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Variability in transport of fish eggs and larvae. I. Modelling the effects of coastal reclamation

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ABSTRACT: Dispersal of eggs and larvae of herring, plaice and sole in the southern North Sea was studied by modelling using real-time hydrodynamic forcing (with wind, air pressure and river discharge) and species-specific knowledge of larval behaviour (incorporating salinity triggers), temperature-dependent growth and spawning characteristics. Larval transport was simulated using a finite-volume advection-diffusion model (Delft3D-WAQ) coupled to a 3-dimensional hydrodynamic model (Delft3D-FLOW). Model parameter settings were refined following a sensitivity analysis. Validation of modelled hydrodynamics and larval distribution patterns showed broad agreement with field data. Differences in model results for larval distribution, transport success and timing of arrival at nursery grounds between baseline conditions and a scenario that incorporated a proposed 1000 ha coastal reclamation (protruding 6 to 7 km from the Dutch coastline) for the expansion of the Port of Rotterdam (Maasvlakte-2) were insignificant in comparison to the interannual variability in larval dispersal for these species. Results suggest that effects of the proposed coastal reclamation on the transport success of fish larvae (flatfish and herring), an issue over which public stakeholders had expressed concern, will be negligible.

KEY WORDS: Fish larvae · Dispersal modelling · Coastal reclamation · Impact assessment · North Sea · Herring · Plaice · Sole

INTRODUCTION

The Wadden Sea and the shallow coastal zone of the North Sea are essential as nursery areas for a range of fish species, including plaice *Pleuronectes platessa* and sole *Solea solea* (Zijlstra 1972, van Beek et al. 1989, van der Veer et al. 2001). For several other species, including herring *Clupea harengus*, the Wadden Sea and the shallow coastal waters along the North Sea are, relatively, less important as nursery areas, but the presence of juveniles of these species in these shallow waters is of ecological significance (e.g. important and abundant prey item for birds). Plaice spawn in offshore areas and their eggs and larvae are transported from the spawning grounds to the nursery areas by a combination of passive transport and selective tidal transport (Talbot 1977, Creutzberg et al. 1978, Rijnsdorp et al. 1985, Fox et al. 2006). Sole spawn closer to the shore than plaice, and their eggs and larvae are transported further inshore, mainly by passive transport (Koutsikopoulos et al. 1991, Champalbert & Koutsikopoulos 1995). Herring larvae are transported from the offshore spawning and hatching grounds to the coastal areas, mainly by passive transport (Bartsch et al. 1989, Heath 1989, Heath et al. 1991). Currents and tidal movements are crucial for the larval transport of each of these fish species, and indeed for the dispersal of many types of marine larvae (Sammarco & Heron 1994).

Along the southern part of the Dutch coast, a substantial expansion of the Port of Rotterdam is planned. This new port and industrial area, known as Maasvlakte-2 (MV2), will comprise 1000 ha of industrial sites for (petro)chemical industry, container handling

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and associated distribution activities. In an ecological risk assessment, potential changes to the transport of silt, nutrients and fish larvae in the vicinity of the Maasvlakte and along the Dutch coast were identified as the main ecological problems to be expected as a result of the seaward expansion of the Maasvlakte. Such changes may have an impact on the Wadden Sea Area and the North Sea Coastal Zone, both of which have been identified as Special Areas of Conservation (SACs).

Coastal structures are known to interfere with littoral currents and transport processes (see Mangor 2004). Coastal current patterns depend (at least in part) on coastline morphology and bathymetry. Any anthropogenic change to the morphological and bathymetrical configuration of a coastline is likely to modify coastal currents, wave regime and depositional processes. Depending on the scale of the modification, this may range from local effects (<1 km), such as in the case of coastal defense structures (Martin et al. 2005), to effects at much larger scales (10s to 100s of km), such as may be the case with massive land reclamation schemes (Walker 1984, Tkalich et al. 2002, Salahuddin 2006). We use the term 'coastal reclamation' throughout the present study to indicate 'reclamation of coastal areas by filling in wetlands and/or shallow coastal waters, diking, and building dams and other barriers to exclude coastal waters' (Cicin-Sain & Knecht 1998, p. 25).

Substantial changes in coastal current patterns could potentially affect the transport of fine sediments and influence transport routes (and thus the final destination) of fish larvae along the Dutch coast. As larval transport is an essential element for the recruitment of several commercially important fish species, altered larval transport could affect the size of exploited stocks and/or prey availability for avian predators. In the case of the MV2 reclamation, concerns were particularly high because of the fact that the dominant current pattern in the southern North Sea is from southwest to northeast, and the main spawning areas of economically important fish species are located in the southwest while their main nursery grounds lie in the northeast. As such, the MV2 reclamation (located midway between spawning and nursery grounds) could, potentially, create a major barrier to the transport of fish larvae (and fine sediments) to the Wadden Sea, an important nature area protected under both the EU Habitats and Bird Directives (Enemark 2005).

The expression of concern by public stakeholders (including the Dutch Fish Product Board) over the potential effects of the MV2 reclamation gave rise to the decision by the Dutch Council of State to order an Appropriate Assessment, in accordance with the EU Habitats Directive (Hommes et al. 2009). Part of this Appropriate Assessment included a detailed modelling study of the potential effects of the proposed reclamation scheme on silt transport (Van Kessel 2005) and the dispersal of fish larvae (present study).

The objectives of the present study were to assess the potential effects of the planned coastal reclamation on the transport success of fish larvae, expressed as the timing and number of larvae reaching the coastal nursery areas, in particular the Wadden Sea. Transport success in the present situation (baseline) was quantified for 3 fish species (sole, plaice and herring) through a combination of hydrodynamic and behavioural modelling of fish larvae. In addition to the baseline situation, the effects of 2 autonomous developments that will take place before the construction of MV2 (i.e. an offshore wind farm, and changes to the discharge regime of the Haringvliet sluices) were also considered. Effects of the reclamation were assessed by comparing the model results of the baseline situation (with and without autonomous developments) with the results of a modelling scenario that included the reclamation scheme. The present study has wider implications for future assessments of the impact of coastal developments on the transport success of fish larvae.

DATA AND METHODS

For the present study, a model was developed in which concentrations of fish eggs and larvae with certain characteristics (buoyancy, growth and behaviour) were transported by hydrodynamic flows. In the model setup, the output from hydrodynamic modelling was used as input for the biological modelling.

Hydrodynamic model. Recent advances in computer technology, hydrodynamic modelling and larval and seed ecology have opened the way to successfully simulate the transport of marine larvae, seeds and propagules using oceanographic modelling techniques (Sammarco & Heron 1994, Orth et al. 2006, Thiel & Haye 2006, Erftemeijer et al. 2008). The present modelling exercise was carried out using Delft3D. Delft3D is a modelling system that can simulate flows, waves, sediment transports, morphological developments and ecological processes and consists of several modules (Roelvink & Van Banning 1994, Lesser et al. 2004). Three-dimensional unsteady flow and transport phenomena resulting from tidal and meteorological forcing are simulated in Delft3D-FLOW by solving well-established shallow-water hydrostatic pressure equations (Stelling 1983, Lesser et al. 2004). The model equations, formulated in orthogonal curvilinear coordinates, are discretised onto a staggered Arakawa-C grid and time-integrated by means of an alternating direction implicit (ADI) numerical scheme in horizontal directions and by the Crank-Nicolson method along the vertical, which is either discretised by terrain following coordinates (σ-transformation) or through horizontal z-layers (Stelling 1983, Leendertse 1987). The solution is mass-conserving at every grid cell and time step. This code is extended with transport of salt and heat content and with 4 turbulence models such as the k-ε model (Launder & Spalding 1982) for vertical exchange of horizontal momentum and matter or heat, possibly subjected to density stratification, and with other models for lateral mixing. Along the open sea boundaries, tidal harmonics for water level or currents and concentration patterns for constituents are imposed. The thus computed flow and mass-transport patterns can be coupled off-line to other Delft3D modules, such as the advection-diffusion model Delft3D-WAQ (see below). In this off-line coupling, aggregation in time step and/or grid cells is optional for speeding up subsequent analyses. The applicability of Delft3D to modelling of shallow-water hydrodynamics has been proved in a number of studies performed by the Coastal Research Station and others (see e.g. Roelvink & Van Banning 1994, Luijendijk 2001).

Model grid resolution and water layers. A model grid (ZUNO-DD) covering the southern North Sea (including the Wadden Sea), consisting of 76 340 computational elements, was developed specifically for the present study (De Goede & Van Maren 2005). By applying a domain decomposition approach (local grid refinement), it was possible to apply a much higher grid resolution in areas of particular interest, such as the region around the proposed MV2 reclamation site, the Dutch coastal zone and the Wadden Sea (Fig. 1). In

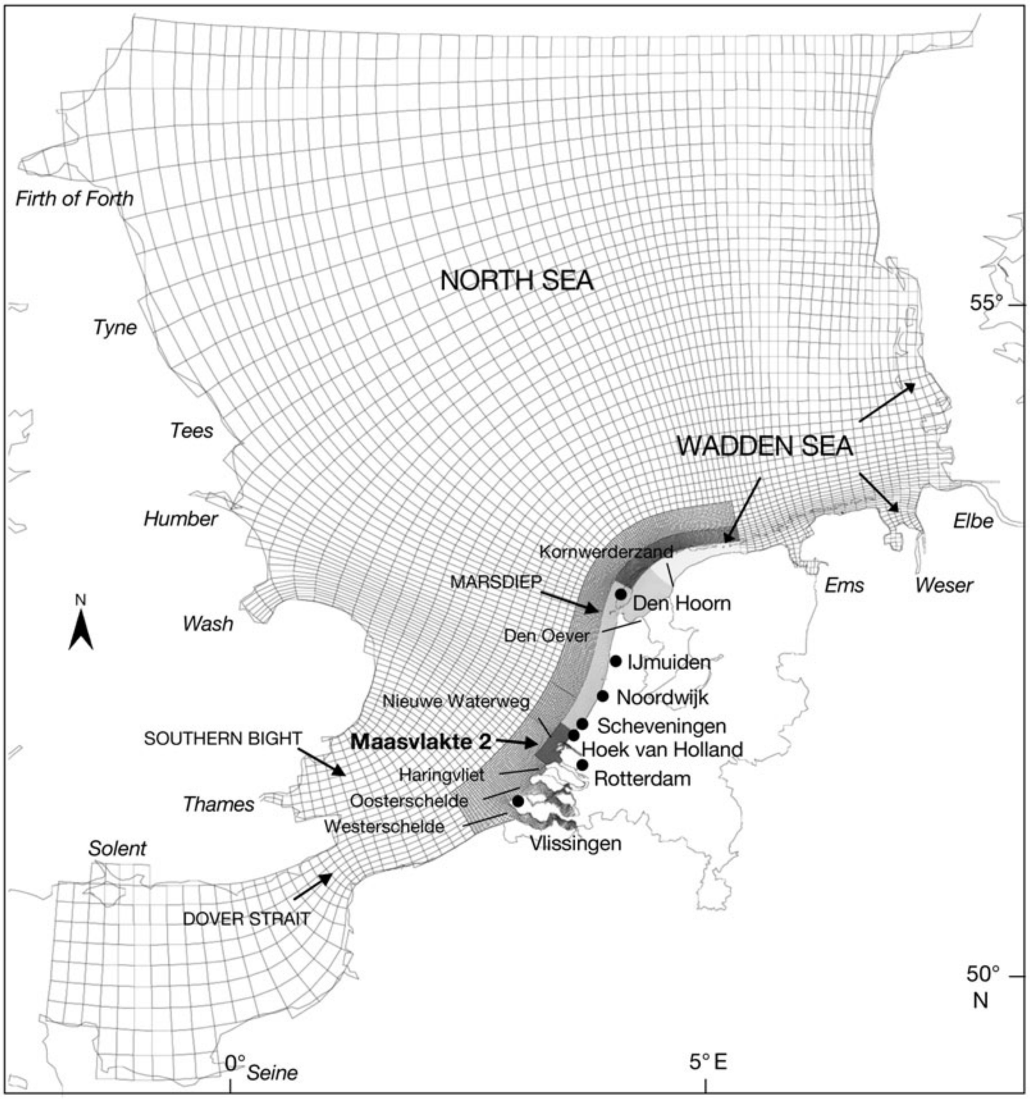

Fig. 1. Overview of the ZUNO-DD model grid (very high resolution in the shaded areas), showing the location of geographical names mentioned in the text

this way, the overall model grid consisted of 5 different sub-domains, each with a different grid resolution. The horizontal model grid resolution along the Dutch coast (in particular near the Maasvlakte area) and in the Wadden Sea was on the order of a few hundred meters (100 to 500 m), with the area of the reclamation and its immediate surroundings covered by approximately 7800 grid cells. The run time of the hydrodynamic model for a year-long simulation on the fastest available multi-node LINUX PC cluster required approximately 16 d.

Faster calculation times (about 15 h per year-simulation on a 3.2 GHz Intel processor) with comparable results were achieved by using a model grid with a coarser resolution (consisting of 8710 computational elements) without domain decomposition (ZUNOGROF). This coarser model grid could not be used for the impact study described in the present study, as this required greater detail in specific areas around the proposed coastal reclamation, but was applied successfully to study interannual variability in larval transport of flatfish and herring under baseline conditions (Bolle et al. 2009, this volume, Dickey-Collas et al. 2009, this volume). Comparison of the hydrodynamic results obtained for the baseline situation using ZUNO-DD and ZUNOGROF revealed no significant differences in water levels, current velocities, mean transport times, spatial and temporal variation in salinity and residual currents between the 2 grids (De Goede & Van Maren 2005).

For the vertical dimension, the water column was subdivided into 10 layers in the model, using a sigma-coordinated approach to ensure sufficient vertical resolution in the near-coastal zone (Stelling & Van Kester 1994). From top to bottom, these layers respectively represented 4.0, 5.9, 8.7, 12.7, 18.7, 18.7, 12.7, 8.7, 5.9 and 4.0 % of the water depth.

The original output from the hydrodynamic modelling (10-layered coupled communication files generated every 30 min for ZUNO-DD and every 1 h for ZUNOGROF) was used as input for the transport modelling of herring larvae. For modelling of the transport of flatfish larvae (plaice and sole), these communication files were first vertically aggregated to 2 layers (representing the lower 4 % and upper 96 % of the water depth), justified by the fact that vertical mixing in the southern North Sea is high and flatfish eggs and larvae are found throughout the water column (Coombs et al. 1990, Sundby 1991), despite the positive buoyancy of eggs and potential vertical migrations of larvae. Horizontal aggregation of grid resolution was not applied in any of the model runs.

Model forcing. The ZUNO-DD hydrodynamic model was forced with spatially and temporally varying meteorological modelling data for the period December 1988 to July 1989, derived from the earlier NOMADS project (Delhez et al. 2004). These data comprised 2 horizontal wind velocity components (at 10 m above mean sea level) and air pressure, and were archived every 6 h. All data were enclosed between 14° W and 15° E and 46 and 65° N (ensuring complete coverage of the ZUNO-DD grid). The orientation and projection of the meteorological data were adjusted so as to obtain the same orientation and projection as the ZUNO-DD grid. ZUNOGROF model calculations for different years (see Bolle et al. 2009, Dickey-Collas et al. 2009) were forced using corresponding data from the high resolution limited area model (HIRLAM) obtained from the Royal Dutch Meteorological Service (KNMI). Data were interpolated bi-linearly in space from the meteorological model grid and linearly in time within Delft3D-flow to obtain the same time step and grid resolution as the hydrodynamic model. Data quality was validated against available measured hourly wind data for the locations of Vlissingen, Hoek van Holland, IJmuiden and Den Hoorn. Modelled and measured wind data showed good agreement (De Goede & Van Maren 2005). ZUNOGROF calculations for different years were all run using the same model with the same schematisation and parameter settings, varying only in meteorological forcing and river discharges between years.

Eighteen discharge points were defined in the model, each of which was associated with a river that discharges freshwater into the open sea. For 7 of these points, i.e. Westerschelde, Oosterschelde, Haringvliet, Nieuwe Waterweg, IJmuiden, Den Oever and Kornwerderzand, time-varying discharges were applied, using daily average discharge rates derived from the Dutch Ministry of Transport, Public Works and Water Management (see www.waterbase.nl/). For the 11 remaining discharge points, a constant discharge rate was used, based on long-term averages for these rivers (Table 1) (adapted from Jones & Howarth 1995). Temperature and salinity were assumed to be constant for all discharges (10°C and 0 ppt, respectively).

Table 1. Constant discharges ($m^3 s^{-1}$) from rivers/estuaries used in the hydro-dynamic model (adapted from Jones & Howarth 1995)

Location	Discharge ($m^3 s^{-1}$)
Thames	82
Solent	15
Seine	461
Humber	246
Tyne	41
Tees	21
Firth of Forth	63
Wash	48
Ems	125
Weser	326
Elbe	726

Calibration and validation of hydrodynamics. Calibration of the ZUNO-DD hydrodynamic model was carried out with a focus on accurate simulation of the tidal water levels for the southern North Sea, Dutch coast, Wadden Sea and flow routes through Wadden Sea tidal inlets. Calibration was done by making adjustments to certain model parameters (boundary conditions, bathymetry and bottom roughness) to find an optimal similarity between modelled and observed water level amplitudes and phases for a large number of tidal constituents. Accuracy of computed hydrodynamics was validated with currents and salinity patterns. Residual flows (which are only a small % of the absolute currents) cannot be reliably measured in the field, but are usually derived as estimates through a combination of modelling and monitoring. The net flow through Dover Strait has been the subject of many studies, with estimates ranging from 50 000 to 150 000 m^3 s^{-1} (Prandle et al. 1996). Residual (net) flow through Dover Strait calculated by the hydrodynamic model was 90 468 m^3 s^{-1}, which is well within the range of estimates reported in the literature (Prandle et al. 1996). Residual (net) flow through the Marsdiep (entrance to Wadden Sea) predicted by the model was –306 m^{3}s^{-1}, which is roughly in the same order of magnitude as values reported in the literature (Ridderinkhof et al. 2002). There was broad agreement (Fig. 2) between the modelled predictions and actual field measurements from monitoring campaigns (DONAR database, www.waterbase.nl) in both the spatial and temporal variability of surface water salinity (De Goede & Van Maren 2005).

Goodness-of-fit between model results and field measurements for salinity was analysed by means of 2 approaches: (1) root mean squared error (RMSE, normalised to the mean of the observed data) and (2) cost function, CF (OSPAR 1998, Radach & Moll 2006), calculated as:

$$C_x = \sum \frac{|M_{x,t} - D_{x,t}|}{\mathrm{SD}_x} / \mathrm{n}[(1-\mathrm{c}) + \mathrm{c}(1-r_x)]$$

where C_x is the normalised deviation per station (annual value), $M_{x,t}$ the mean value of the model results per station per month, $D_{x,t}$ the mean value of the *in situ* data per station per month, SD_x the standard deviation of the annual mean based on the monthly means of the *in situ* data (df = 11), n is 12 mo, c is 0.5 and r_x the correlation over time between $M_{x,t}$ and $D_{x,t}$ (OSPAR 1998). The validation results were classified according to the following ratings criteria for the CF: $0 < \mathrm{CF} \leq 1$ = very good; $1 < \mathrm{CF} \leq 2$ = good; $2 < \mathrm{CF} \leq 3$ = reasonable; $3 < \mathrm{CF}$ = poor (Radach & Moll 2006).

Results of the goodness-of-fit analysis are presented in Table 2. Cost function results indicate that model results for salinity can be classified as good to very good in 21 out of 25 stations for which data are available, and reasonable in the remaining 4 stations. RMSE values were lower than 0.05 for 18 of the 25 stations, indicating a good model performance at these stations. Slightly higher RMSE values (between 0.05 and 0.1) at most of the Noordwijk stations (NW 1 through 30 km) and a particularly high RMSE value at Goeree 6 km indicate that at these stations the model performed poorly (or reasonable at best). Overall, the results of the validation indicate that the performance of the hydrodynamic model was good and can thus be considered as acceptable for the purpose of larval dispersal modelling.

Advection-diffusion model. Transport of fish eggs and larvae was modelled using Delft3D-WAQ, the water quality module of Delft3D (Postma 1988). This module contains the physical schematisation, calculates transport of substances as a function of the advective and dispersive transport, processes and loads, accumulates fluxes and computes resulting concentrations for each timestep and includes a large selection of numerical solution schemes. The actual water system is represented within Delft3D-WAQ by means of computational elements (segments). Transport between segments is derived from dedicated models (e.g. simulated in Delft3D-FLOW). Internally, Delft3D-WAQ multiplies fluxes with concentrations to obtain masses across internal and external boundaries. Delft3D-WAQ has been used successfully in the simulation of dredging plumes, thermal discharges, dispersal of seagrass seeds and various water pollution studies (Van Gils et al. 1993, van der Molen et al. 1994, Ouboter et al. 1997, Erftemeijer et al. 2008).

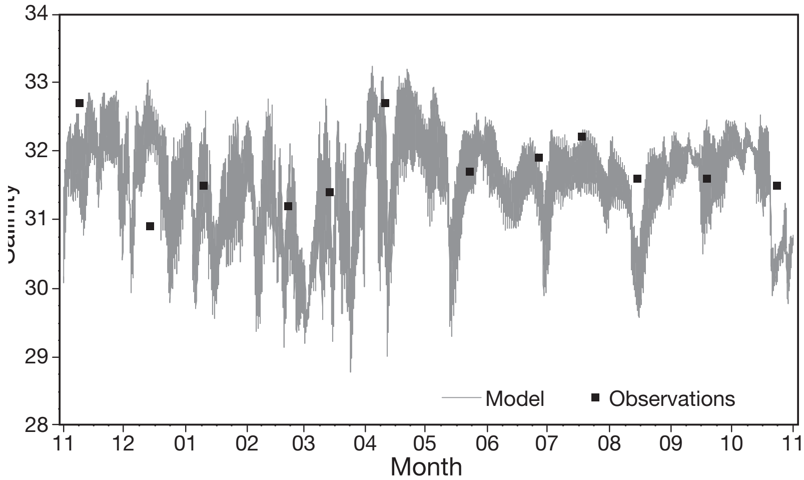

Fig. 2. Time series of modelled surface salinity (ZUNO-DD) (time step = 30 min) and measured surface salinity (points) at Walcheren (2 km offshore) during November 1988–November 1989

Table 2. Validation of the ZUNO-DD hydrodynamic model. Results of goodness-of-fit analysis between model results and field measurements for salinity. n: no. of field measurements; RMSE: root mean squared error (normalised to the mean). Measurements were at fixed distances in km along transects perpendicular to coastline; for exact location of stations see www.waterbase.nl

Station Distance (km)	n	RMSE	Cost function
Walcheren			
2	12	0.037	0.52
30	12	0.013	0.49
50	12	0.006	0.74
70	12	0.009	0.57
Schouwen			
10	12	0.021	0.76
20	12	0.029	1.39
Goeree			
6	12	0.176	1.10
20	12	0.036	0.87
Noordwijk			
1	12	0.099	0.95
2	12	0.082	1.44
4	19	0.077	1.51
10	46	0.076	2.10
20	19	0.086	2.81
30	12	0.072	2.94
50	12	0.021	0.61
70	19	0.005	0.97
Terschelling			
4	12	0.048	0.94
10	19	0.033	0.60
50	12	0.013	0.85
100	19	0.022	2.30
135	12	0.013	1.41
175	19	0.049	0.43
235	11	0.004	0.51
275	7	0.002	0.33
370	7	0.004	1.70

For the present study, a generic advection-diffusion model was developed which—by choosing different parameter settings—could be applied to simulate transport of eggs and larvae of different fish species. We have chosen the finite-volume method offered by Delft3D-WAQ (applying a scheme that was explicit in time and with a central discretisation in space), rather than a particle tracking method. When properly used, both finite-volume methods and particle tracking model approaches can (in principle) provide comparable results (Zhang & Chen 2007).

We opted for the finite-volume model approach for pragmatic reasons, the first of which was that particle tracking models are generally used for studies of near-field (or mid-field) effects, where the main focus of interest is at the level of sub-grid resolution. Delft3D-WAQ offered more than sufficiently detailed results at the far-field scale of fish larval transport, with negligible relative differences within grid cells. Secondly, unlike Delft3D-WAQ, most particle tracking models (such as Delft3D-PART) cannot operate with domain decomposition model grids, as their numerical implementation demand the full matrix. The finite-volume approach as compared to the particle approach cannot follow individual particles or give them specific properties. To overcome this disadvantage, different cohorts were introduced as modelled 'substances' representing larvae from different spawning grounds or different spawning times. The different cohorts each had their own stage development and as such their own properties.

Definition of processes and parameters. Information on the temporal and spatial distribution of egg production and knowledge of the behavioural characteristics of eggs and larvae were used to simulate larval transport. These characteristics are known to change during larval growth and development and were described in terms of specific weight (buoyancy) and behaviour (passive versus active vertical migration). The transport of concentrations of eggs and larvae were modelled from specific release points that represent schematised approximations of the known spawning grounds of the 3 species (Fig. 3). The delineation of spawning grounds in the model was primarily based on Harding et al. (1978) for plaice, unpublished RIVO (Netherlands Institute for Fisheries Research) data on distribution of Stage 1 eggs (presented in Bolle et al. 2005) for sole and ICES (2007) for herring. Published data indicate that there is little variation in the spatial distribution of spawning between years (Bolle et al. 2005, 2009, Dickey-Collas et al. 2009). Timing of spawning in the model was based on Harding et al. (1978) and Heessen & Rijnsdorp (1989) for plaice, van der Land (1991) for sole and ICES (2007) for herring. For each of the modelled fish species, different stages of larval development (with different behavioural rules) were incorporated into the model. Behaviour of larvae included diel vertical migration for herring (Munk et al. 1989), passive demersal transport (DEM) for sole (Koutsikopoulos et al. 1991) and selective tidal stream transport (STST) for plaice (Rijnsdorp et al. 1985). Larval growth and development—and thus the duration of the various phases—were related to temperature (calculated continuously during the hydrodynamic modelling). Mortality of larvae was not taken into consideration in the model. The present study focused on transport variability; details on larval stages, specific behavioural rules, processes and parameters incorporated into the model are described in Bolle et al. (2005, 2009) and Dickey-Collas et al. (2009).

Sensitivity analysis, validation and interannual variability. The final model settings, other than the hydrodynamic settings, were all based on the outcome of a detailed sensitivity analysis and validation described elsewhere (Bolle et al. 2005, 2009, Dickey-Collas et al. 2009). Flatfish spawning was simulated as a single

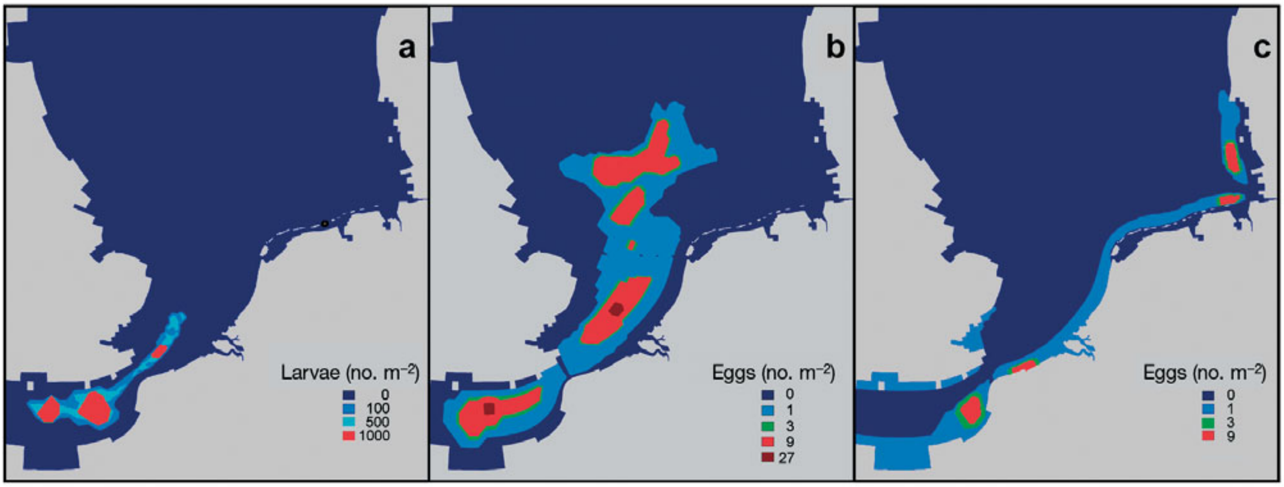

Fig. 3. Release points/areas representing schematised spawning grounds of North Sea (a) herring, (b) plaice and (c) sole based on literature and survey data

event for each spawning ground, coinciding with published information on timing of peak spawning. Hatching date for herring larvae was set at 16 December 1988, which was the peak time of hatching in the 1988–1989 season, as determined from field data and simple hindcast modelling. Horizontal dispersion was set at 1 $m^2 s^{-1}$ for herring and 100 $m^2 s^{-1}$ for flatfish. The higher dispersion for flatfish was needed to compensate for the effects of vertical aggregation as applied in the flatfish module. The value of 100 was derived from a calibration exercise carried out as part of a related study on the effects of the proposed coastal reclamation on nutrient dynamics and primary production (Nolte et al. 2005). The transport mechanism of the last larval stage for the flatfish species was modelled as DEM for sole and STST for plaice, as these are the most likely mechanisms involved for this stage in these species (Bolle et al. 2005, 2009). Validation of the fish larval distribution was carried out by comparing modelled transport with empirical estimates of abundance, growth and timing of delivery from surveys of larvae, post-larvae and juveniles. The modelled transport was broadly in agreement with estimates from the field: (1) modelled transport for plaice larvae corresponded well with the general distribution of recruits in autumn (survey data); (2) timing of settlement of plaice larvae (model) compared well with survey data; and (3) modelled stage duration for plaice corresponded well with the results of otolith day-ring analysis (see Bolle et al. 2009). Similar results were obtained for herring (Dickey-Collas et al. 2009).

Scenarios. For the study of the impact of the MV2 reclamation on the transport of fish larvae from their spawning grounds in the southern part of the North Sea to their nursery areas (especially the Wadden Sea), the following 3 scenarios were considered:

(1) Current situation (T_0): this scenario represented the present situation (i.e. the baseline), modelled using the hydrodynamics from the year-run for 1988–1989.

(2) T_0 + autonomous developments: this scenario was similar to Scenario 1, but included 2 autonomous developments that will take place before the construction of MV2 and are likely to affect baseline conditions: (i) the so-called Kierbesluit, which refers to proposed changes to the discharge regime of the Haringvliet sluices, and (ii) a proposed offshore wind mill park, consisting of 2 areas each with 60 wind mills.

(3) MV2: this scenario not only included the autonomous developments but also one design for the MV2 extension (Doorsteekvariant). The overall impact of MV2 was assessed by looking at differences in model results between Scenarios 2 and 3.

The main thrust of the project was the influence of the MV2 reclamation on the transport of larvae. The effect of the reclamation phase on spawning was not investigated because there was no spatial overlap between the proposed areas of aggregate extraction or reclamation and the spawning grounds.

Analysis of model output. To describe and quantify current larval transport patterns and quantify the effects of MV2, post-model processing was carried out to calculate the following output parameters:

- Distribution patterns — graphic contour plots of the temporal and spatial distribution of eggs and larvae (densities m^{-2}) on a certain date.
- Transport success — relative proportion of fish larvae (% of total number spawned) that has arrived in a certain nursery area by the end of the model run. For this, the model grid area was subdivided into a number of compartments: 4 offshore areas and a number of coastal areas, delimited by the 20 m depth contour (Fig. 4). The number of larvae per compartment was

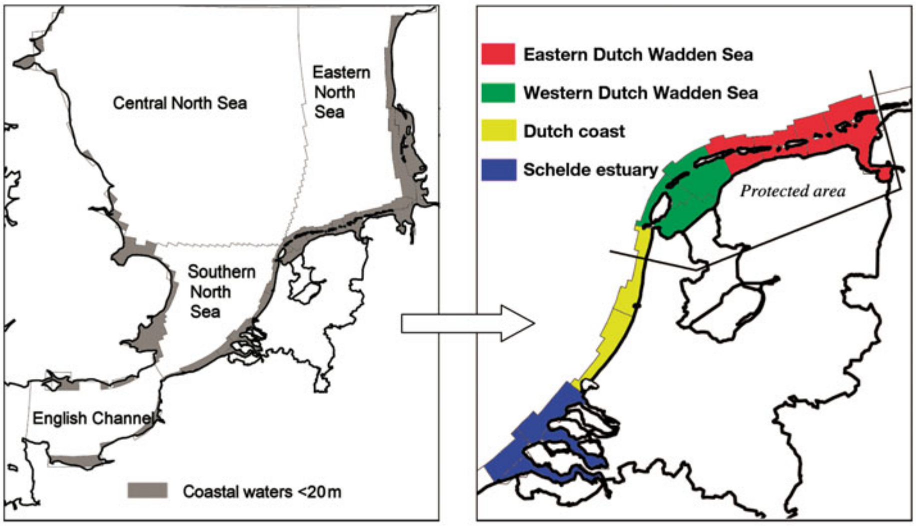

Fig. 4. Areas used to estimate transport success. Offshore areas (left panel, important for juvenile herring) correspond with those distinguished in the International Bottom Trawl Survey (IBTS). The smaller compartments within the Dutch coastal zone (right panel, important as nursery areas for plaice and sole) correspond with areas distinguished in the demersal fish survey (DFS)

summed to calculate the transport success for larger geographic units, such as the western Dutch Wadden Sea or the protected area. The protected area (see Fig. 4, right panel) refers to the Dutch Wadden Sea and adjacent coastal waters (from Petten to the German border, to a depth of 20 m) which are protected under the EU Habitats and Bird Directives (Enemark 2005).

- Timing of arrival. This output parameter, in the form of a time series plot, described the timing of arrival of fish larvae in a certain coastal area. It enabled plotting of larval density (no. m^{-2}) in the model at an observation point (usually 1 grid cell) showing the accumulation of larvae entering a coastal area.

RESULTS

Herring

There was no discernable difference in the distribution of the concentrations of larvae between the 3 scenarios (Fig. 5). By area, there was also no major difference between the 3 scenarios (Fig. 6). For transport to the protected area, the simulations suggested a reduction of 1 % between the autonomous development scenario and the MV2 scenario (Table 3). For the Dutch coast as a whole, the simulations suggest a reduction of 3 % due to the MV2 construction. None of this change occurred in the Wadden Sea itself, but along the Dutch

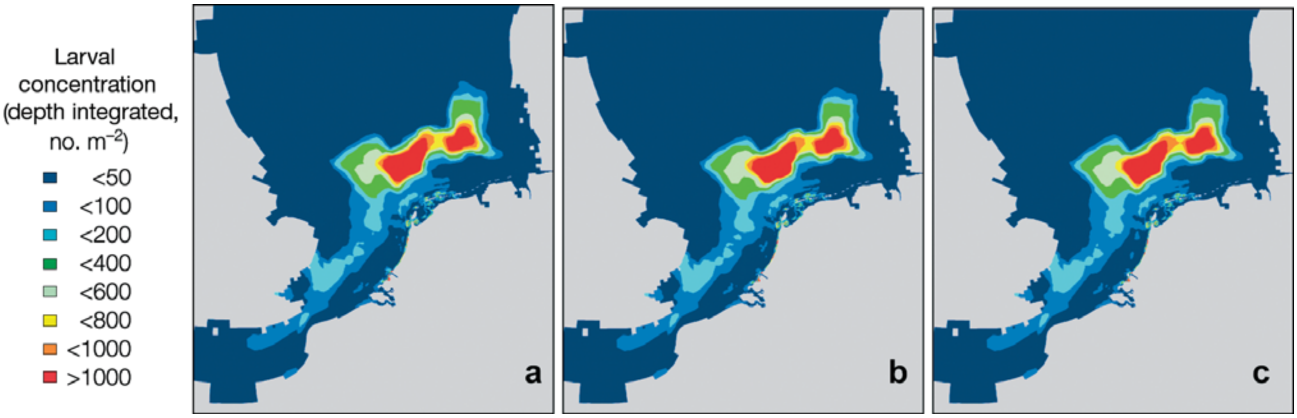

Fig. 5. Distribution of herring late post-larvae by the end of May 1989 for 3 scenarios: (a) current situation, (b) autonomous developments and (c) autonomous developments + Maasvlakte-2 reclamation

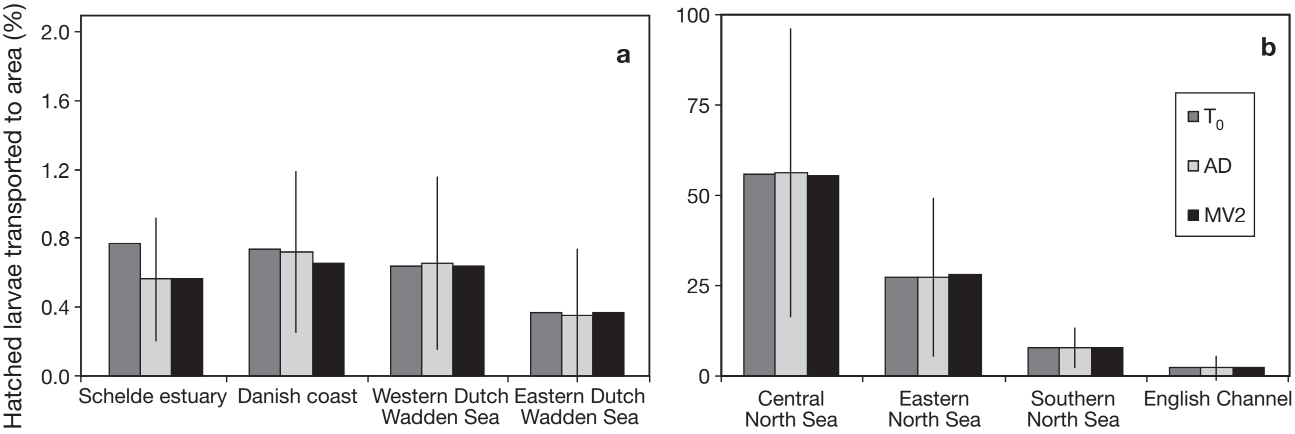

Fig. 6. Percent of hatched herring larvae transported to each location by the end of May 1989 for the 3 scenarios: current situation (T_0), autonomous developments (AD) and autonomous developments + Maasvlakte-2 (MV2). Note different scale of *y*-axes. (a) Dutch coastal zone; (b) offshore areas (areas described in Fig. 4). Error bars: simulated SD of inter-year variability of transport to each location (see Dickey-Collas et al. 2009, this volume)

coast and Scheldt estuary. There was no difference in terms of the timing in any area.

Plaice and sole

The spatial distribution was compared for the 3 scenarios for plaice larvae from the Southern Bight spawning ground, plaice larvae from the English Channel spawning ground and sole larvae from all spawning grounds combined. Spawning grounds of sole are more inshore and appear to be much less segregated. The precise location of the spawning grounds and their degree of concentration is less certain for sole than for plaice. This makes spatial segregation of their spawning grounds in the model much less obvious than for plaice, for which clearly defined spawning grounds are well-documented, with little variation in spatial distribution between years. Scenario comparisons for flatfish were carried out with the assumptions of DEM (sole) and STST (plaice) in late-larval and early juvenile stages.

Table 3. Proportion of larvae reaching the protected area or, in the case of plaice and sole, all nursery areas for 3 scenarios—current situation (T_0), autonomous developments (AD) and autonomous developments + Maasvlakte-2 (MV2)—and the (inter)annual variability in transport success for a 9 yr range (Bolle et al. 2005, 2009, this volume, Dickey-Collas et al. 2009). The relative effect compares AD to T_0, MV2 to AD and the (inter)annual range to the mean. Plaice originate from the spawning grounds in the Southern Bight and English Channel; selective tidal stream transport (STST) is assumed for the late larval and early juvenile stages. Sole originate from the spawning grounds in the Southern Bight and English Channel; passive demersal transport (DEM) is assumed for the late larval and early juvenile stages. Relative effects: MV2 vs. AD = (MV2 – AD)/AD; AD vs. T_0 = (AD – T_0)/T_0; annual variability = (max – min)/mean

Transport mechanism	Scenario	Transport success (%)		Relative effect (%)	
		Protected area	All nurseries	Protected area	All nurseries
Herring					
Diel vertical migration	T_0	1.15			
	AD	1.17		1.2	
	MV2	1.16		–0.8	
	Annual variability	0–2.7		273	
Plaice					
STST	T_0	11.72	36.8		
	AD	11.84	36.8	1.0	0.0
	MV2	11.86	36.7	0.2	–0.5
	Annual variability	3–15	23–42	126	54
Sole					
DEM	T_0	1.37	21.38		
	AD	1.43	21.20	5.0	–0.8
	MV2	1.34	21.25	–6.3	0.2
	Annual variability	0.7–2.0	19–25	93	24

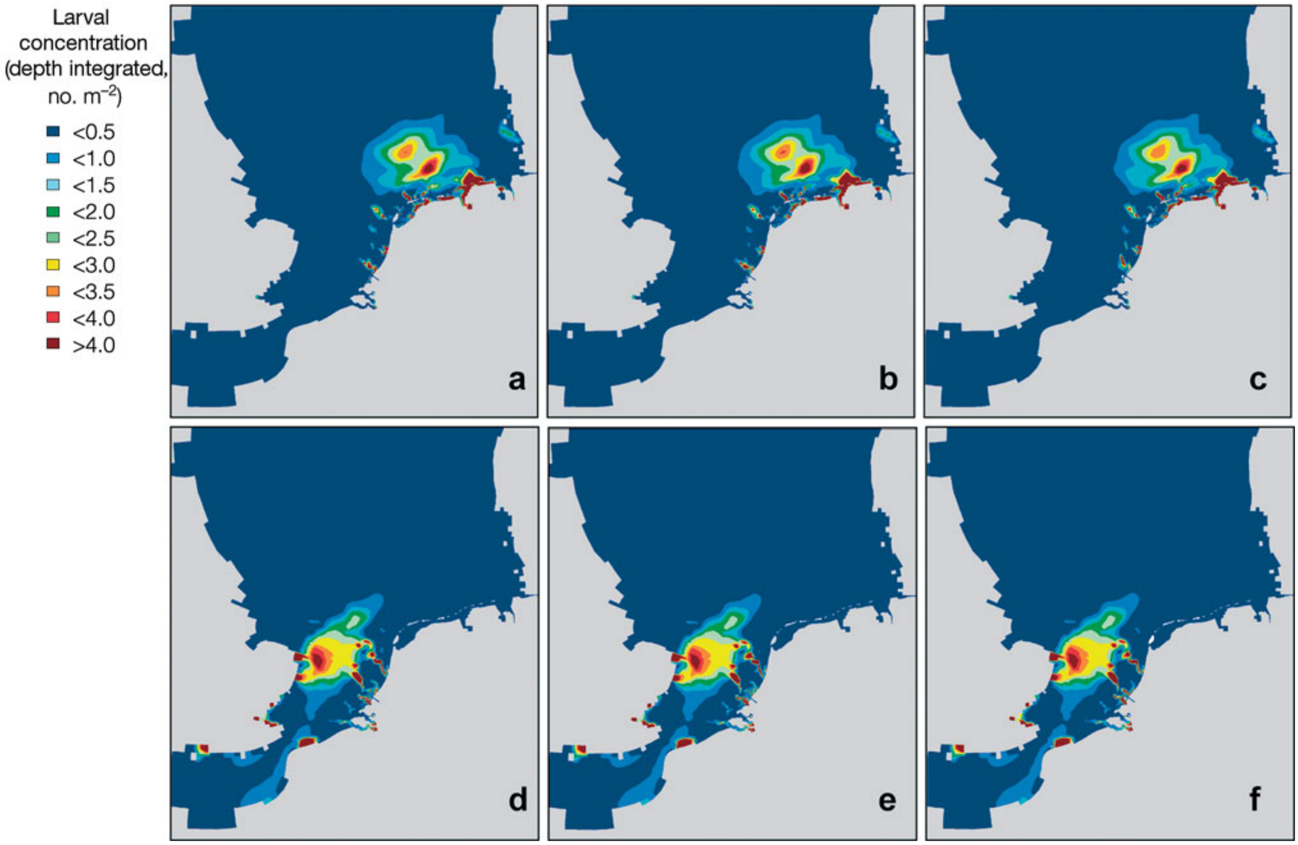

Fig. 7. Distribution pattern of plaice at the end of the transport phase for 3 scenarios: (a,d) current situation, (b,e) autonomous developments and (c,f) autonomous developments + Maasvlakte-2, showing results for the (a–c) Southern Bight and (d–f) English Channel spawning grounds

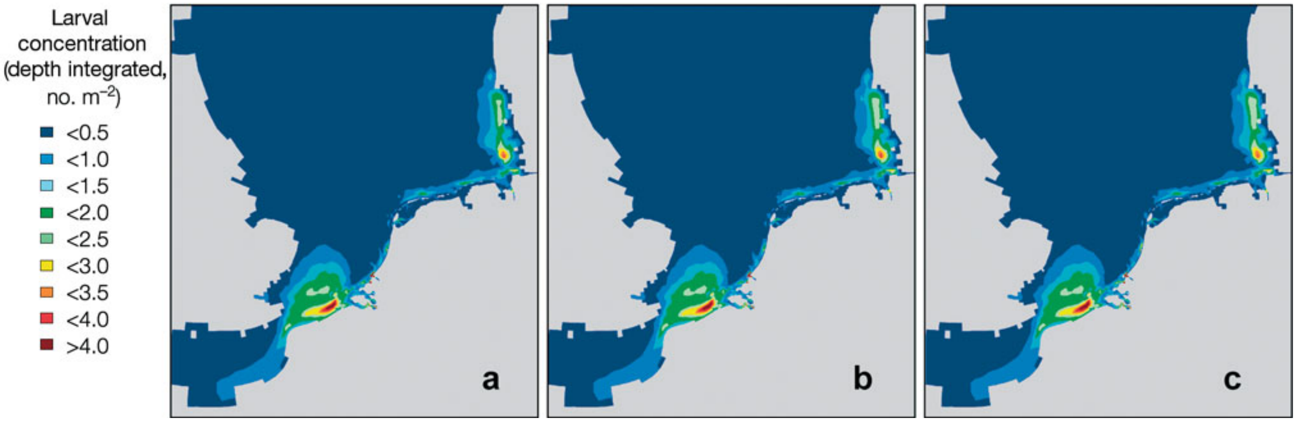

Fig. 8. Distribution pattern of sole for all spawning grounds combined at the end of the transport phase for 3 scenarios: (a) current situation, (b) autonomous developments and (c) autonomous developments + Maasvlakte-2 (MV2)

None of the distribution maps (Figs. 7 & 8) showed any discernable differences between scenarios. For both plaice and sole, the percentage of larvae that reached certain regions differed only slightly between the 3 scenarios (Fig. 9). These small differences were negligible when compared to the between-year variations (Bolle et al. 2005, 2009).

For plaice, the percentage of larvae that reached the protected area increased by 0.2 % in the MV2 scenario compared to the autonomous development scenario

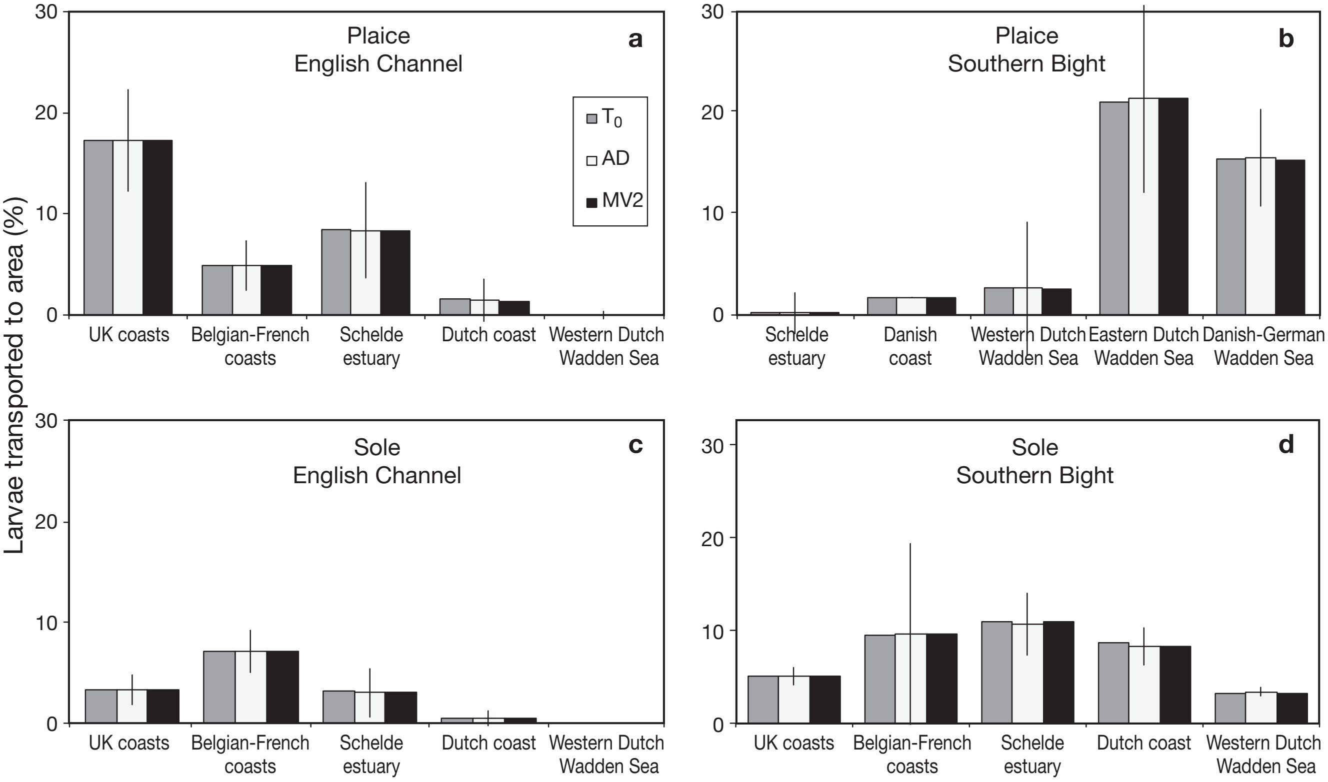

Fig. 9. Percent of larvae—(a,b) plaice and (c,d) sole larvae originating from spawning ground in (a,c) the English Channel and (b,d) the Southern Bight—reaching specific locations for 3 scenarios: current situation (T_0), autonomous developments (AD) and autonomous developments + Maasvlakte-2 (MV2). Error bars: simulated SD of inter-year variability of transport to each location (see Bolle et al. 2005, 2009)

(Table 3). This is considered to be negligible compared to the interannual variability (126 %). Transport success to all nursery areas decreased by 0.5 % due to the MV2 land reclamation.

For sole, the percentage of larvae that reached the protected area decreased by 6.3 % in the MV2 scenario compared to the autonomous development scenario (Table 3). Despite the fact that this difference was larger than in plaice, and interannual variability was smaller (93 %) than in plaice, it is considered to be of no biological significance and below the detection limits of larval monitoring surveys. Transport success for sole to all nursery areas increased by 0.2 % due to the MV2 land reclamation.

The timing of arrival was examined at 4 observation points close to the coast or in the inlets of estuarine areas (Fig. 10). Comparison of these time series for the 3 scenarios showed slight differences in the densities of the larvae, but did not indicate any differences in the timing of arrival.

Model results were sensitive to the timing of spawning, growth parameters and duration of transport phase used in the simulations, but these primarily affected the transport success (% of larvae reaching nurseries) rather than the spatial distribution patterns of the larvae, and thus represent scaling effects. Detailed results of the sensitivity analyses are described in Bolle et al. (2005, 2009) and Dickey-Collas et al. (2009).

DISCUSSION

The present study is one of the first modelling studies that looked at transport of fish larvae in the southern North Sea using real-time hydrodynamic forcing (with wind, air pressure and river discharge), considering interannual variability and incorporating behaviour rules (including temperature and salinity triggers). Transport of the larvae of 3 fish species was modelled: herring, plaice and sole. Model results were different between species because different, species-specific behaviour, growth parameters and spawning grounds were incorporated into the model. Previous modelling studies by Bolle et al. (2005, 2009) and Dickey-Collas et al. (2009) have indicated large interannual variability in the transport of herring, plaice and sole larvae, which showed a broad agreement with available field data.

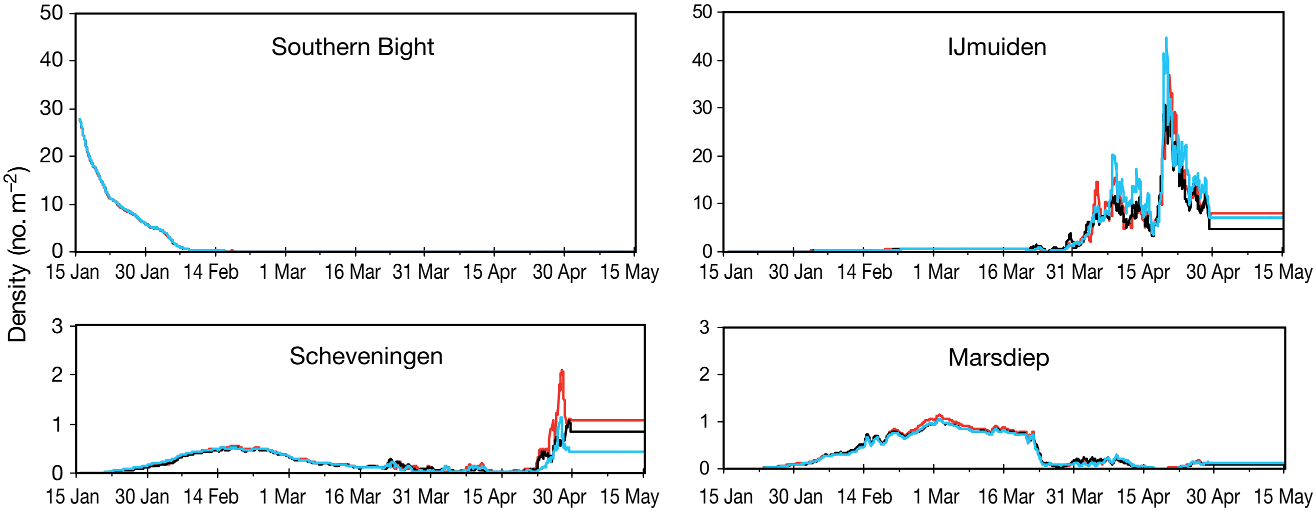

Fig. 10. Time series of modelled densities of plaice larvae at 4 stations (selected on the model grid) for 3 scenarios: current situation (red), autonomous developments (black) and Maasvlakte-2 (blue). Plaice originate from the Southern Bight spawning grounds

Changes in larval transport success to nursery areas due to the proposed coastal reclamation for MV2 were very small (in the order of <3% for herring, <0.5% for flatfish), and insignificant in comparison to the large interannual variability in larval transport (Bolle et al. 2009, Dickey-Collas et al. 2009). These results obtained through the present model and its inherent assumptions suggest (at least for the year that was modelled) that the effects of the proposed coastal reclamation scheme on the transport of fish larvae (flatfish and herring) will be negligible. In a parallel study on the impact of the reclamation on fine sediment transport along the Dutch coast, the model was also run for 2 additional years (for a 14 d spring–neap cycle), and yielded no major differences in the magnitude of predicted impacts from those obtained for the base year (1989). While this could not be repeated for the fish larvae study, which would require an 8 mo model run period rather than a 14 d spring–neap cycle, these findings confirm that the impact of the reclamation on current patterns was relatively insignificant in comparison with the year-to-year variability in current patterns (and thus fish larval transport).

The findings of the present study should be carefully interpreted, accounting for all of the assumptions of the model. This investigation has looked purely at the transport patterns of concentrations of larvae incorporating behaviour, the delivery to specific locations from specific sources and whether future constructions will impact on that delivery. As such, calculated transport and delivery rates should not be interpreted as reliable predictions of recruitment success. At no point was mortality applied to the concentrations of eggs or larvae. Mortality cannot be considered as just a scaling factor, as it is selective in terms of space, time and physical rates (Pepin et al. 2002, Pepin 2004). Furthermore, annual egg production was considered to be constant. Hence this model, even disregarding the structural and theoretical differences, is in no way comparable to the types of individual-based models used to investigate recruitment variability (e.g. Heath et al. 1997, Hinrichsen et al. 2003, Peck et al. 2003).

For flatfish, one of the most important knowledge gaps is the potential survival outside the nursery areas after metamorphosis is completed. The outcome of the present model is sensitive to the assumptions on this aspect, but this is a scaling effect (Bolle et al. 2009) and will probably not affect our conclusions on the effects of the land reclamation. Another uncertainty for flatfish is the relative importance of STST and the environmental factors that trigger this behaviour (see Bolle et al. 2009).

The present study found no significant differences in the timing of arrival of fish larvae at their nursery grounds as a result of the proposed land reclamation. If there were a delay in arrival, the longer period larvae spend at sea might pose a greater risk of predation (mortality). However, since no difference in the timing of arrival was found, no effect of land reclamation on mortality is expected. The proposed reclamation area (1000 ha) is part of the wider nursery area for the investigated flatfish species, but negligible in scale (0.1%) relative to the total nursery area along the Dutch coast, which covers approximately 890 000 ha (Fig. 4).

For each of the 3 species modelled, the location of the spawning grounds was fixed for all model runs. For plaice, this assumption is plausible as published data indicate that the position of the spawning grounds for plaice has not changed over the last century (Harding et al. 1978, Taylor et al. 2007). For herring, the choice of hatching sites was based on the survey time series from ICES (2007) and found to be in broad agreement with those described in earlier literature from the 1950s and 1970s (Dickey-Collas et al. 2009). For sole, the delineation of spawning grounds is less certain than for plaice. It is clear that sole spawn in coastal waters, but the degree of concentration is uncertain. Sensitivity analysis of the model shows that the variability in transport success by region is largely determined by the spatial distribution of spawning hot spots (spatial concentrations in spawning activity) (Bolle et al. 2005).

The effect of the construction phase of the reclamation scheme (including aggregate extraction) on fish spawning or breeding success was not part of this investigation. However, since the proposed areas of aggregate extraction and reclamation site are far away from the spawning and nursery grounds, such effects (which will be temporary) are expected to be negligible (as elaborated in the ecological risk assessment).

Besides the fish larvae dispersal study presented in this paper, a parallel modelling study (Van Kessel 2005) of silt transport was carried out, which revealed localised effects of the proposed MV2 reclamation on silt transport in the nearshore zone along part of the Dutch coast. The silt concentration and net flux would decrease by approximately 10% within a band of ca. 20 km from the Dutch coast, partly compensated by a slightly higher suspended sediment concentration and flux farther offshore. Similar to the results obtained for fish larvae, this silt transport study found no significant effects on the Wadden Sea system or elsewhere in the southern North Sea area (Van Kessel 2005). Apparently, the impact of the 1000 ha coastal reclamation scheme MV2 (protruding approximately 6 to 7 km from the Dutch coastline) on coastal currents is limited to a nearshore area extending several 10s of km (a scale of relevance to silt transport processes) along the coast, while the effects further offshore and at larger spatial scales (of relevance to larval transport processes) are negligible.

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