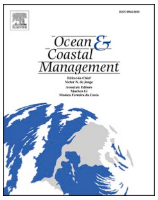
Ocean and Coastal Management 213 (2021) 105849

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman



Improvement of aquaculture management practice by integration of hydrodynamic modelling

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ARTICLE INFO

Keywords:
Aquaculture
Coastal management
Contingency plan
Hydrodynamics
Numerical modelling

ABSTRACT

Aquaculture has grown to become an important export industry in Norway. The Norwegian Food Safety Authorithy (NFSA) is responsible for the management of the production zones designated to aquaculture. Fish diseases and fish parasites are among the main threats to the aquaculture industry. It is therefore of great interest to minimize the risk of fish disease agent transmission. To date, the NFSA has assigned specific subzone divisions for aquaculture installations without assessing the effects of water contact for larger areas. Transmission of infection by water contact is believed to predominate the dispersal of important fish pathogens such as salmon pancreas disease virus (SPDV), infectious salmon anaemia (ISA) virus, *Aeromonas salmonicida* bacterias (held efficiently under control now by effective vaccines and not a major problem), and salmon lice.

In this article we present a three-dimensional hydrodynamic model system (AquaStrøm) which gives detailed information about a network of 48 fish farm sites with varying degrees of mutual water contact in a Norwegian fjord area (the Nordfjord). By adding information on winds and currents, a better understanding of the mechanisms for the risk of transmission of fish disease agent between fish farms is gained. The risk of infection can be assessed in much more detail, and the production zones can be designed and optimized based on the level of water contact between various clusters of fish farms. Key sites which connect clusters of fish farms and hence increase the areas of mutual water contact can be identified.

1. Introduction

Most sitings for aquaculture, like other use of marine space, have been undertaken on an ad hoc basis for a single farm or collection of farms without integrated or broader strategic planning (Gentry et al., 2017). However, there is an increasing emphasis on the need for proactive planning and zoning for mariculture in locations across the globe. A growing number of national and regional authorities are beginning to engage in aquaculture planning processes or wider marine spatial planning processes that involve aquaculture, highlighting the need for more comprehensive scientific guidance (Amundrud and Murray 2009; Buschmann et al., 2009; Salama and Rabe 2013; Gentry et al., 2017; Groner et al., 2018).

Marine salmon farming in Norway is one of the most industrialized fish farming enterprises in the world (Bostock et al., 2010; Jansen et al., 2012) producing close to 1.24 million tons of Atlantic salmon (*Salmo salar* L) in 2016. In order to reduce the occurrence of disease episodes in aquaculture, an expert committee for efficient and sustainable aquaculture management ("Gullestadutvalget", Anon. 2011) has suggested that the coastline (production area) should be divided into distinct areas/zones with minimal water contact to minimize the infection risk between them. However, this requires that several distinct subzones are available for each company allocated within a region for growing different generations of fish. In a two-year cycle there are generally four different generations in the sea: spring generation year 1 (Spring 1), autumn generation year 1 (Autumn 1), spring year 2 (Spring 2) and autumn year 2 (Autumn 2). Each generation usually has a cycle of about 21 months, with 2–3 months of fallowing before the start of a new cycle

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https://doi.org/10.1016/j.ocecoaman.2021.105849
Received 5 January 2020; Received in revised form 28 July 2021; Accepted 9 August 2021

at the same site. All four generations overlap in time over at least 4 months (Spring 1 and Autumn 2). This can lead to a continuous cycle of pathogen transmission from each generation to the next, in spite of that the fallowing in each site is successful in eradicating the pathogen, and even if the pathogen does not exist in broodfish. This is the case for salmon pancreas disease virus (SPDV), infectious salmon anaemia (ISA) virus and salmon lice.

1.1. Todays management practice

The authorities coordinate the aquaculture activity in the production areas and subzones by:

1. General licence for production at a location.
2. Yearly licence for production time in subzones

1. The authorities receive applications for an aqua farm license at a specific location. The location must have good water circulation, and a minimum distance to nearby fish farming sites of at least 3–5 km (3 km for small production locations, 5 km for bigger locations). Locations in transport areas for live slaugtherfish and nearby abattoirs for farmed fish must be avoided. The application contains information about the maximum peak production expected at that site. An approved licence does not allow production at any time.

2. Yearly licence for production in subzone: The fish farm must apply every year for the next 2-years production in a subzone. All the stakeholders' plans in a subzone must be coordinated for inset of smolt, production time, delicing and fallowing.

The “Gullestad” expert committee has suggested the Nordfjord area as a potential production region for consumption fish. Today, the Nordfjord region is divided into various production zones and subzones. Both the authorities and the industry demand improved knowledge about the risk of disease agent transmission between these zones by integrating hydrodynamic modelling such as the “AquaStrøm” concept (Viljugrein et al., 2009). In the AquaStrøm framework, a numerical ocean model is used to asess the risk of disease agent transmission between fish farming sites through a matrix showing the mutual degree of water contact between all pairs of sites (Viljugrein et al., 2009). This allows integrating more quantitative criteria regarding the risk of disease transmission than was available in the past.

2. Material and methods

2.1. Hydrodynamic modelling - the AquaStrøm concept

The AquaStrøm model system is a combination of hydrodynamical ocean modelling, using the Regional Ocean Modelling System (ROMS, Haidvogel et al., 2008) and calculation of mutual water contact between fish farm sites within an area (Viljugrein et al., 2009).

The Nordfjord ocean model, used in this application, is set up with a fine horizontal resolution of 160 m, and 20 vertical, terrain-following layers. The layer thickness is about 1 m near the surface, and between 1 and 8 m near the bottom (for water depths of 20 and 100 m respectively). The model simulates currents, sea level, salinity and temperature for each grid cell. In addition, the model calculates concentrations and drift of passive tracers, which are discharged substances with neutral buoyancy following the water currents. The Nordfjord model area is 3115 km^2. Within the area, there were 48 fish farm sites that farmed salmonids at some point in time during the study period (Fig. 1).

The model is spun up from rest, with horizontally homogeneous stratification, based on observations at five locations within the Nordfjord region, during the first part of 2010. The tides are the dominant driving forces for the circulation. The tidal forces are large in the Nordfjord area, with a difference in sea level elevation of up to 2 m. Tidal parameters are extracted and downscaled from the NorKyst800 model (Albretsen et al., 2011), which covers the entire Norwegian coast.

The stratification of the water column varies throughout the year. In an open fjord like the Nordfjord, salinity and temperature in the water column are mainly determined by the water masses on the coast and the freshwater discharge from rivers.

In the model setup the initial stratification is based on measurements from the first half of 2010 and a corresponding freshwater regime.

Fresh water discharges from rivers are provided by the Norwegian Water Resources and Energy Directorate (NVE). Information about

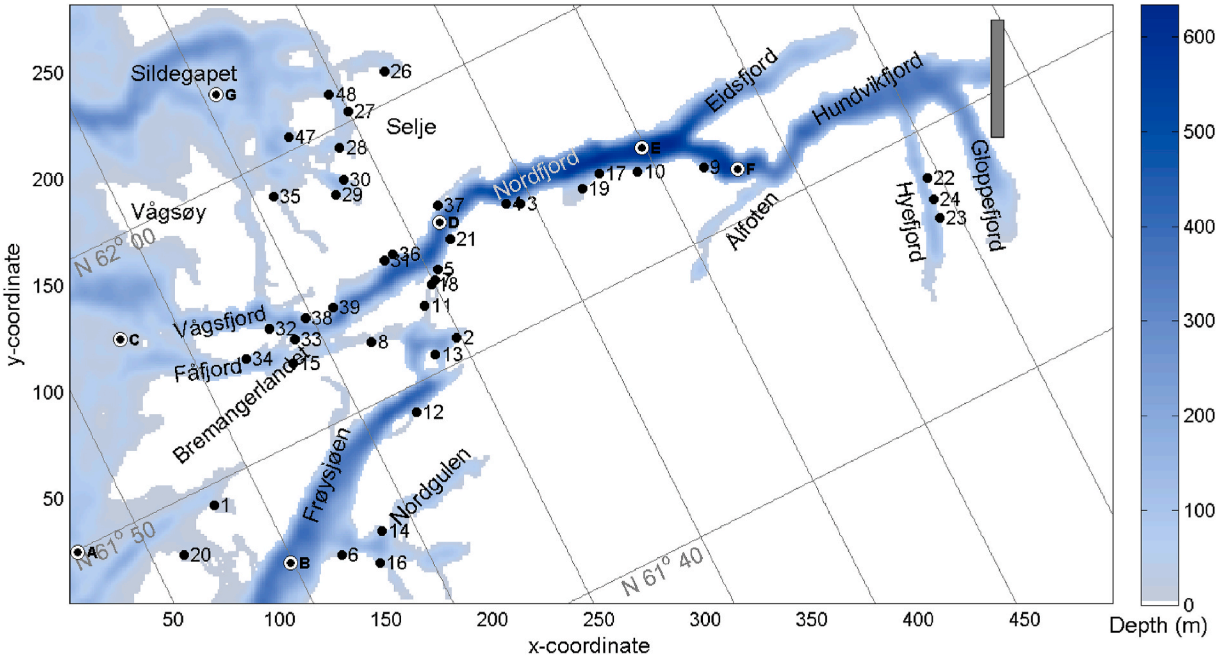


Fig. 1. Overview of the Nordfjord model region. Fish farming sites are indicated by numbered black dots. Additional test sites are indicated by white and black dots. The blue shadings represent the bathymetry variations. The gray bar indicates where the inner part of the fjord was cut off in order to reduce computation time. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

prevailing wind scenarioes in the area was obtained from the Norwegian Meteorological Institute's observation stations at Kråkenes (on the open coast) and Sandane Airport (further into the fjord). We ran simulations with three different wind scenarios, scenario (1) without wind, (2) with wind directed into the fjord, and (3) wind directed out of the fjord. For the scenarios with wind, the wind speed decreases gradually from the coast and into the fjord according to the measured mean wind speed at Kråkenes and Sandane Airport.

The model uses open boundary conditions along the southern, western, and northern boundaries. The open boundaries are forced with output (hydrography, currents, tides) from Norkyst800, a larger ROMS-model with 800 m horizontal resolution (Albretsen et al., 2011). Wind forcing is applied to the top layer in all grid cells in the model domain, while hydrography (temperature and salinity), currents and tides is specified along the open boundaries, from the sea surface to bottom.

2.2. Water contact network

A water contact parameter, WC, measuring the strength of water contact between farm sites is calculated for all marine farm sites in an area. The WC parameters are arranged in a matrix with source sites along the columns and receiving sites in the rows. This matrix is here termed a water contact network.

Three factors are crucial to describe the water contact between different sites. (1) How fast is the water moving from one site to another? (2) How much water moves from one site to another and (3) what degree of mixing is present before the contaminant reaches a site. In order to quantify these three factors, distinct passive tracers are released from each fish farming site in the model simulation, at time t0. The concentrations of these tracers are calculated at each fish farming site throughout the simulation period of 10 days. The dilution of the tracer reaches the order of 1000–10000 times. The concentration of the tracers is hence set to ml/l since the released tracer originally was l/l. The tracer concentration varies with time and can be extracted as a time series in any position in the model area.

An example of the calculated concentration at a receiving site is shown in Fig. 2. Water contact in the direction of a discharging site *j* to a receiving site *i* was estimated as:

$$WCij = 38 + 10\cdot\ln\left(\frac{T}{A}\right) \tag{1}$$

where WC_{ij} is relative water contact (no dimension), T is the response time (h) from discharge until the concentration of the discharged tracer exceeds the background level at the receiving site, and A is the integrated area under the concentration curve (Fig. 2). The analytical function (1) is constructed so that low values of response time (T) and high values for concentration (A) yields low values for the water contact parameter and indicate high degrees of water contact between sites. The logarithmic scale was used to improve the separation between sites where the water contact was low. The parameters are scaled such that water contact values are comparable to physical distances. The details on the development of this analytical model is found in Viljugrein et al., (2009).

On the coast, the tidal currents are often influenced by bathymetry, creating complicated flow patterns with eddies moving along the dominant currents. The highest current speeds are found in the narrow straits and shallow areas in the outer part of the Nordfjord system, as shown in Fig. 3. The water contact between two sites is usually not symmetrical. If strong currents are present, an aquaculture facility located upstream may infect a facility located downstream stronger than it infects itself. However, if two neighbouring facilities are located in an inlet where the current is mainly tidally forced, we could expect a more symmetrical water contact.

The tidal influence is significant in the modelled area. Observed tidally forced sea level variation near Måløy is around 160 cm. We have forced the model with tidal components representing strong (spring) tides. We initially made contact networks using current from different depth levels from the model. This resulted in some variations in the calculated number (0–100) for each contact but did not result in significant changes to the coarser contact levels shown with colour. We chose to use the surface current in our calculations since this gives the strongest contact between the fish farm locations and can be viewed as an upper limit of contact.

3. Results

3.1. Validation of current speed

The key parameters in the AquaStrøm model system are current speed and direction since these are essential for water contact calculations. To assess how well the model reproduce the current system, we compared modelled and observed current from a total of 103 measurement series from different depths and seasons, and from 48 different sites. We here matched the current meter instruments' depth with the

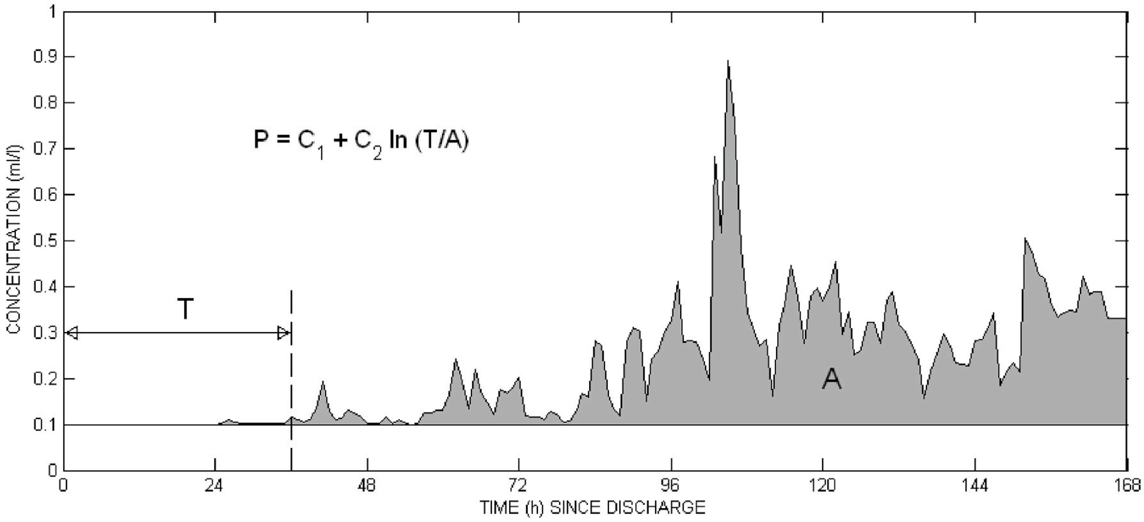


Fig. 2. Concentration of contaminants released from one site recorded at another site. T is the time from the contaminant is released until it first appears at the receiving site. A is the integrated area under the concentration curve. The figure shows concentrations through a period of 7 days but can be replaced by other period lengths. In this project we applied a period of 10 days.

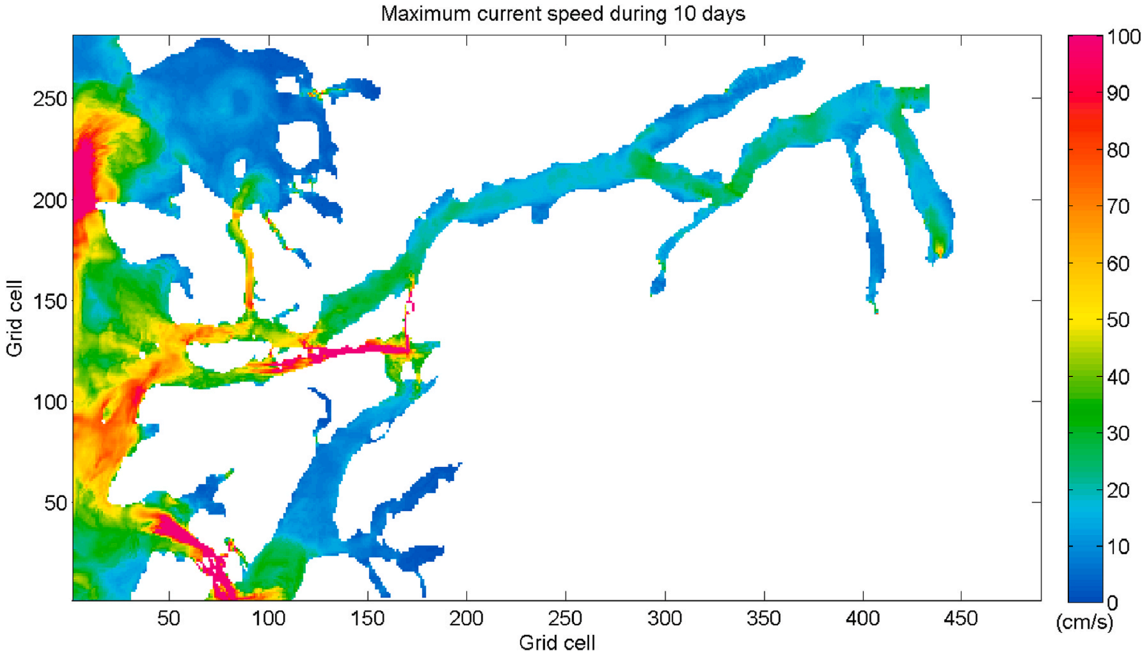
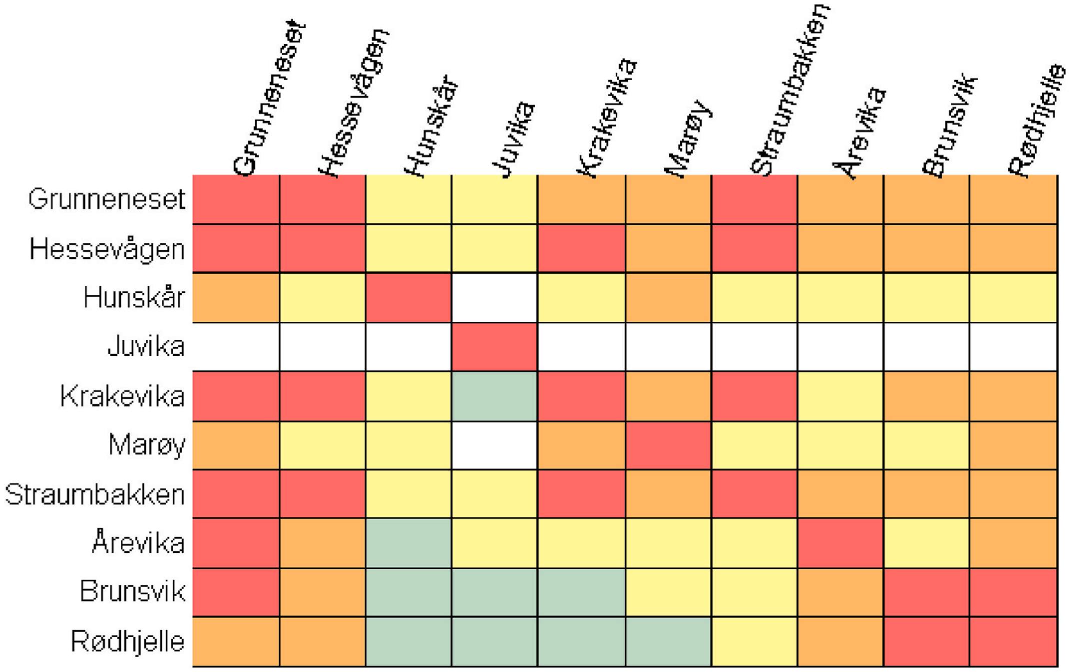


Fig. 3. Simulated maximum surface current speed during 10 days of simulations. The colour bar indicates the current speed with units cm/s. The highest current speeds are found in the narrow straits and shallow areas in the outer part of the fjord system. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

corresponding model depth bin for each instrument wich ensures the most accurate comparison.

Fig. 3 shows the maximum current speed near the surface throughout the model period (10 days). Characteristic current speeds are 10–40 cm/s. The strongest currents are found in the narrow and shallow straits around Bremangerlandet and northwest of Vågsøy (Vågsfjord), near the model boundary. The main tide is the main driver of the strong currents in these areas.

In addition to comparing the mean current speed and direction from the model and the *observations*, we have applied a more generalized comparison method yielding information about the accuracy of AquaStrøm. The method is based on the OSPAR cost function, where the parameter CF (normalized mean absolute error) is calculated from the formula (2) below (Los and Blaas, 2010):



	Grunneneset	Hessevågen	Hunskår	Juvika	Krakevika	Marøy	Straumbakken	Årevika	Brunsvik	Rødhjelle
Grunneneset	🟥	🟥	🟨	🟨	🟧	🟧	🟥	🟧	🟧	🟧
Hessevågen	🟥	🟥	🟨	🟨	🟥	🟧	🟥	🟧	🟧	🟧
Hunskår	🟧	🟨	🟥	⬜	🟨	🟧	🟨	🟨	🟨	🟨
Juvika	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜
Krakevika	🟥	🟥	🟨	🟩	🟥	🟧	🟥	🟨	🟧	🟧
Marøy	🟧	🟨	🟨	⬜	🟧	🟥	🟨	🟨	🟨	🟧
Straumbakken	🟥	🟥	🟨	🟨	🟥	🟧	🟥	🟧	🟧	🟧
Årevika	🟥	🟧	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟧
Brunsvik	🟥	🟧	🟩	🟩	🟩	🟨	🟨	🟧	🟥	🟥
Rødhjelle	🟧	🟧	🟩	🟩	🟩	🟩	🟨	🟧	🟥	🟥

Fig. 4. Water contact network for a selection of farming sites in Nordfjord. The red colour indicates very high degree of contact and white colour indicates little or no contact. See Table 1 for further descriptions of the colour codes. In addition to the colours, a water contact parameter (P-value) ranging from 0 to 100 was calculated. For simplicity, the P-value is not shown in the contact network. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$CF = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|\overline{x}_{iMod} - \overline{x}_{iObs}\right|}{\sigma_{x_{iobs}}}, \tag{2}$$

where N is number of measurement points for comparison, $\overline{x}_{iMod}$ is mean current speed calculated by the model, $\overline{x}_{iObs}$ is mean current speed from the *in situ* measurements and $\sigma_{x_{iobs}}$ is the standard deviation of the current speeds measured at the sites.

Models are classified according to the following criteria: $CF < 1 =$ very good, $1 < CF < 2 =$ good, $2 < CF < 3 =$ satisfying, and $CF > 3 =$ poor. For the Nordfjord model we get $CF = 1.98$ if all the measurements are considered and $CF = 1.38$ if only the results from measurements deeper than 5 m are included. Both approaches result in the classification ‘good’.

3.2. *Water contact network*

The mutual water contact network for 10 farming sites in Nordfjord is shown in Fig. 4. We initially made four contact networks for each wind scenario using current from different depth levels from the model (surface, 5m, 10 m, and depth mean over 0–20m). This resulted in some variations in the calculated P-number (0–100) for each contact but did not result in significant changes to the five main categories (described by the color code). In the network presented in Fig. 4, we use the minimum P-value (worst case scenario) from each pair of fish farms based on these four networks. This gives an upper limit of contact. The figure illustrates the water contact from the source sites (columns) to the receiving sites (rows). The intensity of the water contact is colour coded, based on Table 1, with e.g. high water contact represented by red, and little or no water contact represented by white. The water contact network is useful to identify which fish farming sites have the potential of affecting other sites most strongly. Grunneneset, Hessevågen, Kråkevika and Straumbakken (columns) all have very high water contact (red) with three or more fish farms (rows). We can also identify the fish farming sites that have the lowest infection risk. Juvika (row), for instance is only affected by itself, although Juvika as a source (column) has moderate water contact (yellow) with four other sites.

The water contact can also be visualized as water contact maps. Figs. 5–7 show examples of water contact maps from three different source sites and with two different wind scenarios; wind directed into the fjord, and wind directed out of the fjord.

The wind direction is critical in the determination of the infection risk towards the inner and outer fjord. Fig. 5 shows how the direction of the wind results in quite different water contact areas for release of tracers at Juvika, located in the central part of the fjord. When the wind is directed into the fjord, only two sites west of Juvika have moderate water contact, or higher. When the wind is directed out of the fjord, the area with moderate water contact (yellow colour) reaches the outer islands, and covers a large number of fish farm sites.

Moving over to a source at Sandvikneset (Fig. 6), located in the outer, northwestern region of the model domain, the water contact is limited to the closest fish farm sites in both wind-scenarios. When the wind is directed into the fjord, the water contact is highest with the fish farming sites north of Sandvikneset, while the fish farming sites southwest of Sandvikneset experience the highest water contact when the wind is directed out of the fjord.

At fish farms in the straits north and east of the Nordfjord, the variability due to wind direction is of less importance. At site Marøy (Fig. 7), for example, the dispersion pattern is approximately the same for both wind scenarioes. However, the current speed near Marøy is very high (see Fig. 3), and the area with high water contact with Marøy is very large. This illustrates that not only the wind direction, but also the mean current speed is of importance for deciding on the area with high water contact with a given source site.

3.3. *Zone classification based on the water contact network*

The water contact network indicates which sites are in contact, the degree of contact between the sites, and whether or not the water contact between two sites is mutual. This information could be useful to design production zones. By taking into account the water contact between fish farming sites, we can minimize the cross-zone infection risk. As an example, the site Hessevågen (Fig. 4) has strong water contact with the sites Grunneneset and Straumbakken ($P < 20$; red code). Both Grunneneset and Straumbakken have strong water contact with Årevika. By adding new sites that are in contact with one ore more of the already listed sites, we can construct groups of fish farming sites wthat are in contact with each other, either as primary contacts, secondary contacts or via other fish farms. These groups form zones or clusters of fish farms with internal water contact (Fig. 8).

In this example, Rødhjelle should be included in the production zone with Hessevågen since there is substantial water contact between Rødhjelle and the site Brunsvik, which is already in the zone with Hessevågen.

Production zones based on different wind scenarios, and including different degrees of water contact (WC-level), are given in Fig. 9. Only active farming sites, or sites planned to be operational are included. By applying the water contact parameter $WC < 20$ (red colour), the resulting zones resembles in some way the production zones applied by the authorities today. The model gives 13 separate zones based on $p <$

Table 1
Classification of water contact.

Color and *P*-value	**Description**
⬜ 80-100	Little or no water contact
🟩 60-80	Some water contact
🟨 40-60	Moderate water contact
🟧 20-40	High water contact
🟥 1-20	Very high water contact

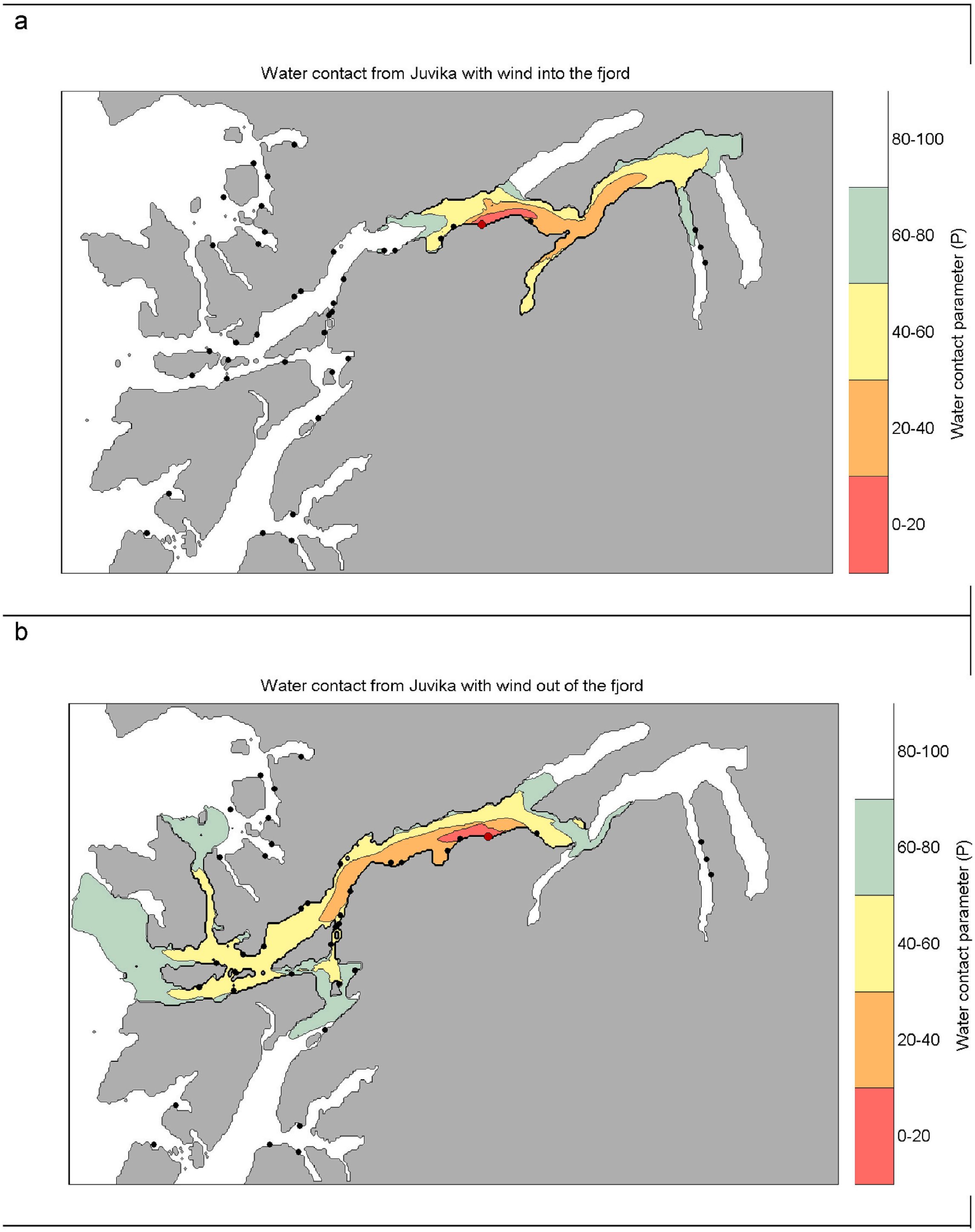


Fig. 5. Water contact areas from site Juvika (red dot) calculated from the surface layer with wind (1.5–5 m/s) (a) into the fjord and (b) out of the fjord. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

20 WC (no wind), whereas the authorities and the aquaculture companies today uses 7 separate zones (Fig. 9).

These zones (based on WC < 20) are particularly relevant with regard to SPDV, which is highly contagious over a period of a few days (half life of around 3–5 days at 15 °C) (Graham et al., 2007). The efficiency of infection falls rapidly with dilution and time. Viruses, especially coated viruses like the ISA virus, are easily damaged in the natural environment outside the fish, but it seems that the SPDV can survive for longer periods, at least at low sea temperatures. The half life of SPDV increases to 8–13 days at 10 °C and 10–25 days at 4 °C and has been found to be quite consistent among SPDV subtypes (Graham et al., 2007). The distances, over which horizontal transmission by sea currents may occur, seem to be shorter for ISA compared to pancreas disease (PD) (Aldrin et al., 2010).

When the water contact parameter is increased to WC < 40 (red and orange colour), the zones become fewer and larger. If the contact parameter up to WC < 40 is chosen, the three southernmost farming sites are isolated from other farms in all scenarios (Fig. 9). Farming sites in eastern part of the Nordfjord are in contact with each other regardless of wind scenario.

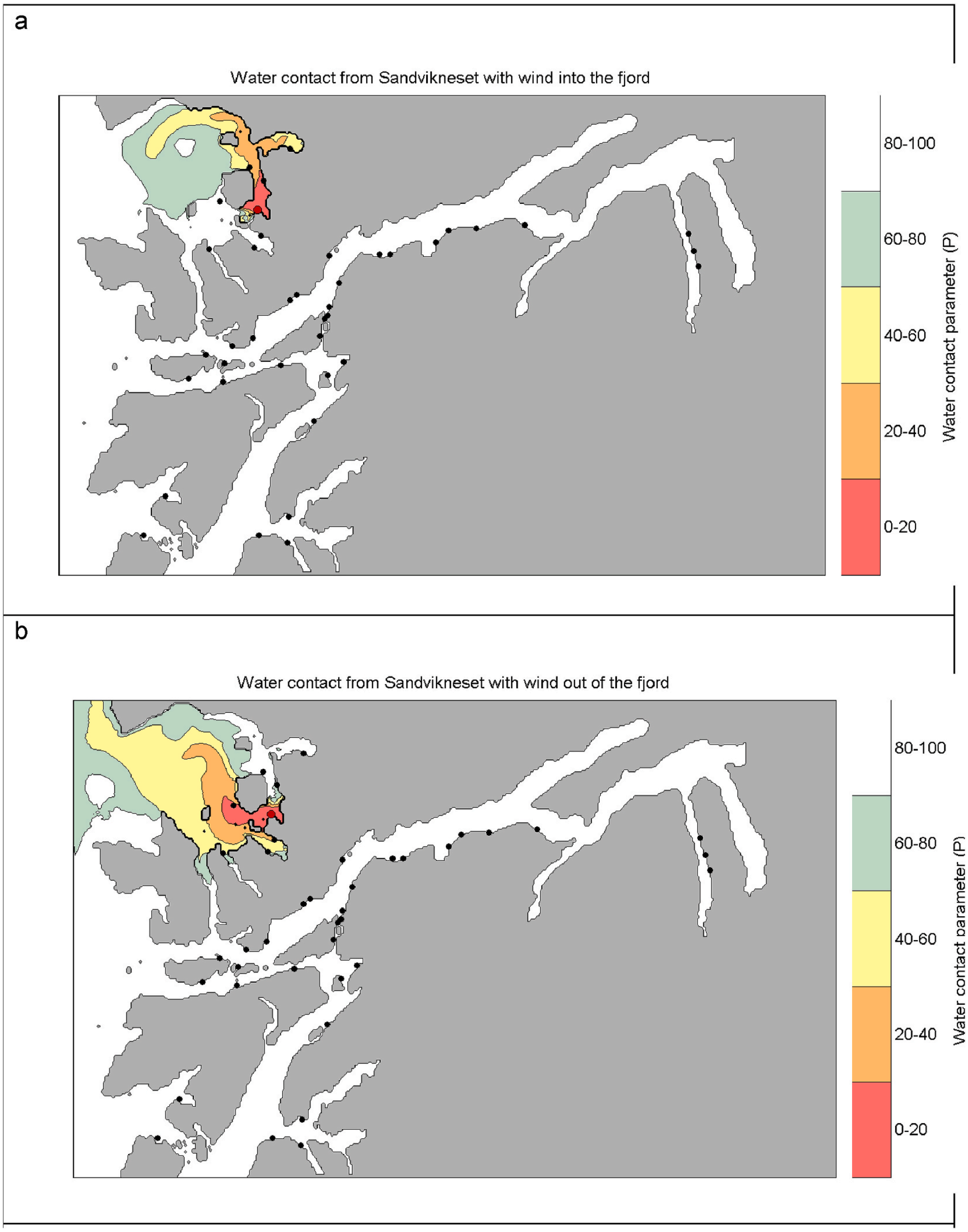


Fig. 6. Water contact areas from site Sandvikneset (red dot) calculated from the surface layer with wind (1.5–5 m/s) (a) into the fjord and (b) out of the fjord. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

4.1. Assessment of the current model and the water contact network

The AquaStrøm model system "fills the gaps" between single observation points, and provides a unique overview of the circulation pattern, and the relevant dynamics, over a larger coastal area. However, the Aquastøm model is not an alternative to traditional observations. Observations are important, both for providing realistic input to the model, and to assess the quality of the model and how well the model represents the flow regimes in different parts of the model area.

The modelled currents agree well with most of the observations. However, the horizontal resolution of 160 m leads to some discrepencies in narrow straits and bays, such as in Vågsfjord. Here, the model overestimates the current, causing faster spreading of contaminants, but also more intense mixing and dilution of the contaminant. In other areas close to the shore, sub-grid scale topographic features (features smaller than 160 m) also causes discrepencies between the model and the observations.

We have shown that wind direction is important for the water contact in the inner part of the fjord. Wind into the fjord enhances spreading of contaminants far into the fjord, while wind out of the fjord greatly limits such behaviour. In the outer coastal area the wind influence is of limited importance due to stronger tidal currents. The wind scenarios applied here are greatly idealized. We run the model for 10 days, applying a constant wind forcing directed either into the fjord, or out of

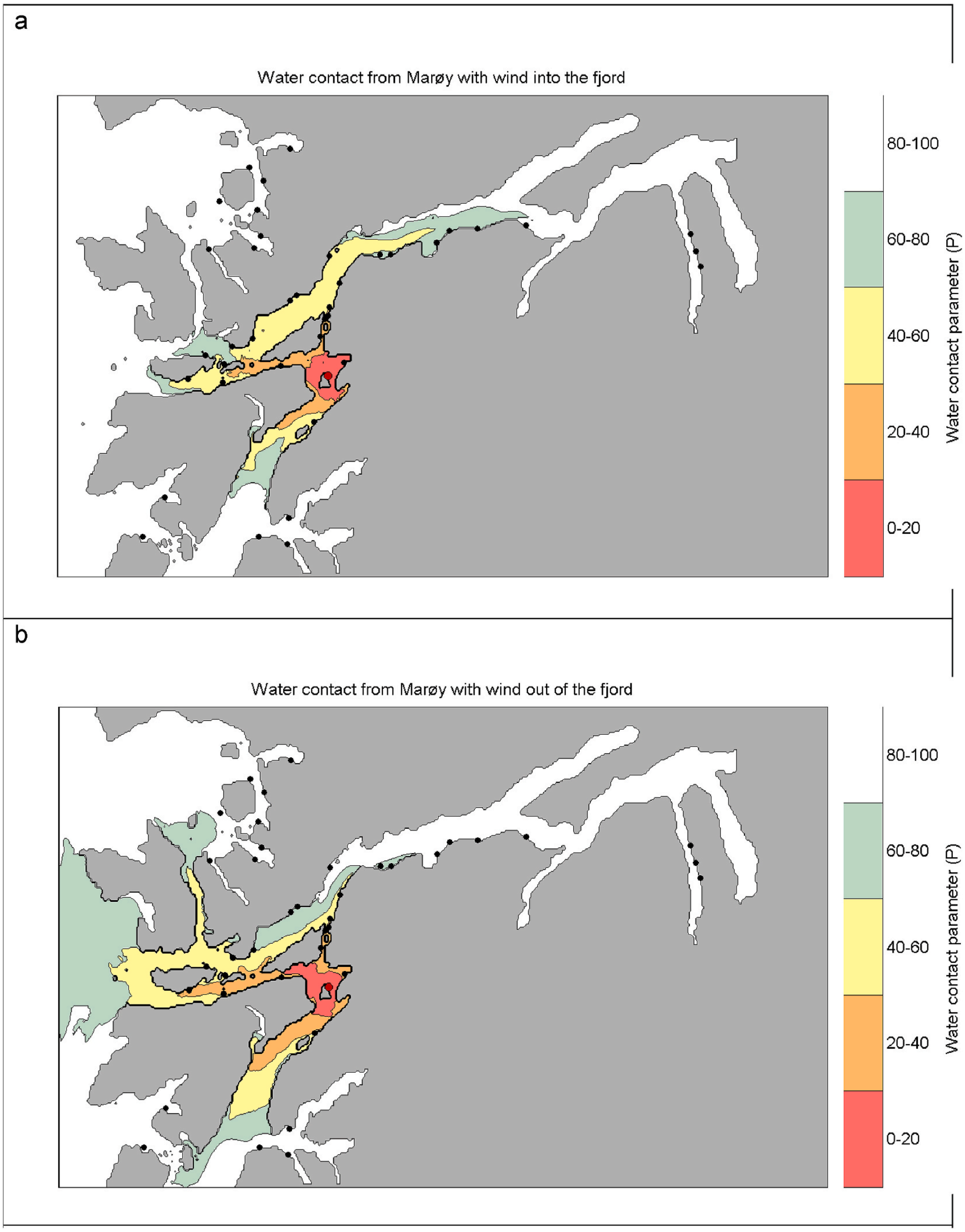


Fig. 7. Water contact areas from site Marøy (red dot) calculated from the surface layer with wind (1.5–5 m/s) (a) into the fjord and (b) out of the fjord. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the fjord. In the real world, the wind pattern would differ in both direction and speed over a 10 day period. However, we have chosen to use these idealized wind pattern to learn something about the effect of the wind direction, although other scenarios with more variation in wind and weather conditions can be added in later versions.

In the inner part of the fjord, where the water contact is strongly affected by the wind direction, our simulations could be thought to illustrate a "worst case" scenario. With a varying wind direction, the fish disease agent would not be transmitted as strongly in one direction, and the extent of the spreading could be less. However, if an infection breaks out at a fish farming site, the authorities could use the water contact network, combined with the prevailing wind direction at the time of the outbreak to give an early warning for neighbouring fish farming sites at risk.

Seasonality is important also because pathogen survival will vary according to seasonal changes in temperature, salinity etc (e.g. Graham et al., 2007; Jansen et al., 2012). When conditions for virus survival are good, viable virus particles may be spread for much longer distances than usual. Hence, the efficiency of subzones as barriers for disease transmission may vary according to season.

4.2. *Improvement of management practice*

It was demonstrated that unexpected current patterns caused infections in unexpected directions. At the site Krabbestig, for example, *in situ* current measurements at one sample station on the site indicated

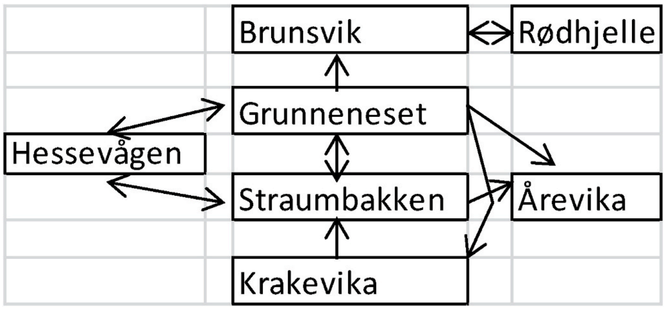


Fig. 8. Example of a group with water contact starting from Hessevågen, when the criteria P < 20 is used. Grunneneset and Straumbakken are directly affected by Hessevågen, while Brunsvik, Rødhjelle, Krakevika and Årevika ar indirectly affected.

that the westerly currents are present 90 % of the time. This measurement, which suggests little contamination to neighbouring fish farms, was used by the NFSA as basis for the approval for the expansion of the local fish farm. The AquaStrøm model, however, demonstrates that the current strongly follow the tidal movements and flushes both east and west in the area. Hence, the site can affect farms in the fjord more than was expected from the results of the point measurement. We also demonstrate that two sites, Kleppeneset and Lindeneset (number 23 and 24 according to Fig. 1) (owned by the same company), experienced a very large mutual water contact regardless of the wind scenario. This entails that generation separation and fallowing will be of no effect if it is only performed in one of the sites. Therefore, the company should acquire at least one new site outside the infection risk zone.

A production area with four subzones can be an area of a continuously going epidemic with a few cases of different causes scattered around):

1. Direct spreading by water contact: Pathogens which do not exist in the broodfish when set to sea are transmitted between the subzones (and 4 different generations) in the sone by water contact and streams. As the pathogens are always present in one or more of the subszones, the epidemic is never eradicated. This is the theme of this paper, and this is also regarded as the main pathway of transmission of SPDV and ISA virus, Aereomonas salmonicida and salmon lice.
2. Indirect spreading by slaughter fish transport and equipment: Pathogens are also spread by input from other infected production areas (which can be far away) and subzones by direct transmission into the zone by transport of infected fish to slaughter through the zone, not disinfected used equipment and well-boats, and also by infected broodfish in some cases. In that case the scenario in 1) also gets a new starting point that enhances the cycle of disease. These "hit-and-run" inputs of pathogens from the outside also makes epidemiology a difficult task, since their source is difficult to trace, and make assessment of biosecurity inside the zones itself difficult, by masking effects of zones and fallowing procedures. The NFSA are therefore planning stronger measures and legislations for the transport of both slaughterfish and broodfish.
3. General biological security: A production area including subzones should not be infected directly by water contact from the neighbourhood macro production area with ISA virus or SPDV-subtypes. Transmission of salmon lice and Aereomonas salmonicida may still be possible but minimized. Since we now have effective vaccines against Aeromonas salmonicidae, the main unsolvable pathogen is salmon lice, which also spreads between the macro production areas, not only between subzones. But the efficiency of spreading can probably be ten times higher between subzones, and even higher between locations inside subzones. Therefore, disease-control strategies are expected to be more effective if they are applied in collaborations with neighbours (Murray and Peeler 2005). Theoretical simulation studies have shown that concentration of production into separate areas with synchronized fallowing slows the spread of simulated disease, particularly where long-distance transmission of the pathogen is weak compared to local transmission (Green 2010; Werkman et al., 2011). If transmission rate between subzones (and generations) are lower compared to transmission rate among farm sites within a subzone, an infection will have reduced transmission rate of ISA, PD, salmon lice and Aeromonas salmonicidae compared to a corresponding production area not organized into subzones. By adapting to this, an epidemic could be stopped or delayed in time and not infect every farm or subzone with highly pathogen viruses, even if the pathogen exists all the time in the production area.

Regarding safety distances between fish farms 3–5 km: Security depends on water contact and not on the distance. Longer distances can be unsafe and shorter distances can be safe. This depends on direction, amount and speed of water containing pathogens, in addition to survival rate of the pathogens. A space-time transmission model of sea lice in Norwegian aquaculture showed that the influence of infection pressure was relatively much higher within a sea distance of about 20 km from the aquaculture site than outside (Aldrin et al., 2013). Guarrcino et al., (2018) used a regression analysis to evaluate the effectiveness of coordinated fallowing on the progression of external salmon lice infestation pressure and abundance in Atlantic salmon farming sites in 2 areas (zones) in Norway. The overall results show that external infestation pressure was higher inside than outside the management zones, and the external infestation pressure increased with increasing biomass throughout the production cycle. However, within the zones, the external infestation pressure at the beginning of a production cycle was high and, in many cases, even higher than the general external infestation pressure in the non-coordinated areas. This indicates that the farms/sites in each zone in the Guarracino et al., (2018) study were not sufficiently functional separated regarding water contact sutiable for handling the biology and dispersal potential for salmon lice and therefore the wanted effect of fallowing were not achived. The examples from sites Krabbestig and Rødhjelle in this paper illustrate that both the strengths and weaknesses of the different zones must be evaluated. The hydrodynamics play a fundamental role and must be considered in addition to sea distance to form a more functional site structure. Further, Salama & Murray (2011) demonstrated that as farm size increases in areas where faster currents prevail, there is a need to increase the separation distance between farms to prevent pathogen transmission.

The AquaStrøm framework may provide a very useful tool for evaluating various production and treatment strategies with respect to salmon lice infections. The model output; current direction, temperature and salinity provide the environmental information, while data on salmon lice developmental rates and survival under various environmental conditions will provide the biological input needed to estimate the effects of various production and treatment strategies on a local and regional scale (Groner et al., 2018; Guarracino et al., 2018; Myksvoll et al., 2018; Skarðhamar et al., 2018).

One important contribution from this study is the tabulation of relative water contacts between farm sites in the study area (Fig. 4). This water contact network is potentially useful in risk assessments aimed at controlling and preventing disease emergencies (Murray 2008; Stene et al., 2013). For example, it may be used by the operators of the farm sites as a basis for developing an early warning system with respect to infectious diseases in the area. An operator of a given farm site should then pay special attention to upstream farm sites with respect to water contact. Obviously, such a system applies only to infections that transmit by passive drift in the water current, such as suggested for the viral diseases ISA (Murray et al., 2005; Gustafson et al., 2007) and PD (Viljugrein et al., 2009; Stene et al., 2015; Jansen et al., 2017).

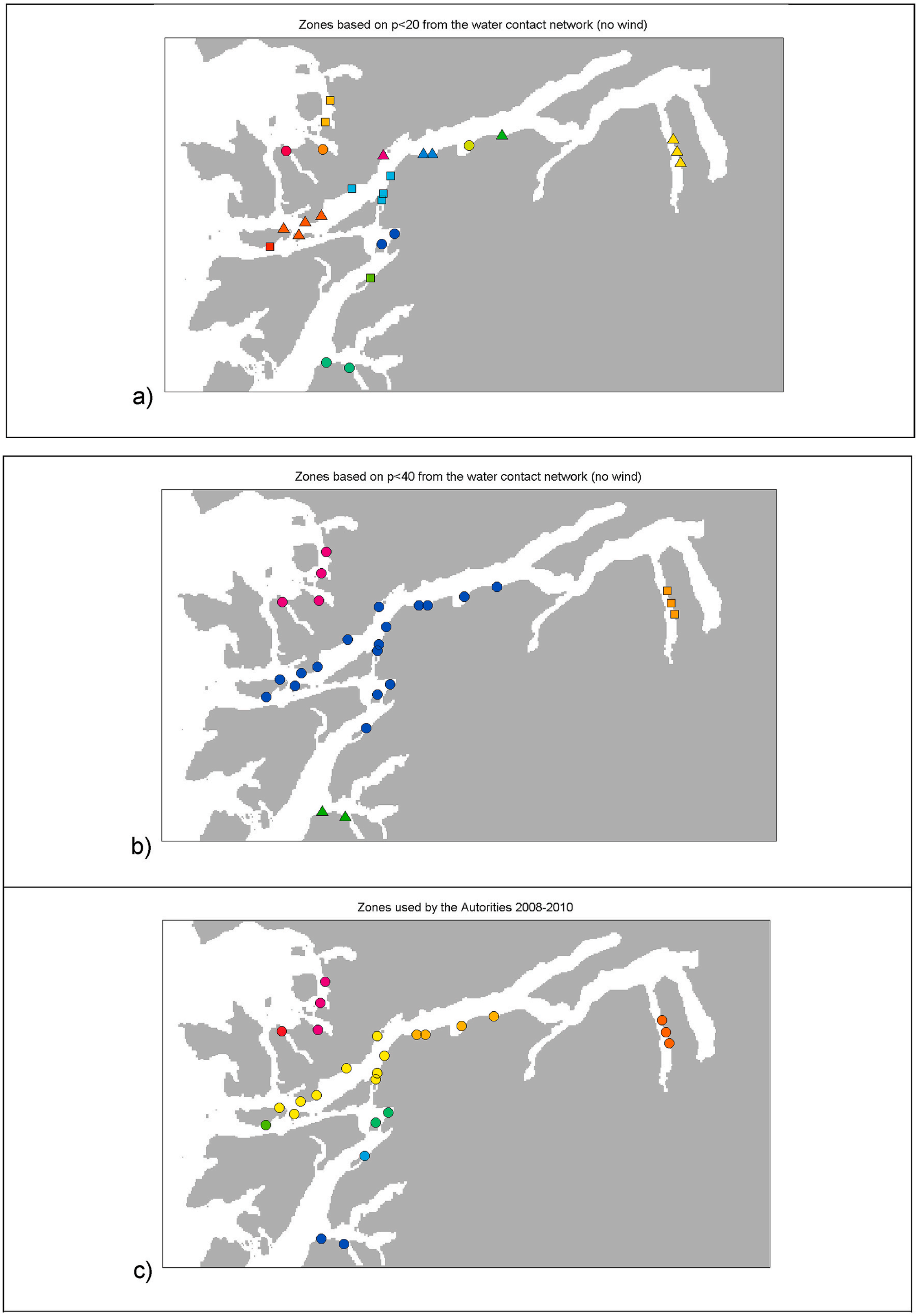


Fig. 9. Zones based on the water contact network for (a) very high degree of contact ($P < 20$) and (b) high degree of contact ($P < 40$). The zones in (c) shows the actual zones the authorities are using today (2008–2011).

5. Conclusion

Hydrodynamical modelling can be used to develop production zone maps based on water contact network between existing and planned fish farming sites. The water contact network can be used to identify fish farming sites with high water contact with other sites, and to identify key sites that tie together several smaller zones. By removing these key sites, the risk of fish disease agent transmission between the other sites in the production area might be substantially reduced.

There are two noticeable features of the estimated water contact matrix. Firstly, the number of receiving farm sites for the discharging farm sites was relatively variable. Farm sites that discharge water to many other farm sites may play a key role in transmission of fish disease agent locally. Secondly, there was a pronounced asymmetry in the contact direction due to prevailing current directions. Both these features are worth considering when assessing risks of local disease agent transmission. As aquaculture production continues to increase, advances made in modelling sea louse and salmon epidemiology should inform the sustainable management of marine resources (Groner et al., 2018; Myksvoll et al., 2018).

The aquaculture industry is bound to the newly implemented industry-driven contingency plan areas on the coast. The industry will therefore benefit greatly from the simulation tools presented in this study. Integration of hydrodynamics will be useful regarding management of an aquaculture site, coordination of management between different companies and planning of measures during disease outbreaks. These tools should be used wisely and with the realisation of their limitations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank A.N. Bø, Norwegian Food Safety Authority, District of Nordfjord and F. Hovland, the county of Sogn and Fjordane for participation in the study. We are grateful for cooperation by the fish farming companies Marine Harvest Norway AS/MOWI AS, K. Strømmen Lakseoppdrett AS, Nordfjord Havbruk AS and Hyen Laks AS. Fjordlab AS, SubAquaTech AS and Fiske-Liv AS supplied environmental information from the area.

Norwegian Food Safety Authority, 190484/S40, through project no. 09/3091 “AquaStrøm” and The Research Council of Norway through project no.190484/S40 “Transmission routes and infection dynamics of salmonid alphavirus (SAV)” provided financial support. Funding of manuscript preparation was kindly provided by Norwegian Institute of Water Research, the Norwegian Veterinary Institute, and the Research Council of Norway.

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