Aquacultural Engineering 97 (2022) 102243

Contents lists available at ScienceDirect

Aquacultural Engineering

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

Simulating emergency response for large-scale fish welfare emergencies in sea-based salmon farming

Hans Tobias Slette [a,*], Bjørn Egil Asbjørnslett [a], Sigurd Solheim Pettersen [a,b], Stein Ove Erikstad [a]

[a] Department of Marine Technology, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway
[b] Ocean Space Programme, Group Technology and Research, DNV GL, 1363 Høvik, Norway

ARTICLE INFO

Keywords:
Emergency response
Fish farming
Biomass hazards
Fish welfare
Discrete event simulation
Response distributions

ABSTRACT

This paper presents a simulation model for analyzing emergency response for fish welfare emergencies in sea-based fish farming. The model enables decision-makers to evaluate the emergency preparedness level against incidents harming fish welfare and the benefit of additional measures such as dedicated emergency response vessels. The proposed model simulates how the vessel operations of a sea-based fish farming system develops over time and tests the emergency preparedness at regular intervals by simulating the emergency responses. The progress of each emergency response is logged and is used to establish first response time, response progression, and response completion duration. A case study is performed assessing the emergency preparedness of two sea-based fish farming systems, and the effects of adding a dedicated emergency response vessel. The results indicate that when there are fewer vessels that can contribute to the emergency response, a dedicated emergency response vessel represents a higher relative capacity increase, and can have a more significant impact on the response completion.

1. Introduction

Sea-based fish farming can be exposed to certain events and conditions that have negative impacts on fish welfare (Sommerset et al., 2020). Some of these hazards can lead to situations necessitating vessel responses such as moving, delousing or slaughtering the fish (Norwegian Food Safety Authority, 2017; Sommerset et al., 2020). In 2016 Chile experienced the most severe harmful algae bloom (HAB) to date, killing 100,000 metric tons of Atlantic salmon (Mardones et al., 2021). In the early summer of 2019 a HAB killed an estimated 8 million farmed salmon along the Norwegian coast, and in 2021 Chile saw another HAB that resulted in the transfer of 5.4 million salmon to safer sites away from the affected area (FishFarmingExpert, 2021; Sommerset et al., 2020). The following winter, sea-based fish farmers on the Faroe Islands lost approximately 1 million fish to winter ulcer at one single occasion (Buanes, 2020). However, the severity of hazards may vary, and locations can experience situations with no serious effects on the fish welfare, such as minor algae blooms. Thus, in this paper the term "emergency" is reserved for serious realizations of the hazards, which will lead to loss of biomass if the emergency response is inadequate.

After the mentioned emergencies in Norway and the Faroe Islands the lack of emergency preparedness was said to contribute to the high losses (Fenstad, 2019; Ilaks.no, 2020; Osnes, 2019; Ytreberg and Berglihn, 2019). Hence analyzing the response preparedness for large scale biomass emergencies in sea-based aquaculture systems could help operators enhance their emergency preparedness and response capabilities. Improvements in emergency management in sea-based aquaculture systems is becoming more important, given changes in the risk picture induced by the move of fish farms into more exposed locations and the impact of rising sea temperatures.

The traditional way of assessing the emergency response capability of a system is through expert opinion and rules based on experience. For example, Wang et al. (2018) determines the emergency response capability for oil-spills in an area based on rules for the necessary amount of available resources. Haixiang et al. (2017) breaks down the rescue capability into subcomponents, and grade them based on expert opinion. A similar approach is used in Kang et al. (2016) where linguistic variables are used to evaluate oil-spill emergency response capability. Omorodion et al. (2021) use expert opinion to assess safety terms of the failure probability of operations performed by Emergency Rescue and

---

Abbreviations: DERV, dedicated emergency response vessel; GIS, geographic information system; LNG, liquid natural gas; ECMWF, European Centre for Medium-Range Weather Forecasts.

[*] Corresponding author.

E-mail address: hans.t.slette@ntnu.no (H.T. Slette).

https://doi.org/10.1016/j.aquaeng.2022.102243
Received 24 September 2020; Received in revised form 1 March 2022; Accepted 8 March 2022

Response Vessels. A method for combining machine learning and historical accident data to predict emergency scenarios, and thereby support emergency response decision-making is presented in Li et al. (2021).

An alternative to experience-based assessment is to test the emergency response performance. Siljander et al. (2015) proposes the use of geographic information system (GIS) based methods for evaluating the response times in maritime search and rescue to support strategic planning in Finnish waters. The presented approach considers weather conditions and vessel types. Zhou et al. (2020) present a three-step framework for assessing maritime search and rescue capabilities, covering response times, demand, and coverage. Response time is estimated using GIS. Simulation models are used to evaluate system design under environmental impacts in Berle et al. (2013), Bergström et al. (2014) and Brachner (2015). Berle et al. (2013) assesses the vulnerability of a maritime liquid natural gas (LNG) transportation system by quantifying the impact of disruption scenarios and mitigating measures. Bergström et al. (2014) proposes an approach for the design of robust arctic maritime transportation systems where the system performance is tested for different ice conditions and ice mitigation strategies. Brachner (2015) presents a model for evaluating the response capacity to helicopter ditches in the Barents Sea for different configurations of response unit positioning over a year with changing weather conditions. The fleet deployment with maximal covering problem and epoch-era analysis is combined in Pettersen et al. (2019) to optimize allocation of emergency response vessels, thereby providing insights into the effectiveness of alternative fleet designs. In another paper, Pettersen et al. (2020) study how latent capabilities can support large-scale emergency response. While they look at the case of the Macondo oil spill, the principle of repurposing assets for novel emergency situations can also be useful in aquaculture, e.g., the role of live fish carriers in emergency response.

This paper contributes to the literature by applying simulation-based performance analysis to determine the emergency preparedness for large scale biomass emergencies in sea-based fish farming. The presented method analyzes three stages of emergency response and covers both non-dedicated emergency response vessels and dedicated emergency response vessels (DERVs). DERVs are not used by the industry today, but could provide additional benefits in emergency response.

2. Material and methods

This section describes the system and emergencies considered, and presents the model structure, model specific temporal definitions and key assumptions. Thereafter, a case study setup is presented, the results of which are given in Section 3.

2.1. Fish farming system and emergency types

Sea-based fish farming systems can be defined as sets of hatcheries, fish cages, slaughterhouses, and vessels, where the vessels constantly change both status and position according to the various operations they perform in the system. Operation types cover daily maintenance and routine tasks performed by small vessels belonging to the location, more complex operations necessitating the assistance of larger external vessels, and finally operations directly handling large volumes of fish which are performed by large, specialized vessels such as live fish carriers. For responding to large-scale fish welfare emergencies, only large vessels handling large volumes of fish are of interest due to the scale of such emergencies.

Therefore, the presented method is intended for live fish carriers, stun & bleed vessels, processing vessels, and the likes. These vessels follow work schedules set up by the fish farmers, meaning that the emergency response capability they provide is time dependent and hard to estimate for a given point in time without considering the dynamics of the system. They may be busy performing planned operations at the time emergency response is initiated, in which case they must complete their current operations before responding to the emergency event. This decision is based on the goal of minimizing loss of fish welfare and end-product quality; aborting an initiated operation is certain to incur an extra load on the fish while the benefit of a quicker response is uncertain. In addition, the vessels may need to recommission before arriving at the emergency location. Recommissioning will depend on organizational resilience and ability to repurpose assets for operations they were not designed for (Pettersen et al., 2020). This may cover change of crew, picking up equipment, supplies, disinfecting the vessel or the likes. Supplementing the emergency response capability with DERVs on stand-by means that there are vessels that are available to respond to emergencies immediately. However, their emergency response contributions still depend on their positions relative to the emergency location and the impact of bad weather conditions.

Examples of emergency types for sea-based fish farming and relevant emergency responses are presented in Table 1. The time frame parameter indicates a rough generalization of how long a situation can be sustained before significant fish welfare consequences are experienced, and amount gives an indication of the possible scope of consequences. Fig. 1 shows the development of three example emergencies as the amount of lost fish as a function of time. The shape and steepness of such development functions in relation to the progress of the emergency response determines the amount of lost fish during an emergency.

2.2. Model structure

The model evaluates the emergency response of the sea-based fish farming system at regular intervals, Δt^{RI}, over a given period $[t_0, t_0+T]$, as presented in Fig. 2. Emergency response capabilities change as the state of the fish farming system changes with time; therefore, the first step of the method makes a prediction of how the fish farming system develops during normal operation based on the input for the initial state, task schedules and weather covering the period. Emergency response is thereafter simulated, and three emergency response measures are recorded at the different testing times, also referred to as response initiation times, e.g., t_1^{RI} in Fig. 2. The first measure is the first response time, defined as the time it takes from response initiation until the first vessel has commissioned and arrived at the emergency fish farm. The second is the response progress, which covers what response activities that are performed and when, for example the times and amounts for when fish is transported away from the emergency fish farm. Finally, the third is the response completion duration, defined as the time from response initiation until the emergency is over, for example when the last fish is pumped up from the emergency fish farm.

Both the simulation of the normal operations in the fish farming

Table 1
Examples of common fish welfare hazards in sea-based farming of Atlantic salmon, including response measures, typical time frame and scope.

Type	Response	Time frame	Amount
Pancreas disease (PD)	Slaughter	Weeks	One/several farms
Infectious Salmon Anemia (ISA)	Slaughter	Weeks	One/several farms
Lice	Delouse	Weeks	One/several farms
Algae	Slaughter/ Move	Days	One/several farms
Jellyfish	Slaughter/ Move	Days	One/several farms
Oil spill	Slaughter/ Move	Days	One/several farms
Oxygen/ temperature	Slaughter/ Move	Days	One/several farms
Storm/ winter ulcer	Slaughter/ Move	Days	One/several farms

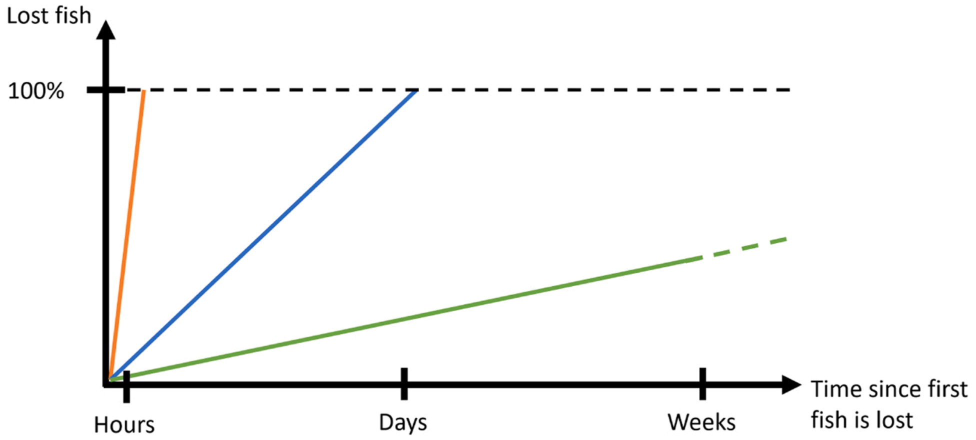

Fig. 1. Examples of simplified linear emergency development functions. Amount of fish lost as a function of time if no emergency response measures are taken.

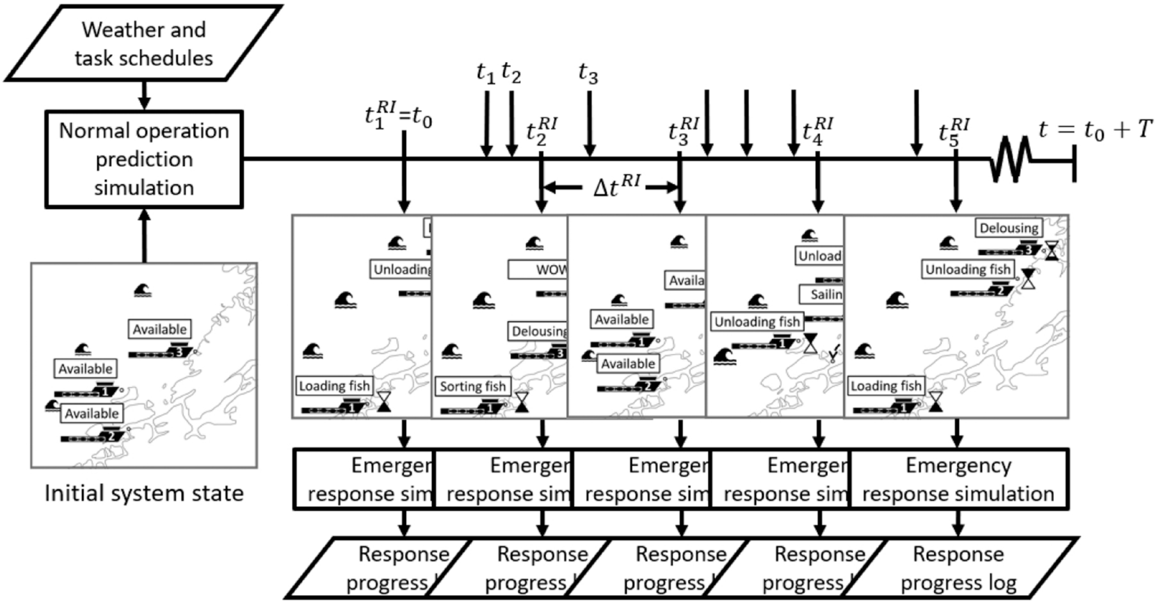

Fig. 2. Conceptual illustration of the method. Based on the initial system state, future system states are predicted, with the system state changing at irregular intervals, e.g., at t_1 and t_2. The response is tested at regular intervals, Δt^{RI}, over the time period T.

system and the emergency response simulation in Fig. 2 are discrete-event simulations where the system state changes at discrete points in time (Henderson et al., 2006; Nelson, 2013). A system state can be illustrated as a snapshot of the system, for example, including the position and status of each vessel and the weather conditions at that point in time, so that the development of a system over time can be described by a series of such snapshots. However, because the simulations are event driven, the system state changes do not occur at regular intervals. The system state is constant for the whole period between two system state changes, e.g., between the event at t_2 and t_3 in Fig. 2. Changes in the system state happens every time a vessel commences or ends a given operation or changes geographical position with more than one nautical mile. Any change in the initial sea-based fish farming system, including changes to the task schedule or the weather time series, will result in a different list of predicted system states. Uncertainty in the evaluation of the emergency preparedness of the system is reduced by applying several sets of historical data for the task schedules and hindcast weather time series.

The emergency response simulation is run once for each simulated emergency event, logging all details of the response. An emergency event is partly defined by the time at which it occurs, thus two identical emergencies occurring at different times are two different emergency events. Hence, every emergency event must be matched with the correct predicted system state for each emergency response simulation.

2.3. Temporal definitions

Following an emergency response initiation each vessel has a response duration, T_e^R, defined as the time it takes before the vessel is at the emergency location ready to start emergency response actions. In Fig. 3 response initiation for an emergency event e takes place at time t_e^{RI}, and the vessel takes T_e^R hours to arrive at the emergency location at time t_e^A. The response duration is the result of the time spent on ending the current mission, T_e^M, commissioning to be ready for emergency response actions, T_e^C, and transit sailing to the emergency location, T_e^S. The execution duration, T_e^E, is the time spent on emergency response actions, and varies depending on the emergency, the weather and the vessel's capabilities. Execution duration covers all time activities from the arrival at the emergency fish farm to the response is completed. The response completion duration, T_e^{RC}, is the total time it takes from the response initiation until the response is completed.

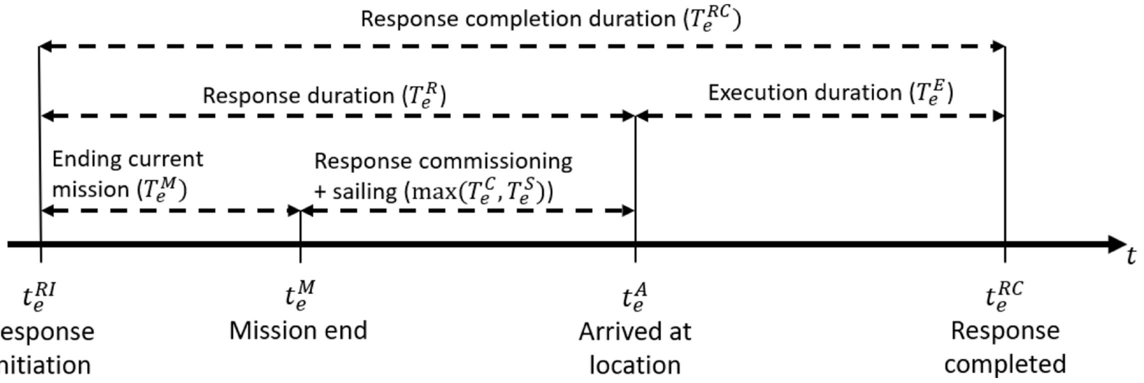

Fig. 3. t_e^{RI} is the time of response initiation for emergency event *e*. t_e^M is when the vessel is ready to respond to the emergency event. t_e^A is the time at which the vessel has arrived at the emergency location ready to start emergency response actions. The response is completed at t_e^{RC}.

The duration of the response for each vessel depends on its state at response initiation. The main difference between a non-dedicated and a DERV is the response duration T_e^R. In general, the response duration of a DERV will only consist of the sailing duration. In situations where more than one vessel is involved in the emergency response, T_e^{RC} is the result of the combined effort of the fleet. However, since there are limitations on the number of vessels that can operate at a fish farm or at a cage simultaneously, more vessels will not necessarily lead to a reduced T_e^{RC}. How T_e^{RC} is built up of response duration and execution duration differs for each vessel due to different states of the vessels at t_e^{RI}, the vessel characteristics and the weather. In Fig. 4, $t_{e,1}^A$, $t_{e,2}^A$ and $t_{e,3}^A$ indicate the times at which vessel 1, vessel 2 and vessel 3, arrive at the emergency location for emergency event *e*.

2.4. Case study setup

A case study will present how the method can be applied to evaluate the emergency preparedness of a sea-based fish farming system, assessing the three measures: first response time, response progress and response completion duration. First response time is defined as the time until the first vessel is at the emergency location and ready to commence emergency response, as $\min([T_{e,1}^R, T_{e,2}^R, \ldots, T_{e,V}^R])$. This gives valuable insight on how the "responsiveness" of the emergency response changes over time. Response progress provides the details on when the steps of response actions are completed enabling stakeholders to assess the emergency response with respect to how the hazard develops as a function of time, as described in Fig. 1. Response completion duration, T_e^{RC}, is the total time from response initiation until the response is completed and can be compared to the time frame parameter of the hazard to indicate the emergency preparedness.

The case study covers four different setups, varying in geographical size, number and type of emergency resources, and weather conditions, as seen in Table 2. Two configurations of vessel fleets are tested, one with and one without a DERV. Each case is run for a 30-day period and the emergency response is tested every 4th hour. The emergency response is to transport fish to the slaughterhouse from a fish farm approximately ~30 nautical miles (nm) away, for six different volumes of fish to be transported: 100, 400, 800, 1 600, 3 200 and 12 800 tons, respectively.

The small and large geographical areas referred to in Table 2 are presented in Fig. 5, with the corresponding differences in the related infrastructure. For the configurations with a DERV, it is positioned at the location marked "DV" in Fig. 5.

Perfect weather, as specified for case setup 1 and 3, means that the effect of weather is ignored in the emergency response simulation, as opposed to realistic weather where hindcast weather time series affect sailing and operation during emergency response, according to Table 3. The applied weather time series is retrieved from ECMWF's ERA5 reanalysis through Climate Data Store (ECMWF, 2018) and covers significant wave height for combined wind waves and swell, see Fig. 6. The weather in Fig. 6 is an example of what is experienced at the exposed locations, while more sheltered locations experience lower wave heights.

All the vessels used in the case study are identical live fish carriers

Table 2
Case setup and fleet configurations in the case studies. Two geographical areas of different size with associated fleets of vessels, and two weather situations.

Case setup	Geography size	Weather	# Dedicated ER vessels	# Total vessels
1	Small	Perfect	0/1	3/4
2	Small	Realistic	0/1	3/4
3	Large	Perfect	0/1	6/7
4	Large	Realistic	0/1	6/7

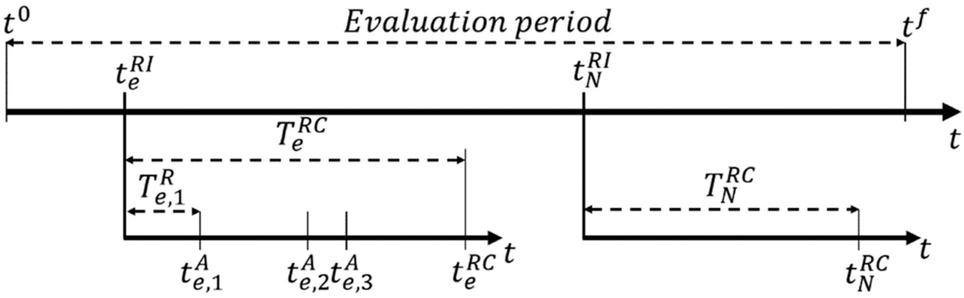

Fig. 4. Relations between time variables when considering more than one vessel and more than one emergency event. $T_{e,1}^R$ is the response duration for vessel 1 in emergency event *e*, corresponding to the difference between its arrival time $t_{e,1}^A$ and t_e^{RI}.

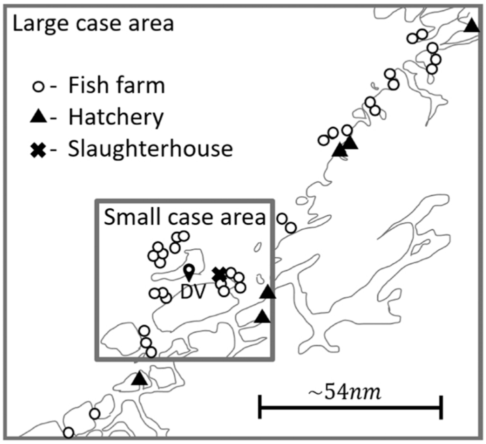

Fig. 5. Geographical areas, and corresponding infrastructure, used in the case study. The DERV is stationed as indicated by "DV". The smaller geographical area is a subset of the larger.

Table 3
Weather factor: effect of weather on sailing durations and vessel operations durations. Duration = expected duration * weather factor.

	$H_s < 0.5m$	$0.5m < H_s < 1m$	$1m < H_s$
Sailing durations	1	1.5	2
Operations durations	1	1.5	*No operation*

with a sailing speed of 13 knots, a carrying capacity of 450 tons of live fish, and a maximum continuous processing rate of 250 tons/hour both for loading and unloading. The given sailing speed is the perfect weather speed, both during normal operations and emergency response, while the achieved speed at any given time is subject to the weather conditions as given by Table 3.

The implemented task schedules are sequences of randomly generated missions, either transporting smolt from a hatchery to a cage in the sea, sorting or delousing aside the cage, or transporting fish from a cage to a slaughterhouse. All cases using the small geographical area use the same task schedules, the corresponding is true for the cases using the large geographical area. This means, for example, that all differences in results between case 1 and case 2 are due to the difference in weather. All vessels start the evaluation period at the location of their first scheduled task. Limitations on the number of vessels that can occupy a location at the same time is only implemented for fish farms at which emergency response is being executed. The implemented response strategy is that all vessels respond as soon as they have completed their current mission and become available for emergency response, meaning that no commenced operations are aborted prematurely.

3. Results

The presented results follow the development of the emergency response, and cover the time measures of first response, response progress and response completion, in that order. Finally, we present an example of how the response measures can be used to evaluate the costs and benefits of emergency response vessels.

3.1. First response

First response is a measure of how long it takes before the first vessel in the fleet has commissioned and arrived at the emergency location following response initiation. Fig. 7 shows the first response times of case setup 3 and case setup 4, where the results of the emergency response simulations are indicated every 4th hour of the evaluation period. The x's indicate the first response time of the fleet with no DERV and the circles indicate the first response time for the fleet with one DERV.

We see that the first response times vary more, and are generally higher, for the fleet with no DERV compared to the fleet with one DERV, see e.g. the x's versus the circles in Fig. 7(a), at respective times. This means that for the former the first response time is highly dependent on the time of the response initiation. Including weather effects increases the variation for the fleet with a DERV as seen in Fig. 7(c). In Fig. 7(c) there is a spike at about $t = 620 \textit{hours}$ of the evaluation period for the fleet without a DERV, which is the result of several vessels becoming unavailable at the same time from commencing new scheduled operations. Sometimes, the DERV is not the first responder to the emergency, in which case the first response times of the fleet with a DERV and the fleet without a DERV are the same, and lower than that of the DERV. This situation is illustrated by the points that are plotted below the line in Fig. 7(a). These are the results of another vessel happening to be closer to the emergency location, than the DERV is, at the time of the response initiation.

Fig. 7(b) and (d) shows the spread of the first response times for both the fleet with and without a DERV, for case setup 1 and case setup 4. One observation is that the mean response time of the fleets with and without a DERV are close. This may seem to contradict the observation from Fig. 7(a) and (c), however, considering that there are 180 first response times plotted for each fleet in each of the sub-figures, many are on the same line as the circles, only behind them. On the other hand, there are several occasions where the system with no DERV experiences far higher first response times than the average. This is especially prominent for case setup 4 in Fig. 7(d), where the first response time, at one occasion, is

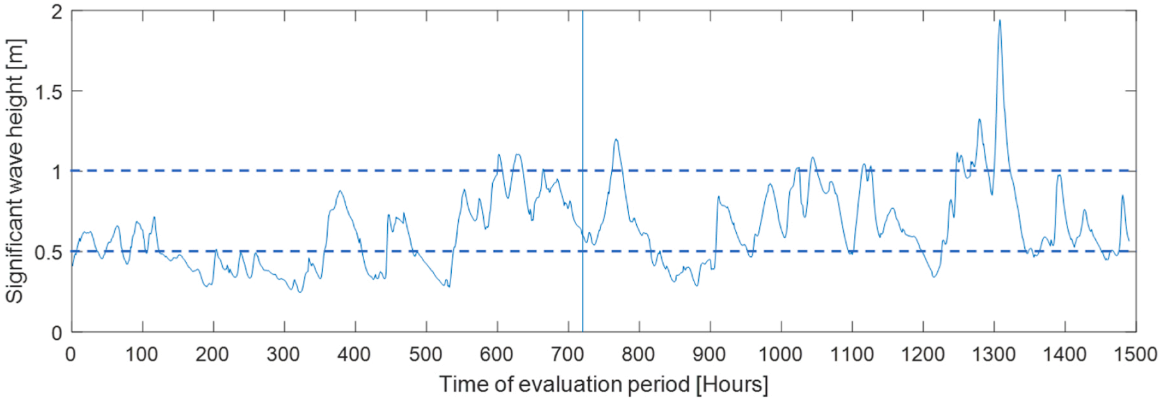

Fig. 6. Significant wave height dataset used in the case study. The evaluation period is $t = [0, 720]$. The remaining weather $t = \langle 720, 1500]$ is needed to play out the emergency responses that last beyond the end of the evaluation period.

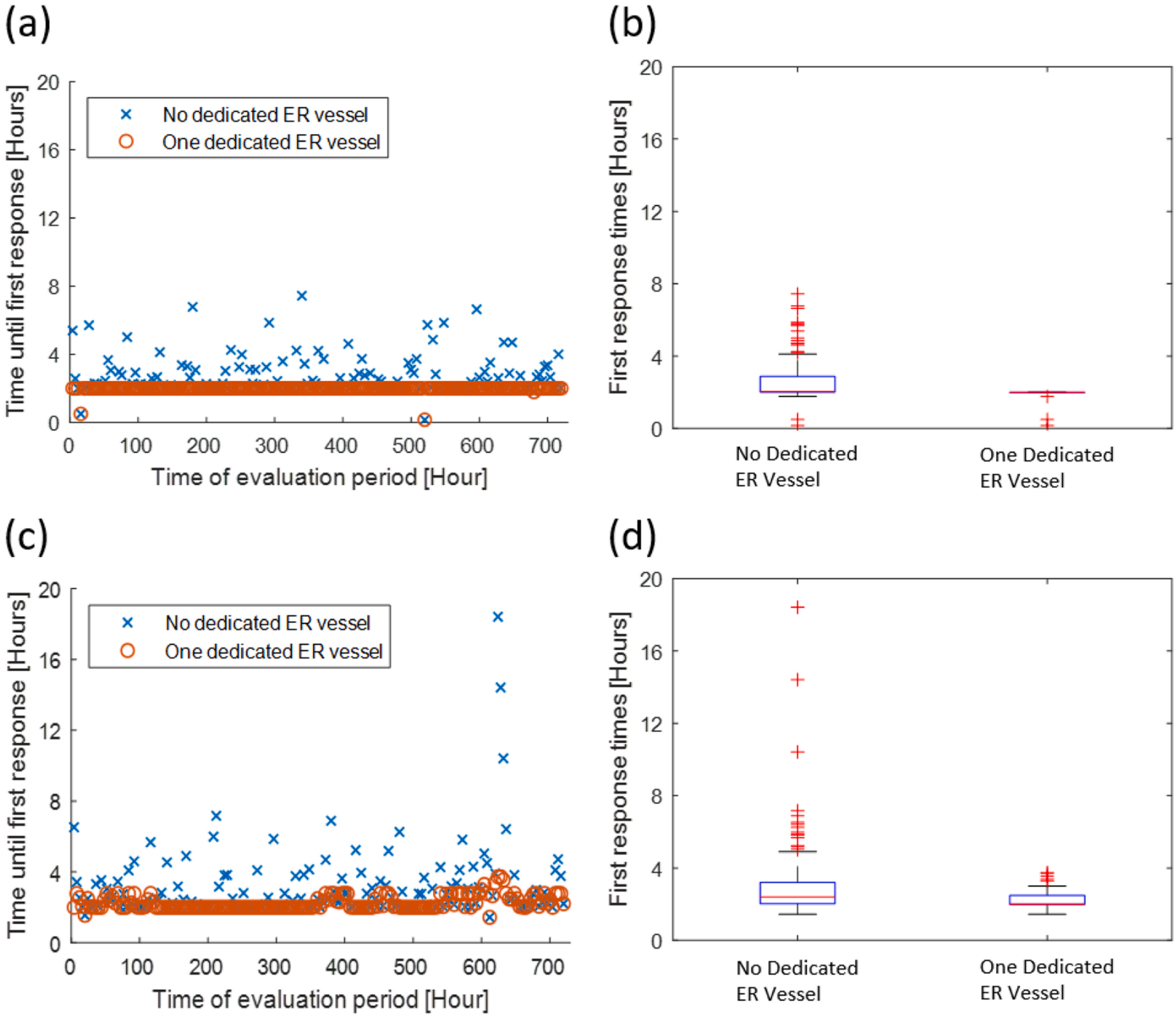

Fig. 7. Time from emergency initiation until the first vessel arrives at the emergency location, every 4th hour of the evaluation period. (a) and (b) case setup 1 – small area, perfect weather. (c) and (d) case setup 4 – large area, realistic weather.

approximately five times the 75th percentile value, meaning that considerable deviations must be expected.

3.2. *Response progress*

Response progress shows the times of vessel arrivals at the emergency location and the emergency response progress development. Fig. 8 shows the details of the response progress for two different emergency response situations, both with the objective of transporting 3 200 tons of salmon from the emergency location. The arrows indicate the first arrival of each vessel of the fleet to the emergency location, with the downwards pointing arrows being the fleet with a DERV, the first of which is the DERV in both Fig. 8(a) and (b). Response progress is measured as the total amount of fish that has been transported away from the emergency location as a function of time. The response progress must be seen in relation to the emergency development function, see Fig. 1, to determine the quality of the response.

The first observation is that the DERV is the first to arrive in both Fig. 8(a) and (b), and that the fleet with a DERV is the first to complete the response in both cases, respectively 9 and 14 h earlier than the fleet with no DERV. Secondly, the weather delays the emergency response in Fig. 8(b), so that the third vessel of the fleet with a DERV does not start loading fish until $t = t_e^{RI} + 23\mathit{hours}$, even though it arrives at the location at $t = t_e^{RI} + 6\mathit{hours}$. Therefore, in Fig. 8(b), two vessels load at the same time at $t = t_e^{RI} + 23\mathit{hours}$, because both were at the emergency location, only waiting for better weather to start loading fish. A third observation is that the two last vessels have their first arrival at the emergency location much later in Fig. 8(a) than in (b). This is due to the unfavorable position and status of those vessels at $t_e^{RI} = 400\mathit{hours}$ compared to $t_e^{RI} = 616\mathit{hours}$. The fourth observation is that the response progress of the fleet with no DERV and the fleet with a DERV may be very close at times even though the response completion durations for the full 3 200 tons are not.

These results indicate that the benefit of a DERV is more apparent for the response progress than the benefit of shorter first response times would indicate. For example, in Fig. 8(a) the difference in first response times is less than one hour while the difference grows to 9 h towards response completion. This is also true for emergency response in realistic weather where the response is completely halted for some time, see Fig. 8(b).

The results also show that the full evacuation of a mid-sized sea-based fish farm takes in the range of one to two full days. Whether this is acceptable, and the system's vulnerability of the 10-hour gap between the fleets with a DERV and those without, must be seen in relation to the

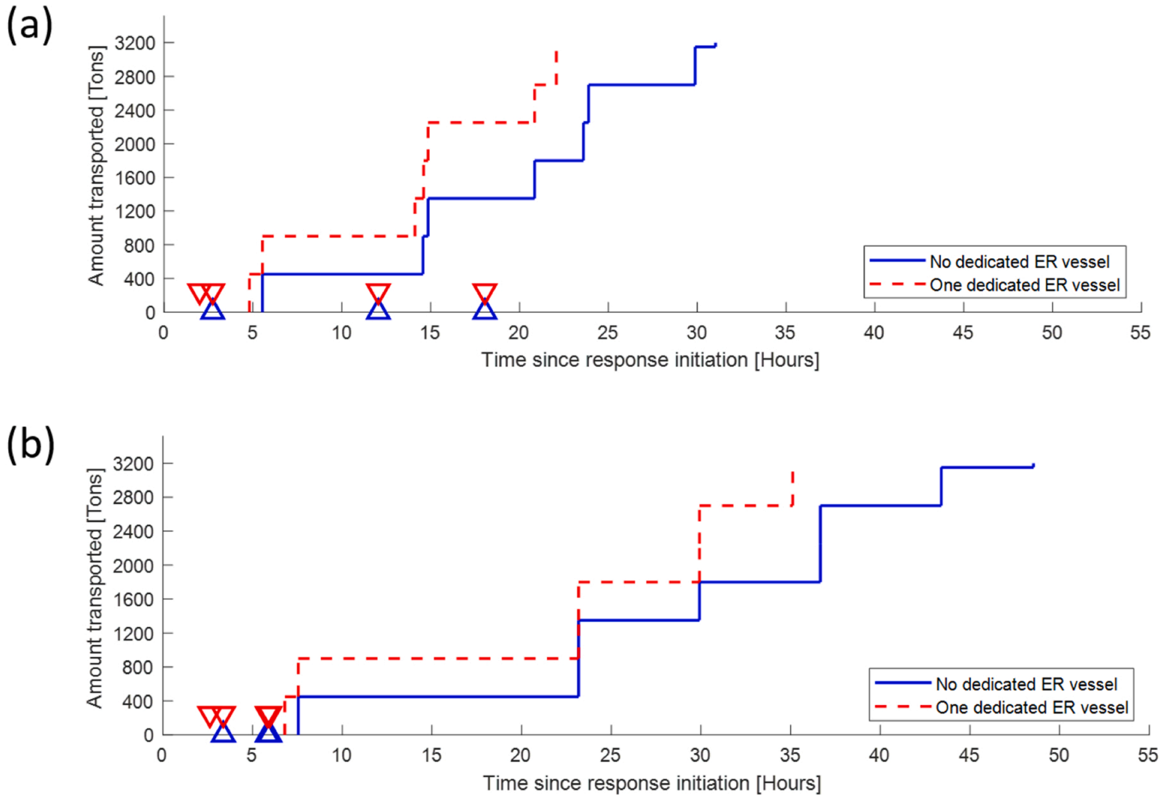

Fig. 8. Response progress for two selected emergency events. Dashed line and downwards pointing arrows indicate fleet with a DERV. (a) case setup 1. Small area, perfect weather. $t_e^{RI} = 400$ hours into the evaluation period. (b) case setup 2. Small area, realistic weather. $t_e^{RI} = 616$ hours into the evaluation period. The arrows indicate the first arrival for each vessel at the emergency fish farm.

implementation of early warning systems for the relevant emergency event and how far the situation has developed before the response is initiated.

3.3. Response completion

Fig. 9 shows the response completion durations, T_e^{RC}, for transporting 3 200 tons of fish away from an emergency location, for case setup 2 and case setup 4.

The first observation is that the difference between the fleet with and without a DERV is clearer for case setup 2, in Fig. 9(a) and (b), than for case setup 4, in Fig. 9(c) and (d). It is also evident that the large system has a significantly lower response completion duration, in general. Both observations match the expectations well considering that more vessels contribute in the emergency response in the large system, and that the relative contribution of the DERV therefore is lower. This effect is dependent upon the system's capability to utilize the higher number of emergency response vessels, which in turn is given by the physical constraints on, e.g., how many vessels that can operate at the farm simultaneously. If the limit is reached, so that the emergency response vessels are not fully utilized, a line corresponding to the lower limit for the response completion duration appears in the plot, as seen in Fig. 9(c) between $t = 120$ and $t = 350$. Increasing the number of emergency response vessels will drive the response completion durations at all times of the evaluation period towards that line, which is around 12 h, in Fig. 9(c). However, the effects of harsh weather conditions during the emergency responses affects the marginal change from adding an emergency response vessel and may even establish a higher limit, e.g., if t_e^{RI} is at a time when the weather does not allow for operations to be commenced. Finally, as expected the variations in the response completion durations closely follow the development of the weather conditions in Fig. 6.

3.4. Emergency consequences

Consider a simplified emergency where a fish farm holding 3 200 tons is exposed to an algae bloom taking out all fish that remains in the fish farm more than 24 h after the response initiation, a realistic scenario during the algae bloom in Northern-Norway in 2019 (Vikøyr and Oddstad, 2019). Table 4 presents the resulting consequences of the emergency in case setup 2 and 4 based on the 180 emergency preparedness evaluations that were performed with 4-hour intervals over the evaluation period of 30 days.

4. Discussion

Understanding emergency preparedness is crucial both to ensure good fish welfare and a sound operational practice in sea-based fish farming. The insight gained from model-based simulations enables the stakeholders to quantitatively assess their ability to effectively handle the various situations that might arise, and how to prepare for such situations. Based on the results of the case study, the method can be used to evaluate both the responses to individual emergencies and the general emergency preparedness level of a fish farming system. It can be used to indicate how well a basic operational system is set up for emergency response, and the improvement in emergency response capabilities from having additional emergency response resources. In Table 4, we see that the effect of having a DERV is more significant for the smaller system, which is expected as the relative capacity of an extra vessel is higher than in the larger system, and the emergency does not scale with the system size. Whether the first response times, response progress or response completion durations advocate for additional resources or other measures must however be seen in relation to specific emergency events and their required response times and statuses. A cost-benefit analysis of possible emergency response measures, for instance adding

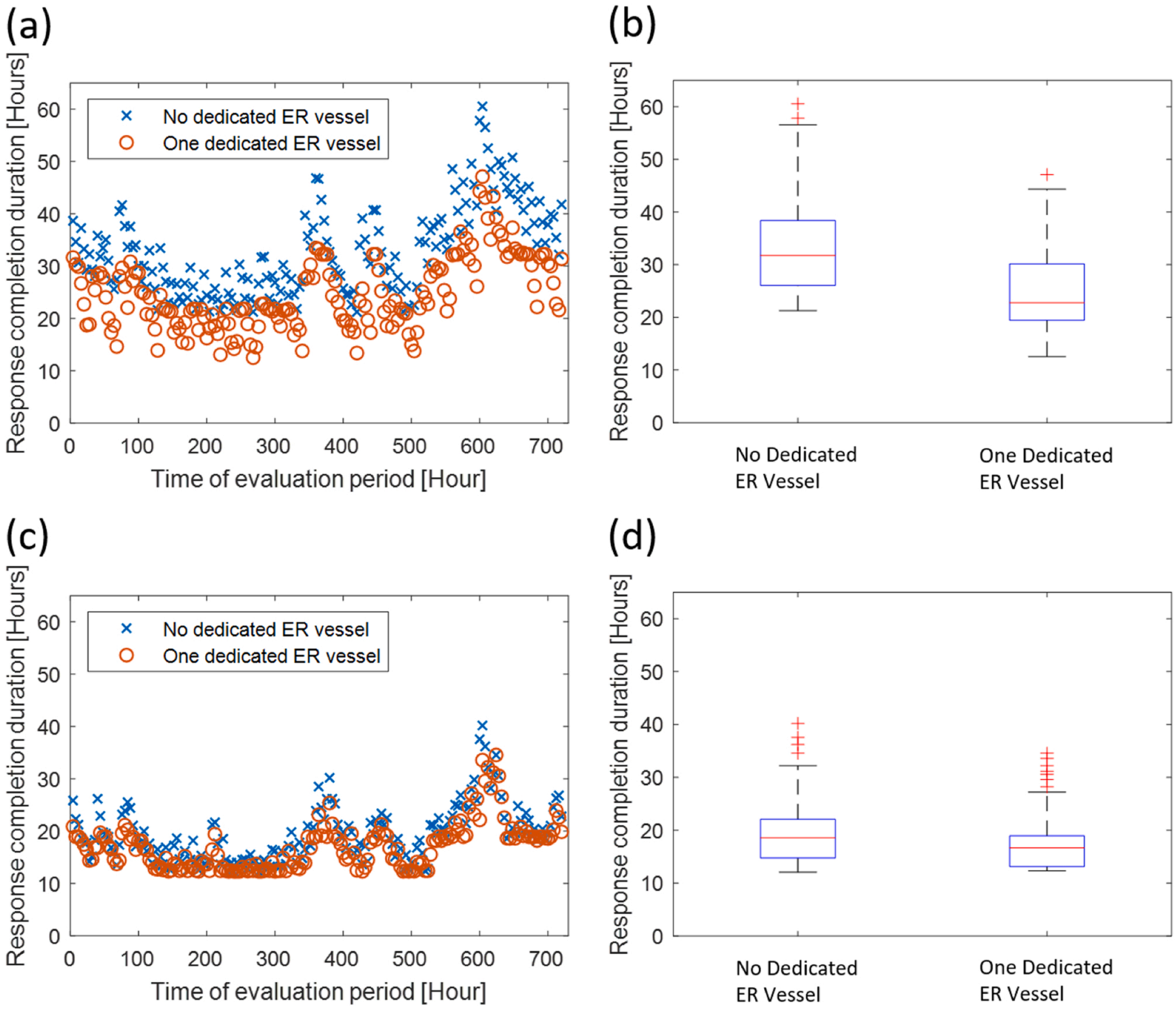

Fig. 9. Response completion durations for transporting 3 200 tons of fish away from the emergency location to the slaughterhouse. (a) and (b) show case setup 2 – Small system, realistic weather. (c) and (d) show case setup 4 – Large area, realistic weather.

Table 4

A complete rescue means that all the fish was moved before the 24-h limit. Average loss is the total loss of all 180 evaluations divided by 180. Max loss is the result from the worst performing evaluation out of the 180.

Case setup	Complete rescues (out of 180)	Average loss of biomass	Max loss of biomass
2 (no DERV)	29 / 180 = 16%	966.67 = 30%	2750 = 86%
2 (one DERV)	97 / 180 = 54%	341.11 = 11%	2300 = 72%
4 (no DERV)	149 / 180 = 83%	139.17 = 4%	2300 = 72%
4 (one DERV)	168 / 180 = 93%	59.72 = 2%	1850 = 58%

a DERV, would be one way to make such evaluations. However, formulating a cost benefit analysis is not straight forward due to both the cost and benefit side being highly dependent on, e.g., the system boundaries and to what degree a vessel is going to be dedicated.

Testing for two different system sizes is of interest because regulations can divide fish farms into geographical areas, e.g., in the case of Norway where there are defined production areas. Biosecurity restrictions related to crossing the production area borders can be both costly and time consuming. This means that response vessels, to a large extent, can be assumed not cross production area borders within the time span of an emergency response situation.

Given quick response initiation the emergency response of most of the tested cases could be characterized as acceptable, based on the time frames of Table 1. For both weather scenarios and system sizes, the longest response completion durations for emergencies up to 3200 tons were in the order of two days. However, for the 12 800 tons emergencies, response completion durations were found to be as high as a week. The case results could be regarded as optimistic bounds as the response strategy made all vessels respond to the emergency event. Also, the results are based on predictions of the vessel activities, i.e., the mission schedules. New missions may suddenly arise, and the weather forecasts are not certain. The further into the future the evaluations go, the more uncertain are the predictions. However, the assumption that commenced operations may not be aborted prematurely might make the vessels less responsive than they are in reality.

In a real-life scenario, two conditions are likely to delay the emergency response, making the response times longer than shown in the results. First, the hazard must be identified, and then the appropriate decision makers in the companies must decide to implement response actions. Early detection of HABs is not easy as the identification of the algae type and concentration usually is done by taking water samples and sending them to laboratories for analysis (Mowat and Chadwik, 2021). Systems for early detection based on satellite imaging of algal concentrations, artificial intelligence identification of algae types, and monitoring of the potential for algal blooms are being developed (Davidson et al., 2021; Mowat and Chadwik, 2021; Osnes, 2019). Potential for algal blooms is evaluated based on secondary indicators such as water temperature, oxygen levels and the level of blue-green algae. After a threat or unwanted event has been identified emergency response resources are not deployed until the appropriate decision makers give the order. In situations like severe HABs, the potential large scale of the required emergency response means that the response is costly and is likely to negatively affect other parts of the business, e.g., occupying company resources that are needed in normal operation. This means that a thorough assessment of the situation must be made before initiating a full emergency response, and action may not be deemed beneficial until the emergency has escalated.

Considering the two delaying factors in real-life situations, response time could probably be improved if DERVs were positioned according to real-time assessments of harm potential and the probability of an emergency. Such a problem would resemble the maximal covering problem addressed in (Pettersen et al., 2019) Probability of emergency could, e.g., be based on the degree to which environmental conditions favor a HAB, as proposed in (Mowat and Chadwik, 2021).

Insurance companies provide insurances against losses related to natural events such as algae blooms. Analyses of emergency response performance can be useful in understanding and quantifying risk (Holmyard, 2017). Enabling operators to show insurers that they reduce the consequences of adverse events can also provide benefits for both parties.

Stakeholders should be aware that the method is not meant to give exact information far into the future, rather it is meant to indicate the emergency preparedness level of a sea-based fish farming system. Therefore, a sufficient number of evaluations should be performed, with different input data, so that they trust the results and the value of the information in the results. However, this depends on what the interests of the stakeholders are and what they want to study. If testing for general preparedness, then the uncertainty of task schedules and weather forecasts is less of a problem since hindcast data can be used. If they want to perform what-if analyses on specific emergencies, the evaluation period should not be stretched too far.

5. Conclusion

The method presented in this paper is suited for assessing the emergency preparedness for large-scale fish welfare emergencies in sea-based fish farming. It provides a useful way of studying the time-dimension for emergency preparedness needs and resources in sea-based fish farming by giving information on the three response measures; first response times, response progress and response completion durations, enabling decision makers to perform detailed analyses to determine the emergency preparedness of any given sea-based fish farming system. The method also provides information which can be used in cost benefit analyses to evaluate the implementation of emergency response measures.

The results of the test cases indicate that the emergency preparedness of large sea-based fish farming systems with many vessels is better than for smaller systems with fewer vessels. They also show that when there are fewer vessels that can contribute to the emergency response, a dedicated emergency response vessel can have a more significant impact on the response completion. First response times and response completion durations are strongly time dependent for systems without a DERV, and the time dependency increases with realistic weather. In the small system, the DERV effectively creates an upper boundary for the first response times, while for the large system there is still some spread towards longer response times. However, the most extreme outliers are effectively reduced with the introduction of the DERV. The effect of a DERV on the response completion duration depends on the relative capacity increase it represents in the system.

CRediT authorship contribution statement

Hans Tobias Slette: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualization. **Bjørn Egil Asbjørnslett**: Conceptualization, Writing – review & editing, Supervision. **Sigurd Solheim Pettersen**: Writing – review & editing. **Stein Ove Erikstad**: Conceptualization, Software, Validation.

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.

Acknowledgements

This research has been funded by the Research Council of Norway, grant number 237790, through SFI EXPOSED Aquaculture Research Centre. The funding source had no influence on the research or the preparation of the article. The authors would like to thank Dagfinn Breivik Skomsø and Barbo Klakegg at Åkerblå for support in understanding the fish welfare hazards.

References

Bergström, M., Ehlers, S., Erikstad, S.O., 2014. An approach towards the design of robust arctic maritime transport systems. In: Maritime-Port Technology and Development, pp. 185–192. https://doi.org/10.1201/b17517-23.

Berle, Ø., Norstad, I., Asbjørnslett, B.E., 2013. Optimization, risk assessment and resilience in LNG transportation systems. Supply Chain Manag. 18, 253–264. https://doi.org/10.1108/SCM-03-2012-0109.

Brachner, M., 2015. A simulation model to evaluate an emergency response system for offshore helicopter ditches. In: Proceedings of the 2015 Winter Simulation Conference. Institute of Electrical and Electronics Engineers Inc., pp. 2366–2377. https://doi.org/10.1109/WSC.2015.7408348

Buanes, F., 2020. Én million oppdrettsfisk døde under kraftig storm (Norwegian) [One million farmed fish died during severe storm] [WWW Document]. DN.no. URL ⟨https://www.dn.no/havbruk/havbruk/faroyene/bakkafrost/en-million-oppdrettsfisk-dode-under-kraftig-storm/2–1-769193⟩. (Accessed 3.9.20).

Davidson, K., Whyte, C., Aleynik, D., Dale, A., Gontarek, S., Kurekin, A.A., McNeill, S., Miller, P.I., Porter, M., Saxon, R., Swan, S., 2021. HABreports: online early warning of harmful algal and biotoxin risk for the Scottish shellfish and finfish aquaculture industries. Front. Mar. Sci. 8, 350. https://doi.org/10.3389/FMARS.2021.631732/BIBTEX.

ECMWF, 2018. ERA5 [WWW Document]. Reanalysis datasets. ⟨https://doi.org/10.24381/cds.adbb2d47⟩.

Fenstad, A., 2019. Satellitter og maskinlæring kan hindre framtidig fiskedød fra giftalger (Norwegian) [Satellites and machine learning can stop fish deaths from algae in the future] [WWW Document]. tu.no. URL ⟨https://www.tu.no/artikler/satellitter-og-maskinlaering-kan-hindre-framtidig-fiskedod-fra-giftalger/465881⟩. (Accessed 9.2.20).

FishFarmingExpert (Eds.), 2021. 5.4m fish moved out of harm's way in Chile [WWW Document]. FishFarmingExpert.com. URL ⟨https://www.fishfarmingexpert.com/article/4244-tonnes-of-fish-killed-by-algal-blooms-in-chile/⟩. (Accessed 2.13.22).

Haixiang, P., Yijia, M., Tianyu, M., Shengjing, L., Yajie, Z., 2017. Evaluation of maritime emergency rescue capability based on network analysis. IOP Conf. Ser. Earth Environ. Sci. 100. https://doi.org/10.1088/1755-1315/100/1/012121.

Henderson, S.G., Nelson, B.L., L'Ecuyer, P., Devroye, L., Biller, B., Ghosh, S., Leemis, L. M., Kelton, W.D., Alexopoulos, C., Chik, S.E., Szechtman, R., Juneja, S., Shahabuddin, P., Lemieux, C., Whitt, W., Cheng, R.C.H., Goldsman, D., Glynn, P.W., Kim, S.-H., Barton, R.R., Meckesheimer, M., Fu, M.C., Andradóttir, S., Ólafsson, S., 2006. Handbooks in Operations Research and Management Science: Simulation, first ed, vol. 13. Elsevier.

Holmyard, N., 2017. Recent farmed salmon losses put aquaculture insurance in focus - responsible seafood advocate. Glob. Seaf. Alliance 7–10.

Ilaks.no, 2020. Arnarlax har tapt 570 tonn fisk: Styreleder tror laksedøden kunne vært unngått (Norwegian) [Arnalax lost 570 tons of fish: Chairman thinks slamon death could have been avoided] [WWW Document]. ilaks.no. URL ⟨https://ilaks.no/arnarlax-har-tapt-570-tonn-fisk-styreleder-tror-laksedoden-kunne-vaert-unngatt/⟩. (Accessed 3.9.20).

Kang, J., Zhang, J., Bai, Y., 2016. Modeling and evaluation of the oil-spill emergency response capability based on linguistic variables. Mar. Pollut. Bull. 113, 293–301. https://doi.org/10.1016/j.marpolbul.2016.09.056.

Li, B., Lu, J., Lu, H., Li, J., 2021. Predicting maritime accident consequence scenarios for emergency response decisions using optimization-based decision tree approach. Marit. Policy Manag. 1–23. https://doi.org/10.1080/03088839.2021.1959074.

Mardones, J.I., Paredes, J., Godoy, M., Suarez, R., Norambuena, L., Vargas, V., Fuenzalida, G., Pinilla, E., Artal, O., Rojas, X., Dorantes-Aranda, J.J., Lee Chang, K.J., Anderson, D.M., Hallegraeff, G.M., 2021. Disentangling the environmental processes responsible for the world's largest farmed fish-killing harmful algal bloom: Chile, 2016. Sci. Total Environ. 766, 144383 https://doi.org/10.1016/J.SCITOTENV.2020.144383.

Mowat, R., Chadwik, P., 2021. Early Detection of Harmful Algal Blooms [WWW Document]. ecomagazine.com. URL 〈http://digital.ecomagazine.com/publication/?i=719166&article_id=4103423&view=articleBrowser&ver=html5〉. (Accessed 2.13.22).

Nelson, B.L., 2013. International Series in Operations Research & Management Science, Foundations and Methods of Stochastic Simulation. https://doi.org/10.1007/978-1-4614-6160-9.

Norwegian Food Safety Authority, 2017. Fish diseases PD and ISA [WWW Document]. BarentsWatch.no. URL 〈https://www.barentswatch.no/en/articles/fish-diseases/〉. (Accessed 3.9.20).

Omorodion, O.A., Ikimi, J.A., Nwaezeapu, A., Peace, O.A., Esiri, K.H., Ajoboru, F.J., Ebokpo, A.A., Dennar, O., Okitikpi, J., John, A., 2021. Analysis of emergency response and rescue operation using fuzzy expert system. Ships Offshore Struct. 1–10. https://doi.org/10.1080/17445302.2021.1935608.

Osnes, L., 2019. Algevarsling 4.0: - Vi trenger mer informasjon om alt som skjer rundt, før og etter en slik krise (Norwegian) [Algae alert 4.0: -We need more information about what happens around, before and after such a crisis] [WWW Document]. ilaks.no. URL 〈https://ilaks.no/algevarsling-4–0-vi-trenger-mer-informasjon-om-alt-som-skjer-rundt-for-og-etter-en-slik-krise/〉. (Accessed 3.9.20).

Pettersen, S.S., Fagerholt, K., Asbjørnslett, B., 2019. Evaluating fleet effectiveness in tactical emergency response missions using a maximal covering formulation. Nav. Eng. J. 131, 65–82.

Pettersen, S.S., Garcia Agis, J.J., Rehn, C.F., Asbjørnslett, B.E., Brett, P.O., Erikstad, S.O., 2020. Latent capabilities in support of maritime emergency response. Marit. Policy Manag. 47, 479–499. https://doi.org/10.1080/03088839.2019.1710611.

Siljander, M., Venäläinen, E., Goerlandt, F., Pellikka, P., 2015. GIS-based cost distance modelling to support strategic maritime search and rescue planning: a feasibility study. Appl. Geogr. 57, 54–70. https://doi.org/10.1016/j.apgeog.2014.12.013.

Sommerset, I., Walde, S.C., Bang Jensen, B., Bornø, G., Haukaas, A., Brun, E. (red), 2020. Fiskehelserapporten 2019 (Norwegian) [The fish health report 2019] (Report No. 5a/2020). Norwegian Veterinary Institute.

Vikøyr, H., Oddstad, G., 2019. Algedramaet i Lødingen: – Uten noen gode år i forkant, ville vi ikke klart dette (Norwegian) [The algae drama in Lødingen: -Without some good years behind us, we would not make it] [WWW Document]. VG.no. URL 〈https://www.vg.no/nyheter/innenriks/i/GGOV44/algedramaet-i-loedingen-uten-noen-gode-aar-i-forkant-ville-vi-ikke-klart-dette〉. (Accessed 9.14.20).

Wang, Y., Liu, X., Yu, X., Zheng, X., 2018. Assessing response capabilities for responding to ship-related oil spills in the Chinese Bohai Sea. Int. J. Disaster Risk Reduct. 28, 251–257. https://doi.org/10.1016/j.ijdrr.2018.02.040.

Ytreberg, R., Berglihn, H., 2019. Lakseoppdrettere rammet av verste algedød på over 25 år (Nowregian) [Salmon farmers hit by worst algae death in over 25 years] [WWW Document]. dn.no. URL 〈https://www.dn.no/havbruk/lakseoppdrett/fiskeridirektoratet/nordland/-vi-ma-berge-det-som-berges-kan/2–1-606428〉. (Accessed 9.2.20).

Zhou, X., Cheng, L., Min, K., Zuo, X., Yan, Z., Ruan, X., Chu, S., Li, M., 2020. A framework for assessing the capability of maritime search and rescue in the south China sea. Int. J. Disaster Risk Reduct. 47, 101568 https://doi.org/10.1016/J.IJDRR.2020.101568.