Assessment of the ecological implications when installing an SRA between Belgium and the Netherlands

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Definitions and acronyms

IMO: International Maritime Organisation.
BWM: International Convention for the Control and Management of Ships' Ballast Water and Sediments.
SRA: Same Risk Area.
Biogeographic region: a large natural region defined by physiographic and biologic characteristics within which the animal and plant species show a high degree of similarity.
The economic study: "the economic effects of a ballast water management SRA" by the University of Antwerp (Department of Transport and Regional Economics or TPR) and the Erasmus Centre for Urban Port and transport economics (UPT).
IBM: Individual-Based Model.
EEC: Eastern English Channel.
SNS: Southern North Sea.
CNS: Central North Sea.
Nycthemeral migration: migration designating or characterised by a variation that occurs in a period of twenty-four hours, especially corresponding to the contrast between day and night.
Passive behaviour: behaviour where species drift along with the currents.
Tidal behaviour: behaviour where a species moves to the surface when the tide is rising and to the bottom during ebb tide.
Counter tidal behaviour: behaviour where a species moves to the surface during falling tide and to the surface during rising tide.
Scheldt zone: the river mouth area of the Scheldt. Zeebrugge and Vlissingen are included in this area, Antwerp is not included.
Target species: species identified by a Party that meet specific criteria indicating that they may impair or damage the environment, human health, property or resources and are defined for a specific port, State or biogeographic region.
Species of concern: species of concern are species whose presence indicate that the proposed SRA is not feasible because ballast water transports within that SRA would significantly increase the risk that these alien species pose to the environment, human health, natural resources (e.g. fisheries, aquaculture), properties and/or on economics.

List of tables

List of figures

Table of content

1 Summary

In February 2004, the International Maritime Organisation (IMO) adopted by consensus the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM). The BWM requires all ships to implement a ballast water management plan by 2024. In order to anticipate on - and react to - this future situation, several governments around the world have started analyses to determine the viability of a so-called Same Risk Area (SRA). An SRA is an exemption area within the ballast water management convention; in this SRA, it is not necessary to treat the ballast water and it can be loaded and unloaded anywhere within the SRA. Ministries within the Netherlands and Belgium have taken the initiative to analyse the viability of an SRA for certain parts of their territory.

The aim of this pilot study was to investigate the possible ecological implications when such a Same Risk Area was to be installed containing the ports of Antwerp, Zeebrugge, Vlissingen and Rotterdam. The possibility of including Amsterdam, Hull and London in this SRA was very briefly discussed as well. The ecological impact was assessed by looking at the available biological data in combination with hydrodynamic simulations of the sea current circulation patterns for the year 2011 in the studied region.

The biological analysis highlights that in total 115 alien species were recorded in the area. Analysing the life history traits and distribution of these species allowed to conclude that only few of them should be considered as species of concern. The species that clearly could be identified as a species of concern based solely on biological data was *Heleobia cf australis*. There is no information of the effect of this species on human health, natural resources (e.g. fisheries, aquaculture), properties and/or on economics, though it is assumed that these effects are minor. Other species should be eliminated in combination with knowledge of their dispersal behaviour.

The oceanographic study revealed that connectivity varies greatly with season and behaviour. This part of the study only demonstrated a potential direct, strong and natural connection in the area of the river mouth of the Scheldt containing the ports of Vlissingen and Zeebrugge, but not the port of Antwerp. Antwerp, the only port that is a non-marine harbour, shows a low unilateral connection with the other ports during the year 2011, species are able to move from Antwerp to the other ports, but not the other way around. This oceanographic study suggests that water ballast exchange may at increase the spreading of species or may create new connections at the scale of the studied area. The main uncertainty of this study is the absence of inter-annual variability assessment and the simplified behaviour of species in the model.

Oceanographic and biological results re-enforce each other. The case study of *Ruditapes philippinarum* shows that a species-specific analysis can greatly nuance the outcome of the oceanographic analysis. Such a species-specific analysis is only necessary in certain cases, as illustrated in the biological section by means of a decision tree.

This study shows that the Scheldt zone can be considered as an SRA (Antwerp is not included in this zone), for Rotterdam and Antwerp the results of this study are less conclusive. Further investigation should clarify how an SRA between Belgium and the Netherlands can be finetuned. During a final meeting with stakeholders at which both the economic and ecologic study were presented, the following possibilities for further investigation were mentioned:

I. Study the consequences of doing nothing.
II. Line exemptions, these exemptions may be given to specific vessels for a route between two ports.
III. The Scheldt zone as an SRA is investigated with some extra research. This research should investigate the interannual variability with the oceanographic model and execute

OSPAR/HELCOM surveys where necessary, this to further study the possibility to include Rotterdam and Antwerp in the SRA.

IV. A combination of line exemption(s) and an SRA (scenarios II and III.).

V. Investigate SRA at the regional scale; scenario IV including French and German regions.

2 Introduction

In February 2004, the International Maritime Organisation (IMO) adopted by consensus the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM). The BWM requires all ships to implement a ballast water management plan. All ships have to keep a ballast water record book and are required to carry out ballast water management procedures according to a given standard. Parties of the convention are given the option to take additional measures based on criteria set out in the convention and IMO guidelines. The BWM entered into force on 8 September 2017. In 2024, all ships that sail in international waters should have a ballast water management system. In order to anticipate on - and react to - this future situation, several governments around the world have started analyses to determine the viability of a so-called Same Risk Area (SRA). An SRA is an exemption area within the ballast water management convention; in this SRA, it is not necessary to treat the ballast water and it can be loaded and unloaded anywhere within the SRA. Ministries within the Netherlands and Belgium have taken the initiative to analyse the viability of an SRA. The analysis described in this report investigates if there is ecological evidence that an SRA can be installed without a significant impact on the ecosystem of this area by quantifying the overlap between the SRA and the biogeographic region. A biogeographic region, as defined in the BWM, is a natural region defined by physiographic and biologic characteristics within which the animal and plant species show a high degree of similarity. There are no sharp and absolute boundaries but rather more or less clearly expressed transition zones. This investigation was executed in parallel to an economic study called “the economic effects of a ballast water management SRA” by the University of Antwerp (Department of Transport and Regional Economics or TPR) and the Erasmus Centre for Urban Port and transport economics (UPT), hereafter called the economic study.

In this exploratory study the ports taken into consideration for the SRA are Zeebrugge, Antwerp, Vlissingen and Rotterdam (see Figure 1). The role of the Eastern Scheldt as a hub for connectivity in the SRA is also investigated. The economic study has chosen to include the ports of Ostend and Terneuzen in their study because the data were easily available. For the type of analysis done in this pilot study, it was not feasible to include these ports in the oceanographic study due to a lack of data and time. The biological data available for the studied ports are attached as an appendix (Appendix I). In agreement with the commissioning parties of this study the inclusion of London, Hull and Amsterdam in the SRA was briefly tested, this to test the assumption that there is no relevant connectivity between these ports and the SRA considered in this study. Amsterdam and Den Helder were lumped in the model grid for this exploratory study.

The approach followed to investigate the ecological basis for assigning an SRA was two-fold. On one hand available biological data on the occurrences of alien species within the biogeographic region of the SRA were collected and analysed (Section 4). On the other hand the connectivity between the ports was tested by verifying that all the water bodies of the ports connected to the seaside in the SRA are connected through natural water circulation, which would allow organisms to disperse by means of water currents (Section 5). This was done by means of numerical mathematical model. The extra information gained from both the biological data and the physical feasibility study is analysed in Section 6 of this report. In that section the link with the economic study is made as well. The report ends with the conclusions of this pilot study in a clear overview (Section 7) where an overview of the results are presented together with the limitations of this exploratory study.

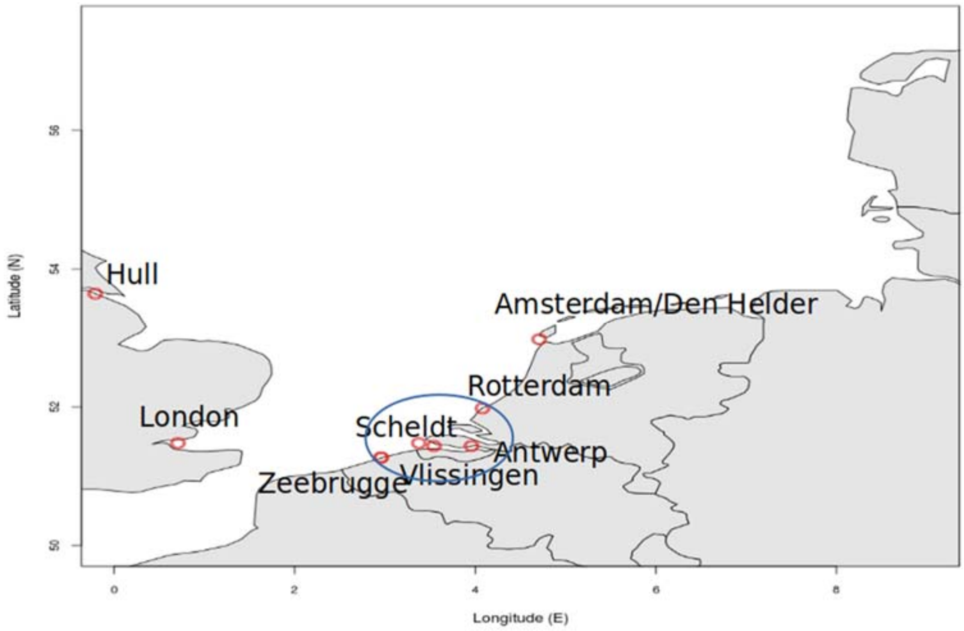

Figure 1: Map of the ports considered in the study. The region within the blue circle contains the Same Risk Area (SRA) of which the viability is tested in this project. This SRA would include the ports of Rotterdam, Vlissingen, Zeebrugge and Antwerp. Within this project only the risk of ballast water exchange between these four ports is assessed.

3 Project flow

The aim of this investigation is to assess the potential ecological impact of the desired SRA Antwerp-Zeebrugge-Rotterdam, hereafter called proposed SRA. Note that Zeebrugge is not explicitly mentioned as it lies within the triangle Antwerp-Zeebrugge-Rotterdam. Relevant biological and physical circulation data are gathered and analysed in two separate work packages: ‘biological data’ (WP1) and ‘oceanographic model results’ (WP2) respectively. In a third work package, ‘Ecological assessment’ for the SRA Antwerp-Zeebrugge-Rotterdam (WP3), the biological and oceanographic results are combined, and the viability of the proposed SRA is further discussed. In this work package, the final assessment is done by considering further arguments coming from expert judgement. The main outcome of the project is then summarised in a final work package ‘Conclusions’ (WP4). The project flow is summarised in Figure 2.

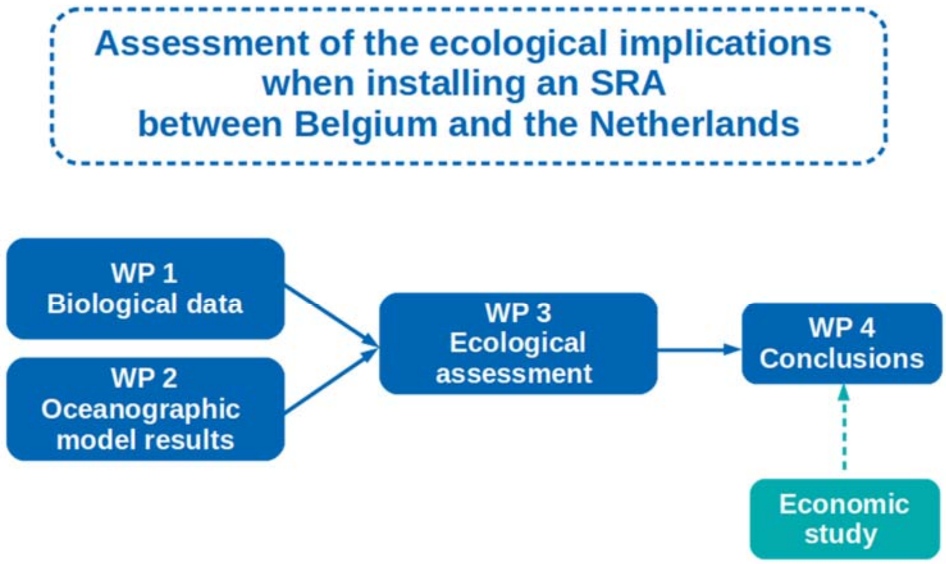

Figure 2: Overview of the workflow followed in this study. Hereby evidence is assessed that would support an SRA and evidence that does not support the viability of an SRA between Belgian and Dutch ports.

Biological data to assess the viability of an SRA (WP1)

In this work package (Section 4), an overview is provided of the alien species that have been recorded in ports that are included in the proposed SRA Antwerp-Zeebrugge-Rotterdam. For comparison, alien species recorded in the ports of Hull, Amsterdam and Den Helder are also mentioned. Based on the distribution of the species, their habitat preferences and their potential spread in ballast water, a species biogeographical risk assessment is done. This assessment is followed by a species environmental risk assessment in combination with a species-specific risk assessment, for some selected species only. Starting with the complete list of alien species recorded in the proposed SRA, in each of these assessments the species that are identified as potential species of concern for the proposed SRA are identified. Species of concern are according to IMO: “species whose presence indicate that the proposed SRA is not feasible because ballast water transports within that SRA would significantly increase the risk that these alien species pose to the environment, human health, natural resources (e.g. fisheries, aquaculture), properties and/or on economics”. The results of this work package are used as a basis for the WP3 (ecological assessment in Section 6).

Oceanographic data to assess the viability of an SRA (WP2)

In this work package (Section 5) oceanographic evidence for or against the proposed SRA is gathered based on a water circulation model of the southern part of the North Sea coupled to an Individual-Based Model (IBM). The results will allow to quantify the connectivity between the ports based on the outcome of the models. Connectivity is an important condition for the assignment of an area as a biogeographic region. The summary of the results and a discussion about the uncertainties are discussed at the end of Section 5. They will serve as a basis for the discussion about the ecological assessment of the SRA in Section 6.

Ecological implications from the SRA (WP3)
The knowledge gathered in Sections 4 and 5 will be used to answer the research question and reduce the uncertainties found in the results of both sections as much as possible. The possibility of expanding the SRA to the ports of Hull and Amsterdam will be briefly discussed here as well.

Conclusions (WP4)
The results will be briefly summarised in Section 7 together with the comments of the experts.

4 Biological data to assess the viability of the desired SRA

An SRA should be based on a risk assessment related to identified target species and it defines an area that exhibits acceptable risk regarding transfer with ballast water of target species compared to the estimates of natural dispersal over time (connectivity) (JTG-Ballast, Brussels, 29-30 November 2016). The present report focuses on the added risk for invasive species spreading when an SRA would be appointed. As an SRA concerns an exemption to the ballast water convention, only species for which ballast water transport is relevant for their dispersal are considered. Furthermore, only invasive species that have colonised a part of the SRA and have the potential to expand to other areas, are accounted for. How to handle new invasions is discussed in Section of this report. This chapter 4 concentrates on the situation at hand. Ideally, all alien species present within the ports of the proposed SRA should be known to assess whether an exemption could be granted. The risk assessments in the following sections are based on port surveys done following the OSPAR-HELCOM port survey protocol in the ports of Antwerp, Vlissingen and Rotterdam (Gittenberger et al., 2014, 2017b, 2018). This protocol includes the monitoring of most of the habitats present in ports, aiming at recording most alien species present. Alien species recorded in the proposed SRA in other review reports and studies were also included in the risk analyses. In the port of Zeebrugge for example, the OSPAR-HELCOM port survey protocol was not conducted. Instead, a list of alien species provided by an expert was used (Kerckhof, pers. comm.). This inconsistency is further discussed in Section 7.1 on remaining uncertainties. This section also deals with potential future introductions of alien species inside and outside the proposed SRA. The risk analyses that are done in this report are based on data that were available on alien species occurrences within the proposed SRA. These analyses are in concordance with the guidelines provided by IMO resolution MEPC 17/17/Add.1, Annex 10: 2017 guidelines for risk assessment under regulation A-4 of the BWM (G7), and the joint harmonised procedure for the granting of exemptions under the international convention for the control and management of ship's ballast water and sediments, as proposed by HELCOM/OSPAR (2013).

4.1 Inventory of the species of concern for an exemption on the BWM

A total of 115 alien species were recorded in the ports of the proposed SRA and in the neighbouring ports of Hull in the UK, and Amsterdam and Den Helder in the Netherlands (Appendix I). Of these 115 species, 114 have been recorded within the proposed SRA Antwerp-Zeebrugge-Rotterdam, either within these four ports or in the Western Scheldt (Appendix II). The sites within the proposed SRA from where data on the occurrences of alien species were used, are indicated in Figure 3. Hereby it is taken into account that vessels within the proposed SRA may exchange their ballast water in the four ports Zeebrugge, Antwerp, Vlissingen, Rotterdam, and possibly in the Western Scheldt but not in the North Sea. This assumption and the possibility that ballast water exchange takes place outside the main ports, is further discussed in Section 7.1.

Figure 3: Locations within the proposed SRA Antwerp-Zeebrugge-Rotterdam from which alien species records were included in the analyses: Gittenberger et al. (2017a, 2017b, 2017c), Wijnhoven et al. (2017) ; Kerckhof (Pers. Comm.). In addition to records from these sites, alien species records from nine zones in the Western Scheldt, as described by Wijnhoven et al. (2017) were included in the dataset on alien species occurrences presented in Appendix II.

Several of these 114 recorded alien species (Appendix II), were also assessed by Heyer (2015) on behalf of the OSPAR/HELCOM committee dealing with potential exemptions to the ballast water convention. The results of the assessments by Heyer (2015) are used by OSPAR/HELCOM within their online ballast water risk assessment tool (http://jointbwmexemptions.org). The risk assessments in the present report will not only focus on the 45 species assessed by Heyer (2015), but also include the remaining alien species that were recorded in the proposed SRA. Heyer (2015) listed 22 species as target species on the OSPAR/HELCOM target species list (Heyer, 2015). Three additional species are included on this list as so-called "Watch list" species (Heyer, 2015). They are also considered in this report (Table 1).
In this report an additional assessment was done for the alien species, this assessment is based on the methodology of Heyer (2015). For the 25 official target species and the remaining alien species that were recorded in the proposed SRA, it is assessed in this study whether they could potentially be species of concern for the proposed SRA. Figure 4 clarifies the decision process that was followed to identify potential species of concern. Remaining uncertainties when using a risk assessment method

similar to the one used by Heyer (2015) and supported by OSPAR/HELCOM are described in Section 7.1 on remaining uncertainties.

Table 1: Target species in the OSPAR area according to Heyer (2015), which have been recorded in the SRA Antwerp-Zeebrugge-Rotterdam. (a) = Target species; (WL) = Watch List, insufficient information for assessment. Note that some species are present in the SRA but not in all ports of the SRA The absence of a species within a port may have several (ecological) reasons and should not automatically be seen as a risk that it will be imported into that port by ballast water.

	Species	Order	Phylum	OSPAR area	Port of Antwerp	Western Scheldt	Port of Vlissingen	Port of Zeebrugge	Port of Rotterdam
1	*Ficopomatus enigmaticus*	Sabellida	Annelida	a	1	1	1	1	1
2	*Marenzelleria viridis*	Spionida	Annelida	a	0	1	0	0	0
3	*Caprella mutica*	Amphipoda	Arthropoda	a	0	1	1	1	1
4	*Gammarus tigrinus*	Amphipoda	Arthropoda	a	0	1	0	0	0
5	*Eriocheir sinensis*	Decapoda	Arthropoda	a	0	1	0	1	0
6	*Hemigrapsus sanguineus*	Decapoda	Arthropoda	a	1	1	1	1	1
7	*Hemigrapsus takanoi*	Decapoda	Arthropoda	a	1	1	1	1	1
8	*Palaemon macrodactylus*	Decapoda	Arthropoda	a	1	1	0	1	0
9	*Rhithropanopeus harrisii*	Decapoda	Arthropoda	a	1	1	0	0	1
10	*Austrominius modestus*	Sessilia	Arthropoda	a	0	1	1	1	1
11	*Codium fragile*	Bryopsidales	Chlorophyta	a	0	1	0	0	0
12	*Didemnum vexillum*	Aplousobranchia	Chordata	a	0	1	1	0	0
13	*Neogobius fluviatilis*	Perciformes	Chordata	WL	0	0	0	0	1
14	*Blackfordia virginica*	Leptothecata	Cnidaria	WL	0	1	0	0	0
15	*Mnemiopsis leidyi*	Lobata	Ctenophora	a	1	1	1	1	1
16	*Ensis leei*	Adapedonta	Mollusca	a	0	1	1	0	0
17	*Crepidula fornicata*	Littorinimorpha	Mollusca	a	0	1	1	1	1
18	*Dreissena bugensis*	Myida	Mollusca	a	0	1	0	0	1
19	*Dreissena polymorpha*	Myida	Mollusca	a	0	1	0	0	1
20	*Mytilopsis leucophaeata*	Myida	Mollusca	a	1	1	0	0	0
21	*Rangia cuneata*	Veneroida	Mollusca	a	1	0	0	0	1
22	*Karenia mikimotoi*	Gymnodiniales	Myzozoa	a	0	1	0	0	0
23	*Coscinodiscus wailesii*	Coscinodiscales	Ochrophyta	a	0	1	0	0	1
24	*Undaria pinnatifida*	Laminariales	Ochrophyta	a	0	1	0	1	0
25	*Melanothamnus harveyi*	Ceramiales	Rhodophyta	WL	0	1	1	0	0

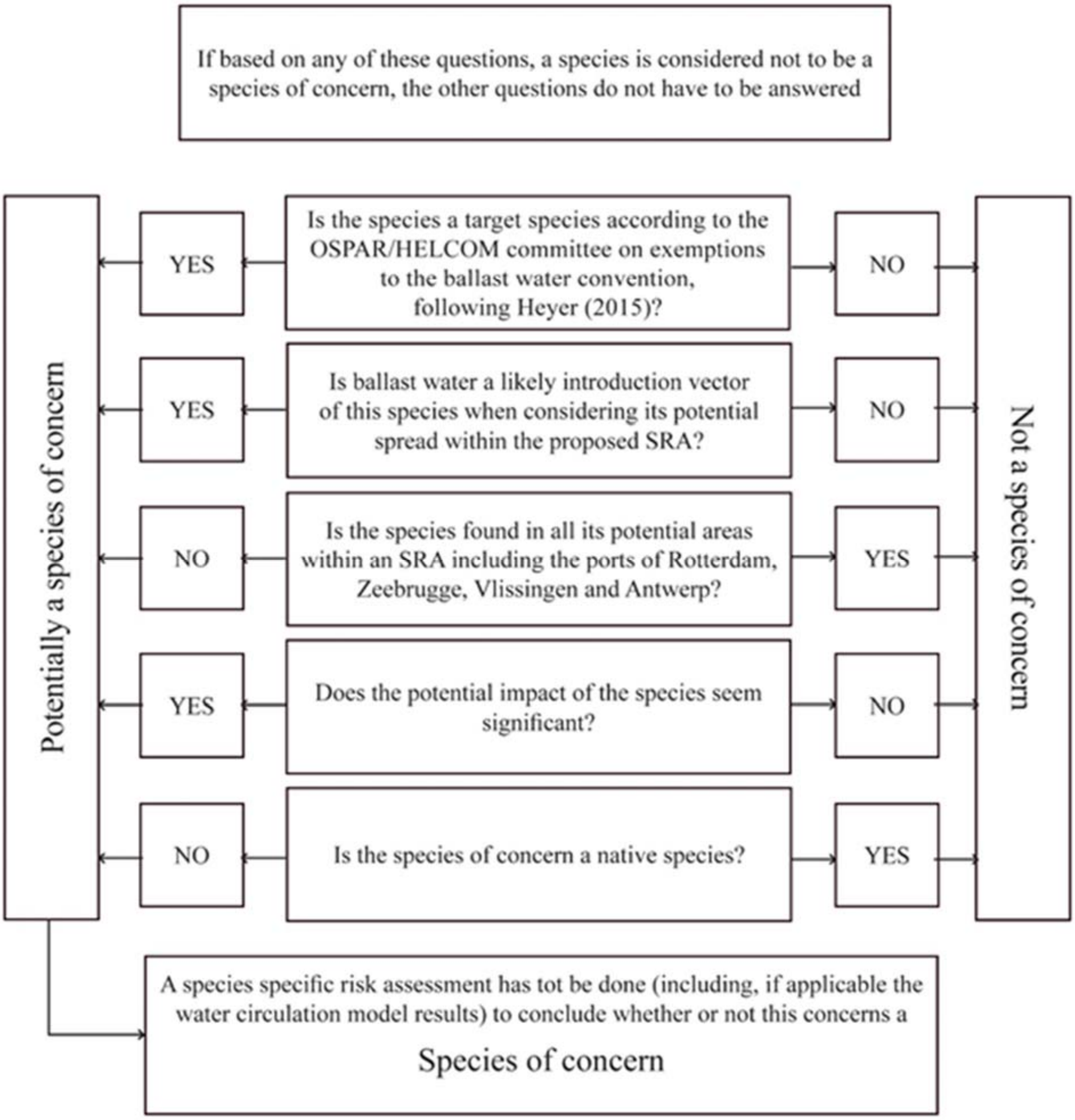

Figure 4: Decision tool for assessing whether a species should be considered a species of concern when appointing a SRA including the ports of Rotterdam, Zeebrugge, Vlissingen and Antwerp.

4.2 Species of concern

Species of concern are species whose presence indicate that the proposed SRA is not feasible because ballast water transports within that SRA would significantly increase the risk that these alien species pose to the environment, human health, natural resources (e.g. fisheries, aquaculture), properties and/or on economics. Not only biogeographical considerations are taken into account (Section 4.2.1), but if relevant also the environmental risk (Section 4.2.2) and other species-specific arguments (Section 4.2.3), including their dispersal potential are taken into account. The dispersal potential is investigated in Section 5 based on water circulation modelling.

4.2.1 Species biogeographical risk assessment

Seven species, which were recorded in the proposed SRA Antwerp-Zeebrugge-Rotterdam, are not considered target species (Heyer, 2015) in this desired SRA as they have already spread to all their potential areas in the OSPAR area. Two additional species are even considered indigenous to the OSPAR region by Heyer (2015) where other authors consider them alien or at the least cryptogenic (Wijnhoven et al., 2017). Regardless of their origin, these species are widespread in the OSPAR area. They are therefore assumed to have spread to all their potential areas and/or have the potential to disperse naturally to all potential areas (with a suitable habitat) within the OSPAR region, including the proposed SRA. This is also the case for two alien species that were introduced over 100 years ago (Table 2; Heyer, 2015). Within the present study it is concluded that the eleven species included in Table 2, should not be considered species of concern.

Table 2: Alien species which have been recorded in the SRA Antwerp-Zeebrugge-Rotterdam, but are not considered to be target species in the OSPSAR area by Heyer (2015) because they are (b) = found in all its potential areas; (e) = indigenous species; (j) = first introduced very long ago > 100 years.

	Species	Order	Phylum	OSPAR area	Port of Antwerp	Western Scheldt	Port of Vlissingen	Port of Zeebrugge	Port of Rotterdam
1	*Acartia (Acanthacartia) tonsa*	Calanoida	Arthropoda	b	0	1	0	0	0
2	*Amphibalanus improvisus*	Sessilia	Arthropoda	b	1	1	0	1	1
3	*Styela clava*	Stolidobranchia	Chordata	b	0	1	1	1	1
4	*Cordylophora caspia*	Anthoathecata	Cnidaria	j	0	1	0	0	1
5	*Teredo navalis*	Myida	Mollusca	b	0	1	0	1	0
6	*Magallana gigas*	Ostreida	Mollusca	b	1	1	1	1	1
7	*Alexandrium ostenfeldii*	Gonyaulacales	Myzozoa	e	0	1	0	0	0
8	*Prorocentrum cordatum*	Prorocentrales	Myzozoa	b	1	0	0	0	1
9	*Thalassiosira nordenskioeldii*	Thalassiosirales	Ochrophyta	e	0	1	0	0	1
10	*Biddulphia sinensis*	Triceratiales	Ochrophyta	j	0	1	1	0	1
11	*Dasysiphonia japonica*	Ceramiales	Rhodophyta	b	0	1	1	1	1

Four of the target species in the proposed SRA have been recorded in all four ports, i.e. Zeebrugge, Antwerp, Vlissingen and Rotterdam (Table 3). As these species are present in all ports and areas of the SRA (Table 3), they are not considered to be of concern when appointing an SRA Antwerp-Zeebrugge-Rotterdam.

Table 3: Target species (a) according to Heyer (2015) occurring in all ports of the proposed SRA Antwerp-Zeebrugge-Rotterdam.

	Species	Order	Phylum	OSPAR area	Port of Antwerp	Western Scheldt	Port of Vlissingen	Port of Zeebrugge	Port of Rotterdam
1	*Ficopomatus enigmaticus*	Sabellida	Annelida	a	1	1	1	1	1
2	*Hemigrapsus sanguineus*	Decapoda	Arthropoda	a	1	1	1	1	1
3	*Hemigrapsus takanoi*	Decapoda	Arthropoda	a	1	1	1	1	1
4	*Mnemiopsis leidyi*	Lobata	Ctenophora	a	1	1	1	1	1

Of the alien species that are not assessed in Heyer (2015), there is one species that was recorded in all ports, i.e. the sea-squirt *Molgula manhattensis*. This species is therefore also considered not to be a species of concern for the proposed SRA.

4.2.2 Species environmental risk assessment

Natural dispersal within the SRA

Species with permanent or very long pelagic life stages are tested for their dispersal ability in chapter 5 (Oceanographic results). Examples of such species, recorded within the proposed SRA are dinoflagellates like *Prorocentrum cordatum* and ctenophores like *Mnemiopsis leidyi* (Appendix II). Also bacterial species like *Vibrio* cf *brasiliensis* should be tested for their dispersal abilities This *Vibrio* species was detected solely in the port of Rotterdam. It is unclear whether that record indicates the settlement of this species in this port or a recent release of ballast water in the port from a ship originating from South America. Hereby it is also uncertain whether the ballast water cleaning systems made mandatory by the ballast water convention would eradicate such alien bacterial species.

Ballast water as an unlikely transport vector

When assessing whether ballast water may be transport vector of alien species, most studies assume that this concerns organisms in their pelagic life stages, sometimes also including seeds or resting stages (e.g. cysts or eggs) in ballast water (Katsanevakis et al., 2013). This also appears to have been the approach of Heyer (2015) when appointing target species. In the present assessment, also non pelagic life stages that may end up and survive in the ballast water tank are considered. When the bottom or wall in a port gets disturbed by for example tidal currents or the accelerating propellers of a vessel, benthic and wall fouling organisms may end up in ballast water tanks. Some of these species may therefore be identified as species of concern for the proposed SRA. In this section it is assessed whether species are likely to survive ballast water transport or whether it is not much more likely that such species are transported within hull fouling communities.

As ballast water tanks do not provide a good environment for certain marine species to be transported in, Heyer (2015) concluded for various species that they should not be considered to be target species. As vessels travelling between ports within the proposed SRA cover very short distances, species with relatively short pelagic life stages may be transported within the ballast water of these ships while they would not survive the transport within such a ballast water tank over long distances, e.g. inter-continentally. Alien species that have a relatively short pelagic life stage like sea-squirts and bryozoans, but are known to disperse rapidly between ports and marinas, are often hull fouling species. This also includes small calcareous tube forming worms like *Neodexiospira brasiliensis* and *Pileolaria berkeleyana*, which Faasse (2011) assumes to have been imported by hull fouling. Hull fouling on pleasure crafts and larger vessels is therefore considered to be the main transport vector of these species, especially over short distances (Gittenberger et al., 2017b, 2017d). They are therefore not assumed to be species of concern for the proposed SRA in the present report, although there may be a small chance that they could also be transported by ballast water. This also accounts for the six species in Table 4, which are not considered to be target species according to Heyer (2015), as ballast water is not considered to be their introduction vector. Among the alien species that have not been assessed by Heyer (2015) but were recorded in the proposed SRA, there are several closely resembling species. For these species it is therefore also concluded that ballast water is probably not their main transport vector (Table 4). As the larvae of sea-squirts have a relatively short pelagic life stage of only a few minutes to a few days (Fish & Fish, 2011), hull fouling as a transport vector is considered to be a much more important vector than ballast water exchange. These species are therefore mostly assumed to be spread by hull fouling, shellfish transports (Gittenberger et al., 2017d) or more generally on either artificial (e.g. plastic bottles) or natural (e.g. macroalgae) floating objects. This assumption is supported by the fact that adults, possibly reproducing solitary and colonial sea-squirt species are commonly recorded in hull fouling communities (Gittenberger et al., 2017b), which may not survive inter-continental shipping but will probably survive the short distance transports on hull within the proposed SRA.

Most bryozoans also have very brief pelagic stages of only a few hours (Fish & Fish, 2011; Yang et al., 2018). Heyer (2015) therefore concluded for alien bryozoans like *Tricellaria inopinata* and *Bugula neritina* and alien ascidians like *Botrylloides violaceus* and *Corella eumyota* that ballast water is not their introduction vector. Heyer (2015) also concluded for most macroalgae that they are not target species as ballast water is not the introduction vector. This hypothesis is supported by Engelen et al. (2015) indicating for macroalgae worldwide that there are only a few cases of macroalgae being introduced via ballast water, in comparison to transport vectors related to hull fouling, shellfish transports, accidental release with aquaria and cultivation of macroalgae. As macroalgal species need light to settle, most species are assumed to be transported by hull fouling (Engelen et al., 2015; Gittenberger et al., 2017b). In addition, species like *Sargassum muticum* (Table 4) are known to be spread not only on the hulls of pleasure crafts but also by drifting of mature individuals. Such macroalgal species are therefore not considered to be species of concern for the proposed SRA, although there may be slight chance that floating individuals are transported by ballast water. As *S. muticum* is widespread along the west European coast, its absence in all but one of the ports within the proposed SRA is assumed to be environmental. Similar examples of species for which not all ports within the proposed SRA provide suitable habitats for settlement, are given in the next section.

Table 4: Non-target species for the OSPAR area according to Heyer (2015) because: (c) = ballast water is not the introduction vector.

	Species	Order	Phylum	OSPAR area	Port of Antwerp	Western Scheldt	Port of Vlissingen	Port of Zeebrugge	Port of Rotterdam
1	*Telmatogeton japonicus*	Diptera	Arthropoda	c	1	1	0	1	0
2	*Tricellaria inopinata*	Cheilostomatida	Bryozoa	c	0	1	1	1	0
3	*Perophora japonica*	Phlebobranchia	Chordata	c	0	1	1	0	0
4	*Botrylloides violaceus*	Stolidobranchia	Chordata	c	0	1	1	1	0
5	*Petricolaria pholadiformis*	Venerida	Mollusca	c	0	1	0	0	0
6	*Sargassum muticum*	Fucales	Ochrophyta	c	0	0	0	1	0

Table 5: Alien species recorded in the proposed SRA Antwerp-Zeebrugge-Rotterdam that are not considered to be species of concern for the proposed SRA because ballast water is not considered to be a significant introduction vector.

	Species	Order	Phylum	Port of Antwerp	Western Scheldt	Port of Vlissingen	Port of Zeebrugge	Port of Rotterdam
1	*Biflustra grandicella*	Cheilostomatida	Bryozoa	0	1	0	0	0
2	*Bugula simplex*	Cheilostomatida	Bryozoa	0	0	0	1	0
3	*Bugulina stolonifera*	Cheilostomatida	Bryozoa	0	1	1	1	0
4	*cf Conopeum chesapeakensis*	Cheilostomatida	Bryozoa	1	0	0	0	0
5	*Fenestrulina delicia*	Cheilostomatida	Bryozoa	0	1	1	0	0
6	*Fenestrulina malusii*	Cheilostomatida	Bryozoa	0	1	1	0	0
7	*Smittoidea prolifica*	Cheilostomatida	Bryozoa	0	1	1	0	0
8	*Aplidium glabrum*	*Aplousobranchia*	Chordata	0	1	1	1	0
9	*Didemnum vexillum*	*Aplousobranchia*	Chordata	0	1	1	0	0
10	*Diplosoma listerianum*	*Aplousobranchia*	Chordata	0	1	1	1	0
11	*Perophora japonica*	*Phlebobranchia*	Chordata	0	1	1	0	0
12	*Botrylloides violaceus*	*Stolidobranchia*	Chordata	0	1	1	1	0

Salinity and water temperature impact on settlement success of species

Although ballast water tanks may not provide an ideal environment for the transport of pelagic life-stages of bryozoans, ascidians and macroalgae, it is possible that specimens attached to harbour walls break off and end up in a ballast water tank. Some of these species, like the colonial carpet sea-squirt *Didemnum vexillum*, are known for breaking into pieces, which can then be distributed over large distances by the currents. After drifting along with the currents, they may “settle” and grow out again into new colonies (Gittenberger, 2007). As a species like the carpet Sea-squirt may therefore also be distributed by ballast water, it is considered a target species by Heyer (2015). Within the proposed SRA five alien ascidians were recorded, which are well known from the region but also in close waters like the Wadden Sea. There they have only been found in relatively high saline waters and are never recorded in harbours and ports directly connected to rivers (Gittenberger et al., 2015b). This also explains their absence in the ports of Antwerp and Rotterdam (Table 6) and their presence in, for example, the port of Vlissingen and the Scheldt (Gittenberger, 2009). As these ascidian species have probably already spread to all their potential areas within the proposed SRA, they are not considered to be species of concern. The fact that *Didemnum vexillum* and *Perophora japonica* were not recorded in the port of Zeebrugge (Table 6; Appendix II), although habitats may be present suitable for the settlement of these species, can be explained by the fact that this was the only port where an OSPAR/HELCOM port survey was not conducted yet. Both species are not easily spotted as *Didemnum vexillum* colonies tend to settle relatively deep in similar ports (~2 meter deep and deeper in the port of Vlissingen, unpublished data from Gittenberger et al., 2017a) and *P. japonica* individuals are very small (usually < 0.5 cm) and therefore easily overlooked (Gittenberger, 2007). Although such species may be considered potential species of concern as long as an OSPAR/HELCOM port survey is not conducted in the port of Zeebrugge, one can also assume that they should be able to reach the port of Zeebrugge from the port of Vlissingen by natural distribution. As may be concluded based on the water circulation model presented in the next chapter *Didemnum vexillum* for example may either reach Zeebrugge with naturally dispersing larvae that remain viable for about 12 to 24 hours or fragmented within its adult stages. This is possible as *D. vexillum* colonies are known to fragment after which the living fragments can drift over large distances (Gittenberger, 2010).

Another example of a species, which is not present in all ports of the proposed SRA, but has settled in all environments suitable for settlement, concerns *Rangia cuneata*. This species, known for being transported by ballast water, prefers the brackish water of port systems that are connected to rivers (Gittenberger et al., 2014b). Its preference for brackish water is also supported by the other locations where the species has invaded in last decade, i.e. in the North Sea Canal of the port of Amsterdam, close by the port of Delfzijl (the Netherlands), and in the Baltic Sea in the Russian part and Polish part of the Vistula lagoon (Gittenberger et al., 2014b). The port of Antwerp, where it was present from approximately 2000 on (Kerckhof et al., 2007), may concern the first port of entry for this American bivalve species. Its preference for brackish waters may explain why it was recorded in the ports of Antwerp and Rotterdam, but not in the ports of Zeebrugge and Vlissingen (Table 6). *Rangia cuneata* is therefore also not considered to be a species of concern for the proposed SRA.

For species like the Chinese mitten crab *Eriocheir sinensis*, salinity also plays an important role. This species, which is assumed to have been aided in its dispersal by ballast water transports, is not recorded for all ports in the proposed SRA (Appendix II). This may be due to the fact that it tends to live upstream in freshwater for most of the year and only comes downstream to more saline waters for its reproduction. Such alien species may be missed in rapid assessments of ports if they are not conducted in exactly the right time of the year. Herborg et al. (2003) show that the Chinese mitten crab is already widespread in both Belgium and the Netherlands since at least the 1940s. Where it concerns the proposed SRA, this species is therefore not considered a species of concern, although it was not recorded in all ports and could be transported by ballast water.

A final example concerns the bryozoan *Biflustra grandicella*, which is only recorded in the Western Scheldt just outside of the port of Vlissingen next to the cooling water outlet of a nuclear plant (Gittenberger et al., 2017c). As this “warm water” species was probably only able to settle at that site in the Western Scheldt because of the warm water coming out of the cooling water inlet (Gittenberger et al., 2017c), it is not likely to be able to settle anywhere else in the proposed SRA. It is therefore not considered to be a species of concern.

Table 6: Alien species recorded in the proposed SRA Antwerp-Zeebrugge-Rotterdam that are not considered to be species of concern for the proposed SRA because of environmental mismatching.

	Species	**Order**	**Phylum**	**Remarks**	**Port of Antwerp**	**Western Scheldt**	**Port of Vlissingen**	**Port of Zeebrugge**	**Port of Rotterdam**
1	*Biflustra grandicella*	Cheilostomatida	Bryozoa	Ballast water is not the main transport vector. Warm water species, which is only recorded near the cooling water outlet of a nuclear plant.	0	1	0	0	0
2	*Aplidium glabrum*	Aplousobranchia	Chordata	Species settles in relatively high salinities	0	1	1	1	0
3	*Didemnum vexillum*	Aplousobranchia	Chordata	Species settles in relatively high salinities	0	1	1	0	0
4	*Diplosoma listerianum*	Aplousobranchia	Chordata	Species settles in relatively high salinities	0	1	1	1	0
5	*Perophora japonica*	Phlebobranchia	Chordata	Species settles in relatively high salinities	0	1	1	0	0
6	*Botrylloides violaceus*	Stolidobranchia	Chordata	Species settles in relatively high salinities	0	1	1	1	0
7	*Rangia cuneata*			Species settles in relatively low salinities	1	0	0	0	1

Alien fresh water related species with limited tolerance towards increased salinity

Some alien species which were only recorded at and near fresh water inlets, concern alien fresh water related species with limited tolerance towards increased salinity. Such species may enter a ballast water tank in the brackish to saline parts of a port when they are flushed into these waters when for example a sluice towards a freshwater stream opens. The risk that such fresh water species survives the transport in a ballast water tank to a different port is assumed to be limited. If it does survive the transport, the risk that it is able to survive and successfully settle in that port after being released there in saline to brackish waters, is assumed minimal. The present report focuses only the brackish to saline parts of the ports in the proposed SRA. Most freshwater species (possibly with limited salinity tolerances) got distributed throughout Western Europe with their natural dispersal abilities after "new" watershed connections (channels, etc.) were made enabling the introduction of alien species from the Ponto-Caspian region. As such species are spread (sometimes also with ballast water) throughout fresh water systems and have limited tolerance to salinities (Table 7), they are not considered species of concern in the present study.

Table 7: Alien species recorded in the proposed SRA Antwerp-Zeebrugge-Rotterdam that are fresh water related species with limited tolerance towards increased salinity (see e.g. Table 3b in Wijnhoven et al., 2017).

	Species	Order	Phylum	Port of Antwerp	Western Scheldt	Port of Vlissingen	Port of Zeebrugge	Port of Rotterdam
1	*Laonome calida*	Sabellida	Annelida	0	1	0	0	0
2	*Chelicorophium curvispinum*	Amphipoda	Arthropoda	0	1	0	0	0
3	*Gammarus tigrinus*	Amphipoda	Arthropoda	0	1	0	0	0
4	*Sinelobus vanhaareni*	Tanaidacea	Arthropoda	1	1	0	0	1
5	*Neogobius fluviatilis*	Perciformes	Chordata	0	0	0	0	1
6	*Neogobius melanostomus*	Perciformes	Chordata	0	1	0	0	1
7	*Cordylophora caspia*	Anthoathecata	Cnidaria	0	1	0	0	1
8	*Potamopyrgus antipodarum*	Littorinimorpha	Mollusca	0	0	0	0	1
9	*Dreissena bugensis*	Myida	Mollusca	0	1	0	0	1
10	*Dreissena polymorpha*	Myida	Mollusca	0	1	0	0	1
11	*Physella acuta*		Mollusca	0	1	0	0	1

4.2.3 Species-specific risk assessment

The previous sections show that many species can be eliminated as species of concern by asking some general questions. For some species a more detailed species-specific risk assessment is necessary. This section will go into detail about the recorded species that need such a species-specific assessment.

The alien clam *Ruditapes philippinarum*, was recorded in the vicinity of the Port of Vlissingen (Appendix II). This species, which is also known from the Eastern Scheldt, prefers lagoon like habitats where the currents ensure that most of the larvae that are released in the water column, will settle close by the site where they were released (Humphreys et al., 2007). Although such a lagoon like ecosystem is present in the Eastern Scheldt and the interconnected Veerse Meer, no such ecosystem appears to be present in the proposed SRA. *Ruditapes phillipinarum* has a pelagic larval stage of on average 40 days (Helm & Pellizzato, 1990; Solidoro *et al.*, 2003). It may therefore be argued that this clam may already have dispersed naturally to all its potential habitats within the proposed SRA. This could potentially be concluded based on the water circulation model presented in Section 5. Natural dispersal of most of the alien species recorded in the proposed SRA could be possible based on results of the water circulation model when considering that the Eastern Scheldt may be a potential stepping stone in their spread. Most species occurring in the ports of the proposed SRA, including the bivalve *R. phillipinarum* have already settled in the Eastern Scheldt, which lies halfway in between the outlet of the Western Scheldt and the port of Rotterdam (Gittenberger et al., 2017d). If the larvae of these alien species occurring in the Eastern Scheldt flush into the North Sea with the tidal currents, it is assumed that they can naturally disperse with the residual coastal currents to the port of Rotterdam in the north, and to the ports of Vlissingen and Zeebrugge to the south. This hypothesis, which is tested with the water circulation model in Section 5, should be supported by this model before concluding that these species should not be considered species of concern for the proposed SRA. Hereby the water circulation models will also give clarity on the question of whether or not these species will not be able to disperse naturally from the port of Zeebrugge and Vlissingen "upstream" to the port of Antwerp. If this is not the case, it should be assessed in more detail where such species may have an impact and whether vessels docking in the ports of Antwerp, Zeebrugge and Vlissingen may exchange their ballast water in the Western Scheldt, and if so where. Of the 114 species in Appendix II only 72 were recorded in the four ports of the proposed SRA. The rest of the species records refers to records from within the Western Scheldt. Such records both in the direct neighbourhood and inside of the ports, are especially of importance if stepping stones in between the ports are needed to make it possible for species to naturally disperse between the ports as appears to be the case. These uncertainties within the present study are described in Section **Error! Reference source not found.** on remaining uncertainties.

For some alien species, natural dispersal between the ports within the proposed SRA is probably not possible, regardless of the water circulation. This concerns mainly brackish water species that cannot or are unlikely to disperse through waters with relatively high salinities, such as in the North Sea in comparison to the more inland parts of for example the ports of Antwerp and Rotterdam.

Although most of the known invasive brackish water species like the Australian tubeworm *Ficopomatus enigmaticus* and the American mud crab *Rhithropanopeus harrisii* were already recorded in the brackish waters of the ports of Rotterdam and Antwerp, the gastropod *Heleobia* cf *australis* was only recorded in the port of Antwerp. As this record in 2017 (Gittenberger et al., 2018) concerns the first for Europe, nothing is known on the dispersal behaviour. The bottom samples in which it was found in the port of Antwerp did indicate that is could be quite abundant, and that the species appears to have a preference for brackish waters. Preliminary morphological and molecular analyses have indicated that it probably concerns a South American species (unpublished data). Although its shell morphology indicates that it may be the South American species *H. australis*, its identity remains uncertain as for its identification, it may be necessary to study its anatomy and the anatomy of several South American *Heleobia* species. As no previous monitoring has been done in the port of Antwerp that would specifically target such species, it may have been missed in monitoring in the past as the shells are only a few millimetres in size and there are several closely resembling native gastropod species that may have led to miss-identifications. It is therefore uncertain whether *Heleobia* cf *australis* was recorded relatively short after its arrival or whether it has been living in the port of Antwerp for decades already. As the same OSPAR-HELCOM survey protocol was conducted by the same research team in the port of Rotterdam, it is unlikely that the species was missed there. Although it may be absent, it may also have been introduced in the port of Rotterdam after the last OSPAR-HELCOM port survey that was conducted there in 2014. A sister species of *Heleobia* cf *australis*, i.e. *Heleobia stagnorum*, which occurs in brackish waters throughout Western Europe, lays egg-capsules with one egg each and has no pelagic phase (Bruyne et al., 2013). It is not unlikely however that the small eggs and adult shells (up to ~6 mm) may end up in ballast water tanks when the bottom in the port is disturbed by turning propellers, possibly in combination with tidal currents. As these gastropods can close their shells with an operculum (door), protecting them from hostile environments and sudden environmental changes, one can assume that they probably will survive the transport within a ballast water tank between the ports within the proposed SRA. Although one may assume a low potential impact of such minute alien gastropod species, this is uncertain as little is known about this species, which is therefore here considered to be a species of concern for the proposed SRA.

Much is known about the dispersal behaviour of alien species that have shown to be invasive like the Pacific oyster *Magallana gigas*. Such species have already settled in all potential habitats within the proposed SRA however (Appendix II). They are therefore not considered to be species of concern when assessing the feasibility of this SRA.

4.3 Alien species distribution in the proposed SRA

Species occurrences Zeebrugge-Vlissingen-Scheldt (Scheldt zone)

Virtually all alien species occurring in the ports of Zeebrugge and Vlissingen are also known from the Eastern Scheldt. Only a relatively small selection of alien species known from the Eastern Scheldt is known for the ports of Zeebrugge and Vlissingen, possibly because of the much larger variety of habitats available for settlement in the Eastern Scheldt. Species that are present in the port of Vlissingen and are not known for the port of Zeebrugge, like the sea lettuce species *Ulva australis*, the bryozoan *Fenestrulina delicia*, and the colonial sea-squirt *Didemnum vexillum* may have been missed in the port of Zeebrugge as they may not be easy to spot without doing an alien species focused rapid assessment like the one described in the OSPAR/HELCOM port survey protocol.

Species occurrences Rotterdam-Antwerp

In the ports of Rotterdam and Antwerp similar species are found as similar habitats appear to be present. Some differences are found, which appear to be mainly related to higher salinities in the port of Rotterdam. The salinities in the port of Antwerp are for example too low for the settlement of sea-squirts, while several sea-squirts species were recorded in the more saline areas within the port of Rotterdam.

Species occurrences Rotterdam-Scheldt zone & Antwerp-Scheldt zone

A much higher diversity of alien species is present in the ES-zone than in the ports of Rotterdam and Antwerp. This may be linked to the larger variety of more saline habitats present in the ES-zone where there is no direct impact of a river. As rivers are directly connected to the ports of Antwerp and Rotterdam, some alien species, like the bivalve *Rangia cuneata*, do occur in these two ports, but not in the ES-zone.

4.4 Conclusions

In total 115 alien species were recorded in the proposed SRA Antwerp-Zeebrugge-Rotterdam, including records from the Western Scheldt, and neighbouring ports like Hull in the UK, and Amsterdam and Den Helder in the Netherlands. Only focusing on the proposed SRA, including records from the Western

Scheldt, 114 alien species were identified. Of these 114 species in total 72 were recorded in the ports of Antwerp, Zeebrugge, Vlissingen and Rotterdam. Based on the assessment of Heyer (2015), supported by the OSPAR-HELCOM committee working on exemptions to the ballast water convention, it was concluded that 22 of the recorded alien species concerned target species within the OSPAR-HELCOM region and 23 of the alien species were not considered target species based on criteria used by Heyer (2015). These criteria, which included for example the likeliness of species being transported by ballast water, were subsequently used for the remaining alien species (not mentioned by Heyer, 2015) that were recorded and 22 target species to assess whether they should be seen as potential species of concern within the proposed SRA. During the assessment several categories of species were distinguished. The most common being:

[1] Species for which **hull fouling** is assumed to be a much more likely vector of distribution within the proposed SRA than ballast water. This includes species like ascidians, bryozoans and some calcareous tube worms.

[2] Species, which are known to be widespread in Western Europe, but **may not have been recorded** in some of the ports because they are only detected in certain seasons. This includes for example the Chinese mitten crab, which can only be found in more saline waters during its breeding season, as it remains in fresh water for most of the rest of its life.

[3] Species, which may not be recorded in all ports, but are assumed to be **settled already in all suitable habitats**. For these species the environmental conditions in some of the ports are deemed unsuitable for settlement. This accounts for example for various alien sea-squirts, which are only recorded in the more saline ports. Within the proposed SRA most of the alien species recorded in these four ports appear to be settled already with suitable habitats based on this assessment. The water circulation model presented in the next section may further support whether species may be considering species of concern or not.

[4] Species, which have relatively long pelagic life stages of at least a month or more. This includes for example dinoflagellates, ctenophores and medusa stages of hydroids, which have not been recorded on all potential ports, possibly explained by their seasonality. In support of not considering them species of concern they are assumed to be able to disperse naturally throughout the proposed SRA as may be tested in the next chapter on **water circulation.**

[5] A final category of species concerns **brackish water** related alien species, which may not disperse naturally throughout more saline waters from the port of Rotterdam to the port of Antwerp and vice versa. Most of these species are already widespread whereby some may also disperse through freshwater streams and canals.

Species from category 4 are tested against the results of Section 5 but one species that can clearly be defined as a species of concern based on biological knowledge only, is the gastropod *Heleobia* cf *australis*. This species [1] was not recorded in all suitable habitats yet, [2] may not have a pelagic larval stage, but [3] may be transported by ballast water. This brackish water species recorded solely in the port of Antwerp, is therefore considered to be a species of concern for the proposed SRA. There is no information of the effect of this species on human health, natural resources (e.g. fisheries, aquaculture), properties and/or on economics, though it is believed by the authors of this study that these effects are minor.

5 Oceanographic results

In marine environment many species have a pelagic phase during their early life stages, during which small organisms with a limited swimming capacity are strongly constrained in the direction of their movements by the currents. In the previous chapter the current situation with dispersal in the water ballast tanks was described. In this chapter the natural connectivity between the ports of the SRA is assessed for organisms independently of their behaviour or pelagic life stage duration. Table 8 gives a conceptual overview of how water ballast exchange compares itself to natural connectivity. When all points of the SRA are connected by water circulation in such a way that during their pelagic phase, marine organisms can directly settle everywhere there is a suitable habitat, water ballast exchange has little impact on the dispersal process. If the water circulation pattern is so that exchange between two different points of the SRA is only possible by secondary contact (or through the so-called stepping stone principle) water ballast exchange could potentially accelerate the dispersal process. In the absence of natural connectivity within the SRA, water ballast exchange could represent the main vector of dispersal.

In this pilot study the stepping stone principle was only briefly considered, the focus was on the hypothesis that the whole SRA is directly connected, and that species can settle in new suitable habitats in one generation. Based on oceanic circulation results, the connection among seven harbours of the North Sea, four of the desired SRA (Antwerp, Zeebrugge, Vlissingen and Rotterdam) and three additional ones (Amsterdam, Hull and London) was tested. The main focus was on the ports of the SRA. In addition to these ports, the Scheldt estuary was also considered, this to briefly explore the possibility that this zone acts as a stepping stone to connect Rotterdam with the other ports. Water circulation was simulated by means of the hydrodynamic model described in Section 5.1. The ability to use oceanic currents as a means of transport was studied by using the individual-based model (IBM) described in Section 5.2.

Table 8: Comparison between natural connectivity and the likely impact of water ballast exchange and potential impact on SRA management.

Natural situation	Effect of water ballast exchange	Management
Areas are directly connected	No impact	Nothing
Areas are connected by stepping stone	Potential acceleration of natural spread	Depends on the acceptable cost/delay
Areas are disconnected	Potential creation of artificial connection	Important impact

5.1 Water circulation model

In this study, the water circulation model software COHERENS (Luyten et al., 1999) developed and implemented for the North Sea by RBINS was used to simulate the currents for the year 2011. . Water circulation models are based on the discretisation of the Navier-Stokes equations. These equations are only valid in a closed system, hence the model needs to be fed with boundary conditions. In order to model the proposed SRA, river inflow values and water flows at the boundaries are needed for velocity, water temperature and salinity. The study area for the water circulation model covers the eastern English Channel (EEC) and the southern (SNS) and central North Sea (CNS) (the region between 4°W and 9°E, and 48.5°N and 57°N, see in Figure 5). Currents in these shallow coastal seas are mainly tide- and wind-induced. Average circulation is from South to North (Turrell 1992) with strong seasonal variability and some inter-annual variability in the flow field linked to the North Atlantic Oscillation (NAO). The net water inflow from the eastern English Channel to the southern North Sea displays a strong seasonal variability. The net inflow equals 0.05 x 10^6 m³ s^{-1}, -0.01 x 10^6 m³ s^{-1}, 0.02 x 10^6 m³ $s^{-1}$and 0.05 x 10^6 m³ s^{-1} respectively from 1st to 4th quarter on average over the period 1955-1998 (OSPAR Commission, 2000). Mean local temperatures (1997-2006) vary from 12.8°C (EEC), 11.7°C (SNS) to 10.7°C (CNS) with an important seasonal variation. While in winter the mean temperatures were equal to 9.8°C (EEC), 7.3°C (SNS) and 6.9°C (CNS), they were equal to 16.9°C (EEC), 17.2°C (SNS) and 15.9°C (CNS) during summer. In winter, the water column is well mixed. In late spring, a thermocline is established over the northern deeper part of the domain, resulting in the formation of oceanic fronts in summer. Two fronts draw our attention: in the north-west across the Dogger Bank and perpendicular to the Dutch coast, in combination with outflow of rivers (Otto et al. 1990). The bathymetry of the domain and the wind flow (bottom and surface boundary of the domain) are also needed to feed the model.

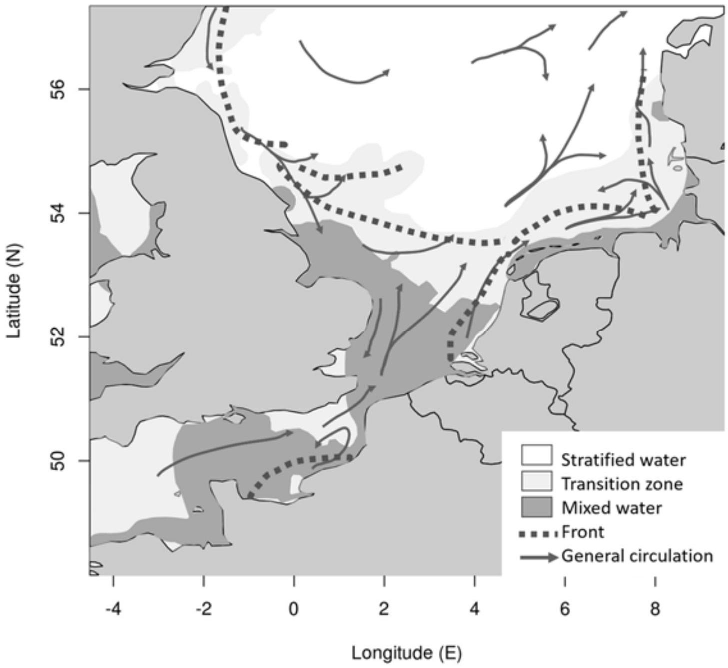

Figure 5: Map with the physical features of the modelled area

The model is forced by 6-hourly wind and atmospheric pressure fields from the analysed data of the UK Meteorological Office and by weekly sea surface temperature (SST) data (Bundesanmt für Seeschifffahrt und Hydrographie, Loewe 2003). Daily river discharges are included for the main North Sea rivers. The 3D set up used in this study has a resolution of 5' in longitude and 2.5' in latitude, and 20 sigma-coordinate vertical layers. Details about the model implementation (equations, forcing, initial and boundary conditions) and its validation are given in Savina et al. (2010). The domain resolution is too coarse to model the architecture of harbours in detail.

5.2 Individual-based model (IBM) for species transport

The ability of species to use the water flow as a means of transport can be quantified by using an IBM. This type of model allows to add larvae (or particles) in the water circulation model described in Section

5 and to follow their track in time. Like in a computer game, the particles can be subjected to certain rules or limitations imposed by the programmer (f.e. after a certain amount of time in the water a particle disappears, imitating mortality for instance). Some organisms (ex. plants, algae) are transported passively along with the water currents and in that case, there is no need of extra input to run the model. Other living species like eggs and larvae have limited swimming capabilities but can easily control their buoyancy. This change in buoyancy allows early life stages of marine organisms to have vertical swimming behaviours such as upward-swimming, hovering or sinking. The capacity to navigate along the vertical in the water column allows them to feed, to avoid predators or to actively select the currents regime they favour. This behaviour can be induced by the day and night cycle or by the tidal cycle and is known to have an important impact on species dispersal (e.g. Fox et al., 2006; North et al., 2008; Robins et al., 2013). In the North Sea, where the water column is well mixed, nycthemeral migration (migration designating or characterised by a variation that occurs in a period of twenty-four hours, especially corresponding to the contrast between day and night) has a limited impact on the dispersal patterns. However, tidal currents are strong in this area and migration synchronous with tide is an important behaviour (Jager 1999). In this study, the focus will be on three behaviours: passive, tidal and counter tidal. In the case of passive behaviour, the particles drift with the water current. Tidal behaviour means that the particles go to the surface when the tide is rising and to the bottom during ebb tide. On the contrary, counter tidal behaviour means that the particles go to the surface during falling tide and to the bottom when the tide is rising. A visual representation of these three behaviours can be found in Figure 6. Tide-related behaviours are known to influence dispersal (Hill, 1991). Counter tidal behaviour is not common in the North Sea but is observed in regions with upwelling systems such as South America where some of our alien species originate from (Miller and Morgan, 2013).

In this study the LARVAE&CO model is adapted to the needs of the research question. The IBM was initially developed for sole and described in Lacroix et al. (2013). It simulates sole egg and larval dispersal in the eastern English Channel and the North Sea and couples the 3D hydrodynamic model described in Section 5 with a Lagrangian particle-tracking model. The different behaviours described above are simulated by assigning a vertical migration rate to the particles. To simulate tidal behaviour the vertical migration rates changed from positive values (0.001 m s^{-1}) during rising tide (when the sea surface level increases in the grid cell in which the considered particle is located) to negative values (-0.003 m s^{-1}) during falling tide (when the sea surface level decreases in the grid cell considered). With counter tidal behaviour the positive and negative values are inversed. Values for vertical migration rates have been defined within the range of the values observed in the literature (Berntsen et al. 1994; van der Molen et al. 2007), in order to obtain tidally associated vertical migration in the appropriate part of the water column.

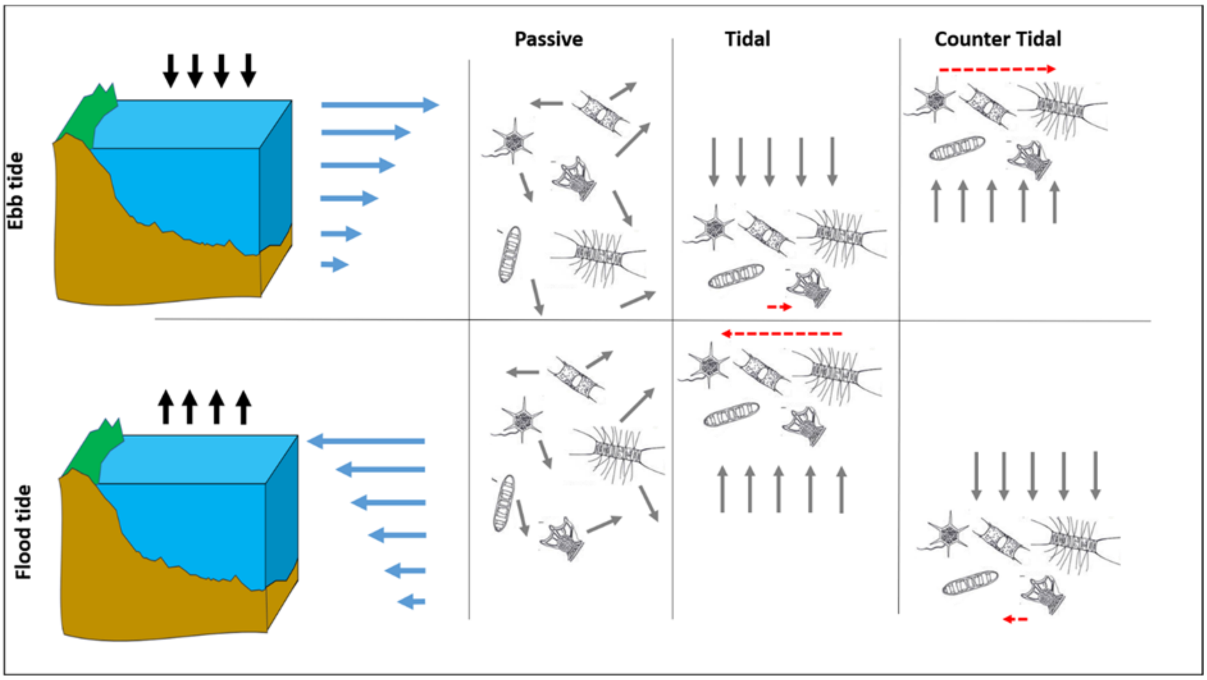

Figure 6: Schematic representation of the tidal and counter tidal behaviour considered in the present study. Black arrows represent the sea elevation movement, blue arrows the residual current, grey arrows the active movement of organisms (vertical migration) and the red arrows, the net displacement of larvae under the action of the governing currents.

Figure 7: different released areas considered in the model

Figure 7 gives a detailed view on where the particles were released. The particles were released at the bottom, in the middle and at the top of the water column, every day at midnight in the year 2011. In total 1.3 x 10^6 particles were released. The individual position of particles was tracked every day. The time for a particle originating from a harbour to reach another one was stored in output files.

5.3 Analysis of the results

The physical evidence for or against a well-connected region or an area that forms a biogeographic region, is assessed in this part by recording the time a simulated species needs to travel between the ports and by tracking its path. The time a particle needs to travel from its point of release to another

point is called here the **oceanic distance**. Particles with an oceanic distance longer than 200 days were excluded from the analysis. This length was chosen because it is assumed that this broadly exceeds the time of a species dispersal phase.
We have chosen three metrics to assess the connectivity between two ports: the minimum, the mean and the maximum oceanic distance. The mean oceanic distance between ports is the average oceanic distance of all particles released in port A that successfully reached port B. This indicator is more representative for the whole period than the minimum oceanic distance but is strongly skewed by long oceanic distances and hence can easily overestimate the oceanic distance. In the frame of dispersal of non-native species, it is interesting to focus on exceptional events to assess the dispersal ability of species. The minimum oceanic distance between port A and port B is the smallest recorded oceanic distance of all particles released in port A arriving in port B. This metric indicates how fast dispersal from port A to port B can be, but it depends highly on characteristic seasonal water circulation patterns and exceptional events. This indicator has the advantage that is represents the shortest possible pelagic duration for connecting two harbours. The maximum oceanic distance between port A and port B represents the longest time it took for all particle to disperse. After this time, no other particles bridged the distance between port A and B. This indicator is interesting to check whether particles with a long pelagic duration can reach the other ports. The model is a simplification of the real circulation pattern of the species. Some sources of uncertainties at small scale, which could increase local retention or increase travel drift, are not represented. The maximum oceanic distance is an interesting indicator, but due to the model uncertainties, it is less reliable than the other indicators used in this study.
The different metrics were summarised in a connectivity matrix. Since seasonality has a considerable impact on the minimum oceanic distance between two ports, a different matrix is produced for each season. The release date of the particles was used to differentiate between the different seasons. Particles released from January to March, from April to June, from July to September and from October to December were used to compute the connectivity matrices for winter, spring, summer and autumn respectively.
In Section 5 it was mentioned that particles were assigned three different behaviours (passive, tidal and counter tidal) and they were released at three different heights of the water column (bottom, surface and middle), hence this resulted in the production of 36 (4x3x3) connectivity matrices. Since the release depth had little to no effect on the results, results from the different release depths were merged. Finally, only matrices for different seasons and behaviours are presented in Appendix III (12 matrices).
In order to assess the connectivity between two ports for any organism, a summarising matrix has been produced by taking the longest duration for minimum and mean indicators and the shortest duration for the maximum metric. This final matrix allows to estimate the uncertainties of the dispersal.
The maxima of the dispersal matrices show very wide distributions. 75% of the maximum are longer than 150 days, 91% longer than 100 days and only one value is shorter than 50 days. This distribution shows that if you can reach a destination in a short period, you can also reach it in a longer period. This is important because some pelagic life stages of organisms require a long duration in the open water.

The next section will discuss the connectivity matrices presented in Appendix III. All the geographic dispersal patterns produced during the different seasons in 2011 and with the different dispersal behaviours can be found in Appendix IV. Where useful, these pictures are also shown in the main text of this report.

5.3.1 Connectivity of the Scheldt, Zeebrugge and Vlissingen (Scheldt zone)

Based on the minimum oceanic distances (see connectivity matrices of Appendix III), it becomes clear that during every season of 2011 the Scheldt, Vlissingen and Zeebrugge have a strong bilateral connection with each other. A bilateral connection between two ports means that both receive species from and provides species to the other port. So, there is a strong connection found for Zeebrugge-Vlissingen, Vlissingen-Scheldt and Zeebrugge-Scheldt. From the oceanographic point of view this means that the three ports can be considered as an area with natural exchange of species, whatever their behaviour (passive, tidal or counter tidal). If the stepping stone principle is applied, in theory Rotterdam or Antwerp only have to be connected to one of those ports to be indirectly connected with the others as well. This possibility is not the focus of this study and from biological knowledge we can argue for or against the validity of applying the stepping stone principle. Hereafter we will refer to the cluster of Zeebrugge, Vlissingen and Scheldt as the Scheldt zone.

5.3.2 Rotterdam-Antwerp connection

During spring, summer and autumn there is no connectivity between Rotterdam and Antwerp for species with passive and tidal behaviour. Species with a tidal behaviour could travel from Antwerp to Rotterdam during all seasons but not the other way around. The analysis of connectivity matrices shows that species could travel from Rotterdam to Antwerp only in winter and for species displaying counter tidal behaviour. A connection between Antwerp and Rotterdam cannot then be supported for the year 2011 from this analysis.

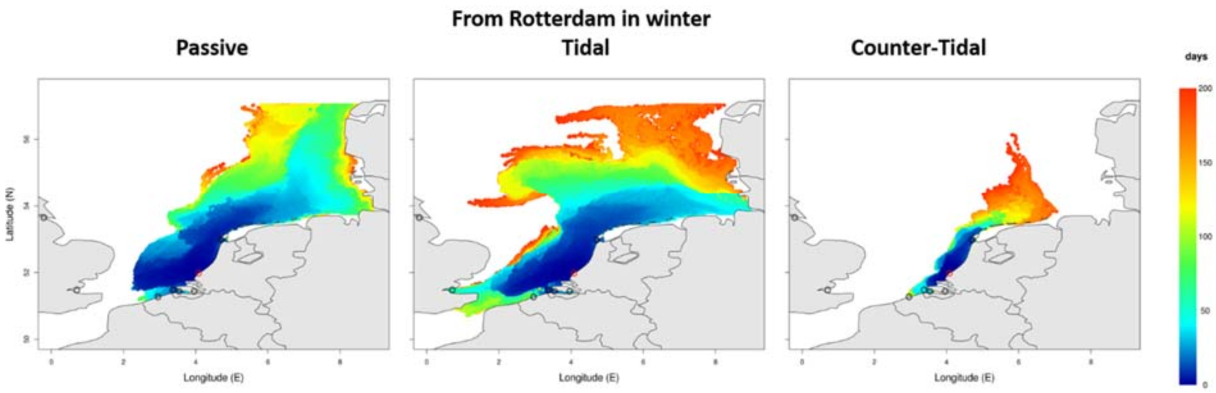

Figure 8: Map of the dispersal minimum oceanic distance (days) for particles released from Rotterdam (red circle) during winter under three different behaviours (left: passive, middle: tidal and right: counter tidal). The colour bar shows the oceanic distance in days.

The connection of Rotterdam with the other ports is not very strong according to the connectivity matrices and is strongly depending on seasonality and behaviour. shows that during winter a counter tidal behaviour allows the larvae to disperse slowly along the coast, whereas a passive behaviour accelerates the dispersal along the eastern coast of the North Sea and a tidal behaviour would allow the particles to cross the North Sea and even arrive to London.

5.3.3 Rotterdam-Scheldt zone connection

Rotterdam has a weak bilateral connectivity with the Scheldt zone during all seasons provided that the species are passively drifting with the currents. For species which would have a tidal dispersal behaviour they could only travel from Rotterdam to maximum one of the ports of the Scheldt zone, except during autumn 2011. Species having a counter tidal behaviour would present a weak bilateral connectivity with the Scheldt zone during spring, summer and winter. During autumn species only travel from the Scheldt zone to Rotterdam.

5.3.4 Antwerp-Scheldt zone connection

According to the model results, Antwerp only has a weak bilateral connectivity during spring, provided the individuals drift passively along with the currents. For all the other possible combinations of season and behaviour type, the connectivity is unilateral. For tidal behaviour there is a strong unilateral connectivity during all seasons, and species could reach Antwerp from the Scheldt zone. For counter tidal behaviour the opposite trend, that means a strong connection from Antwerp to the Scheldt zone is predicted. It is clear that the dispersal behaviour plays an important role in the conclusions. It is unclear if this behaviour is species-related or if it is related to the environmental conditions. The biological study might give more insight in how to interpret these results. The importance of the dispersal behaviour is demonstrated by Figure 9 which shows the dispersal pattern of particles released from Antwerp during the summer and resulting from the three different behaviours. According to these calculations, counter tidal behaviour would push the particles out of the Scheldt estuary quickly and then the particles would stay along the eastern coast of North Sea. In the case of passive dispersal, particles would need more time to leave the Scheldt Estuary and then disperse quickly after reaching the open sea. With a tidal behaviour the larvae would remain in the estuary and particles would not be able to reach another harbour according to these simulations.

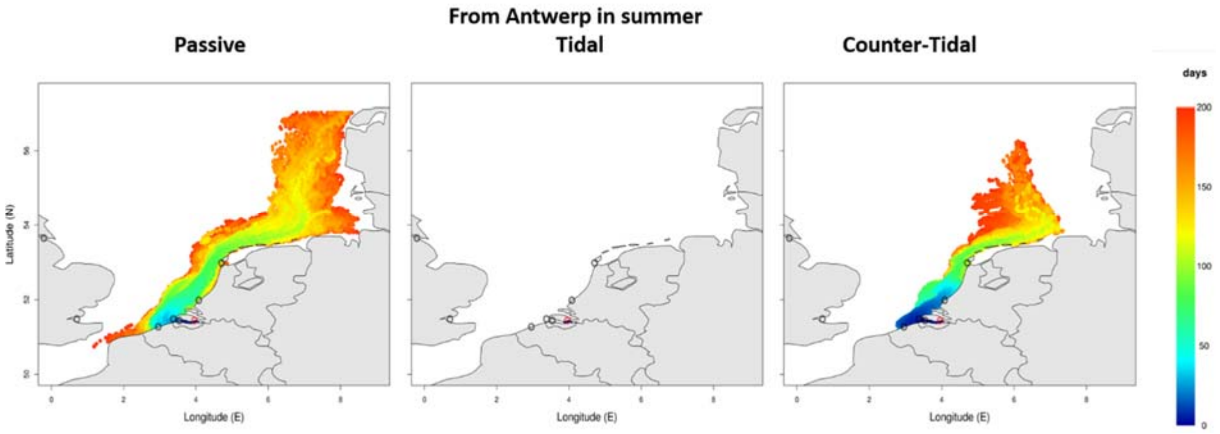

Figure 9: Map of the dispersal minimum oceanic distance (days) for particles released from Rotterdam (red circle) during winter under three different behaviours (left: passive, middle: tidal and right: counter tidal). The colour bar shows the oceanic distance in days.

5.3.5 Connection with other area's

The results also show that there would be a possibility of connectivity from Rotterdam to Amsterdam in all calculated scenarios, but not the other way around except for a very weak connection during winter.

Counter tidal behaviour would prevent the connectivity of the London, Hull and Antwerp estuaries. Hull would be isolated because no particles from other areas would arrive in that port in any of the scenarios. Particles released from Hull could be exported to Rotterdam or London but only under certain conditions and with a long drift time (more than 150 days, see Figure 16 in Appendix IV).

5.4 Conclusions of the modelling study

Connectivity during the year 2011 for the oceanic distance between ports can be summarised as follows:

1. **Scheldt zone** (Zeebrugge, Vlissingen, Scheldt): highly connected and does not need the stepping stone principle.
2. **Rotterdam-Scheldt zone:** weak connectivity highly depending on species dispersal behaviour
3. **Antwerp-Scheldt zone:** only unilateral connection, but a strong one and the direction is depending on the species dispersal behaviour.
4. **Rotterdam-Antwerp:** only connected in winter (the least likely season for dispersal). It would need the Scheldt zone as a stepping stone to be connected, but there is no strong evidence for such a connection.
5. **Connection of the SRA ports with Amsterdam, Hull, London**: the oceanic distance is always longer than 60 days, so no strong connection between these ports is demonstrated in this study.

Details on the oceanic distances between ports can be found in appendix III. There are also some general trends to deduce from the results:

1. The connectivity matrices are asymmetrical with -for the studied area- a higher connectivity from south to north than the other way around.
2. The timing of the dispersal phase and the behaviour of the dispersing species have a huge impact on the connectivity results
3. Ports in estuaries like Antwerp and Hull are less connected with other ports

The results found are coherent with another study performed in the same area. With the high-resolution model DELFT 3D of the Scheldt estuary and North Sea, the results of van der Molen et al. (2015) also showed that passive particles released in front of the Scheldt estuary could reach Vlissingen or Zeebrugge under 61 days and Amsterdam under 122 days.

Our results did not allow to demonstrate a clear, strong and direct connection among all the ports included in this study. Considering the Scheldt estuary as a potential step between the port of Antwerp and the one of Rotterdam is not enough to demonstrate a high level of connection between these two harbours. However, several uncertainties remain in this study, some that could argue for a less conservative approach in establishing an SRA based on these results, others could argue for an even more conservative approach. The uncertainties that are not answered in this physical approach for the establishment of an SRA are:

1. The Scheldt estuary could play an important role as a stepping stone that would allow to ensure the link between the Belgian and Dutch ports, but this needs to be supported by biological evidence.
2. By considering only one year of simulation, it did not allow to investigate the interannual variability in oceanic circulation. This could change the connectivity patterns found, probably that some years would be less/more favourable to dispersal than the year 2011.
3. Larval dispersal is a complex process depending on the species characteristics and the environmental conditions. Uncertainties on life history traits impact the estimations of dispersal. In this study we have considered three distinct behaviours, but in many cases these behaviours change in function of the developmental rate of larvae. Further on, some species could be passively transported during their early life stage and then change to specific migration behaviour before settlement to select a specific settlement area. Independently of uncertainties in life history traits, the three behaviours aforementioned and tested in this

study were over-simplified. In reality, organisms exhibit more complex behaviour. In particular active behaviour like changing their buoyancy when in their latest stage of development or the distribution of eggs in the water column is not taken into consideration.

4. The port architecture is not explicitly modelled in this study and a higher model resolution could help to understand the ability of pelagic organisms present in the port to disperse in open sea.
5. There is also an uncertainty on where exactly water ballast is exchanged, the results show that this could have an influence on the interpretation of the results.

This study demonstrates that water ballast exchange could at least accelerate the spread or create new connections at the scale of the North Sea. More investigations are needed to understand the specific effects of SRA installation.

6 Possible ecological implications when the desired SRA Zeebrugge-Antwerp-Rotterdam is installed

In this section the biological and oceanographic results are compared, and it is checked if they are in agreement with each other and how this comparison can strengthen the conclusions. Other factors that can influence the outcome of this analysis that provides evidence for the ecological basis of the SRA are also discussed in this section. One of the factors that should be taken into account is the ballast water procedure. Questions like where exactly the ballast water is loaded and discharged and about how much ballast water is transported can influence the interpretation of the results. This information coming from the economic study is included in our analysis.

6.1 Ecological basis for individual connections between ports

The oceanographic data need some extra support from the biological species study because the species life traits and characteristics are not included. For example, Rotterdam and Antwerp would only be connected during winter, but from the biological study it is not clear if species of concern are reproducing and if larvae would be released during that period of the year. Other traits such as the tolerance to salinity and temperature should also be checked. Moreover, the effect of the model set-up (ex. grid resolution, particle behaviour, model year) on the results should be critically reviewed. This information will be discussed for the Scheldt zone (Section 6.1.1), the Rotterdam-Scheldt zone connection (Section 6.1.2), the Antwerp-Scheldt zone connection (Section 6.1.3) and the Antwerp-Rotterdam connection (Section 6.1.4). The environmental and economical parameters against which the results were assessed by the researchers and an expert panel during a workshop are:

1. Species live traits
2. Spawning period and duration
3. Seasonality
4. Interaction with physical environment (salinity, temperature, turbidity...)
5. Behaviour
6. Relation with economic study

7. Importance of water ballast movements between the ports of the SRA

8. Modelling of the ports

6.1.1 Scheldt zone

There is a strong oceanographic and biological evidence for a high connectivity in the Scheldt zone. The environment of the three zones is so similar that habitat suitability should not be a limiting factor in the assignment of an SRA for this zone. It was shown that *Biflustra grandicella* found around Vlissingen is not of concern because there is no suitable habitat in the other ports. Since there is a strong connection in this zone during all seasons, spawning period and duration would also not be a limiting factor. Same arguments are valid for the dispersal behaviour, there is a strong connection for all types of behaviour in this zone. Two uncertainties are remaining to assign an SRA. The first one is that there is no official OSPAR/HELCOM study performed for the port of Zeebrugge, the other one is the way the ports are implemented in the modelling study. The species are released at the border between the port and the open sea. When ballast water is picked up inside the port, there might be an added retention of the species, because of the port architecture. It is unclear where the exact position of the ships is when exchanging water ballast, according to the ports this is variable.

6.1.2 Rotterdam-Scheldt zone

Even though there is no strong evidence from the modelling part of the study, the biological evidence shows that most species appear in all the ports. Some members of the expert panel stated that they are convinced, based on their knowledge about spreading species, that these zones are connected. The modelling part did not take interannual variability patterns into account, and thus, it can be said that at least for the year 2011 there was a weak connectivity so untreated water ballast could potentially accelerate the natural dispersal process.

6.1.3 Antwerp-Scheldt zone

The species behaviour plays an important role in the oceanographic results. The species *Heleobia* cf *australis* is the only species that could be labelled a species of concern by looking at biological data only. The model results show that there is a unilateral connection where Antwerp is well connected to the other studied ports but not the other way around. During the expert meeting it was noticed that Antwerp is the only non-marine port considered in the desired SRA. The panel also remarked that special care should be given to the treatment of brackish water species, because of the special position of Antwerp.

6.1.4 Antwerp-Rotterdam

The model results show no direct connection for the year 2011, possibly a very weak one during winter from Antwerp to Rotterdam. However, due to yearly varying water circulation patterns this outcome might change. Here as well the impact on the existing ecosystem of the *Heleobia cf autralis* is critical in the assessment.

6.1.5 Can Amsterdam, Hull or London be included in the SRA?

Neither the biological nor the modelling study showed any indication that these ports could be included, hence there was no further motivation to discuss this. During the mid-term meeting with the expert panel, there was some discussion if this could be possible or not. From the results shown in this report it is clear that a direct one generation connection between the ports of the desired SRA and these ports is most unlikely.

6.2 The importance of an exchange between biological and oceanographic results: the case study of *Ruditapes philippinarum*.

In addition to predict potential connectivity for a broad range of pelagic organisms, the connectivity matrices can be used to predict the connectivity for certain specific non-native species as *R. philippinarum*. This shellfish is native from Asia and has, due to its interest in aquaculture, dispersed throughout the world. This clam is euryhaline, in China, Manila clam spat are capable of growth in salinities of 12-33.5 psu, with 20.5 as the optimum. Spawning occurs in Spring (starting from mid-March to June) with the possibility of a second spawning event in late-summer (Herbert *et al.*, 2012). This species has a pelagic larval stage of on average 12-15 days (Ishida *et al.*, 2005; Ishii *et al.*, 2005) to less of 40 days (Humphreys et al. 2007). Those characteristics make it an interesting test case. The behaviour of this species is related to salinity after 6 days (Ishida *et al.*, 2005; Herbert *et al.*, 2012) to target specific salinity. This specific behaviour is not specifically taken into account so in the model we considered dispersal as passive in well mixed North Sea.
The connectivity matrix adapted for this species was built by selecting the most favourable dispersal event during spring and summer in the case of a passive behaviour to estimate its ability to disperse.

Table 9: Connectivity matrix for *R. phillipinarum* showing the minimum oceanic distance (in days), which represents the time needed for a particle released from an area (lines) to reach another area (columns). > 200 means that particles are not able to reach the destination within 200 days. Green represents a potential connectivity in less than 40 days.

	Zeebrugge	Vlissingen	Scheldt	Antwerp	Rotterdam	Amsterdam	Hull	London
Zeebrugge	0	10	6	>200	33	48	>200	>200
Vlissingen	3	0	2	38	26	82	>200	>200
Scheldt	3	2	0	>200	22	55	>200	>200
Antwerp	33	19	24	0	91	146	>200	>200
Rotterdam	24	19	17	>200	0	12	>200	>200
Amsterdam	>200	>200	>200	>200	>200	0	>200	>200
Hull	>200	>200	>200	>200	>200	>200	0	181
London	>200	>200	>200	>200	>200	>200	>200	0

Table 9 shows the natural connectivity among harbours of the desired SRA, ES area and the ports of Hull, Amsterdam and London. In this specific case, due to the multiplication of spawning events during a large period (from March to September) and with the upper limit of dispersal duration found in the literature of 40 days, Zeebrugge-Vlissingen-Antwerp-Rotterdam are well connected and able to export larvae to Amsterdam. However, the lowest pelagic duration of 12-15 days reported in the literature would lead to two separated areas. One area which contains the ports of Zeebrugge and Vlissingen and the other one with Rotterdam and Amsterdam.
This example illustrates how dispersal for a specific species can be more important than the one showed in the summary matrix which is valid for a broad range of species. It shows that the model predictions should be further interpreted by means of biological information when available.

6.3 Conclusions

Most of the findings of the oceanographic and biological study keep their ground or reinforce each other. By combining results from both approaches, some of the conclusions were refined. The main uncertainties in this study are the implementation of the ports in the model, the interannual variability that is not included in the current oceanographic model assessment, the water ballast discharge/load procedure and how to deal with brackish water species. See Section 7.1 for a more detailed elaboration.

7 Conclusions and recommendations

In this section the findings of the study are summarised and the remaining uncertainties are discussed. Recommendations are given on how to resolve the remaining uncertainties in the future.

7.1 Methodology considerations and recommendations

7.1.1 Connectivity modelling among ports

The results show that estuaries would have a retention effect on the species. It would be interesting to test if this retention effect is also valid for the ports. A case study could be set up to verify this, though this might unnecessary complicate things, hence this type of research is not recommended as a priority.

7.1.2 Interannual variability

The modelling study should be run with other years than 2011, such as the year 1996 which was a very eventful year with regards to the invasion of tropical species to our region or the year 2013 which was relatively warm. In addition, simulations over a longer period covering at least 10 years would allow to capture most of the connectivity pattern variability due to interannual variability of hydrodynamics (Berglund et al., 2012).

7.1.3 Ecosystem evolution

As relatively cold winters are getting scarce and maximum sea water temperatures in summer are increasing (https://waterinfo.rws.nl), it is to be expected that alien species that were not able to settle, survive the winter and reproduce in the area of the proposed SRA in the past, may be able to do so in the coming years. This climate change impact is already becoming clear for a variety of southern European marine species including gastropods and crabs that tend to thrive off the Belgian coast during warmer years and are now also extending their ranges into Dutch and German waters (Birchenough et al., 2015). As the marine ecosystem in the proposed SRA is changing in a relatively fast pace, continuous monitoring of alien species in the region will remain necessary if the SRA Zeebrugge-Antwerp-Rotterdam would become a reality. Alien species that are settled in European waters to the south of Belgium and the Netherlands, may further spread north if temperatures keep rising. Off course, the BWM would prevent new arrivals of alien species.

7.1.4 Insufficient knowledge of dispersal behaviour of species like *Heleobio cf. Australis*.

In general, much is known about the dispersal behaviour of invasive alien species that occur widespread along the western European coast and have a distinct impact on the existing ecosystem or human health, properties or economics. Little is known about alien species that are newly introduced in European ports. Most of the alien species recorded within the proposed SRA are rare and/or have little impact, hence little information about their dispersal behaviour is known. A dispersal study for *Heleobia* cf *australis* could be a good start to develop a protocol on what to do with new arrivals. The assessment of this tropical species, which only appears in Antwerp (though there was no sampling of Zeebrugge done in compliance with OSPAR/HELCOM regulations) is critical for the installation of the

SRA. Whether this knowledge gap concerning the dispersal behaviour should stand in the way of assigning the SRA Zeebrugge-Antwerp-Rotterdam, can be questioned. One may argue that there are no examples of *Heleobia* species worldwide, which have had a distinct impact as an alien on any ecosystem. Therefore, it may be considered unlikely that *Heleobia* cf *australis* will have a distinct impact on any ecosystem within the proposed SRA. As this would be a subjective assessment of the risk, one may decide to conduct a focused risk assessment on this species, recording its exact habitat preferences in the port of Antwerp and possibly doing some aquarium tests assessing its salinity preferences.

It is a small species with probably a low impact on the ecosystem, nonetheless it should be considered with care when interpreting this study.

7.1.5 OSPAR-HELCOM target species selection

Within the present assessment the target species list and selection criteria used by Heyer (2015) were used as a basis for this risk assessment as Heyer (2015) selected target species based on the risk assessment proposed by the OSPAR-HELCOM committee working on exemptions to the ballast water convention. In principle this committee aims at keeping the target species list for OSPAR and HELCOM regions updated on a continuous basis. It is unclear however whether this has been done after the target species list of Heyer (2015) was set. Another aspect to take under consideration is that the risk assessment method proposed by this OSPAR-HELCOM committee for selecting target species, may not completely comply with national alien species focused risk assessment methods used within Belgium and the Netherlands. For the risk assessment done in the present report, no comparison between risk assessment methods was done. As an SRA concerns an exemption to the ballast water convention, Heyer (2015) was followed where possible.

7.1.6 Ballast water transport over short distances

For some alien species found in literature and possibly also by Heyer (2015) it is assumed that they are not transported by ballast water as they have relatively short pelagic larval stages. Within the proposed SRA the distances between the ports are relatively small, which may enable the transport of such species with ballast water. Although species with such short pelagic life stages, like most sea-squirts and bryozoans, may be transported by ballast water within the proposed SRA, most of these species are more likely to be transported by hull fouling. It is therefore still assumed that ballast water does not concern their main vector of transport. If in the future, the risks of alien species transported with hull fouling are dealt with, this assumption has to be re-assessed.

7.1.7 Impact seems not significant

For some alien species cited in literature and also by Heyer (2015) it is assumed that for some species the impact seems not significant. They are therefore not considered to be target species. Assessing whether the impact of a species is significant, is a subjective assessment therefore depending on the risk assessment method used, the nature values and the opinion of the researcher based on the best available scientific knowledge. For a species of concern like *Heleobia* cf *australis*, such an assessment remains uncertain as little is known about this species.

7.1.8 Alien species occurring outside of the ports of an SRA

Within the four ports of the proposed SRA 72 alien species were recorded. When also including alien species that were reported in between these ports in the Western Scheldt as a potential ballast water exchange site, in total 114 alien species were recorded. Whether one should also include alien species records within the Western Scheldt in an assessment of the viability of an SRA depends on whether or not ballast water exchange may also take place within the Western Scheldt and whether or not a stepping stone principle is assumed for natural species dispersal through the Western Scheldt. More in general, if one would assume that all larvae of alien species settled close to the ports should also be considered as potentially being transported by ballast water, it has to be (subjectively) decided what is seen as an acceptable risk. By suggesting that such species should be included, one may also need to consider that larvae of marine alien species occurring along the French Atlantic coast may also be present in the water of the port of Zeebrugge, regardless of whether or not they are settled there. If such a risk should also be considered, the proposed SRA would not be viable.

7.2 Summary of the results per port or zone

This section gives an overview of the main conclusions.

The economic study shows there is an advantage to be gained from installing an SRA. The advantage remains when Antwerp is taken out the equation, but it is a lot smaller.
The conclusions of the ecological report will be given per port combination.

7.2.1 Zeebrugge-Vlissingen: Scheldt zone

- The biological study showed that all recorded alien species have probably been dispersed to all the suitable habitats in this region. Differences in species occurrences between the two ports may be partly due the use of different port survey methodologies in these two ports.
- The oceanographic study shows a very strong connectivity between these ports.
- The experts agreed that this is a well-connected area.

7.2.2 Rotterdam-Scheldt zone

- Some hydroids (medusa stages) and dinoflagellates are found in Rotterdam, but not in the Scheldt zone. Differences in species occurrences between these two areas may be due to differences in salinities (lower salinities in some parts of the port of Rotterdam), and the timing of the surveys done, e.g. dinoflagellate species are not found all year around
- The oceanographic study only shows connectivity only for passive behaviour. In spring, the model predicts connection when species show counter tidal behaviour, and in winter when they show tidal behaviour for the year 2011. The model predicts a shorter oceanic distance from the Scheldt zone to Rotterdam than the other way around.
- Both the biological and oceanographic study showed there is weak connectivity.

7.2.3 Antwerp-Scheldt zone

- Some alien species that are recorded in Antwerp are not recorded in the Scheldt zone and vice versa. Differences in species occurrences between these two areas may be due to differences in salinities (lower salinities in most of the port of Antwerp). For example, species like the low salinities preferring bivalve *Rangia cuneata* were only recorded for Antwerp, while high salinities preferring sea-squirt species like *Didemnum vexilum* are only found in the Scheldt zone.

- The model shows a strong, but unilateral connection depending on behaviour (species could spread from Antwerp to the Scheldt zone with passive and counter tidal behaviour, but only with tidal behaviour they can travel from the Scheldt zone to Antwerp, according to the model for the year 2011). Behaviour played an important role in the spreading of the species.
- Antwerp is not a marine port and the freshwater species are not addressed in this study. For the connection Antwerp-Scheldt zone this is not relevant as freshwater species can't survive in the saltier waters of the Scheldt zone area. The model did not show bi-lateral connectivity for the year 2011.

Either the stepping stone principle or modelling different years could probably demonstrate a bilateral connectivity, this study demonstrates that untreated ballast water accelerates the spreading of newly introduced species between Antwerp and the Scheldt zone.

7.2.4 Antwerp-Rotterdam

- There is an alien species in Antwerp than in not known for the port of Rotterdam yet, for which ballast water appears to be the only vector with which it would be able to reach Rotterdam, i.e. Heleobia cf. australis. Although it does not have a pelagic larval stage, the millimeters small shells are likely to enter ballast water tanks when the bottom in the port is disturbed by for example the currents or propellers of the vessels. More in general natural dispersal between these two ports for brackish water preferring alien species, may be difficult because of the higher saline waters that have to be crossed.
- The oceanographic results show a weak connection between the two ports. The impact of behaviour and season on dispersal is very important.
- The river system connecting Antwerp and Rotterdam is not taken into account, in this study. The fresh and brackish water species that could be connected through this system, are not included in this study.

References

Berglund M, Jacobi MN, Jonsson PR (2012) Optimal selection of marine protected areas based on connectivity and habitat quality. Ecological Modelling, 240, 105-112.

Berntsen, J., Skagen, D. W., and Svendsen, E. 1994. Modelling the transport of particles in the North Sea with reference to sandeel larvae. Fisheries Oceanography, 3: 81–91. Wiley/Blackwell (10.1111).

Birchenough, S. N. R., Reiss, H., Degraer, S., Mieszkowska, N., Borja, Á., Buhl-Mortensen, L., Braeckman, U., *et al.* 2015. Climate change and marine benthos: a review of existing research and future directions in the North Atlantic. Wiley Interdisciplinary Reviews: Climate Change, 6: 203–223. Wiley-Blackwell.

Bruyne, R. de, van Leeuwen, S., Gmelig Meyling, A. & R. Daan (red.) 2013. Schelpdieren van het Nederlandse Noordzeegebied. Ecologische atlas van de mariene weekdieren (Mollusca). Tirion Natuur, Stichting ANEMOON.

Engelen, A.H., Serebryakova, A., Ang, P., Britton-Simmons, K., Mineur, F., Pedersen, M. F., Arenas, F., Fernandez, C., Steen, H., Svenson, R., Pavia, H., Toth, G., Viard, F. and Santos, R. 2015. Circumglobal invasion by the brown seaweed *Sargassum muticum*. Oceanography and Marine Biology: An Annual Review 53: 81-126.

Faasse, M. 2011. *Pileolaria berkeleyana*, a spirorbin polychaete worm introduced to the Netherlands (polychaeta: serpulidae: spirorbinae). 36: 99-102.Fish, J.D. & S. Fish, 2011. A student's guide to the seashore. Third edition. Cambridge University Press, New York: 527 pp.

Fox, C. J., McCloghrie, P., Young, E. F., and Nash, R. D. M. 2006. The importance of individual behaviour for successful settlement of juvenile plaice (*Pleuronectes platessa* L.): A modelling and field study in the eastern Irish Sea. Fisheries Oceanography, 15: 301–313. Blackwell Publishing Ltd.

Gittenberger, A., 2007. Recent population expansions of non-native ascidians in The Netherlands. Journal of Experimental Marine Biology and Ecology 342(1): 122-126.

Gittenberger, A., 2009. Exoten in de Oosterschelde. GiMaRIS rapport 2009_08: 9 pp. Issued by the Ministerie van Landbouw, Natuur en Voedselkwaliteit, Directie Visserij.

Gittenberger, A., 2010. Risk analysis of the colonial sea-squirt *Didemnum vexillum* Kott, 2002 in the Dutch Wadden Sea, a UNESCO World Heritage Site.

Gittenberger et al., in prep. Native and non-native species of the Dutch Wadden Sea in 2018. Issued by Office for Risk Assessment and Research, Netherlands Food and Consumer Product Safety Authority.

Gittenberger, A., Rensing, M., Niemantsverdriet, P, Schrieken, N. & H. Stegenga, 2014a. Port of Rotterdam survey and monitoring non-native species conform HELCOM/OSPAR protocol. GiMaRIS rapport 2014_31: 111 pp. i.o.v. Office for risk assessment and research, the Netherlands Food and Consumer Product Safety Authority.

Gittenberger, A., Rensing M., Dekker, R., Niemantsverdriet, P., Schrieken N. & H. Stegenga, 2015a. Native and non-native species of the Dutch Wadden Sea in 2014. GiMaRIS rapport 2015_08: 93 pp. i.o.v. Ministerie Economische Zaken; Bureau Risicobeoordeling en Onderzoeksprogrammering (BuRO).

Gittenberger A, Rensing M. & E. Gittenberger, 2015b. *Rangia cuneata* (Bivalvia, Mactridae) expanding its range into the port of Rotterdam, The Netherlands. Basteria 78: 4–6

Gittenberger, A., Rensing, M., Wesdorp, K., Niemantsverdriet, P., Schrieken, N., D'Hont, A. & H. Stegenga, 2015c. Species survey of the Port of Hull, summer 2015. GiMaRIS rapport 2015_38: 44 pp. i.o.v. P&O Ferries.

Gittenberger, A., Rensing, M. & H. Stegenga, 2015d. Non-native species survey 2014 in the military harbour of Den Helder. GiMaRIS rapport 2015_03: 10 pp. i.o.v. Office for risk assessment and research, The Netherlands Food and Customer Product Safety Authority of the Ministry of Economical Affairs.

Gittenberger, A., Wesdorp, K.H. & M. Rensing, 2017a. Biofouling as a transport vector of non-native marine species in the Dutch Delta, along the North Sea coast and in the Wadden Sea. GiMaRIS rapport 2017_09: 45 pp. i.o.v. Office for Risk Assessment and Research, Netherlands Food and Consumer Product Safety Authority.

Gittenberger, A. Rensing, M., Schrieken, N. & H. Stegenga, 2017b. Port of Vlissingen survey and monitoring non-native species in 2016 conform HELCOM/OSPAR protocol. GiMaRIS rapport 2017_05: 49 pp. Issued by Office for Risk Assessment and Research, Netherlands Food and Consumer Product Safety Authority.

Gittenberger, A. & M. Rensing, 2017c. Risk Assessment of the bryozoan *Biflustra grandicella*. GiMaRIS rapport 2017_42: 17 pp. Issued by the Office for Risk Assessment and Research of the Netherlands Food and Consumer Product Safety Authority.

Gittenberger, A., Rensing M. & K.H.Wesdorp, 2017d. Non-indigenous marine species in the Netherlands. GiMaRIS rapport 2017_13: 39 pp. i.o.v. The Department of Nature & Biodiversity of the Ministry of Agriculture, Nature and Food Quality & the Office for Risk Assessment and Research of the Netherlands Food and Consumer Product Safety Authority.

Gittenberger, A., Rensing, Wesdorp K.H. & D'Hont A., 2018. Monitoring non-native species in the port of Antwerp in 2017 conform the joint HELCOM/OSPAR port survey protocol. GiMaRIS rapport 2018_01: 46 pp. i.o.v. Antwerp Port Authority.

HELCOM/OSPAR, 2013. Joint harmonised procedure for the contracting parties of HELCOM and OSPAR on the granting of exemptions under the international convention for the control and management of ship's ballast water and sediments, regulation A-4. Adopted as OSPAR Agreement 2013-09 and by HELCOM Ministerial Meeting Copenhagen 3 October 2013.

Helm, M.M., Pellizzato, M., 1990. Riproduzioneed allevamento in schiuditoio della specie *Tapes philippinarum* in ESAV *Tapes philippinarum* biologia e sperimentazione a cura di G. Alessandra, pp. 115, 140.

Herbert, R. J. H., Willis, J., Jones, E., Ross, K., Hübner, R., Humphreys, J., Jensen, A., *et al.* 2012. Invasion in tidal zones on complex coastlines: modelling larvae of the non-native Manila clam, Ruditapes philippinarum, in the UK. Journal of Biogeography, 39: 585–599.

Herborg, L.M., Rushton S.P., Clare A.S., Bentley M.G. (2003) Spread of the Chinese mitten crab (*Eriocheir sinensis* H. Milne Edwards) in Continental Europe: analysis of a historical data set. In: Jones M.B., Ingólfsson A., Ólafsson E., Helgason G.V., Gunnarsson K., Svavarsson J. (eds) Migrations and Dispersal of Marine Organisms. Developments in Hydrobiology 174: 21-28.

Heyer, K., 2015. Draft Target Species List for the purposes of A4-exemptions, v2.

Hill, A. E. 1991. Vertical migration in tidal currents. Marine Ecology Progress Series, 75: 39–54. Inter-Research Science Center.

Humphreys, J., Caldow, R.W.G., McGrorty, S., West, A.D. & A. C. Jensen, 2007. Population dynamics of naturalised Manila clams *Ruditapes philippinarum* in British coastal waters. Marine Biology 151: 2255-2270.

Ishida, M., Momoko, O., Chisato, M., Mikio, M., Tetsuya, I., and Teruaki, S. 2005. Changes in Behavioral Characteristics, in Relation to Salinity Selection and Vertical Movement at different growth stages of the planktonic larvae of the japanese littleneck clam, Ruditapes phillipinarum. Bulletin of the Japanese Society of Fisheries Oceanography, 69: 73–82.

Ishii, R., Sekiguchi, H., and Jinnai, Y. 2005. Vertical Distributions of Larvae of the Clam Ruditapes philippinarum and the Striped Horse Mussel Musculista senhousia in Eastern Ariake Bay, Southern Japan. Journal of Oceanography, 61: 973–978. Kluwer Academic Publishers-Consultants Bureau.

Jager, Z. 1999. Selective Tidal Stream Transport of Flounder Larvae (*Platichthys flesus* L.) in the Dollard (Ems Estuary). Estuarine, Coastal and Shelf Science, 49: 347–362.

Katsanevakis, S., Zenetos, A., Belchior, C., and Cardoso, A.C. 2013. Invading European Seas: Assessing pathways of introduction of marine aliens. Ocean & Coastal Management, 76: 64-74.

Kerckhof, F., Haelters, J. & Gollasch, S., 2007. Alien species in the marine and brackish ecosystem: the situation in Belgian waters. Aquatic Invasions 2: 243–257.

Lacroix, G., Maes, G. E., Bolle, L. J., and Volckaert, F. A. M. 2013. Modelling dispersal dynamics of the early life stages of a marine flatfish (*Solea solea* L.). Journal of Sea Research, 84: 13–25.

Loewe, P. 2003. Weekly North Sea SST Analyses since 1968, in: Hydrographie, O.d.a.h.b.B.f.S.u. (Ed.), D-20305 Hamburg, P.O. Box 301220, Germany.

Luyten, P. J., Jones, J. E., Proctor, R., Tabor, A., Tett, P., and Wild-Allen, K. 1999. COHERENS a coupled hydrodynamical–ecological model for regional and shelf seas: user documentation. Belgium. 911 pp.

Miller, S. H., and Morgan, S. G. 2013. Interspecific differences in depth preference: Regulation of larval transport in an upwelling system. Marine Ecology Progress Series, 476: 301–306.

North, E. W., Schlag, Z., Hood, R. R., Li, M., Zhong, L., Gross, T., and Kennedy, V. S. 2008. Vertical swimming behaviour influences the dispersal of simulated oyster larvae in a coupled particle-tracking and hydrodynamic model of Chesapeake Bay. Marine Ecology Progress Series, 359: 99–115. Inter-Research Science Center.

OSPAR Commission. 2000. Quality Status Report 2000. London.

Otto, L., Zimmerman, J. T. F. T. F., Furnes, G. K. K., Mork, M., Saetre, R., and Becker, G. 1990. Review of the physical oceanography of the North Sea. Netherlands Journal of Sea Research, 26: 161. Elsevier.

Robins, P. E., Neill, S. P., Giménez, L., Jenkins, S. R., and Malham, S. K. 2013. Physical and biological controls on larval dispersal and connectivity in a highly energetic shelf sea. Limnology and Oceanography, 58: 505–524.

Savina, M., Lacroix, G., and Ruddick, K. 2010. Modelling the transport of common sole larvae in the southern North Sea: Influence of hydrodynamics and larval vertical movements. Journal of

Marine Systems, 81: 86–98.

Solidoro, C., Canu, D.M. & R. Rossi, 2003. Ecological and economic considerations on fishing and rearing of *Tapes phillipinarum* in the lagoon of Venice. Ecological Modelling 170: 303-318.

Turrell, W. R., Henderson, E. W., Slesser, G., Payne, R., and Adams, R. D. 1992. Seasonal changes in the circulation of the northern North Sea. Continental Shelf Research, 12: 257–286.

van der Molen, J., Rogers, S. I., Ellis, J. R., Fox, C. J., and McCloghrie, P. 2007. Dispersal patterns of the eggs and larvae of spring-spawning fish in the Irish Sea, UK. Journal of Sea Research.

van der Molen, J., Van Beek, J., Augustine, S., Vansteenbrugge, L., Van Walraven, L., Langenberg, V., Van Der Veer, H. W., *et al.* 2015. Modelling survival and connectivity of Mnemiopsis leidyi in the south-western North Sea and Scheldt estuaries. Ocean Science, 11: 405–424.

Wijnhoven, S., Gittenberger A., Faasse M., & T. Schellekens, 2017. Overview alien species monitoring in the Western Scheldt: Current status of monitoring efforts and presence of alien species among macrofauna and algae. Commissioned by the Netherlands Food and Consumer Product Safety Authority (NVWA) of the Netherlands Ministry of Economic Affairs (EZ). Ecoauthor Report Series 2017 - 01, 55 pp.

Yang, X.-X., Zhang, Y., Wong, Y.-H. & P.-Y. Qian, 2018. HSP90 regulates larval settlement of the bryozoan *Bugula neritina* through NO pathway. Journal of experimental biology. doi: 10.1242/jeb.167478.

Appendix I. List of all the recorded alien species sampled in the studied ports

All alien species, which have been recorded in the ports of Hull, Den Helder, Amsterdam, Rotterdam, Vlissingen, Zeebrugge and Antwerp. As the focus of the study is on the proposed SRA Antwerp-Zeebrugge-Rotterdam, species recorded outside of these ports in the Western Scheldt are also included. For a more detailed dataset on the distribution of alien species within this SRA see Figure 3 and Appendix II. Where available the conclusion of the EASIN assessment (alien species risk) and target species for the OSPAR area assessment by Heyer (2015) is indicated: (a)=Target species; (WL)=Watch List, insufficient information for assessment. Not as target species proposed, since (b)=found in all its potential areas; (c)=ballast water is not the introduction vector; (d)=warm water species; (e)=indigenous species; (f)=marine species; (g)=parasite; (h)=impact seems not significant; (i)=salinity is not matching; (j)=first introduction is very long ago > 100 years; (k)= cold water species; (l)= Introduced but did not build up new populations; (m)= Taxonomy is unclear.

	Species	**Order**	**Phylum**	**OSPAR area**	**EASIN assessment**	**Port of Antwerp**	**Western Scheldt**	**Port of Vlissingen**	**Port of Zeebrugge**	**Port of Rotterdam**	**Port of Den Helder**	**Port of Amsterdam**	**Port of Hull**
1	*Alitta virens*	Phyllodocida	Annelida			0	1	0	0	0	1	0	0
2	*Microphthalmus similis*	Phyllodocida	Annelida			0	1	0	0	0	0	0	0
3	*Proceraea cornuta*	Phyllodocida	Annelida			0	1	0	0	0	0	0	0
4	*Syllidia armata*	Phyllodocida	Annelida			0	1	0	0	0	0	0	0
5	*Syllis gracilis*	Phyllodocida	Annelida			0	1	0	0	0	0	0	0
6	*Ficopomatus enigmaticus*	Sabellida	Annelida	a	High	1	1	1	1	1	1	1	1
7	*Laonome calida*	Sabellida	Annelida			0	1	0	0	0	0	0	0
8	*Neodexiospira brasiliensis*	Sabellida	Annelida			0	1	1	0	0	0	1	0
9	*Pileolaria berkeleyana*	Sabellida	Annelida			0	1	0	0	0	0	0	0
10	*Boccardia proboscidea*	Spionida	Annelida			0	1	0	1	0	0	0	0
11	*Boccardiella hamata*	Spionida	Annelida			0	1	0	1	0	0	0	0
12	*Marenzelleria viridis*	Spionida	Annelida	a	High	0	1	0	0	0	0	0	0
13	*Streblospio benedicti*	Spionida	Annelida			0	1	0	0	0	0	0	0
14	*Aphelochaeta marioni*	Terebellida	Annelida			0	1	0	0	0	0	0	0
15	*Ampithoe valida*	Amphipoda	Arthropoda			0	1	0	0	0	0	0	0
16	*Caprella mutica*	Amphipoda	Arthropoda	a	High	0	1	1	1	1	1	1	0
17	*Caprella scaura*	Amphipoda	Arthropoda			0	1	0	0	0	0	0	0
18	*Chelicorophium curvispinum*	Amphipoda	Arthropoda			0	1	0	0	0	0	0	0
19	*Gammarus tigrinus*	Amphipoda	Arthropoda	a	High	0	1	0	0	0	0	1	0
20	*Incisocalliope aestuarius*	Amphipoda	Arthropoda			0	1	0	0	0	0	0	0
21	*Jassa marmorata*	Amphipoda	Arthropoda			0	1	1	1	1	0	0	0
22	*Melita nitida*	Amphipoda	Arthropoda			1	1	1	1	0	0	0	1
23	*Monocorophium sextonae*	Amphipoda	Arthropoda			0	1	0	0	0	0	0	0
24	*Ptilohyale littoralis*	Amphipoda	Arthropoda			0	1	0	1	0	0	0	0
25	*Acartia (Acanthacartia) tonsa*	Calanoida	Arthropoda	b	High	0	1	0	0	0	0	0	0
26	*Pseudodiaptomus marinus*	Calanoida	Arthropoda			0	1	0	0	0	0	0	0
27	*Mytilicola intestinalis*	Cyclopoida	Arthropoda			0	1	0	0	0	0	0	0
28	*Eriocheir sinensis*	Decapoda	Arthropoda	a	High	0	1	0	1	0	0	0	0
29	*Hemigrapsus sanguineus*	Decapoda	Arthropoda	a	High	1	1	1	1	1	1	1	0
30	*Hemigrapsus takanoi*	Decapoda	Arthropoda	a	High	1	1	1	1	1	1	1	0

31	*Palaemon macrodactylus*	Decapoda	Arthropoda	a	High	1	1	0	1	0	0	0	0
32	*Rhithropanopeus harrisii*	Decapoda	Arthropoda	a	High	1	1	0	0	1	0	1	0
33	*Telmatogeton japonicus*	Diptera	Arthropoda	c	High	1	1	0	1	0	0	0	0
34	*Synidotea laticauda*	Isopoda	Arthropoda			0	1	0	0	0	0	0	0
35	*Amphibalanus amphitrite*	Sessilia	Arthropoda			0	1	0	0	0	0	0	0
36	*Amphibalanus improvisus*	Sessilia	Arthropoda	b	High	1	1	0	1	1	1	1	1
37	*Austrominius modestus*	Sessilia	Arthropoda	a	High	0	1	1	1	1	1	1	1
38	*Megabalanus coccopoma*	Sessilia	Arthropoda			0	1	0	0	0	0	0	0
39	*Sinelobus vanhaareni*	Tanaidacea	Arthropoda			0	1	0	0	0	0	0	0
40	*Biflustra grandicella*	Cheilostomatida	Bryozoa			0	1	0	0	0	0	0	0
41	*Bugula simplex*	Cheilostomatida	Bryozoa			0	0	0	1	0	0	0	0
42	*Bugulina stolonifera*	Cheilostomatida	Bryozoa			0	1	1	1	0	1	0	0
43	cf *Conopeum chesapeakensis*	Cheilostomatida	Bryozoa			1	0	0	0	0	0	0	0
44	*Fenestrulina delicia*	Cheilostomatida	Bryozoa			0	1	1	0	0	0	0	0
45	*Fenestrulina malusii*	Cheilostomatida	Bryozoa			0	1	1	0	0	0	0	0
46	*Smittoidea prolifica*	Cheilostomatida	Bryozoa			0	1	1	0	0	0	0	0
47	*Tricellaria inopinata*	Cheilostomatida	Bryozoa	c	High	0	1	1	1	0	1	0	0
48	*Codium fragile*	Bryopsidales	Chlorophyta	a	High	0	1	0	0	0	0	0	0
49	*Ulva australis*	Ulvales	Chlorophyta			0	1	1	0	1	1	0	0
50	*Aplidium glabrum*	Aplousobranchia	Chordata			0	1	1	1	0	0	0	0
51	*Didemnum vexillum*	Aplousobranchia	Chordata	a	High	0	1	1	0	0	0	0	0
52	*Diplosoma listerianum*	Aplousobranchia	Chordata			0	1	1	1	0	0	0	0
53	*Neogobius fluviatilis*	Perciformes	Chordata	WL	Low/Unknown	0	0	0	0	1	0	0	0
54	*Neogobius melanostomus*	Perciformes	Chordata			0	1	0	0	1	0	0	0
55	*Perophora japonica*	Phlebobranchia	Chordata	c	Low/Unknown	0	1	1	0	0	0	0	0
56	*Botrylloides violaceus*	Stolidobranchia	Chordata	c	High	0	1	1	1	0	1	1	0
57	*Molgula manhattensis*	Stolidobranchia	Chordata	h	High	1	1	1	1	1	1	1	1
58	*Styela clava*	Stolidobranchia	Chordata	b	High	0	1	1	1	1	1	0	0
59	*Diadumene cincta*	Actiniaria	Cnidaria			0	1	1	1	0	1	0	0
60	*Diadumene lineata*	Actiniaria	Cnidaria			0	1	0	0	0	0	0	0
61	*Cordylophora caspia*	Anthoathecata	Cnidaria	j	High	0	1	0	0	1	1	0	0
62	*Garveia franciscana*	Anthoathecata	Cnidaria			0	1	0	0	0	0	0	0
63	*Nemopsis bachei*	Anthoathecata	Cnidaria			0	0	0	1	1	0	0	0
64	*Blackfordia virginica*	Leptothecata	Cnidaria	WL	High	0	1	0	0	0	0	0	0
65	*Mnemiopsis leidyi*	Lobata	Ctenophora	a	High	1	1	1	1	1	1	0	0
66	*Ensis leei*	Adapedonta	Mollusca	a	High	0	1	1	0	0	0	0	0
67	*Crepidula fornicata*	Littorinimorpha	Mollusca	a	High	0	1	1	1	1	1	0	0
68	*Heleobia* cf *australis*	Littorinimorpha	Mollusca			1	0	0	0	0	0	0	0
69	*Potamopyrgus antipodarum*	Littorinimorpha	Mollusca	b/j	High	0	0	0	0	1	0	1	0
70	*Dreissena bugensis*	Myida	Mollusca	a	High	0	1	0	0	1	0	0	0
71	*Dreissena polymorpha*	Myida	Mollusca	a	High	0	1	0	0	1	0	0	0
72	*Mya arenaria*	Myida	Mollusca	b/j	High	0	1	1	1	0	0	1	0
73	*Mytilopsis leucophaeata*	Myida	Mollusca	a	High	1	1	0	0	0	0	1	0
74	*Teredo navalis*	Myida	Mollusca	b	High	0	1	0	1	0	0	0	0
75	*Magallana gigas*	Ostreida	Mollusca	b	High	1	1	1	1	1	1	1	0
76	*Corbicula fluminalis*	Venerida	Mollusca			0	0	0	0	1	0	0	0
77	*Petricolaria pholadiformis*	Venerida	Mollusca	c/i/j	High	0	1	0	0	0	0	0	0
78	*Ruditapes philippinarum*	Venerida	Mollusca			0	1	0	1	0	0	0	0
79	*Physella acuta*		Mollusca			0	1	0	0	1	0	0	0
80	*Rangia cuneata*		Mollusca	a	Low/Unknown	1	0	0	0	1	0	1	0
81	*Alexandrium ostenfeldii*	Gonyaulacales	Myzozoa	e	Low/Unknown	0	1	0	0	0	0	0	0
82	*Alexandrium tamarense*	Gonyaulacales	Myzozoa			0	1	0	0	0	0	0	0
83	*Protoceratium reticulatum*	Gonyaulacales	Myzozoa			0	1	0	0	1	0	0	0
84	*Karenia mikimotoi*	Gymnodiniales	Myzozoa	a	High	0	1	0	0	0	0	0	0
85	*Scrippsiella trochoidea*	Peridiniales	Myzozoa			0	1	0	0	0	0	0	0
86	*Prorocentrum cordatum*	Prorocentrales	Myzozoa	b	Low/Unknown	1	0	0	0	1	0	0	0
87	*Prorocentrum triestinum*	Prorocentrales	Myzozoa			0	1	0	0	0	0	0	0

88	*Cephalothrix simula*		Nemertea			0	1	0	0	0	0	0	0
89	*Chattonella marina*	Chattonellales	Ochrophyta			0	1	0	0	0	0	0	0
90	*Fibrocapsa japonica*	Chattonellales	Ochrophyta			0	1	0	0	0	0	0	0
91	*Heterosigma akashiwo*	Chattonellales	Ochrophyta			0	1	0	0	0	0	0	0
92	*Corethron pennatum*	Corethrales	Ochrophyta			0	1	0	0	0	0	0	0
93	*Coscinodiscus wailesii*	Coscinodiscales	Ochrophyta	a	High	0	1	0	0	1	0	0	0
94	*Asterionella glacialis*	Fragilariales	Ochrophyta			0	1	0	0	0	0	0	0
95	*Sargassum muticum*	Fucales	Ochrophyta	c	High	0	0	0	1	0	1	0	0
96	*Undaria pinnatifida*	Laminariales	Ochrophyta	a	High	0	1	0	1	0	0	0	0
97	*Pleurosigma simonsenii*	Naviculales	Ochrophyta			0	1	0	0	0	0	0	0
98	*Rhizosolenia indica*	Rhizosoleniales	Ochrophyta			0	1	0	0	0	0	0	0
99	*Ethmodiscus punctiger*	Thalassiosirales	Ochrophyta			1	1	1	0	0	0	0	0
100	*Thalassiosira hendeyi*	Thalassiosirales	Ochrophyta			1	1	0	0	0	0	0	0
101	*Thalassiosira nordenskioeldii*	Thalassiosirales	Ochrophyta	e	Low/Unknown	0	1	0	0	1	0	0	0
102	*Biddulphia longicruris var. longicruris*	Triceratiales	Ochrophyta			0	1	0	0	0	0	0	0
103	*Biddulphia sinensis*	Triceratiales	Ochrophyta	j	High	0	1	1	0	1	0	0	0
104	*Mediopyxis helysia*		Ochrophyta			0	0	0	0	1	0	0	0
105	*Euplana gracilis*	Polycladida	Platyhelminthes			0	0	0	0	0	0	0	1
106	*Haliclona (Soestella) xena*	Haplosclerida	Porifera			0	1	0	1	0	0	0	0
107	*Sycon scaldiense*	Leucosolenida	Porifera			0	1	0	0	0	0	0	0
108	*Mycale (Carmia) micracanthoxea*	Poecilosclerida	Porifera			0	1	0	1	0	1	0	0
109	*Antithamnionella spirographidis*	Ceramiales	Rhodophyta			0	1	1	1	0	1	0	0
110	*Ceramium tenuicorne*	Ceramiales	Rhodophyta			0	0	0	0	0	1	0	0
111	*Dasya baillouviana*	Ceramiales	Rhodophyta			0	1	0	0	0	0	0	0
112	*Dasya sessilis*	Ceramiales	Rhodophyta			0	1	0	0	0	0	0	0
113	*Dasysiphonia japonica*	Ceramiales	Rhodophyta	b	Low/Unknown	0	1	1	1	1	1	0	0
114	*Melanothamnus harveyi*	Ceramiales	Rhodophyta	WL	Low/Unknown	0	1	1	0	0	0	0	0
115	*Caulacanthus ustulatus*	Gigartinales	Rhodophyta			0	1	0	1	0	0	0	0

Appendix II. List of alien species in the desired SRA

Exact locations are illustrated in Figure 3.

Alien species	Phylum	Zeebrugge	Breskens	Vlissingen	Terneuzen	Hoedekenskerke	Hansweert	Bath	Zoutelande	Breskens	Vlissingen (jachthaven)	Vlissingen (Sloehaven)	Terneuzen	Hoedekenskerke	Hansweert	Walsoorden	Bath	Zandvliet	Everingen – Anchorage A	Borssele	Fort Rammekens	Baarland	Kruiningen	Ellewoutsdijk	Ritthem	s'Gravenpolder	Western Scheldt region 0	Western Scheldt region I	Western Scheldt region II	Western Scheldt region III	Western Scheldt region IV	Western Scheldt region V	Western Scheldt region VI	Western Scheldt region VII	Western Scheldt region VIII	8e Petroleumhaven	Beneluxhaven	Brittaniëhaven	1e Eemhaven	Sloehaven Area A 2016	Sloehaven Area B 2016	Sloehaven Area C 2016	Sloehaven Area D 2016	Antwerpen Area A 2017	Antwerpen Area B 2017	Antwerpen Area C 2017	Antwerpen Area D 2017
Alitta virens	Annelida																										1	1	1	1	1	1			1												
Aphelochaeta marioni	Annelida																											1	1	1	1	1	1	1	1												
Boccardia proboscidea	Annelida	1								1	1									1																											
Boccardiella hamata	Annelida	1							1	1	1	1	1	1		1																															
Ficopomatus enigmaticus	Annelida	1		1		1					1	1	1	1		1	1													1						1	1	1	1	1				1	1	1	1
Laonome calida	Annelida												1																																		
Marenzelleria viridis	Annelida																													1	1	1	1	1	1												
Microphthalmus similis	Annelida																											1		1		1															
Neodexiospira brasiliensis	Annelida		1	1	1		1			1		1	1																													1					

Pileolaria berkeleyana	Annelida											1																																			
Proceraea cornuta	Annelida																											1		1																			
Streblospio benedicti	Annelida																										1	1	1	1	1	1	1	1	1												
Syllidia armata	Annelida																											1																			
Syllis gracilis	Annelida																													1																	
Acartia (Acanthacartia) tonsa	Arthropoda												1		1	1	1	1																													
Amphibalanus amphitrite	Arthropoda																			1																											
Amphibalanus improvisus	Arthropoda	1	1	1	1	1	1	1		1		1	1	1	1	1	1														1	1	1	1		1	1	1	1					1	1	1	1
Ampithoe valida	Arthropoda											1																																			
Austrominius modestus	Arthropoda	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1																				1	1	1		1	1	1					
Caprella mutica	Arthropoda	1		1								1								1																	1	1		1	1	1					
Caprella scaura	Arthropoda																			1																											
Chelicorophium curvispinum	Arthropoda																1																														
Eriocheir sinensis	Arthropoda	1								1							1						1																								
Gammarus tigrinus	Arthropoda												1																					1													
Hemigrapsus sanguineus	Arthropoda	1							1	1	1	1	1	1	1	1	1																			1	1	1			1	1		1			1

Hemigrapsus takanoi	Arthropoda	1				1	1	1		1	1	1	1	1	1	1	1			1				1	1	1		1				1			1	1	1	1		1	1	1					1
Incisocalliope aestuarius	Arthropoda													1		1															1			1													
Jassa marmorata	Arthropoda	1								1	1	1								1	1						1										1			1	1						
Megabalanus coccopoma	Arthropoda																			1																											
Melita nitida	Arthropoda	1								1		1	1	1	1	1	1														1	1		1	1							1		1		1	1
Monocorophium sextonae	Arthropoda																								1																						
Mytilicola intestinalis	Arthropoda																													1																	
Palaemon macrodactylus	Arthropoda	1											1	1	1	1								1								1												1	1	1	1
Pseudodiaptomus marinus	Arthropoda												1		1		1	1																													
Ptilohyale littoralis	Arthropoda	1									1	1	1																																		
Rhithropanopeus harrisii	Arthropoda							1					1																					1					1					1	1	1	1
Sinelobus vanhaareni	Arthropoda												1																																		
Synidotea laticauda	Arthropoda															1																															
Telmatogeton japonicus	Arthropoda	1									1			1			1																													1	
Biflustra grandicella	Bryozoa																		1																												

Bugulina simplex	Bryozoa	1																																													
Bugulina stolonifera	Bryozoa	1										1																												1							
cf *Conopeum chesapeakensis*	Bryozoa																																												1		1	1
Fenestrulina delicia	Bryozoa			1																																													
Fenestrulina malusii	Bryozoa			1																																													
Smittoidea prolifica	Bryozoa		1		1					1		1																													1							
Tricellaria inopinata	Bryozoa	1	1	1	1	1	1					1																												1	1	1						
Codium fragile	Chlorophyta											1															1																						
Ulva australis	Chlorophyta									1		1	1	1	1																					1	1				1								
Aplidium glabrum	Chordata	1		1						1		1																												1	1	1							
Botrylloides violaceus	Chordata	1	1	1	1		1			1		1	1																											1	1	1							
Didemnum vexillum	Chordata										1	1																												1	1	1							
Diplosoma listerianum	Chordata	1	1	1	1																																					1							
Molgula manhattensis	Chordata	1	1	1	1	1	1			1		1	1	1	1	1	1															1				1	1	1		1	1	1				1			
Neogobius fluviatilis	Chordata																																						1										
Neogobius melanostomus	Chordata												1																										1										

Perophora japonica	Chordata			1								1																													1						
Styela clava	Chordata	1	1	1	1					1		1																								1	1	1		1	1	1					
Blackfordia virginica	Cnidaria													1			1																														
Cordylophora caspia	Cnidaria												1																										1								
Diadumene cincta	Cnidaria	1	1																																					1							
Diadumene lineata	Cnidaria									1	1		1	1	1	1				1		1																									
Garveia franciscana	Cnidaria																																	1													
Nemopsis bachei	Cnidaria	1																																				1									
Mnemiopsis leidyi	Ctenophora	1								1		1								1								1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
Corbicula fluminalis	Mollusca																																						1								
Crepidula fornicata	Mollusca	1							1		1	1	1															1		1	1	1					1	1		1							
Dreissena bugensis	Mollusca												1																										1								
Dreissena polymorpha	Mollusca												1																										1								
Ensis leei	Mollusca											1																1	1	1	1	1		1	1					1							
Heleobia cf *australis*	Mollusca																																											1	1	1	1
Magallana gigas	Mollusca	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1										1			1	1	1	1	1	1	1	1	1		1	1	1		1		1	1
Mya arenaria	Mollusca	1										1																1	1	1	1	1	1	1	1					1	1						
Mytilopsis leucophaeata	Mollusca												1																					1										1	1	1	1

Petricolaria pholadiformis	Mollusca																										1	1	1	1	1	1	1	1													
Physella acuta	Mollusca																1																				1		1								
Potamopyrgus antipodarum	Mollusca																																				1		1								
Rangia cuneata	Mollusca																																						1					1	1	1	1
Ruditapes philippinarum	Mollusca	1										1																																			
Teredo navalis	Mollusca	1														1	1																														
Alexandrium ostenfeldii	Myzozoa														1																																
Alexandrium tamarense	Myzozoa									1																																					
Karenia mikimotoi	Myzozoa									1					1																																
Prorocentrum cordatum	Myzozoa																																			1	1	1						1		1	1
Prorocentrum triestinum	Myzozoa									1					1		1																														
Protoceratium reticulatum	Myzozoa														1																					1	1										
Scrippsiella trochoidea	Myzozoa									1					1		1																														
Cephalothrix simula	Nemertea										1																																				
Asterionella glacialis	Ochrophyta									1					1		1																														

Biddulphia longicruris var. longicruris	Ochrophyta								1					1																																
Biddulphia sinensis	Ochrophyta								1					1																				1	1	1		1	1	1					
Chattonella marina	Ochrophyta								1					1																																
Corethron pennatum	Ochrophyta								1																																					
Coscinodiscus wailesii	Ochrophyta								1					1																						1									
Ethmodiscus punctiger	Ochrophyta								1					1		1																						1	1	1					1
Fibrocapsa japonica	Ochrophyta								1					1																																
Heterosigma akashiwo	Ochrophyta								1					1		1																														
Mediopyxis helysia	Ochrophyta																																		1											
Pleurosigma simonsenii	Ochrophyta								1					1		1																														
Rhizosolenia indica	Ochrophyta								1																																					
Sargassum muticum	Ochrophyta	1																																												
Thalassiosira hendeyi	Ochrophyta								1					1		1																										1			1
Thalassiosira nordenskioeldii	Ochrophyta								1					1																						1									
Undaria pinnatifida	Ochrophyta	1								1																																				

Haliclona (Soestella) xena	Porifera	1	1							1		1																																			
Mycale (Carmia) micracanthoxea	Porifera	1								1		1	1																																		
Sycon scaldiense	Porifera									1		1																																			
Vibrio cf *brasiliensis*	Proteobacteria																																					1									
Antithamnionella spirographidis	Rhodophyta	1										1																												1							
Caulacanthus ustulatus	Rhodophyta	1										1													1																						
Dasya baillouviana	Rhodophyta					1																																									
Dasya sessilis	Rhodophyta												1																																		
Dasysiphonia japonica	Rhodophyta	1										1																								1	1			1	1	1					
Melanothamnus harveyi	Rhodophyta											1															1													1							

Appendix III. Connectivity matrices

Connectivity matrices of oceanic distances for the different behaviours (passive, tidal and counter tidal) and all seasons for the year 2011. The followings matrices indicate the time needed for a particle released from an area (lines) to reach another area (columns), 200 means that particles are not able to reach the destination within 200 days.

- Mean and minimum oceanic distance among the areas (in days) for the different behaviours

Spring

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Passive Spring	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**
Zeebrugge	0	0	33	15	23	8	200	200	86	64	70	48	200	200	200	200
Vlissingen	34	3	0	0	25	2	38	38	75	59	98	93	200	200	200	200
Scheldt	12	3	15	2	0	0	200	200	39	25	66	55	200	200	200	200
Antwerp	129	33	113	20	127	25	0	0	192	178	181	147	200	200	200	200
Rotterdam	68	24	55	19	51	17	200	200	0	0	46	12	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	181	181
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0
	Zeebrugge		**Vlissingen**		**Scheldt**		**Antwerp**		**Rotterdam**		**Amsterdam**		**Hull**		**London**	
Tidal Spring	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**
Zeebrugge	0	0	70	10	43	8	83	18	200	200	200	200	200	200	109	61
Vlissingen	13	4	0	0	9	2	9	5	200	200	200	200	200	200	97	78
Scheldt	16	3	12	2	0	0	20	6	200	200	200	200	200	200	99	75
Antwerp	200	200	200	200	200	200	0	0	200	200	200	200	200	200	200	200
Rotterdam	82	50	95	32	95	31	102	42	0	0	63	14	200	200	194	194
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0
	Zeebrugge		**Vlissingen**		**Scheldt**		**Antwerp**		**Rotterdam**		**Amsterdam**		**Hull**		**London**	
Counter Spring	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**	**Mean**	**Min**
Zeebrugge	0	0	37	16	28	9	200	200	59	17	198	193	200	200	200	200
Vlissingen	9	3	0	0	7	2	200	200	53	16	198	193	200	200	200	200
Scheldt	9	3	22	2	0	0	200	200	49	15	198	194	200	200	200	200
Antwerp	15	9	8	5	12	6	0	0	57	22	198	193	200	200	200	200
Rotterdam	200	200	71	26	62	23	200	200	0	0	195	102	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	98	45	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	185	160	0	0	200	200
London	200	200	200	200	200	200	200	200	146	56	160	110	200	200	0	0

Summer

Passive Summer	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	34	10	25	6	200	200	109	33	104	80	200	200	200	200
Vlissingen	30	3	0	0	20	2	100	100	121	26	138	82	200	200	200	200
Scheldt	14	3	18	2	0	0	200	200	100	22	108	73	200	200	200	200
Antwerp	139	33	116	19	127	24	0	0	159	91	173	146	200	200	200	200
Rotterdam	86	37	84	37	65	23	200	200	0	0	62	12	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

Tidal Summer	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	60	10	40	6	73	17	200	200	131	114	200	200	190	171
Vlissingen	17	4	0	0	13	2	12	5	200	200	125	125	200	200	180	166
Scheldt	19	3	14	2	0	0	23	6	200	200	200	200	200	200	190	165
Antwerp	200	200	200	200	200	200	0	0	200	200	200	200	200	200	200	200
Rotterdam	141	141	89	33	95	31	94	65	0	0	51	14	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

Counter Summer	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	38	11	22	7	200	200	54	19	162	101	200	200	200	200
Vlissingen	10	3	0	0	7	2	200	200	53	17	162	101	200	200	200	200
Scheldt	9	3	22	2	0	0	200	200	51	15	162	101	200	200	200	200
Antwerp	16	10	9	5	12	6	0	0	57	24	162	102	200	200	200	200
Rotterdam	200	200	50	50	147	31	200	200	0	0	158	101	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	87	59	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	179	154	182	119	0	0	200	200
London	200	200	200	200	200	200	200	200	177	145	180	113	200	200	0	0

Autumn

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		London		Hull	
Passive autumn	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	34	14	25	6	200	200	65	26	102	61	200	200	200	200
Vlissingen	29	4	0	0	16	2	200	200	74	27	114	65	200	200	200	200
Scheldt	18	3	17	2	0	0	200	200	56	20	103	46	200	200	200	200
Antwerp	103	18	83	9	95	15	0	0	122	67	152	126	200	200	200	200
Rotterdam	75	40	63	36	63	19	200	200	0	0	50	18	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0
London	200	200	200	200	160	160	200	200	200	200	200	200	0	0	200	200

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		London		Hull	
Tidal autumn	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	43	12	29	7	51	17	200	200	200	200	164	115	200	200
Vlissingen	19	4	0	0	9	2	12	4	200	200	200	200	160	117	200	200
Scheldt	21	3	14	2	0	0	22	6	200	200	200	200	164	116	200	200
Antwerp	200	200	200	200	200	200	0	0	200	200	200	200	200	200	200	200
Rotterdam	162	94	116	48	115	53	122	54	0	0	39	14	174	139	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0
London	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		London		Hull	
Counter autumn	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	30	12	22	6	200	200	67	18	137	72	200	200	200	200
Vlissingen	14	4	0	0	7	2	200	200	63	14	133	66	200	200	200	200
Scheldt	11	3	16	2	0	0	200	200	62	13	136	79	200	200	200	200
Antwerp	18	11	8	3	11	5	0	0	69	21	140	69	200	200	200	200
Rotterdam	70	70	83	43	104	42	200	200	0	0	122	55	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	96	46	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	167	122	181	130	200	200	0	0
London	200	200	200	200	65	63	200	200	157	70	173	108	0	0	200	200

Winter

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Passive Winter	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	27	5	16	3	200	200	29	15	79	32	200	200	200	200
Vlissingen	30	3	0	0	18	2	200	200	45	36	77	41	200	200	200	200
Scheldt	13	3	12	2	0	0	200	200	27	15	52	31	200	200	200	200
Antwerp	94	8	69	3	85	5	0	0	71	41	128	49	200	200	200	200
Rotterdam	53	29	47	23	45	15	200	200	0	0	37	12	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	130	130	200	200	200	200	200	200	200	200	0	0

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Tidal Winter	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	32	5	26	3	41	12	200	200	200	200	200	200	144	22
Vlissingen	17	3	0	0	6	2	8	4	200	200	200	200	200	200	150	35
Scheldt	18	3	7	1	0	0	14	5	200	200	200	200	200	200	152	31
Antwerp	200	200	200	200	200	200	0	0	200	200	200	200	200	200	200	200
Rotterdam	163	62	67	15	64	11	70	32	0	0	59	16	200	200	119	51
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Counter Winter	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	41	13	25	4	200	200	62	11	98	52	200	200	200	200
Vlissingen	12	4	0	0	9	2	200	200	58	13	95	41	200	200	200	200
Scheldt	8	4	22	2	0	0	200	200	50	11	93	37	200	200	200	200
Antwerp	14	7	7	3	12	4	0	0	59	16	96	42	200	200	200	200
Rotterdam	107	104	108	36	103	35	200	200	0	0	86	17	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	99	42	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	197	186	199	190	0	0	200	200
London	200	200	200	200	200	200	200	200	168	84	184	141	200	200	0	0

- Range of variability (minimum and maximum oceanic distances in days)

Spring

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Passive Spring	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
Zeebrugge	0	0	142	15	125	8	200	200	108	64	97	48	200	200	200	200
Vlissingen	200	3	0	0	178	2	38	38	113	59	103	93	200	200	200	200
E. Scheldt	199	3	89	2	0	0	200	200	57	25	75	55	200	200	200	200
Antwerp	200	33	200	20	200	25	0	0	200	178	200	147	200	200	200	200
Rotterdam	175	24	139	19	169	17	200	200	0	0	135	12	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	181	181
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Tidal Spring	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
Zeebrugge	0	0	200	10	197	8	200	18	200	200	200	200	200	200	200	61
Vlissingen	104	4	0	0	109	2	189	5	200	200	200	200	200	200	163	78
E. Scheldt	185	3	200	2	0	0	200	6	200	200	200	200	200	200	199	75
Antwerp	200	200	200	200	200	200	0	0	200	200	200	200	200	200	200	200
Rotterdam	113	50	200	32	200	31	200	42	0	0	200	14	200	200	194	194
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Counter Spring	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
Zeebrugge	0	0	138	16	121	9	200	200	200	17	200	193	200	200	200	200
Vlissingen	66	3	0	0	85	2	200	200	200	16	200	193	200	200	200	200
E. Scheldt	64	3	110	2	0	0	200	200	200	15	200	194	200	200	200	200
Antwerp	112	9	118	5	92	6	0	0	200	22	200	193	200	200	200	200
Rotterdam	200	200	180	26	179	23	200	200	0	0	200	102	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	184	45	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	194	160	0	0	200	200
London	200	200	200	200	200	200	200	200	200	56	196	110	200	200	0	0

Summer

Passive Summer	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Zeebrugge	0	0	121	10	137	6	200	200	197	33	158	80	200	200	200	200
Vlissingen	194	3	0	0	163	2	100	100	200	26	196	82	200	200	200	200
E. Scheldt	156	3	116	2	0	0	200	200	196	22	187	73	200	200	200	200
Antwerp	200	33	200	19	200	24	0	0	200	91	200	146	200	200	200	200
Rotterdam	167	37	173	37	172	23	200	200	0	0	164	12	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

Tidal Summer	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Zeebrugge	0	0	200	10	179	6	197	17	200	200	161	114	200	200	200	171
Vlissingen	167	4	0	0	192	2	194	5	200	200	125	125	200	200	199	166
E. Scheldt	161	3	198	2	0	0	200	6	200	200	200	200	200	200	200	165
Antwerp	200	200	200	200	200	200	0	0	200	200	200	200	200	200	200	200
Rotterdam	141	141	162	33	199	31	146	65	0	0	200	14	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

Counter Summer	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Zeebrugge	0	0	180	11	200	7	200	200	200	19	200	101	200	200	200	200
Vlissingen	128	3	0	0	154	2	200	200	200	17	200	101	200	200	200	200
E. Scheldt	69	3	200	2	0	0	200	200	200	15	200	101	200	200	200	200
Antwerp	76	10	86	5	166	6	0	0	200	24	200	102	200	200	200	200
Rotterdam	200	200	50	50	197	31	200	200	0	0	200	101	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	157	59	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	154	200	119	0	0	200	200
London	200	200	200	200	200	200	200	200	200	145	200	113	200	200	0	0

Autumn

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Passive Autumn	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Zeebrugge	0	0	110	14	107	6	200	200	200	26	200	61	200	200	200	200
Vlissingen	183	4	0	0	180	2	200	200	200	27	178	65	200	200	200	200
E. Scheldt	146	3	116	2	0	0	200	200	200	20	181	46	200	200	200	200
Antwerp	200	18	200	9	200	15	0	0	187	67	188	126	200	200	200	200
Rotterdam	129	40	104	36	104	19	200	200	0	0	156	18	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	160	160	200	200	200	200	200	200	200	200	0	0

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Tidal Autumn	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Zeebrugge	0	0	200	12	200	7	200	17	200	200	200	200	200	200	164	115
Vlissingen	182	4	0	0	179	2	192	4	200	200	200	200	200	200	160	117
E. Scheldt	200	3	200	2	0	0	200	6	200	200	200	200	200	200	164	116
Antwerp	200	200	200	200	200	200	0	0	200	200	200	200	200	200	200	200
Rotterdam	200	94	188	48	186	53	196	54	0	0	194	14	200	200	174	139
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Counter Autumn	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Zeebrugge	0	0	169	12	197	6	200	200	200	18	199	72	200	200	200	200
Vlissingen	60	4	0	0	195	2	200	200	200	14	199	66	200	200	200	200
E. Scheldt	114	3	121	2	0	0	200	200	200	13	195	79	200	200	200	200
Antwerp	200	11	76	3	195	5	0	0	200	21	197	69	200	200	200	200
Rotterdam	70	70	131	43	200	42	200	200	0	0	200	55	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	168	46	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	122	200	130	0	0	200	200
London	200	200	200	200	67	63	200	200	200	70	200	108	200	200	0	0

Winter

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Passive Winter	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Zeebrugge	0	0	90	5	112	3	200	200	54	15	161	32	200	200	200	200
Vlissingen	193	3	0	0	191	2	200	200	65	36	139	41	200	200	200	200
E. Scheldt	187	3	101	2	0	0	200	200	57	15	89	31	200	200	200	200
Antwerp	200	8	200	3	200	5	0	0	122	41	175	49	200	200	200	200
Rotterdam	113	29	176	23	174	15	200	200	0	0	138	12	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	130	130	200	200	200	200	200	200	200	200	0	0

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Tidal Winter	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Zeebrugge	0	0	200	5	200	3	199	12	200	200	200	200	200	200	200	22
Vlissingen	200	3	0	0	146	2	192	4	200	200	200	200	200	200	200	35
E. Scheldt	200	3	192	1	0	0	199	5	200	200	200	200	200	200	200	31
Antwerp	200	200	200	200	200	200	0	0	200	200	200	200	200	200	200	200
Rotterdam	200	62	182	15	196	11	178	32	0	0	200	16	200	200	200	51
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
Counter Winter	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Zeebrugge	0	0	193	13	193	4	200	200	200	11	181	52	200	200	200	200
Vlissingen	135	4	0	0	185	2	200	200	200	13	200	41	200	200	200	200
E. Scheldt	97	4	184	2	0	0	200	200	200	11	196	37	200	200	200	200
Antwerp	75	7	147	3	181	4	0	0	200	16	134	42	200	200	200	200
Rotterdam	109	104	198	36	200	35	200	200	0	0	200	17	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	42	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	186	200	190	0	0	200	200
London	200	200	200	200	200	200	200	200	200	84	200	141	200	200	0	0

- Combination of all the connectivity matrices for minimum and maximum in days.

Green represent a high level of connectivity (less than 25 days for minimum distances) and orange a possibility of connection within less than 200 days.

	Zeebrugge		Vlissingen		Scheldt		Antwerp		Rotterdam		Amsterdam		Hull		London	
	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
Zeebrugge	0	0	70	16	43	9	200	200	200	200	200	200	200	200	200	200
Vlissingen	34	4	0	0	25	2	200	200	200	200	200	200	200	200	200	200
Scheldt	21	4	22	2	0	0	200	200	200	200	200	200	200	200	200	200
Antwerp	200	200	200	200	200	200	0	0	200	200	200	200	200	200	200	200
Rotterdam	200	200	116	50	147	53	200	200	0	0	195	102	200	200	200	200
Amsterdam	200	200	200	200	200	200	200	200	200	200	0	0	200	200	200	200
Hull	200	200	200	200	200	200	200	200	200	200	200	200	0	0	200	200
London	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0

Appendix IV. Dispersal patterns

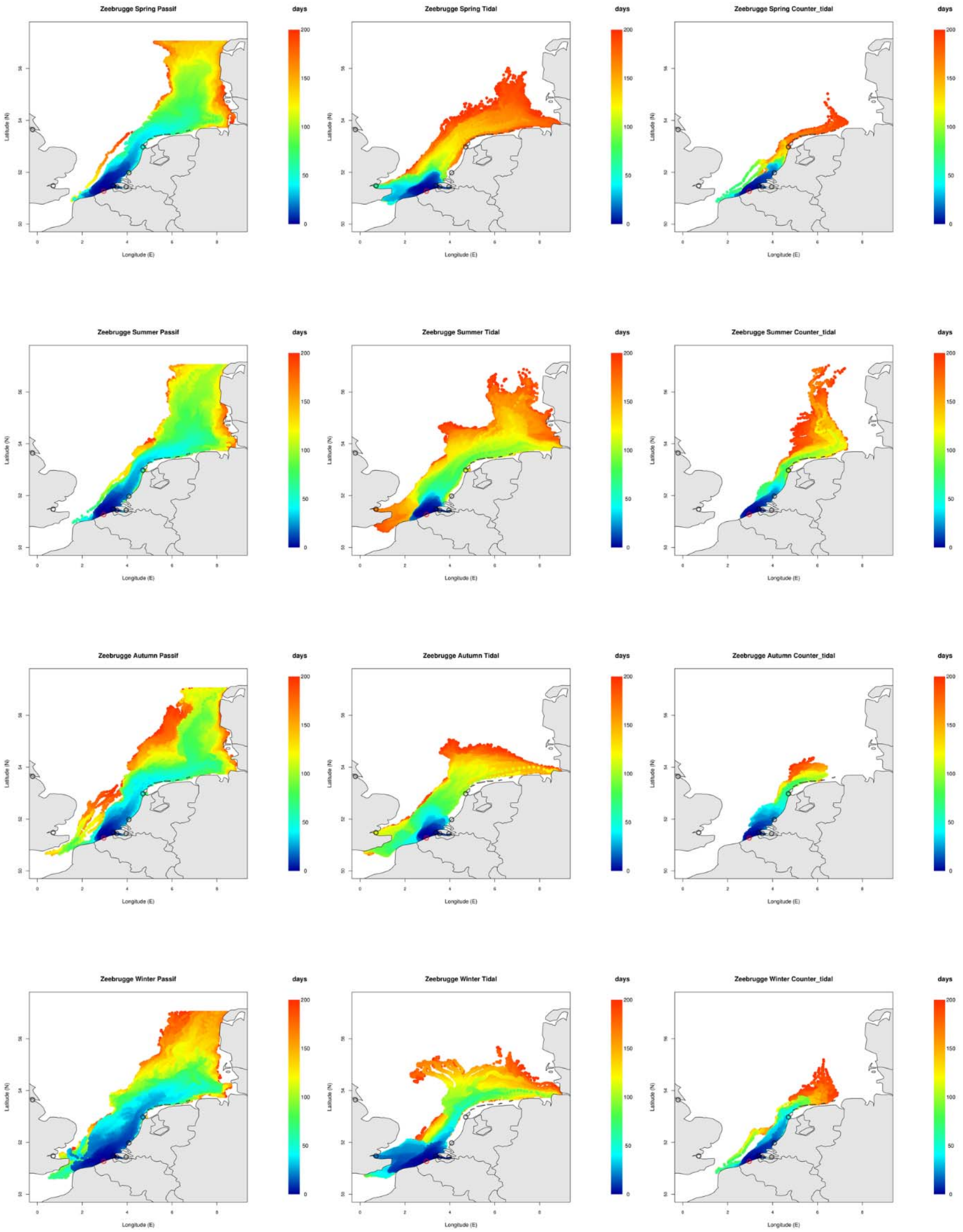

Figure 10: Maps of the dispersal minimum distance (days) for particles released from Zeebrugge (red circle) under three different behaviours (left: passive, middle: tidal and right: counter tidal). From top to bottom: Spring, Summer, Autumn, Winter. The colour bar shows the oceanic distance in days.

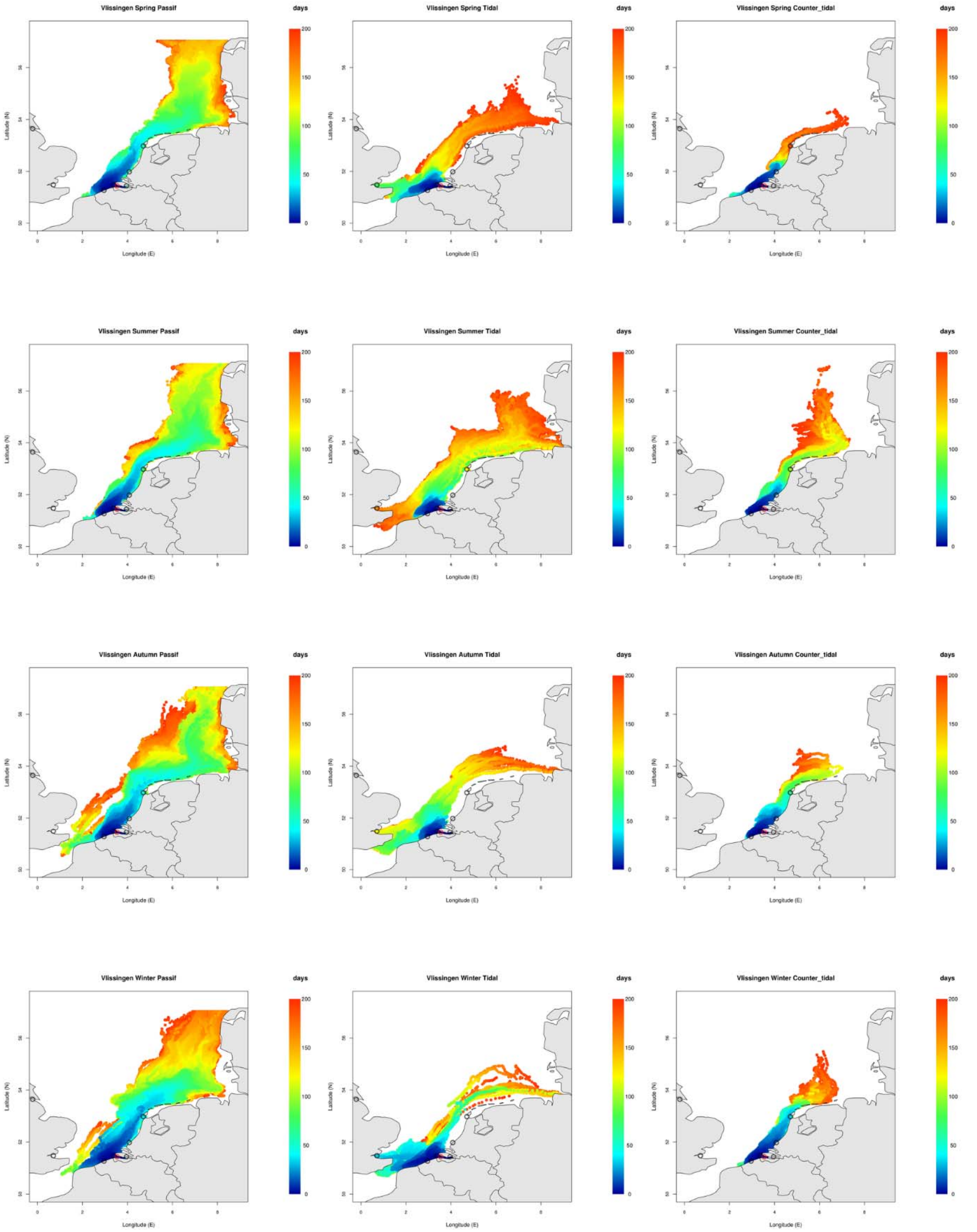

Figure 11: Maps of the dispersal minimum distance (days) for particles released from Vlissingen (red circle) under three different behaviours (left: passive, middle: tidal and right: counter tidal). From top to bottom: Spring, Summer, Autumn, Winter. The colour bar shows the oceanic distance in days.

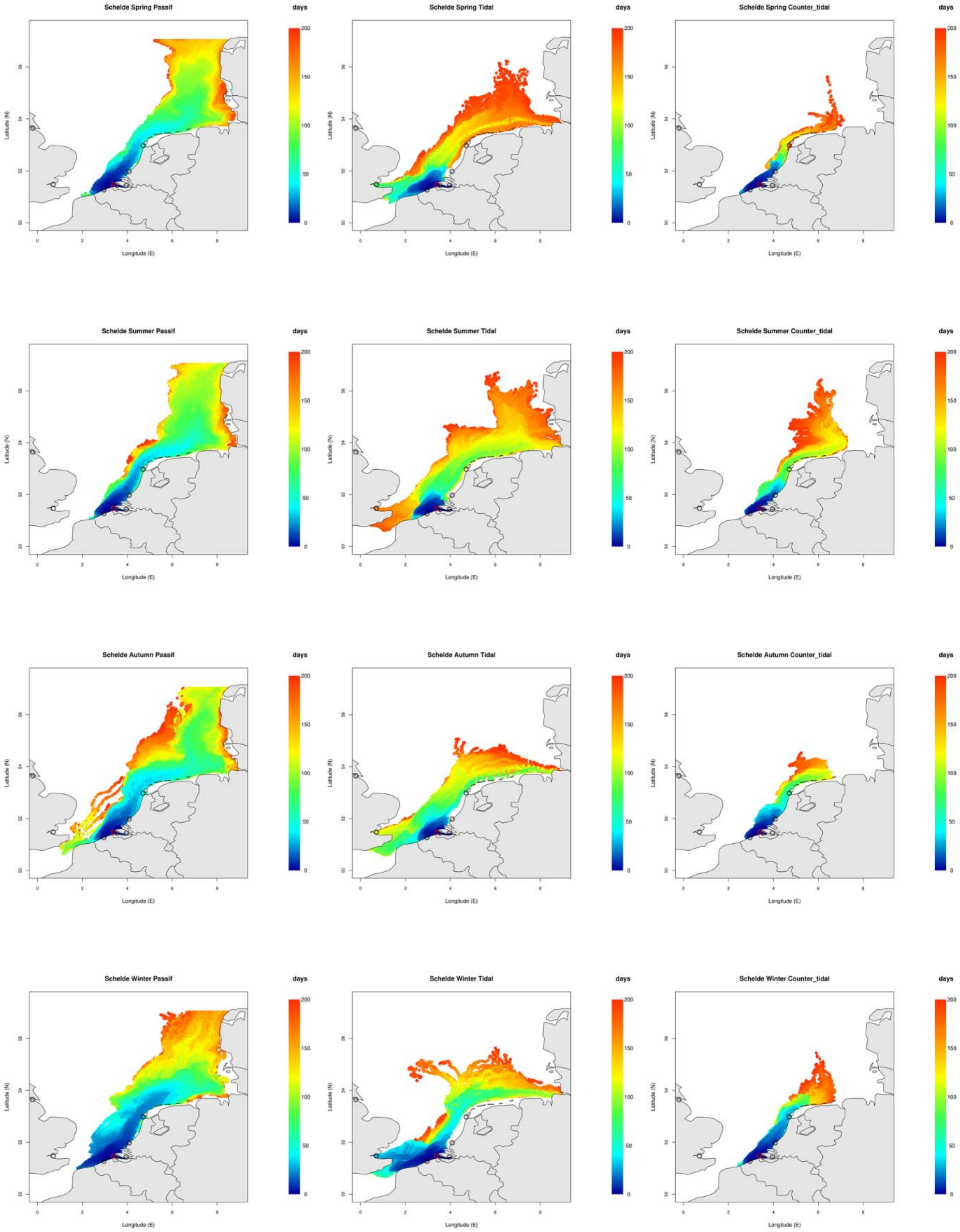

Figure 12: Maps of the dispersal minimum distance (days) for particles released from Scheldt (red circle) under three different behaviours (left: passive, middle: tidal and right: counter tidal). From top to bottom: Spring, Summer, Autumn, Winter. The colour bar shows the oceanic distance in days.

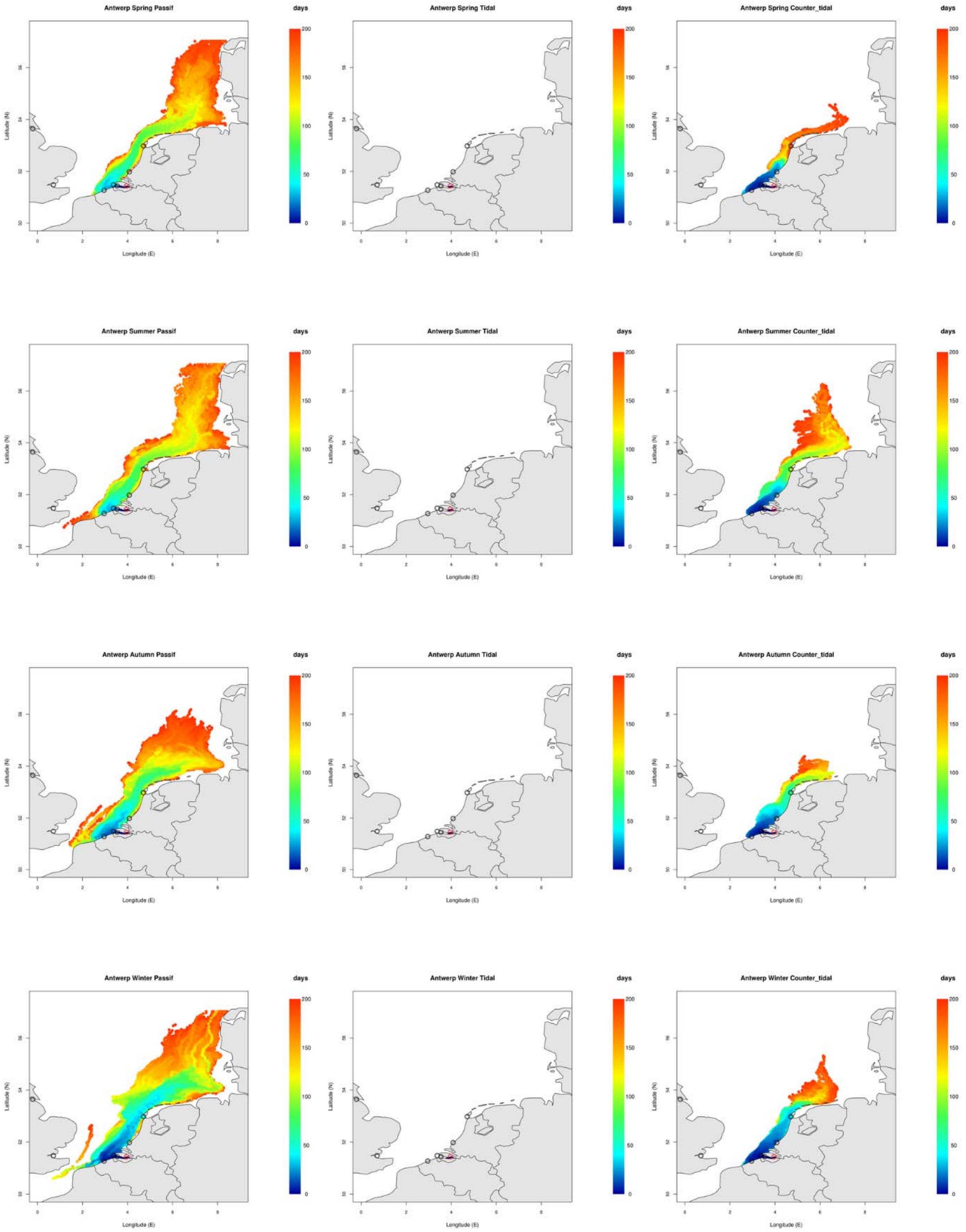

Figure 13: Maps of the dispersal minimum distance (days) for particles released from Antwerp (red circle) under three different behaviours (left: passive, middle: tidal and right: counter tidal). From top to bottom: Spring, Summer, Autumn, Winter. The colour bar shows the oceanic distance in days.

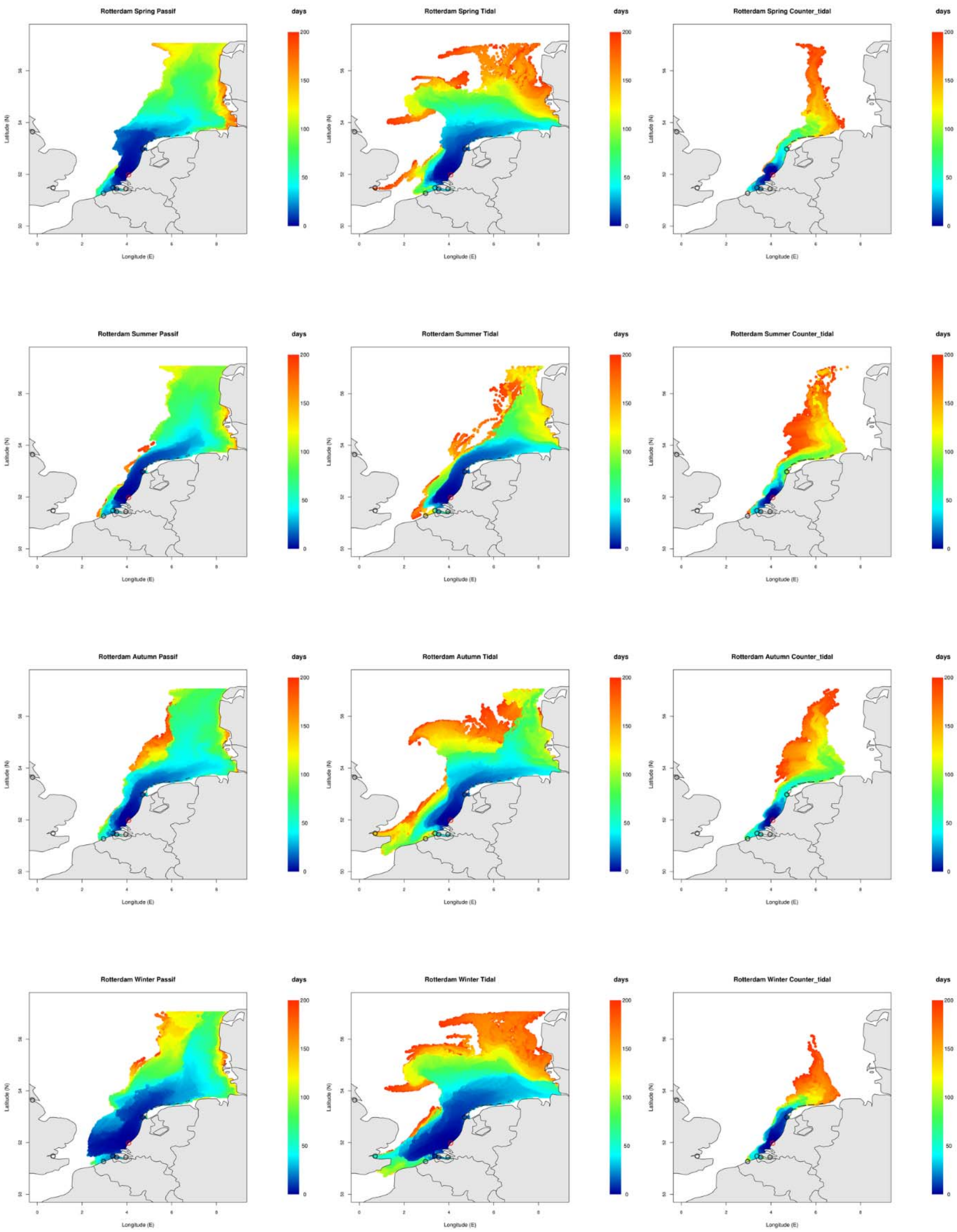

Figure 14: Maps of the dispersal minimum distance (days) for particles released from Rotterdam (red circle) under three different behaviours (left: passive, middle: tidal and right: counter tidal). From top to bottom: Spring, Summer, Autumn, Winter. The colour bar shows the oceanic distance in days.

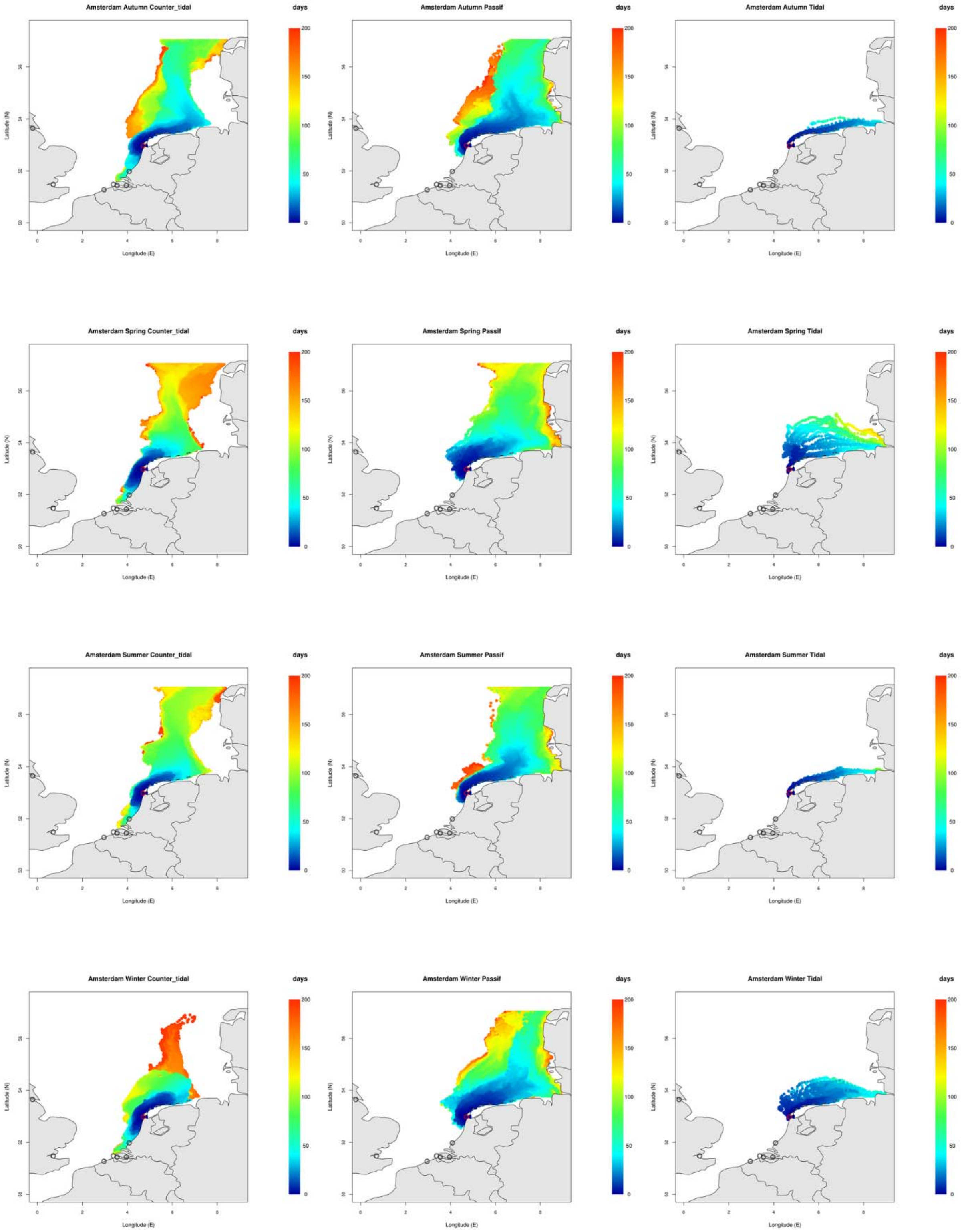

Figure 15: Maps of the dispersal minimum distance (days) for particles released from Amsterdam (red circle) under three different behaviours (left: passive, middle: tidal and right: counter tidal). From top to bottom: Spring, Summer, Autumn, Winter. The colour bar shows the oceanic distance in days.

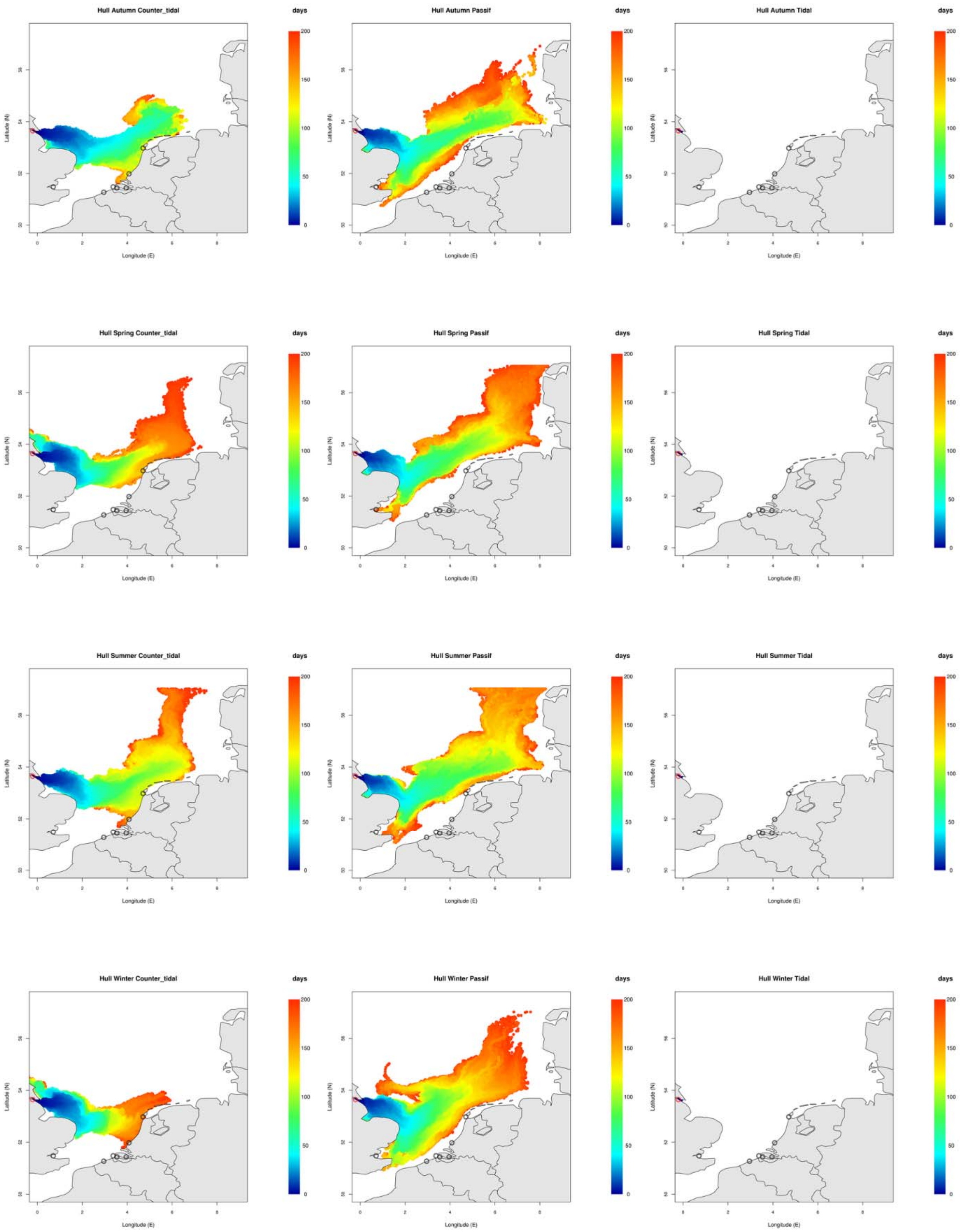

Figure 16: Maps of the dispersal minimum distance (days) for particles released from Hull (red circle) under three different behaviours (left: passive, middle: tidal and right: counter tidal). From top to bottom: Spring, Summer, Autumn, Winter. The colour bar shows the oceanic distance in days.

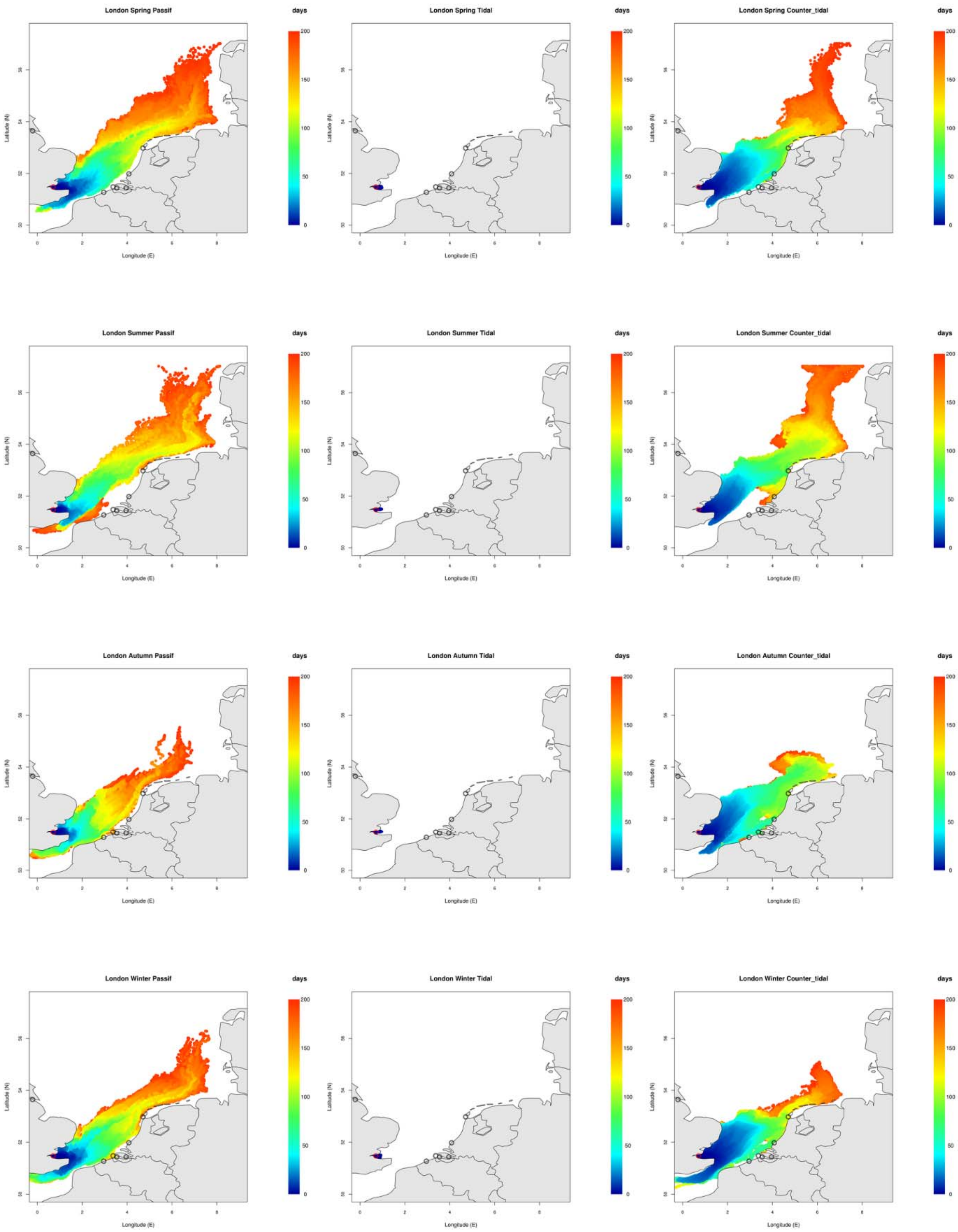

Figure 17: Maps of the dispersal minimum distance (days) for particles released from London (red circle) under three different behaviours (left: passive, middle: tidal and right: counter tidal). From top to bottom: Spring, Summer, Autumn, Winter. The colour bar shows the oceanic distance in days.