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1 Summary - D 4.5: Fish farming opportunities

The past decades trend in aquaculture production strongly suggest that the industry will continue to grow globally, particularly in the marine sector. Because of competition over space with other uses in the coastal waters it is likely that future growth will occur in offshore environments. Moving offshore could potentially reduce environmental impacts and improving fish health. Waterborne transmission of fish diseases between fish farms is a potential thread for marine fish production. In order to minimize the risk of waterborne transmission of fish diseases between production sites it is important, prior to the location of new sites, to ensure that the sites have no or only little “connectivity” with other existing or planned production sites.

The risk of waterborne transmission between individual fish farm can be assessed based on hydro-dynamic- and decay- modelling. As part of WP 4 a model tool has been established to provide decision basis for planners, managers and marine aqua culture producers to select the most optimal location of new production site with respect to waterborne transmission risk.

2 Background

The past decades trend in aquaculture production strongly suggest that the industry will continue to grow globally, particularly in the marine sector. And because of competition over space with other users in coastal waters it is likely that future growth will occur in offshore or open ocean environments. Moving offshore could potentially reduce environmental impacts and improving fish health by sufficient water movement to continuously refresh oxygen levels within cages and disperse wastes, although there is little evidence for these claims. Producing in offshore environments implies used of sturdier equipment to withstand physical impacts from waves and currents, all leading to higher establishment costs. Along with additional transportation costs offshore farms need to be larger, probably around 10.000 tons production annually to be profitable (James and Slaski 2006).

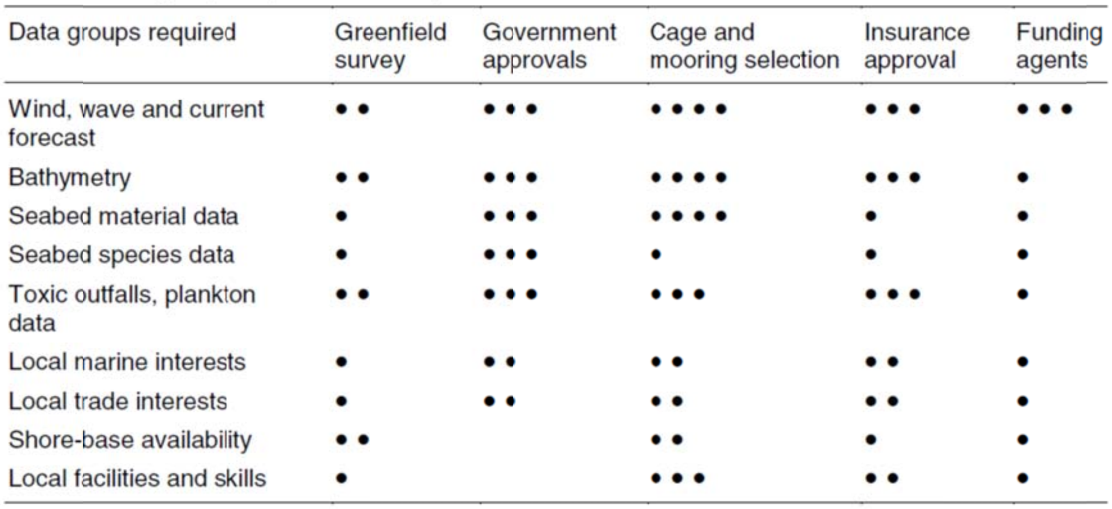
Given the immense establishment costs of large offshore aquaculture farms capital from outside the traditional aquaculture investors will be needed. To be successful to attract capital producers are obliged to present and document all important aspects including engineering, biological, logistic constraints and marketing issues and importantly, also the associated risks and including losses e.g. caused by catastrophic storms. To that end, careful selection of “optimal” sites of offshore aquaculture operations is crucial influencing the social and environmental impacts of aquaculture, as well as their profitability, and the investor’s interests. With a Mediterranean perspective Muir (2000) defined offshore conditions and reviewed how such conditions affect production, Turner (2000) laid the foundation how to evaluate sites focussing on physical conditions and later, James and Slaski (2006) analysed opportunities and constraints for offshore salmon production in North European waters focussing on logistics, financial requirements and profitability.

With the proposal currently being discussed for an EU Directive “Maritime Spatial Planning and Integrated Coastal Management” (EC 2013) EU have acknowledged the need for providing space for marine aquaculture in Europe along with sites for renewable and fossil energy installations, maritime transport, fishing and nature conservation sites. Hence, aquaculture business must be considered as a legitimate player in the integrated maritime spatial planning process.

2.1 Site selection process for offshore fish farms

Turner (2000) discussed a long list of issues to consider when planning for an offshore fish farm (Table 1). The list primarily included meteorological and hydrodynamic issues such as wind, waves and currents that all contribute to physical stress on cages and moorings. Other important issues discussed by Turner were bathymetry, seabed characteristics including resident flora and fauna, outfalls, risks for blooms of toxic algae and assess to nearby facilities providing the necessary logistics for harbour, local trade and skilled people. What Turner did not explicitly consider was how spread of disease from one farm to another can be mediated by currents creating “linkages” between individual farms (e.g. Murray et al. 2005).

Table 1. Overview of issues to consider when planning for an offshore fish farm (from Turner 2000)



Data groups required	Greenfield survey	Government approvals	Cage and mooring selection	Insurance approval	Funding agents
Wind, wave and current forecast	• •	• • •	• • • •	• • •	• • •
Bathymetry	• •	• • •	• • • •	• • •	•
Seabed material data	•	• • •	• • • •	•	•
Seabed species data	•	• • •	•	•	•
Toxic outfalls, plankton data	• •	• • •	• • •	• • •	•
Local marine interests	•	• •	• •	• •	•
Local trade interests	•	• •	• •	• •	•
Shore-base availability	• •		• •	•	•
Local facilities and skills	•		• • •	• •	•

1.1.1 Risk of hydrodynamic dispersal of pathogens

On the one hand a minimum level of currents is required to refresh oxygen levels within cages and disperse wastes, but on the other hand strong currents hydrodynamic “connecting” farms can increase risks of infections by carrying germs so fast from one farm to another farm located downstream that germs may survive and maintain their infectious ability when arriving at a down-stream located farm. Generally, this risk for hydrodynamic dispersal of pathogens would be highest where currents are directional such as along coasts or “canyons” in seabed. In such location, high currents can be seen as a two-edged sword for fish farm, on the one hand promoting oxygen input to cages and dispersing waste and on the other hand strong currents may be a vector that increases spread of diseases.

In the following we examine the beneficial effects of current speed on dispersal and dilution of waste from marine fish farms on the one hand and on the other, the impact of high currents on the risk for promoting spread of pathogens from one farm to another. We use the inner Danish waters as an example because of a large spatial variation in mean current speed can be found depending if farms are located in the main “highway” of outflowing water from the Baltic Sea or in less energetic waters. We have used calibrated hydrodynamic models to describe currents (and water level, salinity, temperature etc.) in the model domains.

Scope

Waterborne transmission of fish diseases between fish farms is a potential thread for marine fish production. In order to minimize the risk of waterborne transmission of fish diseases between production sites it is important, prior to the location of new sites, to ensure that the sites have no or only little “connectivity” with other existing or planned production sites. Thus, the scope of the activity has been to establish the decision basis for planners, managers and marine aqua culture producers in Denmark to select the most optimal location of new production site form a waterborne transmission risk point-of-view.

Methodology

The risk of waterborne transmission between individual fish farm can be analyzed based on hydro-dynamic modeling predicting the water current in time and space, and transport (~advection-dispersion) and 1st order decay modeling describing the dissolution and transport of dissolved or suspended disease “agents” (e.g. vira , bacteria or parasite). The relative transmission risk between sites can be analyzed based on these model results:

- Disease dispersal maps – for visual pairwise comparison of transmission risk between production sites
- Similarity index – a statistical method for identifying those productions sites with least (or most) risk of waterborne transmission

Potential production sites

Here we examine 35 proposed locations of marine aquaculture sites in Denmark. The 35 locations include a few existing production sites, otherwise potential sites were selected in collaboration by Danish Aquaculture organisation considering optimal conditions for production for rainbow trout as well as restriction in terms of e.g. ship traffic, marine protected areas, geological resources etc. These latter areas of restriction is available from the website (http://miljoegis.mim.dk/cbkort?profile=miljoegis_havbrugskort) hosted by the Danish Agency for Environmental Protection. In addition AIS data available from Danish marine Authorities on intensity and density of ship traffic was used to avoid areas not suitable due to ship traffic.

The 35 proposed production sites are shown in Fig.Figure.

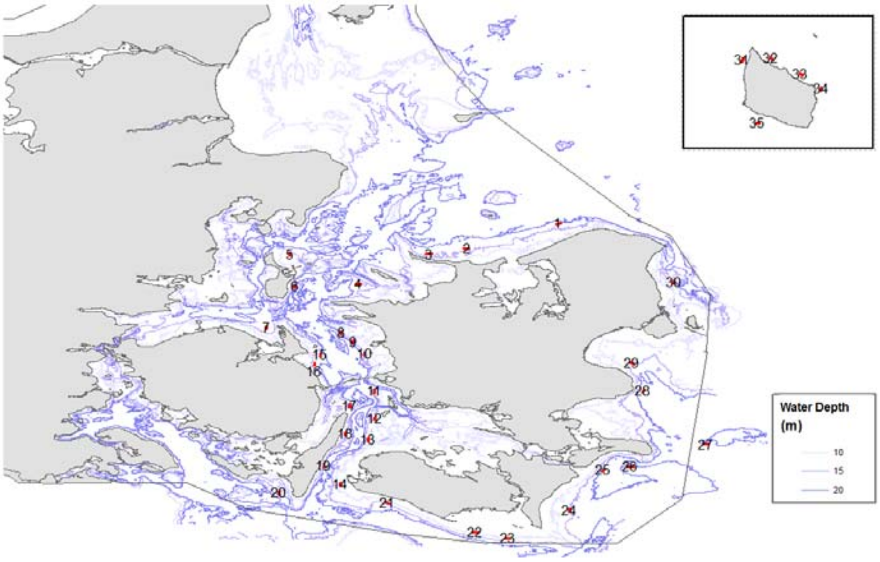


Figure 1. The 35 proposed aquaculture sites in the inner Danish Water and around Bornholm (insert upper right) indicated by red rectangles (100*300 meter). Numbers refer to site ID for later reference. Blue lines indicate depths curves (10, 15 and 20 meters). Grey coloured areas are Danish land territory.

Hydrodynamic models

The applied hydrodynamic models, or current models, described below are based on the MIKE 3 modeling system developed by DHI. The MIKE 3 models are dynamic time-dependent3-D baroclinic models for free surface flows. The mathematical foundation of the models are the Reynolds-averaged Navier-Stokes equations in three dimensions, including the effects of turbulence and variable density, together with conservation equations for mass, heat and salt, an equation of state for the density, a turbulence module and a heat exchange module. The equations are solved on either a Cartesian grid by means of the finite difference techniques (MIKE 3) or the equations are solved on an unstructured (flexible) mesh by means of finite volume/finite element techniques (MIKE 3 FM). The hydrodynamic models provide full 3-D model representation of the water levels, flows, salinity, temperature and density within the modeling domain.

For more information on the MIKE 3 modeling system reference is made to (DHI 2009, DHI 2011).

Inner Danish Waters (HD-dkbs)

The hydrodynamic model applied for location of sites for fish farms in the Inner Danish Waters and hydrodynamic spread of diseases is based on DHIs Water Forecast services for the Inner Danish Waters and the Baltic Sea. The model named HD-dkbs has been calibrated and validated for 2010. The model setup, calibration and validation have been thoroughly documented in a technical note from 2011 (Grode et al. 2011). Below is given a summary of the model. For more details, see (Grode et al. 2011).

The model mesh applied in the HD-dkbs model is shown in Fig. 2, and in Figs. **Error! Reference source not found.** a section of the model mesh and bathymetry covering the Inner Danish Waters is shown.

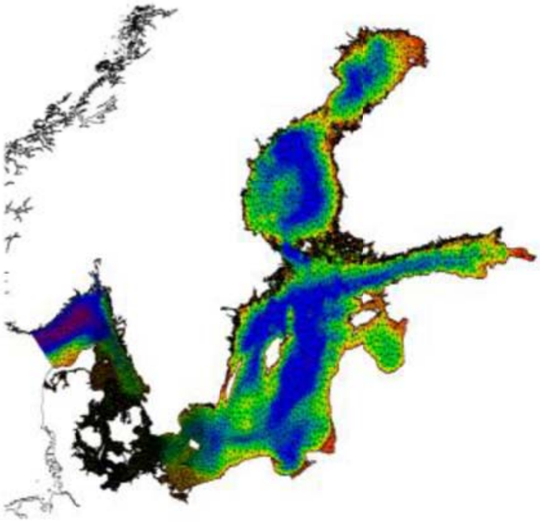


Figure 2. Model mesh of the hydrodynamic model, HD-dkbs, covering the inner Danish Waters and the Baltic Sea. Colours indicate depth intervals, - shallow as red/green and deep as blue.

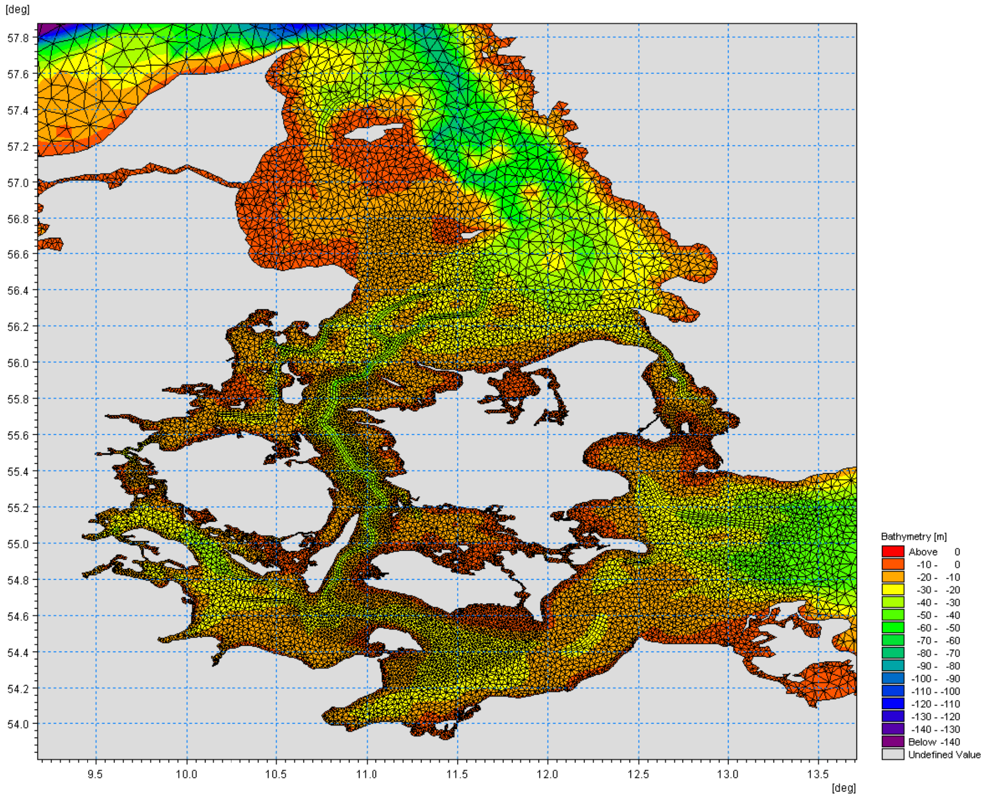


Figure 3. Section of the computational mesh for the hydrodynamic model covering the inner Danish waters. Colors indicate depth intervals in meters.

The mesh has a resolution ranging from 500-1000 m in the Fehmarnbelt area, to 1.0-2.5 km in western Baltic and Belt Sea, to 2-4 km in Kattegat and west of Bornholm, to 5-12 km in Skagerrak, and finally to 5-20 km in Baltic Sea east of Bornholm.

The vertical domain is a combined sigma-z domain with the upper 10 m of the water column represented by 10 sigma-layers and the remaining water column represented by a number of z-layers depending on the local water depth. The adopted vertical resolution allows for the main part of the western Baltic Sea and the Belt Sea including Fehmarnbelt to be resolved entirely by 1 m layers.

Meteorological input data (wind, air temperature, air pressure, clearness and precipitation) is provided by StormGeo (Norway).

Boundary data for the Skagerrak model boundary including water level, current, salinity and temperature are provided by DHIs larger operational forecast models: - water level and current from the Hydrostatic North Sea-Baltic Sea operational model and temperature and salinity are provided by the so-called BANSAI operational model (Hansen and Christensen 2006).

In order to account for the freshwater runoff within the model domain, the hydrodynamic model includes 82 model sources. These sources represent the total freshwater input to the model domain. Data is based on combination of modelled and climatological data from SMHIs (Swedish Meteorological and Hydrological Institute) HBV runoff model and from the data sources applied for the Danish NOVANA modeling program.

The model is calibrated by comparing simulated and measured time series of water level, water temperature and salinity at various locations within the model domain. Available monitoring stations used for calibration are shown in **Error! Reference source not found.**4.

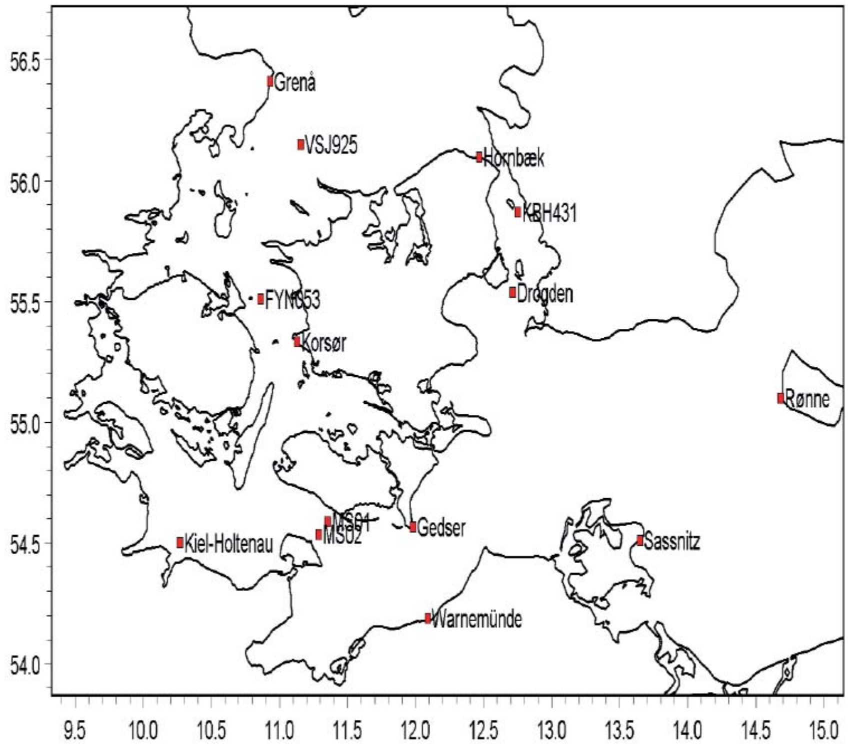


Figure 4. Location of station available for visual comparison between measurements and model results of salinity and temperature.

Figures **Error! Reference source not found. Error! Reference source not found.** and 7 show the comparison between measured and simulated temperature and salinity for 3 stations, FYN-053, VSJ-925 and MS-02, located Great Belt, Kattegat and Fehmernbelt respectively. The figures show both surface and bottom values in order to illustrate the ability of the model to simulate the stratification of the water column. A 10-month period in 2010 has been selected for the comparisons.

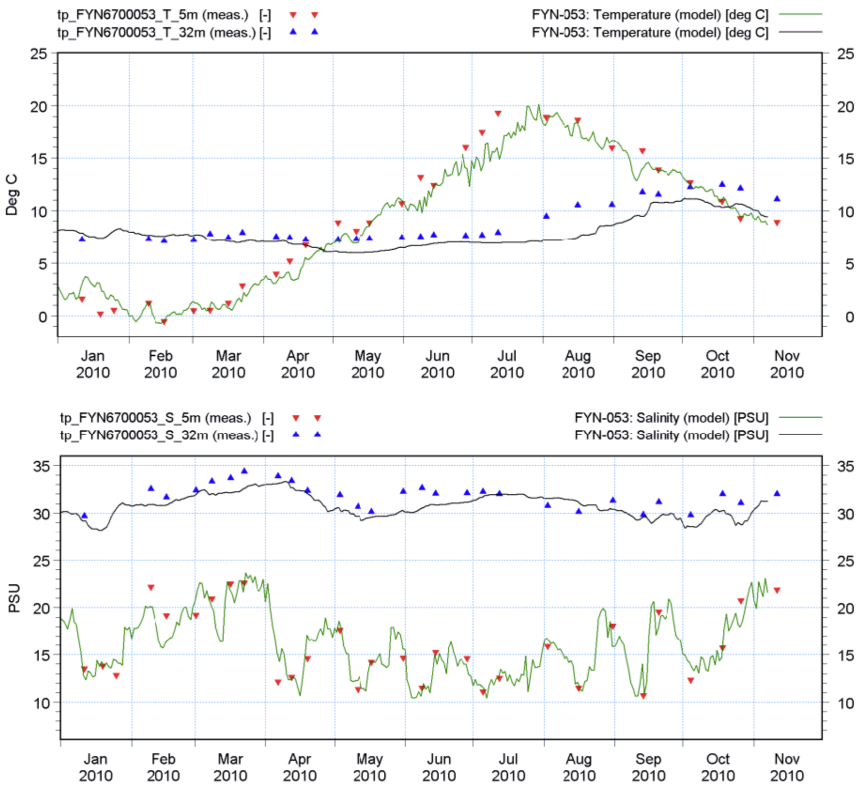


Figure 5. Comparison of measured and modelled temperature and salinity at station FYN053.

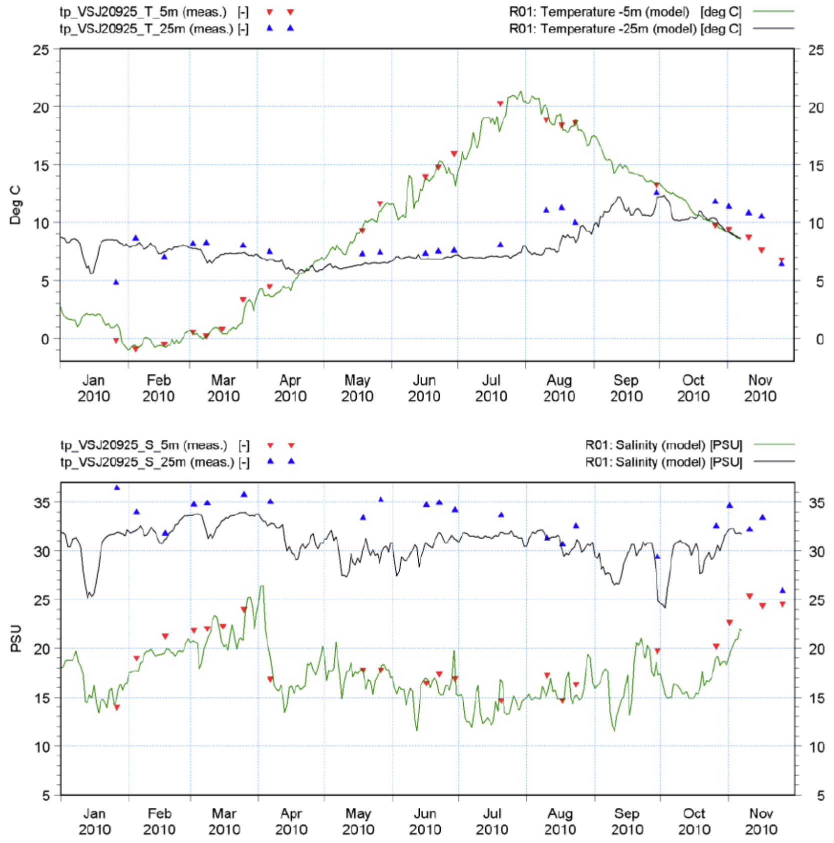


Figure 6. Comparison of measured (triangles) and modelled (lines) temperature (upper) and salinity (lower) at station VSJ925.

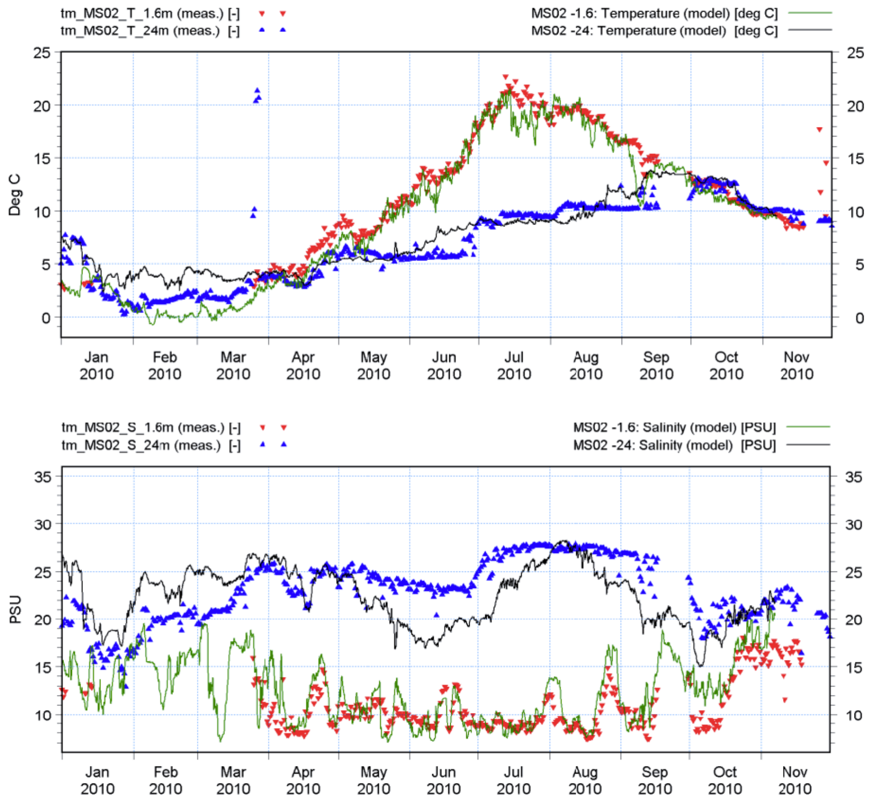


Figure 7. Comparison of measured (triangles) and modelled (lines) of temperature (upper) and salinity (lower) at station MS02.

Error! Reference source not found.8 shows comparison of simulated and measured water level at 3 stations (harbours) in the inner Danish Waters: Korsør, Grenå and Hornbæk. The comparison shown is for a 1-month period in September-October 2010.

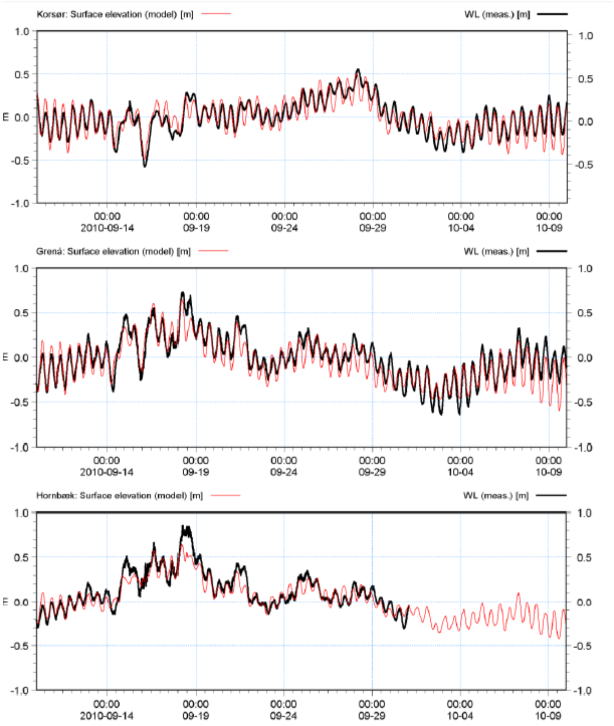


Figure 8. Comparison of measured and modelled water level at stations Korsør, Grenå and Hornbæk

1.1.2 Disease transmission model

The disease transmission modelling was carried out using the ECO Lab module for MIKE 3 FM. The ECO Lab module is an add-module for simulating the reactive transport of dissolved or suspended substances in water represented by the computational nodes (~water volumes) in the MIKE 3 FM model. ECO Lab is designed as an open equation solver for full customization and specification of model algorithms and variable definitions. For details on the ECO Lab module, see (DHI 2012a, 2012b, 2012c).

The disease transmission was modelled as simple 1st order decay in combination with advection dispersion processes. In order to propose most likely first order decay constants for model simulations two common fish diseases were selected, *VHS* and *Furunculosis* respectively based on available literature e.g., Østergård and Midtlyng (2001) and Cipriano and Bullock (2001). Proposed decay rates for VHS and *Furunculosis* are shown in Table . No temperature or salinity dependency on decay was included.

The model was setup including 35 state variables, each state variable representing each of the proposed fish production sites.

Table 2. Proposed likely 1st order decay rates for two selected fish diseases *VHS* and *Furunculosis*. Based on Østergård and Midtlyng (2001) and Cipriano and Bullock (2001).

Disease	**VHS**		**Furunculosis**	
	Days	**Rate (1/day)**	**Days**	**Rate (1/day)**
Max survival	**30**		**10**	
Applied in model*	**20**	**0.25**	**10**	**0.1**

* corresponding to <1% survival of initial numbers of vira/parasites

Four simulations were run with different first order decay of 0, 0.1, 0.25 and 0.5 per day the 0.1 and 0.25 decay rates representing *VHS* and *Furunculosis* and the additional two, - one including no decay, and one including a high decay rate 0.5 per day, included for comparison.

For each of the 4 simulations, 35 sources (i.e. release of germs from a marine fish farm containing infected fish) were specified at the centre of the 35 production sites considered. In site number 1 a constant discharge of 10^6 units per seconds was specified for state variable number 1, the remainder of the state variables were set to zero. This was repeated for each of the 35 sources. The simulations were carried out for a 3 month period 1 June to 30 August, which is the time of year when fish are most likely to be sick because of peak temperatures occurring on host and calm days.

1.1.3 Results & Discussion

Based on disease transmission model results from the simulation representing a decay rate of 0.5 per day, 35 disease transmission maps were produced by extracting the maximum concentration values calculated during the simulation period for all model grid points. Two examples of the resulting disease transmission map for production site number 9 is shown in Figure 9, and disease transmission map for production site number 25 is shown in Gig. 10. Similar maps can be produced for simulation results of applying decay rates of 0, 0.1 and 0.25 per day. These are not included. Instead we refer to the similarity index calculations below.

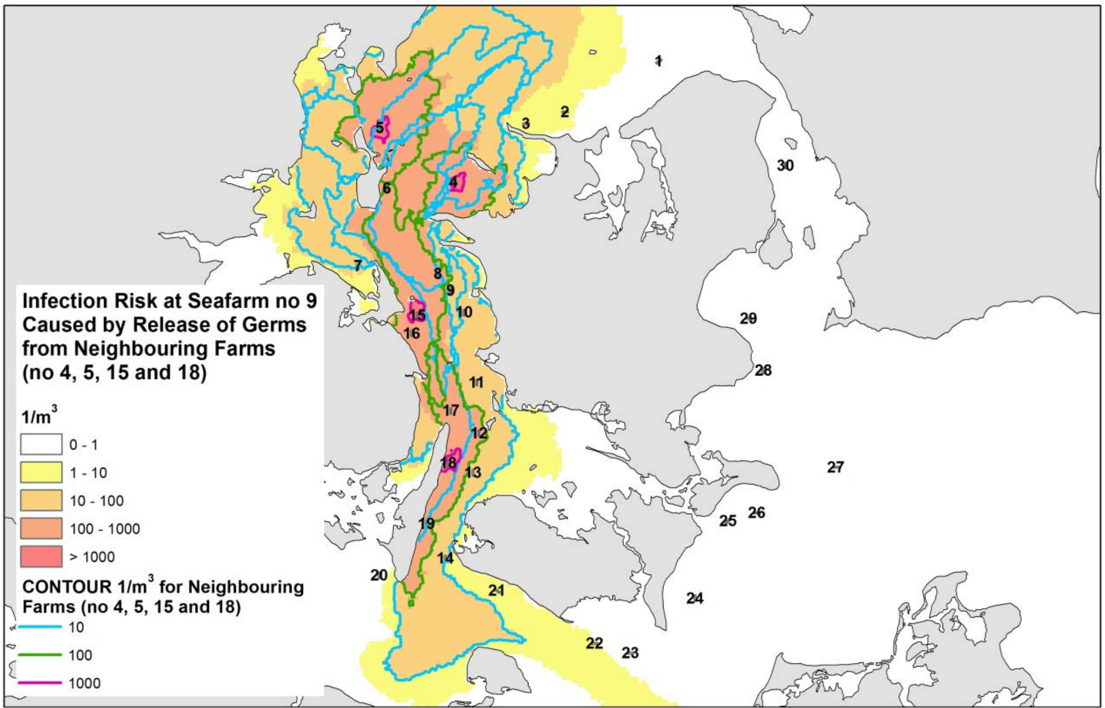


Figure 9. Disease transmission map for production site no. 9. Source was strength 10^6 units per second from farms neighbouring farm no. 9 (4, 5, 15, 18). First order decay constant of 0.5 per day. Yellow-red colour legend indicates simulated Maximum concentrations registered during the 3 month simulation period June – August 2005 in the upper part of the water column. Blue colours indicate depth curves of 10, 15 and 20 meters. Grey area represents land territories.

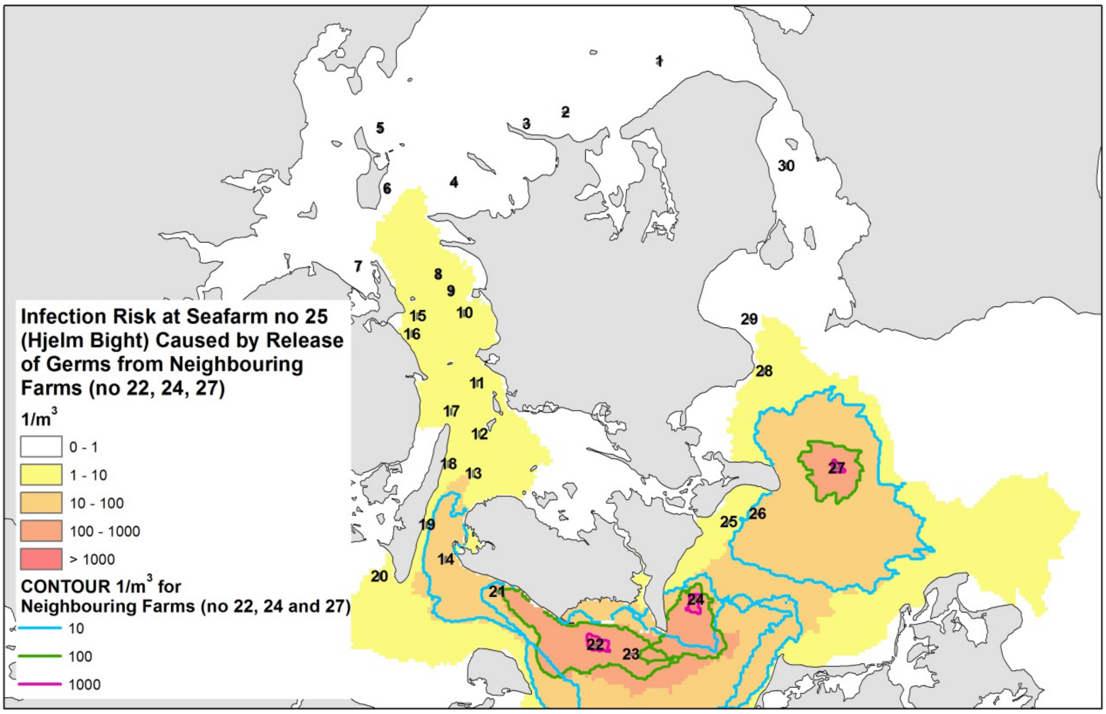


Figure 10. Disease transmission map for production site no. 25. Source was strength 10^6 units per second from farms neighbouring farm no. 25 (27, 24, 22). First order decay constant of 0.5 per day. Yellow-red colour legend indicates simulated Maximum concentrations registered during the 3 month simulation period June – August 2005 in the upper part of the water column. Blue colours indicate depth curves of 10, 15 and 20 meters. Grey area represents land territories.

In order to identify the production sites with the least likely disease transmission, or connectivity, a Bray-Curtis similarity index was calculated using Primer 6 (version 6.1.14) based on the 95 percentile concentration levels registered at each production site during the simulation period. Extracted data was compiled into an “abundance” matrix, one for each of the four scenarios. All data was square root transformed prior to calculating the Bray-Curtis similarity indices. Results are shown in terms of cluster diagrams in Figure 11 - 14.

Irrespective of decay rates of gems applied fish farms located around of Bornholm (#31 - #35) fell in a common group that differed majorly from all other farms. Another pattern was that with increasing decay rates similarities between farms decreased illustrating that decay rate of gems is very important for the hydrodynamic transmission of infections between farms. Similarity in of germ concentrations was high in neighbouring farms especially those located in the Great Belt (#8 to #19), see Fig. 10 and Fig. 15. Great Belt is an area with high current speeds (average 0.35 m/s) driven by the freshwater surplus in the Baltic Sea catchment area. Therefore, from a transmission risk perspective future farms should not be located closely in areas characterised by high current speeds.

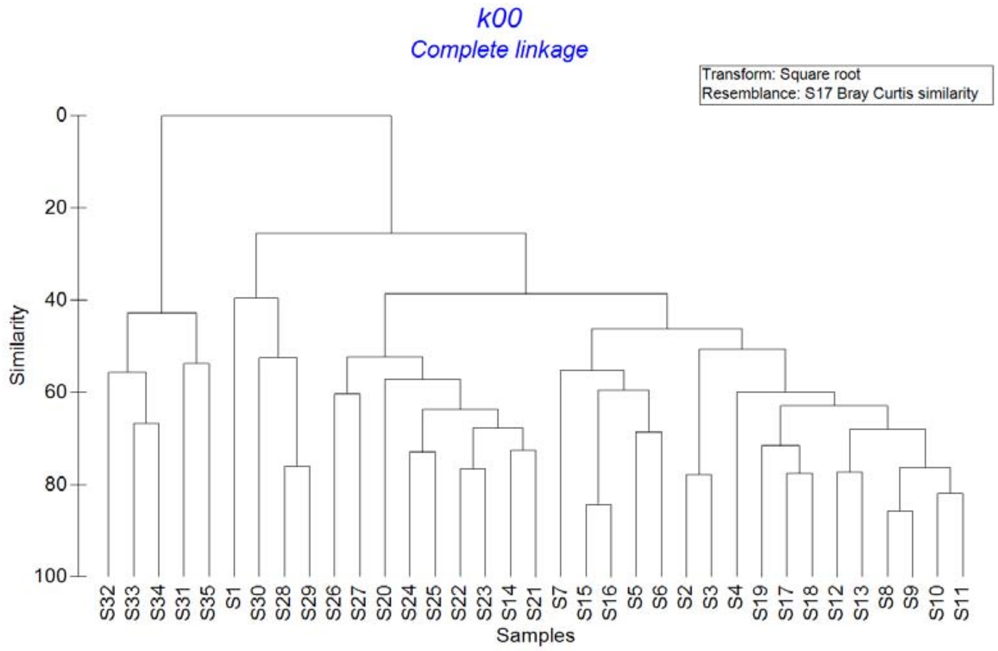


Figure 1. Cluster diagrams of Bray Curtis Similarity index calculated for the 95 percentile values registered at each production site location. The analysis has been done for the simulation results without decay of infecting agents.

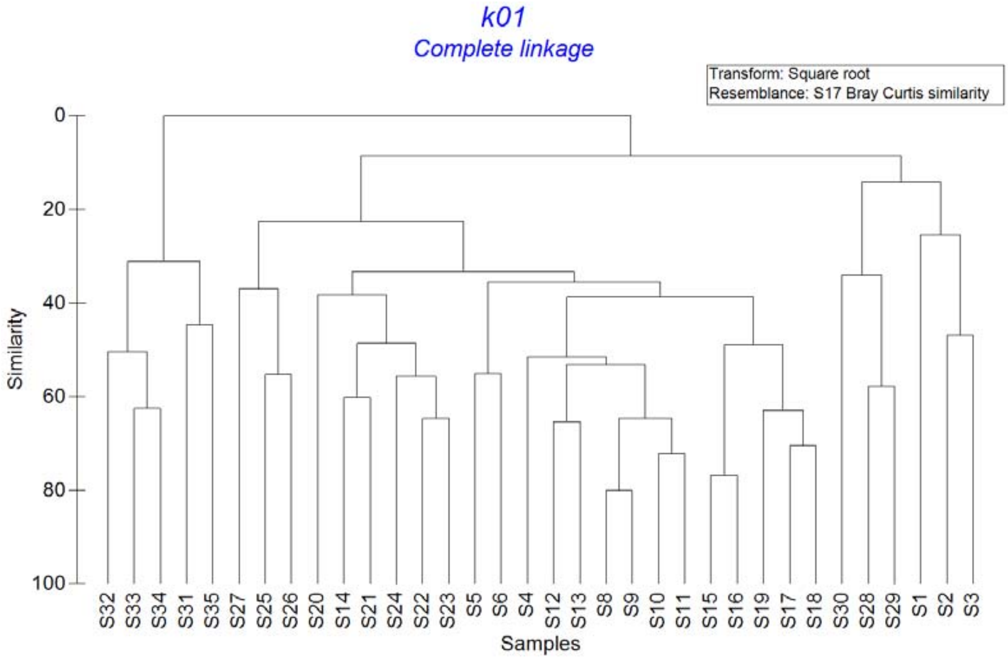


Figure 12. Cluster diagrams of Bray Curtis Similarity index calculated for the 95 percentile values registered at each production site location. The analysis has been done for the simulation results including a first order decay rate constant of 0.1/d.

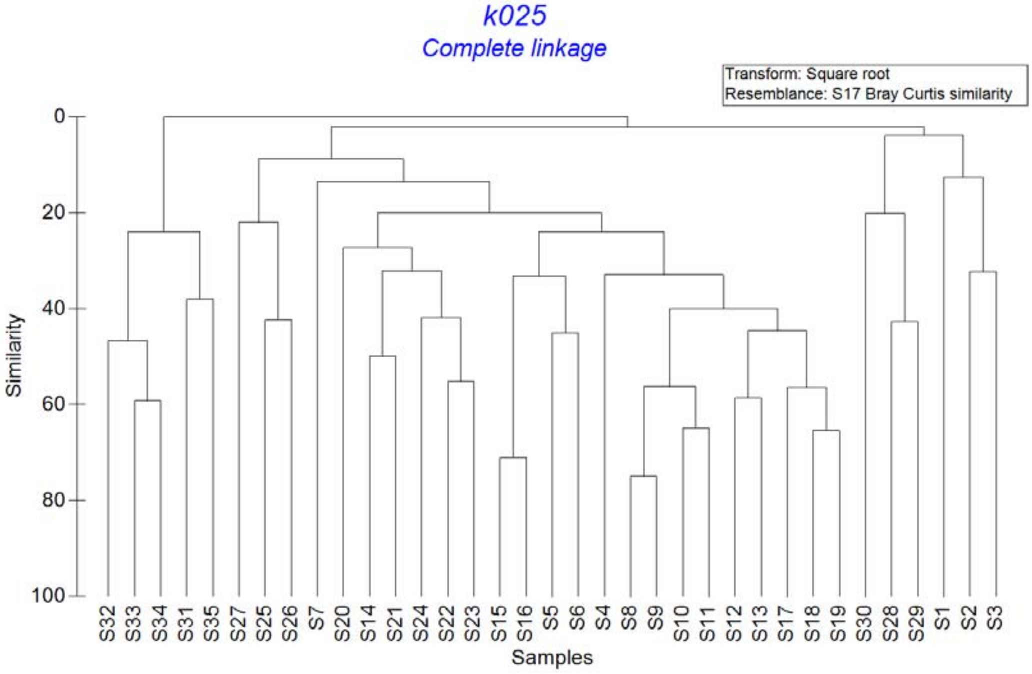


Figure 2. Cluster diagrams of Bray Curtis Similarity index calculated for the 95 percentile values registered at each production site location. The analysis has been done for the simulation results including a first order decay rate constant of 0.25/d.

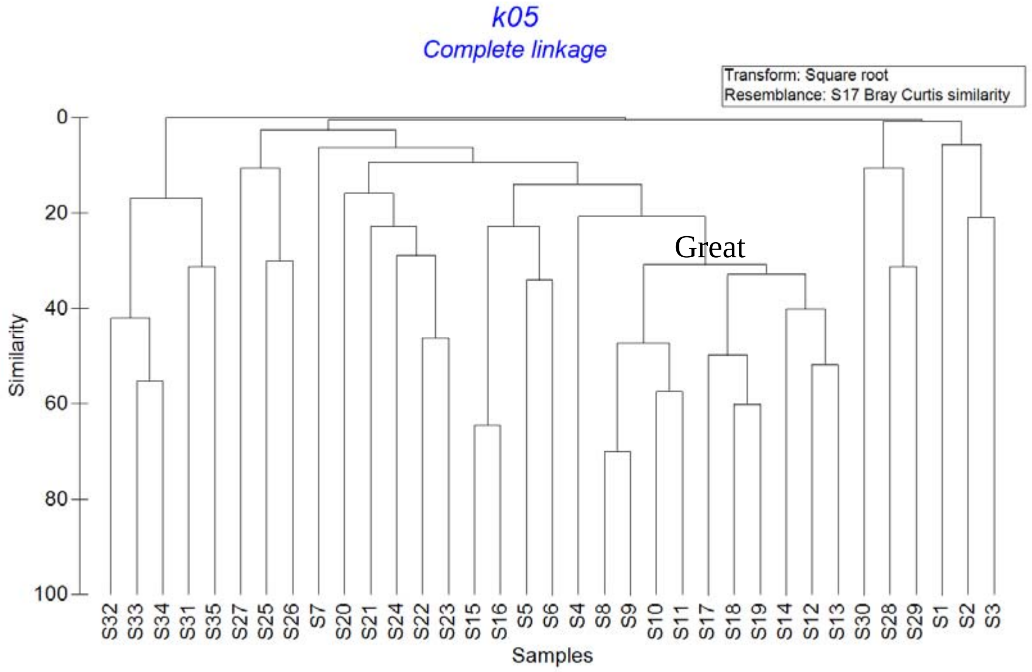


Figure 14. Cluster diagrams of Bray Curtis Similarity index calculated for the 95 percentile values registered at each production site location. The analysis has been done for the simulation results including a first order decay rate constant of 0.5/d.

2.2 Dilution analysis

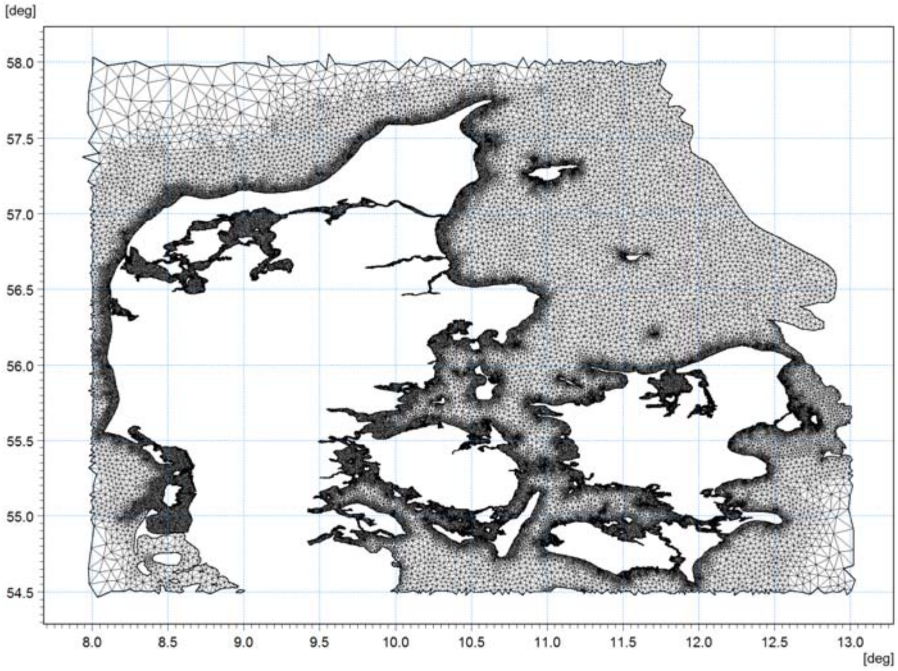
Medicine and biocides (e.g. copper) are used in finfish aquaculture to treat infected fish and as antifouling agents (copper) on nets. Depending on concentrations medicine and biocides may have direct toxic effects on aquatic plants and animals, and to that end measured or predicted environmental concentration of these substances outside fish farms are regulated according to water quality criteria such as the EU EQS values. As an initial screening approach current speeds and dilution rates calculated based on models can provide information on where to and not to plan future fish farms. Such information can be presented in GIS formats which allow integration with other information and thus be used in marine spatial planning process.

1.2.1 Method

Dilution rates in Inner Danish Waters, Western Baltic Sea and in the coastal waters of Skagerrak and the North Sea was quantified using a calibrated 2-dimensional hydrodynamic model (MIKE 21 HD) set-up for the purpose and characterised by fine resolution (50x 50 m) in shallow waters (less than 20 m depth) gradually increasing to 1000 x 1000 m in the deeper parts of the model area (Fig. 15). Being 2-dimensional the model averages current speed over depth. Hence, at larger depth (i.e. > 20 m) current speeds in surface waters will be underestimated as speed will be lower and the current direction often opposite in the saline bottom waters compared to surface waters.

The model was executed for the year 2005 and forced by meteorology, run-off, and water level, salinity and temperature at the boundaries. The model provided water level, current speed and direction in every model cell (Fig. 15).

For every model cell and at every stored time step (1 h) dilution rate was estimated as a near-field study by adding a tracer in fixed concentration and calculate tracer concentration 1000 m downstream of the release point (i.e. the fish farm) assuming default values of momentum dispersion coefficients. In order to take account of the underestimated currents speeds at larger depths we assumed that tracer concentration in surface waters (0-10 m) was representative of the real dilution. Yearly values of dilution were subsequently calculated for each model cell as medians.



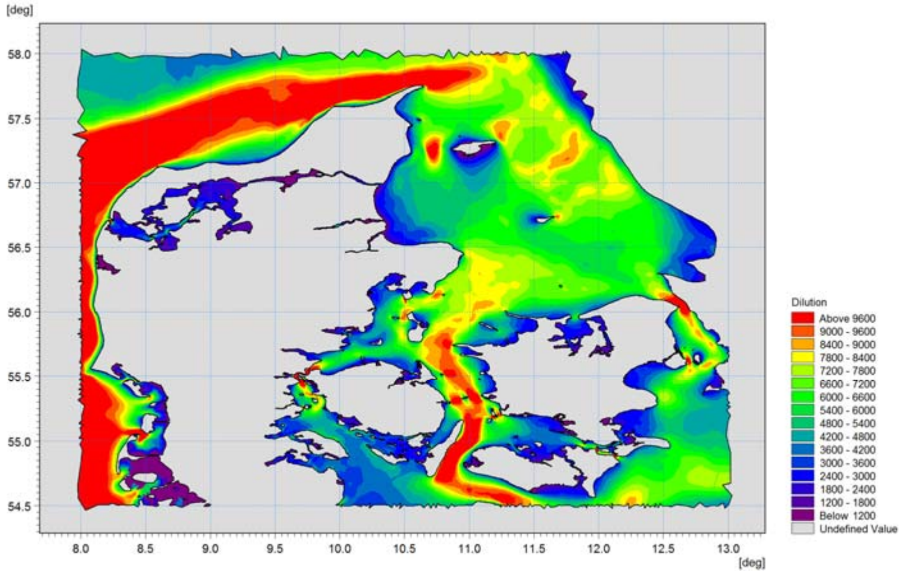
Figur 16. Modelområde samt horisontal opløsning af hydrodynamisk model anvendt til at beregne fortyndingsforhold i indre farvande samt de kystnære dele af Nordsøen og Skagerrak

2.3 Results and discussion

In the model area the dilution rate varied between 1.000 to 10.000 with the highest rates in Femernbelt, the Great Belt, in the North Sea and the coastal parts of the Skagerrak (Fig. 16). The lowest dilution rates was found in shallow bays (Det sydfynske Øhav, Smålandsfarvandet, Køge Bugt, Fakse Bugt, Århus Bugt, Hevring Bugt og Ålborg Bugt), in fjords and in the Southern Little Belt.

Intuitively, all other things being equal fish farmers would select production areas where current speed is rather high and consistent to avoid periods of stagnant waters and increased risks for high temperatures and low oxygen in cages. In accordance, the newest and largest fish farm in Danish waters is located in the Great Belt where current speeds are high.

Preliminary studies based on comparison between dilution map (Fig. 16), disease transmission maps (Figs. 9 and 10), and detailed fate modelling of medicines and copper released from fish farms with a production capacity of 3.000 tons suggest that areas with dilution rates between 2.500 and 6.000 probably is a good compromise not exceeding EQS for medicines and copper 50 m outside the farm area and without challenging the risk for infection transported with currents from nearby farms.



Figur 16.
Dilution rate in surface waters (0-10 m) in inner Danish waters and the coastal parts of the North Sea and Skagerrak.

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