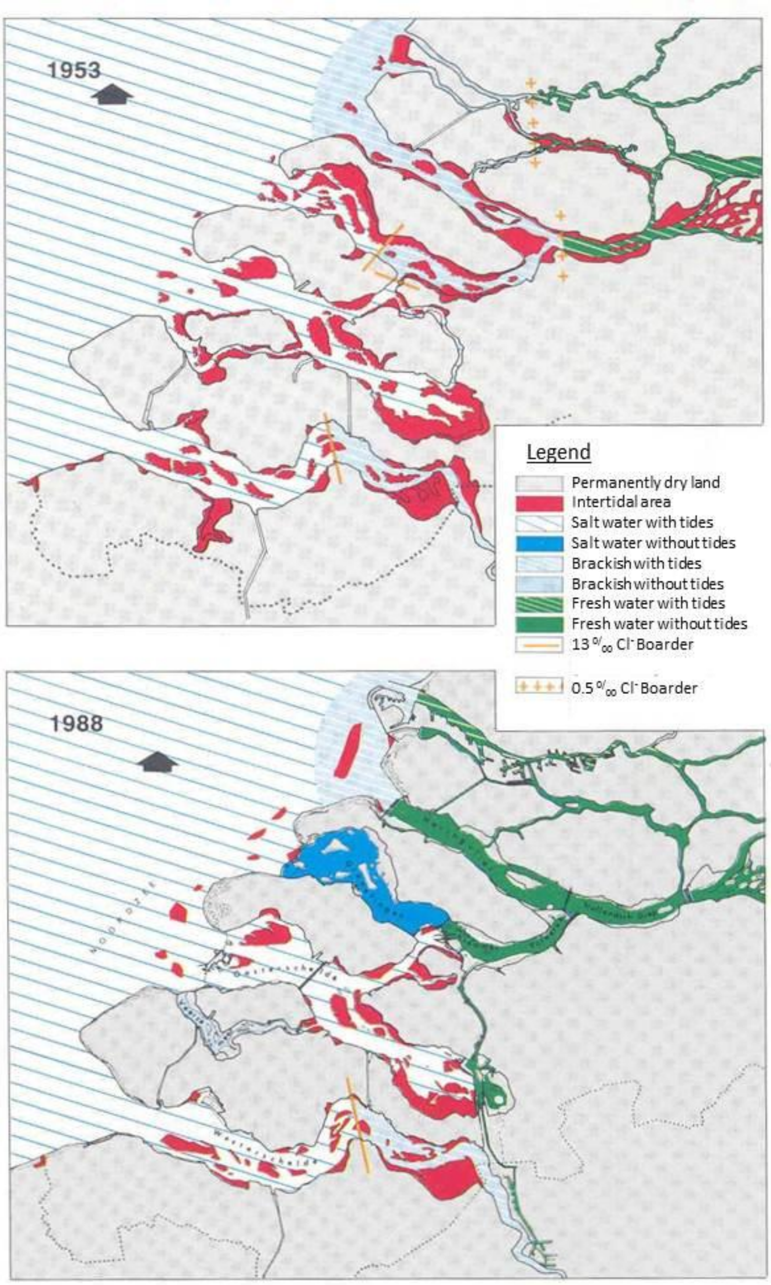


Figure 2) Schematic overview of the delta in the Southwest of the Netherlands. 1953 before the construction of extended dams, sluices and storm surge barriers, 1988 when the ACDS were completed and in function.

2. The idea of integrating aquaculture with coastal defence

The idea of combining aquaculture with coastal defence originated from the need for space in the Southwest Delta. Many activities and functions are located on a relatively small area. Instead of approaching this unisectoral, an intersectoral approach might be more beneficial for all stakeholders involved. Space could be used more efficiently when used for multiple purposes. Not all activities will be compatible, but at first sight there seems to be no objection for a combination of coastal defence and aquaculture. The combination seems promising as both coastal defence and aquaculture generate structures that can reduce wave attenuation in the water column.

A search in literature and on the internet provided little information on the combination of aquaculture and coastal defence. The idea seems not yet explored in detail.

The few associations between aquaculture and coastal defence can be subdivided in two types:

1) Negative associations that refer to the clear-cutting and degradation of natural coastal habitats like mangroves, sea grass beds and coral reefs in order to create space for aquaculture. The structures of these natural habitats are important to coastal protection (Barbier 2006; EEA 2006; Koch, Barbier et al. 2009). In general this literature states that the absence or degradation of highly structured coastal habitats make coasts more prone to flooding and tsunami's (Danielsen, Sørensen et al. 2005; Barbier 2006; Pattanaik and Narendra Prasad).

2) Positive associations which refer to restoration projects in Africa, Asia and Australia. These projects aim to restore natural habitats (mangroves and coral reefs) that provide coastal defence structures, while simultaneously restoring (direct and indirect) profits for fishing, and extensive crab and oyster culturing (personal observations) (Danielsen, Sørensen et al. 2005; Barbier 2006). Here the existence of natural coastal barriers benefits locals through provided ecosystem services (Cat, Tien et al. 2011). Participatory planning in collaboration with local communities and space availability are key factors in the success of these projects (Barbier 2006; Cat, Tien et al. 2011).

3. Natural coastal defence

In undisturbed coastal areas a variety of natural habitats form a transition zone with barriers between land and sea. By hampering wave attenuation (see textbox), the natural mixture of soft and hard substrate habitats can effectively protect the back land from erosion and flooding (Gedan, Kirwan et al. 2011; Mangi, Davis et al. 2011). In addition to Artificial Coastal Defence Structures (ACDS), coastal habitats also generate additional ecosystem processes and services. To be able to value nature in an economic way, ecosystem processes and services are defined as: "direct and indirect contributions of ecosystems to human well-being" (Fletcher, Saunders et al. 2011). Examples of ecosystem processes and services are biochemical cycling, primary production, the supply of larvae and gametes, fisheries and the presence of recreational areas (Fiselier, Jaarsma et al. 2011; Mangi, Davis et al. 2011). Because of these benefits, the support for using natural coastal defence strategies is growing (Mangi, Davis et al. 2011; Scyphers, Powers et al. 2011).

The use of natural habitats in coastal defence also has its disadvantages. Coastal habitats are resilient to natural disturbances, but additional anthropogenic disturbances can disrupt this equilibrium (Koch, Barbier et al. 2009). Stressed habitats have generally lower biomass and density and hence a lower capacity to attenuate the forces of waves and currents (Koch, Barbier et al. 2009), or provide other services. Additionally, time scale and spatial scale are important factors determining the strength of natural coastal defence. Healthy and sufficiently structured habitats must be situated at the right elevation level to protect the coasts under critical conditions of storms and high tides (Koch, Barbier et al. 2009; Gedan, Kirwan et al. 2011). Otherwise their function as coastal protection will be marginal.

Despite some disadvantages, coastal habitats show great potential for coastal defence as they grow naturally, and trap and stabilize sediments (Koch, Barbier et al. 2009; Gedan, Kirwan et al. 2011). The physical structure of organisms reduces water velocities and initiates trapping of sediments (Temmerman, Govers et al. 2004; Koch, Barbier et al. 2009). Examples of these are mussels, oysters and sea grasses.

Shellfish additionally trap sediments by secretion of waste products (i.e. biodeposition) (Forrest, Keeley et al. 2009). Over time the sediments consolidate under the organisms.

Because of their ability to change their own environment, the organisms are referred to as ecosystem engineers (Jones, Lawton et al. 1994). When sufficient sediment is available salt marshes can grow with sea level rise (Temmerman, Govers et al. 2004). The same may be true for other structural habitats such as oyster reefs and mangroves. A remarkable advantage compared to ACDS. When we refer to ecosystem engineers later in this study we refer to organisms with the ability to attenuate waves and currents and trap and consolidate sediments.

Text box 1.

Wave attenuation

Coastal defence aims to prevent erosion and flooding. Coastal protection against erosion reduces the forces of the waves also called wave attenuation or wave dampening. Wave attenuation itself depends on the bathymetry of the area and structure in the water column.

A big difference between ACDS and natural habitats is that vertical coastal defence structures mainly reflects wave energy, while sloped structures or vegetation canopies can dampen and absorb wave energy (Scyphers, Powers et al. 2011). When wave energy is reflected by ACDS it can lead to erosion in other places (Boers, van Geer et al. 2011).

Structures like vegetation canopies and oyster reefs, but also suspended structures in the water column cause friction with incoming waves thereby reducing current velocity and wave energy and hence wave attenuation (Koch, Barbier et al. 2009). Wave shoaling, wave regeneration and wave breaking leads to 100% wave attenuation (Koch, Barbier et al. 2009).

The addition of (semi-)natural structures in front of existing coastal defence can dampen part of the wave action. Its use is growing worldwide (Gedan, Kirwan et al. 2011; Scyphers, Powers et al. 2011). Natural habitats in front of ACDS reduce pressures on the ACDS and hence reduce strengthening and maintenance costs. It has been calculated that use of natural barriers may reduce construction costs of sea walls by 20-40% at some locations in the Netherlands (Fiselier, Jaarsma et al. 2011). Additionally, natural barriers also contribute to recreational and nature value of the area (Fiselier, Jaarsma et al. 2011). One disadvantage is that natural barriers need more space than ACDS. Mostly, natural habitats will support ACDS, in some sheltered areas natural habitats can also replace ACDS.
Depending on the climate, hydrology, morphology and sediment input (marine, estuarine), different natural transition zones can be distinguished. As for the additional benefits for the use of natural habitats in coastal defence, we listed ecosystem processes and services they provide in table 1, 2 and 3.

3.1 Coastal vegetation

Salt marshes

Salt marshes and mangroves are mostly described as coastal vegetation. Salt marshes grow on the highest zones of beaches and mud flats at sheltered coastal areas (figure 3). They contain a natural age and elevation gradient from the sea towards the land (Van Wijnen and Bakker 2001). For decades, the growth of salt marshes has been stimulated to offer coastal protection (Unknown 2012) and speed up land reclamation. But, as salt marshes only grow up to about 30 cm above spring tide sea level, they do not provide sufficient coastal protection under all critical conditions which cause floods (Koch, Barbier et al. 2009). Their function in coastal protection is therefore mainly defined as protecting higher habitats or ACDS under average weather conditions (Fiselier, Jaarsma et al. 2011; Mangi, Davis et al. 2011). This may sound disappointing, but based on two estimates at the Tetney marshes and the St. Peter's Flats in Essex, UK, revealed that reducing the required height for a seawall with wetlands could reflect to 1026 – 14622 euro per square meter savings in production costs (Mangi, Davis et al. 2011). A study by Wijnen and Bakker (2001) in the Netherlands found that salt marsh growth initially can keep up with sea level rise. Yet, when accumulation rates are not high enough, they will disappear or shift to higher elevations, if these sites are available (Van Wijnen and Bakker 2001). Currently, the presence of steep artificial coastal defence structures is a threat to coastal vegetation as it limits the availability of higher sites. Hence, the surface of land on which coastal vegetation can thrive will decrease with sea level rise. The phenomenon is also called coastal squeeze (see figure 4).

Figure 3)

Dutch salt marsh meadow

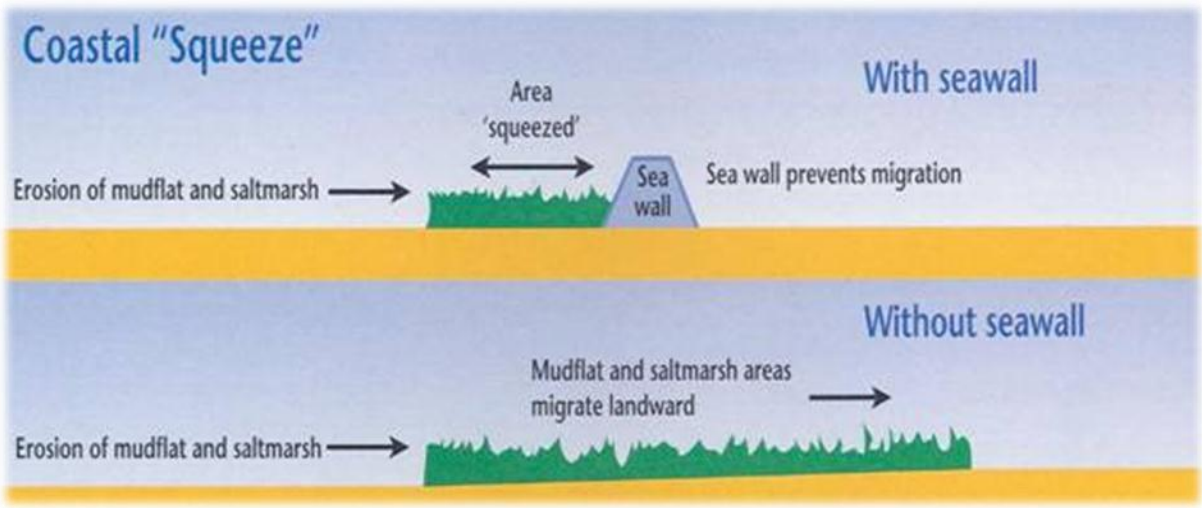


Figure 4

Schematic overview of coastal squeeze. Source: www.eloisegroup.org

Mangroves

Over the last decades many mangroves disappeared in order to create space for aquaculture (Barbier 2006). Unfortunately, the effects of destructive floods and tsunami's emphasized the importance of this coastal vegetation in coastal protection (Danielsen, Sørensen et al. 2005). Trees or mangroves can form extensive forests along tropical coasts that can grow with sea level rise (McKee, Cahoon et al. 2007; Cat, Tien et al. 2011). Coastal forests trap sediments and form rigid structures that rise like a forest above the sea. Because of these features, mangroves are efficient in reducing wave action on shores, even under critical conditions of storms and tsunamis (Danielsen, Sørensen et al. 2005; Koch, Barbier et al. 2009). Ecosystem processes and services provided by coastal vegetation are summarized in table 1.

Table 1. Ecosystem processes and services provided by coastal vegetation. According to The Economics of Ecosystems and Biodiversity approach (TEEB) (Fletcher, Saunders et al. 2011).

Beneficial Ecosystem processes	**Beneficial Ecosystem Services**
• Primary production • Secondary production • Larval/Gamete supply • Food web dynamics • Erosion control • Formation of species habitat • Formation of physical barriers • Climate regulation • Biogeochemical cycling • Water purification	• Fisheries Fertiliser / Food • Natural hazard protection • Regulation of pollution • Tourism Recreation / Sport • Spiritual / Cultural wellbeing • Nature watching • Research and Education

3.2 Beaches and mudflats

Beaches and mud flats have an important function in reducing the forces of waves and currents by creating extended shallow areas in which waves will remain smaller (see figure 5). Their presence and conservation hence contributes to a reduction of wave action on ACDS and in turn a reduction of construction and maintenance costs of sea defence (Mangi, Davis et al. 2011). Mudflats occur in more sheltered sites like estuaries, while beaches also occur at exposed sites such as the Dutch North Sea coasts. If local sediment deposition and erosion are in balance, beaches can form stable habitats at exposed coasts. In the Netherlands erosion of beaches occurs during stormy weather while accretion takes place during average weather conditions. Mudflats will disappear when current velocities increase.

Figure 5
Picture of a Dutch mudflat

When existing ACDS are threatened by deep gullies with strong currents, beach fills into these gullies can contribute to the restoration of beaches and avert further negative effects of erosion (Fiselier, Jaarsma et al. 2011). Ecosystem processes and services provided by beaches and mudflats are summarized in table 2.

Table 2. Ecosystem processes and services provided by beaches and mudflats. According to The Economics of Ecosystems and Biodiversity approach (TEEB).

Beneficial Ecosystem Processes:	**Beneficial Ecosystem Services**
• Primary production • Secondary production • Larval/gamete supply • Food web dynamics • Erosion control • Formation of species habitat • Climate regulation • Biochemical cycling	• Fisheries • Other wild harvesting • Natural hazard protection • Regulation of pollution • Recreation/sport • Spiritual/cultural wellbeing • Nature watching • Research and education

3.3 Reef structures

Most well-known examples of reefs are coral reefs, but bivalves like mussels and oysters can also create extensive reef structures that determine the local morphology and ecology of intertidal and shallow subtidal habitats (Coen and Luckenbach 2000)(fig 6). Less known are some worms which generate external tubes (e.g. *Lanice conchilega*) that create reef-like structures (Rabaut, Vincx et al. 2009). By trapping nutrients and sediments reefs can grow to extensive structures in the water column. Reefs dissipate wave energy and hence protect higher situated habitats or ACDS from erosion. (Scyphers, Powers et al. 2011; Unknown 2012). For example, oyster reefs are often found seaward of salt marshes, where their presence reduces marsh retreat by stabilizing the sediment (Scyphers, Powers et al. 2011). Shellfish have the additional benefit to reduce turbidity and improve water quality (Coen, Brumbaugh et al. 2007). Ecosystem processes and services provided by reefs are summarized in table 3.

Figure 6

Oyster reef in the Dutch Oosterschelde

Table 3. Provided ecosystem processes and services of reef structures. According to The Economics of Ecosystems and Biodiversity approach (TEEB)(Fletcher, Saunders et al. 2011).

Beneficial Ecosystem processes	Beneficial Ecosystem Services
• Primary production • Secondary production • Larval/Gamete supply • Food web dynamics • Species diversification • Erosion control • Formation of species habitat • Climate regulation • Biochemical cycling • Water purification	• Fisheries • Other wild harvesting • Aquaculture • Fertiliser / Feed • Natural hazard protection • Environmental resilience • Spiritual/cultural wellbeing • Research and education

4. Artificial coastal defence

In this chapter we give a brief overview of artificial coastal defence structures. It is mainly based on Bendell (2006), who gives a good overview of different coastal defence techniques.
Artificial coastal defence structures interfere with the existing balance between sedimentation and erosion. There are two types of Artificial Coastal Defence Structures: 1) soft measures using vegetation or sand and 2) hard measures using e.g. concrete, rocks and poles. This paragraph provides a short overview of commonly used techniques (Also see table 4 for an overview).

4.1 Soft measures:

4.1.1 Vegetation control

Vegetation control is the most natural way of creating coastal defence as it essentially is the restoration of natural transition zones with coastal vegetation (figure 7). These natural wetlands like marshes and swamps or mangrove forests are created to prevent further erosion of coastal areas. The vegetation provides a buffer dissipating wave energy. In some places natural growth or planting can occur directly on the shoreline. In other places coastlines have to be adjusted to create suitable sites for coastal vegetation. Dead vegetation can also be used as a temporary biologic component of coastal defence. Examples of these are dead trees and trunks which create temporally shelter so that other vegetation can recover and take over the role of coastal protection. More information on vegetation control can be found on www.ccrm.vims.edu/livingshorelines/.

Figure 7
Planted mangroves

4.1.2 Beach fill

When sand or other "soft" sediments are lost by erosion, beach nourishments can be executed (figure 8). Sediments with the same characteristics of the sediment in the eroded place, are added to the eroded shore. Instead of the original sediment, now the nourished sediment is lost in the erosion process. When periodically repeated beach nourishments can sustain coastlines over longer time periods. Apart from the large scale displacements of sediments this technique is relatively natural as there is no hard substrate involved.

Figure 8
Beach fill

4.2 Hard measures

4.2.1 Sills

Sills are long continuous structures build parallel to the shore with the aim to reduce wave action on the original beach (figure 9). Most of the time they are built as rock armoured, rubble-mount structures, but artificial rocks or oyster shell bags are also used as sills. The sill retard offshore sand movements by introducing a structural barrier on the beach profile (Burcharth and Hughes 2002). On the landward side the sediment is held on a higher elevation than at the seaward side. The result is that the sill itself and the shallow area between the sill and the original shore dissipate wave action. Sometimes submerged sills are placed within the shallower area between the outermost sill and the shoreline which also retain beach material. In other examples sills are combined with vegetation control (figure 8). Sills are used at both exposed and sheltered sites (Bulleri and Chapman 2010).

Figure 9

Sills protecting the vegetation

4.2.2 Groynes

Groynes are vertical open structures built perpendicular to the shoreline (figure 10). By reducing flow rates along the coasts groynes reduce sediment erosion rates. The orientation, length, height, permeability, and spacing of the groynes determine the actual change in the shoreline and the beach level. Groynes function only when longshore sediment transport occurs. The use of groynes can be perfectly combined with beach nourishments, but also in the protection of (new) mashes (Burcharth and Hughes 2002). Groynes are mainly used on exposed sites (Bulleri and Chapman 2010).

Figure 10

Groins against longshore sediment transport

4.2.3 Breakwaters

Breakwaters can be build connected to the coast, detached and floating (Burcharth and Hughes 2002). Breakwaters are separated barriers that create a lee area between the structure and the shoreline. They are usually situated parallel to the shore. The lower wave action behind breakwaters may lead to the deposit of sediment creating so called pocket beaches (figure 11). Once formed the pockets help to stabilize the coastline. Multiple detached breakwaters spaced along the shoreline can provide protection to substantial lengths of shoreline frontages (Burcharth and Hughes 2002). Floating breakwaters are used in protected regions that experience mild wave climates with very short-period waves. Other breakwaters are also used at exposed coastal areas (Bulleri and

Figure 11

Breakwaters and pocket beaches

Chapman 2010). In some cases submerged detached breakwaters are used because they do not spoil the view (Burcharth and Hughes 2002). Some suggest the use of biogenic breakwaters like oyster and mussel reefs in such cases (Scyphers, Powers et al. 2011).

4.2.4 Sloped structures

These structures run parallel to the shore (figure 12). They can be watertight or porous and are built on a bank with the principal function of protecting the shoreline from erosion while absorbing wave energy. They typically consist of a placed rock or riprap (randomly placed and sized stone, concrete, or asphalt pieces), but can be constructed from oyster shell bags as well (Burcharth and Hughes 2002). Sloped structures are also used as a protection along the seaside of wetlands. Then the structure is generally smaller (around 15 cm above the wetland) and only functions to protect the marsh or wetland roots from undermining. Sloped structures are used at both exposed and sheltered sites (Bulleri and Chapman 2010).

Figure 12

Sloped structures

4.2.5 Vertical structures

This kind of sea defence includes seawalls and bulkheads. They are a reinforcement of the coastline and prevent or elevate the point of flooding (figure 13). Seawalls can consist of concrete, steel or concrete piling, and stone-filled cribwork, concrete armour units, or stone rubble (Burcharth and Hughes 2002). Bulkheads are primarily intended to retain or prevent erosion of steep coasts. They are built as soil retaining structures, with a less significant role in dissipating wave energy (Burcharth and Hughes 2002). Vertical structures are used at both exposed and sheltered sites (Bulleri and Chapman 2010).

Figure 13

Sea wall

Table 4 Overview and characteristics of ACDS by (Bulleri and Chapman 2010).

Table 1. Purposes and characteristics of common urban infrastructures deployed in near-shore waters

Type of structure	Action and purposes	Materials used	Positioning/ orientation respect to the shore	Position respect to the sea surface	Wave exposure
Breakwaters	Reduce the intensity of wave forces in inshore waters; used for protecting ports, harbours and marinas and as coastal defences	Sandstone; geo-textile; granite; sandbags; concrete; wood	Not connected to shore parallel or fish tail	Emergent; low crested; submerged	Exposed
Groynes	Reduce along-shore transport of sediments; used in coastal defence schemes, often in association with breakwaters	Sandstone; geo-textile; granite; concrete; wood; sandbags	Connected to shore perpendicular	Emergent; low crested; submerged	Exposed
Jetties	Reduce wave- and tide-generated currents; used for developing, ports, harbours, marinas and as constituents of coastal defence schemes	Sandstone; geo-textile; granite; concrete; wood; sandbags	Connected to shore perpendicular	Emergent; low crested; submerged	Exposed
Seawalls Bulkheads	Reduce the impact of waves on shore; used as a tool against coastal erosion and as a constituent of ports, docks and marinas	Sandstone; geo-textile; granite; concrete; steel; vynil; sandbags; wood	Onshore parallel on open coasts, but variable in enclosed waters	Emergent	Exposed to sheltered
Pilings	Sustain infrastructure, such as bridges, piers, docks and for the mooring of vessels	Concrete; wood; fibreglass; metal	Onshore to offshore	Emergent	Exposed to sheltered
Floating docks	Create boating facilities	Concrete; wood; plastic fibreglass; metal	Connected to shore varying orientation	Emergent	Sheltered
Ropes-poles cages-nets	Constituents of aquaculture facilities	Fabric; plastic; wood; fibreglass; metal	Not connected to shore varying orientation	Emergent; submerged	Moderately exposed to sheltered

5 Aquaculture techniques

Aquaculture has the aim to boost nature's natural productivity for harvesting by improving the survival and growth of target species (www.fao.org). The most productive aquaculture takes place under strictly monitored/controlled conditions and with the enhancement of nutrient or food availability (www.fao.org). Aquaculture under field conditions in coastal regions is less productive. In the Southwest Delta low productive aquaculture is present as mussel and oyster farming. This kind of aquaculture is highly appreciated for its local products and represents an important economic value (Delta 2011). In this chapter we outline aquaculture techniques in the coastal zone that potentially contribute to coastal defence. A qualitative comparison is made with the natural coastal defence structures and the ACDS with respect to their possible function as a coastal defence structure.

5.1 Bottom culture

Methods: bottom culture is commonly used for shellfish because of the low maintenance costs and relatively simple preparation requirements (Toba 2002). Seed is cultured or harvested and put onto beds with favourable conditions for optimal growth (ODUS 2001). Preferably these places are sheltered, high productive coastal waters with firm mud bottoms (Toba 2002), as erosion or deposition of sediments can induce loss or coverage. The sufficient supply of fresh, plankton rich water determines the growth of shellfish. The density at which the shellfish are placed on the lots is important for the yields as too many shellfish on a small area will hamper growth through food competition (Toba 2002).

In the bottom culture fish farmers distribute young mussels or oysters spat on their lots and harvest the adults after several years using bottom trawls (board 2011). The mussel spat itself is collected on natural seed beds with dredges or by hanging hard substrate like "Christmas" ropes or nets in the water column (mussel seed capture devices). In spring, small planktonic shellfish larvae settle on these substrates and grow up to around one centimetre. In autumn, the spat is harvested from the substrates and transported to the bottom plots. The bottom culture technique is broadly used in The Netherlands, Ireland and the UK (board 2011). Depending on the location it can be used in the subtidal and intertidal. The reef structures associated with mussel and oyster culture attract local fauna like fish and invertebrates. Bottom culture may hence also provide some of the ecosystem processes and services associated with reef habitats.

Figure 14

Mussel boat

Habitat contribution and application in coastal defence: Bottom cultures resemble natural reef structures. When this comparison is valid, rafts, bottom cultures may also provide some of the ecosystem processes and services associated with natural reef structures. When bottom culture is situated in the intertidal it can dissipate wave action like natural reef structures and also stabilize the sediment (pers. comm. Tom Ysebaert). In contrast to natural reefs, bottom cultures will always have regular disturbance regimes due to the culturing techniques and harvesting. Subtidal bottom cultures are also comparable to natural reefs but have less influence on coastal defence, especially when placed in the deeper parts. Shallow submerged bottom cultures can dissipate wave action through creating more shallow areas and may possibly be comparable to submerged breakwaters or pilings (Scyphers, Powers et al. 2011), although the height of these structures is often much higher and the way they reflect/absorb waves is different from bivalve reef structures.

5.2 Rafts, long lines and floating cages

Figure 25

Floating rafts

Methods: Rafts, long-lines and floating cages can fixate or hold organisms like shellfish, fish and sea weeds (figure 15). They are used in areas where the effects of wind and waves are low or moderate and conditions are favourable for the growth cultured organisms (Toba 2002; Bulleri and Chapman 2010). These techniques have some big advantages. First, the suitability of the bottom is not an issue anymore (Toba 2002). Shellfish and seaweeds are also less prone to predation when in the water column. And in many areas their growth and quality increases compared to bottom culture (Toba 2002). Hence, the yield of off-bottom aquaculture can be substantially higher than bottom culturing.

There are also several disadvantages in the use of off-bottom aquaculture. First, fouling is a threat, especially with the use of cages. The growth of fouling organisms on aquaculture structures and the natural products themselves, reduces circulation rates and food and light availability (www.bayosters.com), which hamper growth. An additional disadvantage of shellfish growing outside the intertidal areas, is that they are more brittle than shellfish cultured in the intertidal zone (Toba

2002). Because the animals are less exposed to changing conditions, they develop a brittle shell that breaks easily during transport or opening. The muscles of the animals are also less developed, which may cause them to gape and spoil during transport. To strengthen the shells and the flesh some oyster farmers put their products in the intertidal area before marketing (Toba 2002).
The use of rafts in aquaculture is common around the world (www.fao.org). However, each location has its own culturing and maintenance techniques. How to use tables and rafts in the Southwest delta will therefore be a process of trial and error. For example, Oyster farmers in Chesapeake Bay, Virginia, shake their floating oyster cages and dry them in the sun to avoid fouling and stimulate growth rates. Besides the turning, oysters are transferred to bigger bags with bigger mesh sizes several times during the production process. In winter rafts are sunken to an off-bottom position to avoid high mortality rates associated with ice forming. In general, the maintenance of the products can considerably enhance the quality, but the labour intensiveness is also one of the bigger disadvantages of these techniques (Toba 2002).
The Dutch currently only use long-lines and rafts to collect young bivalves (i.e. spat collectors or mussel seed capture devices) which are subsequently placed on the bottom to grow up . In some sheltered places mussels are cultured to adulthood with off bottom techniques (Kamermans, Bouma et al. 2002). There is no use of fish cages as this technique cannot compete with the production in other countries such as Denmark and Norway.

Habitat contribution and application in coastal defence: The presence of long-lines, rafts and floating cages provide structure in the water column. The structure of long-lines, rafts and floating cages might be compared to the structure found in seaweed meadows or kelp forests and may hence promote the local biodiversity. When this comparison is valid, rafts, long-lines and floating cages may also provide some of the ecosystem processes and services associated with seaweed meadows and kelp forests. The periodically disturbance due to harvesting may however partly counter ecological gains. Compared to ACDS, long-lines, rafts and floating cages are best related to floating jetties and docks. Like these structures long-lines reduce local water flow rates (McKindsey, Archambault et al. 2011). The function of floating structures in coastal defence is still under discussion, as they are mainly used in sheltered areas (Bulleri and Chapman 2010). Heavy weather conditions often lead to damage of floating structures, but experiments are running to make offshore mussel farming possible under the turbulent conditions of the North Sea (Kamermans, Schellekens et al. 2011).

5.3 Poles and tables

Methods: this technique is commonly used in France, but also in the United States. Juvenile shellfish like oysters or mussels are collected on ropes or fished and put in long meshed bags. These are placed as strings on poles or tables to grow to adulthood (board 2011). Strong nets fix the mussels on the poles and protect them for the heaviest weather. After at least one year, the shellfish can be picked by hand or machines (pleinemer.com 2011). Tables are particularly useful in bay areas with extremely muddy bottoms (Toba 2002). The combination of mussels and poles is called the "Bouchot" technique and is well-known from France. Bouchot poles have a plastic skirt at the foot to prevent crabs and predators to predate on the shellfish.
Habitat contribution and application in coastal defence: It is difficult to compare poles and tables to natural habitats. Comparing to ACDS poles and tables best resemble to groynes, sills and jetties.

Figure 16

Bouchot poles

Groynes are used in the Netherlands to prevent erosion of sandy beaches. In the future similar structures might be used as Bouchots to culture mussels or oysters (figure 16). The cultured bivalves on the poles may enlarge the structure of the poles and therefore contribute to wave dissipation. It has been found that Bouchots reduce local flow rates significantly (McKindsey, Archambault et al. 2011), but it is unknown whether the culturing of shellfish on Bouchots is possible in relation to the lower tide regimes and food availability in The Netherlands. Another point of attention is the number of Bouchots needed to make the combination of aquaculture and this kind of coastal protection profitable. Poles and cages are used in moderately exposed to sheltered sites (Bulleri and Chapman 2010).
Tables can only be used as coastal defence under the condition that they are built to withstand heavy weather conditions. They must both dissipate wave action and protect the fixed goods. Possibly the conditions in the Southwest Delta are too rough for the use of tables. Both poles and tables contribute to the environmental heterogeneity and may hence contribute to an increase of biodiversity of fish and invertebrates. Poles and tables may hence also provide some of the ecosystem processes and services associated with coastal vegetation or reef habitats.

6 Integrating aquaculture and coastal defence

To explore possibilities for the combination of coastal defence and aquaculture we combined the knowledge of the previous chapters with information gathered from stakeholder interviews. People interviewed were experts in morphology, aquaculture science, ecology, the current Dutch regional and national policy, and people from the aquaculture sector itself. All participators where asked the same questions (presented in appendix 2), however each conversation was unique, highlighting the different backgrounds of the respondents and the many possibilities for combining aquaculture and coastal defence.
Based on the general interpretation of the interviews and the literature research this chapter first gives an overview of the general conditions for a successful combination of coastal defence and aquaculture. Instead of discussing all possible combinations in which aquaculture and coastal defence can mutually benefit, we focus on four combinations:

1. Long-lines - resembling to the subchapter rafts, long lines and floating cages.
2. Bouchots - resembling to the subchapter poles and tables.
3. Create habitat for lobster farming – ACDS adjustments on very local scales.
4. New sheltered areas for bottom culture – ACDS adjustments on very large scales.

In line with the integrated water management, we review the combinations from an aquaculture, coastal defence and ecology perspective. For each of these combinations a matrix of Strengths, Weaknesses, Opportunities and Threads (SWOT) is presented at the end of each paragraph. Ecology is not included in the SWOT analyses because a connection between coastal defence and ecology is already made in chapter 5.

6.1 General conditions

Most of the respondents are familiar with the idea of combining aquaculture with coastal defence and in general their attitude is optimistic and open. However some respondents point out that the combination of aquaculture and coastal defence may be challenging as aquaculture needs a certain degree of shelter, while coastal defence is most needed at exposed sites (pers. comm. van Stralen, Schot, van Geesbergen and Bouma). As discussed below, others state several important conditions for a profitable combination.
To make a combination of aquaculture and coastal defence gainful, both sectors should benefit from the combination. The aquaculture sector must make profits and some of the current problems with ACDS must be solved. Respondents agreed that subsidies should only be used in the start-up phase and be

redundant in the long term (most respondents). The next paragraphs describe conditions for profitable aquaculture techniques and secure coastal defence.

6.1.1 Profitable aquaculture

Techniques

The bottom culture is currently the most profitable aquaculture in the Southwest Delta (most respondents). But given the need for space and a steady supply of seafood, there are opportunities for rafts, long-lines and floating cages, poles and tables especially in combination with shellfish (most respondents). Fish aquaculture is probably not profitable due to the low marked prices in Norway and Denmark (pers. comm. Jaap Schot).

Need for Shelter

The combination of aquaculture and coastal defence is initially contradictive as aquaculture needs a degree of shelter and coastal defence is most needed at sites that are exposed or eroding (most respondents). This means that the combination is not applicable at all places. A profitable combination will include relatively sheltered places and robust forms of aquaculture (most respondents). Scyphers et al. (2011) also found that an artificial oyster reef initially needs shelter to create rigid and living reefs (Scyphers, Powers et al. 2011). Conditions in the Southwest Delta are probably too rough for the use of tables (Hans van Geesbergen).

Legislation

In order to balance anthropogenic use and nature conservation the Southwest Delta is protected by N2000, the Water Framework Directive, the Marine Strategy Framework Directive and several other legislations. All initiatives in the region must therefore answer to the policy restrictions of the area. An increase of hard substrate will lead to an increase of non-natural substrates in the Southwest Delta of the Netherlands. The presence of new habitats will probably increase the local biodiversity, but hard substrates also enable the introduction of invasive species (Chapman and Underwood 2011). Apart from the negative effects of aquaculture, the presence of suspended and off-bottom mussel culture on local habitats might overall be positive (Forrest, Keeley et al. 2009). As far as we know a study that weights all benefits and losses of such culturing techniques does not yet exist, but it should take into account that aquaculture also creates disturbances during maintenance and harvesting. The disturbance of sediments and fauna may lead to a (temporary) reduced functioning as coastal defence and lowered nature values. Due to the nature values and ecological function of some water basins, the start of new initiatives in the Southwest Delta can be difficult, even if the aim is to combine several uses (most respondents). The local government and the Dutch ministry of Economy, Agriculture and Innovation do however support new initiatives to combine multiple use of the area (pers. comm. Jaap Broodman & Wilbert Schermer Voest).

Experimental phase

Time is needed to make the combination between aquaculture and coastal defence profitable. Growth of products must be optimized while negative influences like fouling and mortality can be minimized (pers. comm. Aard Cornelisse). The most profitable aquaculture is achieved by finding a balance between techniques, species and the local environment (pers. comm. Jaap Schot and Marnix Poelman) and its implementation will therefore be a process of trial and error (pers. comm. (Marnix Poelman en Jaap Schot). Time and experience are crucial in finding the right balance between techniques, organisms and environmental influences.

6.1.2 Secure coastal defence

Strength coastal defence under critical conditions

Coastal defence must be in function under the most critical conditions. Storms push water levels up to 3 meters above the High Astronomical Tide (HAT) (pers. comm. Jaap de Rooij). Mudflats and salt marshes may therefore hamper wave action under normal circumstances, but might be insufficient under the most critical conditions. Additionally, natural coastal defence or aquaculture techniques are subject to natural variations such as seasonal variations in density and biomass (Koch, Barbier et al. 2009). Pest and diseases like oyster drills and Bonamiosis can also temporally reduce the function of natural coastal defence (Scyphers, Powers et al. 2011). We can only use natural coastal defence and aquaculture under the condition that safety is guaranteed under critical conditions. For this reason it is best not to harvest structure providing organisms themselves, but the ecosystem services associated to the natural habitats. Examples are crab and oyster culturing in mangroves, mussels from **B**ouchot poles and lobster fishing with pods. Natural reefs are easier to protect if they cannot be harvested themselves (Scyphers, Powers et al. 2011). Although the constructions of floating structures are getting stronger over time, they do damage during bad weather (pers. comm. Hans van Geesbergen). The use of floating structures will probably be inefficient and must be applied over vast areas to effectively dissipate wave action (pers. comm. Han Winterwerp).

6.2 Combination

6.2.1 Combination 1) Coastal defence for aquaculture: Long-lines

Aquaculture

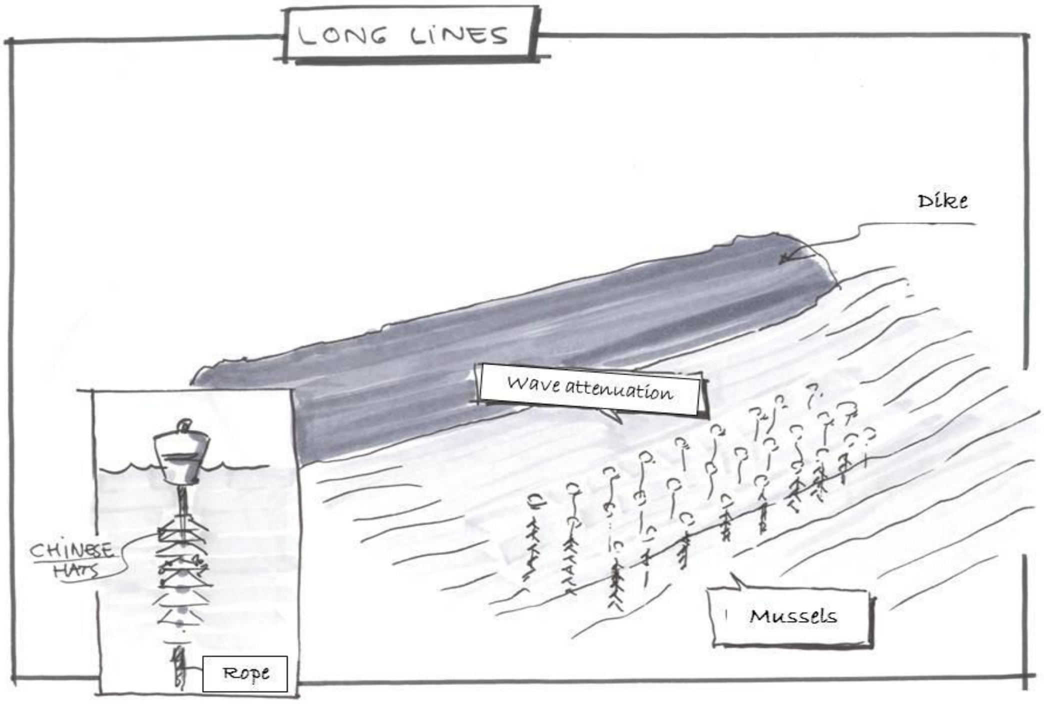
Long-lines are increasingly used in the Southwest Delta to collect mussel seed, instead of fishing for mussel seed from the bed which disturbs the bottom. Although the technique is more expensive than bottom fishing, it provides most of the mussel seed to farmers when the settlement of mussel spat on the bottom is limited (pers. comm. Jaap Schot). The technique hence contributes to a more stable mussel production. Long-lines are occasionally used to grow commercial mussels, but their use needs to be optimized as many adult mussels are lost in the culturing process (pers. comm. Jaap Schot).

Coastal defence

Floating structures must probably be very big and cover extended areas in front of artificial coastal defence structures in order to contribute to coastal defence (pers. comm. Han Winterwerp). It will therefore be difficult to strengthen coastal defence with this aquaculture technique itself. New possibilities arise when long-lines are combined with coastal defence techniques such as beach fills that create shelter (Jaap Shot, Wilbert Schermer Voest, Hans van Geesbergen). In such combination coastal defence would benefit aquaculture.

Ecology

Within the Southwest Delta an increased fish density of sea bass and mullet can be found around the long-lines with young mussels (pers. comm. Jaap Schot). It is unknown whether fish and free moving invertebrates are attracted to the added vertical structure, the presence of the aquacultural product, the associated fauna or a combination of these factors (McKindsey, Archambault et al. 2011). Mussel cultures and their biodeposits have positive effects on epibenthic macrofauna, eutrophication, fish and vagile macroinvertebrates, but may hamper the presence of eelgrass and benthic infauna due to increase biodeposition on the bottom underneath the long-lines causing organic enrichment and possibly anoxic conditions (McKindsey, Archambault et al. 2011).



Artist impression by Joost Fluitsma

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Strengths

<u>Aquaculture</u>

- Displaceable
- Suitable for self-settling species
- shellfish
- Fast growth
- Experience in the Southwest Delta
- High profits per acre

<u>Coastal defence</u>

- Relatively strong structures

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Weaknesses

<u>Aquaculture</u>

- Technique needs optimisation for coastal defence
- Need for relatively sheltered places
- Relatively high maintenance costs
- Fouling
- Weak shell of shellfish

<u>Coastal defence</u>

- Little effect on coastal defence
- High maintenance costs
- Function coastal defence vs. profits

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Opportunities

<u>Aquaculture</u>

- Government supports innovations
- Use highly valuable species
- Avoid diseases by fast growth
- Application on larger scales

<u>Coastal defence</u>

- Connect ropes to solid structures that diminish wave action
- Improve biodiversity
- Integrate with tourism

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Threats

<u>Aquaculture</u>

- Licences and other users
- Profitability
- Loss of products
- Gains biodiversity partly lost by harvesting
- Limited food availability possible for bivalves

<u>Coastal defence</u>

- High costs for structures
- Change of the visual landscape

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6.2.2 Combination 2) Combining aquaculture and coastal defence: Dutch Bouchots

Aquaculture

The bouchot culture is a combination of the mussel aquaculture and groynes. The Bouchot culturing technique has proven to be profitable in France and produces small mussels which are an exclusive delicacy. However, application of the technique in the Southwest Delta is by some stakeholders received with reservation because of concerns about the visual landscape of the Southwest Delta and the risk to loose bivalves with due to the forces of the waves (pers. comm. Jaap schot, Aard Cornelisse, Tjeerd Bouma and Hans van Geesbergen). Others see multiple possibilities to integrate Bouchots with oyster, mussel and seaweed culturing (pers. comm. Marnix van Stralen, Jaap Broodman, Jaap de Rooij and Mindert de Vries). Tidal amplitude, accessibility and damage are main concerns. Still, all respondents point out that trails are needed to find out the profitability of the technique. In 2002 a small scale study (2 bouchots) failed. This was probably due to bad settlement of the mussel spat, predation by birds and/or a short inundation time (Kamermans, Brummelhuis et al. 2004).

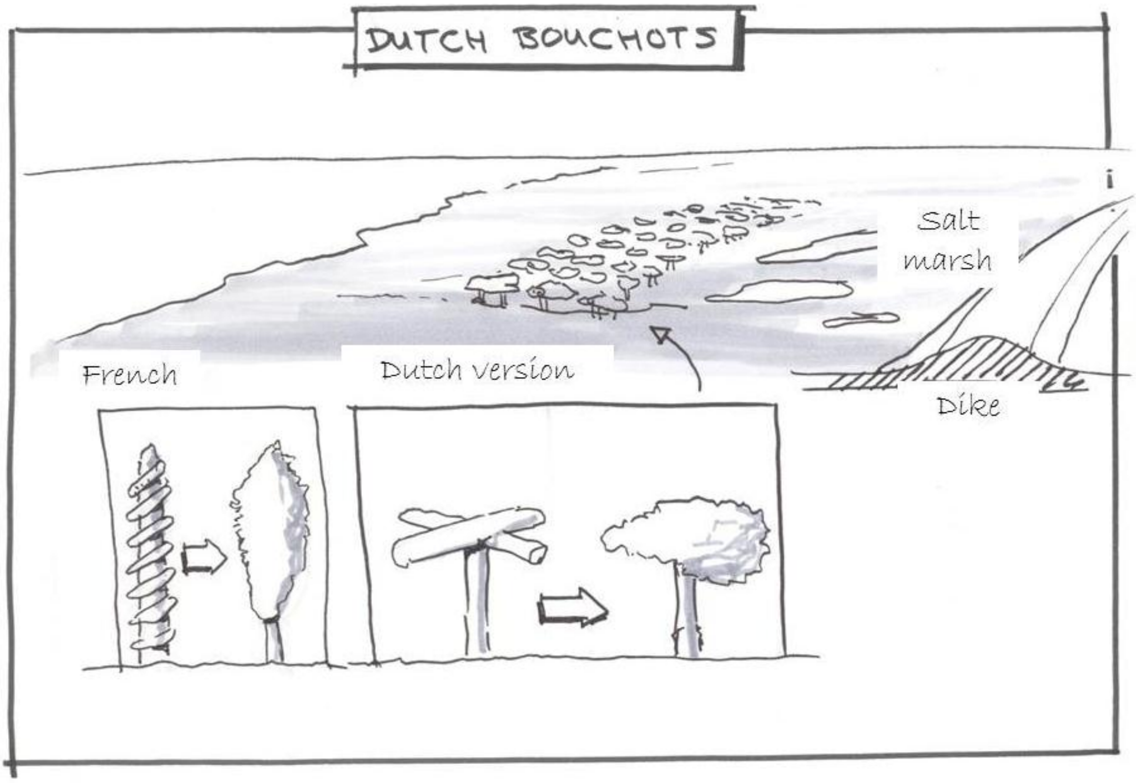
The problem with the marginal tidal amplitude might be circumvented by culturing mussels or oysters on poles with horizontal projecting structures. Because the Southwest Delta is still relatively rough, goods might get lost in stormy weather and harvesting might be too expensive to compete on the market. Accessibility is therefore of main importance (pers. comm. Jaap Schot, Marnix Poelman). The good quality of Bouchot mussels or oysters and expected faster growth rates however, might compensate for higher production costs (pers. comm. Jaap Broodman, Jaap de Rooij). Additionally, the Province of Zeeland suggests to combine new aquaculture techniques with high valued regional products (with certificate) and tourism (pers. comm. Jaap Broodman).

Coastal defence

As Bouchots create drag they can be used at exposed sites to dampen waves and to hamper sediment transport. During ebb tide, currents within fields off Bouchots can be reduced by 25 to 66 % (McKindsey, Archambault et al. 2011). Wave energy may be reduced by 50% and friction coefficients are assumed to be up to ten times higher compared to reference sites (Allard, Bertin et al. 2008; McKindsey, Archambault et al. 2011). The reduction of currents and wave action generally leads to more sheltered areas with increased sedimentation and finer sediments than reference sites (McKindsey, Archambault et al. 2011). Therefore Bouchots can possibly be used to protect more vulnerable aquaculture techniques.

Ecology

Most respondents say that the addition of hard substrate and structures in the water column will benefit local biodiversity.



Artist impression by Joost Fluitsma

Strengths	Weaknesses
Aquaculture	Aquaculture
• Shellfish with strong shells • Higher growth rates (off bottom) • Exclusive delicacy • Gulls can eat predators • The idea seems appealing • Examples abroad • Compatible with other aquaculture techniques like long-lines and rafts • Relatively low maintenance costs	• Harvesting difficult • Need for large tidal amplitude • Shellfish can feed 12 hours a day • Need for sheltered places • Gulls may also eat goods • Loss of goods during bad weather • Function coastal defence vs. profits • Accessibility determines profits • No experience in the Southwest Delta • Relatively small surface • Change of the visual landscape
Coastal defence	Coastal defence
• Strong function in coastal defence	

	• Change in the visual landscape
Opportunities <u>Aquaculture</u> • Make horizontal Bouchots • Government supports innovations • Culturing highly valuable species • Avoid diseases through fast growth • Improve biodiversity • A combination with tourism • Avoid pathogens by faster growth • Alternated harvesting to maintain biodiversity and coastal defence • Fitting iron baskets on poles • Combination with algae • Combination with fishing <u>Coastal defence</u> • Decreasing erosion of sand flats • Harvest poles alternatingly	**Threats** <u>Aquaculture</u> • Accessibility • Freezing in winter • Increased erosion of sand flats • Profitability aquaculture, low yields • Tidal amplitude • Licenses and other users • Predation • Damage goods during harvesting • Some biodiversity lost during harvesting • Limited nutrient availability <u>Coastal defence</u> • Existing poles cultural inheritance • Unknown effect on sand transport • Large scale required to contribute to coastal defence

6.2.3 Combination 3) Coastal defence, aquaculture and ecology: lobster farming

Lobsters are found in relatively high densities in the Southwest Delta. They have a broad diet and live at the rocky substrates or oyster reefs at lower end of dikes. Here they live in the crevices and excavated tunnels (www.marlin.ac.uk)

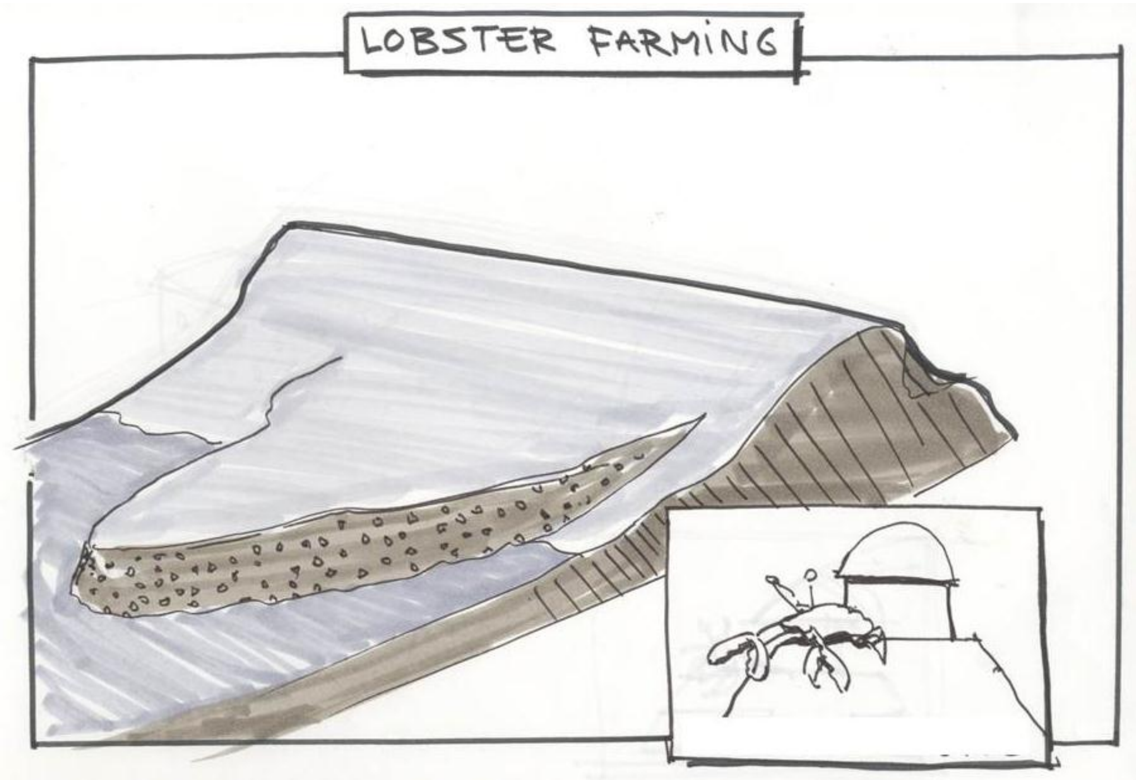
<u>Aquaculture</u>
Only the creation of crevices in artificial coastal defence structures will potentially lead to increased population densities of lobsters. A phenomenon that can be called habitat facilitation. Providing food might increase local production rates, but may also lead to eutrophication which conflicts with nature conservation.

<u>Coastal defence</u>

In this combination coastal defence is used to facilitate aquaculture though habitat facilitation. The disadvantage of such combination is that the financial gains for coastal defence will be marginal in relation to construction costs. The advantage of a combination were coastal defence facilitates aquaculture, is that the design of the ACDS can be optimized to dissipate wave action while some additional profits can be realised by creating new space for aquacultural exploitation. Any kind of coastal defence structure can be built as long as it contains crevices in which lobsters can live.

Ecology

Lobsters are easily caught with pods causing little effects on the ecosystem or the visual landscape. This combination would probably be most beneficial for nature restoration through the attraction of associated fauna. However, the profitability of such aquaculture is not elaborated in this study.



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Strengths

<u>Aquaculture</u>

- Low start-up costs
- Low maintenance costs
- No conflict with nature restoration

<u>Coastal defence</u>

- Aquaculture only dependable on the bottom surface not the coastal defence technique

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Weaknesses

<u>Aquaculture</u>

- Profits maybe limited

<u>Coastal defence</u>

- Coastal defence structures might be comparable to current ACDS
- Maybe no reduction of building costs

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Opportunities

<u>Aquaculture</u>

- Integrate with tourism
- Additional feeding of lobsters possible
- Synergy with nature conservation

<u>Coastal defence</u>

- Combination with natural coastal defence

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Threats

<u>Aquaculture</u>

- High costs for structures
- Lobster fishing during migrations

<u>Coastal defence</u>

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6.2.4 Combination 4) Coastal defence for aquaculture: new sheltered areas

<u>Aquaculture</u>
The creation of sheltered areas in the Southwest Delta or the North Sea will provide new opportunities for the expansion of the commonly used bottom aquaculture. In this combination aquaculture will not be an alternative for the coastal protection itself, but an additional feature that can be incorporated in newly built coastal defence. When situated at the exposed site of the newly created area, aquaculture could contribute to coastal defence, for instance by reducing maintenance costs. When situated at the lee side, conditions might be more favourable for aquaculture, but in this case no contribution to coastal defence is made. According to stakeholders this combination will be most profitable for aquaculture (most respondents). Another advantage is that the techniques for both aquaculture and coastal defence can be similar to currently used techniques.

<u>Coastal defence</u>
The coastal defence will be designed to create lee areas and thus benefit aquaculture. This can be achieved by hard and soft measures. Preferably, the coastal defence will also contain natural habitats that absorb wave action.

Ecology

Whether the ecology will benefit from this combination between aquaculture and coastal defence is questionable and depends on the coastal defence measures taken. When lee areas are created at the expense of subtidal habitats nature is changed. Whether nature values improve is questionable. For instance, while the local biodiversity levels might increase through the presence of physical structures that form abiotic gradients, it will be for the loss existing subtidal habitats. The result is that more land is reclaimed from the sea than we already have, which may have a negative impact on the morphological development of an estuary as a total. We should therefore also think of combinations in areas that are currently reclaimed from the sea (pers. comm. Tjeerd Bouma).

Artist impression by Joost Fluitsma

Strengths	**Weaknesses**
Aquaculture • Cheap culturing method • Applicable at large scales • No hard substrates visible at low tide • Currently applied and profitable Coastal defence • Strong function as coastal defence	Aquaculture • Aquaculture has less function as Coastal defence Coastal defence • Possibly still negative effects ACDS • Building costs expensive
Opportunities	**Threats**
Aquaculture • Creation of new lee areas Coastal defence • Planned beach fillsIslands in the North Sea • Planned adjustments of coastal defence • Incorporate use of natural habitats • Use of bioengineers to create lee areas	Aquaculture • Change in the visual landscape • Limited nutrient availability possible when applied at large scales Coastal defence • Nature conservation

7. Conditions for combining aquaculture and coastal defence

Literature and the interviews revealed that the need to adapt coastal defence to climate change and the need to integrate human activities, create opportunities for the integration of coastal defence and aquaculture. However, the combination itself seems contradictive as coastal defence is often situated/needed at exposed sites while aquaculture calls for more sheltered sites. Conclusively not all locations are suitable for this combination. Yet, all respondents were able to give a new perspective to the matter and brought up new opportunities for the combination of aquaculture and coastal defence. The combination might be viable if:

- coastal defence structures are designed to create relatively sheltered areas in which aquaculture can dissipate remaining wave action (In this example coastal defence mainly contributes to aquaculture).
- coastal defence structures are already situated in relatively sheltered areas.

Apart from this general conditions, the respondents listed several essentials to make the combination between aquaculture and coastal defence applicable and profitable:

Place and Scale

Accessibility and scale are important for making aquaculture profitable (pers. comm. Jaap Schot, Marnix van Stralen, Marnix Poelman en Hans Geesbergen). Some of the respondents thought of islands that create new sheltered areas while others thought of long-lines and Bouchots poles on local sites. Both principles are applicable, but the large scale applications will probably be more profitable for aquaculture. Accessibility determines profitability though the applicability of different harvesting techniques.

Loss of natural values

Aquaculture can be applied in the intertidal area and thereby contribute to the protection of these transition zones between land and sea. The use of aquaculture in coastal defence hence creates opportunities for intertidal nature values and species to hard aquacultural structures (pers. comm. Jaap Schot). However, the increase in intertidal nature values will probably lead to a loss of subtidal area when the aquaculture will be situated at the seaside of ACDS. As some coastal defence will also introduce more hard substrate in the area it is not obvious if the combination will contribute to nature restoration and impacts should be studied (pers. comm. Tjeerd Bouma). Moreover, it may also lead to (visual) homogenisation of landscapes. A possible solution to this problem would be the use of so called "growth lands" (in Dutch: "wisselpolders") for the combination between aquaculture and coastal defence. In grow lands a connection between land and sea is established in such a way that sedimentation takes place in the land areas. After growing in height by natural accretion promoted by bioengineers the area is less prone to flooding (pers. comm. Tjeerd Bouma). When the growth lands remain connected to the sea it may also be used for aquaculture and further accretion of the sediments (De Mesel et al, in prep.).

Negative sand balance & total aquaculture population

One of the main problems of ACDS are the induction of negative sand balances. About half of the respondents thought aquaculture could help to solve this problem. The other half of the respondents pointed out that with aquaculture more hard substrate is brought into the environment and the negative sand balance might be increased.

Another problem with introducing more aquaculture in the Southwest Delta region is its carrying capacity. Nutrients and primary production might not be sufficient to support an unlimited amount of shellfish. Increasing nutrient loads with river runoff might be a solution, but the government aims at nutrient neutral aquaculture systems (pers. comm. Wilbert Schermer-Voest).

Legislation

The Oosterschelde is currently the most profitable place for aquaculture in the Southwest Delta, but the inlet is also a national park in which natural values are strongly safeguarded (N2000 area). Leases for new aquacultural activities might be hard to get and thereby obstruct the development of areas with multiple uses. Even if the use of reefs or other natural habitats in front of ACDS could mitigate losses of fish-, shellfish- and bird habitats. A great opportunity is the planned adjustment of the "Oesterdam" at the Eastern side of the Oosterschelde (respondents). A beach fill is planned at this location. The government is currently looking for ways in which sediments can be fixated for longer times (pers. comm. Mindert de Vries). We suggest that it may be possible to organise a workshop with the respondents of the current study, and look at possibilities for coastal defence and aquaculture.

<u>Willingness to collaborate</u>

In order to combine multiple uses within an area there must be grounds for collaboration. In the long term these grounds will be (mutual) profits, however in the near future the collaboration between scientific research, the aquaculture sector and the government have to be based on the willingness to work together. In the past, there has been severe collisions between governance, nature conservation and fisheries. However, the interviews showed that there is a great willingness to participate in the current project. Many of the respondents emphasized the importance of collaboration and their willingness to discuss and collaborate in future pilot studies. The interviews also revealed that a balance between coastal defence, aquaculture and nature values that optimizes total use of the area, can only be achieved through collaboration. Without collaboration the effort to solve multiple problems may deteriorate the situation. Pilot studies can be a great opportunity to show how policy, nature conservation and exploitation can actually work together.

It is of the utmost importance that the primary aim of managing the area becomes the optimisation of all functions and uses at the appropriate scales. The area must therefore not be destined solely for aquaculture, or coastal defence, or conservation, but as an innovative area in which trade-offs are recognized and defined gains are balanced. It is also clear that in many cases certain combinations will not be possible.

The combination of coastal defence with aquaculture might reduce building and especially maintenance costs for coastal defence and increase the overall profits of aquaculture in the region. However, the combination between aquaculture and coastal defence will not optimize the separate functions of aquaculture, coastal defence or nature values, but rather optimizes overall profits. (for example see figure 17).

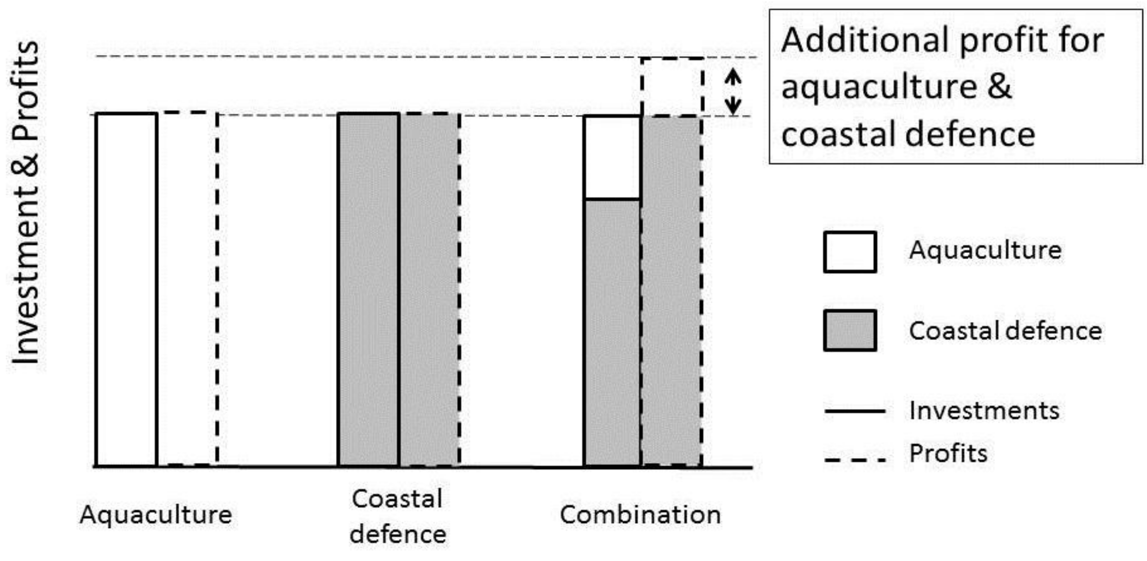

Figure 17) Schematic overview of investments and profits from aquaculture and coastal defence when the two uses are combined. In the columns "Aquaculture" and "Coastal defence" investments of aquaculture and coastal defence are proportional to the profit. When the two are combined ("Combination"), the investments cost for both aquaculture and coastal defence are lower with respect to the profits. This is caused by the effect of aquaculture on wave attenuation or erosion reduction and the design of coastal defence to incorporate aquaculture.
The overall profits for aquaculture and coastal defence increase, however, designing an area for only aquaculture or coastal defence creates more productive applications and more efficient coastal defence respectively. Profits will not be made solely on aquaculture or coastal defence, but on the synergy of their combination.

8. Conclusions

The Southwest Delta region clearly represents the Dutch skills on water management. It is renowned for the unique coastal defence (the Delta works) and at the same time provides supreme shellfish that form a local delicacy. Yet, with the expected sea level rise, negative effects of ACDS and increasing pressures of multiple uses, the current water management approach is challenged. In the future, adverse effects of ACDS must be avoided, building and maintenance costs reduced and opportunities created to combine nature (i.e. ecologically resilient) and economy (i.e. economically vital). Accordingly, we looked if infrastructure coastal defence can be built to meet engineering requirements, while incorporating the use in aquaculture and natural habitats. In other words, are there viable combinations of coastal defence and aquaculture?
We verified whether a combination between aquaculture and coastal defence provides gains for both sectors in the Southwest Delta. This qualitative study shows that there are difficulties related to shelter, regulations and accessibility. The combination of aquaculture and coastal defence is therefore not applicable in all areas. Still, the literature study and interviews reveal many opportunities and good potential, when combinations are customized to the local natural, economic and political environment. For this reason, and to find the right balance between locations, species and techniques, long-term pilot studies should be executed. These will reveal the quantitative benefits of different combinations. Crucial in these studies is the participation, commitment and planning of stakeholders for their local knowledge.
The four combinations in this report reveal that combining aquaculture and costal defence has potential benefits for both sectors. It also appears that different aquaculture and coastal defence strategies can be integrated at small and large scales. Of the four combinations in this report, the combinations where coastal defence facilitates aquaculture will probably be the easiest to implement and most profitable. However, in areas are more sheltered aquaculture may reduce maintenance costs of coastal defence structures by reducing current velocities and by dissipating wave energy under average weather conditions. Local delicacies, recreation and tourism are opportunities to make combinations more profitable. An example are Dutch Bouchot mussels combined with fishing and diving. Last, but of utmost importance, is the willingness of policy makers, researchers, and the aquaculture sector to explore and test further applications in an interdisciplinary way.

We therefore conclude that:

1) This study gives a qualitative description of the possibilities to combine coastal defence with shellfish aquaculture, and which perspectives they might offer for each other. Many questions remain, but potential benefits for both have been identified. After pilot studies and fine tuning, specific combinations between aquaculture and coastal defence may be possible in coastal and estuarine areas.
2) For a profitable combination it is essential to acknowledge the trade-offs between gains for coastal defence and gains for aquaculture and in some areas nature conservation. Aquaculture most likely can profit more from (new) infrastructural defence structures than vice versa. The

added value of aquaculture or other services like nature values to coastal defence structures might contribute to a more cost-efficient and socially accepted shoreline management.

3) Implementation of combinations between aquaculture and coastal defence can only be achieved through collaboration between policy makers, researchers, and especially the aquaculture sector with their practical experience.

For further research on the combination of coastal defence and aquaculture within the Building with Nature programme we advise to organise a series of workshops in which real word coastal defence projects are being evaluated on the potential benefits of adding other services like shellfish aquaculture. From this, pilot experiments should be set up. Because all applications will be site and species specific, participators should visualize their own interpretation on the combination of aquaculture and coastal defence.

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Figures

Figures front page: see references to figure 3, 13 and 14.

Figure 1: Schematic overview based on Dutch Deltaplan
Figure 2: Schematic overview of the Southwest delta
Figure 3: Dutch salt marsh meadow. Photo by: Oscar Bos
Figure 4: Schematic overview of coastal squeeze. Source: www.eloisegroup.org
Figure 5: Picture of a Dutch mudflat. Photo by: Oscar Bos
Figure 6: Oyster reef in the Oosterschelde. Photo by: Brenda Walles
Figure 7: Planted mangroves. Source: www.carbonsimplicity.com.au
Figure 8: Beach fill. Source: www.oceancitysurfreport.com
Figure 9: Sills protecting the vegetation. Source: www.ccrm.vims.edu/livingshorelines/
Figure 10: Groins against longshore sediment transport. Source: http://s0.geograph.org.uk/geophotos/
Figure 11: Breakwaters and pocket beaches:
Source: http://golearngeo.files.wordpress.com/2010/08/breakwaters.jpg
Figure 12: Sloped structures. Photo by: Christiaan van Sluis
Figure 13: Sea wall. Source: http://www.eriding.net/geography/lpp.shtml
Figure 14: Common Dutch mussel vessel. Source: www.stichtingwad.nl
Figure 15: Floating rafts. Source: http://www.jmarior.net/wp-images/bateas-ria-de-vigo2.jpg
Figure 16: Bouchot poles. Source: www.fr.wikipedia.org
Figure 17: Schematic overview of investments and profits. Source: self-made

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Appendixes

<u>Appendix 1:</u> Respondents stakeholder analysis:

Tjeerd Bouma:	Senior researcher Spatial Ecology at NIOZ Yerseke
Jaap Broodman:	Senior policy advisor fisheries and aquaculture at Province Zeeland
Aard Cornelisse:	Oyster farmer in the Oosterschelde and Grevelingen.
Hans van Geesbergen:	Secretary “PO Mosselcultuur”
Marnix Poelman:	Researcher and advisor on sustainable shellfish aquaculture at IMARES and Co coordinator of “kenniskring oesterkweek”
Jaap de Rooij:	Secretary “Oester vereniging”
Wilbert Schermer Voest:	Senior policy advisor coastal fisheries and shellfish aquaculture at the ministry of Economic affairs, Agriculture and innovation
Jaap Schot:	Mussel farmer at Zierikzee.
Marnix van Stralen:	Senior researcher and policy advisor in the shellfish industry at Marinx
Mindert de Vries:	Lector at the department Building with Living Nature and coordinating lector at the Delta Academy of Hogeschool Zeeland.
Han Winterwerp:	Senior morphology researcher and advisor at Deltares and Delft University of Technology, The Netherlands

Appendix 2

Inquiry form on combining aquaculture and coastal defence. The inquiry form was made before the first interview so that the same questions are posed to all respondents. While many respondents agreed on several questions, it was clear that each had his own experiences and all interviews where unique.

Inquiry form

Aquaculture and Coastal defence

Background: for different aquaculture techniques structures are used that may dissipate wave attenuation. Aquaculture may hence potentially contribute to coastal defence. Examples of these structures are poles, tables and long-lines. To withstand the forces associated with climate change and sea level rise, the Dutch coastal defence must be strengthened in the coming years. The team of Building with Nature wonders if aquaculture can contribute to coastal defence. Would it be mutual beneficial by cutting building costs for coastal defence and creating new opportunities for aquaculture?

Questions:

Could you shortly describe your background?

What was your first impression when you heard about combining aquaculture with coastal defence?

Do you think there are combinations possible in the Southwest Delta?

Yes / No Why / Why not?

Could a combination be profitable?

Yes / No Why / Why not?

Which species that are currently used in aquaculture can contribute to coastal defence without additional structes?

Which other species can be cultured on structures that contribute to coastal defence?

Could you indicate the advantages and the disadvantages of the previously listed species for the use in coastal defence?

Species	Aquaculture technique	Advantage	Disadvantage

-	- Rafts	-	-
-	- Long lines	-	-
-	- Poles	-	-
-	-	-	-
-	-	-	-

Could aquaculture be executed within older artificial oyster or mussel reefs?

Yes / No Why / Why not?

Could aquaculture products be harvested from artificial hard structures?

Yes / No Why / Why not?

Under which circumstances is the combination between aquaculture and coastal defence the least labour intensive?

Do you think that using aquaculture in coastal defence could counter the problem of negative sand balances in the Oosterschelde?

Yes / No Why / Why not?

Do you think that the combination between aquaculture and coastal defence could also benefit the ecologic value of an area?

Yes / No Why / Why not?

Do you think that the use of aquaculture in coastal defence has a future?

Yes / No Why / Why not?

If there would be a pilot study how would you design it?

Please describe:

- Species used
- Aquaculture techniques used
- The optimal location

Last but not least, what are the most important bottlenecks for the implementation of using aquaculture in coastal defence?

Justification

Rapport C191/11
Project Number: 4306111026

The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Drs. P. Kamerman
Researcher

Signature:

Date: 30 November 2012

Approved: Dr. B.D. Dauwe
Head of department Delta

Signature:

Date: 30 November 2012