A habitat suitability model for Pacific oysters (*Crassostrea gigas*) *in the Oosterschelde*

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Summary

In the coming century, the effects of climate change, such as sea level rise, river peak discharges and the increase of the sea water temperature, will influence the functioning of the marine ecosystem of the Southwestern Delta of the Netherlands (hereafter abbreviated to Delta). In the last century, the average sea level in the North Sea increased with 20 cm. For the future it is predicted that the sea level rise will continue. Also the seasonal variance in river discharge will increase. As a reaction, various infrastructural initiatives will be developed within the Delta region to protect this region for on-going sea level rise and changes in river discharges. The goal of these adaptations is to make the Delta more resilient to sea level rise and river discharges and increase both its natural and production values.

An important management question is: What are the effects of climate change and infrastructural adaptations on the natural values within the Delta? Within this project, effects of climate change scenarios (connection of basins and see-level rise) on environmental conditions have been translated to habitat suitability, which allowed us to evaluate effects of climate change on the potential for species to settle. As a model species in this pilot study, the Pacific oyster (*Crassostrea gigas*) has been chosen.

The modelled habitat suitability maps show a reasonable estimation of the suitability for oysters throughout the Delta and can be used to broadly indicate the consequences of the effect of climate change and infrastructural changes on the habitat suitability for oysters. The largest effect on the suitable area for oysters is when the Volkerak-Zoommeer is connected to the salt water of the Grevelingenmeer, whereas the increase in seawater-level only affect suitability for oysters on a local scale.

The model produces detailed habitat maps for the whole delta area. However, is should be clear that the model is based on a 1 D model that is extrapolated to 2D maps. This results in some local artefacts.

The method can also be applied to other species or functions within the Delta. This requires knowledge rules relating the environmental conditions to habitat suitability. Species of interest might be species that are presently or in the future of ecological importance.

1 Introduction

1.1 Effects of climate change in the Dutch Delta

In the coming century, the effect of climate change, such as sea level rise, river peak discharges and the increase of the sea water temperature, will influence the functioning of the marine ecosystem of the Southwest Delta in the Netherlands (hereafter abbreviated to Delta). In the last century, the average sea level in the North Sea increased with 20 cm (Douglas et al. 2001). Various initiatives will be developed within the Delta region to prepare this region for on-going sea level rise and changes in river discharges. Many of these adaptations will be focused on restoration of estuarine dynamics (tidal ranges, salinity, morphology, nutrients) by restoring connections with the North Sea and rivers (Baptist et al. 2007). Moreover, also the individual basins will be re-connected with each other. The goal of these adaptations is to make the Delta more resilient to sea level rise and river discharges and increase both its natural and production values.

The increase of water temperatures will enable species from more Southern regions to establish themselves in the Delta region. Depending on their invasive capacity they might influence functioning of the ecosystem. Moreover, the restored connections between the individual basins will facilitate their distribution over the Delta. An important factor for a successful introduction of a particular species is the presence of suitable habitat and environmental conditions for settlement.
Many scenarios have been defined in relation to the restoration of estuarine dynamics for the various basins (e.g. Volkerak-Zoommeer, Grevelingenmeer). Additionally, various integral scenarios will be devised in relation to connecting the basins. This will have effect on restoration of estuarine dynamics and ecological functioning.

However, there is a lack of knowledge to predict response of the ecosystem to climate change. What changes in species composition can be expected in the future and will there be opportunities for new species that can be of ecological or economic importance to the Delta region?

1.2 Knowledge for Climate project

The Dutch Knowledge for Climate (Kennis voor Klimaat) Research Programme is focussed on the development of knowledge to better assess investments for spatial planning and infrastructure over the coming twenty years in terms of their resistance to climate change (Knowledge for Climate website, 2011).

The present study is part of the Knowledge for Climate project “Climate change effects on restoration of estuarine dynamics within the Delta region”, which is part of the Hotspot “South-West Netherlands Delta”. The aim of this project is to develop a tool to predict the effects of climate change on natural values within the Delta area. The Pacific oyster (*Crassostrea gigas*) has been chosen as a model species since a lot of background knowledge is available for this species. In future applications, this tool can be applied to other relevant species.

Within this project, effects of climate change scenarios (connection of basins and sea-level rise) on environmental conditions have been calculated by means of the 1D Delta model (Martini and Van Wesenbeeck 2010). This model is an application of the SOBEK hydrodynamic and water quality model. With the model, three scenarios were run.

1. Present situation
2. 0.8 meter sea level rise
3. Adjustment of tidal range in Lake Grevelingen and Volkerak-Zoommeer

With the model various environmental conditions have been calculated such as current velocity, salinity and chlorophyll-a concentration. The 1-D results are transformed to 2-D maps by interpolation on 20x20 meter grids. The resulting environmental variables are translated to habitat conditions, which allows us to evaluate effects of climate change on the potential for Pacific oysters to settle. The resulting habitat suitability maps for Pacific oysters for the different scenarios are presented in this report.
NIOZ-Yerseke has conducted field studies on the conditions that that influence the settlement of Pacific oysters (Van IJzerloo and Bouma 2012). Silt content was measured within and outside an oyster bed. Dynamics of different hard substrates (cobbles, shells and living oysters) were measured in intertidal areas and compared with each other. Attachment strength of oysters within various types of oyster beds is measured.
As indicated the Pacific oyster functioned as a model species in this study. The ambition is to use the same approach to evaluate the effect of climate change on species that are presently regarded as important species in terms of nature protection and species that might become important in the future. A first step to identify important species is made in the report of Van den Brink (2012). In her report, she focusses on the effect of climate change on the existing marine exotic species in the South-western Delta and the exotic species that might invade the Delta area in the future as a result of the sea water temperature increase.

1.3 Approach

In this study a habitat suitability model for Pacific oysters in the Oosterschelde is developed. Univariate knowledge rules for habitat suitability are formulated based on literature data, field observations and expert knowledge (Chapter 3). The habitat model is applied to the predicted maps of hydrodynamics and water quality that have been created with the Deltamodel for the different scenario's (Martini and Van Wesenbeeck 2010). The resulting habitat suitability maps are evaluated and compared with each other. The approach used here on Pacific oysters can also be applied to evaluate the effect of climate change on other species like the species identified in the report of Van den Brink (2012).

2 Pacific oysters

2.1 Spread and development of Pacific oysters in the Oosterschelde

The Pacific oyster (*Crassostrea gigas*) is an important species for aquaculture throughout the world (Figure 2.1). The oyster is native to the waters around Japan and along the east coast of China. It was deliberately introduced for aquaculture purposes into various regions around the world where it has since established and spread. Currently, the Pacific oyster is present in the wild on all continents (Nehls and Büttger 2007).

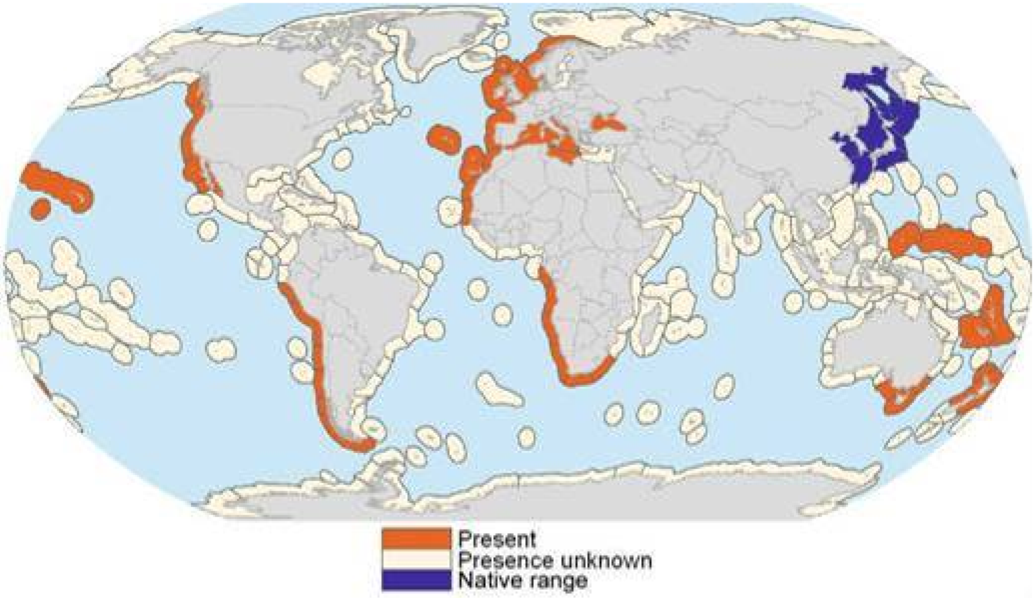

Figure 2.1 Distribution of the Pacific oyster (Crassostrea gigas) throughout the world, including introduced areas (orange) and native region (blue) (Molnar et al. 2008).

In the Netherlands, the Pacific oyster was first introduced into the Oosterschelde from British Columbia in 1964, on an experimental scale to support the oyster fishery. The original populations of flat oysters (*Ostrea edulis*) were decimated during the harsh winter of 1962-63 (Drinkwaard 1999; Smaal et al. 2009). At the time it was assumed that the Pacific oyster could not reproduce successfully in the relatively cold waters of the Oosterschelde (Drinkwaard 1999; Smaal et al. 2009). Furthermore, the potential culture of Pacific oysters in the Oosterschelde was considered a temporary solution as the construction of the Deltaworks would result in the water becoming more brackish, thereby becoming an unsuitable habitat for the oysters.

After the first successful experiments with different varieties of Pacific oyster, the oyster famers began importing the oyster from various locations. The first record of natural recruitment of Pacific oysters in the Oosterschelde date from 1971 (Kerckhof 2011). In 1976, the first recorded spat fall of the Pacific oyster in the Oosterschelde occurred after a warm summer where the water temperature reached over 20°C for more than 50 days, (Drinkwaard 1999). The following year, the import of the oysters was banned (Kater and Baars 2004). The population and distribution of the Pacific oyster greatly increased following successful spat falls during the warm summers of 1982 and 1986. Since then the oyster population has spread dramatically and become strewn along most of the dikes surrounding the estuary (De Kluijver and Dubbeldam 2003; Drinkwaard 1999; Perdon and Smaal 2000; Wijsman et al. 2008). Warm summers are considered the most important factor contributing to the successful development and reproduction of the Pacific oyster in the Waddensea (Diederich et al. 2005) and Troost (2010) notes more factors than just temperature are of influence on development and reproduction in the Oosterschelde.

2.2 Characteristics of the Pacific oyster

The Pacific oyster is a sessile bivalve mollusc. The shell is particularly variable in shape and texture. The shape of the oyster is dependent on the type of substrate and exposure of the habitat. The two valves of the oyster also differ from each other in size and shape. The bottom valve is convex while the upper valve is more concave (thus the oyster is also known as the 'cupped oyster'). One of the valves (the cupped valve) is completely attached to the substrate (Nehring 2006). Pacific oysters can live up to 30 years and grow to a shell length of up to 40 cm while a single individual can weigh up to 1kg (Nehls and Büttger 2007).

Oysters are filter feeders which filter food particles from the water with the help of their gills. An oyster of 200 gram total wet weight can filter approximately 8 litres of water per hour (Bougrier et al. 1995). Edible particles are absorbed through the mouth while particles of less quality are excreted in the form of pseudo faeces. The inedible particles taken up are combined and excreted in the form of faecal pellets.

As larvae, Pacific oysters are either male or female until they settle when they can change sex depending on environmental conditions. If there is sufficient food available, they will become female, and if the food supply diminishes, they will become male (Wang et al. 2007).
During the breeding season up to 50% of the body volume is comprised of reproductive organs (references in Nehring 2006).

In the Dutch waters, reproduction in the Pacific oyster occurs during the summer months when the water temperature reaches over 20°C (Nehls and Büttger 2007). Pacific oysters can produce 50 to 100 million eggs during a single spawning event (references in Nehring 2006). Spawning takes 10 to 15 hours during which the larvae join the plankton in the water column.

After three to four weeks (depending on water temperature) the larvae settle out of the plankton onto the substrate. Throughout their relatively long pelagic stage, oyster larvae can distribute widely by travelling long distances on water currents (Brandt et al. 2008). When settled, the larvae gather together and crawl towards suitable hard substratum where they attach their bottom valve to the substrate with calcium. The oysters can attach to a variety of hard substratum such as the sides of dikes, stones, wood and rope, but also biological structures such as the shells of other bivalves, crabs and crayfish. Once established, the adult oysters form substrate new oyster larvae prefer to settle on (Diederich 2006).

3 Habitat model Pacific oysters

For the majority of their lives, Pacific oysters live as sessile organisms. Once the larvae are settled they cannot migrate actively. Although the habitat of the oysters is therefore fixed, the oysters are able to close their valves during times when environmental conditions are unsuitable, such as at low tide to prevent drying out. If, however, the oysters remain in an unsuitable environment for too long, they will eventually die.

In general, the suitability of a habitat for a certain species depends on the environmental variables in each specific area (Wijsman 2002). For example, the suitability of a certain location for the development of an oyster bed can depend on a specific variable (e.g. Figure 3.). When the value of a variable is between a lower and upper threshold, growth and development of the Pacific oysters is optimal, and the habitat suitability of the location (with regards to the one variable) has a value of 1. If the value decreases to below the lower threshold, or increases to above the upper threshold the oysters become stressed and the location becomes less suitable for them, resulting in a value of < 1. If the value becomes too low or too high, the location is unsuitable and no oysters will survive there. The shape of the curve is different for each environmental variable.

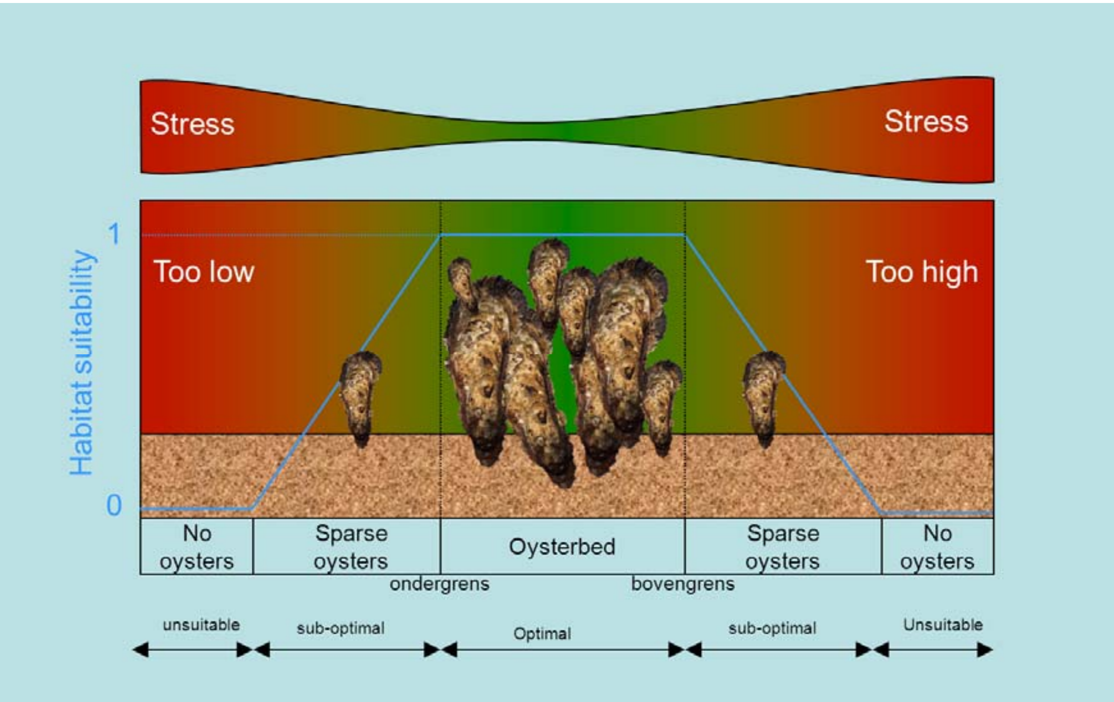

Figure 3.0 Influence of environmental variables on the suitability of a habitat for oysters. If the environmental variable is unsuitable (too low or too high) oysters will fail to establish. If the environmental variable is suboptimal, no or few oysters will establish. If the environmental variable is optimal, then the area is in principle a suitable location for oysters to establish.

The suitability of a habitat is dependent on a combination of environmental conditions, each of which affect the habitat suitability to varying degrees. In order to develop to an oyster bed, the environmental conditions must be suitable for all life stages of the oyster (establishment of larvae, development of juveniles and reproduction). Suitable substrate is of highest importance for the establishment of larvae, but water quality (e.g. temperature, salinity, acidity) must also be suitable for their survival. For the successful development of juvenile oysters, it is important that there is enough food supply in the water, and that the water quality (temperature and salinity) is also suitable.

3.1 Approach

To assess the effects of sea level rise and infrastructural changes to protect the Delta against climate change on the possibilities for oysters to find suitable habitat, we constructed a habitat suitability model. Literature search and analyses are combined to form knowledge rules in a Habitat model for the Pacific oysters in the Oosterschelde. Only the cover of littoral oysterbeds in the Oosterschelde are used as a basis for the formulation of these knowledge rules, because the complete cover of sublittoral oysterbeds is not known. Purpose of this model is to predict habitat suitability in the Delta considering three scenarios that may occur with climate change. 1) a scenario describing the present state of the delta. 2) a scenario where, in comparison with the first scenario, water level was increased in response to sea-level rise. 3) a scenario where, in contrast to the first scenario, water connections between the North Sea and the Grevelingenmeer, and the Grevelingenmeer and the Volkerak-Zoommeer were restored.

The responses on two variables (temperature and salinity) are calculated/determined from literature. The responses on other variables (exposure time, current velocity, ecotypes and geomorphology) are estimated comparing the occurrences on the oyster map in the Oosterschelde with maps of values of these variables. The availability of data on these variables in the complete Delta eventually largely determined what variables could be used in the formulation of a habitat model; temperature, ecotypes and geomorphology were excluded as variables in the model because a lack of data. Wind-induced sheer stress was left out as a variable because it could not define the presence or absence of oysters in the Oosterschelde. Considering the scenarios under investigation, however, the variables most likely to be affected in the different scenarios, salinity in scenario 3 and exposure time in scenario 2, could be incorporated in the habitat model along with current velocity.

The habitat model is calculated from a set of univariate variables of the Habitat Suitability Index (HSI) for Pacific oyster reproduction as a function of each variable. The HSI for a given variable varies between 0 (unsuitable) and 1 (suitable). The overall suitability is determined from the minimum value of the diverse univariate HSI's.

3.2 Temperature

The physiology of the Pacific oyster is strongly dependent on temperature. The activities of the oyster (feeding and respiration) are influenced by temperature, and reproduction is triggered by temperature. Growth in oysters is the result of the balance between assimilation and respiration. Both processes are influenced by temperature as well as size of the oyster (Bougrier et al. 1995). Unfortunately, however, the available data on pacific oysters and temperature in the Delta do not permit any meaningful formulation of a HSI on temperature. Experiments have shown that *Crassostrea gigas* is sensitive to short periods of exposure to extreme high temperatures. Death has been observed with water temperatures of 30°C. 100 % mortality occurred in one hour exposure to temperatures of 42°C (Rajagopal et al. 2005). Although Pacific oysters are particularly tolerant to extreme cold winter temperatures (Nehls and Büttger 2007), temperatures too low can also cause death. Juvenile oysters are particularly sensitive to cold temperatures and will die if the water temperature remains below 3°C for three weeks over winter (Child and Laing 1998). During periods of exposure, oysters can tolerate air temperatures as low as -4°C (Pauley et al. 1988). During summer, morality increased in the oysters when water temperatures rose above 20°C when the oysters had just spawned. Females are primarily sensitive to this summer mortality (Child and Laing 1998). To incorporate the different effects temperature has on the suitability of a habitat, one would have to incorporate the time- and seasondependency of these effects. Data provided by the MWTL (www.waterbase.nl) shows that the average water temperature in the Oosterschelde is generally between 5 and 25 °C (Wijsman and Smaal 2011). It can, therefore, be assumed that temperature is not a limiting factor for the Pacific oysters. However, on a local and temporal scale, temperature can lead to increased mortality during a harsh winter for oysters on exposed mudflats. With the available data-sets we cannot account for these spatial and temporal dependencies. At the intertidal mudflats for example temperature is not measured regularly. Consequently only the reaction on a single temperature can be assessed, that does not discriminate between locations. Even though the average temperature in the Oosterschelde (15 degrees Celsius) was assumed to be too low for oysters to sustain a viable population prior to introduction of pacific oysters in the Oosterschelde, present abundance and expansion of oysters in the Oosterschelde shows that the average temperature is not a constraint for oysters. In the model we therefore do not consider the average temperature to limit habitat suitability.

3.3 Ecotopes and geomorphology

Oyster presence in the Oosterschelde can also be defined by geomorphology and ecotopes. Geomorphology pertains to the substrate present in an area, while an ecotope is described in terms of a combination of physical attributes such as water depth and dynamics.

The largest parts of the flats in the Oosterschelde are low energy, sand flats. Most oysters are also found in these geomorphological areas. A relatively large amount (>10 %) of the area is covered with oysters on the culture plots and on the flats. The hard substrates, clay and peat bog banks with around 25 % sand cover and the cultured slopes or troughs also have a relatively high cover of oysters, but are rare habitats. It should be noted here that oyster cover on the dike slopes in the Oosterschelde are not included in this analysis.

On the other hand, for instance low wave relief areas in the low energy flats appear not to be preferred habitats for oysters. Similarly, in salt marshes there are also few oyster beds present.

The presence of oysters in the Oosterschelde can be related to the ecotope map according to the Zoute Wateren Ecotopen Stelsel 2001 (Salt Water Ecotope System 2001) (Bouma et al. 2005; Wijsman 2003). On the basis of aerial photographs, the ecotope map is divided into nine different classes that define exposure time, water depth and dynamics.

The largest proportion of ecotopes in the Oosterschelde were sublittoral ecotopes; Sublittoral high dynamic, Gullies low dynamic, Shallow low dynamic and Middle littoral low dynamic. From monitoring surveys in the Oosterschelde we know that in the sublittoral Pacific oysters only sparsely occur (Brummelhuis et al. 2011). The largest proportion of oysters were found in the Shallow low dynamic ecotope. A large proportion of these oyster beds were located in the eastern part of the Oosterschelde where the substrate becomes exposed during the spring floods or a strong easterly wind.

Most oysters in the littoral zone were found in the Low littoral low dynamic and littoral water ecotopes. The High dynamic high littoral and the High littoral ecotopes are probably unsuitable habitats for wild oyster beds, either because of the long exposure time, or because of the highly dynamic substratum. The Littoral water ecotope appears to be particularly suitable for wild oyster beds. In the Littoral water ecotope, there may be a bottom layer of water through which the underlying substrate is not visible.

In general, on the basis of the ecotope map it can be concluded that oyster beds are predominantly present around the low tide line in relatively sheltered areas. The high dynamic littoral mudflats are likely to be unsuitable habitats for oysters.

Even though ecotypes and geomorphology do define habitat suitability for oysters in the Oosterschelde, no data on ecotypes or geomorphology is available in maps for the complete Delta. For the calculation of habitat suitability maps of the Delta therefore, we have neglected these dependencies.

3.4 Salinity

Salinity also influences the physiology of the Pacific oyster. The optimal salinity for Pacific oysters is 25 - 35 ppt. Salinities lower than 20 ppt have a negative effect on the oysters. At salinities around 13 ppt, filtration rates decrease significantly and at 10.5 ppt oysters are physically damaged (Pauley et al. 1988). Pacific oysters can grow and reproduce in salinities between 10 and 42 ppt, but fertilisation is optimal in salinities of 23 -36 ppt (Nehring 2006; Wang et al. 2007). Oyster larvae cannot survive salinities lower than 10 ppt, but can tolerate salinities between 16 and 34 ppt, however, variable salinities can have a damaging effect on larvae.

Hyun et al. (2001) investigated the effect of salinity on the filtration rate of Pacific oysters. Hyun et al. (2001) found that filtration ceases when salinities drop below 10 ppt, while they found that above 20 ppt salinity no longer has an effect on the filtration rate.

Escaravage et al. (2006) state respiration is also influenced by salinity. At salinities higher than 20 ppt, respiration is no longer dependent on salinity (but is determined by temperature). It appears that oysters survive best in salinities above 20 ppt. If there is sufficient food availability or if the temperature is not too high, oysters can tolerate salinities as low as 15 ppt.

3.4.1 Salinity HSI

Optimal salinity for the Pacific oyster is above 25 ppt. In lower salinities the habitat suitability decreases, and the habitat is considered unsuitable in salinities below 10 ppt (Figure 3.1). The salinity in the Oosterschelde is generally optimal for the oysters. Salinity can vary locally and temporarily become a limiting factor such as during a period of heavy rainfall. These relatively short periods are, however, no problem for the oysters as they can simply close their valves.

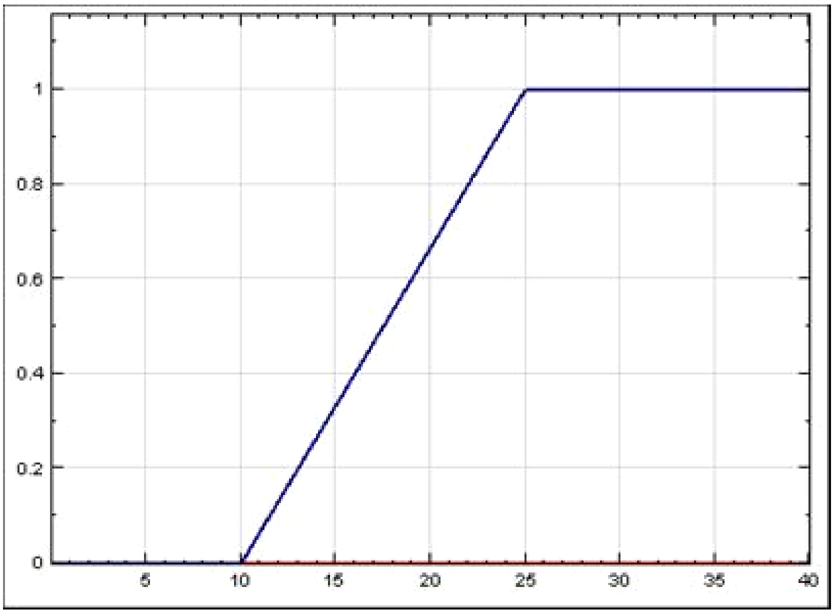

Figure 3.1 Habitat suitability index for the Pacific oyster as a function of salinity (ppt).

3.5 Exposure time

Exposure time is calculated from water depth and tidal fluctuations. The Delta model reproduced the tidal fluctuations (in m NAP) per hour in the Oosterschelde for the year 2000. Determining the fraction (1, 0.95, 0.9, 0.8, 0.7 ,0.6 ,0.5 ,0.4 ,0.3 ,0.2 ,0.1 ,0.05 ,0) of water level in time, a function of water level in fractions of time was created. This function was then combined with the bathymetric map (Figure 3.2). to determine what fraction of time a certain area of a certain depth was exposed. The exposure time map was created by combining the bathymetric maps of the different compartments with the map "Algemeen Hoogtebestand Nederland". This exercise resulted in the map in Figure 3.3.

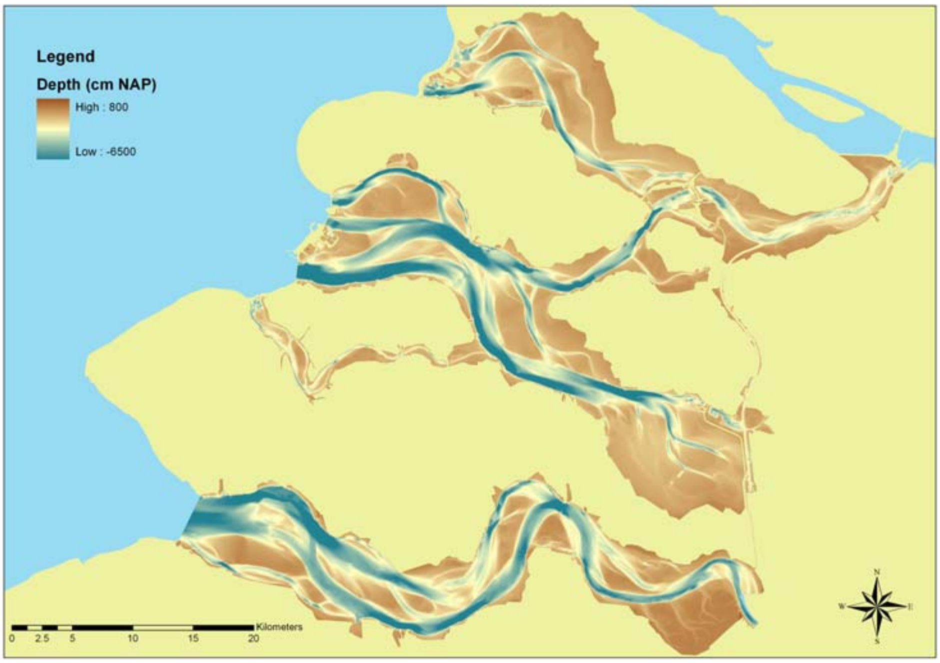

Figure 3.2 Bathymetric map of the Delta area.

Exposure time is considered an important predictor variable for the presence of Pacific oysters (Wijsman 2007). Oysters can tolerate exposure, but if exposed for too long they can no longer filter feed or breathe. While exposed, the oysters are vulnerable to the cold during frosts in the winter and the heat in the summer.

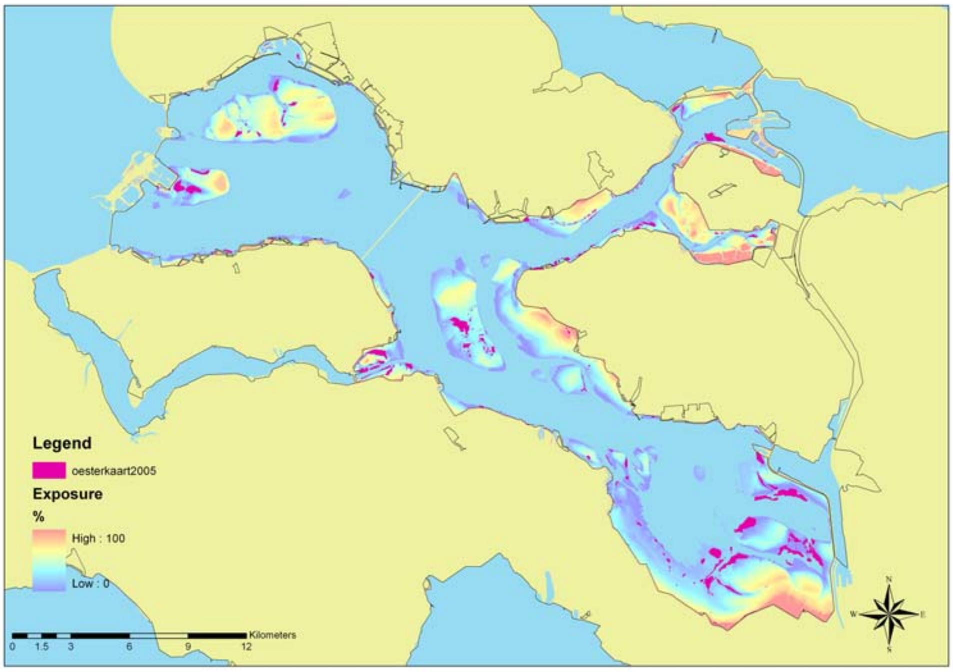

Figure 3.3 Exposure time of areas throughout the Oosterschelde and the presence of Pacific oysters in 2005 (purple).

Exposure time is divided into 100 classes of 1 % each. For each class the total number of gridcells were determined and the percentage of grid cells in each class containing oysters was calculated (Figure 3.3). More than 85 % of the oysters in the intertidal zone existed in areas with exposure times below 40 %. Few oysters were recorded in the areas with exposure times between 40 % and 70 % with a relatively large surface area. Although there appear to be oysters conspicuously high in the littoral zone where exposure time is over 80 %, the total number of oysters in this area is limited due to the limited intertidal surface area.

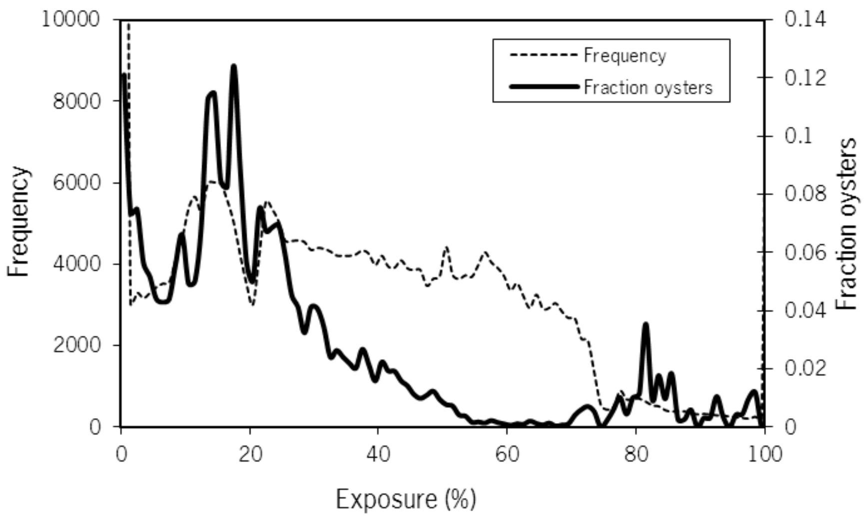

Figure 3.4 Frequency distribution of the different exposure time classes (% of the time exposed) in the Oosterschelde (dashed line) and the fraction of total oyster presence where oysters are present (solid line).

3.5.1 *Exposure time HSI*

Figure 3.4 leads to an assumed response curve for exposure time. Exposure time of less than 30% is optimal for the oysters, but exposure time above 60% is unsuitable (Figure 3.5).

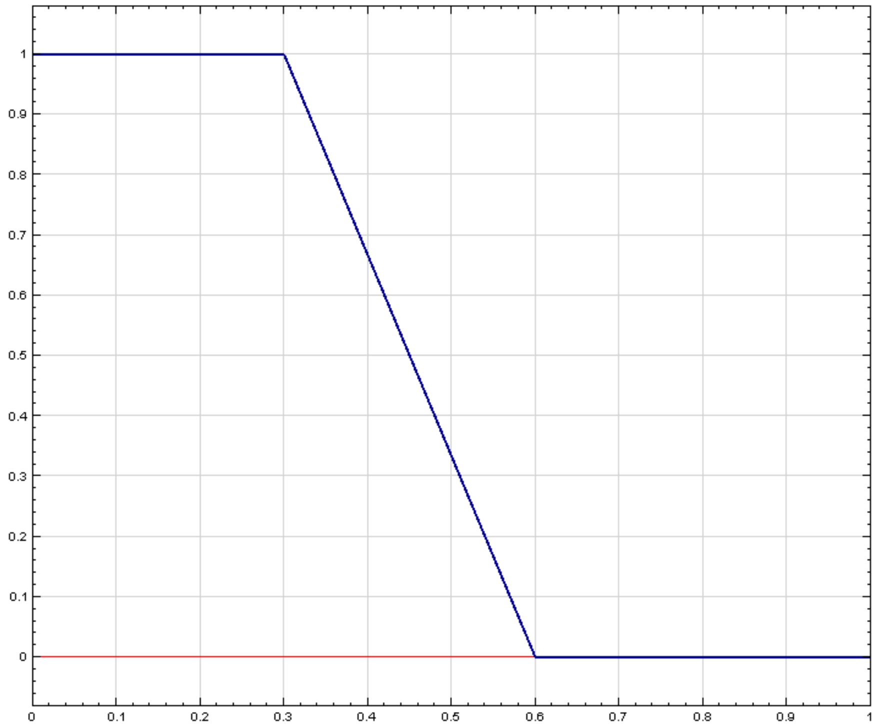

Figure 3.5 Habitat suitability index for the Pacific oyster as a function of exposure time (fraction).

3.6 Current velocity

Current velocity in the Oosterschelde is calculated with the ScalOost model for 1996. From the modeled current velocity, the average velocity is determined. The highest current velocity is in the channels, while the current velocity is much lower in the intertidal zones where the littoral oyster beds are (Figure 3.6).

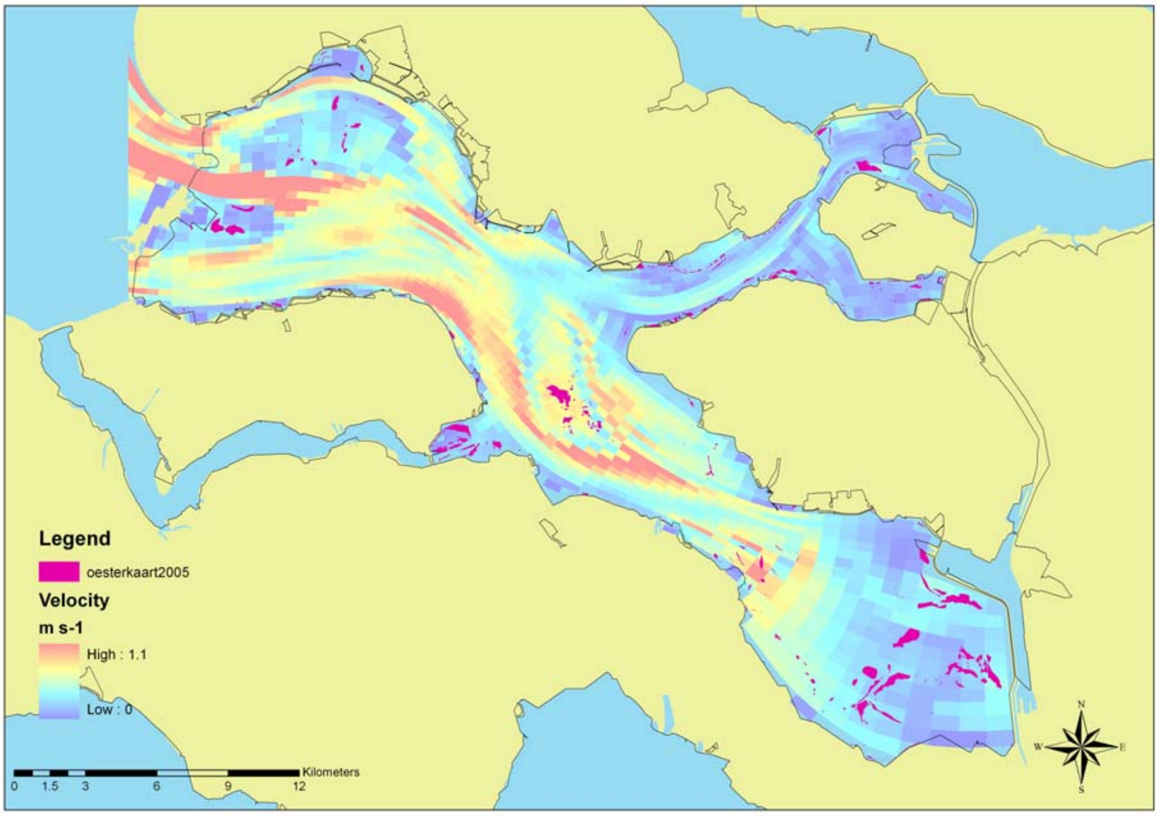

Figure 3.6 Current velocity (m s^{-1}), calculated with the ScalOost Model for the Oosterschelde in 1996 and the presence of Pacific oysters in 2005 (in purple).

Current velocity was divided into 100 classes of 1.8 cm s^{-1} each. For each class the total number of gridcells was determined and the percentage of gridcells containing oysters was calculated. Most oysters in the littoral zone were present in areas with current velocities below 40 cm s^{-1} (Figure 3.7). Current velocities above 40 cm s^{-1} tend to be located in the sublittoral deep channels, where no oyster beds are found (Brummelhuis et al. 2011). Virtually no oysters were present in areas with particularly low current velocities (below 2 cm s^{-1}).

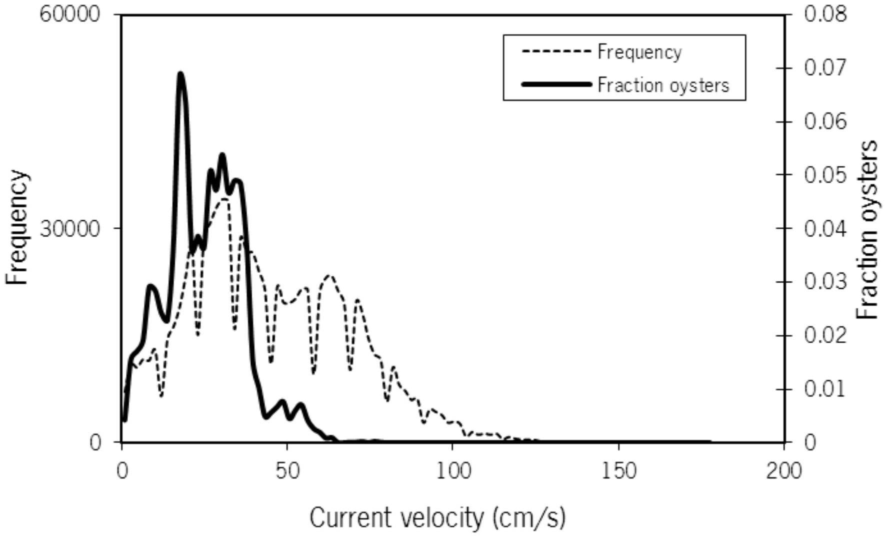

Figure 3.7 Frequency distribution of different current velocity classes in the Oosterschelde (cm s^{-1}) (dashed line) and the fraction where oysters are present (solid line).

3.6.1 *Current velocity HSI*

The current velocity on the mudflats in the Oosterschelde is generally low (<50 cm per second). Littoral oysters appear to be present only where current velocity is below 50 cm s^{-1} (Figure 3.8). From this no direct conclusion can be made that oysters cannot survive in current velocities above 50 cm s^{-1} as it is possible that oysters in the sublittoral survive in current velocities this high. However, sublittoral oysters are not included in the analysis.

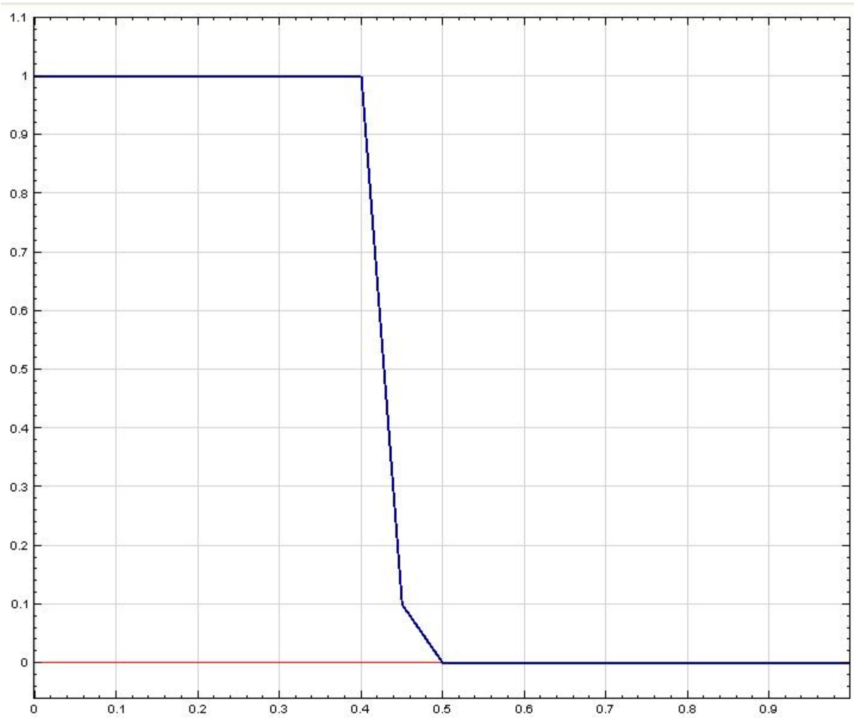

Figure 3.8 Habitat suitability index for the Pacific oyster as a function of current velocity (m s^{-1})

4 Model scenario's

In this study, we considered three scenarios:

1) Current situation (baseline scenario)
2) Current situation with sea level rise of 0.8 m
3) Increased water flow between the North Sea and Grevelingenmeer, and an opening between Grevelingenmeer and Volkerak –Zoommeer

A scenario with both sea-level rise (2) and reconnecting the compartments (3) was not possible with the current version of the Delta model (Martini and Van Wesenbeeck 2010).

These three scenarios were simulated in Deltares model to obtain maps in each scenario of maximum current velocity and salinity. The results of the model simulations are presented in Martini and Van Wesenbeeck (2010).

Also in each scenario, exposure time at each water depth given the water levels was calculated following the same method explained in section 2.5, but then for each compartment in the delta (Oosterschelde, Westerschelde, Grevelingenmeer, Volkerak-Zoommeer, Veerse Meer) in each of the three scenarios separately. Again, the tidal fluctuations in each compartment of the Delta in each scenario was calculated by Deltares.

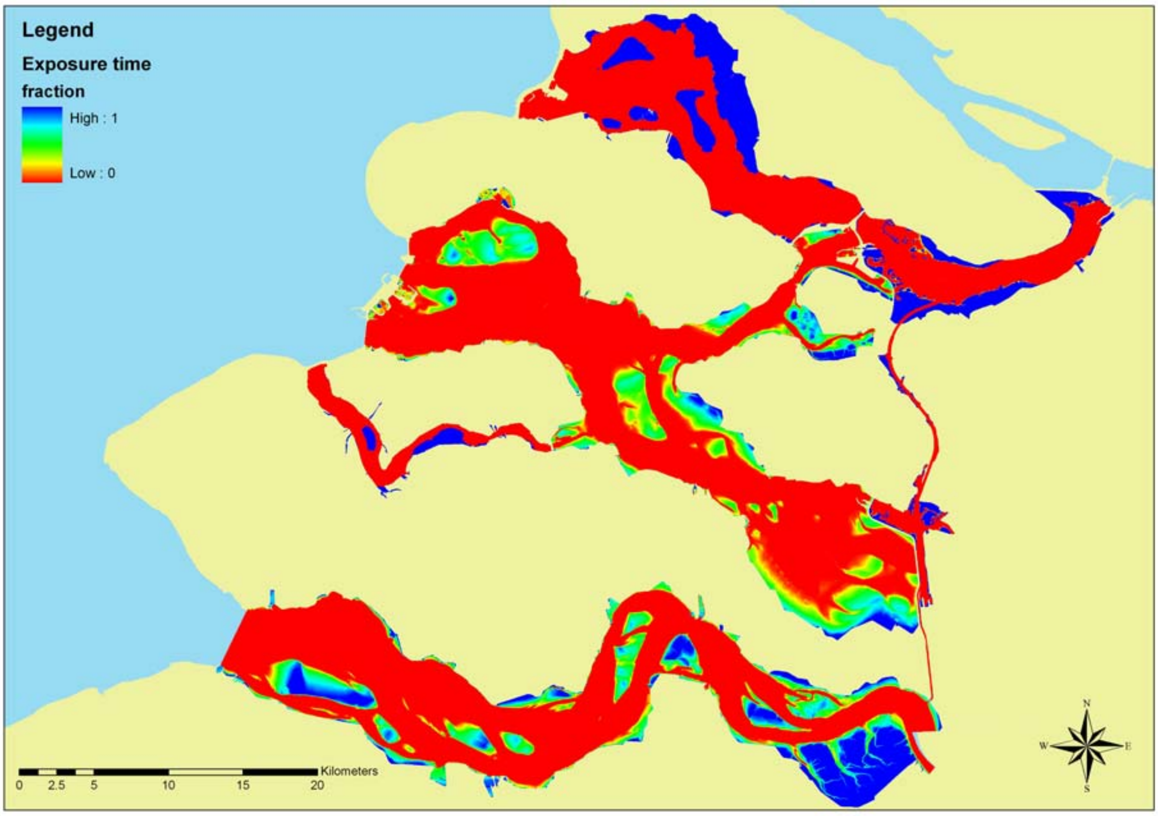

Figure 4.1 Calculated exposure time (fraction) Current situation.

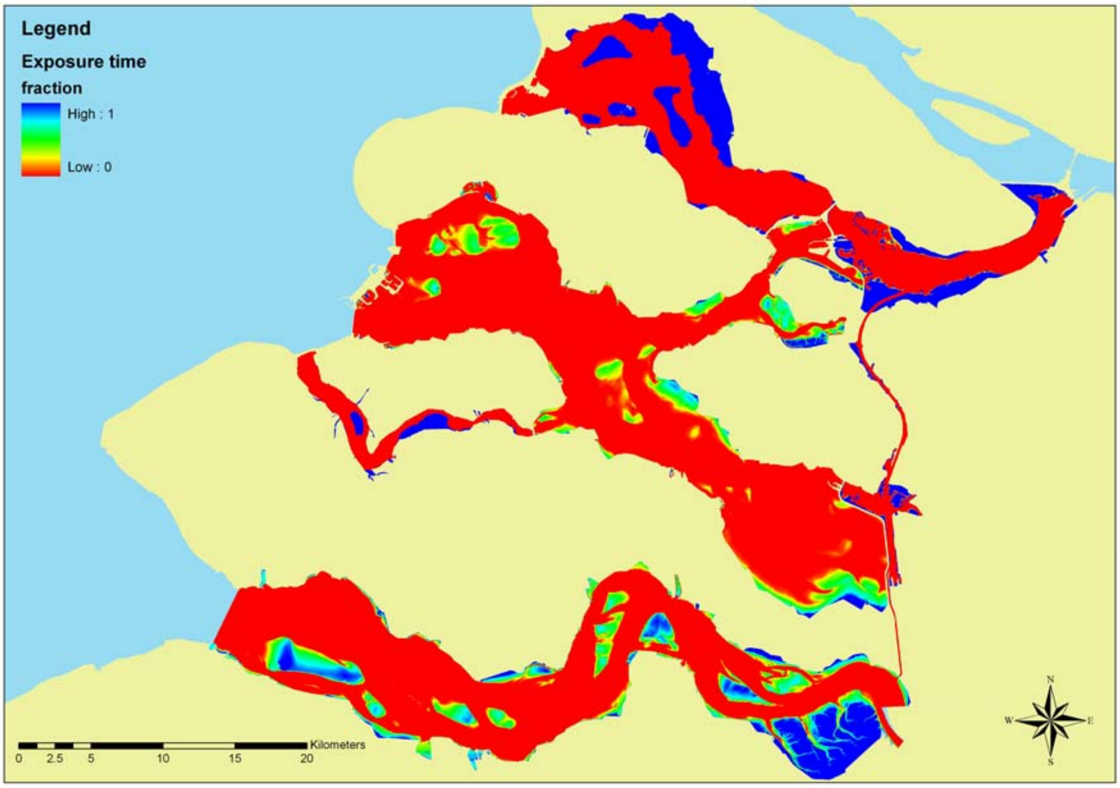

Figure 4.2 Calculated exposure time (fraction) scenario 2: Sea level rise.

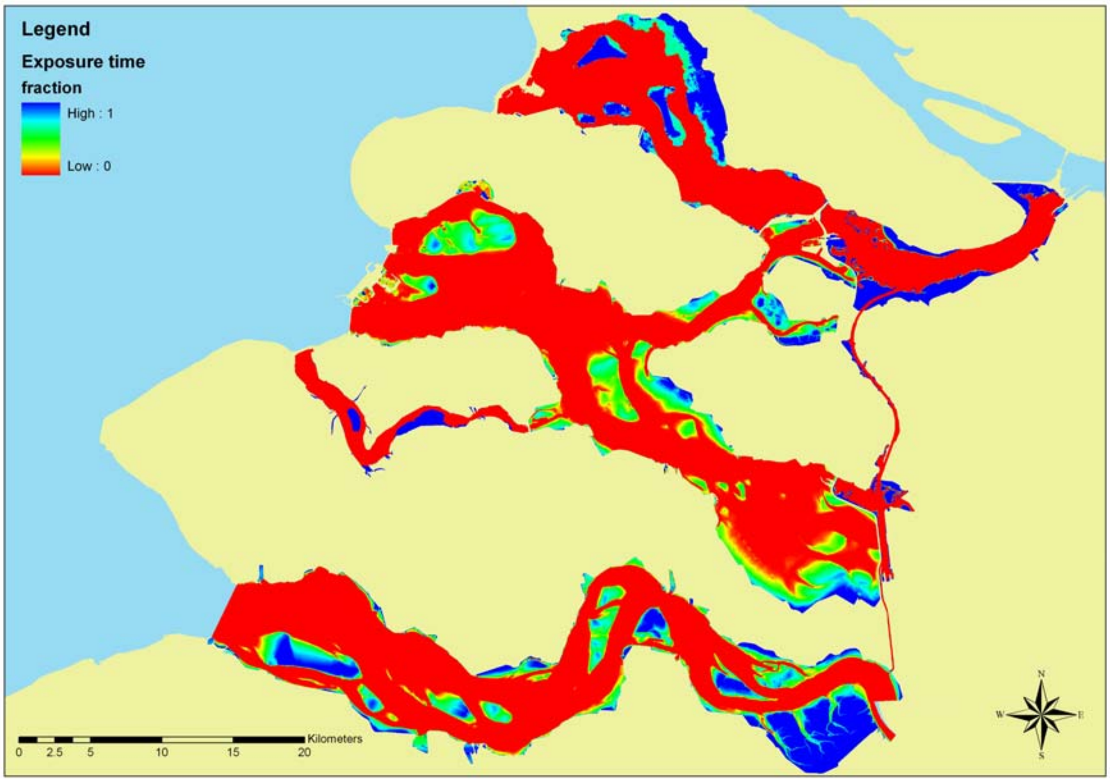

Figure 4.3 Calculated exposure time (fraction) scenario 3: connecting the basins.

The values of the variables in these maps determined the suitability of the habitat at each grid cell according to each variable following the knowledge rules formulated in Figure 3.1, Figure 3.5 and Figure 3.8. The lowest value of HSI of these variables on a location then determined the final habitat suitability for oysters on that location. This procedure resulted in the habitat suitability maps in each of the three scenarios (Figure 5.1, Figure 5.3 and Figure 5.5).

5 Results

5.1 Overall habitat suitability for baseline scenario

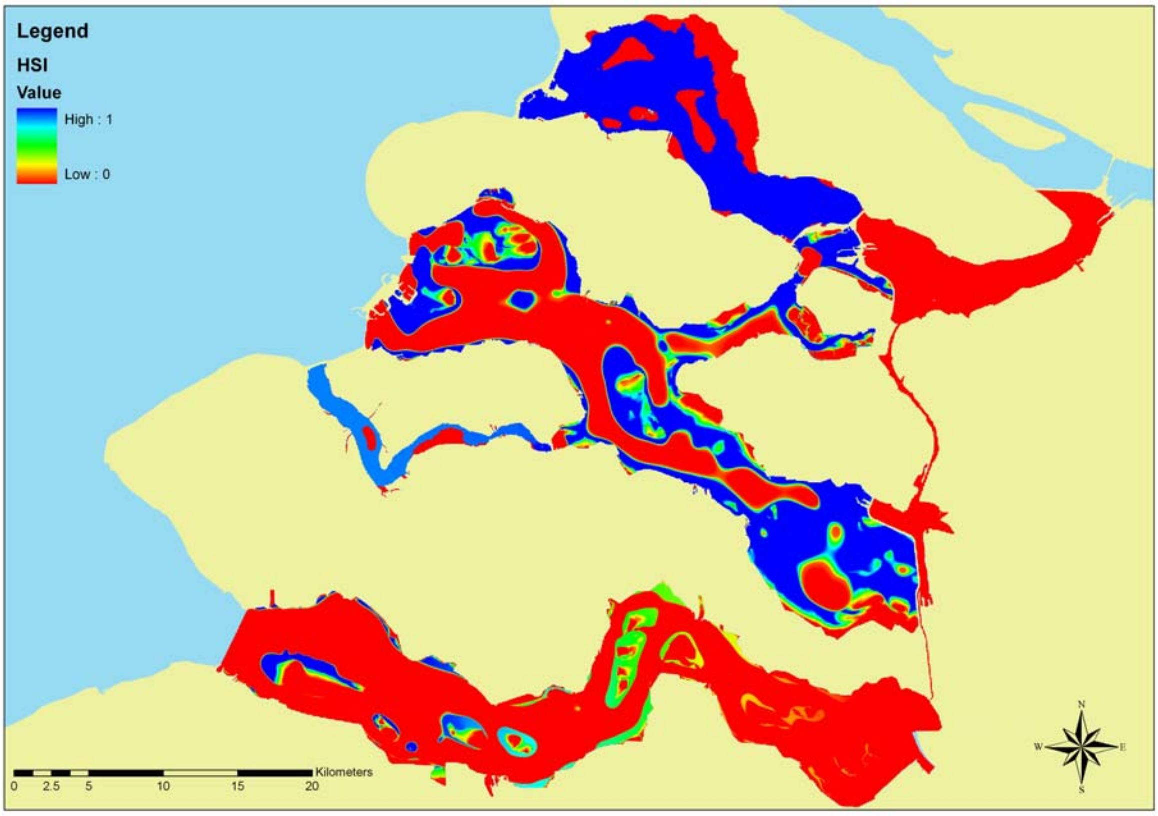

Figure 5.1 Habitat suitability index for the Pacific oyster in the Delta, present situation.

The habitat suitability map shows that a large proportion of the exposed mudflats in the Oosterschelde and Westerschelde are potentially suitable for Pacific oysters. The most suitable areas are in the eastern part of the Oosterschelde, the Vondelingsplaat and the mudflats of the Dortsman. Smaller areas in the Westerschelde, along mudflats and coast, are also highly suitable for settlement.

Each location has at least one limiting factor influencing the overall habitat suitability. Especially when overall habitat suitability is low in Figure 5.1, it is informative to known what limits its suitability most. We considered an overall HSI < 0.3 to be low and plotted the limiting factors determining HSI <0.3 in Figure 5.2. These results suggest that exposure time is an important parameter limiting the distribution of the Pacific oyster throughout the delta. Current velocity is limiting in large areas in the Oosterschelde and Westerschelde, whereas salinity limits habitat suitability in the Volkerak-Zoommeer and the eastern part of the Westerschelde.

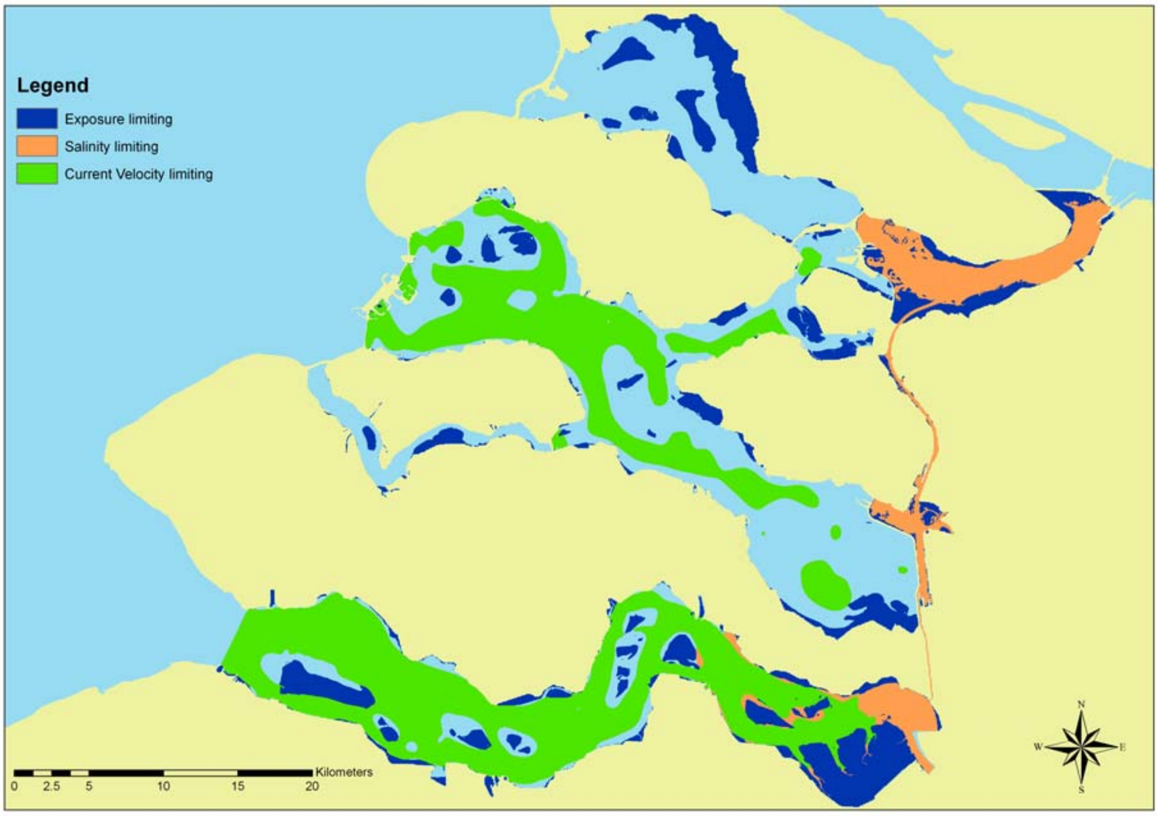

Figure 5.2 Map indicating the limiting factors for the habitat suitability for Pacific oysters in de Delta in the current situation. In the dark blue area's exposure time is too high. In the orange area's salinity is too low and in the green areas, current velocity is too high. In the other areas (light blue), the habitat suitability is more than 0.3.

5.2 Overall habitat suitability for sea-level rise scenario

Compared to the baseline scenario, sea-level rise increases the habitat suitability for oysters mainly because the exposure time decreases. Consequently, regions suitable for oysters along mudflats and coasts become larger. There are no changes in habitat suitability for the Volkerak-Zoommeer in this scenario. Some areas, especially in the Veerse meer and along the gullies of the Oosterschelde, actually decrease in suitability due to an increase in current velocity in these areas in this scenario.

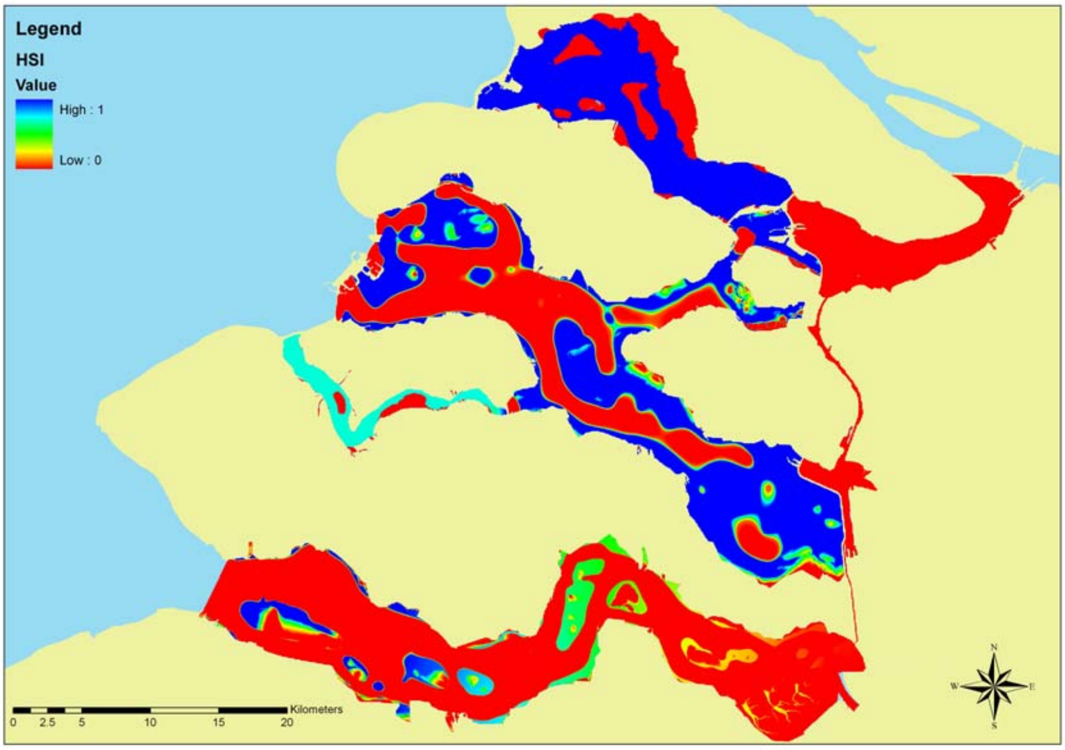

Figure 5.3 Habitat suitability index for the Pacific oyster in the Delta, in the sea-level rise scenario.

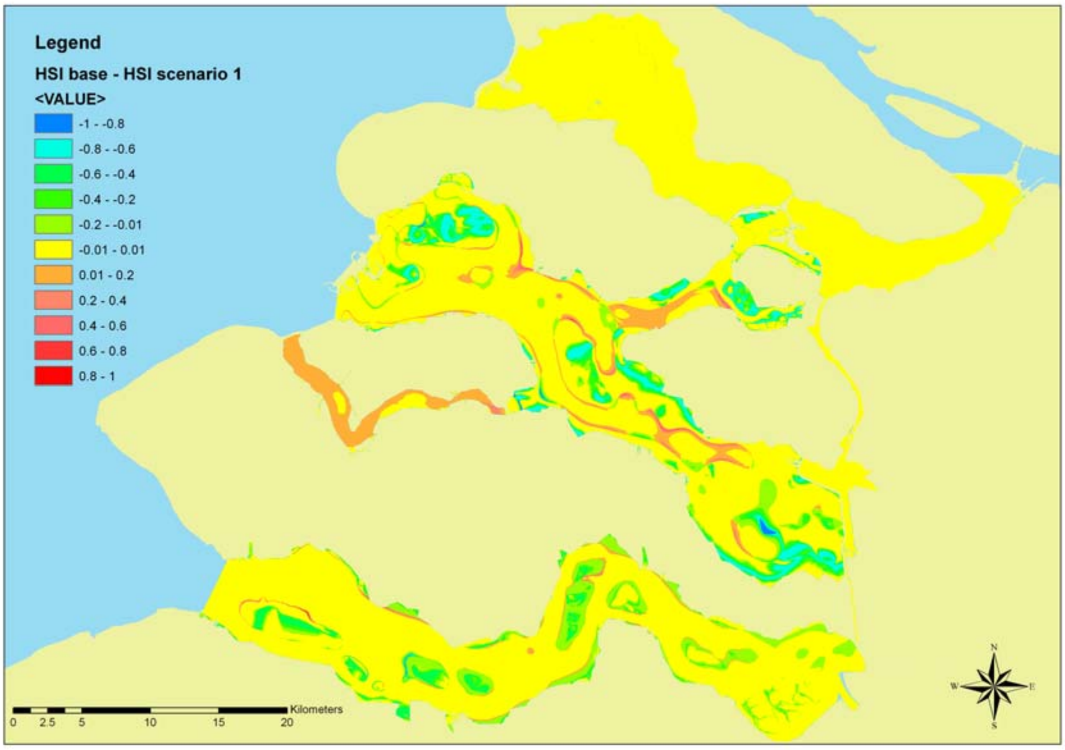

Figure 5.4 Difference in Habitat suitability index between the baseline scenario and the sea level rise scenario. Positive values (reddish colours) indicate a decrease in HSI and negative values (green and blue colours) indicate an increase in HSI.

Current velocity is mainly limiting in the Oosterschelde and Westerschelde, whereas exposure time is limiting throughout the delta at the coasts and mudflats. Salinity is a limiting factor in the Volkerak-Zoommeer and some areas in the eastern Westerschelde.

5.3 Overall habitat suitability for connecting basins scenario

Compared to the baseline scenario, connecting the basins enhances habitat suitability for oysters in the Volkerak-Zoommeer. However, there still remains a gradient of habitat suitability in the Volkerak-Zoommeer. This scenario connects the salty Grevelingenmeer with the sweet/brackish waters of the Volkerak-Zoommeer. The increase in suitability is mainly due to the increase in salinity and also the gradient in habitat suitability is determined by a gradient in salinity. The Westerschelde is also affected by this scenario; small changes in the habitat suitability compared to the baseline scenario do occur because of a small increase in salinity in the eastern part of the Westerschelde.

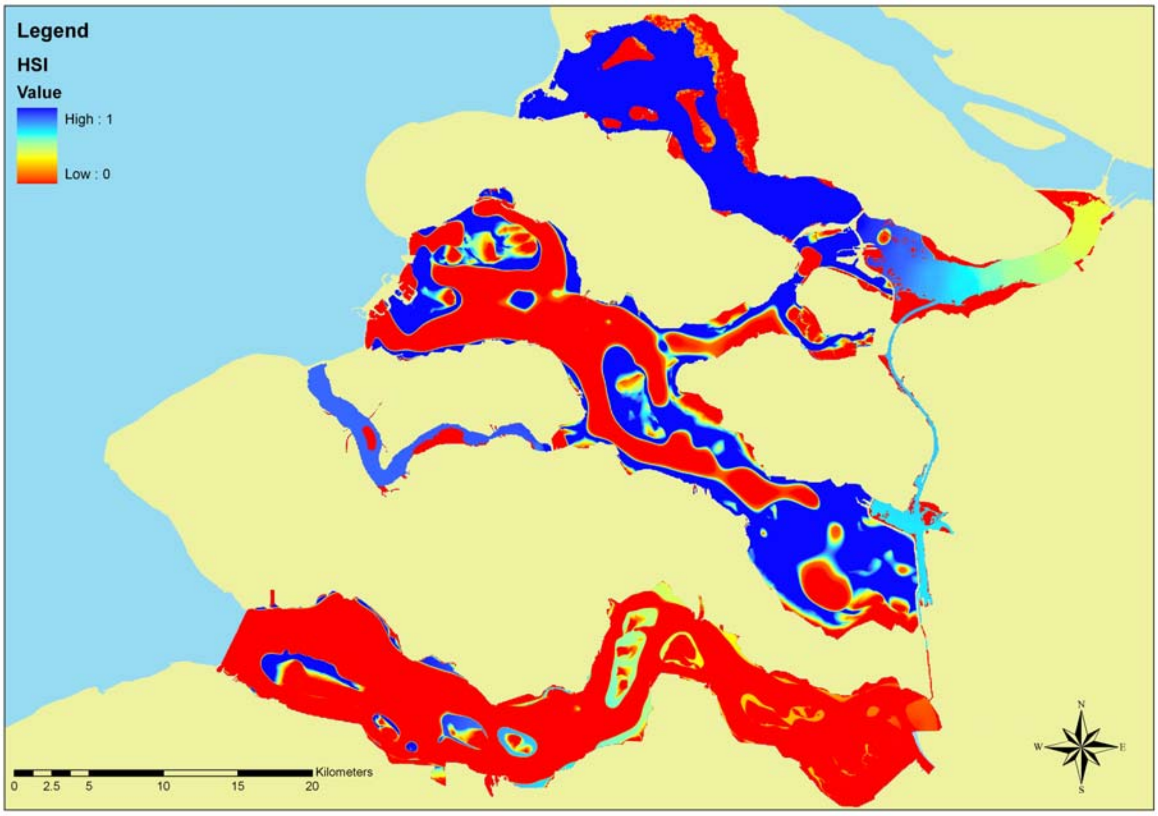

Figure 5.5 Habitat suitability index for the Pacific oyster in the Delta, in the connecting basins scenario.

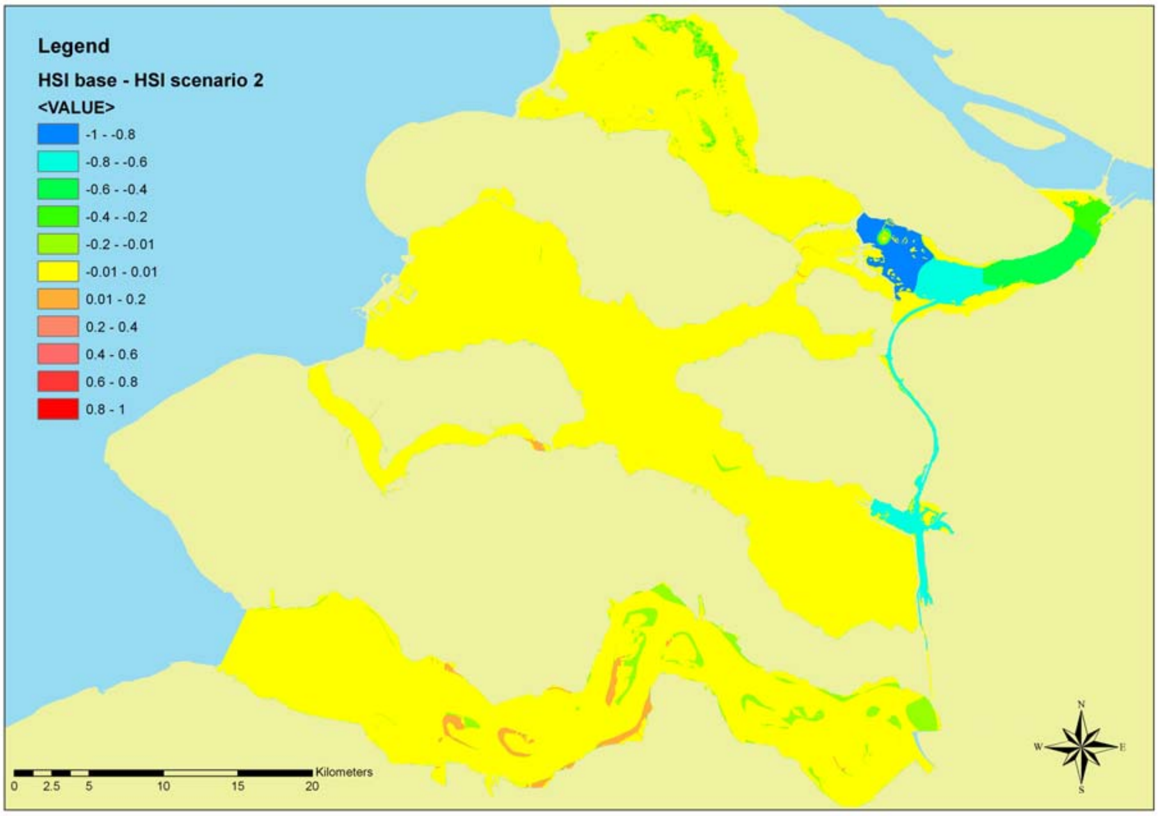

Figure 5.6 Difference in Habitat suitability index between the baseline scenario and the connecting basins scenario. Positive values (reddish colours) indicate a decrease in HSI and negative values (green and blue colours) indicate an increase in HSI.

Like in the previous scenarios current velocity is limiting mainly in the Oosterschelde and Westerschelde, exposure time throughout the Delta on coast, mudflats, but salinity in this scenario is only limiting in the eastern part of the Westerschelde.

6 Conclusions

There is a multitude of available methods to produce habitat suitability maps. These methods can be broadly separated into two classes. One class of methods is data based; a data set of presence/absence data of a species is linked to environmental variables and 'response curves' are formulated that can be used to predict suitability in other areas with these variables. This class of methods is highly dependent on the quality of the data-set one builds the model on. The other class of methods is knowledge based; experimental evidence for the dependencies on certain variables is formulated into 'knowledge rules' that serve the same purpose as 'response curves' in making maps of suitability. In essence, given these knowledge rules one can predict suitability even without a monitoring data-set. Both classes of methods, however, need to project the model on data of environmental variables. For different variables we have used different methods. For exposure time and current velocity we have used a data based approach, whereas for salinity we used literature based knowledge. Even though a monitoring data-set is not as important in both classes, all habitat suitability maps are subject to the quality of the maps of environmental variables that it should be projected on.

If we compare the modelled habitat suitability of the Oosterschelde in the baseline scenario with the oyster map of 2005, there are many differences. The oyster map maps the oysters in the littoral zone, whereas sublittoral oyster beds are known, but rare (Brummelhuis et al. 2011). Also, the oyster map of 2005 might give an overestimation of suitability in some areas where shells are empty. The cover of oyster beds has likely not reached an endpoint yet, however, based on habitat suitability; the cover of oysters in the Oosterschelde is still expanding. Because of the high expansion rate of oyster beds, some areas unsuitable for settlement may nevertheless be covered by oysters at some point in time, but perish over a longer timespan because of the unsuitability of the area. Also, some areas may have not been covered yet but will be in the near future. The oyster map of 2005 may therefore overestimate the suitability of certain areas, but neglect and underestimate suitability of hard-to-reach areas. The habitat suitability map on the other hand is not influenced by hard-to-reach areas. Instead, the knowledge rules on exposure time and current velocity in sections 3.5.1 and 3.6.1 are based on the oyster map of 2005. Because the habitat suitability maps are not constrained by time and all areas covered by oyster beds are considered suitable, the habitat suitability maps probably overestimate the suitability of certain habitats. Consequently, the areas predicted by the model to be suitable for oysters is much larger than that shown in the oyster map of 2005.

A second reason for the overestimation of habitat suitability maps is that all constraining variables might not have been taken into account. As mentioned in section 2, variables such as temperature or ecotopes were not available in enough detail for all scenarios Additions of these variables into the model and data on these variables throughout the Delta could improve the habitat suitability map.

As indicated before the quality of the habitat suitability maps is dependent on the quality of the maps of the environmental variables on which the model is projected. Therefore, another reason for the disparity between the habitat suitability map and the oyster map of 2005 may be the quality of the maps of environmental variables. For instance, if we compare the current velocity map of the Oosterschelde (Figure 3.6) with the current velocity map of the Deltamodel (figure 3.10 in Martini and Van Wesenbeeck 2010) we see differences in both the flows and velocity of water in the Oosterschelde. These differences are a result of the different models used to make these maps. Figure 3.6 is calculated with the ScalOost Model (3-D model) for the Oosterschelde in 1996, whereas that used for the complete Delta is an interpolation of a simpler 1-D model on the bathymetric map of 2001. As a simplification of the interpolation: the deeper a location the more water can flow through. The interpolation causes some unfortunate mistakes in the calculation of current velocity. For instance, as a consequence of this interpolation, an area that in reality is used for commercial oyster farming (in the south-eastern part of the Oosterschelde) becomes unsuitable in the modelled map because of high current velocities in that area. In Figure 3.6 however, it can be seen this area is not constrained by high current velocities at all, even though a small gully runs through the culture plots to access these plot by boat. A better (3D) calculation of the current velocities throughout the Delta may therefore result in better habitat suitability maps.

Given these difficulties and circumstances, the habitat suitability maps nevertheless show a reasonable estimation of the habitat suitability for oysters throughout the Delta and can be used to broadly indicate the consequences of the effect of climate change and infrastructural changes on the habitat suitability for oysters. The biggest effect on the cover of suitable area for oysters is when the Volkerak-Zoommeer is connected to the salt water of the Grevelingenmeer. This connection increases salinity in the Volkerak-Zoommeer and also slightly in the eastern part of the Westerschelde. Since in those areas salinity was the most limiting factor, the increase in salinity opens up the possibility for oysters to settle there. The change in infrastructure also affects the exposure time and current velocity to some extent, but that hardly affects suitability compared to the baseline scenario (Figure 5.6).

In contrast to the scenario with infrastructural changes, the increase in seawater-level only affect suitability for oysters on a local scale. With a seawater-level rise the exposure time of mudflats and coasts decreases, increasing the HSI for exposure time (Figure 3.5) and increasing overall suitability on those spots. Since exposure time in the baseline scenario is limiting throughout the Delta, a relief of limitation affects suitability throughout the Delta as well. Exposure time with sea-level rise, however, remains an important limiting factor throughout the Delta. The other variables do change with sea level rise in this scenario, but hardly affect suitability (Figure 5.4).

The technique that has been applied to Pacific oysters in this pilot study could also be applied to other species. Spatial maps of environmental conditions throughout the Delta area can be generated by interpolating the 1D results of the Delta model to a bathymetric grid. When the habitat rules for the species are known from literature of experiments, the potential habitat suitability can be calculated and predictions can be made on future developments.

Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 57846-2009-AQ-NLD-RvA). This certificate is valid until 15 December 2012. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Environmental Division has NEN-AND-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

References

Baptist, M. J., I. De Mesel, L. C. P. M. Stuyt, R. Henkes, H. De Molenaar, J. W. M. Wijsman, N. Dankers et al. 2007. Herstel van estuariene dynamiek in de zuidwestelijke Delta, Pages 172. Texel, IMARES.

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

Bouma, H., D. J. De Jong, F. Twisk, and K. Wolfstein. 2005. Zoute wateren Ecotopenstelsel (ZES. 1) Voor het in kaart brengen van het potentiële voorkomen van levensgemeenschappen in zoute en brakke rijkswateren, Pages 156. Middelburg, RIKZ.

Brandt, G., A. Wehrmann, and K. W. Wirtz. 2008. Rapid invasion of *Crassostrea gigas* into the German Wadden Sea dominated by larval supply. Journal of Sea Research 59:279-296.

Brummelhuis, E.B.M., K. Troost, D. van den Ende en C. van Zweeden, 2011. Inventarisatie van Japanse oesterbanken in de Oosterschelde en Waddenzee in 2011. IMARES Rapport C175/11

Child, A. R., and I. Laing. 1998. Comparative low temperature tolerance of small juvenile European, *Ostrea edulis* L., and Pacific oysters, *Crassostrea gigas* Thunberg. Aquaculture Research 29:103-113.

De Kluijver, M. J., and M. Dubbeldam. 2003. De sub-littorale hard-substraat levensgemeenschappen in de Oosterschelde: Evaluatie van de ontwikkelingen in de periode 1985-2002. Amsterdam, Aquasense.

Diederich, S., G. Nehls, J. E. E. Van Beusekom, and K. Reise. 2005. Introduced Pacific oysters (*Crasostrea gigas*) in the nothern Wadden Sea: invasion accelerated by warm summers? Helgoland Marine Research 59:97-106.

Diederich, S., 2006. High survival and growth rates of introduced Pacific oysters may cause restrictions on habitat use by native mussels in the Wadden Sea. Journal of Experimental Marine Biology and Ecology 328, 211–227.

Douglas, B. C., M. S. K. Bruce, C. Douglas, and P. L. Stephen. 2001. Sea level change in the era of the recording tide gauge, Pages 37-64 International Geophysics, Academic press.

Drinkwaard, A. C. 1999. Introductions and developments of oysters in the North Sea area: A review. Helgoländer Meerseuntersuchungen. 52:301-308.

Escaravage, V., P. Van Avesaath, M. Dubbeldam, and J. Craeymeersch. 2006. Onderzoek naar de ontwikkeling van de Japanse oester in het Veerse Meer onder verschillende peilalternatieven, Pages 47, Monitoring taakgroep (KNAW/NIOO-CEME).

Hyun, K. H., I. C. Pang, J. M. Klinck, K. S. Choi, J. B. Lee, E. N. Powell, E. E. Hofmann et al. 2001. The effect of food composition on Pacific oyster *Crassostrea gigas* (Thunberg) growth in Korea: a modeling study. Aquaculture 199:41-62.

Kater, B. J., and J. M. D. D. Baars. 2004. The potential of aerial photography for estimating surface areas of intertidal Pacific oyster beds (*Crassostrea gigas*). Journal of Shellfish Research 23:773-779.

Kerckhof, F. 2011. Een vroege waarneming van verwilderde Japanse oesters *Crassostrea gigas* in de Oosterschelde. Zeepaard 71.

Martini, E., and B. K. Van Wesenbeeck. 2010. Climate change effects on restoration of estuarine dynamics within the Delta region. Modelling effects of sea level rise and increased connectivity, Pages 17, Deltares.

Molnar, J. L., R. L. Gamboa, C. Revenga, and M. D. Spalding. 2008. Assessing the global threat of invasive species to marine biodivesity. Frontiers in Ecology and Environment.

Nehls, G., and H. Büttger. 2007. Spread of the Pacific Oyster *Crassostrea gigas* in the Wadden Sea. Causes and consequences of a successful invasion, Pages 54, HARBASINS.

Nehring, S. 2006. NOBANIS - Invasive alien species fact sheet: *Crassostrea gigas*. Online database of the North European and Baltic Network of Invasive Alien Species - NOBANIS www.nobanis.org.

Pauley, G. B., B. Van der Raay, and D. Troutt. 1988. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest) - Pacific oyster, Pages 28, U.S. Fish and Wildlife Service Biological Reports.

Perdon, K. J., and A. C. Smaal. 2000. Het bestand aan Japanse oesters op de platen van de Oosterschelde., Pages 1-25, RIVO.

Rajagopal, S., G. Van der Velde, J. Jansen, M. Van der Gaag, G. Atsma, J. P. M. Janssen-Mommen, H. Polman et al. 2005. Thermal tolerance of the invasive oyster *Crassostrea gigas*: Feasibility of heat treatment as an antifouling option. Water Research 39:4335-4342.

Smaal, A. C., B. J. Kater, and J. W. M. Wijsman. 2009. Introduction, establishment and expansion of the Pacific oyster *Crassostrea gigas* in the Oosterschelde. Hegoländer Meeresuntersuchungen 63:75-83.

Van Den Brink, A. 2012. Identifying the exotic species for which possible changes may occur as a result of Climate Change induced temperature rise in the Delta. Yerseke, IMARES.

Van IJzerloo, L., and T. J. Bouma. 2012. Onderzoek naar beperkende en faciliterende randvoorwaarden voor de vestiging van de invasieve soorten: een case studie aan Japanse oester met als doel het demonstreren van een methode, Pages 23. Yerseke, NIOZ.

Wang, J., K. Christoffersen, S. Buck, and Y. Tao. 2007. The Pacific oyster (*Crassostrea gigas*) in the Isefjord, Denmark, Roskilde University, Department of Environmental, Social and Spacial Change.

Wijsman, J. W. M. 2002. Onderzoek naar de toekomstige waterkwaliteit en ecologie van het Veerse Meer. Studie naar het effect van het doorlaatmiddel en aanvullende maatregelen. Deel 2: Opzet en verificatie van de Habitat Evaluatie Procedure, WL | Delft Hydraulics.

—. 2003. Verkennende studie voor de validatie van het Zoute wateren EcotopenStelsel (ZES) aan de hand van bodemdiergegevens, WL | Delft Hydraulics.

—. 2007. Effecten van zandhonger in de Oosterschelde op kokkels, oesters en de kweek van oesters en mosselen, Pages 28. Yerseke, IMARES.

Wijsman, J. W. M., M. Dubbeldam, M. J. De Kluijver, E. Van Zanten, and A. C. Smaal. 2008. Wegvisproef Japanse oesters in de Oosterschelde. Eindrapportage, Pages 95. Yerseke, Wageningen IMARES.

Wijsman, J. W. M., and A. C. Smaal. 2011. Growth of cockles (*Cerastoderma edule*) in the Oosterschelde described by a Dynamic Energy Budget model. Journal of Sea Research 66:372-380.

Justification

Rapport C057/11
Project Number: 4301900902

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

Approved: Dr. Karin Troost
Scientist Department Delta

Signature:

Date: 5 September 2012

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Head Department Delta

Signature:

Date: 5 September 2012