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ABSTRACT

Vessel underwater noise (VUN) is one of the main threats to the recovery of the endangered St. Lawrence Estuary Beluga population (SLEB). The 1% yearly population decline indicates that the cumulative threats are already beyond sustainable limits for the SLEB. However, a potential threefold increase in shipping traffic is expected within its critical habitat in the coming years resulting from proposed port-industrial projects in the Saguenay River. Current data indicate that SLEB typically use multiple sectors within their summer range, likely leading to differential VUN exposure among individuals. The degree of displacement and spatial mixing among habitats are not yet well understood but can be simulated under different assumptions about movement patterns at the individual and population levels. Here, we propose using an agent-based model (ABM) to explore the biases introduced when estimating exposure to stressors such as VUN, where individual-centric movement patterns and habitat use are derived from different spatial behaviour assumptions.

Simulations of the ABM revealed that alternative behavioural assumptions for individual belugas can significantly alter the estimation of instantaneous and cumulative exposure of SLEB to VUN. Our simulations also predicted that with the projected traffic increase in the Saguenay River, the characteristics making it a quiet zone for SLEB within its critical habitat would be nullified. Whereas spending more time in the Saguenay than in the Estuary allows belugas to be exposed to less noise under the current traffic regime, this relationship is reversed under the increased traffic scenario. Considering the importance of the Saguenay for SLEB females and calves, our results support the need to understand its role as a possible acoustic refuge for this endangered population. This underlines the need to understand and describe individual and collective beluga behaviours using the best available data to conduct a thorough acoustic impact assessment concerning future increased traffic.

1. Introduction

1.1. St. Lawrence Estuary Beluga

The St. Lawrence Estuary (Fig. 1) is habitat for several at-risk whale populations such as the St. Lawrence Estuary beluga (SLEB) (*Delphinapterus leucas*), the Atlantic fin whale (*Balaenoptera physalus*) the Northwest Atlantic blue whale (*Balaenoptera musculus*), and occasionally the North Atlantic right whale (*Eubalaena glacialis*). Vessel-generated underwater noise (VUN) is identified as a threat to their recovery (Beauchamp et al., 2009; Fisheries and Oceans Canada, 2016, 2014, 2012).

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The SLEB population is considered *endangered* under the Canadian Species at Risk Act (Fisheries and Oceans Canada, 2012). Despite years of recovery efforts, the population continues to decline (Fisheries and Oceans Canada, 2018) suggesting that the cumulative threats are already beyond sustainable limits (Lesage, 2021). During summer, SLEB habitat extends over a large portion of the St. Lawrence Estuary and includes the Saguenay River (referred to as Saguenay Fjord or Saguenay hereafter) (Fig. 1). In 2020, an Action plan was released by Fisheries and Oceans Canada under the Species at Risk Act to reduce VUN in beluga habitat (Pêches et Océans Canada, 2020), focusing mainly on the merchant and whale-watching fleets. This Action plan developed with the participation of a broad range of stakeholders including the shipping industry, illustrates a rare consensus on the need to mitigate the effects of VUN in the habitat of SLEB and other marine mammals.

Beluga whales are gregarious, exhibiting sexual spatial segregation and natal philopatry to summer concentration areas and to migratory circuits within regions, with migration routes and site fidelity being culturally learned (Caron and Smith, 1990; Colbeck et al., 2013; De March and Postma, 2003; O'Corry-Crowe et al., 2018; Ouellet et al., 2021; Turgeon et al., 2012). Within their habitat, belugas use some areas preferentially where they occur on a regular basis or where they spend relatively large proportions of their time (called "high residency areas or high density areas") (Lemieux Lefebvre et al., 2012; Michaud, 1993; Mosnier et al., 2016). The presence of localized sources of pollution in the environment such as VUN may have differential effects on individuals depending on their specific patterns of movement and habitat

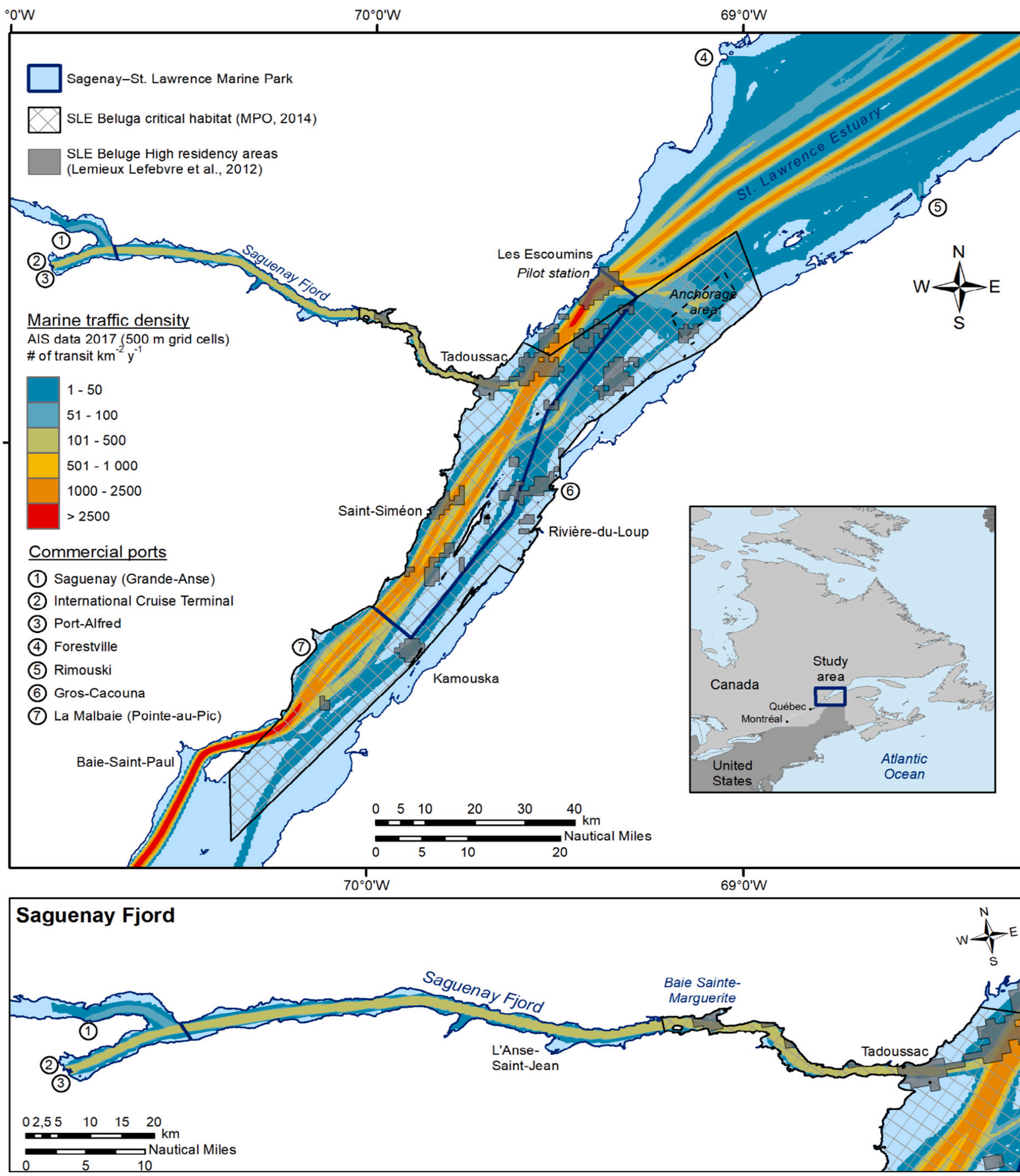

Fig. 1. study area.

use. Therefore, conducting VUN impact assessments at the habitat level and ignoring individual behaviour (i.e., movement and habitat use) is likely to introduce biases in the estimation of both the cumulative and instantaneous exposure of individuals to VUN (Pêches et Océans Canada, 2018). In the context of a declining population such as the endangered SLEB, such errors might lead to a severe underestimation of VUN exposure for animals using the most insonified areas.

Beluga whales are considered to be a mid- to high-frequency species (Southall et al., 2019). Wild belugas' maximum hearing sensitivity is between 40 and 80 kHz (Mooney et al., 2018) with hearing extending to low frequencies below 100 Hz (Awbrey et al., 1988; Johnson et al., 1989). Non-echolocation calls are generally below 8 kHz (Faucher, 1988; Garland et al., 2015; Lesage et al., 1999; Sjare and Smith, 1986) and most of beluga call types extend to low frequencies below 1000 Hz (Booy et al., 2018; Finneran et al., 2005; Sjare and Smith, 1986). Hearing range reductions and call masking by large vessel noise have been documented at low frequencies below 1000 Hz in belugas and other odontocetes whose maximum hearing are at even higher frequencies than belugas (Erbe and Farmer, 2000; Gervaise et al., 2012; Hermannsen et al., 2014). This highlights the relevance to study how a significant increase of shipping would affect beluga exposure to low-frequency noise in their critical habitat.

1.2. Vessel-generated underwater noise

Vessel-generated underwater noise (VUN) is widely acknowledged as a major source of acoustic pollution threatening marine life (Duarte et al., 2021) including marine mammals (Erbe et al., 2019). Impacts of VUN on whales such as belugas include behavioural disruption (affecting all kinds of behaviour including nursing, parturition, feeding or socializing) (Gomez et al., 2016), changes in vocal behaviour (Lesage et al., 1999), masking of environmental, social or echolocation signals (Erbe et al., 2016b), and hearing loss (Finneran et al., 2002; Schlundt et al., 2000).

Vessel traffic is a major contributor to anthropogenic underwater noise in Canadian waters including the St. Lawrence Estuary and Saguenay (Gervaise et al., 2012; McQuinn et al., 2011) where the proximity of commercial shipping lanes and a vibrant whale-watching industry result in a particularly high frequentation by commercial and recreational vessels. VUN is influenced by several design characteristics (e.g. engines and mountings, vessel size and draught) and operational factors (e.g. speed, propeller damage and engine revolutions) (Chion et al., 2019b; Wittekind, 2014). The broadband underwater noise emitted by large ships ranges from 170 to 210 dB re 1μPa^2 (Chion et al., 2019b, 2017; Lesage et al., 2014; Simard et al., 2016) mostly (although not exclusively) in the low-frequency band (Gassmann et al., 2017; Simard et al., 2016), spreading over hundreds of kilometers (Duarte et al., 2021). In contrast, the broadband source levels from smaller vessels generally lie between 150 and 180 dB re 1μPa^2 depending on size and operational factors (Erbe et al., 2016a; McQuinn et al., 2011; Wladichuk et al., 2019), with most of the acoustic energy contained in the mid- and high-frequency domains which attenuate faster than low frequencies. A typical 20-30 dB re 1μPa^2 difference in source level means that a ship may release 100 to 1000 times more acoustic energy, respectively into the environment than a small recreational vessel, with low frequencies dominating noise spreading over greater distances. However, when smaller vessels such as whale-watching boats go closer to the whales, their instantaneous impact on whales' soundscape can be very high, all the more if the species is a mid- or high- frequency cetacean (Southall et al., 2019). Although this is beyond the scope of this paper (detailed in the Scope section), this highlights the need to consider all the variability in VUN from different vessel categories to conduct a complete noise impact assessment and mitigate their cumulative effects on whales.

1.3. Use of the Saguenay by the SLEB

The Saguenay (Fig. 1) is part of the designated critical habitat for SLEB as it is used at least between June and October by all age- and sex-classes, but especially by females with calves and juveniles (Conversano et al., 2017; Mosnier et al., 2016). While the Saguenay mouth represents the noisiest of the SLEB habitats, the river itself is currently among the quietest and is where periods of elevated noise are the least frequent given the relatively low amount of shipping traffic compared to the St. Lawrence Estuary (McQuinn et al., 2011).

The analysis of 44 aerial surveys estimated that 1.8% of the population (and up to 5%, assuming a population size of 1100) is present at any given time in this sector (Gosselin et al., 2017; Ouellet et al., 2021). Long-term (2003-2016) observations at the Saguenay mouth between June and August indicate beluga presence in this sector on 86% of observation days (Conversano et al., 2017). Two recent studies using information collected over 28 and 18 years respectively, on herd movements and identifiable individuals, provided insights into the proportion of the population using this area. The habitat connectivity study based on herd movements suggested that at least 37% of the population use the Saguenay (Ouellet et al., 2021), whereas the photo-identification study suggests that 40–50% of the population and 66% of the adult females use the Saguenay (Bonnell et al., in prep.; Chion et al., 2019a).

1.4. Marine traffic in the SLEB's summer habitat

The Saguenay–St. Lawrence Marine Park was created in 1998 at the confluence of the Saguenay and the St. Lawrence Estuary to promote the recovery of the SLEB population (Fig. 1). The Marine Park includes about 37% of the population's critical habitat (Ménard et al., 2018). However, it is within the Marine Park that the SLEB are most exposed to marine traffic (Turgeon, 2019).

The Marine Park includes the high traffic lanes of the St. Lawrence Seaway, connecting the Atlantic Ocean to many ports upstream of the St. Lawrence and Saguenay Rivers (Fig. 1). Annually, about 5000 merchant ship transits are counted (about 14 per day during beluga presence from May to October), of which about 9% (average of 1.2 per day) navigate through the Saguenay (Turgeon, 2019). Based on 2017 statistics, over 6500 whale-watching excursions were conducted mainly (66%) in July—August (Turgeon, 2019). In addition to this activity, which was centered at the head of the Laurentian Channel and the Saguenay mouth, three ferry routes cross the park, including one that operates year-round at the mouth of the Saguenay with approximately 40,000 crossings annually. The Marine Park is also frequented by recreational boaters with 11 marinas nearby, more than half of which are in the Saguenay. Finally, other navigation components add to this portrait, like pilot vessels, research vessels, tugboats, barges, kayak and maritime safety vessels.

Due to this high volume and diversity of navigational activities, several conservation measures were put in place in the Marine Park, including a permit system for the different classes of activity, speed limits and rules concerning the observation and approach to marine mammals. However, few articles of this regulation apply to commercial shipping. To date, a voluntary 10-knot speed restriction to reduce collision risk for large whales and a recommendation to avoid navigating into SLEB habitats on the south shore are the only conservation measures aimed at reducing the impacts of marine transportation on marine mammals in the SLE (Chion et al., 2018; Lesage et al., 2014).

Marine traffic is expected to dramatically increase worldwide by 2030 (Kaplan and Solomon, 2016). The St. Lawrence Estuary is no exception given the growing number of trade agreements between Canada and foreign countries, and the growing number of associated port-industrial development projects both in the St. Lawrence Estuary and Saguenay (Gouvernement du Québec, 2015; Pêches et Océans Canada, 2018). In the absence of appropriate VUN mitigation measures, the expected traffic increase will conflict with the goals of the SLEB Action Plan (Pêches et Océans Canada, 2020). Therefore, there is a need to accurately estimate the expected impacts of such a traffic increase on belugas, the first step being to estimate the level of noise that animals would be exposed to.

1.5. Scope

Ignoring spatial patterns of SLEB's ecology at the individual level in the estimation of their exposure to noise is equivalent to using an aggregate habitat-centric approach (Aulanier et al., 2016). Current data indicate that SLEB are likely to use multiple sectors of their summer range (Chion et al., 2019a; Ouellet et al., 2021), likely leading to differential VUN exposure among individuals. The degree of spatial mixing and amount of movements among habitats are not well understood but can be tested under different assumptions about movement patterns at the individual (e.g., movement parameters) and population (e.g., spatial distribution) levels.

In this study, we used simulation to address three distinct questions. The first question (Q1) we address in this study is: Can we quantify the potential biases introduced by alternative SLEB behaviour assumptions on the estimation of beluga exposure to VUN? We address this question by using an individual-centric approach, i.e., an agent-based model (ABM) to explore the biases introduced into estimated exposure to stressors such as VUN, where individual movement patterns and habitat use are derived from different spatial behaviour assumptions. Specifically, we compare noise exposure under three sets of behavioural scenarios. The first behavioural scenario is based on belugas moving and using their habitat based on current available data, e.g., telemetry data, long-term photo-identification, and aerial survey programs. We then contrast this behavioural scenario to two alternative extremes: 1) belugas can move randomly throughout all parts of their habitats (100% spatial mixing); 2) belugas stay static and never leave their habitat (0% spatial mixing). We refer to these behavioural scenarios as *data-driven*, *spatially mixed*, and *spatially static*, respectively. The comparison between beluga exposure to shipping noise for these three behaviour scenarios will be illustrated for the Saguenay habitat where several proposed port-industrial projects could triple the current volume of shipping traffic.

The second question (Q2) we address is “Could the Saguenay be used by belugas as refuge from shipping noise compared to the St. Lawrence Estuary?” Here we use the *data-driven* behaviour scenario to estimate the effect of time spent by belugas in the Saguenay on the amount of low-frequency VUN received under current and projected traffic increase. The focal low-frequency band [11—1122] Hz has relevance in this study as it allows for isolating changes in received levels associated with shipping – the traffic component of interest here – from those of smaller watercrafts. Large ships are much louder at low-frequencies than small watercrafts, whose energy is mostly concentrated at higher frequencies (Gervaise et al., 2012; Richardson et al., 2013; Simard et al., 2016). Small watercrafts are so abundant in the Saguenay during summer (Chion et al., 2009; Turgeon, 2019) that the contribution of large ships to the cumulative traffic noise at higher frequency is diluted. While beluga hearing is most acute and their calls generally centered at frequencies greater than 1000 Hz, belugas are not deaf at low frequencies (Awbrey et al., 1988; Johnson et al., 1989) and most of their call types extend to these low frequencies (Finneran et al., 2005; Sjare and Smith, 1986). Hearing range reductions and call masking as a result of large vessel noise have been documented at these lower frequencies in belugas and other small odontocetes such as harbor porpoises, whose maximum hearing capabilities are at even higher frequencies than belugas (e.g., (Erbe and Farmer, 2000; Gervaise et al., 2012; Hermannsen et al., 2014)).

Given the Saguenay is much narrower compared to the St. Lawrence Estuary, the geography of the river might determine the maximum separation distance for beluga-ship encounters (Fig. 1). In a third question (Q3) we quantify how the distances between belugas and nearby ships in the *data-driven* behavioural scenario differ within and outside the Saguenay, and how these differences change with additional ship transits in the Saguenay.

2. Material and methods

2.1. Methods

2.1.1. Agent-based model

Agent-based models (ABMs) have been used for more than two decades as a tool to explore management scenarios in the context of natural resource management (Bousquet et al., 2002, 2001; Bousquet and Le Page, 2004; Gimblett, 2002). This modelling paradigm comes from Artificial Intelligence (Ferber, 1999) and is particularly suited to represent the dynamics of complex systems emerging from interactions between components (Grimm et al., 2005). ABMs of social-ecological systems are often considered to be in silico laboratories allowing the exploration of scientific hypotheses and to do projections on the likely effects of natural resource management scenarios.

Agent-based models are also well suited for modelling animal movement processes and patterns (Tang and Bennett, 2010) and play an important role in wildlife ecology and management (McLane et al., 2011).

2.1.2. The Marine Mammal and Maritime Traffic Simulator (3MTSim)

3MTSim is a social-ecological ABM representing the movements and interactions of vessels and whales in the St. Lawrence Estuary and the Saguenay (Fig. 1) (Chion et al., 2017; Parrott et al., 2011). 3MTSim is spatially explicit and simulates vessel and whale movement at a 1-min interval over periods that span from hours to months. The primary goal of 3MTSim is to test management scenarios to mitigate the impact of marine traffic on whales (Chion et al., 2013, 2012). Several modules of 3MTSim have already been described (Chion, 2011; Chion et al., 2017, 2011; Parrott et al., 2011) so we provide below an overview of the main modules that were improved to come up with the version of the simulator used in this study. More details about these modules are presented in Appendix A.

The current version of 3MTSim is made of four main modules (Fig. 2) calibrated and validated using multiple datasets (Table 1):

- Environment: this module is made of static (e.g., seabed composition) and dynamic processes (e.g. tides) which are known to influence whales, vessels, and acoustic propagation.
- Vessels: the current version of the simulator includes three broad categories of vessels, namely ocean-going commercial ships, cruise ships, and whale-watching vessels. Ferry and pleasure craft submodules are in the development phase. Only ocean-going commercial ships and cruise ships are included in the current study and the simulated traffic is based on 2017 vessel movements obtained from Automatic Identification System (AIS) data (Table 1).
- Whales: five species are included in 3MTSim, namely beluga, blue, fin, humpback, and minke whales. Only beluga whales are considered in this study and the datasets used to build the *data-driven* movement model are presented in Table 1.
- Acoustic: 3MTSim includes a model of large ship source level (Wittekind, 2014) and propagation loss algorithms to cover the broad range of frequencies relevant to the SLEB (Collins, 1993; Porter, 2011). The current study focuses on low frequencies as they allow for isolating changes in received levels with shipping – the focal traffic component in the study – from those of smaller watercraft. Moreover, high absorption by water molecules and instrumentation challenges have led to very limited development of medium to high frequencies models of ship source levels (Hermannsen et al., 2014).

In its current version and for the purpose of this study, 3MTSim

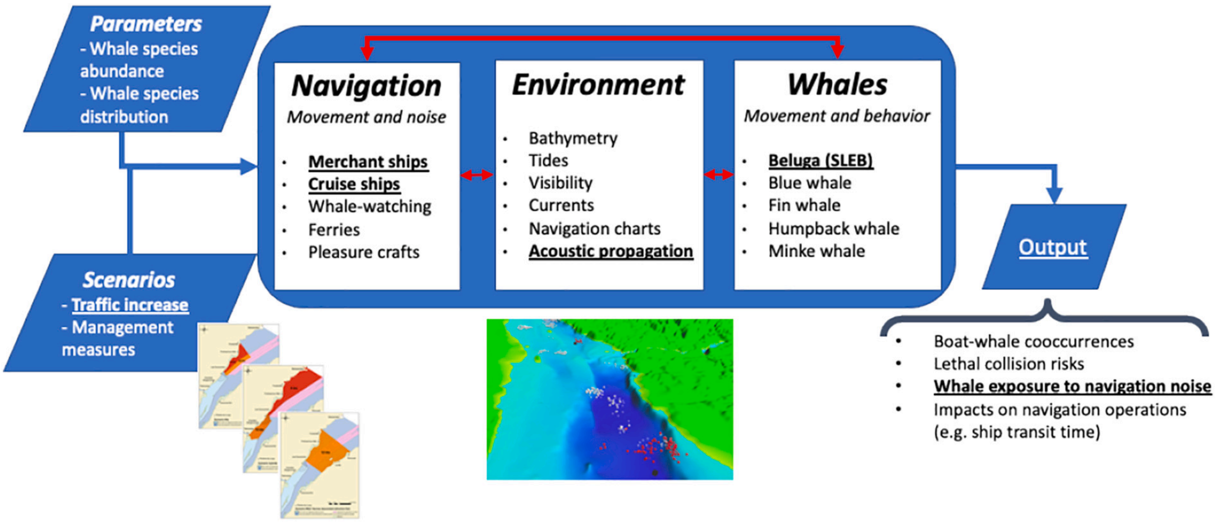

Fig. 2. Overview of 3MTSim structure, inputs, and outputs.

Table 1
Datasets used to inform the implementation of 3MTSim.

Dataset	Reference	Time frame	Description	3MTSim module
Beluga photo ID	Groupe de recherche et d'éducation sur les mammifères marins (GREMM)	1989-2007 (June–October)	Community and spatial structure	SLEB
Beluga VHF telemetry tracking and diving patterns	Fisheries and Oceans Canada and GREMM	2001-2005	3D-movement patterns	SLEB
Tracking of beluga herds	GREMM	1989-2017 (June-October)	Communities' territorial appropriation	SLEB
Beluga spatial distribution from aerial surveys	Fisheries and Oceans Canada	1990-2009 (August)	Population summer spatial distribution and high-density areas.	SLEB
AIS data	Canadian Coast Guard	2011-2018	Description of the marine traffic in the SLEB habitat	Navigation
SIM (Système d'Information Maritime) data	Innovation Maritime	2018-2019	Quantitative information on the merchant fleet	Navigation
Bathymetry	Canadian Hydrographic Service	N.A.	2D chart providing depth values across the simulator's computational area (resolution = 100 m)	Navigation& Acoustic
Seabed geoacoustic properties	(Jensen et al., 2011; Loring & Nota 1973)	N.A.	Geoacoustic properties retrieved from the sediments' nature	Acoustic
Water column geoacoustic properties	Observatoire global du Saint-Laurent (OGSL)	2004-2018 (Summer)	1) Temperature and salinity profiles as a function of depth in areas of interest (resolution = 1 m). 2) Conversion in speed-of-sound profiles as a function of depth. 3) Polynomial fitting of the speed-of-sound profiles.	Acoustic
Monopole source level signatures of merchant ships	(Wittekind et al. 2014)	N.A.	Frequency-dependent model providing the amplitude of the sound emitted by a source as a function of the source's static (e.g., length, width, draught) and dynamic (speed) properties.	Acoustic
Noise levels in the summer habitat of the SLEB	(McQuinn et al., 2011)	2004-2005	Noise levels measured at a depth of 15 m in different areas of interest	Acoustic

estimates the broadband (frequency-integrated) instantaneous (dB re 1μPa^2) and cumulative levels (dB re 1μPa^2·s over 24 h) of low-frequency noise (between 11 and 1122 Hz) received by individual belugas from large vessels in direct line of sight (i.e., without underwater landscape interference). Focusing on low frequencies allows for isolating changes in received levels associated with shipping from smaller watercrafts. While belugas hearing is most acute at frequencies greater than 1000 Hz, their audiogram also extends to low frequencies (e.g. sensitivity of 120 dB at 125 Hz (Awbrey et al., 1988)). Different scenarios of traffic intensity, noise mitigation, and beluga movement patterns can be examined using 3MTSim for their consequences on beluga VUN exposure levels.

2.2. Material

Agent-based modelling is a purposeful paradigm to integrate a variety of heterogeneous datasets about a complex system into the same environment. ABMs designed to support management decisions are generally based on multiple datasets used to parameterize, calibrate and select appropriate representations of the different components and modules following pattern-matching procedures (Grimm et al., 2005).

The main datasets used to develop the various modules of the current version of 3MTSim are presented in Table 1. The pattern-matching approaches used to calibrate the main modules of 3MTSim used in this study are presented in Appendix A.

2.2.1. Simulation experiments

To simulate the impact of a hypothetical increase in ship traffic on belugas in the Saguenay, we used the projection data provided by the port-industrial projects proponents, which include the number of additional ship transits in the Saguenay (up to 770 transits per year) along with the main characteristics of the expected chartered ships. It is important to note that these additional transits in the Saguenay also add to the traffic in the Lower Estuary as they transit to and from the Atlantic Ocean, thus insonifying that portion of the SLEB's critical habitat as well.

We thus simulated two different traffic scenarios:

- Reference scenario: 2017 traffic (450 transits in the Saguenay);
- Traffic-increase scenario: 2017 traffic +770 transits/year in the Saguenay.

According to project proponents, the additional ship transits would be evenly distributed throughout the year, leading to a mean increase from the current 1.2 transits/day to approximately 3.3 transits/day.

To compare beluga noise exposure levels between the two scenarios, we ran 10 replicates of 10 days for each traffic scenario, using different random seeds to account for stochastic processes occurring during simulations. The post-processing steps of simulation outputs are described below.

2.2.2. Post-processing of simulation outputs

For computational reasons, only ship-to-beluga pairs separated by less than 35 km were considered in this work.[1] Individual contributions for up to five ships were added incoherently[2] to give broadband (11–1122 Hz) received noise levels (RLs) for each animal at each timestep (see Section Material and Methods/3MTSim/Acoustic module). A default value of 0 dB re 1μPa^2 was attributed to RL when:

- an animal was in no direct line-of-sight with any ships present in the simulation at a given timestep, or,
- an animal was in direct line-of-sight of some ships but they were all located more than 35 km away from the receiving animal, or,
- an animal was in direct line-of-sight with ships closer than 35 km, but sound attenuation and water absorption along these lines-of-sight exceeded noise source levels hence leading to negative RL values.

Frequency-integrated 24-h sound exposure levels (SELs; see Section 3.1.3.5 in (ISO 18405, 2017)) were computed for each animal and each of the 10-day period that constituted a simulated run according to:

$$SEL_{24h-sim} = 10 \cdot log_{10}\left(\sum_{i=1}^{1440} 10^{(RL_i/10)} \times 60 \times 60 \times 24\right) for\ RL_i \neq 0\ dB\ re\ 1\mu Pa^2 \quad (1)$$

where i is the number of minutes elapsed since midnight of a given simulated day (1440 min/day). In some cases where all RL_i equalled 0 dB re 1μPa^2 during the whole 24 h period (see above), a default value of $SEL_{24h\text{-}sim} = 0$ dB re 1μPa^2·s was attributed to the beluga. The reader will notice the use of logarithmic metrics in this work, hence relative differences of +3 dB are equivalent to twice the amount of acoustic power (i.e., factor of $10^{3/10}$). This applies for both RL and SEL acoustic metrics.

2.2.3. Noise exposure under three beluga whale behaviour scenarios (Q1)

We computed $SEL_{24h\text{-}sim}$ from instantaneous RL values (Eq. (1)) generated during beluga-ship interactions in the simulation, with a special focus on the Saguenay. For the *data-driven* behavioural scenario, RL values from each simulated individual beluga was used to calculate an $SEL_{24h\text{-}sim}$ for each day in the simulation. This behavioural scenario was based on estimated use of the Saguenay from a long-term photo-identification program (Bonnell et al., in prep.; Chion et al., 2019a), and thus represents our current understanding of habitat use by individuals in this population. A total of 100 belugas were simulated using the *data-driven* behavioural scenario for each replication, and $SEL_{24h\text{-}sim}$ values were calculated for all belugas who visited the Saguenay at least once.

The estimation of $SEL_{24h\text{-}sim}$ for the *spatially static* and *spatially mixed* behavioural scenarios used RL values output from the *data-driven* behavioural scenario simulations. For the *spatially static* behavioural scenario, $SEL_{24h\text{-}sim}$ values were calculated from 1440 randomly sampled RLs that were generated within the Saguenay to represent a population where belugas using the Saguenay are always the same, and reside in the Saguenay 100% of their time. This sampling strategy was repeated until the sample size matched with the outputs of the *data-driven* behavioural scenario. In contrast, $SEL_{24h\text{-}sim}$ values for the *spatially mixed* behavioural scenario were also based on 1440 randomly sampled RLs, except that we sampled RLs only from belugas who spent ~5% of their time in the Saguenay. This scenario was meant to mimic the other extreme of beluga exposure, i.e., where individuals make use of the Saguenay in proportion to its contribution to estimated population density but use all other areas of the summer habitat as well. This sampling strategy was repeated until the sample size matched with the outputs of the *data-driven* behavioural scenario.

We ran a series of multilevel models under a Bayesian framework to compare noise exposure of simulated belugas between the different scenarios. We first ran a gaussian multilevel model (Gelman and Hill, 2006) using $SEL_{24h\text{-}sim}$ as the response variable, with the behaviour (*data-driven*, *spatially mixed*, *spatially static*) and traffic (*2017 traffic*, *traffic increase*) scenarios as predictor variables, and beluga ID as a random intercept. The model was run with an interaction between behaviour and traffic scenario to allow for differential effects of traffic on exposure depending on the behavioural scenario. To account for potential differences in variation of $SEL_{24h\text{-}sim}$ values within scenarios, we modeled the sigma parameter of the gaussian distribution using an interaction between behavioural and traffic scenario conditions. Individual beluga ID was also included as a random intercept for the sigma parameter. Variables were scaled and centered, and weakly informative priors centered on zero were used (i.e., normal(0,1)).

In the absence of a widely accepted threshold for impacts of noise on marine mammals (Gomez et al., 2016), we assessed potential impacts on beluga whales by using a long-used 120 dB re 1μPa^2 RMS threshold for potential acoustic impacts on marine mammals or their acoustic environment as a reference (Fisheries and Oceans Canada, 2012; Richardson et al., 1995). We then ran a multilevel model using a zero inflated beta distribution with percentage of RL > 120 dB re 1μPa^2 RMS as the response variable, and the same predictors as for the $SEL_{24h\text{-}sim}$ model with beluga ID as a random intercept. A third multilevel model was also run using a zero-one inflated beta distribution with percentage of RL = 0 dB re 1μPa^2 as the response variable and the same predictors as the $SEL_{24h\text{-}sim}$. This model was used to quantify changes to the amount of quiet time expected under alternative scenarios, i.e., moments when a beluga is not exposed to noise from marine traffic.

2.2.4. The effect of the time spent in the Saguenay on noise exposure levels (Q2)

To assess the value of the Saguenay for belugas as a quiet zone and a potential refuge from shipping noise, we used the outputs of the *data-driven* behavioural scenario and estimated the effect of the percentage of

[1] This was supported by series of 3MTSim runs revealing that, beyond 35 km, broadband received noise levels for singular exposure were on average below 90 dB re 1μPa^2 which is approximately equivalent to the broadband ambient noise in the SLEB habitat. Consequently, we assume that beyond 35 km, the noise contribution of individual ships at the position of the beluga will be indistinguishable from the ambient noise.

[2] Ships are independent from each other. Hence, their combined contribution to the acoustic environment is the sum of out-of-phase independent signals (i.e., incoherent addition). By opposition, the addition of totally-in-phase signals is said to be coherent.

time spent in the Saguenay on an individual's cumulative noise exposure ($SEL_{24h\text{-}sim}$).

Using a gaussian multilevel model with $SEL_{24h\text{-}sim}$ as the response variable, the percentage of time each beluga was seen in the Saguenay in the simulation, and the traffic scenario as predictors. Both response and predictors were scaled and centered, and weakly informative priors centered on zero were used. We ran the model with an interaction between the percentage of time spent by belugas in the Saguenay and the traffic scenario to allow for the percentage of time in the Saguenay to have different impacts on $SEL_{24h\text{-}sim}$ depending on the traffic scenario. Beluga individual ID was added as a random intercept in the model. Given there were few belugas who showed high usage of the Saguenay, we ran the model excluding higher values above the 50% usage to test the robustness of the results. As the results remained qualitatively the same, we present only the full model and present the subsetted model in the supplementary sections (Fig. B.1).

2.2.5. *Contrasting beluga-ship encounter distances within and outside the Saguenay (Q3)*

Distances of encounter between belugas and the closest ship were compared between the Saguenay and the rest of their habitat using kernel density estimates (Chacón and Duong, 2018), as well as gaussian multilevel models. In the latter models, beluga location relative to the Saguenay (in or out) and whether or not additional traffic was in effect were used as binary predictors. This model included an interaction term to allow the effect of additional traffic to impact encounters differently if they took place within or outside the Saguenay.

3. Results and discussion

3.1. *Noise exposure under three beluga whale behaviour scenarios (Q1)*

When we compared exposure characteristics between the behavioural scenarios, we found the results differed both in terms of mean exposure and how exposure changed in response to added marine traffic (Fig. 3).

The mean $SEL_{24h\text{-}sim}$ of simulated belugas under the current volume of traffic was 187.71 dB (95%CI: 187.16, 188.31) for *data-driven*, 193 dB (95%CI: 191.69, 196.49) for *spatially mixed*, and 181.13 dB (95%CI: 178.84, 183.70) for *spatially static* behavioural scenario over 24 h (Fig. 3a, Table B.1). The addition of traffic in the Saguenay led to an increase in their mean exposure of 2.62 dB re 1μPa^2·s (95%CI: 1.94, 2.23) for the *data driven* scenario. For the *spatially mixed* scenario, the increase was 0.60 dB re 1μPa^2·s (95%CI: 0.44, 0.75), while for the *spatially static* scenario, $SEL_{24h\text{-}sim}$ was estimated to increase by 11.41 dB re 1μPa^2·s (95%CI: 11.09, 11.73)(Fig. 3a).

The mean percentage of exposure events greater than 120 dB re 1μPa^2 were 1.80% (95%CI: 1.71, 1.91) for *data-driven*, 3.75% (95%CI: 2.34, 5.16) for *spatially-mixed*, and 0.66% (95%CI: 0.40, 0.91) for *spatially-static* scenarios. When considering the change in percentage of RL > 120 dB re 1μPa^2, we found that the largest increase in exposure with the increase in traffic was obtained under the *spatially-static* scenario (Fig. 3b, Table B.2). High exposures in this scenario increased by 1.20% (95%CI: 0.76, 1.67), compared to 0.70% (95%CI: 0.58, 0.82) for the *data-driven* scenario, and 0.61% (0.38, 0.88) for the *spatially-mixed* scenario (Fig. 3b).

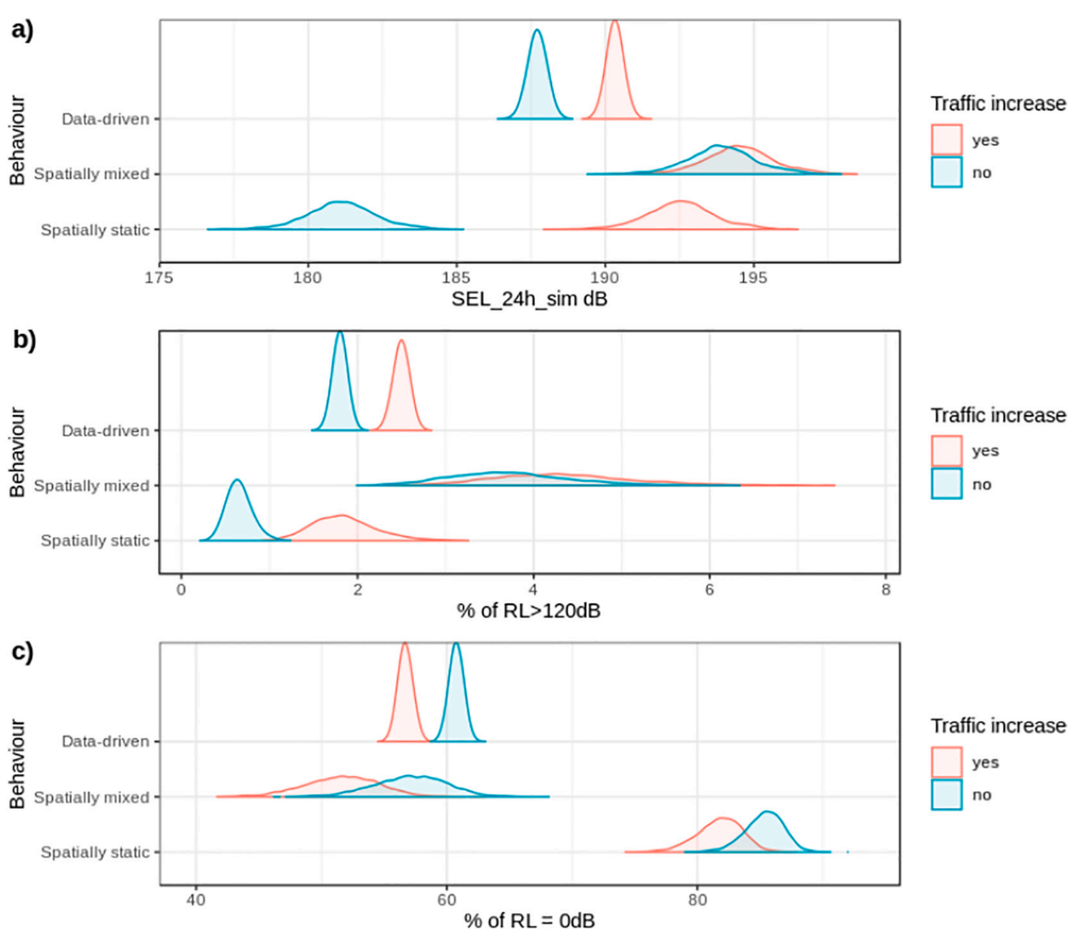

Fig. 3. Exposure for simulated belugas using the Saguenay following the three behavioural scenarios with two traffic conditions. Changes in exposure are measured with: a) cumulative exposure using $SEL_{24h\text{-}sim}$, b) high exposures using the percentage of instantaneous exposures above 120 dB re 1μPa^2 RMS, and c) low exposures using the percentage of instantaneous exposures where there was no noise generated from nearby traffic (i.e., within 35 km).

The mean percentage of time during the day without noise was 60.76% (95%CI: 59.72, 61.75) for data-driven, 57.13% (95%CI: 51.09, 62.94) for spatially-mixed, and 85.33% (95%CI: 82.22, 88.22) for spatially-static (Fig. 3c) scenarios. When considering changes in the percentage of no-noise exposures we found that when traffic increased this percentage dropped most for the *spatially-mixed* scenario: -5.47% (95%CI: −6.04, −4.88) (Fig. 3, Table B.3). This was followed by the *data-driven* scenario with −4.07% (95%CI: −5.21, −2.84), and *spatially-static* scenario with -3.58% (95%CI: −4.30, −2.92) (Fig. 3c).

These results show how the variation in impacts of increased marine traffic to the beluga population is dependent on individual beluga behaviour. Not surprisingly, we see the *spatially static* scenario, which calculates exposures assuming belugas remain within the Saguenay, results in the greatest impacts in terms of both cumulative exposure ($SEL_{24h\text{-}sim}$) as well as high exposure events (>120 dB). Surprisingly, however, the *spatially mixed* scenario, which is calculated assuming only a 5% use of the Saguenay, shows a similar, but slightly less pronounced, reduction of quiet periods. In contrast, the *data-driven* model fell in-between the two extreme scenarios of completely static or mixed movement behaviour, except for estimates of $SEL_{24h\text{-}sim}$ where the *data-driven* model showed the lowest mean $SEL_{24h\text{-}sim}$ under the traffic increase scenario. Overall, these results point to the potential variability expected in exposure due to variation in individual beluga behaviour.

3.2. *The effect of time spent in the Saguenay on noise exposure levels (Q2)*

Our model estimtes that individuals who used the Saguenay more had higher $SEL_{24h\text{-}sim}$ under the scenario with additional traffic (Fig. 4a, Table B.4). When we looked at the estimated effect of time spent in the Saguenay under the current traffic scenario, we found that each additional percentage of time within the Saguenay reduced $SEL_{24h\text{-}sim}$ by -0.07 dB re 1μPa^2·s (95%CI: -0.10, -0.03) (Fig. 4b). While in the scenario with increased marine traffic, we found that increased use of the Saguenay no longer showed a decreasing effect on $SEL_{24h\text{-}sim}$: 0.03 dB re 1μPa^2·s (95%CI: 0.00, 0.07) (Fig. 4b).

This result suggests that under the current traffic scenario, the Saguenay appears to be a less noisy habitat for belugas compared to the St. Lawrence Estuary with regard to low frequencies. This result is in line with acoustic measurements which clearly identified the Saguenay as one of the quietest areas of the SLEB core habitat (McQuinn et al., 2011). However, under the increased traffic scenario, simulations suggest that cumulative low-frequency VUN received by belugas in the Saguenay would be similar to that received in the St. Lawrence Estuary, so that the Saguenay would no longer be a quiet zone with respect to low-frequency noise. If belugas prefer quieter areas for some of their vital activities, our results highlight the risk that a projected increase from 1.2 to 3.3 ship transits per day in the Saguenay could lead to a loss of this important feature within part of their critical habitat.

3.3. *Contrasting beluga-ship encounter distances within and outside the Saguenay (Q3)*

When we visually compared the kernel density estimates of the distances to the closest vessel (within 35 km) we found that outside the Saguenay did not differ greatly with additional traffic (Fig. 5). Within the Saguenay, we found that the distribution did show evidence of change, with closer encounters becoming more common (Fig. 5).

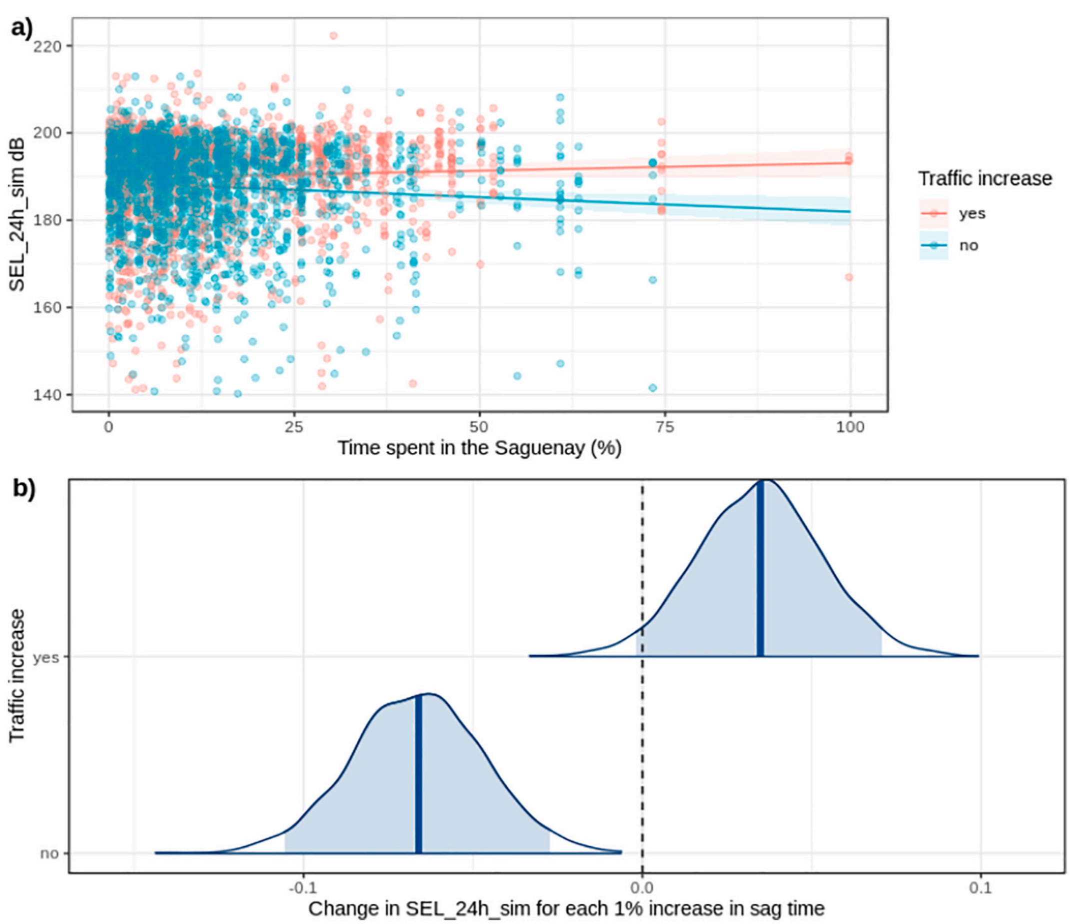

Fig. 4. Estimated impact of the amount of time a beluga spends in the Saguenay on $SEL_{24h\text{-}sim}$, for scenarios with and without extra traffic to the Saguenay: a) scatter plot with modeled mean trend line, and b) estimated slopes for the simulated scenario with and without additional marine traffic in the Saguenay.

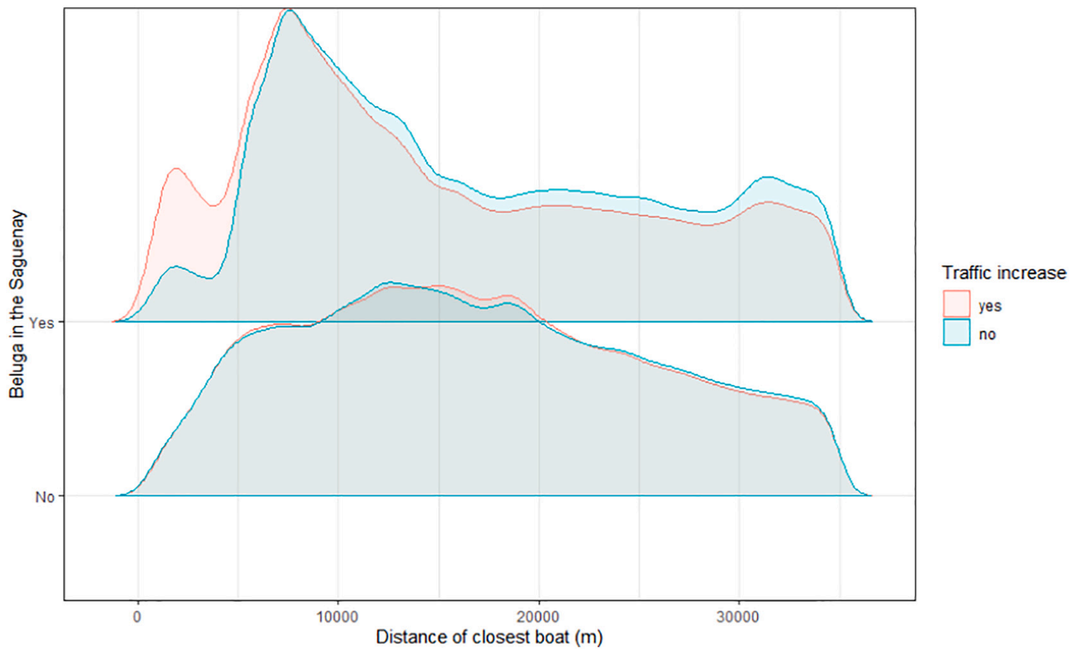

Fig. 5. Kernel density estimates of the distance to the closest vessel within (labeled yes), and outside of (labeled no), the Saguenay. In both cases a kernel density estimate is provided under scenarios where additional traffic is, and is not, present.

To add to the visual comparisons, we estimated differences in mean beluga-ship interaction distances (Table B.5). We estimated that the difference in the mean distance between a beluga and the closest ship in the Saguenay was reduced by -1629 m (95%CI: -1869,-1368) under the increased traffic scenario. Outside the Saguenay, additional traffic was estimated to have a minimal impact on the mean distance of beluga-ship interactions; i.e. only by -115 m (95%CI: -147, -87). When beluga-ship interactions inside the Saguenay were compared to interactions outside, we found that the mean within Saguenay interactions was -15 m (95%CI: -228, 182) lower under the current traffic scenario. Under the increased traffic scenario, beluga-ship interactions in the Saguenay showed evidence of closer beluga-ship interactions compared to outside, with an estimated difference of -1529 m (95%CI: −1708, −1358).

The kernel density results suggest that the geography of the Saguenay does increase the proportion of close encounters (<5 km) under current conditions, and this geographic effect is exacerbated when traffic into the Saguenay is increased (Fig. 5). In addition, under the scenario with additional traffic, the results also suggest that the mean beluga-ship distances will decrease more in the Saguenay than in the Estuary.

4. Conclusion

Agent-based modelling is well suited to represent spatio-temporal behaviours of wildlife populations at different scales of aggregation, from individual to communities. We used a spatially explicit ABM that represents the movements of ships and belugas along with their acoustic interactions in the St. Lawrence Estuary and the Saguenay Rivers to assess how noise exposure within the SLEB population might change.

We first assessed the impact introduced by different assumptions of beluga movement behaviour on noise exposure. Our simulations showed that the estimation of beluga exposure to VUN (instantaneous and cumulative) at the individual level is significantly influenced by the behaviour assumption underlying their movements. This is potentially important when constructing and testing how uncertainty in individual movement models might impact resulting exposure. It also illustrates the importance of understanding the variability in movement and habitat use behaviour within a population.

Our simulation results also suggest a loss of the Saguenay as a quiet zone and a potential low-frequency acoustic refuge under an increased ship traffic scenario. We found that in terms of low-frequency noise, the Saguenay reduced SLEB exposure to VUN under the current shipping regime. This quiet zone effect was no longer present in the scenario with increased shipping. Similarly, when considering distances of beluga-ship interactions in the Saguenay, while there were no large differences under current traffic regime, distances were found to be closer by 1629 m when traffic was increased. This also suggests a degradation of the value of the Saguenay in terms of interactions with marine traffic, with a disproportionate effect on females and calves.

Results obtained at the individual scale based on *data-driven* assumption of beluga behaviour allowed the variability in VUN accumulated by belugas at the individual scale to be identified; these results would go undetected using an approach aiming to assess population-level VUN conducted at the habitat scale. Such a knowledge gap in an acoustic impact assessment approach would lead to an underestimation of the levels of noise received by the most exposed animals. This would underestimate population-level consequences if these animals happen to be the most vulnerable of the population. Given the importance of the Saguenay for beluga females and calves, which are critical for conservation management, our results support the relevance to accurately describe and account for beluga behaviour to achieve a complete acoustic impact assessment.

To estimate the distribution of exposure to VUN within a population there requires some assumption of animal habitat use behaviour. This is true for agent-based modelling approaches as well as for habitat-based approaches which overlay cumulative noise maps with species distribution maps. There is a need to better quantify how individuals within populations make use of their habitats. In our agent-based simulation, belugas were made to move based on a data-driven movement model representing our current best estimates of spatial behaviour. We also contrasted this movement model against the extreme assumptions that beluga stay in a given location or they all have the same probability to be in each location of their habitat. Our findings suggest the importance of these movement behaviour assumptions on subsequent predictions about how individual exposure will change under increased shipping scenarios. Consequently, we advocate for a focus on the importance of these behavioural assumptions, and the need to collect data at the individual level to better inform these behavioural assumptions and models. This is especially important surrounding potential impacts on beluga behaviour by nearby vessels and noise exposure. With increasingly realistic behavioural assumptions more accurate estimates of the distribution of exposure within populations will be possible.

5. Future work

We conducted separate pattern-matching validation for the main modules of our ABM to gain confidence into simulation predictions. However, a sensitivity analysis would help to assess the robustness of our results by varying parameters and assumptions to go through the envelopes of uncertainty. Specifically, we are aiming to test alternative source level models for ships and extend the frequency range to higher frequencies. Shipping noise have been mostly studied at low frequencies where it is dominant. However, traffic noise from large ships and smaller watercrafts extends to higher frequencies that will need to be included in further developments to comprehensively assess VUN impacts on belugas and other species.

Acoustic propagation in the Saguenay is influenced by complex physical effects such as reverberation on rocky underwater cliffs of the fjord. Because these effects are not accounted for by the acoustic propagation algorithm used in the current study, comparing in situ acoustic measurements in the Saguenay with simulated data would allow to quantify 3MTSim prediction error.

The beluga whale is a highly social species characterized by social-spatial patterns at different levels of aggregation that can affect estimates of exposure. We plan to incorporate individual social behaviours that reproduce observed distributions of pod and herd sizes. We also plan to develop fission and fusion behaviour that reproduces observed association patterns within the population.

Finally, Dtag devices deployed on SLEB provide movement data which can be used to determine an animal's response to the presence of nearby vessels that can be subsequently implemented in 3MTSim. After implementing the other main categories of vessels into 3MTSim, the acoustic data obtained from Dtag devices can be used to validate the simulated SLEB exposure to vessel noise by mimicking into the simulator the traffic that was active in the vicinity of the tagged animal.

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.

Acknowledgement

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Model availability

Anyone interested in 3MTSim should contact the corresponding author for any questions about model availability, its potential applications to other contexts, or any other matter.

CRediT authorship contribution statement

CC: Conceptualization; Programming; Data analysis; Funding acquisition; Investigation; Methodology; Writing - original draft; Writing - review & editing.

TB: Programming; Data analysis; Methodology; Writing - original draft; Writing - review & editing.

DL: TB: Programming; Data analysis; Writing - original draft; Writing - review & editing.

RM: Data acquisition/sharing; Funding acquisition; Investigation; Methodology; Writing - original draft; Writing - review & editing.

VL: Data acquisition/sharing; Methodology; Writing - original draft; Writing - review & editing.

AD: Methodology; Writing - original draft; Writing - review & editing.

IM: Methodology; Writing - original draft; Writing - review & editing.

ST: Map creation; Writing - original draft; Writing - review & editing.

Appendix A. Overview of 3MTSim's main modules

A.1. Environment module

A.1.1. Bathymetry

Bathymetric data for the zone of interest were retrieved from the Canadian Hydrographic Service and interpolated on a 100-m mesh grid. This provided the spatial resolution of the acoustic module described below.

A.1.2. Sea-surface and sea-bottom properties

Sea-surface is considered to be ice-free, flat and without sea-level variations. Elastic waves are not modeled in the ocean bottom (fluid equivalent bottom), and its structure has been defined as a 200-m thick sediment deposit lying on a semi-infinite bedrock. Sediment nature has been taken from the geological survey of Loring and Nota which was digitized and geo-referenced to our zone of interest. Geo-acoustical properties of the sediments have been approximated according to Table 1.3 of Jensen et al. (Jensen et al., 2011). In all, 9 distinctive zones were identified in the St. Lawrence Estuary, each with their specific properties in sediment nature.

A.1.3. Sound speed profiles

Water temperature (T) and salinity (S) profiles with 1-m resolution along the depth (z) axis were provided by the Observatoire global du Saint-Laurent (https://ogsl.ca]). Since the number of observations was not enough to reliably interpolate the data to the whole zone of interest, sound speed profiles were considered constant inside each of the 9 areas circumscribed by zones of constant sediment nature described above.

In each of these zones, between 5 and 30 T-z and S-z profiles were selected from the OGSL. For each (T, S, z) pair, the corresponding speed of sound value c_w was provided by Eq. (2) of Leroy et al. (Leroy et al., 2008). A high-order polynomial fit was then applied to the resulting c_w-z data. Coefficients were then stored in the 3MTSim environment. This was repeated for all 9 zones of constant sediment nature.

A.2. Shipping traffic module

The shipping traffic module simulates ship transits throughout the study area that have the same characteristics as the 2017 traffic. Each simulated ship is characterized by a series of attributes such as length, breadth, draught, and operational speed drawn from the 2017 traffic. Ship routes are represented by a series of waypoints drawn from INNAV data and the spatial variability around these waypoints is extracted from AIS data, both datasets provided by the Canadian Coast Guard. Ship speed is based on AIS data and ship positions between each waypoint are interpolated during the runtime using ship speed in combination with a pathfinding algorithm (Chion, 2011).

A.3. Beluga movement and data-driven behaviour model

A.3.1. Overview

Beluga movements are simulated using a *data-driven* movement model. The *data driven* movement model uses areas of high beluga density within the St. Lawrence Estuary and Saguenay as preferential locations underlying the movement patterns of simulated belugas. In this model, belugas are first randomly placed within the St. Lawrence Estuary, weighted by estimated population density. These belugas are then assigned to a high density area (HDA) toward which they preferentially travel. Once they reach their desired HDA they then perform milling behaviour within the high density area (as observed in SLEB within areas considered as high residency areas; (Lemieux Lefebvre et al., 2012)). After a set period of time, chosen from an exponential distribution of waiting times, they initiate a movement toward another HDA. During these movements, simulated belugas choose how long to stay at the surface based on a gamma distribution of surface times. Once the surface time has been reached, the beluga chooses a max depth based on a lognormal distribution of max dive depths and starts a dive. If the dive takes more than one time step to accomplish, the dive trajectory is calculated using a quadratic shape, and the beluga takes multiple steps to complete this trajectory based on a fixed dive velocity.

To parameterize the *data-driven* model we use 1) beluga high density areas identified previously from 35 aerial surveys spanning 18 years, 2) information from a long-term (18 years) SLEB photo-identification program to set the transition probabilities of belugas choosing which HDA to travel to (Bonnell et al., in prep.; Chion et al., 2019a), 3) depth sensor data from 40 belugas equipped with archival tags to describe the diving behaviour of individual beluga (Lemieux Lefebvre et al., 2012), and 4) radio-telemetry data of these 40 individuals to set the step length and turning angles of belugas characteristic of traveling behaviour between HDAs and milling behaviour within them. An exponential distribution with a mean of 2 days was used to draw waiting times for belugas choosing how long to spend around HDAs. The exponential distribution was chosen based on the assumption that most visits to HDAs are short. In a few cases, they could be longer, however, there is a lack of individual-level data around long-term movements and habitat use, e.g., individual follows by telemetry that last for weeks or months. Pattern matching results between simulated and observed belugas are presented in the Section A.3.2 below.

An important aspect of the data-driven model that is currently lacking is a behavioural response on the part of the simulated belugas to the presence of marine traffic. This is due to the need for data on how individual belugas respond to the presence of nearby ships. The collection of behavioural data and incorporation of behavioural adjustments in the simulation is a high priority in future research efforts.

A.3.2. Pattern matching between simulated and observed beluga

A pattern-oriented modelling approach was used to construct the *data-driven* movement model governing the displacement and habitat use behaviour of simulated belugas (Grimm et al., 2005). Given the modelling choices and parameterization of the *data-driven* model, we found that 1000 simulated belugas, over a 30-day period, showed spatial patterns similar to belugas living within the St. Lawrence Estuary. Comparing space use within the St. Lawrence Estuary using kernel density estimates from the simulation, and density estimates from the aerial surveys, found a mean correlation of 0.78 (sd = 0.02). This mean correlation showed no evidence of systematic decline during simulation, suggesting that the *data-driven* movement model was able to maintain a similar spatial distribution of Beluga as seen in the aerial surveys. While the mean percentage of the population that was seen within the Saguenay over the 30-day period in the simulation was 4.09% (sd = 0.79%), compared to 5% which was estimated to be the case in the actual population (Gosselin et al., 2017; Ouellet et al., 2021). Similarly, when we compared observed and simulated distributions of beluga positions in terms of depth, we found a correlation of 0.94 (0.93, 0.94). These results suggest that the simulated 3d spatial distribution of the population well represents the actual observed beluga population. Similarly, when we randomly sampled individuals in the simulation within the Saguenay at the same rate as observed in the photo-ID database, we found a mean of 48 (sd = 2) unique individuals visited the Saguenay over the 30-d period, while in the actual population the observed number was 47-48. These results suggest that in the simulation, the mixing of individuals within the Saguenay region of the St. Lawrence Estuary reproduces similar patterns to the observed population. Overall, these results are promising, but do suggest that there remain opportunities for improving the spatio-temporal patterns of habitat use in the simulated belugas, e.g., increasing the similarity in spatial distribution above 0.79, spatially explicit comparisons of depth behaviour, and expanding beyond the Saguenay when comparing the unique number of individual belugas using particular regions of the St. Lawrence Estuary.

A.4. Acoustic module

A.4.1. Description

The acoustic module is executed for each ship-beluga pair with direct line-of-sight between both parties. The frequency range of interest corresponds to all 20 1/3-octave bands between 12.5 and 1000 Hz. When transposed to integer frequencies in bins of 1 Hz, our approach provides the acoustical information between 11 and 1122 Hz.

Monopole source levels (MSLs) are predicted via the model of Wittekind (Wittekind, 2014) for which a canonical single mass engine of 200 tons was used. This value obtained reasonable success in our attempt to replicate results provided in McQuinn et al. (2011) and Lesage et al. (2014) (see Section A.4.2 below). Block coefficients are calculated as a function of ship length and speed as suggested by Barrass (2004). 1/3-octave band MSL values returned by the Wittekind model were then equally spread to all integer frequencies within the corresponding band (i.e., integration along the frequency domain yields the original 1/3-octave band prediction of the MSL model).

For all timesteps MOD 10 with null residue, transmission loss (TL) along the ship-to-beluga path were calculated using the split-step Padé approximation of the parabolic equation method (Collins, 1993) for the central frequencies of all 1/3-octave bands of interest. Properties of bathymetry, sediments type, and sound speed gradients were implemented in the 3MTSim platform. Although numerically reliable and highly range-dependent, the RAM algorithm is also highly time-consuming (especially when the frequency increases above 200 Hz). For timesteps MOD 10 with non-null residue, the RAM model was replaced by Eq. (3) of Gassmann et al. (2017). With negligible computing time, the Gassmann model corrects for sound attenuation attributed to surface reflections (Lloyd's mirror effects) but is range-independent and does not consider variations of the geomorphological terrain and chemical properties along lines-of-sight connecting sources and receivers. Artificial intelligence via gradient boosting methods (XGBoost) was used to interpolate RAM predictions from timesteps MOD 10 = 0 to timesteps MOD 10 > 0 using Gassmann predictions for timesteps MOD 10 > 0 and the ship-to-beluga bathymetry profile at these specific timesteps. Following data training, our XGBoost approach under R was able to retrieve RAM approximations within 3 dB re 1μPa^2 of the ground-truthed values. Final predictions for TL were fine-tuned to account for frequency-dependent absorption by water molecules according to the François & Garrison equation (Francois and Garrison, 1982a, 1982b). TL was assumed to be roughly constant inside a given 1/3-octave band and, therefore, RAM (for timesteps MOD 10 = 0) and interpolated-RAM (for timesteps MOD 10 > 0) predictions were assumed equal for all integer frequencies within a given band.

Subtraction, frequency-by-frequency, of the TL and MSL vectors yields instantaneous sound pressure received levels (RL) at the position of the animal for each integer frequency under study. The RL calculation is repeated for all ships with direct lines-of-sight to the animal within a given timestep. The individual RL contributions are then summed as non-coherent sources. Integration over the frequency domain of the final RL vector provides the broadband measurement of the instantaneous noise received per timestep.

A.4.2. Choice of a MSL model

Table 2 in Lesage et al. (2014) provides the static parameters of 13 ships for which underwater radiated noise was measured in the summers of 2004 and 2005 in our zone of interest within the St. Lawrence Estuary. The authors' supplementary material gives the tracking information for 8 of those ships including ship and hydrophone positions, ship instantaneous speed and ship broadband RL for 1/12-octave bands between 0.021 and 22.988 kHz. This allowed us to investigate the efficiency of MSL models to replicate data from Lesage et al. (2014). Three models were tested, namely Simard et al. (2016) (Simard et al., 2016), Wittekind (2014) (Wittekind, 2014) and Audoly and Rizzuto (2015, hereafter reffered as AQUO 2015) (Audoly and Rizzuto, 2015). Broadband RL predictions by the three models were computed between 21 and 1108 Hz (which approximately matches the frequency domain explored in the present study) at each minute of the authors' 10-minutes observations. Transmission loss was calculated using the already integrated RAM module of 3MTSim as well as bathymetric information, sediment nature and water column stratification in speed of sound. An example is provided in Fig. A.1 for the Federal Yoshino, a 190-m bulk carrier.

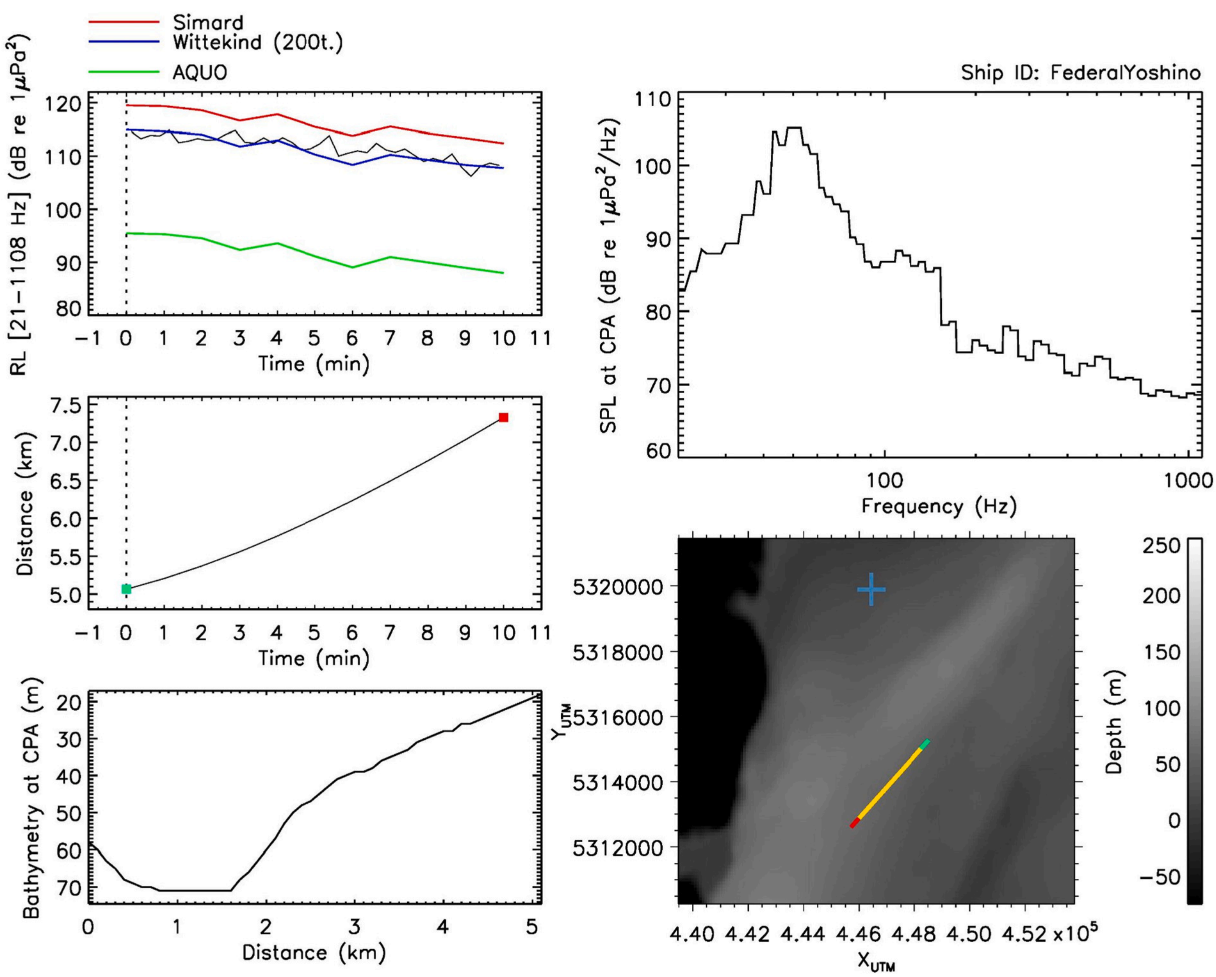

Fig. A.1. Efficiency of the MSL model to reproduce data from Lesage et al. (2014). Left column: Upper panel. Broadband RL predictions between 21 and 1108 Hz by Simard et al. (2016) (in red), Wittekind (2014) (in blue), and AQUO (2015) (in green). Opportunistic measurements by Lesage et al. (2014) are shown in black. Time of the observations are given in abscissa from the start (0th minute) to the end (10th minute) of the recording. The vertical dotted line marks the time of the ship's CPA. Middle panel. Distance in km separating the ship from the hydrophone as a function of time. Green and red squares indicate the start and the end of the recording. Bottom panel. Bathymetric profile as a function of distance between the hydrophone and the ship at CPA. The hydrophone is at the far-left side of the abscissa and the ship is at the far-right end. Right column: Upper panel. 1/12-octave bands of the received noise levels at CPA. Bottom panel. Bathymetric map of the St. Lawrence Estuary. The position of the hydrophone is marked by the blue cross. Yellow line follows the path of the ship between the start (green square) and end (red square) of the recording. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Results have shown that 4 out of 8 ships recorded by Lesage et al. (2014) (Lesage et al., 2014) were effectively reproduced in terms of MSL signature by the Wittekind (2014) model (Wittekind, 2014). 3 out of 8 agreed with the AQUO (2015) model and 1 out of 8 could not be reliably reproduced by any model. For the present study, sources were simulated in terms of MSL profiles using Wittekind (2014).

A.4.3. Validation of the PE solver algorithm

A qualitative investigation of the RAM transmission loss algorithm's reliability was carried out in an attempt to reproduce observational results provided in Fig. 5 in Aulanier et al. (2016) using static receivers on the 3MTSim platform. The authors' Fig. 4 indicates the position of their AS^4 observatory for which received noise levels per frequency bin (dB re 1μPa^2/Hz) were computed at depths of 62, 161, and 288 m. Sources were modeled accordingly using the LBDS model found in Simard et al. (2016). Transmission losses at 16, 20, 40, and 63 Hz were obtained at each tick using 3MTSim's acoustic modules. The simulation was run for 6 computational days (i.e., 8640 ticks). Probability density functions of the received noise levels are shown in Fig. A.2. The agreement with the red curves (observational results corrected for strumming pseudonoise) presented in the Fig. 5 found in Aulanier et al. (2016) is qualitatively asserted.

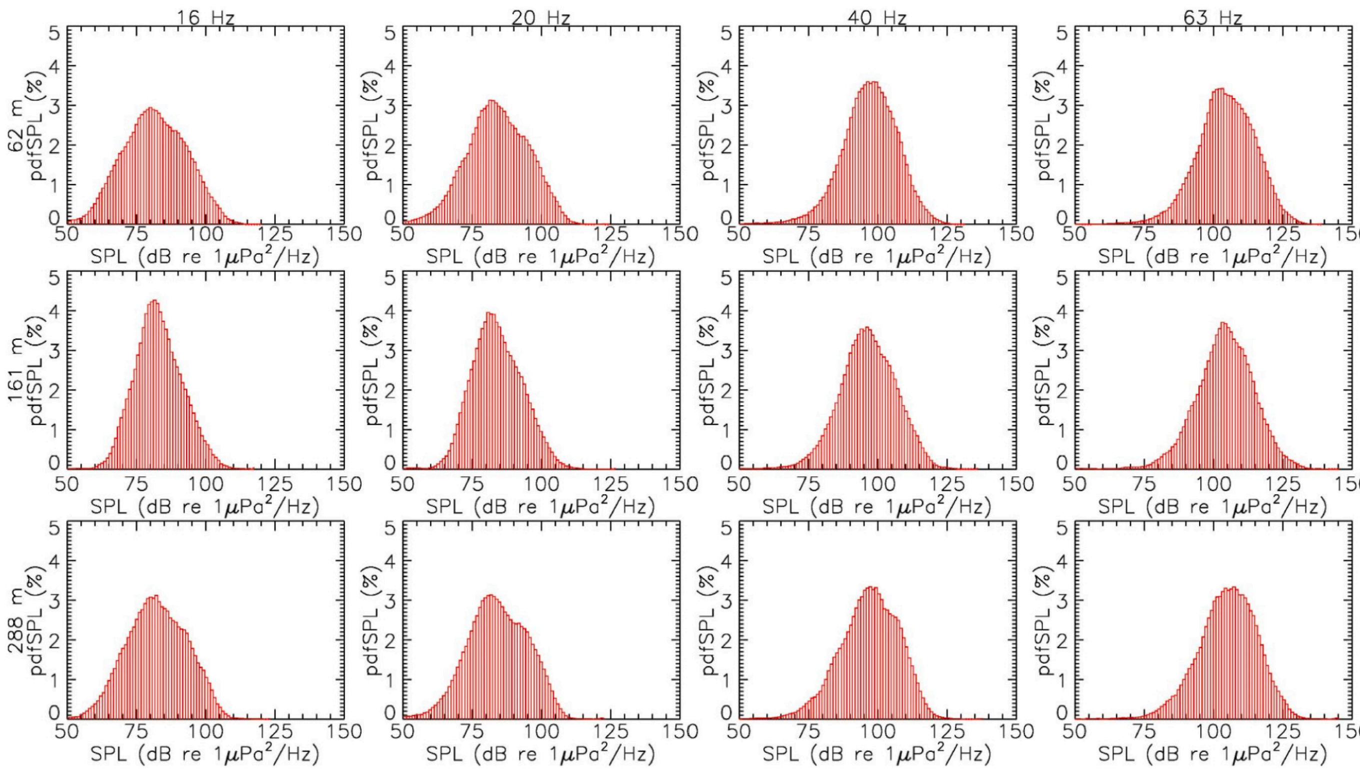

Fig. A.2. Probability density functions of the received noise levels at the position of the AS^4 observatory found in Aulanier et al. (2016). Frequencies increase from left to right, and depths from top to bottom.

Appendix B. Additional statistical results

Table B.1
Model parameter estimates for the differences in cumulative noise exposure ($SEL_{24h\text{-}sim}$) to belugas under the *spatially static*, *spatially mixed*, and *data-driven* behavioural scenarios.

Parameters	Estimate	Est.Error	l-95% CI	u-95% CI
Intercept	−0.29	0.04	−0.36	−0.22
behaviour: Spatially mixed	0.75	0.15	0.46	1.06
behaviour: spatially static	−0.80	0.15	−1.10	−0.49
additional traffic: yes	0.32	0.04	0.24	0.40
Interaction Spatially mixed:added traffic	−0.25	0.04	−0.33	−0.16
Interaction spatially static:added traffic	1.07	0.05	0.98	1.16
sigma_Intercept	0.26	0.02	0.22	0.31
sigma_behaviour: Spatially mixed	−1.27	0.15	−1.59	−0.96
sigma_behaviour: spatially static	−0.57	0.15	−0.87	−0.26
sigma_added traffic	−0.09	0.02	−0.14	−0.04
sigma_behaviour: Spatially mixed:added traffic	−0.20	0.03	−0.26	−0.13
sigma_behaviour: spatially static:added traffic	−0.22	0.03	−0.28	−0.16
sd(Intercept)	0.15	0.03	0.09	0.21
sd(sigma_Intercept)	0.15	0.02	0.11	0.19
r squared conditional	0.31	0.01	0.30	0.32

Table B.2
Model parameter estimates for the differences in the percentage of RL exposures that had greater than 120 dB under the *spatially static*, *spatially mixed*, and *data-driven* behavioural scenarios.

Parameters	Estimate	Est.Error	l-95% CI	u-95% CI
Intercept	−3.72	0.03	−3.78	−3.67
zi_Intercept	−1.17	0.06	−1.29	−1.06
Spatially mixed	0.46	0.20	0.06	0.87
Spatially static	−1.22	0.20	−1.63	−0.82
added traffic	0.25	0.02	0.21	0.30
Spatially mixed:addedyes	−0.10	0.03	−0.15	−0.04
Spatially static:added traffic	0.70	0.03	0.63	0.76
zi Spatially mixed	−13.18	6.92	−31.40	−6.15
zi Spatially static	−1.13	0.26	−1.64	−0.61
zi_addedyes	−0.40	0.08	−0.55	−0.24
zi Spatially mixed:added traffic	0.52	9.39	−19.16	21.47
zi Spatially static:added traffic	−11.11	5.72	−26.09	−4.61
phi	78.68	1.10	76.47	80.79
sd(Intercept)	0.20	0.02	0.16	0.25
sd(zi_Intercept)	0.23	0.07	0.09	0.37
r squared conditional	0.23	0.00	0.22	0.24

Table B.3
Model parameter estimates for the differences in the percentage of RL exposures that had no noise (RL = 0) under the *spatially static*, *spatially mixed*, and *data-driven* behavioural scenarios.

Parameters	Estimate	Est.Error	l-95% CI	u-95% CI
Intercept	0.42	0.02	0.38	0.46
phi_Intercept	1.95	0.04	1.86	2.04
zoi_Intercept	−4.62	0.37	−5.43	−3.99
spatially mixed	−0.14	0.12	−0.39	0.09
spatially static	1.34	0.12	1.09	1.57
added traffic	−0.15	0.02	−0.20	−0.10
spatially mixed:added traffic	−0.07	0.03	−0.12	−0.02
spatially static:added traffic	−0.11	0.03	−0.16	−0.06
phi spatially mixed	3.57	0.31	2.95	4.17
phi spatially static	3.18	0.31	2.55	3.77
phi added traffic	−0.29	0.04	−0.37	−0.20
phi spatially mixed:added traffic	−0.45	0.06	−0.57	−0.33
phi spatially static:added traffic	−0.60	0.06	−0.73	−0.48
zoi spatially mixed	−7.75	6.64	−25.33	0.78
zoi spatially static	−7.47	6.03	−22.85	0.68
zoi added traffic	−1.83	0.38	−2.59	−1.14
zoi spatially mixed:added traffic	2.10	8.59	−15.47	21.24
zoi spatially static:added traffic	2.02	8.04	−14.77	19.41
coi	0.99	0.01	0.95	1.00
sd(Intercept)	0.12	0.02	0.09	0.16
sd(phi_Intercept)	0.30	0.04	0.23	0.37
sd(zoi_Intercept)	1.58	0.32	1.04	2.28
r squared conditional	0.59	0.00	0.58	0.59

Table B.4
Parameter estimates for the model predicting SEL_{sim24} using the time spent in the Saguenay and whether the simulation scenario included additional marine traffic.

Parameters	Estimate	SD	l-95% CI	u-95% CI
Intercept	−0.04	0.04	−0.11	0.04
Time spent in the sag	−0.63	0.19	−1.00	−0.26
Added traffic	0.10	0.05	0.00	0.20
Time spent in sag: added traffic	0.96	0.24	0.48	1.42
Sigma	0.99	0.01	0.96	1.01
r-square conditional	0.03	0.01	0.02	0.05

Table B.5
Parameter estimates for the model gaussian multilevel model of encounter distances between a beluga and the closest ship.

Parameters	Estimate	Est.Error	l-95% CI	u-95% CI
Intercept	0.91	0.02	0.87	0.94
inSag	0.42	0.19	0.06	0.8
added traffic	−0.02	0.03	−0.07	0.04
inSag:added traffic	−0.48	0.24	−0.96	−0.01
sigma	0.46	0.01	0.44	0.48

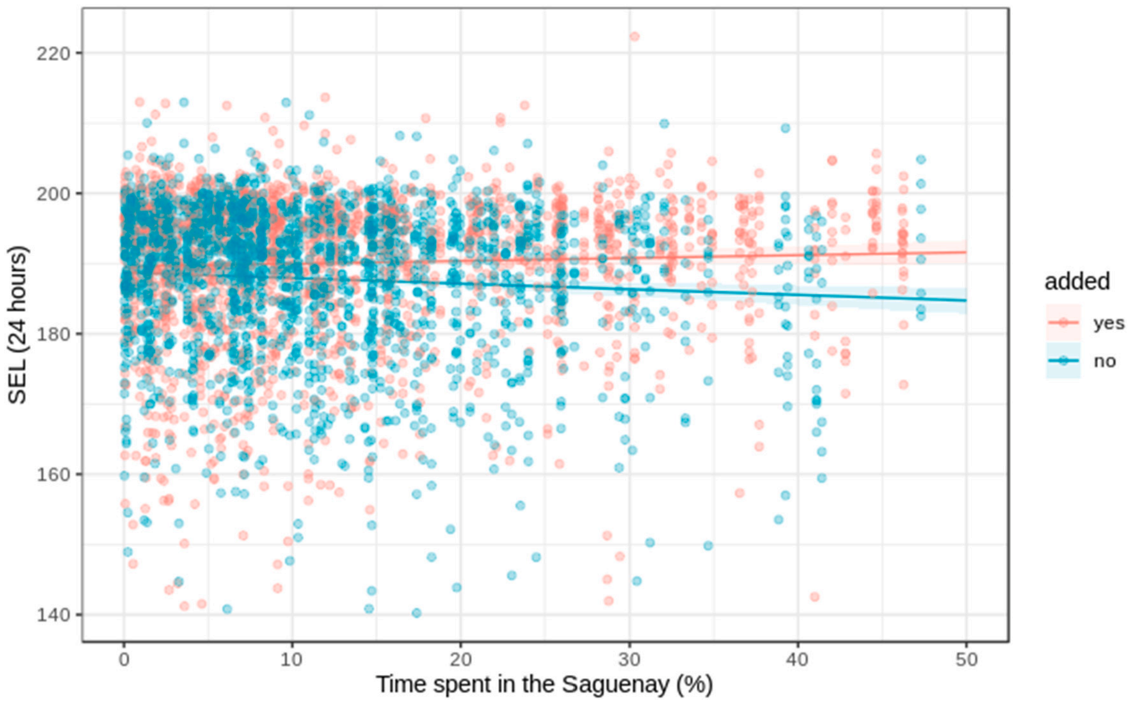

Fig. B.1. Estimated impact of the amount of time a beluga spends in the Saguenay (x-axis) on their SEL value (y-axis), for scenarios with and without extra traffic to the Saguenay. The lines are model estimates for a model using only beluga using the Saguenay less than 50% of the time, and was run as a sensitivity analysis to determine the impact of few data points above 50%.

References

Audoly, C., Rizzuto, E., 2015. Ship Underwater Radiated Noise Patterns. AQUO European Collaborative Project, Deliverable D2.1.

Aulanier, F., Simard, Y., Roy, N., Gervaise, C., Bandet, M., 2016. Spatial-temporal exposure of blue whale habitats to shipping noise in St. Lawrence System. In: Fisheries and Oceans Canada, Ecosystems and Oceans Science.

Awbrey, F.T., Thomas, J.A., Kastelein, R.A., 1988. Low-frequency underwater hearing sensitivity in belugas, D elphinapterusleucas. J. Acoust. Soc. Am. 84, 2273–2275.

Barrass, B., 2004. Ship Design and Performance for Masters and Mates. Elsevier.

Beauchamp, J., Bouchard, H., de Margerie, P., Otis, P., Savaria, J.-Y., 2009. Recovery Strategy for the blue whale (Balaenoptera musculus), Northwest Atlantic population. In: Canada [FINAL], Species at Risk Act (SARA) Recovery Strategy series. Fisheries and Oceans Canada, Ottawa.

T.R. Bonnell R. Michaud A. Dupuch V. Lesage C. Chion, in prep. Extracting Socio-spatial Networks From Photo-ID Data Using Multilevel Multinomial Models.

Booy, K.V., Vergara, V., Losetto, L., Marcoux, M., 2018. CHAPTER THREE: Geographic variation in simple contact calls of Canadian beluga whales (Delphinapterus leucas). In: Acoustic Monitoring of Beluga whales (Delphinapterus leucas): Spatio-temporal Habitat Preference and Geographic Variation in Canadian Populations, p. 51.

Bousquet, F., Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. Ecol. Model. 176, 313–332. https://doi.org/10.1016/j.ecolmodel.2004.01.011.

Bousquet, F., Lifran, R., Tidball, M., Thoyer, S., Antona, M., 2001. Agent-based modelling, game theory and natural resource management issues. J. Artif. Soc. Soc. Simul. 4.

Bousquet, F., Barreteau, O., d'Aquino, P., 2002. Multi-agent Systems and Role Games: Collective Learning Processes for Ecosystem Management. … of Multi-Agent ….

Caron, L.M.J., Smith, T.G., 1990. Philopatry and site tenacity of belugas, Delphinapterus leucas, hunted by the inuit at the nastapoka estuary, eastern Hudson Bay. Can. Bull. Fish. Aquat. Sci. 224, 69–79.

Chacón, J.E., Duong, T., 2018. Multivariate Kernel Smoothing and its Applications. CRC Press.

Chion, C., 2011. An Agent-based Model for the Sustainable Management of Navigation Activities in the Saint Lawrence Estuary.

Chion, C., Turgeon, S., Michaud, R., Landry, J.-A., Parrott, L., 2009. Portrait de la Navigation dans le Parc Marin du Saguenay–Saint-Laurent. Caractérisation des activités sans prélèvement de ressources entre le 1er mai et le 31 octobre 2007. École de techonologie supérieure / Université de Montréal.

Chion, C., Lamontagne, P., Turgeon, S., Parrott, L., Landry, J.-A., Marceau, D.J., Martins, C.C.A., Michaud, R., Ménard, N., Cantin, G., et al., 2011. Eliciting cognitive processes underlying patterns of human-wildlife interactions for agent-based modelling. Ecol. Model. 222, 2213–2226.

Chion, C., Parrott, L., Landry, J.-A., 2012. Collisions et cooccurrences entre navires marchands et baleines dans l'estuaire du Saint-Laurent–Évaluation de scénarios de mitigation et recommandations. Université de Montréal.

Chion, C., Cantin, G., Dionne, S., Dubeau, B., Lamontagne, P., Landry, J.-A., Marceau, D., Martins, C.C., Ménard, N., Michaud, R., et al., 2013. Spatiotemporal modelling for policy analysis: application to sustainable management of whale-watching activities. Mar. Policy 38, 151–162.

Chion, C., Lagrois, D., Dupras, J., Turgeon, S., McQuinn, I.H., Michaud, R., Ménard, N., Parrott, L., 2017. Underwater acoustic impacts of shipping management measures: results from a social-ecological model of boat and whale movements in the St. Lawrence River estuary (Canada). Ecol. Model. 354, 72–87.

Chion, C., Turgeon, S., Cantin, G., Michaud, R., Ménard, N., Lesage, V., Parrott, L., Beaufils, P., Clermont, Y., Gravel, C., 2018. A voluntary conservation agreement reduces the risks of lethal collisions between ships and whales in the St. Lawrence Estuary (Québec, Canada): from co-construction to monitoring compliance and assessing effectiveness. PLoS One 13, e0202560.

Chion, C., Bonnell, T.R., Lagrois, D., Guetté, A., Michaud, R., Dupuch, A., Dupras, J., 2019a. Modélisation du trafic maritime et des déplacements des baleines dans l'estuaire du Saint-Laurent et le Saguenay pour informer le processus de réduction des impacts cumulatifs de la navigation sur les bélugas et les grands rorquals dans le contexte du déploiement de la Stratégie maritime du Québec. Université du Québec en Outaouais.

Chion, C., Lagrois, D., Dupras, J., 2019b. A meta-analysis to understand the variability in reported source levels of noise radiated by ships from opportunistic studies. Front. Mar. Sci. 6, 714.
Colbeck, G.J., Duchesne, P., Postma, L.P., Lesage, V., Hammill, M.O., Turgeon, J., 2013. In: Groups of Related Belugas (Delphinapterus leucas) Travel Together During Their Seasonal Migrations in and Around Hudson Bay, 280, p. 20122552. https://doi.org/10.1098/rspb.2012.2552.
Collins, M.D., 1993. A Split-step Padé solution for the parabolic equation method. J. Acoust. Soc. Am. 93, 1736–1742.
Conversano, M., Turgeon, S., Ménard, N., 2017. Caractérisation de l' utilisation de l'embouchure du Saguenay et de la baie Sainte-Marguerite par le béluga du Saint-Laurent et par le trafic maritime entre 2003 et 2016. Analyse des données d'observation terrestre et recommandations sur des mesures de gestion visant à réduire le dérangement dans les aires de haute résidence du béluga dans le parc marin du Saguenay–Saint-Laurent. Parcs Canada, Tadoussac (QC).
De March, B.G.E., Postma, L.D., 2003. Molecular genetic stock discrimination of belugas (Delphinapterus leucas) hunted in eastern Hudson Bay, northern Quebec, Hudson Strait, and sanikiluaq (Belcher Islands), Canada, and comparisons to adjacent populations. Arctic 111–124.
Duarte, C.M., Chapuis, L., Collin, S.P., Costa, D.P., Devassy, R.P., Eguiluz, V.M., Erbe, C., Gordon, T.A., Halpern, B.S., Harding, H.R., 2021. The soundscape of the Anthropocene ocean. Science 371.
Erbe, C., Farmer, D.M., 2000. Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. J. Acoust. Soc. Am. 108, 1332–1340.
Erbe, C., Liong, S., Koessler, M.W., Duncan, A.J., Gourlay, T., 2016a. Underwater sound of rigid-hulled inflatable boats. J. Acoust. Soc. Am. 139 (EL223–EL227).
Erbe, C., Reichmuth, C., Cunningham, K., Lucke, K., Dooling, R., 2016b. Communication masking in marine mammals: a review and research strategy. Mar. Pollut. Bull. 103, 15–38.
Erbe, C., Marley, S., Schoeman, R., Smith, J.N., Trigg, L., Embling, C.B., 2019. The effects of ship noise on marine mammals—a review. Front. Mar. Sci. 6, 606.
Ferber, J., 1999. Multi-Agent Systems: An Introduction to Distributed Artificial Intelligence.
Finneran, J.J., Schlundt, C.E., Dear, R., Carder, D.A., Ridgway, S.H., 2002. Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. J. Acoust. Soc. Am. 111, 2929–2940.
Finneran, J.J., Carder, D.A., Dear, R., Belting, T., McBain, J., Dalton, L., Ridgway, S.H., 2005. Pure tone audiograms and possible aminoglycoside-induced hearing loss in belugas (Delphinapterus leucas). J. Acoust. Soc. Am. 117, 3936–3943.
Fisheries and Oceans Canada, 2012. Recovery Strategy for the beluga (Delphinapterus leucas) St. Lawrence Estuary population in Canada, Species at Risk Act (SARA) Recovery Strategy series. Fisheries and Oceans Canada, Ottawa.
Fisheries and Oceans Canada, 2014. Recovery Strategy for the North Atlantic Right Whale (Eubalaena glacialis) in Atlantic Canadian Waters, Species at Risk Act Recovery Strategy Series. Ottawa.
Fisheries and Oceans Canada, 2016. Management Plan for the Fin Whale (Balaenoptera physalus), Atlantic Population in Canada, Species at Risk Act Management Plan Series. Ottawa.
Fisheries and Oceans Canada, 2018. St. Lawrence Estuary Beluga: A Science Based Review of Recovery Actions for Three At-risk Whale Populations.
Francois, R.E., Garrison, G.R., 1982a. Sound absorption based on ocean measurements. Part II: boric acid contribution and equation for total absorption. J. Acoust. Soc. Am. 72, 1879–1890.
Francois, R.E., Garrison, G.R., 1982b. Sound absorption based on ocean measurements: part I: pure water and magnesium sulfate contributions. J. Acoust. Soc. Am. 72, 896–907.
Gassmann, M., Wiggins, S.M., Hildebrand, J.A., 2017. Deep-water measurements of container ship radiated noise signatures and directionality. J. Acoust. Soc. Am. 142, 1563–1574.
Gelman, A., Hill, J., 2006. Data Analysis Using Regression and Multilevel/hierarchical Models. Cambridge University Press.
Gervaise, C., Simard, Y., Roy, N., Kinda, B., Ménard, N., 2012. Shipping noise in whale habitat: characteristics, sources, budget, and impact on belugas in Saguenay–St. Lawrence Marine Park hub. J. Acoust. Soc. Am. 132, 76–89.
Gimblett, H.R., 2002. Integrating Geographic Information Systems and Agent-based Modeling Techniques for Simulating Social and Ecological Processes. Oxford University Press.
Gomez, C., Lawson, J.W., Wright, A.J., Buren, A.D., Tollit, D., Lesage, V., 2016. A systematic review on the behavioural responses of wild marine mammals to noise: the disparity between science and policy. Can. J. Zool. 94, 801–819.
Gosselin, J.F., Hammill, M.O., Mosnier, A., Lesage, V., 2017. Abundance index of St. Lawrence Estuary beluga, Delphinapterus leucas, from aerial visual surveys flown in August 2014 and an update on reported deaths. In: DFO Canadian Science Advisory Secretariat, Research Document 2017/019.
Gouvernement du Québec, 2015. La stratégie maritime à l'horizon 2030–Plan d'action 2015-2020. Québec.
Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W.M., Railsback, S.F., Thulke, H.-H., Weiner, J., Wiegand, T., DeAngelis, D.L., 2005. Pattern-oriented modeling of agent-based complex systems: lessons from ecology. Science 310, 987–991.
Hermannsen, L., Beedholm, K., Tougaard, J., Madsen, P.T., 2014. High frequency components of ship noise in shallow water with a discussion of implications for harbor porpoises (Phocoena Phocoena). J. Acoust. Soc. Am. 136, 1640–1653.
ISO 18405, 2017. Underwater Acoustics - Terminology. International Standardization Organization.
Jensen, F.B., Kuperman, W.A., Porter, M.B., Schmidt, H., 2011. Computational Ocean Acoustics. Springer Science & Business Media.
Johnson, C.S., McManus, M.W., Skaar, D., 1989. Masked tonal hearing thresholds in the beluga whale. J. Acoust. Soc. Am. 85, 2651–2654.
Kaplan, M.B., Solomon, S., 2016. A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030. Mar. Policy 73, 119–121.
Lemieux Lefebvre, S., Michaud, R., Lesage, V., Berteaux, D., 2012. Identifying high residency areas of the threatened St. Lawrence beluga whale from fine-scale movements of individuals and coarse-scale movements of herds. MEPS 450, 243–257.
Leroy, C.C., Robinson, S.P., Goldsmith, M.J., 2008. A new equation for the accurate calculation of sound speed in all oceans. J. Acoust. Soc. Am. 124, 2774–2782.
Lesage, V., 2021. The challenges of a small population exposed to multiple anthropogenic stressors and a changing climate: the St. Lawrence Estuary beluga. Polar Res. 40 (S1) (3 Sep.).
Lesage, V., Barrette, C., Kingsley, M., Sjare, B., 1999. The effect of vessel noise on the vocal behaviour of belugas in the St. Lawrence River estuary, Canada. Mar. Mamm. Sci. 15, 65–84.
Lesage, V., McQuinn, I., Carrier, D., Gosselin, J.-F., Mosnier, A., 2014. Exposure of the beluga (Delphinapterus leucas) to marine traffic under various scenarios of transit route diversion in the St. Lawrence Estuary, DFO Canadian Science Advisory Secretariat. In: Fisheries and Oceans Canada, Ottawa.
McLane, A.J., Semeniuk, C., McDermid, G.J., Marceau, D.J., 2011. The role of agent-based models in wildlife ecology and management. Ecol. Model. 222, 1544–1556.
McQuinn, I.H., Lesage, V., Carrier, D., Larrivée, G., Samson, Y., Chartrand, S., Michaud, R., Theriault, J., 2011. A threatened beluga (Delphinapterus Leucas) population in the traffic lane: vessel-generated noise characteristics of the Saguenay-St. Lawrence Marine Park, Canada. J. Acoust. Soc. Am. 130, 3661–3673.
Ménard, N., Conversano, M., Turgeon, S., 2018. La protection des habitats de la population de bélugas (Delphinapterus leucas) du Saint-Laurent: bilan et considérations Sur les besoins de conservation. Le Nat. Can. 142, 80–105.
Michaud, R., 1993. Distribution estivale des bélugas du Saint-Laurent: synthèse 1986-1992. Can. Tech. Rep. Fish. Aquat. Sci. 1906: vi + 28 p.
Mooney, T.A., Castellote, M., Quakenbush, L., Hobbs, R., Gaglione, E., Goertz, C., 2018. Variation in hearing within a wild population of beluga whales (Delphinapterus leuca s). J. Exp. Biol. 221, jeb171959.
Mosnier, A., Larocque, R., Lebeuf, M., Gosselin, J.-F., Dubé, S., Lapointe, V., Lesage, V., Lefaivre, D., Senneville, S., Chion, C., 2016. Définition et caractérisation de l'habitat du béluga (Delphinapterus leucas) de l'estuaire du Saint-Laurent selon une approche écosystémique. In: DFO - Canadian Science Advisory Secretariat. Fisheries and Oceans Canada, Mont-Joli (QC, Canada).
O'Corry-Crowe, G., Suydam, R., Quakenbush, L., Potgieter, B., Harwood, L., Litovka, D., Ferrer, T., Citta, J., Burkanov, V., Frost, K., 2018. Migratory culture, population structure and stock identity in North Pacific beluga whales (Delphinapterus leucas). PLoS One 13, e0194201.
Ouellet, J.-F., Michaud, R., Moisan, M., Lesage, V., 2021. Estimating the proportion of a beluga population using specific areas from connectivity patterns and abundance indices. Ecosphere 12, e03560.
Parrott, L., Chion, C., Martins, C.C.A., Lamontagne, P., Turgeon, S., Landry, J.-A., Zhens, B., Marceau, D.J., Michaud, R., Cantin, G., et al., 2011. A decision support system to assist the sustainable management of navigation activities in the St. Lawrence River Estuary, Canada. Environ. Model. Softw. 26, 1403–1418.
Pêches et Océans Canada, 2018. Effets potentiels des projets de construction de terminaux maritimes dans le fjord du Saguenay sur le béluga du Saint-Laurent et son habitat (No. 2018/025), Secrétariat canadien de consultation scientifique - Réponse des Sciences. Région du Québec.
Pêches et Océans Canada, 2020. Plan d'action pour réduire l'impact du bruit sur le béluga et les autres mammifères marins en péril de l'estuaire du Saint-Laurent., Série de Plans d'action de la Loi sur les espèces en péril. Ottawa.
Porter, M.B., 2011. The bellhop manual and user's guide: preliminary draft. In: Heat, Light, and Sound Research, Inc., La Jolla, CA, USA, Tech. Rep, p. 260.
Richardson, W.J., Greene, C.R., Malme, C.I., Thomson, D.H., 1995. Marine Mammals and Noise. Academic Press, San Diego.
Richardson, W.J., Greene Jr., C.R., Malme, C.I., Thomson, D.H., 2013. Marine Mammals and Noise. Academic press.
Schlundt, C.E., Finneran, J.J., Carder, D.A., Ridgway, S.H., 2000. Temporary shift in masked hearing thresholds of bottlenose dolphins and white whales after exposure to intense tones. J. Acoust. Soc. Am. 107, 3496–3508.
Simard, Y., Roy, N., Gervaise, C., Giard, S., 2016. Analysis and modeling of 255 source levels of merchant ships from an acoustic observatory along St. Lawrence seaway. J. Acoust. Soc. Am. 140, 2002–2018.
Sjare, B.L., Smith, T.G., 1986. The vocal repertoire of white whales, Delphinapterus leucas, summering in Cunningham inlet, Northwest Territories. Can. J. Zool. 64, 407–415.
Southall, B.L., Finneran, J.J., Reichmuth, C., Nachtigall, P.E., Ketten, D.R., Bowles, A.E., Ellison, W.T., Nowacek, D.P., Tyack, P.L., 2019. Marine mammal noise exposure criteria: updated scientific recommendations for residual hearing effects. Aquat. Mamm. 45.
Tang, W., Bennett, D.A., 2010. Agent-based modeling of animal movement: a review. Geogr. Compass 4, 682–700.
Turgeon, S., 2019. Portrait de la navigation dans le parc marin du Saguenay–Saint-Laurent - 2017. Parcs Canada.
Turgeon, J., Duchesne, P., Colbeck, G.J., Postma, L.D., Hammill, M.O., 2012. Spatiotemporal segregation among summer stocks of beluga (Delphinapterus leucas)

despite nuclear gene flow: implication for the endangered belugas in eastern Hudson Bay (Canada). Conserv. Genet. 13, 419–433.
Wittekind, D.K., 2014. A simple model for the underwater noise source level of ships. J. Ship Prod. Des. 30, 7–14.
Wladichuk, J.L., Hannay, D.E., MacGillivray, A.O., Li, Z., Thornton, S.J., 2019. Systematic source level measurements of whale watching vessels and other small boats. J. Ocean Technol. 14.