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Inventory of potential shellfish species and design of conceptual filtration systems

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Wageningen University &
Research Report C078/17

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Publication date: 4 October 2017

Wageningen Marine Research
Yerseke, October 2017

Wageningen Marine Research report C078/17

J.W.M. Wijsman and A.C. Smaal, 2017. *The use of shellfish for pre-filtration* of marine intake water in a reverse electro dialysis energy plant*; Inventory of potential shellfish species and* design of conceptual filtration system. Wageningen, Wageningen Marine Research (University & Research centre), Wageningen Marine Research reportC078/17. 31 pp

Keywords: Renewable Energy, Mussels, Pacific oysters, modelling.

Clients: Waddenfonds
Provincie Fryslân
Rijksbijdrage Ambities Afsluitdijk (Astmafonds)

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https://doi.org/10.18174/424555

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Contents

Summary

In a reverse electro dialysis (RED) power is produced from the chemical potential difference between salt- and freshwater using ion-selective membranes. In order to make a RED plant commercially feasible, huge amounts of salt- and freshwater are needed. At the Afsluitdijk, salt water can be derived from the Wadden Sea and freshwater can be derived from Lake IJssel. The water from the Wadden Sea, however, contains high concentrations of suspended particles (on average ca 50 g l^{-1}). These particles adversely affect the efficiency of the plant and need to be removed from the water before it enters the membrane stacks. In this report the possibilities to pre-filter the water with shellfish is explored based on literature and model calculations.

Shellfish are effective filter feeders that filter organic and inorganic particles larger than 2 - 5 µm from the water with their gills. Clearance rates are species specific and depend on the size of the organism, temperature and water quality. Blue mussels and Pacific oysters have high clearance rates and depending on the size, one mussel or oyster can filter between 2 to 8 litre of water per hour. The inorganic particles that are filtered by the shellfish are excreted as faeces or pseudofaeces and deposited.

Two configurations have been studied for the pre-filtration of Wadden Sea water with shellfish by model simulations. A flume system filled with shellfish where a continuous water flow enters the flume a one side and leaves the flume at the other side. The other system consists of a series of coupled tanks filled with shellfish. Both systems show comparable filtration efficiencies. With the models, is it shown that mussels and Pacific oysters are more efficient to filter the suspended particles from the water than European oysters and cockles. The smaller the shellfish, the higher the filtration rates for a certain biomass.

The model simulations show that a filtration efficiency of 100% by shellfish only is not realistic. This is because the shellfish need to have a certain amount of food (algae) in the water to survive. Additional (mechanical) filtration, therefore, is essential. A filtration efficiency of 50% is feasible. However, since large amounts of Wadden Sea water is needed, large amounts of suspended sediment will be produced by the shellfish. For a 1 MW plant, more than 4 tons sediment needs to be removed out of the water. Assuming half of that will be filtered by the shellfish, more than 2 tons needs to be removed from the shellfish filtration system. This has to be taken into account in the design of the filtration systems. Moreover, large amounts of shellfish are needed. For a 1 MW plant half a million Pacific oysters are needed to filter 50% of the suspended particles from the water. It has to be studied whether the conditions within the filtration systems are good enough for the shellfish to survive for a longer time and eventually to grow.

Probably mussels from the seed mussel collectors (MZI's) in the Wadden Sea are a good option to be used in the filtration systems. The small mussels have a relatively high filtration rate. If the conditions within the filtration system can be controlled in such a way that the survival of the mussels is higher than on the culture plots in the Wadden Sea, the mussels can be sold back to the mussel farmers the next year to be seeded at their culture plots.

In the next phase (WP3) of this project, an experimental set-up will be made with a flume and/or coupled tank system. Measurements will be done to verify the model calculations and to monitor the quality of the shellfish within the system.

1 Introduction

1.1 Project environmental effects Blue Energy

The term Blue Energy is used for energy derived from the salinity difference between fresh water and salt water. The main and best investigated techniques are pressure-retarded osmosis (PRO) and reverse electro dialysis (RED) (Boon and Van Roij, 2011). In 2014, a test site for a 50 kW reverse electrodialysis plant was built on the Afsluitdijk in the Netherlands. This plant uses salt water from the Wadden Sea and an equal amount of fresh water from Lake IJssel. The brackish process water, with a salinity of about 15 ppt is discharged into the Wadden Sea.

For commercial purposes the plant should be scaled-up to about 100 MW, requiring large amounts of water from lake IJssel and the Wadden Sea. During discussions with stakeholders, a number of potential environmental effects have been identified such as removal of pelagic organisms (algae, zooplankton, (jelly)fish), inorganic suspended particles, changes in current patterns in the Wadden Sea and a change in salinity gradients.

In order to study the environmental effects of a Blue Energy plant in the Afsluitdijk, the project environmental effects of Blue Energy, was initiated in 2016. The project is funded by the Waddenfonds, the province of Friesland and Rijksbijdrage Ambities Afsluitdijk. The project is subdivided in 6 workpackages:

- WP1: Inventory study on the potential effects of a Blue Energy plant on the marine environment
- WP2: Monitoring of organisms
- WP3: Pre-filtration of the salt water by shellfish
- WP4: Effects of scaling-up
- WP5: Communication
- WP6: Coordination

This report is a product of task 1.4 (inventory of possibilities of pre-filtration of the marine water from the Wadden Sea with shellfish) within WP1. The results of this study will be used in WP3, where a filtration system with shellfish will be constructed and tested on the site.

1.2 Reverse electro dialysis

Reverse electro dialysis is a technique to retrieve energy from the difference in salt concentration between seawater and freshwater (Weinstein and Leitz, 1976; Post e.a., 2008). A reverse electro dialysis system uses ion-exchange membranes to separate salt from seawater and controls the mixing of ions between the solutions. One type of membrane allows positive charged ions to pass (cation-exchange membrane) and the other allows negatively charged ions to pass (anion-exchange membrane). Salt water and freshwater are led through a stack of alternating cation and anion exchange membranes (Figure 1). The chemical potential difference between salt- and freshwater generates a voltage over each membranes, and the total potential of the system is the sum of the potential differences over all membranes. Stacking cells with alternating anion and cation exchange membranes create a system that is capable of generating high voltages.

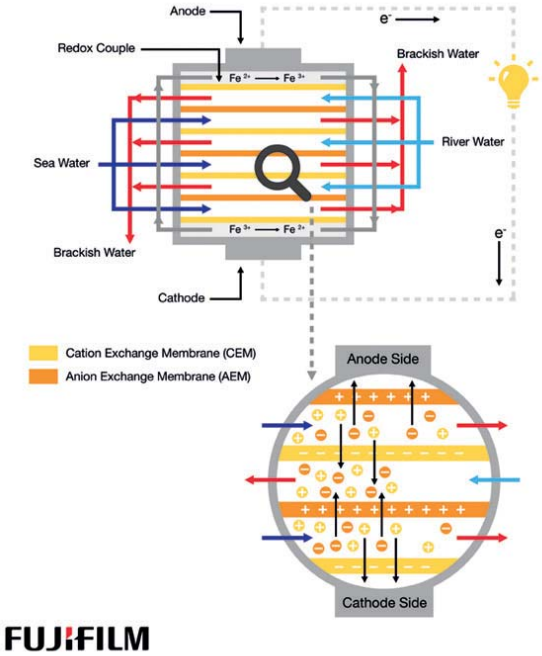


Figure 1: Schematic overview of Reverse Electro Dialysis (RED, www.fujifilmmembranes.com).

1.3 Problem definition

The water from the Wadden Sea is full of inorganic and organic particles. These particles adversely affect the efficiency of the RED process by clogging to the membranes. Presently a pre-filtration of the water is achieved with drum filters with a mesh size of 20-25 µm. Particles smaller than 20 µm (silt, bacteria, phytoplankton) will not be retained on the drum filter and will pass to the RED systems.

Shellfish can affectively filter particles down to a size of 2-5 µm from the water with their gills and can therefore be used to pre-filter the water. The questions to be answered in this inventory study are:

1. Can shellfish be used to pre-filter the water?
2. Which shellfish species can be used?
3. How many shellfish are needed for pre-filtration of the water from the Wadden Sea?
4. How should a pre-filtration system with shellfish be constructed?

1.4 Approach

This report is the result of a literature study in combination with modelling exercises. From literature, information on clearance rates are derived for different shellfish species. This literature information is used to construct models for pre-filtration of water using shellfish. With these models, various designs are evaluated on filtration efficiency. Also sensitivity analyses were run to study the sensitivity of the model to the different input parameters. The models are used to calculate the required dimensions of a shellfish filtration system for different production values of a RED power plant.

1.5 Acknowledgments

Peter Herman, Rik Siebers, Lodewijk van Walraven and Zwanette Jager are acknowledged for their comments to an earlier version of this report.

2 Shellfish filtration

2.1 Filter feeding

Suspension-feeding lamellibranchiate bivalves pump water over their gills by the activity of the lateral cilia of their gills which creates the water flow. The pumping rate is actively controlled by the asynchronous beating of lateral cilia on gill filaments. This creates a water current, which flows into the inhalant siphon, through the spaces between the gill filaments and then out of the exhalent siphon. The effective pumping rate is determined by the autonomous activity of the lateral cilia and the various musculature that affects the shell gape, the exhaling siphon area and the interfilamentary distance of the gill (Riisgård, 2001a; Cranford e.a., 2011). Bivalves like the blue mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) are non-selective filter-feeders, meaning they do not discriminate between individual food particles. They feed by actively filtering particles from the water (for reviews, see Jørgensen, 1996; Cranford e.a., 2011), which passes into and out of the mantle cavity through the frilled siphons (Figure 2, Figure 3 and Figure 4). The gills retain all particles greater than 2 – 5 μm with 100% efficiency (Vahl, 1972; Bayne e.a., 1977) and the filtered material is then transferred to the food grooves (ciliary tracts) on the gills and on to the labial palps (Figure 2). The function of the labial palps is the continuous removal of materials from the lamellar food tracts, whether to be ingested as food or to be rejected as pseudofaeces (Foster-Smith, 1974). Respiration simultaneously occurs as this stream of water passes over the mussels' gills (Figure 4 A). Phytoplankton cells both living and dead, constitute the main source of food, but other sources of carbon such as decomposed macrophytes or resuspended detritus may also supplement their diet. Pseudofaeces can comprise inorganic matter, such as silt, or excess (non-digested) phytoplankton cells, egested under high cell concentrations (e.g. ~>8.5x 10^3 cells ml^{-1} (*Rhodomonas* sp.) or under increased silt concentrations (Clausen and Riisgård, 1996).

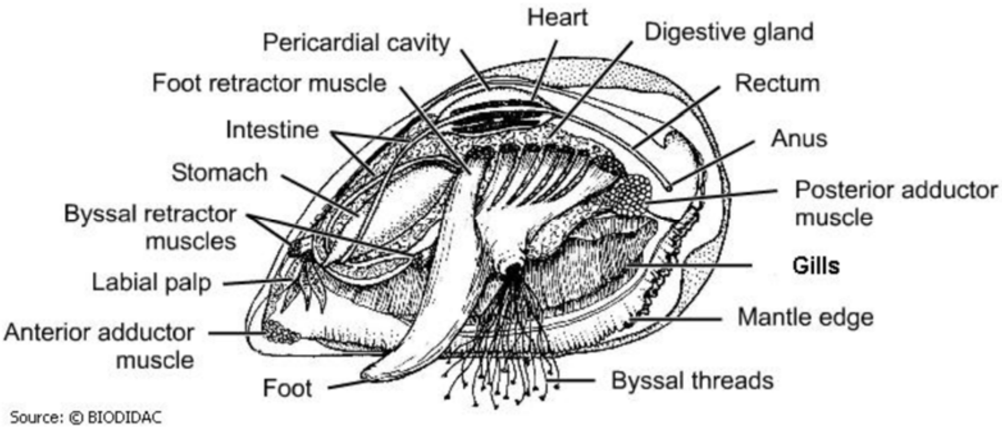


Figure 2: Major internal anatomical features of blue mussel (Mytilus edulis) (Source: BIODIDAC)

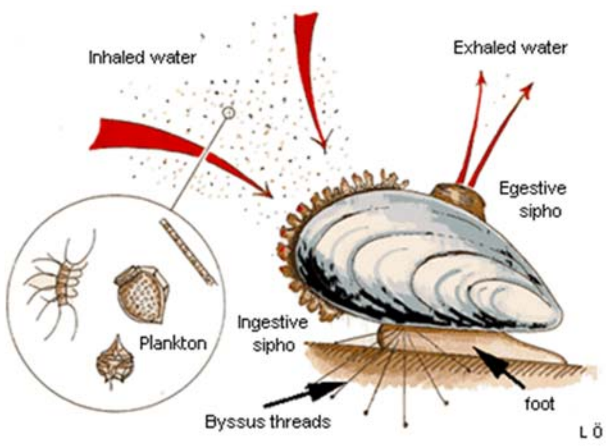


Figure 3: *Filtration by a mussel.*

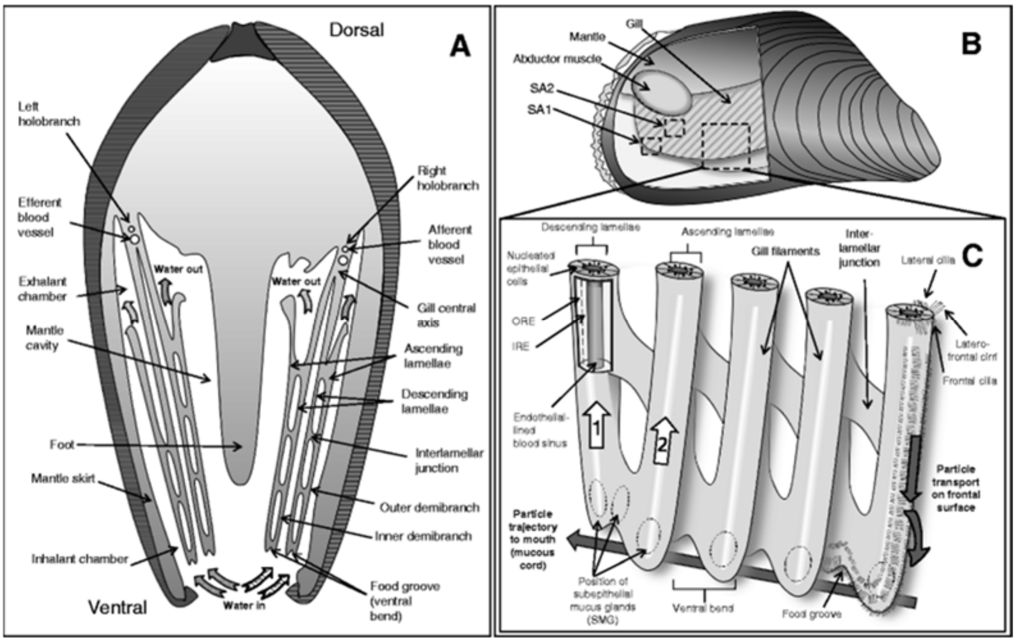


Figure 4: *Schematic representations of the gill morphology of M. edulis. A: cross section (posterior view). B: lateral view from the right side. Part of the right valve and mantle has been removed to reveal the right holobranch. C: detail view of the outer demibranch (Rivera-Ingraham e.a., 2016).*

Mussels have shown the ability to adapt their palp size to variable total particulate matter (TPM) concentrations (Essink, 1999). Furthermore, *M. edulis* can adapt its filtration and ingestion rate to the particle concentration (Clausen and Riisgård, 1996) and particle size (Strohmeier e.a., 2012) in the water. At very low particle concentrations (< 0.25 mg l^{-1}), all suspended material (> 2 - 5 μm diameter) is filtered by the gill, ingested through the mouth and transported to the digestive gland for digestion (Thompson and Bayne, 1974; Widdows, 1978). As the seston concentration increases, the digestive gland cannot digest and assimilate all the material entering the stomach. Such excess material, after bypassing the digestive gland, is transported through the gut undigested and rejected as intestinal faeces (Vanweel, 1961; Bayne e.a., 1993). The ratio of intestinal to glandular faeces, therefore, increases with increasing ingestion rate (mg h^{-1}), which is reflected in a decline in assimilation efficiency (Thompson and Bayne, 1974; Widdows, 1978). Ingestion rate increases with increasing particle concentration and organic matter content (Bayne e.a., 1993) until a threshold (~4 mg l^{-1}, value is dependent on body size) is reached, above which further material filtered by the gills is carried away from the mouth by rejection tracts on the labial palps and deposited as pseudofaeces (Thompson and Bayne, 1974). The amount of pseudofaeces produced can range from zero at 3 mg l^{-1} to about 40% at seston concentrations of ~6-10 mg l^{-1} for low organic content (~0.75 mg l^{-1}) (Bayne e.a., 1993). It has been shown that for an average mussel of 3 cm of length, the maximum filtration occurs at TPM-concentrations of ~125 mg l^{-1}. At ~225 mg l^{-1}, the filtering capacity decreases to ~30% and ceased at a TPM concentration of ~250 mg l^{-1} (Widdows e.a., 1979). More recent studies did not test the effect of such high TPM concentrations on mussels, however, Bayne e.a. (1993) showed that TPM concentration above the critical value of 4 mg l^{-1} resulted in an increased rejection (pseudofaeces production) with time (Table 1).

Table 1: Pseudofaeces production (expressed as % rejection) for mussels (4-5 cm) in 3 experiments (CI, CII and CIII (Bayne e.a., 1993))

Experiment	Seston concentration (mg l^{-1})	% rejection at 2 d	% rejection at 12 d
CI	4.57	19.3	49.6
CII	4.14	25.2	48.9
CIII	4.93	31.7	38.9

For Pacific oysters, similar values as for mussels are observed. In filtration experiments with pacific oysters from the Bay of Marennes-Oléron in France, it was shown that, filtration rate was reduced at TPM levels higher than 150 mg l^{-1} (Barillé e.a., 1997).

The selection efficiency, i.e. the efficiency with which filtered material is sorted in organic and inorganic fractions prior to ingestion, is shown to decrease under increasing organic content of the seston. The absorption efficiency, the efficiency by which the organic fraction of ingested material is absorbed by the animal, increases with the increase in concentration of particulate organic matter (POM) (Bayne e.a., 1993).

2.2 Clearance rates

Pumping rate (PR, l h^{-1}) increases with the size of the gill, which is proportional to the square of the shell length (L^2). Tissue dry weight (W, g) is proportional to L^3, so pumping rate can be expected to scale with $W^{2/3}$. Pumping rates of bivalves show often an allometric relation with body size (Jørgensen and Marais, 1990).

$$PR = a \cdot W^b$$

where *a* and *b* are fitted parameters. The allometric exponent (b) describes how fast the rate increases relative to body size.

Clearance rate (CR; l h^{-1}) is a more generally used measure of water processing and is defined as the volume of water cleared of particles per unit time. Clearance and pumping rates are equal if all particles in the inhalant current are removed from suspension. Small particles (<2 µm diameter are not effectively retained by most species. Therefore, clearance rates should be measured for a particle size that is retained by the species with 100% efficiency. Clearance rates can be measured indirectly by measuring changes in particle concentrations due to the suspension feeding activity of bivalves.

Under laboratory conditions, at optimal food concentrations, the valves of the bivalves are fully open and maximum clearance rates can be measured. Generic maximum clearance rates (Figure 5) have been calculated by Cranford e.a. (2011) based on data from 13 bivalve species summarized by Riisgård (2001b). This resulted in the following average relationships for the maximum clearance rate and dry tissue weight (W, g) and shell length (L, mm) respectively.

$$CR_{max} = 6.54 \cdot W^{0.72}$$

$$CR_{max} = 0.0036 \cdot L^{1.60}$$

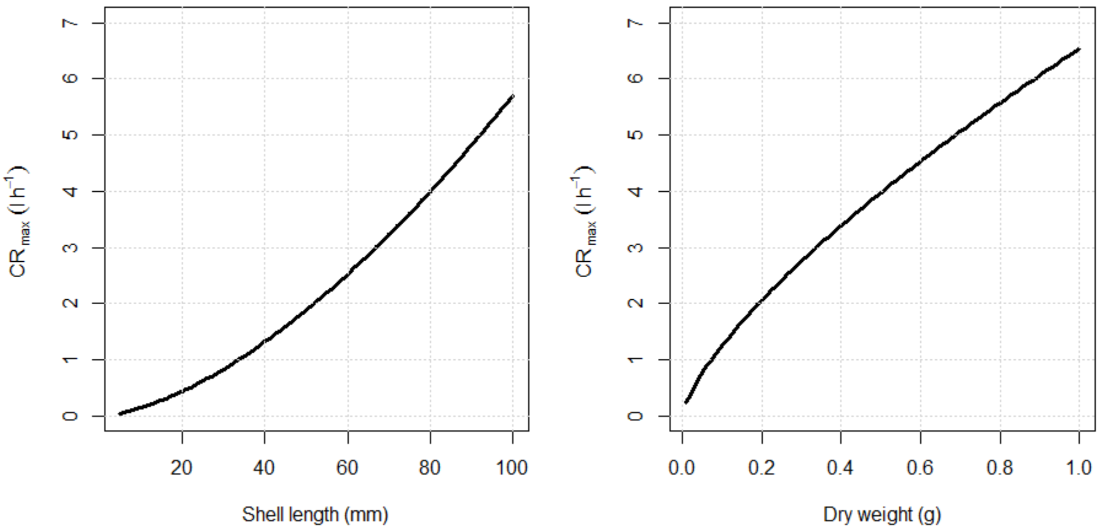


Figure 5: Average maximum clearance rate (CR_{max}) as a function of shell length (mm) and dry tissue weight (g). Relation is based on 13 bivalve species.

The water pumping and clearance rate may be actively controlled (Cranford e.a., 2011) by changing the activity of the lateral cilia of the gill that create the water flow, and by controlling various musculature that affects the shell gape, exhalent siphon area and interfilamentary distance of the gill of shellfish.

Cranford e.a. (2011) give an overview of measured clearance and pumping rates for 21 bivalve species. There is quite some variance in parameters between the different studies. For *M. edulis* for example, the calculated values for parameter *a* range from 1.57 to 1.98 and for parameter *b* they range from 0.38 to 0.70 (Table 2).

Table 2: Allometric relation between clearance rate (CR) or pumping (PR) rate (l h^{-1}) and dry tissue weight (g) (adapted from Cranford e.a., 2011). Relations are plotted in Figure 6.

Species and reference	Size	T (°C)	Weight relationship
Cerastoderma edule			
Smaal e.a. (1986)	-	9.5-15	$CR = 2.59 \pm 0.12 \cdot W^{0.51\pm0.02}$
Smaal e.a. (1997)	0.03-1.4 g	1.4-18.5	$CR = 1.44 \cdot W^{0.69}$
Newell and Bayne (1980)	10-40 mm		$CR = 0.60 \cdot W^{0.51}$
Crassostrea gigas			
Bougrier e.a. (1995a)	0.1-3.0 g	5-25	$CR = 3.92 \pm 0.84 \cdot W^{0.50\pm0.17}$
Gerdes (1983)	0.05-0.81 g	20	$CR = 2.28 \cdot W^{0.73}$
Mytilus edulis			
Jones e.a. (1992)	0.01-2.1 g	10-12	$PR = 1.78 \cdot W^{0.70}$ $PR = 0.0024 \cdot L^{2.19}$*
Smaal e.a. (1997)	0.02-3.9 g	0.4-19	$CR = 1.66 \pm 0.55 \cdot W^{0.57\pm0.17}$
Thompson (1984)	0.07-4.2 g	0-15	$CR = 1.73 \pm 0.19 \cdot W^{0.41\pm0.08}$
Smaal e.a. (1986)	0.01-1.17 g	9-15	$CR = 1.65 \pm 0.79 \cdot W^{0.61\pm0.20}$
Widdows (1978)	0.01-2.4 g	15	$CR = 2.65 \cdot W^{0.38}$
Bayne and Widdows (1978)	0.15-2.9 g	7-21	$CR = 1.98 \pm 0.49 \cdot W^{0.45\pm0.24}$
Bayne and Widdows (1978)	0.13-2.8 g	10-17	$CR = 1.57 \pm 0.36 \cdot W^{0.47\pm0.11}$
Ostrea edulis			
Haure e.a. (1998)	0.1-2.7 g	10-30	$CR = 1.38 \pm 1.15 \cdot W^{0.83\pm0.07}$

* shell length (mm)

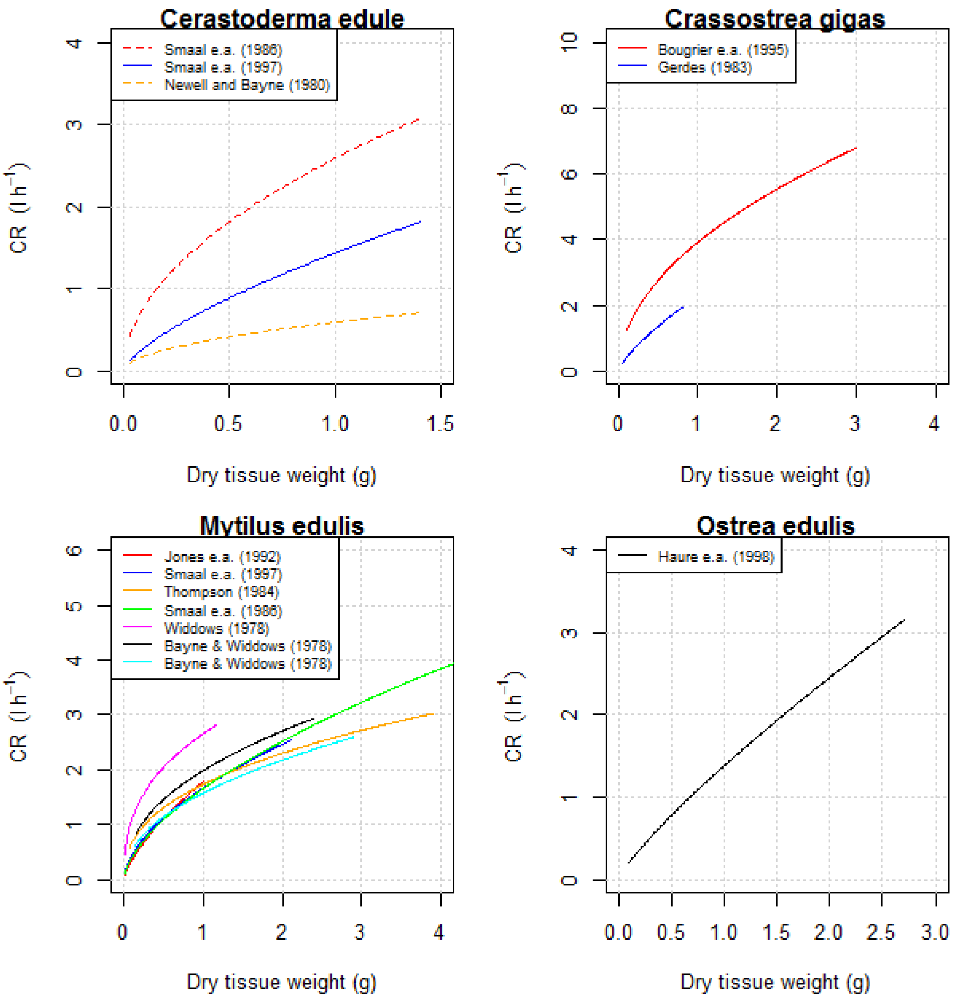


Figure 6: Clearance rates versus tissue dry weight for four different shellfish species, Cerastoderma edule, Crassostrea gigas, Mytilus edulis and Ostrea edulis. Curves are based on relations from Table 2. Broken lines are relations where no size range is given.

The relations from Table 2 are plotted in Figure 6. For the blue mussel (*M. edulis*), there is not much variation between the different relations. Only Widdows (1978) estimate higher clearance rates. The variation in clearance rates for cockles seem to have a large variation. Highest clearance rates are found for Pacific oysters (*Crassostrea gigas*) with filtration rates of more than 6 l hr^{-1} for individual oysters of 2.5 g dry tissue weight. Mussels and European oysters (*Ostrea edulis*) at comparable dry tissue weight filter about 3 l hr^{-1}. The clearance rates of cockles (*Cerastoderma edule*) are lower, but also the size in terms of tissue dry weight is lower.

The filtration rates presented in Table 2 and Figure 6, might be an underestimation of the true filtration rates since many of the data come from measurements in filtration chambers (Cranford, 2001; Riisgård, 2001b; c). In those filtration chambers, small particles might not be 100% efficiently retained by the gills, or due to insufficient mixing the exhalent water might become part of the inhalant water.

The filtration rate of shellfish is depending on the water temperature. In general the filtration rate increases with temperature up till an optimum (Bougrier e.a., 1995b). As a consequence the clearance rates during winter time will be lower than during summer time.

For this study we have selected one relations from Table 2 for each species. The selection was based on the number of individuals and the size range of the shellfish that was used in the experiments. The relationship between individual clearance rates and tissue dry weight that was used in this study are:

Cockle: $CR = 1.44 \cdot W^{0.69}$
Pacific oyster: $CR = 3.92 \cdot W^{0.50}$
Blue Mussel: $CR = 1.66 \cdot W^{0.57}$
European oyster: $CR = 1.38 \cdot W^{0.83}$

The tissue dry weight (W, g) can be calculated from fresh weight (FW, g, including shell) using the following conversion factors:

Cockle: $\frac{\mathrm{W}}{\mathrm{FW}} = 0.03$ (Data Oosterschelde used in Troost e.a., 2010)
Pacific oyster: $\frac{\mathrm{W}}{\mathrm{FW}} = 0.02$ (Data Hogeschool Zeeland (HZ), commercial oysters Kats))
Blue Mussel: $\frac{\mathrm{W}}{\mathrm{FW}} = 0.066$ (data Brey, 2001. Population dynamics in benthic invertebrates (http://www.thomas-brey.de/science/virtualhandbook/navlog/))
European oyster: $\frac{\mathrm{W}}{\mathrm{FW}} = 0.02$ (Same as Pacific oysters)

2.3 Pseudofaeces production

Filter feeding shellfish do not only filter algae out of the water with their gills, but also inorganic suspended particles are retained. Organic-rich particles are selectively ingested and inorganic particles are preferentially rejected by the mussels with pseudofaeces. High concentrations of inorganic particles have negative effects on the food uptake rates by food dilution and pseudofaeces production. Mussels and oysters can efficiently counteract the food diluting effect of suspended particulate matter by selective sorting of particles, by increasing their clearance and ingestion rates, by utilizing food attached to the silt and/or by achieving a higher utilization of ingested algae (Kiørboe e.a., 1980). Pseudofaeces can comprise inorganic matter, such as silt, or excess phytoplankton cells. The rate of pseudofaeces production increases with the concentration of inorganic particles in the water (Widdows e.a., 1979), but also at high algae concentrations, the excess algae are egested as pseudofaeces (Riisgård e.a., 2011).

The sinking velocity of faeces and pseudofaeces is dependent on the size of the particles. Sinking velocities for faeces from mussels are about 0.6 cm sec^{-1}. Sinking velocities for pseudofaeces from mussels are higher, and reach about 1 cm s^{-1} (De Mesel e.a., 2008).

3 Model approach shellfish filtration

3.1 Models for shellfish filtration

There are various designs possible for a system with shellfish to pre-filter suspended particles from the water from the Wadden Sea before it enters the RED power plant. In this study we have worked-out two types of configuration:

1. Shellfish placed in a flume system
2. Shellfish placed in one or a series of coupled tanks.

The effectiveness of shellfish in reducing the amount of suspended particles in the water is dependent on many factors such as shellfish species and size, total biomass, residence time of the water, temperature, suspended particle concentrations, etc. To get a better understanding of the effect of these factors, models for both type of configurations have been developed. With these models, calculations can be made on the effectiveness and feasibility of using shellfish for pre-filtration of the water. Moreover, the configuration of the filtration set-up, that will be built within WP3 of this project, can be optimised with the models.

3.2 Flume system

Shellfish are placed in a flume (*Figure 7*) with a length of tens of meters to a couple of 100 meters. Water with suspended algae and inorganic particles are running through the flume at a constant current velocity. The shellfish filter the algae and the inorganic particles from the water and deposit the sediment (as faeces or pseudo-faeces) on the bottom of the flume of system. From there the sediment has to be collected and dispatched.

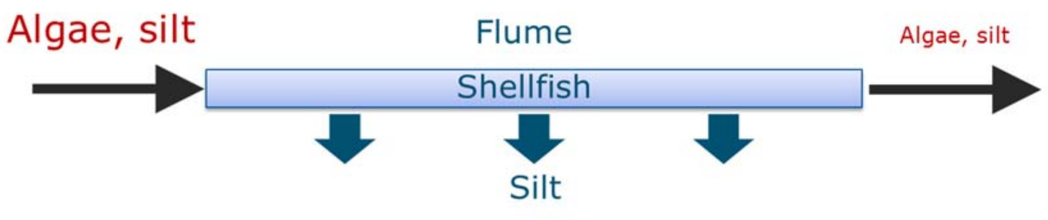


Figure 7: Schematic overview of a flume system with shellfish to pre-filter the water. Water from the Wadden Sea with algae and silt enters the flume at the left side and leaves the flume at the right side with lower concentration of both algae and silt, because the shellfish within the flume have filtered part of the water.

The concentration of silt (and algae) in the flume at a certain point (C_x, g l^{-1}) is a function of the concentration of the incoming water (C_0, g l^{-1}), the distance covered in the flume (x, meters), the flow velocity (v, m s^{-1}) in the flume and the filtration rate (F, s^{-1}):

$$C_x = C_0 \cdot e^{-\frac{F}{v}x}$$

The flow velocity is calculated by the discharge rate (Q, m^3 s^{-1}) and the cross-sectional area of the flume (A, m^2), where the cross-sectional area of the flume is corrected for the volume of the shellfish in each tank assuming a specific density of the shellfish of 1 kg l^{-1}.

$$v = \frac{Q}{A}$$

The filtration rate (F, s^{-1}) is calculated by the total clearance rate of all shellfish within the flume (PR, m^3 sec^{-1}) and the total volume of the flume (V, m^3, calculated as length of the flume multiplied by the cross-sectional area of the flume).

$$F = \frac{PR}{l \cdot A}$$

The individual clearance rate is species and size specific (see Table 2).

The model was used to study the sensitivity of the model to various different input variables:

- Shellfish species
- Size of shellfish
- Shellfish stock
- Flow rate

With the model, the percentage of water filtered was calculated within the flume. Since it is assumed that all the particles are retained on the gills of the shellfish, this percentage of water filtered is equivalent of the percentage reduction of algae and inorganic suspended particles within the flume.

3.2.1 Effect of shellfish species

The model was run for different shellfish species (Pacific oyster, Mussel, Cockle and European oyster) for a flume of 100 meter length and a cross-sectional area of 0.1 m^2 (total volume of the flume = 10 m^3). The discharge rate was 18 m^3 h^{-1} (power production of 5 kW), resulting in a flow velocity in the flume of 5.1 cm s^{-1}. For each of the species 200 kg of shellfish, with an individual size of 30 g fresh weight were evenly spread over the length of the flume. Figure 8 shows the percentage of water filtered by the shellfish as a function of transport distance of the water in the flume. It can be seen from this figure that Pacific oysters and mussels are more effective in filtering the water within the flume than cockles and European oysters. If it is assumed that the suspended silt particles that are filtered by the shellfish are deposited on the bottom of the flume in the form of faeces or pseudo-faeces and that no physical sedimentation and erosion of the silt occurs in the flume, the concentration of suspended silt particles is 32 percent of the concentration in the incoming water in the case of Pacific oysters and 72 percent in the case of European oysters. The total sediment production within the flume at a silt concentration in the incoming water of 50 mg l^{-1} (50 mg l^{-1} is an average for this part of the Wadden Sea (Brinkman, 2015)) is 14.5 kg day^{-1} in the case of Pacific oysters and 6.1 kg day^{-1} in the case of European oysters.

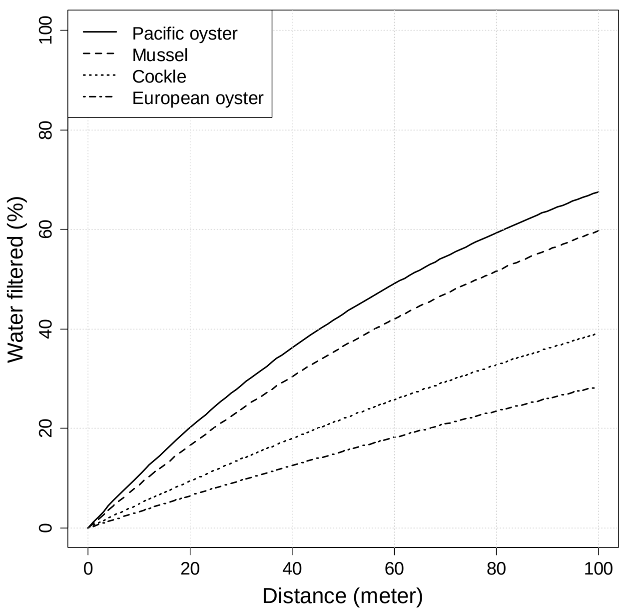


Figure 8: Percentage of water filtered as a function of transport distance of the water in the flume for four different shellfish species with the same individual size (30 g fresh weight) and total biomass (200 kg).

3.2.2 Effect of shellfish size

To illustrate the effect of size of the shellfish, the same modelruns were made for Pacific oyster at different sizes (Figure 9). All other parameter settings were identical to the calculations in the previous simulations (Figure 8). It is clear that the efficiency of filtration decreases with the size of the shellfish. The smaller the shellfish, the more efficient are they in filtering the water. This is a direct consequence of the allometric relation between clearance rate and flesh dry weight (paragraph 2.2). 200 kg oysters with a size of 30 g fresh weight filter 68% of the water in the flume, while the same stock of 200 kg oysters with an individual size of 200 g fresh weight, filter only 35% of the water in the flume.

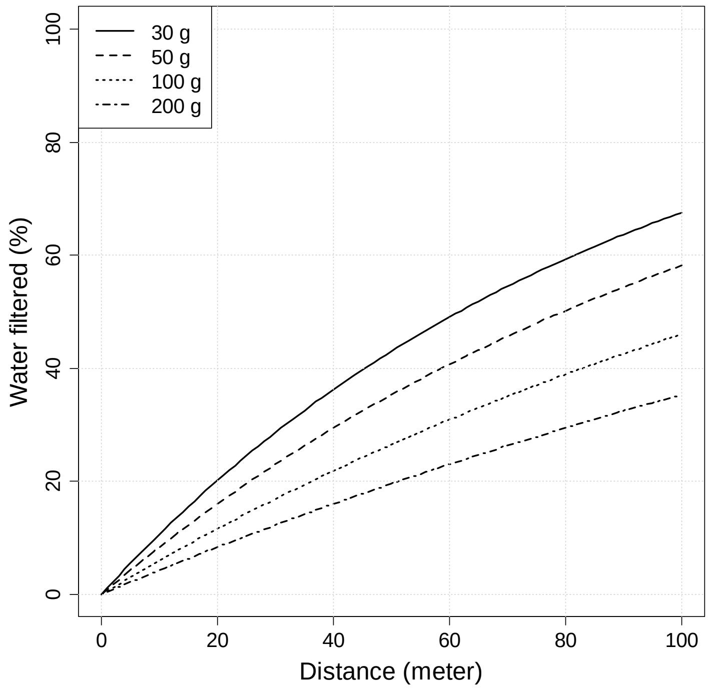


Figure 9: Percentage of water filtered as a function of transport distance of the water in the flume for Pacific oysters of four different sizes (30 g, 50 g, 100 g and 200 g fresh weight). All other settings are identical to four different shellfish species with the same individual size (30 g fresh weight) and total biomass (200 kg).

3.2.3 Effect of total stock

The more shellfish in the tanks, the higher the filtration rate. However, there is a physical, but also a physiological maximum on the number of shellfish that fit in the flume. A sensitivity analysis was run with at total biomass of Pacific oysters ranging from 0 to 1000 kg, with an individual size of 200 g fresh weight. The dimensions of the flume and the flow rate were identical to the previous runs. From Figure 10, it can be seen that the fraction of water filterd within the flume increases with an increasing stock of oysters. However, this relation is not linear, but has an asymptote at 100%. With increasing stock, the oysters will increasingly re-filter the water in the flume. Since the oysters also occupy physical space in the flume, the volume of the water in the flume and the average residence time of the water in the flume decreases with an increasing amount of shellfish in the flume. In the model, the water volume in the flume is corrected for the space occupied by the shelfish.

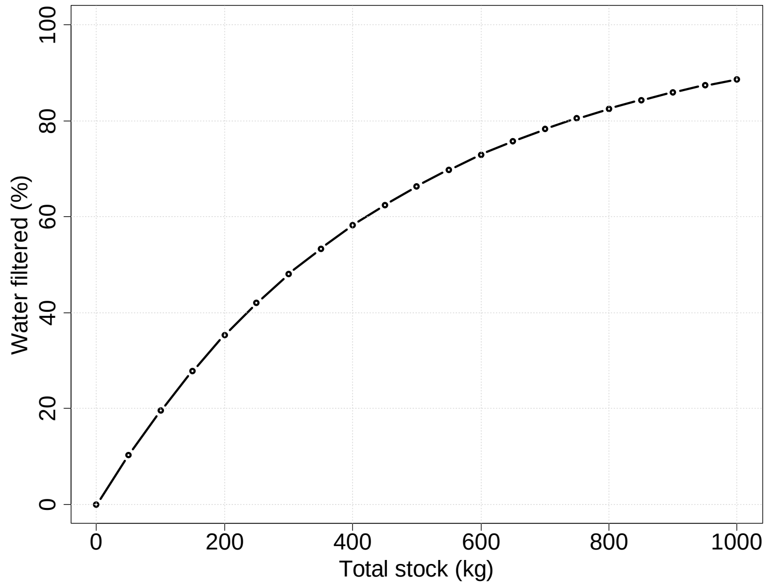


Figure 10: Percentage of water filtered as a function of total stock (kg) of Pacific oysters (size 200 g fresh weight) in the flume.

3.2.4 Effect of flow rate

The higher the flow rate, the lower the residence time of the water in the flume and the less time the shellfish have to filter the water. Simulations were done with a total amount of 200 kg Pacific oyster with an average size of 200 g fresh weight , equally distributed in the flume. The flow rate was varied from 0 to 150 m^3 per hour. As can be seen from Figure 11, the filtration efficiency decreases with the flow rate of the water. A flow rate of 150 m^3 per hour corresponds to a flow velocity of about 40 cm sec^{-1} in the flume. This will probably have an effect on resuspension of the sediment. Moreover, when the flow velocity becomes even higher, the shellfish will stop filter feeding.

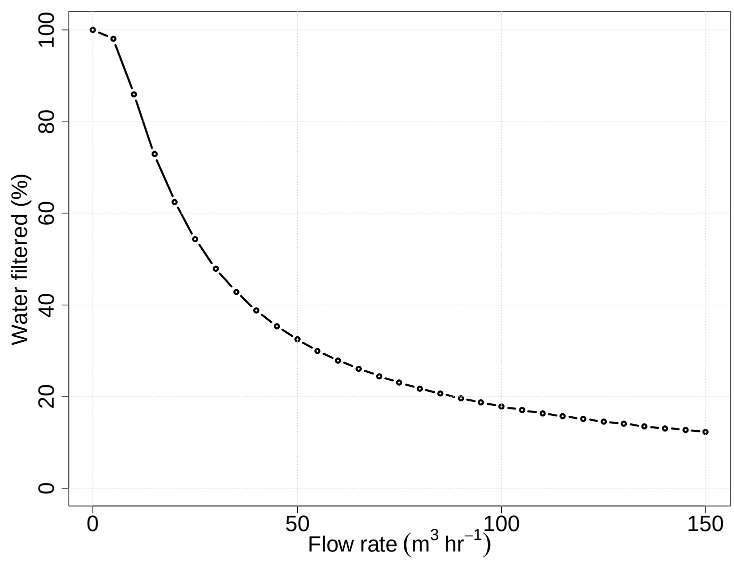


Figure 11: Percentage of water filtered as a function of flow rate through the flume.

3.3 Coupled tanks

Another possible configuration is to place the shellfish in a series of coupled tanks (Figure 12). The output of one tank is the input of the second tank. The advantage of using separate containers is that one tank can be taken out of the system for maintenance purposes, while the system keeps running.

The model consists of a variable number of serial coupled tanks with a given volume (V, l). It is assumed that the water within each tank is completely mixed. The tanks are filled with a certain amount (kg) of shellfish of a selected species, that are evenly distributed over the tanks. The volume of water in the tank is corrected for the volume of the shellfish in each tank assuming a specific density of the shellfish of 1 kg l^{-1}. Water, with a given amount of algae (Chla, µg l^{-1}) and suspended solids (SS, mg l^{-1}) from the Wadden Sea, enters into the first tank with a flow rate Q (l h^{-1}). From the first tank the water flows into the second tank and then to the third tank, etc. The average residence time in a tank (τ, h) can be calculated by $\tau = V/Q$.

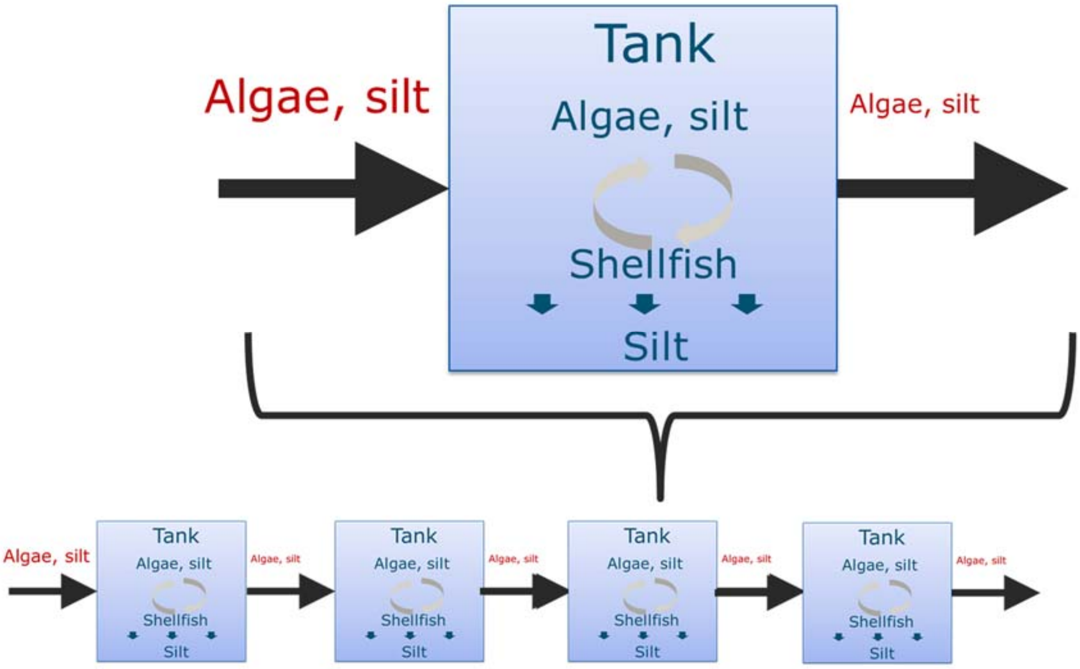


Figure 12: Schematic overview of the model. The model consists of a chain of coupled 0-D (completely mixed) boxes filled with shellfish. Water from Wadden Sea flows into the first tank, where it is filtered by the shellfish. From the first tank the water flows into the second tank, etc.

The changes in algae and suspended matter concentrations ($Chla$ and SS, respectively) in the tanks are described by the following differential equations:

$$\frac{dChla}{dt} = \frac{Chla_{in} \cdot Q - PR \cdot Chla - Chla \cdot Q}{V}$$

$$\frac{dSS}{dt} = \frac{SS_{in} \cdot Q - PR \cdot SS - SS \cdot Q}{V}$$

where $Chla_{in}$ and SS_{in} are the Chl-a and suspended solid concentrations of the incoming water of a tank, respectively. Q is the flow rate (l h^{-1}), V is the volume of a tank (l) and PR is the pumping rate (l h^{-1}) by all the shellfish in the tank. When the variables pumping rate (PR), flow rate (Q) and input concentrations of Chl-a and suspended sediment from the Wadden Sea are constant, the concentrations in the tanks will reach an equilibrium after a couple of hours. At that time, the filtering efficiency can be calculated from the difference between the concentration of the incoming- and the outgoing water.

The total pumping rate (PR, l h^{-1}) of the shellfish in the tank is calculated from the individual clearance rates (see paragraph 2.2), assuming that all particles are effectively retained on the gills.

$$PR = CR \cdot number\ of\ individuals$$

The output of the model is the concentration of algae and suspended solids in the tanks, the concentrations at the end of the shellfish filtration system and the production of silt in each tank. For the last variables, it is assumed that all the suspended matter that is filtered by the shellfish will be deposited as faeces and pseudofaeces on the bottom of the tank. This means that it is important that the tanks are designed in such a way that no resuspension of the deposited material by turbulent water movement will occur. If resuspension occurs, the effect of pre-filtration by the shellfish is undone.

3.3.1 Filtration efficiency coupled tanks

The model was run for a chain of 10 coupled tanks, each with a volume of 1 m^3. The tanks are filled with 500 kg of oysters (50 kg per tank) with an individual biomass of 200 g flesh mass. The water flow into the first tank is 18 m^3 h^{-1}, and the concentration of suspended solids in the incoming water is 50 mg l^{-1}.

The results of the standard run are presented in Figure 13. The left panel shows the cumulative amount of water filtered over the chain of tanks. In the first tank, about 10% of the water is filtered (blue part of the bar). The green fraction of the bars represent the fraction of unfiltered water. By multiplying this fraction to the concentration of the incoming water, the concentration of TPM in each tank can be calculated. The outflow from the last tank in the chain will be the input to the power plant. In this case 64% of the total particulate matter is filtered by the shellfish within the tanks. In the right panel. The total amount of sediment filtered per day within each tank is given. For these calculations, it is assumed that the concentration of suspended solids in the incoming water is 50 mg l^{-1}.

The total amount of sediment collected by the shellfish in the chain of tanks is 14 kg day^{-1}. Most of the sediment is collected in the first tank (2.1 kg day^{-1}).

The results can be compared to the simulation for the flume configuration (Figure 10). At a total stock of 500 kg (Pacific oysters of size 200 g fresh weight), the filtration efficiency was 66 %. This is slightly better than the 64% efficiency in the coupled tanks.

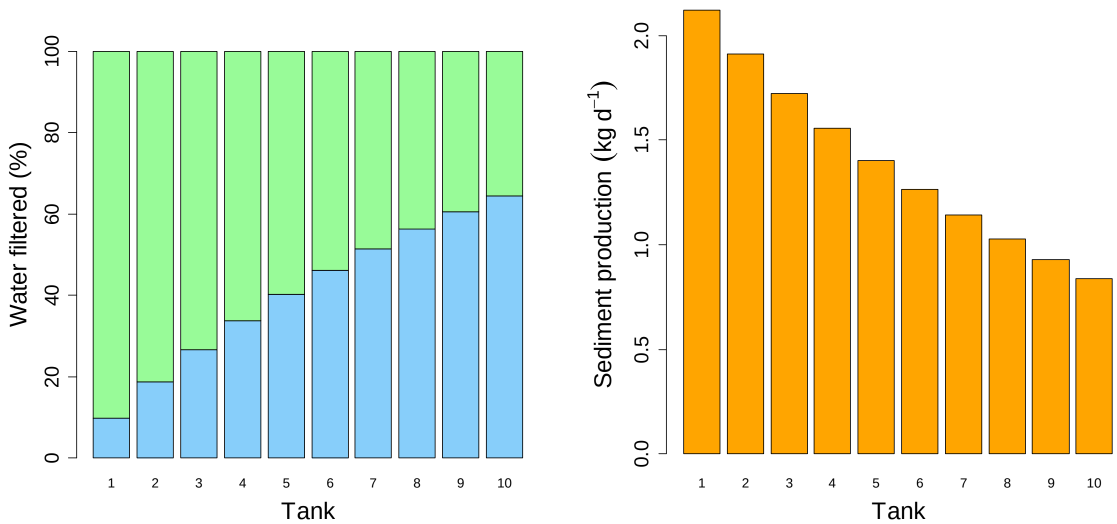


Figure 13: Cumulative percentage of the water filtered (blue fraction), left panel and amount of sediment filtered from the water(right panel) within each tank.

3.3.2 Effect of number of tanks

Two simulations were run to illustrate the effect of the use of a chain of coupled tanks with shellfish compared to 1 large. Simulations were run for Pacific oysters of 200 gram average individual fresh weight. In total 500 kg of oysters were stocked in the tanks. The flow rate of the water was 18 m^3 per hour. The first run was done for 500 kg of oysters in one large tank of 10 m^3. In the second run, 500 kg oysters were equally divided over a chain of 20 tanks with a volume of 0.5 m^3, resulting in 25 kg of oysters per tank.

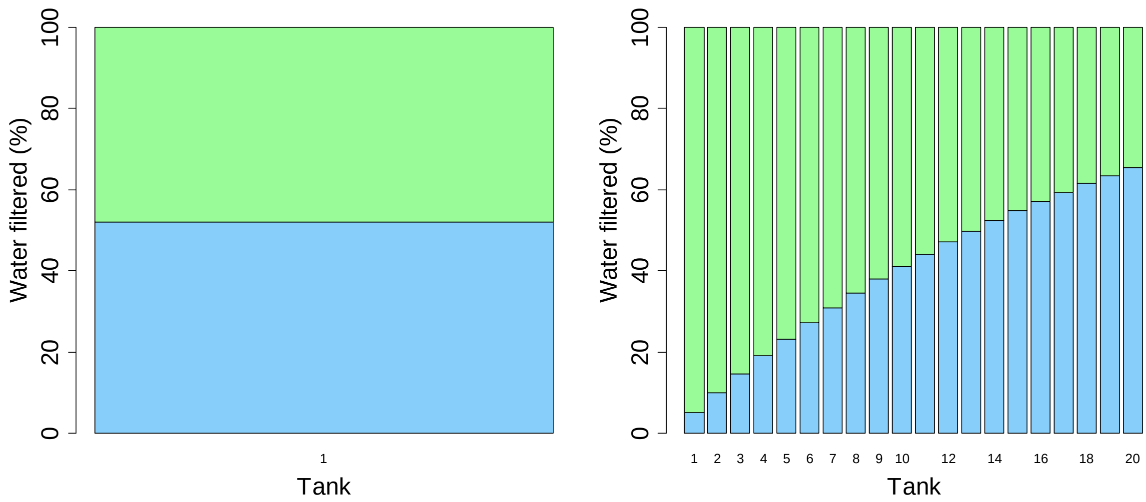


Figure 14: Cumulative percentage of the water filtered (blue fraction) in each tank. The left panel is a situation with one tank. The right panel in the case of a chain of 20 coupled tanks.

As can be seen from Figure 14, the filtration in a chain of coupled tanks (20x0.5 m^3) is more efficient than filtration in only one large (10 m^3) tank. In the case of one large tank (Figure 14, left panel), 52 percent of the water is filtered by the oysters in the tanks. When the same amount of oysters are distributed evenly over 20 tanks (Figure 14, right panel), 65 % of the water is filtered by the shellfish.

In order to show the effect of number of tanks, 30 simulations were done with the same settings (500 kg of 200 g Pacific oysters, water flow of 18 m^3 hr^{-1}) where the number of tanks varied between 1 and 30 (Figure 15). The total volume of water in the system was kept constant (10 m^3), so the volume of the tanks in the simulations varied between 10 m^3 (1 tank) and 0.33 m^3 (30 tanks). As can be seen from Figure 15, the effectiveness of the filtration increases with the number of tanks. However, the efficiency does not increase much after more than 10 tanks (with 10 tanks, 64.4% of the water is filtered and with 30 tanks, 65.7% of the water is filtered).

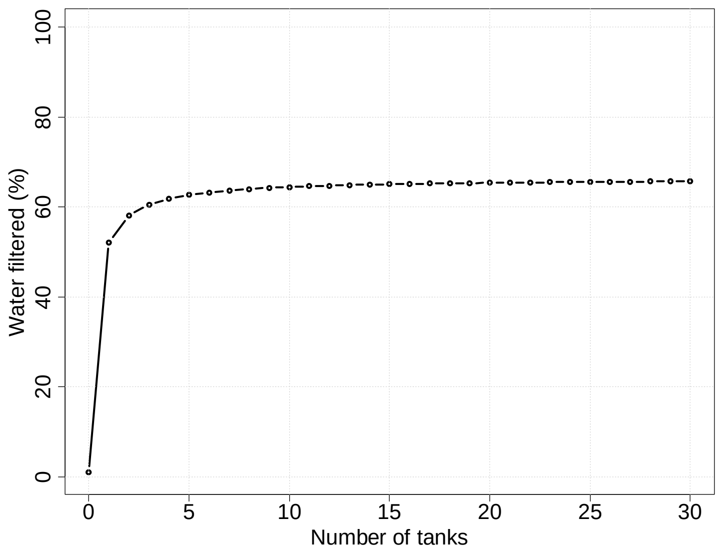


Figure 15: Percentage of the water filtered as a function of the number of tanks in a line.

3.3.3 Effect of volume of tanks

Model simulations were also done where the number of tanks in the line were kept constant where the size of the tanks varied between 0.1 m^3 to 5 m^3 per tank. The 10 tanks were filled with 500 kg pacific oysters with a size of 200 g average individual fresh weight, equally distributed over the tanks. The flow rate of the water was 18 m^3 hr^{-1}. From Figure 16 it can be seen that the volume of the tanks does not influence the filtering efficiency. This is because the residence time of the water in a tank increases linearly with the volume of the tank, whereas the fraction of water filtered deceases linearly with the volume of the tank and the quantity of filtering organisms (and thus pumping rate) is constant, independently from the volume of water to in the tanks.

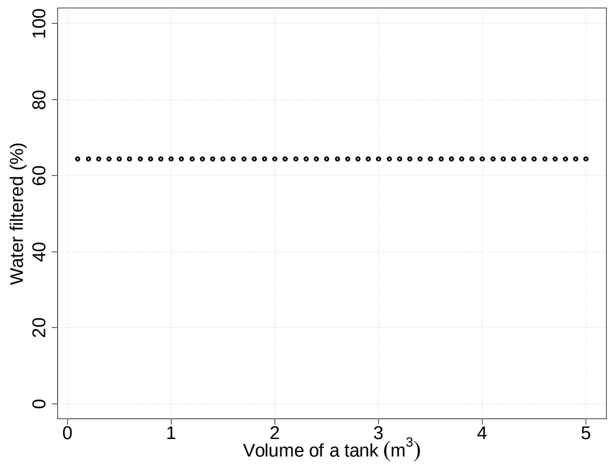


Figure 16: Percentage of the water filtered as a function of the volume of the tanks.

3.4 Scenario runs

For the Blue Energy power plant combining shellfish pre-filtration, the water entering the plant should provide food and the suitable environmental conditions to sustain the survival of the shellfish for a couple of months to years. As it can be seen in sections 3.2 and 3.3, 100% filtration is practically not possible with shellfish. However a pre-filtration efficiency of 50% with shellfish can already be very profitable for the power plant. In this section, the model for a coupled tank system (section 3.3) is used to construct preliminary designs for shellfish filtration systems that are capable to filter different orders of magnitude of water from the Wadden Sea. In the configuration scenarios below, we use the Pacific oyster, but mussels will give comparable results.

In this project four different configurations of the reverse electro dialysis plant are modelled (Table 3). The present site is a 50 kW plant. The idea is to scale this site up to a capacity of 1 MW in the near future. A plant with a capacity of about 100 MW is assumed to be economically feasible. Plants with a capacity of 10 and 50 MW are modelled as an intermediate situation. Finally, a plant of 200 MW is regarded as the absolute maximum size on the Afsluitdijk due to the availability of fresh water from Lake IJssel. As stated before, per MW an amount of 1 m^3 s^{-1} fresh water from Lake IJssel and equal amount of salt water from the Wadden Sea is needed. For the present (50 kW) about 180 m^3 hr^{-1} water from the Wadden Sea is needed. This is about ten times the amount of water that was used in the previous model runs (paragraphs 3.2 and 3.3). The amount of water needed increases linearly with the capacity of the plant (Table 3).

Table 3: Amount of salt water from the Wadden Sea needed for six configurations of the power plant.

Configuration	Capacity (MW)	Flow rate (m^3 hr^{-1})
I	0.05	180
II	1	3 600
III	10	36 000
IV	50	180 000
V	100	360 000
VI	200	720 000

In the following part, suggestions are made for the configurations I, II, V and VI. Configurations III and IV can be seen as intermediates between configurations II and V.

3.4.1 Configuration I

In order to reduce the concentration of microalgae and inorganic suspended particles of water from the Wadden Sea with 50% at a flow rate of 180 m^3 hr^{-1}, a series of 10 coupled tanks of 500 l can be used. Each tank should be filled with 250 kg Pacific oysters with a size of 100 g (Cat III) in order to filter the water with about 50%. In total 25 000 pacific oysters are needed. The price of the oysters depend on the quality. The former Dutch Fish Product Board (Productschap vis) used a price of € 0,10 per oyster to calculate the fees (Wijsman e.a., 2013). The total cost of the oysters in the system can be estimated at minimum €2 500,-.

The ingested food and the sediment particles that are filtered from the water by the shellfish are deposited on the bottom of the tank in the form of faeces and pseudofaeces. Assuming an average concentration of 50 mg l^{-1} of suspended solids in the water of the Wadden Sea (Brinkman, 2015), a total amount of 216 kg solids day^{-1} are pumped from the Wadden Sea into the plant. In the configuration 52% of the suspended solids are filtered out of the water. As a result, a total amount of 113 kg sediment per day will be produced by the shellfish filtration system.

In Figure 17 it can be seen that the sediment production per tank varies over the line. The highest production is in the first tank (more than 15 kg per day) and decreases over the line to 7.9 kg per day in the last tank.

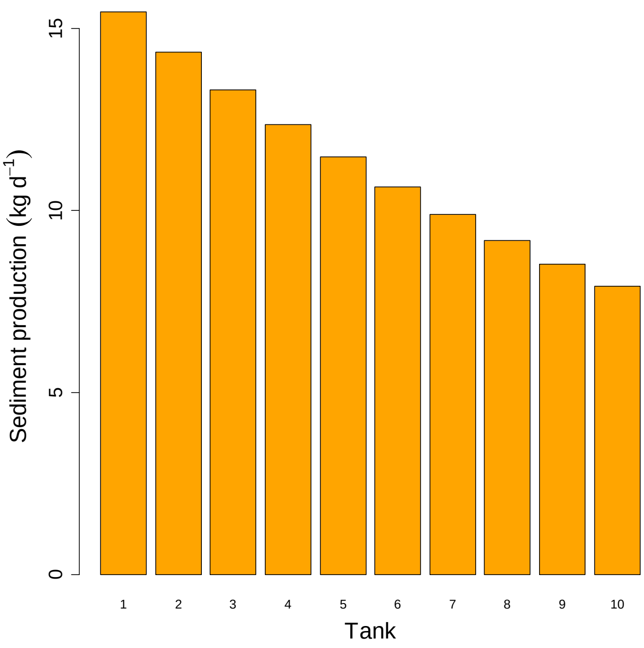


Figure 17: Sediment production (kg day^{-1}) per tank.

3.4.2 Configuration II

The 1 MW plant requires 3600 m^3 water from the Wadden Sea per hour. This scaling-up can be done by increasing the dimensions of the previous configuration with a factor 20, i.e. 10 tanks of 10 m^3 filled with a total of 50 000 kg oysters. However, the upscaling can also be done by 20 parallel systems of configuration I of 10 tanks with a volume of 0.5 m^3. Each system can process 180 m^3 of water per hour. The amount of oysters needed is the same, but lines can be decoupled when maintenance is needed.

3.4.3 Configuration V

The 100 MW plant is 100 times the size of the 1 MW plant. 2000 parallel lines of 10 tanks with a volume of 0.5 m^3 is not practical. For this situation the size of the tanks need to be increased to for example the size of a 20 feet sea container. The volume of such a container is about 33 m^3. One container can contain approximately 15 000 kg of Pacific oysters Cat III (100 g). One line of 10 containers of 33 m^3, filled with 150 ton of oysters can filter 3.2 m^3 water per second with an efficiency of 52%. To filter 100 m^3 per second, 32 parallel lines are needed.

The total amount of suspended solid production for this configuration is 222 ton per day. The production of the first container of each line is 929 kg per day.

3.4.4 Configuration VI

The maximum possible size 200 MW is twice as large as configuration V, and can be reached with 64 parallel lines of 10 containers of 33 m^3. The total amount of sediment production for this configuration is 440 tons per day.

3.4.5 Summary scenario runs

The results of the different configuration scenarios are presented in Table 4. Calculations are based on a 50% reduction of algae and suspended solids in the water and a suspended solid concentration of 50 mg l^{-1} at the water intake. As it can be concluded from this table, there is a linear increase of the dimensions (number of oysters needed, solid phase production) with the size of the plant. In this table it can be seen that a huge, and unrealistic, amount of oysters are needed to filter the water. For each MW half a million oysters are needed to filter the water with 50% efficiency. The total production of pacific oysters of the whole Dutch oyster sector from 2004 to 2009 was about 26 million oysters per year (Taal e.a., 2010).

Also the total amount of solid phase production is high. Each day the oysters needed for 200MW plant produces on average 440 tons of solid waste which has to be removed. Moreover, the same amount of suspended material goes into the plant, and need to be removed from the membranes as well as from the tanks.

Table 4: Overview of the various configurations.

Parameter	I	II	III	IV	V	VI
Power (MW)	0.05	1	10	50	100	200
Salt water supply ($m^3\ s^{-1}$)	0.05	1	10	50	100	200
Size of tank (m^3)	0.5	0.5	5	33	33	33
Number of tanks per line	10	10	10	10	10	10
Number of lines	1	20	20	15	32	64
Amount of oysters (ton)	2.5	50	500	2500	4800	9600
Number of oysters	$2.5\cdot10^4$	$5.0\cdot10^5$	$5.0\cdot10^6$	$2.5\cdot10^7$	$4.8\cdot10^7$	$9.6\cdot10^7$
Size of CAT III oysters (g)	100	100	100	100	100	100
Filtration efficiency (%)	52	52	52	52	51	51
Solid production (ton day^{-1})	0.113	2.26	22.6	113	220	440

4 Conclusions and discussion

4.1 Pre-filter the water with shellfish

Shellfish are capable to filter large volumes of water, removing suspended particles (algae, detritus and inorganic particles) larger than 2-5 µm. The organic particles (algae and detritus) can be used as a food source and the inorganic particles are excreted as faeces or rejected as pseudofaeces. The clearance rate is species specific and depends on the size of the shellfish.

Since the shellfish are living organisms, it is important that the water quality in the tanks is suitable to survive. The water in het whole system should contain enough food and oxygen for the oysters to survive over a longer period and even to grow. Therefore, the shellfish will not be able to filter the water 100%. A reduction of 50% of the suspended sediment concentration, from 50 mg l^{-1} to 25 mg l^{-1}, seems to be feasible.

In general, the water from the Wadden Sea contains enough food and oxygen for shellfish such as Pacific oysters and mussels. However, if the tanks are in a line, the food (and possibly oxygen) concentration will decrease due to the filtration and respiration activity of the shellfish. In the calculations presented in this study, the food concentration in the last tank is only 50% of the food concentration of the incoming water from the Wadden Sea. In order to keep the shellfish in the last tank in a good condition, it is probably necessary to reverse the tanks in the line (or the flume system) from time to time (every week). This can be done by installing bypasses. When the tanks are in cascades, probably also pumps are needed. Particularly at higher temperatures, reaeration of the water is recommended to prevent low oxygen concentrations.

4.2 Shellfish species

Various species, such as mussels, Pacific oysters, European oysters and cockles, can be used in the tanks to pre-filter the water. Pacific oysters and mussels seem to be the best filterfeeders. Besides the differences in filtration capacity between the species there is also a difference in the culture techniques. There is quite some experience in the culture of mussels and Pacific oysters. Both shellfish species can be cultured on ropes (mussels) or in baskets (Pacific oysters/mussels) that are placed in tanks with water. They are also robust against varying environmental conditions. There is less experience with the culture of European (flat) oysters in tanks. Cockles live buried in the sediment with their inhalant and exhalent siphons in the water. In contrast to the 3-dimensional filtration structures of the oysters and the mussels, the cockles create a less efficient 2-dimensional structure. Therefore, the use of cockles to pre-filter the water seems to be less promising than for Pacific oysters and mussels.

4.3 Commercial aspects of using shellfish

To pre-filter the incoming water for the RED power plant, huge amounts of oysters (or mussels) are needed. For a 1 MW power plant, almost 50 tons of Pacific oysters (0.5 million individuals with an average size of 100 g each) are needed to filter 52% of the suspended particles from the water. The Pacific oysters can be bought from oyster farmers. If the oysters come from the Oosterschelde or the Grevelingenmeer, they are not allowed to enter the Wadden Sea. They should be kept on land and measurements should be taken that no organisms could be introduced in the Wadden Sea with the discharge water. Alternatively, the oysters can be collected into the Wadden Sea. Commercial fishery for Pacific oysters in the Wadden Sea, however, is not allowed. Pacific oyster can only be harvested by commercial hand-picking.

Alternatively, small mussels from seed mussel collection devices (MZIs) in the Wadden Sea can be used. The MZIs are harvested at the end of the summer. Since the mussels from the MZIs are small, the filtration capacity per kg is high. During wintertime, the mussels can be used in the filtration systems (tanks or flumes) on land. Since predation can be controlled, the survival of the mussels might be higher than on the commercial culture plots in the Wadden Sea. In the next summer the mussels can be replaced by new mussels from the MZIs and the "old mussels" can be sold back to mussel farmers who can use them on their culture plot.

If the shellfish in the systems are well-managed in the tanks, they can grow and develop over time and sold in a later stage at a higher price. Especially the shellfish in the first tank have access to a relative good quality of water and food from the Wadden Sea and will grow well. If the sequence of the tanks in a line is altered from time to time, all shellfish can profit from the relative high food concentrations in the water from the Wadden Sea. The selling price will depend on the quality of the shellfish, which largely depends on the season. Most probably, there will be some losses in the tanks due to mortality. In order to keep a good water quality, dead shellfish should be removed from the tanks as soon as possible. The growth and mortality of the oysters in the tanks need to be monitored in detail during the planned experiment at the site.

A complicating factor in selling the oysters or mussels from the tanks directly to the market is that the tanks are not regarded as a shellfish production area. This means that they cannot be sold directly for consumption. Eventually, the oysters or mussels can be sold back to an oyster or mussel farmer who can bring the oysters to his culture plot in the Oosterschelde or the Wadden Sea. However, this procedure should be checked at the Netherlands Food and Consumer Product Safety Authority (NVWA).

4.4 Sediment removal

The water from the Wadden Sea contains relative high concentrations of suspended particles. The concentration of suspended particles shows a spatial and seasonal varying pattern (Brinkman, 2015) and is in the order of magnitude of 50 mg l^{-1} (varies between 10 and 100 mg l^{-1}). Specific measurements at the intake location will give more detailed information on the local suspended solid concentrations, particle size distribution and seasonal fluctuations. For the RED process, it is important that the concentration of suspended particles in the water can be reduced before it enters the plant. The shellfish are efficient filter-feeders and are capable to remove particles (> 2-5 μm) from the water. Since 100% sediment removal by shellfish filtration is not feasible, a second (mechanical) filtration is needed. The total amounts of sediment that has to be removed daily is huge. For a 1 MW plant, the total amount of suspended solids that have to be removed is more than 4 tons per day. Assuming that half of this amount is filtered by the shellfish, more than 2 tons of sediment per day needs to be removed from the filtration system (tanks or flume). The system should be designed as such that the collection of the deposited sediment is easy. The tank could be designed with a funnel-shaped bottom with a collection valve. On the bottom of the flume, a conveyor-belt system could be constructed.

The suspended particles that are filtered by she shellfish are excreted in the form of faeces and pseudofaeces and deposited on the bottom of the system. It is important that the flow velocities within the tanks or in the flume are not too high to avoid that the deposited sediment is resuspended. On the other hand, if the flow velocities within the system is low, there will also be natural sedimentation of particles from the water, even without filtration activity of the shellfish.

4.5 Fouling

Since also larvae of various organisms (e.g. barnacles, shellfish, ascidians, macroalgae) will enter the system, they can cause fouling on the walls and on the shellfish themselves. Most of these organisms are also filterfeeders and will help in filtering the water. However, if the biomass becomes too high, they might have an impact on the shellfish or they might obstruct the water flow through the system. In the design of the shellfish filtration system, one should take into account that maintenance works to remove fouling organisms could be applied.

4.6 Experimental design

For the next phase of this project (WP 3), an experimental shellfish filtration system will be constructed at the site on the Afsluitdijk. With this system experiments can be carried out and measurements can be done. The goal of these experiments is to test at which extent the shellfish are capable to pre-filter the water from the Wadden Sea and to verify if the combination of shellfish aquaculture together with energy production is technically and economically feasible.

A construction can be built with a line of 1 m^3 tanks with a funnel-shaped bottom. Also a small-scale flume could be constructed. Oysters and/or mussels will be placed in baskets in the tanks. The tanks will be covered in order to prevent the development of macroalgae in the tank and predation by birds. On a regular basis, measurements will be done to monitor the performance of the filtration system. Parameters that could be measured are:

- Flow rate
- Suspended solid concentration of intake water
- Suspended solid composition (microalgae, solids) of intake water
- Particle size distribution of intake water
- Growth of the shellfish (weight and meat content)
- Mortality of the shellfish
- Product quality of the shellfish
- Concentration of microalgae per tank
- Concentration of suspended solids per tank
- Oxygen concentration in the tanks
- Production of sediment per tank

The results of these measurements can be used to validate the model and to improve the design.

The measurement on the shellfish should be done on a regular basis (e.g. monthly). Shellfish can be marked individually using microchips at the start of the experiment. Sizes of the shellfish (length, fresh weight) can be measured. Mortality can be calculated from the loss of shellfish.

5 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2008 certified quality management system (certificate number: 187378-2015-AQ-NLD-RvA). This certificate is valid until 15 September 2018. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V.

Furthermore, the chemical laboratory at IJmuiden has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation. The chemical laboratory at IJmuiden has thus demonstrated its ability to provide valid results according a technically competent manner and to work according to the ISO 17025 standard. The scope (L097) of de accredited analytical methods can be found at the website of the Council for Accreditation (www.rva.nl).

On the basis of this accreditation, the quality characteristic Q is awarded to the results of those components which are incorporated in the scope, provided they comply with all quality requirements. The quality characteristic Q is stated in the tables with the results. If, the quality characteristic Q is not mentioned, the reason why is explained.

The quality of the test methods is ensured in various ways. The accuracy of the analysis is regularly assessed by participation in inter-laboratory performance studies including those organized by QUASIMEME. If no inter-laboratory study is available, a second-level control is performed. In addition, a first-level control is performed for each series of measurements.
In addition to the line controls the following general quality controls are carried out:

- Blank research.
- Recovery.
- Internal standard
- Injection standard.
- Sensitivity.

The above controls are described in Wageningen Marine Research working instruction ISW 2.10.2.105. If desired, information regarding the performance characteristics of the analytical methods is available at the chemical laboratory at IJmuiden.

If the quality cannot be guaranteed, appropriate measures are taken.

References

Barillé, L., J. Prou, M. Héral and D. Razet (1997) Effects of high natural seston concentrations on the feeding, selection, and absorption of the oyster *Crassostrea gigas* (Thunberg). Journal of Experimental Marine Biology and Ecology 212: 149-172.

Bayne, B. L., J. Widdows and R. I. E. Newell (1977) Physiological measurements on estuarine bivalve molluscs in the field, Pages 57-68 *in* B. F. Keegan, P. O. Ceidigh, and P. J. S. Boaden, eds. Biology of benthic organisms. Oxford, Pergamon Press.

Bayne, B. L. and J. Widdows (1978) The physiological ecology of two populations of *Mytilus edulis* L. Oecologia 37: 137-162.

Bayne, B. L., J. I. P. Iglesias, A. J. S. Hawkins, E. Navarro, M. Heral and J. M. Deslouspaoli (1993) Feeding-behavior of the Mussel, *Mytilus edulis* - responses to variations in quantity and organic content of the seston. Journal of the Marine Biological Association of the United Kingdom 73: 813-829.

Boon, N. and R. Van Roij (2011) Blue energy' from ion adsorption and electrode charging in sea and river water. Molecular Physics 109: 1229-1241.

Bougrier, S., P. Geairon, J. M. Deslous-Paoli, C. Bacher and G. Jonquieres (1995a) Allometric relationships and effects of temperature on clearance and oxygen consumption rates of *Crassostrea gigas* (Thunberg). Aquaculture 134: 143-154.

Bougrier, S., P. Geairon, J. M. Deslous-Paoli, C. Bacher and G. Jonquières (1995b) Allometric relationships and effects of temperature on clearance and oxygen consumption rates of Crassostrea gigas (Thunberg). Aquaculture 134: 143-154.

Brinkman, A. G. (2015) Ecosysteemeffecten van lokaal veranderde slibgehaltes in de westelijke Waddenzee. IMARES, Report number: C157/15, 121 pages.

Clausen, I. and H. U. Riisgård (1996) Growth, filtration and respiration in the mussel *Mytilus edulis*: no evidence for physiological regulation of the filter-pump to nutritional needs. Marine Ecology Progress Series 141: 37-45.

Cranford, P. J. (2001) Evaluating the 'reliability' of filtration rate measurements in bivalves. Marine Ecology Progress Series 215: 303-305.

Cranford, P. J., J. E. Ward and S. E. Shumway (2011) Bivalve filter feeding: variability and limits of the aquaculture biofilter, Pages 81-124 *in* S. E. Shumway, ed. Shellfish Aquaculture and the Environment, Wiley-Blackwell.

De Mesel, I., E. Meesters, A. Meijboom and J. W. M. Wijsman (2008) Impact van MZI's op organische koolstof in de bodem. Analyse aan de hand van het model DEPOMOD en veldmetingen. Wageningen IMARES, Report number: C037/08, 22 pages.

Essink, K. (1999) Ecological effects of dumping of dredged sediments; options for management. Journal of Coastal Conservation 5: 69-80.

Foster-Smith, R. L. (1974) A Comparative Study of the Feeding Mechanisms of *Mytilus edulis* L., *Cerastoderma edule* (L), and *Venerupis pullastra* (Montagu) (Mollusca : Bivalvia), University of Newcastle-upon-Tyne.

Gerdes, D. (1983) The Pacifi c oyster *Crassostrea gigas* Part I. Feeding behaviour of larvae and adults. Aquaculture 31: 195-219.

Haure, J., C. Penisson, S. Bougrier and J. P. Baud (1998) Influence of temperature on clearance and oxygen consumption rates of the fl at oyster *Ostrea edulis*: determination of allometric coefficients . Aquaculture 169 : 211 – 224. Aquaculture 169: 211-224.

Jones, H. D., O. G. Richards and T. A. Southern (1992) Gill dimensions, water pumping rate and body size in the mussel *Mytilus edulis*. Journal of Experimental Marine Biology and Ecology 155: 213-237.

Jørgensen, B. B. and D. Marais (1990) The diffusive boundary layer of sediments: oxygen microgradients over a microbial mat. Limnology and Oceanography 35: 1343-1355.

Jørgensen, C. B. (1996) Bivalve filter feeding revisited. Marine Ecology Progress Series 142: 287-302.

Kiørboe, T., F. Møhlenberg and O. Nøhr (1980) Feeding, particle selection and carbon absorption in *Mytilus edulis* in different mixtures of algae and resuspended bottom material. Ophelia 19: 193-205.

Newell, R. I. E. and B. L. Bayne (1980) Seasonal changes in the physiology, reproductive condition and carbohydrate content of the cockle *Cardium* (= *Cerastoderma*) *edule* (Bivalvia: Cardiidae). Marine Biology 56: 11-19.

Post, J. W., H. V. M. Hamelers and C. J. N. Buisman (2008) Energy Recovery from Controlled Mixing Salt and Fresh Water with a Reverse Electrodialysis System. Environmental Science & Technology 42: 5785-5790.

Riisgård, H. U. (2001a) Physiological regulation versus autonomous filtration in filterfeeding bivalves: starting points for progress. Ophelia 54: 193-209.
Riisgård, H. U. (2001b) On measurement of filtration rates in bivalves - the stony road to reliable data: review and interpretation. Marine Ecology Progress Series 211: 275-291.
Riisgård, H. U. (2001c) The stony road to reliable filtration rate measurements in bivalves: a reply. Marine Ecology Progress Series 215: 307-310.
Riisgård, H. U., P. P. Egede and I. B. Saavedra (2011) Feeding behaviour of the mussel, *Mytilus edulis*: New observations, with a minireview of current knowledge. Journal of Marine Biology 2011: 1-13.
Rivera-Ingraham, G. A., I. Rocchetta, U. Bickmeyer, S. Meyer and D. Abele (2016) Spatial compartmentalization of free radical formation and mitochondrial heterogeneity in bivalve gills revealed by live-imaging techniques. Frontiers in Zoology 13: 17.
Smaal, A. C., J. H. G. Verhagen, J. Coosen and H. A. Haas (1986) Interaction between seston quantity and quality and benthic suspension feeders in the Oosterschelde, The Netherlands. Ophelia 26: 385-399.
Smaal, A. C., A. P. M. A. Vonck and M. Bakker (1997) Seasonal variation in physiological energetics of *Mytilus edulis* and *Cerastoderma edule* of different size classes. Journal of the Marine Biological Association of the United Kingdom 77: 817-838.
Strohmeier, T., O. Strand, M. Alunno-Bruscia, A. Duinker and P. J. Cranford (2012) Variability in particle retention efficiency by the mussel *Mytilus edulis*. Journal of Experimental Marine Biology and Ecology 412: 96-102.
Taal, C., H. Bartelings, R. Beukers, A. J. Klok and W. J. Strietman (2010) Visserij in cijfers 2010. LEI, Report number: 2010-057, 130 pages.
Thompson, R. J. and B. L. Bayne (1974) Some relationships between growth, metabolism and food in the mussel *Mytilus edulis*. Marine Biology 27: 317-326.
Thompson, R. J. (1984) The reproductive cycle and physiological ecology of the mussel Mytilus edulis in a subarctic, non-estuarine environment. Marine Biology 79: 277-288.
Troost, T. A., J. W. M. Wijsman, S. Saraiva and V. Freitas (2010) Modeling shellfish growth with Dynamic Energy Budget models: an application for cockles and mussels in the Oosterschelde (SW Netherlands). Philosophical Transactions of the Royal Society of London 365: 3567-3577.
Vahl, O. (1972) Efficiency of particle retention in *Mytilus edulis* L. of different sizes. Ophelia 12: 45-52.
Vanweel, P. B. (1961) The comparative physiology of digestion in molluscs. American Zoologist 1: 245-252.
Weinstein, J. N. and F. B. Leitz (1976) Electric-power from difference in salinitys Dialytic battery. Science 191: 557-559.
Widdows, J. (1978) Combined effects of body size, food concentration and season on physiology of *Mytilus edulis*. Journal of the Marine Biological Association of the United Kingdom 58: 109-124.
Widdows, J., P. Fieth and C. M. Worrall (1979) Relationships between seston, available food and feeding-activity in the common mussel *Mytilus edulis*. Marine Biology 50: 195-207.
Wijsman, J. W. M., M. Poelman, A. Blanco, T. Troost, T. Schellekens, W. J. Strietman and K. Hamon (2013) Verkenning van de effecten van toelaten nutriënten en verwijderen van wilde oesters op de productie van Kweekoesters in de Kom van de Oosterschelde. Wageningen IMARES, Report number: C010/13, 68 pages.

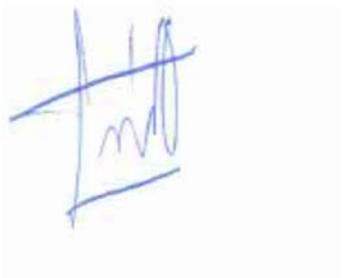
Justification

Report C078/17
Project Number: 4313100040

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Dr. E. Rurangwa
Researcher

Signature:



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