Caractérisation des interactions entre la navigation de plaisance et la population de bélugas de l'estuaire du Saint-Laurent dans leur habitat essentiel (Québec, Canada): fondements pour une modélisation multi-agent

par Camille Kowalski

Thèse présentée à l’Université du Québec en Outaouais en vue de l’obtention du grade de philosophiae doctor (Ph. D.) en sciences naturelles.

Québec, Canada

Résumé

Le dérangement anthropique lié à la navigation de plaisance représente une menace croissante pour la faune marine, en particulier pour les mammifères marins qui dépendent du son pour se déplacer, s'orienter, détecter les proies et interagir socialement. Parmi eux, la population de bélugas de l'estuaire du Saint-Laurent, isolée et en voie de disparition, est particulièrement vulnérable. Il s'agit de la population de bélugas la plus au sud de l'aire de répartition mondiale de l'espèce, et donc aussi la plus exposée aux activités humaines, notamment dans l'estuaire du Saint-Laurent et le fjord du Saguenay, des zones soumises à une forte pression touristique et commerciale. L'observation des baleines constitue une activité économique majeure pour plusieurs communautés côtières du Québec. Or, le maintien de cette activité dépend directement de la bonne santé de la faune marine, ce qui souligne l'urgence de mieux comprendre les effets du trafic maritime sur les cétacés et de mettre en place des mesures de gestion adaptées.

Dans ce contexte, cette thèse vise à approfondir notre compréhension de la navigation de plaisance dans l'habitat estival de la population de bélugas de l'estuaire du Saint-Laurent, ainsi que de ses effets potentiels sur ces individus, un aspect encore peu documenté dans cette région pourtant cruciale pour la conservation de l'espèce. Tout d'abord, des observations terrestres réalisées à l'aide de jumelles et d'une station totale le long du fjord du Saguenay ont permis de documenter l'utilisation d'un site stratégique par les plaisanciers et les bélugas, ainsi que d'évaluer le respect des règles de navigation en vigueur dans le Parc marin du Saguenay–Saint-Laurent. Ensuite, une approche qualitative fondée sur la méthodologie Q a permis d'identifier trois archétypes de plaisanciers, contribuant ainsi à une meilleure compréhension des profils et des logiques d'action à l'origine de leurs comportements en mer. Les données collectées lors des observations terrestres n'ont pas révélé de signes clairs de fuite ou de submersion des bélugas en présence d'embarcations de plaisance, mais ont mis en évidence une corrélation entre l'augmentation du nombre d'embarcations et la probabilité de changement de dispersion au sein des troupeaux. Enfin, les connaissances issues de l'ensemble de ces analyses ont été mobilisées pour développer un modèle conceptuel des interactions entre plaisanciers et cétacés, fondé sur la diversité des profils d'usagers observés et articulée sous forme de schéma décisionnel.

En fournissant des données inédites sur les plaisanciers du Saguenay – Saint-Laurent et leurs interactions avec les bélugas, cette thèse comble un manque de connaissances portant à la fois sur les profils des usagers, la diversité de leurs comportements de navigation et leurs effets potentiels sur les troupeaux de bélugas, des dimensions encore peu documentées dans l'habitat estival de cette population. Elle met en lumière la variabilité des pratiques de navigation, les conditions susceptibles d'intensifier les interactions avec les cétacés, ainsi que les réponses potentielles des bélugas à la présence des embarcations. Ensemble, ces résultats offrent des pistes concrètes pour améliorer la gestion des activités de plaisance dans les aires sensibles, dans une perspective de conservation de la faune marine et de cohabitation durable entre humains et cétacés.

Mots-clés : baleine, bateau, trafic, maritime, impact, prise de décision, archétype, système socio-écologique, conservation marine

Abstract

Anthropogenic disturbance from recreational boating is an increasing threat to marine wildlife, particularly marine mammals that rely on sound for orientation, prey detection, and social interaction. Among them, the isolated and endangered St. Lawrence Estuary beluga whale population is particularly vulnerable. This is the southernmost population within the species' global range and therefore also the most exposed to human activities, particularly in the St. Lawrence Estuary and Saguenay Fjord, areas subject to heavy tourist and commercial pressure. Whale watching is a major economic activity for many of Quebec's coastal communities. Maintaining this activity depends directly on the health of the marine fauna, underscoring the urgent need to better understand the effects of marine traffic on cetaceans, and to implement appropriate management measures.

In this context, this thesis aims to deepen our understanding of recreational boating within the summer habitat of the St. Lawrence Estuary beluga population, as well as its potential effects on these individuals, an aspect of human activity that remains understudied in this critical conservation area. Firstly, land-based observations using binoculars and a total station were conducted to document the use of a key site by both recreational boats and belugas, and to assess compliance with navigation regulations in force in the Saguenay-St. Lawrence Marine Park. Next, a qualitative approach based on Q methodology enabled us to identify different archetypes of recreational boaters, thus contributing to a better understanding of the profiles and motivations behind their behaviour at sea. Data collected during land-based observations also enabled us to examine whether the presence of recreational boats is correlated with certain beluga behaviours, notably the number of individuals visible at the surface and the spatial configuration of herds. Finally, the knowledge gained from all these analyses was mobilized to develop a conceptual model of interactions between recreational boaters and cetaceans, based on the diversity of user profiles observed and articulated in the form of a decision-making diagram.

By providing new data on recreational boaters in the Saguenay–St. Lawrence region and their interactions with belugas, this research fills a major knowledge gap regarding boater profiles, the diversity of navigation behaviours, and their potential effects on beluga herds, dimensions that remain poorly documented in the summer habitat of this population. It highlights the variability of boating practices, the conditions likely to intensify interactions with cetaceans, and the potential responses of belugas to the presence of recreational boats. Together, these findings offer concrete avenues for improving the management of recreational boating activities in sensitive areas, with a view to conserving marine fauna and ensuring sustainable cohabitation between humans and cetaceans.

Keywords: whale, vessel, navigation, marine, traffic, impact, decision-making, archetype, socio-ecological system, marine conservation

Avant-propos

À la fin de mes études secondaires en France, je ne savais pas encore quelle voie universitaire emprunter. C’est au cours d’un voyage au Québec, et plus particulièrement lors d’un séjour en famille à Tadoussac, que les choses se sont éclaircies. Une sortie d’observation des baleines, suivie d’une excursion en kayak sur les eaux du Saint-Laurent et du Saguenay, m’a permis de rencontrer mes premières baleines. Parmi elles, les bélugas. Ces instants de découverte, d’émerveillement et de proximité avec ces grands mammifères marins ont profondément marqué mon imaginaire.

À mon retour, j’ai décidé d’orienter mes études vers les sciences marines, avec l’espoir de revivre de tels moments et, surtout, de contribuer à la protection des espèces qui m’avaient tant impressionnée. Après un parcours universitaire en biologie marine, de la licence à la maîtrise, c’est presque comme un clin d’œil du destin que j’ai découvert une opportunité de doctorat portant sur les interactions entre la navigation de plaisance et les bélugas du Saint-Laurent, ces mêmes bélugas qui, quelques années auparavant, étaient venus encercler mon kayak.

Ainsi, cette thèse m’a permis de retourner là où tout avait commencé, et d’approfondir la compréhension de ces interactions pour mieux contribuer à la préservation de cette espèce emblématique.

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3MTSim	Marine Mammals and Maritime Traffic Simulator
ABM	Agent-Based Model
AIS	Automatic Identification System
ASE	Anse de Saint-Étienne
BDI	Belief-Desire-Intention
BESL	Béluga de l'estuaire du Saint-Laurent
ESL	Estuaire du Saint-Laurent
FS	Fjord du Saguenay
GAM	Generalized Additive Model
GLMM	Generalized Linear Mixed Model
HRA	High Residency Area
ML	Maximum Likelihood
MMA	Modèle multi-agent
MSF	Mouth of the Saguenay Fjord
ODD	Overview, Design concepts, and Details
PCA	Principal Component Analysis
PMSSL	Parc marin du Saguenay–Saint-Laurent
ROMM	Réseau d'Observation des Mammifères Marins
SMB	Sainte-Marguerite Bay
SSÉ	Système socio-écologique

SSL	Saguenay - St. Lawrence
SSLMP	Saguenay−St. Lawrence Marine Park
VBN	Value-Belief-Norms

Remerciements

Cette thèse représente la fin d'un parcours rempli d'apprentissages et de défis, et elle n'aurait pas été possible sans le soutien, la patience et l'inspiration de nombreuses personnes. Je tiens à remercier chaleureusement toutes celles et ceux qui ont contribué, de près ou de loin, à sa réalisation.

Tout d'abord, je tiens à remercier mes directeurs de thèse, Jérôme et Clément, pour leur confiance, leur accompagnement tout au long de ce parcours, et pour m'avoir ouvert des portes en me mettant en relation avec des personnes clés, qui ont grandement enrichi mon travail.

Je souhaite également remercier les étudiants et chercheurs de la Chaire de recherche du Canada en économie écologique et du Laboratoire interdisciplinaire de simulation socio-écologique pour leur écoute et leurs retours constructifs. Une reconnaissance particulière va à Jean-François pour son aide précieuse, ainsi qu'à Emmanuelle pour son soutien moral durant les étapes les plus exigeantes de ce doctorat.

Mes remerciements vont aussi à Cristiane, pour m'avoir initiée à la méthode d'observation au théodolite, ainsi qu'à Robert, dont l'expertise a permis d'adapter mon protocole d'observation. Je remercie également Esther, Sonia, et Charlène du ROMM, pour leur accompagnement lors de mes premières observations de bélugas à Rivière-du-Loup.

Je suis reconnaissante envers tous les plaisanciers qui ont participé aux collectes de données et ont enrichi ce projet par leur collaboration.

Un immense merci à Franck Turcotte, qui m'a permis d'utiliser le belvédère du village vacances de Petit-Saguenay, un cadre exceptionnel pour conduire mes observations. Je remercie aussi mes assistantes d'observations, Anne-Marie et Maude, devenue ma première amie québécoise, ainsi que Manon, qui nous a hébergés et offert des étés inoubliables à Petit-Saguenay. De véritables amitiés sont nées de cette aventure, et j'en garderai un souvenir impérissable.

La réalisation de cette thèse a été un défi autant personnel qu'académique, et je tiens à remercier mes amis et ma famille, qui ont toujours été là pour moi, dans les moments de joie comme dans les périodes plus difficiles.

À ma mère, je dois bien plus qu'un simple merci. Sans elle, jamais je n'aurais osé me lancer dans cette aventure académique. Elle a su, comme toujours, croire en moi bien au-delà de mes propres doutes. Grâce à son amour inconditionnel et à son talent inégalé pour me ramener à l'essentiel, j'ai appris à relativiser et à voir les choses autrement.
À mon père, je tiens à exprimer toute ma gratitude et mon admiration. Avec sa sagesse et sa fierté, il m'a donné la force de croire en moi et m'a transmis des valeurs qui m'accompagnent chaque jour.
Même à des milliers de kilomètres, votre soutien indéfectible a été ma plus grande force. Cette réussite est autant la vôtre que la mienne.

À Rayan, qui partage mon quotidien et m'a accompagnée dans cette aventure. Ensemble, nous avons quitté notre pays pour bâtir une nouvelle vie au Québec, loin de nos repères familiers. Tu as toujours été mon pilier à chaque étape de ce parcours. Merci pour ton soutien indéfectible, pour avoir partagé des instants de terrain avec moi et pour m'avoir épaulée sans jamais faillir. Ta patience et ton amour ont été une force précieuse qui m'a permis d'aller toujours de l'avant.

À mes amies, Julie, Victoria, Marion et Chloé, qui, même de loin, restent des présences précieuses dans ma vie. Merci pour ces moments de rire, de légèreté et de complicité, qui m'ont offert une échappatoire bienvenue face aux défis parfois pesants de ce milieu académique. Votre amitié, simple et sans prétention, a été une bouffée d'air frais et une source inestimable de joie et de soutien.

À Maud, que j'ai eu la chance de rencontrer dans la dernière ligne droite de mon doctorat. Naviguer dans les eaux parfois agitées de cette aventure aurait été bien plus difficile sans toi. Ton soutien et notre entraide ont été comme un phare guidant ma route, transformant les tempêtes en simples vagues. Merci d'avoir partagé cette traversée et d'être devenue une véritable amie au fil des marées.

Ce doctorat, en m'amenant au Québec, m'a permis de faire de belles rencontres, qui se sont transformées en amitiés et m'ont aidée à trouver un équilibre, à décompresser et à savourer des instants de légèreté, rendant cette aventure encore plus enrichissante.

Introduction générale

Depuis des millénaires, l'être humain s'aventure sur les mers et les océans, d'abord pour assurer sa subsistance, puis progressivement pour le commerce et le tourisme. Au fil du temps, l'intensification de ces activités maritimes a renforcé sa présence dans les zones côtières et estuariennes, générant des interactions de plus en plus fréquentes entre les usages humains et la faune marine. Aujourd'hui, ces interactions constituent un enjeu majeur pour de nombreux écosystèmes côtiers. À l'échelle mondiale, de nombreuses études ont montré que les activités humaines en mer, qu'il s'agisse de navigation commerciale ou touristique, ou d'opérations de recherche et industrielles, peuvent modifier les comportements, la communication et l'utilisation de l'habitat chez diverses espèces de cétacés (Tenan et al., 2020 ; Borggaard et al., 1999 ; Morton et Symonds, 2002 ; Vergara et al., 2025).

L'estuaire du Saint-Laurent (ESL) est une zone cruciale pour plusieurs espèces de baleines migratrices, attirées par l'abondance des ressources alimentaires durant la période estivale (Cotté et Simard, 2005; Ramp et al., 2015; Truchon et al., 2013). Parmi ces espèces figurent le rorqual bleu (*Balaenoptera musculus*), le rorqual commun (*Balaenoptera physalus*), le rorqual à bosse (*Megaptera novaeangliae*) et le petit rorqual (*Balaenoptera acutorostrata*). En plus de ces espèces, la population de bélugas (*Delphinapterus leucas*) de l'estuaire du Saint-Laurent (BESL) réside dans ces eaux tout au long de l'année (Lesage et al., 2024). Outre ces espèces de cétacés, l'ESL et le Fjord du Saguenay (FS) forment un écosystème riche, abritant une grande diversité d'autres espèces marines (Bourdages et al., 2016; Brunel et al., 1998; Guse et al., 2013). Cependant, cette région est également le théâtre de nombreuses activités de navigation, allant du trafic maritime commercial et des traversiers reliant les rives de l'estuaire et du FS aux activités récréatives telles que les excursions d'observation des baleines, la navigation de plaisance et les croisières (Turgeon, 2019). Enfin, bien qu'ils soient minoritaires, des bateaux de pêche, des navires de recherche et des bateaux-pilotes naviguent également dans ces eaux (Turgeon, 2019). Ces activités, bien qu'essentielles pour les communautés côtières, exercent des pressions sur les espèces de baleines présentes, notamment des risques de collisions, d'empêtrements dans des engins de pêche et d'exposition au bruit sous-marin (Dolman et Moore, 2017; Laist et al., 2001; Richardson et al., 2013). De plus, des pressions anthropiques supplémentaires, telles que la dégradation des habitats, la diminution des stocks alimentaires et l'introduction de contaminants chimiques, résultant de diverses industries, affectent les mammifères marins (DFO, 2020, 2012). Face à ces menaces, le Parc marin du

Saguenay–Saint-Laurent (PMSSL) a été créé en 1998 afin de protéger cet écosystème fragile qui supporte la population de BESL.

Les activités de la navigation marchande, des traversiers et des bateaux d'excursion commerciale sont relativement bien documentées dans cette région, car ces embarcations doivent être équipées d'un émetteur AIS (*Automatic Identification System*) qui transmet leur position en temps réel (Chion et al., 2009; Turgeon, 2019). Cet outil offre une vision détaillée de leurs activités dans le secteur. En revanche, les embarcations de plaisance ne sont pas soumises à cette obligation au Canada, ce qui limite considérablement les connaissances sur leur utilisation de la zone. Il existe néanmoins des données provenant d'observations et de registres de nuitées dans les marinas situées aux abords de l'habitat de la population de BESL (Conversano et al., 2017; Ménard et al., 2014; Turgeon, 2019). Ces données ont notamment révélé qu'entre 2010 et 2012, l'augmentation des activités récréatives a été corrélée à une hausse de la mortalité des veaux (Ménard et al., 2014), bien qu'aucun lien de causalité n'ait été établi. En effet, le pic des activités récréatives dans l'habitat essentiel de la population de BESL coïncide avec la saison estivale, période durant laquelle les femelles mettent bas et prennent soin de leurs nouveau-nés. À la suite de ces observations, plusieurs mesures réglementaires ont été mises en place, notamment au sein du PMSSL, pour limiter les impacts sur les différentes espèces de baleines, en particulier les BESL, population classée en voie de disparition (COSEWIC, 2014). Ces mesures incluent principalement l'obligation de respecter des distances minimales avec les mammifères marins et des limitations de vitesse applicables dans tout le PMSSL et autour des baleines (DORS/2002-76). De plus, une zone essentielle pour les bélugas, la Baie Sainte-Marguerite (Conversano et al., 2017; Lesage et al., 2024; Mosnier et al., 2010; Simard et al., 2023; Turgeon, 2012), est interdite à la navigation pendant la période estivale depuis 2018.

Cependant, malgré les efforts réglementaires en place, l'efficacité de ces mesures demeure difficile à évaluer, tant en raison de la complexité des dynamiques en jeu que du manque de connaissances sur leur niveau réel de respect sur le terrain. En effet, les systèmes comme celui de l'ESL et du FS sont des systèmes socio-écologiques (Parrott et al., 2012), où de nombreuses interactions entre les activités humaines et le milieu naturel peuvent entraîner des effets indirects ou inattendus. Tester ou évaluer à l'avance l'efficacité de scénarios de gestion devient alors une nécessité (Grimm et al., 2005). Dans cette optique, mieux comprendre les comportements humains, ici, ceux des plaisanciers, ainsi que leurs interactions avec les espèces protégées est une étape essentielle pour concevoir des interventions adaptées. Une approche prometteuse pour explorer ces dynamiques consiste à utiliser des outils de simulation, notamment la modélisation multi-agent (Bonabeau, 2002), qui permet de simuler les décisions et les interactions des différents acteurs dans un environnement donné. Pour que ces modèles soient pertinents, ils doivent reposer sur une compréhension approfondie des composantes sociales, écologiques et réglementaires du système étudié. Le premier chapitre de cette thèse présente les cadres conceptuels et théoriques mobilisés dans cette thèse, en abordant les concepts de systèmes socio-écologiques, modélisation multi-agent et prise de décision. Les objectifs de la recherche y sont également exposés en détail. Par la suite, les deuxième, troisième et quatrième chapitres présentent les résultats de la recherche sous forme d'articles scientifiques, alors que le cinquième chapitre constitue la discussion générale et la perspective conclusive.

Chapitre 1 : Cadres conceptuels, théoriques et objectifs

1.1. Les systèmes socio-écologiques

Les systèmes socio-écologiques (SSÉ) décrivent l'interconnexion des systèmes sociaux et écologiques, où les écosystèmes fournissent des services à la société et sont, à leur tour, affectés par les activités humaines (Berkes et al., 2000). Les dynamiques des SSÉ émergent des interactions et des boucles de rétroaction entre les sous-systèmes à différentes échelles, où les décisions et actions humaines influencent non seulement la structure et le fonctionnement des systèmes naturels, mais également les comportements humains qui en résultent (An, 2012; Ostrom, 2009). En effet, les défis socio-écologiques mondiaux découlent des effets cumulatifs des actions locales, car les individus négligent souvent les coûts sociaux et écologiques de leurs comportements, ce qui peut conduire un SSÉ vers des changements indésirables et avoir un impact négatif sur les écosystèmes (Levin et al., 2013). Un SSÉ apparemment stable peut, en réalité, évoluer vers un régime différent en raison de changements mineurs, ce qui pourrait entraîner une réorganisation structurelle, des dynamiques modifiées, voire un effondrement lorsque certaines variables atteignent un point de bascule (Holling, 1973; Scheffer et al., 2001). Cependant, les SSÉ sont souvent décrits et utilisés afin d'élaborer et de mettre en œuvre des politiques (Filatova et al., 2013): les humains peuvent intervenir pour orienter le système vers un résultat souhaité ou pour maintenir son état actuel (Walker et al., 2004). Pour mettre en œuvre des mesures efficaces et durables qui préservent l'intégrité d'un SSÉ, il est crucial de comprendre chacun de ses composants et les interactions qui influencent ses processus à différentes échelles (Ostrom, 2009). Cela nécessite des approches interdisciplinaires (Levin et al., 2013) car il est essentiel de prendre en compte à la fois les dimensions écologiques et sociales. Il peut falloir des décennies pour comprendre pleinement un système (Folke et al., 2005; Walker et al., 2004). Si un système et ses processus ne sont pas entièrement compris, des résultats inattendus peuvent survenir lors de l'application de règlements (Liu et al., 2007). De plus, les impacts écologiques et socio-économiques des interactions entre les humains et la nature peuvent ne pas être immédiatement observables ou prévisibles en raison de délais temporels, ce qui signifie que les effets des réglementations pourraient ne se manifester qu'après plusieurs années (Liu et al., 2007). En effet, gérer des espèces à dynamique de vie lente, comme les baleines, peut s'avérer particulièrement complexe, car il peut falloir beaucoup de temps avant que les effets d'une mesure de gestion spécifique ne deviennent pleinement apparents (Levin et al., 2013; Parrott et al., 2012).

De nombreuses études de cas (Armitage et al., 2009; Hahn et al., 2008; Liu et al., 2007) ont contribué à l'élaboration de cadres qui soutiennent la conceptualisation et la gestion des changements au sein des SSÉ (Binder et al., 2013; McGinnis et Ostrom, 2014; Ostrom, 2009; Walker et al., 2004). Les SSÉ ne sont ni des systèmes humains intégrés aux systèmes écologiques, ni des écosystèmes intégrés aux systèmes humains; ils nécessitent plutôt l'interaction de ces deux disciplines pour partager des hypothèses communes (Lagadeuc et Chenorkian, 2009).

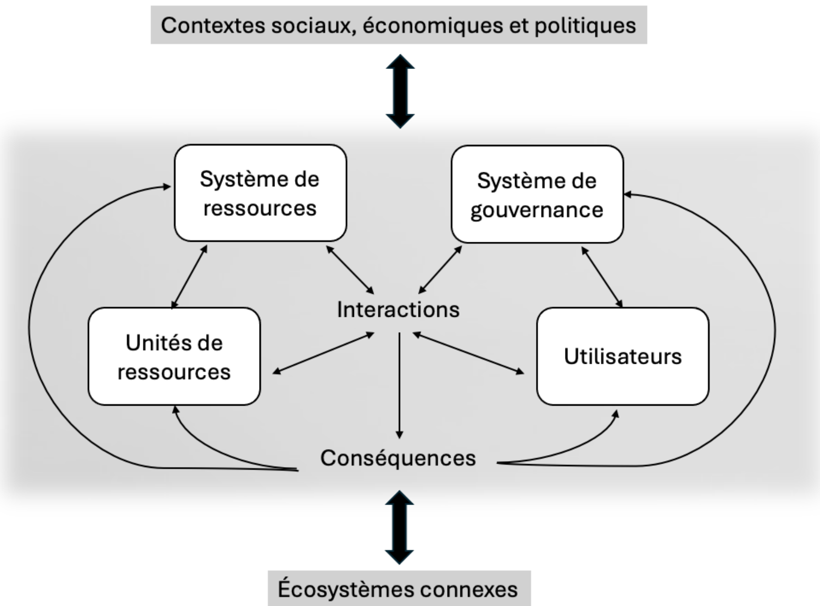


Figure 1.1 Les sous-systèmes de base dans un cadre d'analyse des systèmes socio-écologiques selon la terminologie d'Ostrom (extrait de Ostrom, 2009).

La figure 1.1 regroupe les sous-systèmes de base dans un cadre d'analyses des systèmes socio-écologiques selon la terminologie d'Ostrom. Tout d'abord, les composantes naturelles du système incluent le **système de ressources**, qui désigne une zone géographique spécifiée contenant des habitats, des espèces ou des sous-écosystèmes. À l'intérieur de ce système se trouvent les **unités de ressources**, c'est-à-dire les éléments spécifiques d'intérêt, tels que les arbres, les animaux, l'eau ou d'autres matières organiques. De plus, les composantes sociales se composent, d'un côté, des **utilisateurs**: des agents décisionnels individuels qui poursuivent leurs propres objectifs, interagissent entre eux et adaptent leur comportement en fonction de leur état ainsi que des conditions de leur environnement, qu'il soit vivant ou non (Schulze et al., 2017). Ces agents jouent un rôle central, car ils influencent la dynamique du système de multiples façons. D'un autre côté, elles incluent le **système de gouvernance**, c'est-à-dire les structures et les processus par lesquels les sociétés prennent des décisions et répartissent le pouvoir (Folke et al., 2005). La gouvernance joue aussi un rôle clé en orientant les interactions entre les acteurs et leur environnement par l'établissement de lois, règlements ou politiques. Au-delà de ces composantes formelles, certaines approches soulignent qu'elle se déploie également à travers des interactions entre de multiples acteurs, niveaux et institutions. Le cadre de la gouvernance interactive (Kooiman et al., 2008) conçoit en effet la résolution des enjeux socio-écologiques comme le produit d'interactions continues entre acteurs disposant de rôles, de capacités et de responsabilités variés, évoluant au sein de structures juridiques, techniques ou culturelles qui les contraignent autant qu'elles les habilitent. L'ensemble de ces éléments **interagit** et engendre des **conséquences** sur le système global, qui, à son tour, exerce une influence sur ces éléments, créant ainsi des boucles de rétroaction. Enfin, ce système interagit également avec les contextes sociaux, économiques et politiques, ainsi qu'avec les écosystèmes connexes qui l'entourent.

De tels cadres permettent d'analyser une grande diversité de systèmes où les dynamiques écologiques et sociales sont étroitement imbriquées. À travers le monde, les SSÉ ont été mobilisés pour étudier des interactions humaines–faune dans des contextes très variés. Par exemple, dans plusieurs régions d'Afrique, la cohabitation entre communautés locales et grands herbivores ou prédateurs révèle des compromis complexes entre sécurité, conservation et usage des terres (Constant, 2014 ; Sanare et al., 2022). De même, dans différents systèmes agro-naturels et forestiers européens, les interactions entre usages humains, disponibilité des ressources et conservation de la biodiversité mettent en évidence des compromis similaires, qu'il s'agisse de la gestion des zones humides en contexte agricole ou de l'organisation des services écosystémiques forestiers (Ricart & Rico-Amorós, 2021 ; Sorge et al., 2022). Enfin, des travaux en milieu marin montrent que les SSÉ permettent de mieux comprendre des systèmes multisectoriels où plusieurs activités humaines influencent la faune et les ressources côtières, comme dans une communauté côtière du Quintana Roo, au Mexique, ou au sein des pêcheries artisanales de Rio Formoso, au Brésil, où la diversité des usages, les perceptions locales et l'organisation communautaire conditionnent la durabilité et la gestion des ressources (Palomo & Hernández-Flores, 2021 ; Pelage et al., 2023). Ces exemples montrent qu'appréhender un SSÉ nécessite de le considérer dans son ensemble, en prenant en compte les interactions complexes entre dimensions humaine, écologique et institutionnelle.

1.1.1. Le système socio-écologique de l'estuaire du Saint-Laurent

L'ESL et le FS constituent un système socio-écologique complexe (Parrott et al., 2012), où les activités humaines interagissent avec les composantes naturelles, engendrant des dynamiques émergentes et des boucles de rétroaction. Ce territoire fait partie de l'habitat essentiel de la population de BESL et sert d'aire d'alimentation pour plusieurs espèces migratrices de baleines. Il est structuré par un réseau dense d'usages nautiques, incluant les voies de navigation commerciale, les routes de traversiers, les zones de départ des excursions aux baleines et les principaux points de mise à l'eau des embarcations de plaisance. Afin de protéger cet écosystème fragile, le Parc marin du Saguenay–Saint-Laurent a été créé en 1998 (Figure 1.2).

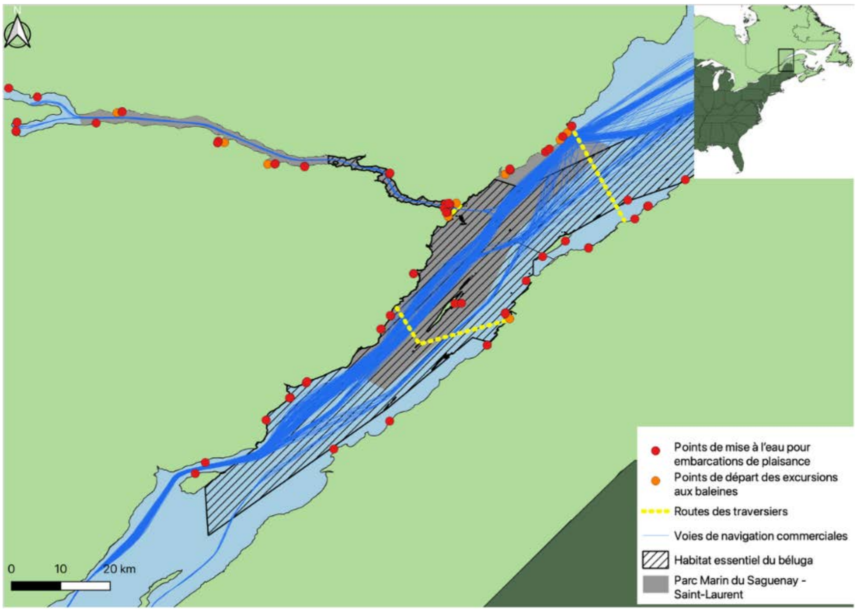


Figure 1.2. Habitat essentiel du béluga, PMSSL, voies de navigation commerciales, routes de traversiers, points de départ des excursions aux baleines et points de mise à l'eau pour la plaisance (Québec, Canada).

Selon la terminologie d'Ostrom présentée dans la figure 1.1, les éléments d'intérêt pour l'étude du système socio-écologique peuvent être décrits comme suit :

- Système de ressources: L'habitat essentiel de la population de BESL, comprenant le FS et l'ESL.
- Unité de ressources: Les cinq espèces de baleines présentes dans ce système, à savoir le béluga, le rorqual bleu, le rorqual commun, le rorqual à bosse et le petit rorqual.
- Système de gouvernance: Les institutions responsables de proposer des règlements et d'en assurer le respect, telles que Parcs Canada et Pêches et Océans Canada.
- Utilisateurs: Les diverses activités de navigation, notamment les cargos, les traversiers, les bateaux d'observation des baleines et les bateaux de plaisance.

Ces composantes interagissent de manière dynamique et produisent des boucles de rétroaction observables dans le système. Par exemple, les activités de navigation peuvent provoquer le déplacement des baleines ou l'abandon de certains territoires. On soupçonne que la baie de Tadoussac ait été désertée par les bélugas après la construction de la marina, en raison de l'augmentation du trafic maritime et de l'exposition accrue au bruit (Pippard, 1985). En réponse à ces déplacements, les bateaux d'excursions et les plaisanciers souhaitant observer les baleines pourraient adapter leurs itinéraires pour continuer de les observer, tandis que les institutions pourraient ajuster les règlements, par exemple en appliquant de nouvelles limitations dans les zones devenues intensivement fréquentées. De manière plus générale, ces interactions illustrent comment les comportements humains influencent la structure et la dynamique écologique, et comment les réponses des baleines peuvent, à leur tour, modifier les pratiques des utilisateurs ainsi que les règlements proposés par les systèmes de gouvernance.

Dans cette description du SSÉ du Saguenay–Saint-Laurent, cinq espèces de baleines présentes dans la région et diverses activités de navigation sont incluses, bien que d'autres espèces ou types d'activités nautiques pourraient également être considérés. Il existe en effet de multiples façons de représenter un SSÉ selon les objectifs de l'étude. La description se concentre ici sur les activités de navigation motorisée et sur les espèces de baleines les plus fréquentes dans l'estuaire et le fjord. Plus spécifiquement, puisque l'objectif de ce projet est de caractériser les interactions entre la navigation de plaisance et les bélugas, l'attention est portée sur les plaisanciers et leurs interactions avec cette espèce.

Bien que la navigation de plaisance puisse être considérée comme une activité légère, en raison de la taille des embarcations et de sa pratique saisonnière, elle peut néanmoins générer des impacts significatifs sur le système, notamment sur les cétacés, qui sont particulièrement sensibles aux bruits sous-marins. À ce jour, aucune étude n'a encore caractérisé la navigation de plaisance dans l'habitat estival de la population du BESL, ni évalué ses effets sur les individus. En comparaison, les segments de navigation plus prévisibles, tels que les navires commerciaux, ferry ou bateaux d'excursions, ont fait l'objet de plusieurs études qui ont permis de mieux comprendre leurs impacts sur la population de bélugas (Blane et Jaakson, 1994 ; Gervaise et al., 2012 ; Lesage et al., 1999 ; Lesage et al., 2014). Cette lacune souligne la nécessité de documenter la navigation de plaisance et ses interactions avec les bélugas afin de compléter la connaissance existante sur l'ensemble du système.

En effet, de nombreuses études montrent que les activités récréatives peuvent entraîner des effets notables sur la faune au sein de divers SSÉ. Par exemple, des activités terrestres comme le vélo de montagne et la randonnée ont été associées à des comportements de fuite ou d'évitement chez plusieurs espèces, notamment les bisons (*Bison bison*), cerfs mulets (*Odocoileus hemionus*) et antilopes d'Amérique (*Antilocapra americana*) en Utah (Taylor et Knight, 2003), les chamois (*Rupicapra rupicapra*) en Suisse (Gander et Ingold, 1997), ainsi que les cerfs de Virginie (*Odocoileus virginianus*) au Québec (Millien et al., 2024). Des perturbations similaires ont également été documentées dans le cadre de sports d'hiver, provoquant des comportements d'évitement chez les chèvres des montagnes Rocheuses (*Oreamnos americanus*) en Alberta (Richard et Côté, 2016) ou des niveaux de stress élevés chez les coqs des bouleaux (*Lyrurus tetrix*) dans les Alpes suisses (Arlettaz et al., 2007). Dans les environnements marins, plusieurs travaux mettent également en évidence l'influence d'activités récréatives. Les grands dauphins (*Tursiops truncatus*) ont montré des comportements d'aversion à l'égard d'embarcations rapides au Royaume-Uni (Goodwin et Cotton, 2004), tandis que les guillemots marbrés (Brachyramphus marmoratus) ont été observés quittant des zones d'alimentation en présence de bateaux en Colombie-Britannique (Bellefleur et al., 2009). Des synthèses plus larges ont compilé ces observations à l'échelle de multiples espèces et types d'activités, montrant que les loisirs motorisés ou non peuvent exercer une variété d'impacts sur la faune, allant des modifications comportementales aux perturbations physiologiques (Larson et al., 2016 ; Higham et Lück, 2007).

1.2. Les modèles multi-agents

1.2.1. Définition

La modélisation multi-agents est une technique de simulation fondée sur l'intelligence artificielle distribuée (Ferber et Weiss, 1999). Elle modélise des environnements en créant des entités virtuelles, appelées agents, qui représentent des acteurs du monde réel et leurs interactions entre eux et avec leur environnement (Bonabeau, 2002). Les propriétés clés des agents incluent généralement l'autonomie (la capacité à fonctionner de manière indépendante), la capacité sociale (l'aptitude à interagir avec d'autres agents et entités), la réactivité (la capacité à répondre aux changements de l'environnement) et la proactivité (l'aptitude à prendre des initiatives pour atteindre des objectifs) (Russell et Norvig, 2016; Wooldridge, 1999). Le niveau de détail de ces aspects peut varier en fonction des objectifs de l'étude. Les types d'agents, les stratégies de prise de décision, les facteurs comportementaux et les caractéristiques sont souvent dérivés empiriquement de méthodes d'enquête sociale et ensuite traduits en bases de règles qualitatives pour les agents (Rounsevell et al., 2012). Ces propriétés permettent aux agents de naviguer efficacement dans des environnements complexes et d'adapter leurs comportements en conséquence.

Cette approche, qui met l’accent sur les processus décisionnels des agents, offre un moyen de représenter et de visualiser clairement les SSÉ, contribuant ainsi à comprendre les processus fondamentaux qui les composent (McLane et al., 2011), notamment les propriétés émergentes ascendantes découlant des comportements individuels des agents (Conte et Paolucci, 2014). De plus, en adoptant des hypothèses réalistes, les modèles multi-agents (MMA) peuvent générer des prédictions qui soutiennent une gestion réfléchie et adaptative du SSÉ modélisé, agissant comme des « laboratoires virtuels » pour explorer des hypothèses causales et les résultats potentiels de nouvelles régulations ainsi que leurs effets combinés (Burgess et al., 2020; Grimm et al., 2005; Van der Wal et al., 2016).

Plusieurs étapes clés sont essentielles dans le développement d'un MMA, notamment la conceptualisation, le développement et la validation (An et al., 2014; Filatova et al., 2013; Villamor et al., 2012). Lors de la phase de conceptualisation, il est crucial d'identifier d'abord les agents impliqués dans le système étudié, puis leurs comportements et interactions (An et al., 2014). Les MMA offrent la flexibilité d'éviter de modéliser chaque agent de manière individuelle. Pour ce faire, il est important de créer des typologies d'agents basées sur des attributs qui décrivent leur comportement (Rounsevell et al., 2012). Le protocole "Overview, Design concepts, and Details" (ODD) est un exemple de cadre standardisé pour décrire les MMA, structuré en trois sections principales (Grimm et al., 2006). La première section présente un aperçu des objectifs du modèle et des processus clés. La deuxième section décrit les concepts fondamentaux sous-jacents à la conception du modèle, tels que les capacités des différents agents. Enfin, la dernière section détaille les procédures d'exécution et d'initialisation du modèle (Grimm et al., 2010, 2006).

1.2.2. Applications

Les MMA sont largement utilisés dans divers domaines, notamment pour représenter les SSÉ afin de gérer les ressources et des territoires (Cascalho et al., 2019; Castillo et Saysel, 2005; Ligtenberg et al., 2001; Mathevet et al., 2003; Schlüter et Pahl-Wostl, 2007), où ils simulent les interactions entre les humains et leur écosystème. De plus, les MMA sont utilisés dans des scénarios de gestion de crise, comme la planification des évacuations en cas de catastrophe (D'Orazio et al., 2014; Tan et al., 2015; Wang et Jia, 2021), permettant d'analyser le comportement humain et la prise de décision en situation de stress. Dans des contextes spécialisés tels que la santé, les MMA aident à gérer le flux des patients et l'allocation des ressources, fournissant des informations sur la dynamique des systèmes et améliorant l'efficacité opérationnelle (Cabrera et al., 2011; Comis et al., 2021). En outre, les MMA ont été utilisés pour étudier les impacts des activités récréatives sur les écosystèmes (Anwar et al., 2007; Itami et al., 2003; Roberts et al., 2002). Ils constituent un outil de gestion précieux, offrant des informations essentielles aux décideurs publics et à d'autres parties prenantes (Chion et al., 2018).

Enfin, de nombreux travaux soulignent que les MMA gagnent à être conçus en lien avec leurs futurs usages et avec les acteurs susceptibles de les mobiliser (Barreteau et al., 2001 ; Bousquet et al., 2002). Dans cette perspective, les MMA ne constituent pas seulement des outils de simulation, mais également des supports d'analyse, de dialogue et parfois d'aide à la décision pour les gestionnaires et les parties prenantes (Étienne, 2014). Plusieurs auteurs ont montré l'intérêt d'intégrer ces acteurs dans des démarches participatives, qu'il s'agisse de coconstruire le modèle, d'explorer collectivement des scénarios, ou d'utiliser les simulations dans des dispositifs tels que les jeux sérieux (D'aquino et al., 2003 ; Guyot et Honiden, 2006). Ces approches, en cohérence avec les principes de la gouvernance interactive, rappellent que la pertinence opérationnelle d'un modèle dépend étroitement de son articulation avec les besoins réels de gestion et de concertation.

1.2.3. 3MTSim

3MTSim (*Marine Mammals and Maritime Traffic Simulator*) est un MMA qui intègre des bases de données géoréférencées avec un simulateur afin de reproduire les mouvements spatio-temporels des mammifères marins et du trafic maritime dans l'ESL et le FS (Figure 1.3) (Chion et al., 2011; Parrott et al., 2011). 3MTSim permet de tester différents scénarios de gestion du trafic maritime, tels que la mise en place de limites de vitesse ou la fermeture de zones, afin d'évaluer leurs effets sur l'ensemble du système, en particulier sur les mammifères marins (Chion et al., 2017; Parrott et al., 2011), et constitue ainsi un outil essentiel pour la gestion de ce site naturel hébergeant une biodiversité fragile. Actuellement, 3MTSim prend en compte quatre grands segments de navigation : le trafic commercial, y compris les croisières et les cargos, les bateaux d'excursion pour l'observation des baleines et les traversiers (Figure 1.3).

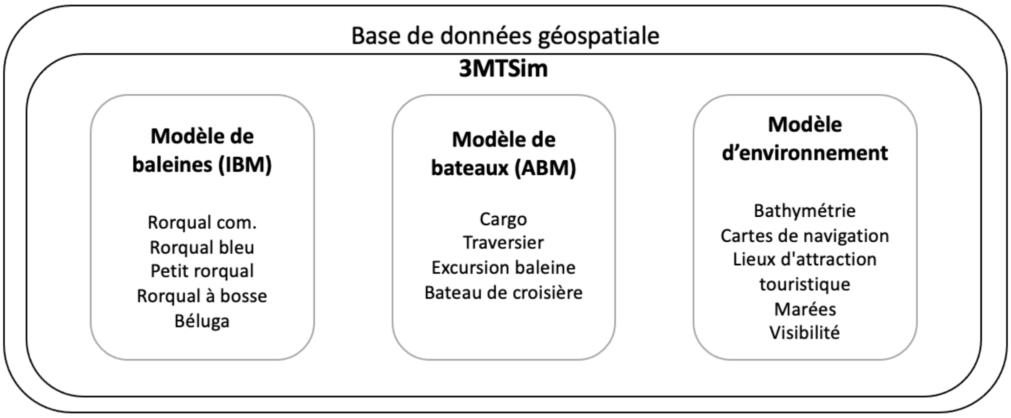


Figure 1.3 Aperçu des composants de 3MTSim (adapté de Parrott et al., 2011).

Il manque cependant un segment important : la navigation de plaisance. Ce type de navigation, qui constitue une composante significative du trafic estival dans l'ESL et le FS (Chion et al., 2009; Turgeon, 2019), se caractérise par une forte variabilité des comportements individuels, influencés par les préférences, les perceptions et les intentions des plaisanciers. Ce projet s'inscrit dans la démarche d'enrichissement progressif de 3MTSim en produisant les connaissances empiriques nécessaires à la conceptualisation d'un module dédié à la plaisance. Il répond ainsi à un besoin clairement identifié d'élargir la couverture comportementale du modèle afin de mieux représenter l'ensemble des usages du Saint-Laurent. L'intégration de ce segment dans un modèle multi-agents exige une compréhension des déterminants des comportements humains, et en particulier des processus cognitifs qui orientent les choix des individus dans des contextes socio-écologiques complexes. La section suivante s'intéresse ainsi aux mécanismes de prise de décision de l'être humain.

1.3. La prise de décision humaine

La prise de décision, un processus cognitif central dans le comportement humain, consiste à choisir une action parmi plusieurs alternatives en fonction des objectifs de l'individu (Simon, 1955).

Il existe plusieurs types de prise de décision en fonction de l'effort cognitif impliqué. Les décisions simples et routinières, par exemple, nécessitent un effort cognitif minimal (comme choisir un repas), tandis que des décisions plus complexes demandent une collecte et une analyse approfondies d'informations (par exemple, élaborer de nouvelles réglementations pour l'utilisation de ressources communes) (Janis et Mann, 1977). De plus, ces décisions peuvent avoir des conséquences de différentes natures : elles peuvent être certaines (les conséquences sont entièrement connues, comme boire un verre d'eau pour étancher la soif), incertaines (la probabilité des conséquences est inconnue, comme la qualité d'une récolte avec un nouvel engrais) ou risquées (les conséquences et leurs probabilités sont connues, comme parier sur le rouge au casino) (Lemaire et Didierjean, 2018). Enfin, les décisions peuvent être prises individuellement ou collectivement. La prise de décision collective, qui découle des interactions sociales, peut également compliquer le processus de décision (Surowiecki, 2004).

Le processus de prise de décision peut être décomposé en une série de phases essentielles :

- Identifier un problème ou une opportunité nécessitant une décision (Nutt, 1984).
- Rassembler des informations pertinentes pour guider la décision (Tversky et Kahneman, 1974).
- Évaluer les options disponibles en tenant compte des risques et des avantages (von Neumann et Morgenstern, 1944).

- Sélectionner l'option la plus appropriée sur la base de l'évaluation effectuée.
- Mettre en œuvre la décision et évaluer les résultats liés à ce choix (Mintzberg et al., 1976).

Décortiquer ces étapes aide à comprendre comment les individus interprètent les informations et prennent des décisions. Cependant, certains biais cognitifs, qui seront abordés ultérieurement, peuvent altérer ce processus de prise de décision (Tversky et Kahneman, 1974).

Comprendre les processus de prise de décision humaine dans des contextes socio-écologiques est essentiel, car les interactions entre les composantes sociales et écologiques façonnent l’évolution du système. En effet, les choix effectués par des individus ou des groupes concernant l’utilisation des ressources ou les politiques environnementales ont un impact direct sur les écosystèmes et leur biodiversité (Berkes et al., 2003). Une compréhension approfondie des processus qui sous-tendent la prise de décision, notamment les informations disponibles pour le décideur, les motivations à l’origine de la décision, et la manière dont celle-ci est prise, peut orienter des pratiques de gestion des ressources plus efficaces. De plus, en examinant la manière dont les individus prennent des décisions, les décideurs peuvent concevoir des cadres qui favorisent la conformité aux réglementations et facilitent la collaboration entre les parties prenantes (Folke et al., 2005).

1.4. Théories de la prise de décision

Les théories de la prise de décision explorent la manière dont les individus traitent l'information, évaluent les options et prennent des décisions. La section suivante propose un aperçu des théories fondamentales et sous-jacentes nécessaires à la compréhension des processus de prise de décision dans des environnements complexes.

1.4.1. Théories fondamentales sous-jacentes

1.4.1.1. La rationalité

Par le passé, la prise de décision était considérée comme régie par des lois de probabilité strictes, impliquant que les agents disposaient d'une connaissance parfaite. La rationalité dans la prise de décision (von Neumann et Morgenstern, 1944) consiste à maximiser l'utilité personnelle, la satisfaction ou le bien-être qu'une personne en retire. On suppose que les acteurs rationnels ont des préférences stables, une connaissance complète de leur environnement et une capacité cognitive illimitée pour évaluer toutes les options possibles et choisir la meilleure pour atteindre leurs objectifs. Cependant, les critiques soutiennent que ce modèle simplifie à l'excès le comportement humain, en particulier dans des environnements complexes et incertains comme les SSÉ (Simon, 1997).

1.4.1.2. La rationalité limitée

Le concept de rationalité limitée (Simon, 1955) a permis une représentation plus réaliste des processus décisionnels réels. Il décrit les limites auxquelles les décideurs sont confrontés en raison des contraintes cognitives, des informations limitées et de l'incertitude environnementale. Dans ces conditions, les individus simplifient souvent des problèmes complexes, ce qui peut aboutir à des décisions qui s'écartent du modèle rationnel idéal. Un acteur doté d'une rationalité limitée s'appuie souvent sur des règles empiriques simples qui simplifient la prise de décision sans nécessiter de calculs approfondis de tous les résultats possibles, car la recherche d'une solution exacte prendrait trop de temps (Gigerenzer et Selten, 2001).

Les heuristiques

Ces règles simples appelées heuristiques sont des stratégies cognitives qui ont été largement étudiées et décrites (Tversky et Kahneman, 1974). Les plus courantes sont brièvement présentées ci-dessous.

La méthode de "***satisficing***" (Simon, 1955) est une stratégie de prise de décision selon laquelle les individus s'arrêtent de chercher dès qu'ils trouvent une solution jugée satisfaisante, plutôt que de continuer à chercher l'option optimale, notamment lorsqu'ils sont confrontés à la complexité et à l'incertitude. Cette approche contraste avec les stratégies d'optimisation, où l'objectif est de trouver la meilleure solution possible en effectuant une analyse approfondie (Simon, 1979). *Par exemple, lorsqu'une personne choisit un restaurant pour le dîner, elle pourrait sélectionner le premier endroit qu'elle voit, qui semble acceptable et respectant son budget, plutôt que de consacrer du temps à chercher l'option la mieux notée ou la plus saine de la région.*

Le **principe de reconnaissance**, tel que décrit par Goldstein et Gigerenzer (2002), suggère que, lorsqu'une personne est confrontée à deux options, l'une familière et l'autre inconnue, l'option familière est supposée avoir une plus grande valeur par rapport au critère donné. *Par exemple, lorsqu'un acheteur cherche une nouvelle voiture, il pourrait choisir une marque bien connue simplement parce qu'il reconnaît son nom, même si une marque moins connue offre une meilleure garantie ou une meilleure efficacité énergétique.*

Avec l'heuristique "***take-the-best***", l'acteur utilise l'information la plus importante, un indice, pour prendre une décision. Après avoir classé les indices disponibles en fonction de leur fiabilité, l'acteur considère l'indice le plus fiable et compare les valeurs des indices pour chaque alternative. La décision est ensuite prise en fonction de l'option qui obtient le meilleur score pour cet indice (Gigerenzer et Goldstein, 1996). *Par exemple, une personne qui doit choisir quel détergent à lessive acheter pourrait se baser sur le critère qu'elle juge le plus important, comme le prix, plutôt que de prendre en compte d'autres facteurs comme l'odeur ou l'impact environnemental.*

Les heuristiques simplifient la prise de décision complexe en réduisant l'effort cognitif nécessaire pour parvenir à une solution. Ces raccourcis mentaux sont souvent influencés par des biais cognitifs, qui peuvent façonner la manière dont les décisions sont prises en situation d'incertitude. Les biais influencent fréquemment l'utilisation des heuristiques, amenant les individus à prendre des décisions qui s'écartent de la rationalité. Tversky et Kahneman (1974) offrent un aperçu de plusieurs biais cognitifs qui conduisent à l'utilisation des heuristiques dans le processus décisionnel. Ces biais incluent, par exemple, le biais de disponibilité, où les individus accordent plus d'importance aux informations facilement accessibles dans leur mémoire, ou encore le biais de représentativité, qui pousse à juger la probabilité d'un événement en fonction de sa similarité avec une catégorie préexistante.

Comprendre les heuristiques et les biais est particulièrement pertinent dans les contextes socio-écologiques, où la prise de décision se fait souvent dans des conditions d'incertitude et de complexité. *Par exemple, les pêcheurs qui choisissent où pêcher peuvent se baser sur des heuristiques, telles que les endroits de pêche ayant été fructueux par le passé, plutôt que d'analyser les données écologiques actuelles.* Ces stratégies de décision simplifiées peuvent conduire à la surexploitation des ressources ou à la négligence de facteurs écologiques importants. Cela souligne l'importance de reconnaître et de prendre en compte les limitations de la cognition humaine dans la gestion environnementale (Tversky et Kahneman, 1974). En intégrant les heuristiques dans les modèles de prise de décision des SSÉ, nous pouvons mieux comprendre comment les individus font des choix ayant un impact sur l'environnement (Pahl-Wostl, 2007).

1.4.2. La prise de décision naturaliste

Bien que les heuristiques simplifient la prise de décision, elles peuvent également entraîner des biais qui affectent la qualité des choix faits, en particulier dans des environnements complexes et incertains. Ce contexte est crucial lorsque l'on considère la prise de décision naturaliste, qui explore comment les décisions sont prises dans des conditions difficiles. La prise de décision naturaliste se concentre sur des situations où les acteurs sont généralement considérés comme des experts dans leur domaine, ayant rencontré des situations similaires à plusieurs reprises. Elle décrit des situations où les acteurs prennent des décisions de manière "naturelle" en reconnaissant des modèles familiers (Montgomery et al., 2005). En effet, l'expérience des décideurs raccourcit le processus décisionnel en utilisant des heuristiques telles que la stratégie de décision par reconnaissance de modèles (Klein, 2008). *Par exemple, un pompier lors d'une intervention peut se baser sur la reconnaissance d'expériences passées plutôt que de suivre un arbre de décision détaillé*. La prise de décision naturaliste est également largement utilisée pour étudier des situations où des décisions erronées pourraient entraîner de graves conséquences (Ash et Smallman, 2010; Cristancho et al., 2013).

1.4.3. Modélisation du processus de prise de décision

Lorsqu'une compréhension approfondie des dynamiques des SSÉ est nécessaire, que ce soit pour expliquer, prédire ou simuler leur comportement dans des conditions spécifiques, on cherche à modéliser ces systèmes. Selon la situation modélisée et les facteurs jugés importants dans le processus de prise de décision, différentes architectures peuvent être utilisées pour représenter la façon dont les agents prennent des décisions. Cela peut aller de systèmes simples basés sur des règles de production à des représentations plus complexes, selon le niveau de détail souhaité et les processus que l'on souhaite intégrer (Balke et Gilbert, 2014). En règle générale, les modèles d'agents simples sont privilégiés lorsque l'objectif est de prédire le comportement global d'un système, tandis que des modèles plus élaborés, offrant une représentation plus fidèle des comportements individuels, peuvent être nécessaires pour des analyses fines au niveau de chaque agent (Carley et al., 1998).

1.4.3.1. Système basé sur des règles de production

Un système basé sur des règles de production est un modèle utilisé pour simuler les processus décisionnels, reposant sur un ensemble de règles définies (appelées « productions ») et une mémoire de travail, qui contient des informations actualisées sur l'environnement de l'agent. Lorsqu'une décision doit être prise, les conditions présentes dans la mémoire de travail sont comparées aux règles, et lorsque celles-ci sont remplies, une action spécifique est déclenchée (Nilsson, 1977). Ces règles suivent une logique du type « si-alors » : si une condition est remplie, une action prédéfinie s'exécute (Forgy, 1981). Un interpréteur de règles gère l'ordre d'application des règles et résout les conflits potentiels entre elles. Ce modèle fondamental a servi de base pour le développement de systèmes décisionnels plus complexes. Cette approche offre un cadre clair et simple, tout en permettant une évolution vers des structures plus détaillées et adaptées à des contextes décisionnels complexes.

1.4.3.2. Croyances, désirs et intentions (*BDI pour Belief-Desire-Intention*)

Le cadre de croyances, désirs et intentions (BDI) (Bratman, 1987; Rao et Georgeff, 1995) est un modèle largement utilisé pour représenter les processus de prise de décision. Dans ce cadre, les agents s'appuient sur leurs croyances (représentation de leur connaissance de l'environnement), leurs désirs (objectifs ou finalités à atteindre) et leurs intentions (engagements envers des actions spécifiques). Concrètement, la structure BDI modélise les processus internes d'un agent, tandis que son comportement observable est simulé dans l'environnement du modèle. Ce cadre permet aux agents de s'adapter à des environnements dynamiques en actualisant leurs croyances et en ajustant leurs actions en fonction de l'évolution des objectifs et des circonstances. De nombreuses extensions du modèle BDI ont été développées pour y intégrer des dimensions supplémentaires comme l'apprentissage, les normes sociales ou encore les émotions. Ces enrichissements permettent de représenter des comportements plus nuancés et réalistes, adaptés à des contextes complexes.

1.4.3.3. Autres cadres conceptuels et architectures

Balke et Gilbert (2014) proposent diverses architectures permettant de représenter des agents décisionnels, allant des systèmes basés sur des règles de production au cadre BDI et à ses variantes, en incluant également des modèles inspirés de processus psychologiques et neurologiques. Plus spécifiquement, Adam et Gaudou (2016) présentent un guide méthodologique pour l'application du cadre BDI dans les simulations sociales, offrant un aperçu des approches existantes et de leur mise en œuvre. De manière générale, le processus décisionnel peut être divisé en trois composantes clés :

- l'entrée (perception),
- la sortie (comportement) et
- les étapes intermédiaires (les règles ou mécanismes qui influencent la sélection et l'adoption d'un comportement).

Schlüter et al. (2017) décrivent un cadre pour représenter le comportement humain : après avoir perçu et évalué les informations de son environnement, un agent peut ajuster son état interne. Les options comportementales sont alors intégrées dans un processus décisionnel où l'agent identifie et adopte le comportement le plus aligné avec ses objectifs. En exécutant ce comportement, l'agent peut modifier l'état de son environnement socio-écologique. Ce cadre permet ainsi de représenter diverses théories de la prise de décision.

Les modèles normatifs décrivent comment les décisions devraient idéalement être prises, en supposant que les acteurs disposent de connaissances parfaites leur permettant d’évaluer tous les résultats possibles. En revanche, les modèles descriptifs se concentrent sur les comportements réels de prise de décision, où les acteurs recourent à divers raccourcis en raison de leurs limitations cognitives (Thaler, 1980).

1.4.3.4. Méthodes pour sonder la prise de décision

Une étape délicate dans la modélisation de la prise de décision humaine consiste à collecter des données permettant de comprendre avec précision comment les individus prennent leurs décisions. Au-delà de la réalisation de questionnaires quantitatifs, une interaction directe avec les décideurs est souvent nécessaire pour recueillir des informations approfondies. Plusieurs méthodes qualitatives permettant d’explorer la prise de décision sont présentées ci-dessous.

Une approche courante consiste à mener des **entretiens** en face à face où les questions sont adaptées au contexte spécifique de la prise de décision étudiée (par exemple, O'Keeffe et al., 2016). Cette méthode, sans contrainte de temps, permet aux chercheurs d'explorer en profondeur les processus cognitifs des décideurs en examinant leurs réponses et en clarifiant les éventuelles ambiguïtés, ce qui conduit à des données riches et détaillées. Cependant, elle peut introduire une distance psychologique entre les situations discutées et l'expérience réelle du décideur, qui raconte souvent des événements passés ou envisage des scénarios hypothétiques, plutôt que de prendre des décisions en temps réel. Par conséquent, les réponses obtenues pourraient ne pas refléter fidèlement les décisions qui seraient prises dans des situations réelles.

Les méthodes basées sur des **scénarios** consistent à présenter une série de situations hypothétiques aux décideurs, en leur demandant d'agir comme ils le feraient dans la réalité. Ces scénarios permettent d'explorer différents contextes décisionnels et de recueillir des données variées. Cependant, tout comme les entretiens, la nature abstraite de ces situations hypothétiques peut limiter leur pertinence immédiate pour le décideur, ce qui risque d'entraîner des choix qui ne reflètent pas pleinement les comportements réels. Pour pallier cette limitation, des jeux sérieux peuvent être utilisés (par exemple, Yiannakoulias et al., 2020). Ces jeux de recherche simulent des environnements réels et des situations de prise de décision, offrant une immersion et un réalisme accrus qui augmentent la validité des résultats obtenus.

L'**observation** sur le terrain est une méthode efficace pour étudier la prise de décision. Les chercheurs observent les décideurs en temps réel, alors qu'ils gèrent des situations d'intérêt, ce qui permet d'obtenir des informations immédiates et précises sur la manière dont les décisions sont prises en pratique (par exemple, Vicente et al., 2004). Des entretiens de suivi peuvent ensuite être réalisés pour explorer les raisons qui sous-tendent certaines actions spécifiques. Cependant, toutes les situations ne sont pas accessibles aux chercheurs (par exemple, les situations d'urgence), ce qui peut les amener à manquer des contextes décisionnels cruciaux lors d'événements clés.

Les **protocoles de verbalisation** consistent à demander aux décideurs d'exprimer leurs pensées à voix haute pendant qu'ils prennent des décisions, permettant ainsi aux chercheurs de collecter des données en temps réel sur les processus cognitifs impliqués (par exemple, Prime et Le Masurier, 2000). Lorsque cela est possible, les chercheurs peuvent également demander aux décideurs de clarifier certains de leurs choix. Cependant, cette approche est limitée aux situations où les décideurs peuvent articuler leurs pensées en toute sécurité et efficacité sans perturber leurs actions, ce qui n’est pas toujours le cas (par exemple, lors de situations d’urgence).

Enfin, une combinaison de ces méthodes peut s'avérer être l'approche la plus efficace. Chacune de ces méthodes offre des informations précieuses et permet aux chercheurs de croiser leurs résultats lorsqu'elles sont utilisées ensemble, offrant ainsi une vision plus complète de la prise de décision humaine.

1.4.4. Cadres communs pour représenter les comportements environnementaux

Les « comportements environnementaux » désignent toutes les actions qui affectent la disponibilité des ressources ou modifient la structure et la dynamique des écosystèmes (Stern, 2000). Le « comportement pro-environnemental » fait référence aux actions consciemment entreprises par les individus pour minimiser leur impact environnemental ou contribuer positivement à l'environnement (Kollmuss et Agyeman, 2002; Steg et Vlek, 2009). Les théories de la prise de décision couramment utilisées pour comprendre les comportements liés à l'environnement incluent des mécanismes cognitifs qui expliquent comment les individus perçoivent, évaluent et adoptent des comportements environnementaux. Voici un aperçu des théories les plus utilisées dans ces contextes et des éléments sur lesquels les individus s'appuient lorsqu'ils adoptent de tels comportements.

La **théorie du comportement planifié** (Ajzen, 1991) explique comment les attitudes (croyances concernant les résultats et la valeur normative d'un comportement), les normes sociales (pression sociale perçue pour adopter ou non un comportement) et le contrôle comportemental perçu (perception de sa propre capacité à réaliser le comportement) influencent les actions. Selon cette théorie, ces trois composants interagissent pour déterminer l'intention d'un individu d'adopter un comportement spécifique, ce qui, à son tour, influence le comportement réel. Cette théorie est couramment appliquée dans des contextes environnementaux pour prédire les comportements pro-environnementaux, tels que la participation aux efforts de conservation, où les normes sociales et les attitudes personnelles jouent un rôle significatif dans la prise de décision (par exemple, De Leeuw et al., 2015; Greaves et al., 2013; Wang et al., 2020).

La **théorie des perspectives** (Kahneman et Tversky, 1979) examine comment les individus perçoivent les gains et les pertes lorsqu'ils prennent des décisions en situation d'incertitude. Selon cette théorie, les pertes et les gains sont valorisés différemment. Bien qu'elle ait été initialement développée pour expliquer le comportement économique, la théorie des perspectives a depuis été appliquée dans la gestion des ressources pour comprendre comment les individus et les groupes prennent des décisions impliquant des risques et de l'incertitude, en particulier dans des situations où des compromis sont liés à l'utilisation des ressources, à la conservation et aux impacts environnementaux (par exemple, Heutel, 2019; Osberghaus, 2017; Song et al., 2017).

La **théorie des valeurs-croyances-normes** (VBN pour Value-Belief-Norms), développée par Stern (2000), suggère que les valeurs fondamentales individuelles, les croyances sur les conditions environnementales et les normes personnelles jouent un rôle crucial dans l'adoption de comportements pro-environnementaux. Selon cette théorie, les valeurs personnelles façonnent la manière dont les individus perçoivent les enjeux environnementaux et leur sens de responsabilité à leur égard. La théorie VBN constitue un cadre précieux pour comprendre les efforts de conservation et l'adoption de pratiques durables (par exemple, Chen, 2015; Gupta et Sharma, 2019; Wynveen et al., 2015).

La **théorie des pratiques sociales** (Bourdieu, 1977; Giddens, 1984; Shove et al., 2012) postule que les comportements ne sont pas uniquement motivés par des choix individuels, mais qu'ils s'inscrivent dans un contexte social comprenant des routines, des ressources et des normes culturelles. Ces éléments influencent la manière dont les individus interagissent avec les problématiques environnementales. En examinant la relation entre les pratiques sociales et les comportements environnementaux, cette approche met en lumière l'influence des normes sociales et des habitudes quotidiennes sur l'utilisation des ressources et les efforts de conservation, facilitant ainsi l'identification de stratégies pour promouvoir des pratiques durables au sein des communautés (par exemple, Barr, 2015; Kropfeld, 2023; Welch, 2016).

La **théorie des normes descriptives** (Cialdini et al., 1991) postule que les individus sont influencés par leurs perceptions de ce qui est couramment pratiqué au sein de leur groupe social. Elle suggère que les individus ajustent souvent leur comportement en fonction de leurs observations des actions des autres, souvent de manière inconsciente. En soulignant l'importance du contexte social dans la formation du comportement, en particulier pour les actions pro-environnementales, cette théorie peut aider à identifier des stratégies pour promouvoir des pratiques durables en tirant parti de l'influence des comportements sociaux au sein des communautés (par exemple, Elgaaied-Gambier et al., 2018; Goldstein et al., 2008; Reese et al., 2013).

Bien que ces théories constituent des outils importants pour décrire la prise de décision humaine, il existe une multitude d'autres approches, y compris des combinaisons de ces théories, telles que l'intégration des normes descriptives dans la théorie du comportement planifié (Rivis et Sheeran, 2003), la combinaison de la théorie du comportement planifié avec la théorie des valeurs-croyances-normes (Chen, 2022), etc.

Schlüter et al. (2017) proposent un cadre précieux pour représenter certaines des théories de la prise de décision humaine décrites ci-dessus et les intégrer dans des modèles. Ce cadre offre un outil et un langage communs pour décrire et comparer différentes théories.

1.5. Objectifs

La navigation de plaisance dans l'habitat estival du BESL constitue un segment de la navigation encore peu documenté. Ce manque d'information limite la compréhension des interactions entre les activités humaines et cette espèce menacée, et rend difficile le développement d'outils d'aide à la gestion adaptés. **L'objectif général de cette thèse est de comprendre et caractériser les interactions entre les plaisanciers et les bélugas afin d'améliorer la représentation des dynamiques humains-faune et soutenir la gestion durable du SSÉ de l'ESL et du FS.** Il s'agit ainsi de produire des connaissances empiriques solides sur la navigation de plaisance, les profils d'usagers, les réponses potentielles des cétacés, et les contextes dans lesquels ces interactions se manifestent. Ce travail s'inscrit dans une perspective de modélisation du SSÉ de l'ESL et du FS et vise à jeter les bases nécessaires au développement futur d'un modèle multi-agent intégrant ces dimensions. Cet objectif général se décline en trois sous-objectifs spécifiques, correspondant aux trois articles scientifiques qui constituent cette thèse :

1.5.1. Sous-objectif n°1 : Décrire l'utilisation de l'habitat estival de la population de BESL par la navigation de plaisance

L'habitat essentiel du BESL couvre une vaste zone exigeante à analyser dans son ensemble. Une section spécifique de cet habitat, l'Anse de Saint-Étienne (ASE), a été choisie comme site d'étude afin de décrire l'utilisation de la zone par les plaisanciers et les bélugas. Ce secteur se situe dans le FS, entre deux secteurs intensivement utilisés par les bélugas, à savoir l'embouchure du fjord et la Baie-Sainte-Marguerite. Des observations terrestres ont été réalisées à l'aide de jumelles binoculaires pour décrire l'organisation spatiale des troupeaux de bélugas, et d'une station totale pour suivre les positions des bateaux de plaisance. Les données recueillies ont permis de dresser un portrait descriptif de la fréquentation de la zone, de la cooccurrence entre bateaux de plaisance et bélugas, ainsi que des éventuelles infractions à la réglementation du parc marin.

Question de recherche n°1 : Comment les plaisanciers utilisent-ils l'ASE durant la période estivale, et dans quelle mesure adaptent-ils leur navigation en présence de bélugas ?

Hypothèse n°1 : La variation des vitesses et/ou des caps des embarcations de plaisance est plus élevée en présence de bélugas, reflétant une adaptation observable des comportements de navigation.

1.5.2. Sous-objectif n°2 : Identifier les archétypes de plaisanciers naviguant dans l'habitat estival de la population de BESL

La modélisation de la navigation de plaisance est complexe en raison des comportements variés et peu documentés des plaisanciers. Pour surmonter cette difficulté, des archétypes de plaisanciers ont été définis à l'aide de la méthodologie-Q. Cette approche qualitative implique que les plaisanciers classent des énoncés préalablement développés, permettant d'identifier des catégories distinctes partageant des perspectives et des comportements communs.

Question de recherche n°2 : Quels profils de comportements et de valeurs structurent les décisions des plaisanciers dans l'habitat estival du béluga ?

Hypothèse n° 2 : Les valeurs et les connaissances des plaisanciers influencent leurs décisions et comportements en navigation, entraînant l'émergence de groupes distincts d'archétypes.

1.5.3. Sous-objectif n°3 : Identification des réactions des troupeaux de bélugas face aux bateaux de plaisance et des facteurs influençant la présence de bateaux de plaisance.

À partir des données collectées lors des observations terrestres réalisées à l'ASE, ce sous-objectif vise à examiner les modifications potentielles des caractéristiques géométriques des troupeaux de bélugas (dispersion, forme et structure) en réponse à la présence d'embarcations de plaisance. Il s'attache également à identifier les facteurs environnementaux et contextuels influençant la fréquentation de la zone par les plaisanciers.

Questions de recherche n° 3 : a) Quels sont les facteurs environnementaux et contextuels qui influencent la présence des embarcations de plaisance dans l'ASE ? b) Comment la présence de bateaux de plaisance influence-t-elle les troupeaux de bélugas ?

Hypothèses n° 3 : a) Les décisions de navigation des plaisanciers sont influencées par des conditions environnementales et contextuelles (ex. : heure, météo), ce qui module la probabilité de présence des bateaux dans la zone d'étude. b) Les troupeaux de bélugas ajustent leur organisation spatiale en fonction de la densité de navigation afin de minimiser la perturbation potentielle par les embarcations.

Enfin, une réflexion intégrative est proposée en discussion générale, sous forme d'une conceptualisation préliminaire des interactions plaisanciers-baleines, comme première étape vers un futur modèle multi-agent.

Chapitre 2 : Assessing recreational boat usage and compliance with marine park regulations in Anse de Saint-Étienne (Saguenay Fjord, Québec): Implications for beluga conservation

Cet article a été publié dans Marine Policy

Kowalski, C., Dupras, J., & Chion, C. (2026). Assessing recreational boat usage and compliance with marine park regulations in Anse de Saint-Étienne (Saguenay Fjord, Québec): Implications for beluga conservation. Marine Policy, 183, 106928.

Contributions des auteurs

J'ai conçu le protocole d'observation à partir de références méthodologiques existantes, en consultation ponctuelle avec des experts externes. J'ai réalisé l'ensemble des observations de terrain, accompagnée de deux assistantes formées sur place, et mené les analyses et la rédaction de l'article. Clément Chion et Jérôme Dupras ont contribué à l'élaboration du projet, au suivi scientifique et à la révision du manuscrit.

Abstract

The Saguenay Fjord, a crucial habitat for the St. Lawrence Estuary beluga whale population, is a popular area for recreational boating. However, recreational boat activities are poorly documented, as these boats are not required to have on-board systems providing information on their movements. The aim of this study is to describe how a portion of the Saguenay Fjord is used by recreational boats and beluga whales, as well as their potential interactions, and to assess whether the Marine Park regulations regarding vessel transit speed and approach distance are respected. Daylight observations and theodolite surveys were conducted during the summers of 2021 and 2022 in an 8 km² area between two key beluga sites: the mouth of the Saguenay Fjord and Ste. Marguerite Bay. These observations allowed us to gather information on the area's use by recreational boats, beluga whales, and their interactions. Recreational boats were present for more than half of the observation time on average. Across all observation days, co-occurrences (distance < 400 m) between recreational

boats and beluga whales were recorded on 45.45% of days. Some recreational boats violated regulations concerning speed limits and the minimum mandatory distance from beluga whales. Recreational boating, whether with its engine on or off, can disrupt essential behaviors in marine mammals through both emitted noise and the mere physical presence of vessels. Adjusting monitoring and enforcement strategies could help address these challenges and enhance protection for the endangered beluga population.

2.1. Introduction

The St. Lawrence estuary and the Saguenay fjord: a place of interaction between whales and recreational activities

The Saguenay Fjord, shaped by the melting glaciers of the last glaciation around 10,000 years ago and flowing into the St. Lawrence estuary (Figure 2.1), is an important habitat for the endangered St. Lawrence Estuary beluga population (*Delphinapterus leucas*) (COSEWIC, 2014; Lesage et al., 2024). They are present year-round, with aggregations up to Sainte-Marguerite Bay (SMB) during the summer (Figure 2.2) (Conversano et al., 2017; Lesage et al., 2024). This bay is crucial for the beluga population, serving as a site for feeding, socialization, and calving, with a gradual increase in beluga presence starting in June and decreasing by October (Conversano et al., 2017; Lesage et al., 2024; Mosnier et al., 2010; Simard et al., 2023; Turgeon, 2012). Despite its protected status, the population continues to decline, primarily due to high mortality rates among newborns and elevated mortality during gestation (Lesage et al., 2024; Mosnier et al., 2015), both of which significantly hinder recovery efforts (Hammill, 2007).

The Saguenay Fjord is also frequently used by recreational boaters. In 2017, 177 unique resident boats were recorded across the five marinas located from the mouth of the Saguenay Fjord (MSF) to the upper part of the fjord (from Tadoussac to La Baie), along with 2,086 overnight stays (nights berthed) by visiting boats in these marinas during summer (Turgeon, 2019). A *resident* is a boater holding a seasonal berth in a marina in the SSL region, while a *visitor* is a boater passing through for a limited time in the SSL region. These data likely underrepresent the actual usage of the fjord itself, as they only reflect the attendance at the marinas. This lack of data regarding recreational boats also arises from the fact that, in Canada, they are not required to have an onboard Automatic Identification System (AIS) transponder, which transmits essential movement information, including the vessel's position, approximately every minute. This absence makes it difficult to obtain information about their visited locations, speeds, and other relevant details.

Between 2010 and 2012, the increase in recreational boating activities was correlated with the increase in calf mortality (Ménard et al., 2014) without a causal relationship being established. Since recreational boating continues to experience strong growth (Boating Industry, 2024; ICOMIA, 2023), concerns remain about its potential impacts on beluga populations. Anthropogenic threats, particularly the degradation of the acoustic environment caused by maritime traffic, continue to pose a major challenge to conservation (DFO, 2020, 2012; Lesage, 2021). Belugas rely heavily on sound for navigation, communication, and feeding (Richardson et al., 2013), making underwater noise from boat motors a critical concern (Castellote et al., 2014; Lagrois et al., 2023; Mooney et al., 2018; Wladichuk et al., 2019). Indeed, introducing underwater noise detectable by belugas can disrupt their communication and echolocation abilities (Vergara, 2019). In response, belugas may increase the amplitude of their vocalizations, adjust the frequencies they use, and also modify their calling rate, which requires additional energy (Au et al., 1985; Lesage et al., 1999; Scheifele et al., 2005).

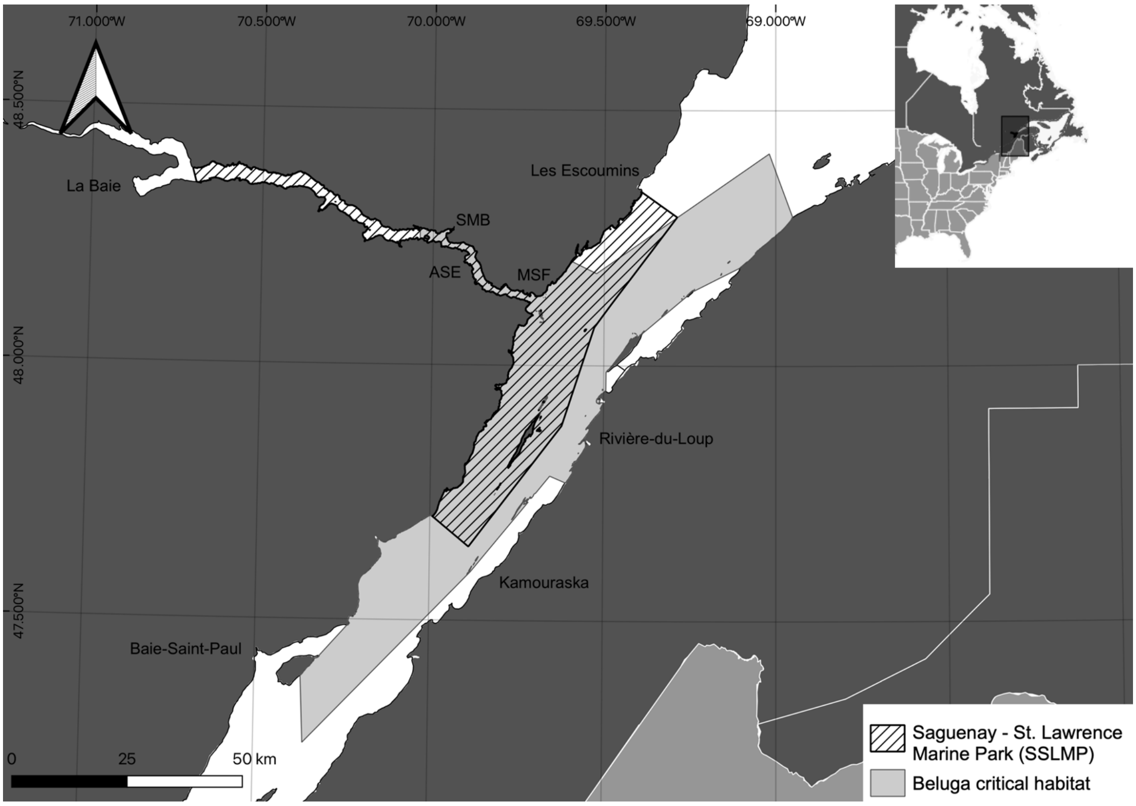


Figure 2.1 The beluga critical habitat within the St. Lawrence Estuary and Saguenay Fjord, Québec, Canada.

Regulatory measures for protecting the St. Lawrence Estuary beluga population

Established in 1998, the Saguenay - St. Lawrence Marine Park (SSLMP) was created to protect the diverse species and habitats of this unique ecosystem, including the beluga whale population. In response to the various threats faced by this endangered species, regulations have been implemented within their habitat to minimize disturbances from boating activities. When belugas are detected within the SSLMP, recreational boaters must remain in motion and are not allowed to stop within ½ nautical mile (926 meters) of the whales. Additionally, they must maintain a minimum approach distance of 400 meters. Although the maximum speed limit within the SSLMP is 25 knots, when belugas are detected, boaters are required to reduce their speed to a steady 5 to 10 knots and maintain their course. Since 2018, navigation within SMB has been prohibited from June to September to minimize disturbances to the population. Additionally, activities that may harm the whales, such as feeding, swimming nearby, touching, displacing, or separating them from their pods, are explicitly prohibited (DORS/2002-76). These regulations aim to reduce the risk of disturbance to belugas, as both vessel noise and physical presence can disrupt essential behaviors (Pirotta et al., 2015). Such disturbances may trigger avoidance reactions or reduce foraging efficiency, leading to increased energy expenditure and, over time, a decline in body condition (Lusseau and Bejder, 2007; Senigaglia et al., 2016; Tennessen et al., 2024).

The MSF and SMB are the areas with the most available information on beluga habitat use (Mosnier et al., 2010) and boating activities (Conversano et al., 2017; Ménard et al., 2014). However, although these two areas are well-documented, there is limited information about activities in the sections between them. Three high residency areas for belugas (HRAs) have been identified in this intermediate region based on tag data, showing where belugas tend to spend more time, indicating the potential importance of these areas as habitats (Lemieux Lefebvre et al., 2012; Michaud et al., 1990). However, there is a lack of data on recreational boating activities in these sections. This study aims to characterize the use of a portion of the Saguenay Fjord situated within the SSLMP, between the two most studied areas of beluga whale activity. It focuses on the presence of recreational boats and belugas, as well as their potential interactions, thereby addressing a knowledge gap in this region. Given the regulatory measures established to mitigate human-induced disturbances within the marine park, understanding how recreational activities overlap with critical beluga habitats is essential for assessing the effectiveness of these regulations. By providing empirical data on boating presence in ecologically sensitive areas, this study offers insights into the challenges of enforcing regulations and informs future strategies to mitigate anthropogenic pressures on this endangered population.

2.2. Method

2.2.1. Observation site

The study was conducted over an 8 km² area located within the regulated boundaries of the SSLMP, where recreational boating activities are predominant. Observations occurred at Anse de Saint-Étienne (ASE) ($\varphi = 48.2092094°$, $\boldsymbol{\lambda} = -69.9081906°$), along the Saguenay Fjord, as shown in Figure 2.2. This specific site was selected for several reasons. Firstly, it is located between the two most documented sites within the Saguenay Fjord: approximately 12 km from the MSF to the ASE, and about 8 km from the ASE to SMB. However, there is a lack of information regarding the area between these two well-documented sites, which highlights the importance of focusing on this intermediate location to fill this gap in knowledge. Moreover, although the area falls under marine park regulations, enforcement efforts primarily operate from Tadoussac (MSF), resulting in less consistent monitoring within the study area. Secondly, the narrow width of this section of the fjord (~2 km) ensured full visual coverage of the observed activities. Additionally, this region is known for its high beluga whale residency (Lemieux Lefebvre et al., 2012). The upstream location of SMB, a key hotspot for beluga whales, also contributes to the frequent passage of beluga whales through the study area. Furthermore, the elevated observation point, situated 50.51 meters above sea level, provided a panoramic view of the observation zone, while the land-based nature of the station prevented recreational boats from detecting observers, minimizing any influence on boater behavior. Data collection occurred during the 2021 and 2022 summer seasons, with two observers conducting all observations during daylight hours and under weather conditions that ensured clear visibility of the opposite shore.

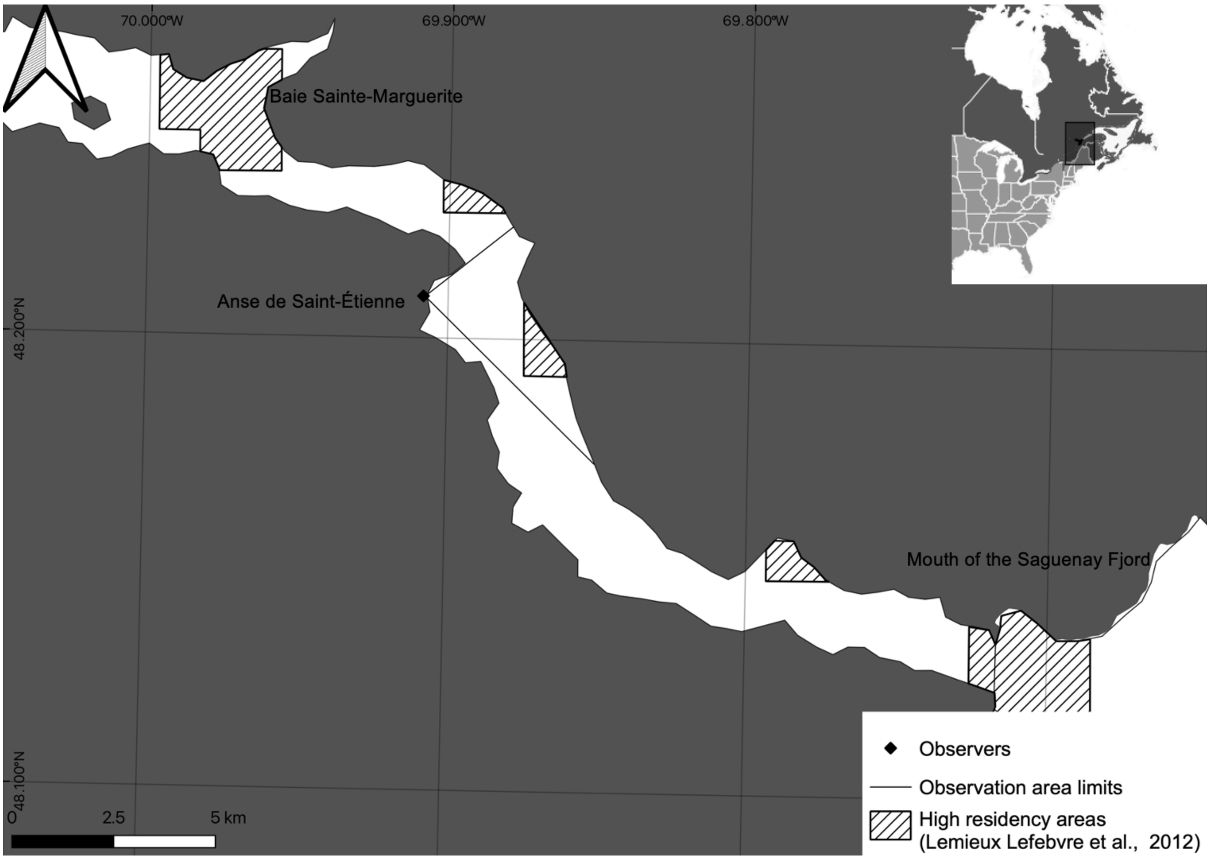


Figure 2.2 Study area within the Saguenay Fjord, Québec, Canada. The figure shows the observers' position (*black diamond*), the viewing angle delineating the observation area, high residency areas identified by (Lemieux Lefebvre et al., 2012) (*dashed polygons*), the location of the mouth of the Saguenay Fjord and the location of Ste. Marguerite Bay upstream.

2.2.2. Collected data

Recreational boats

A Leica TS06 theodolite was positioned at the same location each day to track the movements of recreational boats. The theodolite provided horizontal and vertical angles of pointed targets relative to zero-reference points, enabling the calculation of successive positions within the observation area (Martins et al., 2022). The angle measurements had a precision of 5" (see (Lagrois et al., 2023) for more details on position calculations from the theodolite's data). The observation area was continuously scanned by a first observer to detect the presence of recreational boats. Once a vessel entered the observation zone, the observer identified the type of boat: cruiser, sailboat, skiff, speedboat, or zodiac (Table 2.1) and began recording angles every minute when possible. Multiple passages of the same vessel were treated as separate events. Although kayaks and paddle boards are present in the observation area, they are not considered in this study.

Table 2.1 Types of recreational boats observed within the study area.

Type of boats	Characteristics
Cruiser	Motor boat that can accommodate several passengers and is designed for trips of a day or more (interior cabin). Inboard or outboard motor(s).
Sailboat	Boat that can accommodate several passengers and is propelled primarily by sails. Inboard or outboard motor(s).
Skiff boat	Small, shallow-draft boat with a flat bottom powered by a small outboard motor, designed for trips of less than a day, for few passengers. Usually used to go fishing.
Speedboat	Motor boat that can accommodate several passengers and is designed for trips of less than a day (no interior cabin). Inboard or outboard motor(s).
Zodiac	Rigid inflatable boat that can accommodate several passengers and is designed for trips of less than a day (no interior cabin). Outboard motor(s).

Beluga whales

A second observer scanned the observation area every 10 minutes using binoculars (Bushnell 7x50) to detect the presence of beluga whales. When belugas were sighted, the observer estimated the total number of individuals within the herds. We characterized a *herd* as a collection of groups where the distances between groups were relatively short (typically within a range of a few tens or hundreds of meters) in comparison to the overall size of the herd (Lemieux Lefebvre et al., 2012). The *groups* consisted of animals swimming closely together, typically within one body length of each other, and often exhibited coordinated movements. This information was updated every 10 minutes, and both the direction of the herd's movement and the duration of its passage were recorded. When a recreational boat was suspected to be within 400 meters (the minimum distance authorized by the SSLMP regulations) of a beluga whale, the first observer recorded the positions of both the boat and the belugas involved in the potential co-occurrence with the theodolite. Additionally, if individuals were observed engaging in a milling surface behavior (circular movement at the surface resulting in low net displacement (Lemieux Lefebvre et al., 2018)), their position was recorded. Data were analyzed using basic statistical methods, mapping techniques, and descriptive approaches.

2.3. Results & Discussion

2.3.1. Observations

Observations were conducted over 94 days (59 days in 2021 and 35 days in 2022), for a total of 623 hours and 40 minutes (383 hours and 10 minutes in 2021, and 240 hours and 30 minutes in 2022). An observation day lasted, on average, 6 hours 38 minutes.

2.3.2. Beluga whales

While beluga whales use different habitats seasonally, they are present in the Saguenay Fjord year-round, with a particular concentration during the summer, especially in the upper fjord up to SMB (Lesage et al., 2024).

Table 2.2 Observational days with vs. without beluga sightings by year in ASE.

Year	Number of days beluga were observed	Number of days beluga were not observed	Total observation days
2021	36 (61.02%)	23 (38.98%)	59
2022	30 (85.71%)	5 (14.29%)	35
2021-2022	66 (70.21%)	28 (29.79%)	94

Table 2.3 Proportion of observation time with beluga whales by year at ASE.

	Min (%)	Mean (%)	Median (%)	Max (%)
2021	0.00	11.17	9.81	47.00
2022	0.00	23.50	20.35	70.75
2021-2022	0.00	15.76	12.08	70.75

A chi-squared test indicated that the proportion of observation days with beluga sightings differed significantly between 2021 and 2022 ($\chi^2 = 5.28$, df = 1, $p = 0.022$), with a higher proportion of days with sightings in 2022 (85.7%) compared to 2021 (61.0%) (Table 2.2). Likewise, the mean proportion of observation time with beluga whales within the observation area was higher in 2022 than in 2021 (23.50% in 2022 vs. 11.17% in 2021; Table 2.3). Conversano et al. (Conversano et al., 2017) published data on beluga occupancy rates at the MSF and SMB during the summer months from 2003 to 2016, though some summers were excluded from certain analyses due to low sampling rates (see (Conversano et al., 2017) for more details). According to this report, belugas were present on 78% of the total observation days at the MSF and 66% at SMB. In our study, belugas were observed on 70.21% of days on average (Table 2.2). Although these observations cover different years, this average aligns with the location of our observation area, which lies between the MSF and SMB. Regarding beluga presence relative to total observation time, belugas were observed for 47% of the time at the

MSF and 44% at SMB (Conversano et al., 2017). In contrast, our study recorded an average occupancy rate of 15.76% (Table 2.3), suggesting that our observation area primarily serves as a transit corridor, with minimal beluga engagement in longer activities like resting, socializing, or rearing young, which are more common at the other two sites (Conversano et al., 2017; Lesage et al., 2024). Indeed, during the observations, beluga whales displayed a predominantly unidirectional movement pattern, almost exclusively traveling in either an upstream or downstream direction within the observation area between the MSF and SMB (Table 2.4). Belugas generally traveled upstream more frequently than downstream and took longer on average to transit in that direction (Tables 2.4 and 2.5).

Table 2.4 Beluga herd passages by year and direction through the observation area.

Year	Upstream	Downstream	Mix	Total
2021	39	25	3	67
2022	34	18	3	55
2021-2022	73	43	6	122

Table 2.5 Observed passage time of beluga herds through the observation area by direction.

	Min (hh:mm)	Mean (hh:mm)	Median (hh:mm)	Max (hh:mm)
Upstream	00:10	00:59	00:40	03:40
Downstream	00:10	00:39	00:30	03:30
Mix	00:10	01:17	00:35	05:00

“Mix” direction refers to cases where the herd changed direction during its passage (i.e., entering the observation area going upstream and then changing direction to leave the area going downstream).

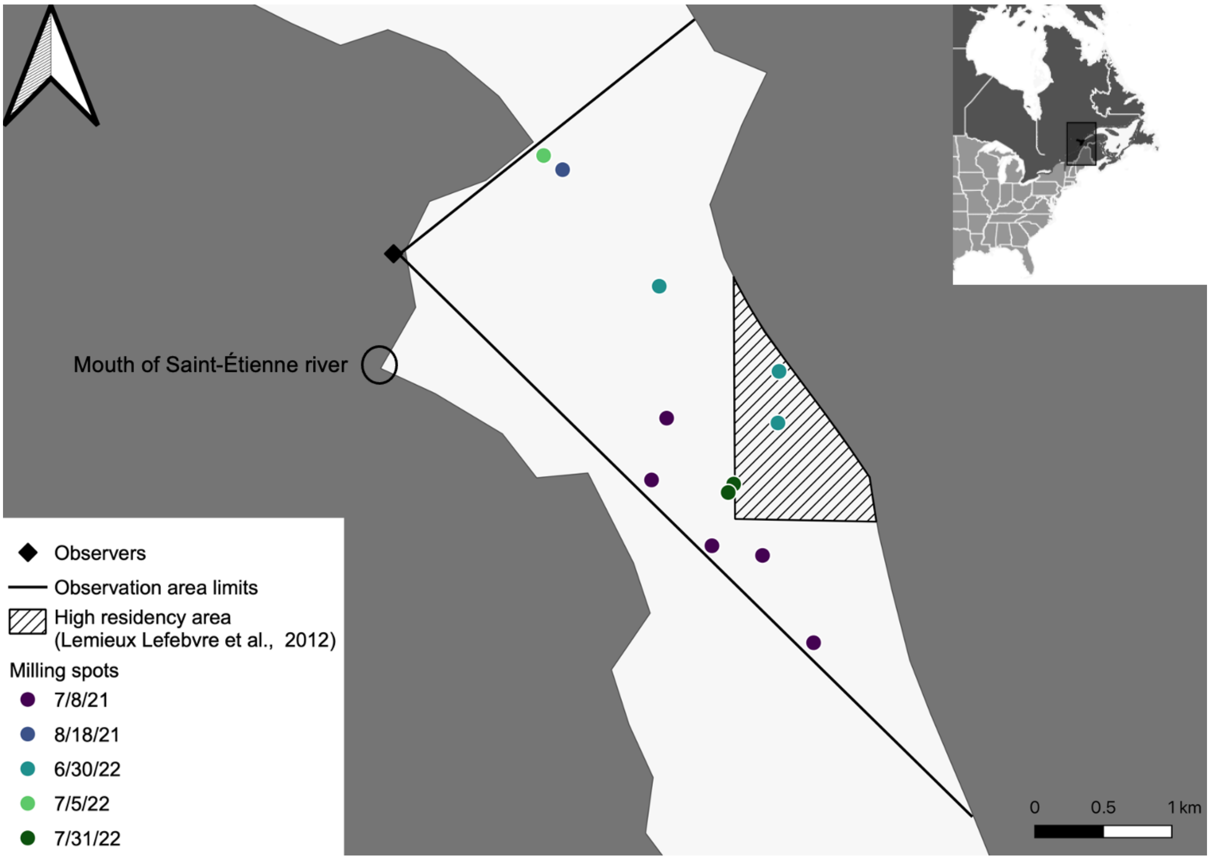


Figure 2.3 Positions where beluga whales were observed milling within the observation area. The black diamond indicates the position of the observers, the black lines show the observation limits, the dashed areas represent the HRAs (Lemieux Lefebvre et al., 2012), and the dots mark the positions where belugas were milling. Each color represents a distinct day (five days in total across 2021 and 2022)

During both observational seasons, beluga whales' herds were almost exclusively transiting through the observation area. Over the course of 94 observation days, belugas were observed milling on only 5 days, both within and outside the area identified as an HRA by Lemieux Lefebvre et al. (Lemieux Lefebvre et al., 2012) (Figure 2.3). This mainly directional behavior contrasts with observations at the other two sites, the MSF and SMB, from 2003 to 2016, where non-specific orientation and alternating directions were more common. This pattern was particularly notable at SMB, where weaker surface currents and longer beluga residency times prevail (Conversano et al., 2017). Due to constraints related to the observation site, the mouth of the Saint-Étienne river is not included in the observation area (Figure 2.3). However, this sector could be a potential zone for socializing, resting, and feeding, due to the rich primary production from the salt marsh and the stream (Audet-Robitaille and Martel, 2023). This may explain why we primarily observed belugas in transit. Conducting observations around this site would provide more information about its potential functions.

Table 2.6 Beluga herd size observed during passage through the observation area by year in ASE.

Year	Min	Mean	Max
2021 ± IC 95%	1	15.03 ± 3.23	61
2022 ± IC 95%	1	13.15 ± 2.56	38
2021-2022 ± IC 95%	1	14.18 ±2.11	61

At the MSF, the average herd size was smaller (5.9 ± 0.8 individuals), as it was at SMB (11.8 ± 4.2 individuals) (Conversano et al., 2017), compared to the estimates from our study, which remained relatively consistent across both years (14.18 ± 2.11 individuals; Table 2.6). In certain peak years at SMB, however, average herd sizes peaked at 23 ± 2.8 individuals in 2016 and 18.3 ± 1.8 individuals in 2006 (Conversano et al., 2017). It is important to note that these estimates may be undercounted due to undetected individuals diving during counts, and differences may also stem from variations in observation protocols.

2.3.3. Recreational boats

Since the 1990s, new recreational activities such as personal watercraft, kayaking, and speedboating have emerged, transforming navigation into both a significant economic driver and a popular leisure activity for coastal communities along the St. Lawrence Estuary and Saguenay Fjord (Ménard et al., 2014). Recreational boaters navigating within the Saguenay Fjord are primarily concentrated between Tadoussac and L'Anse-St-Jean (Chion et al., 2009), which includes our observation area, confirming it as a notable section for recreational boating activity. In addition, regular users have observed an increase in recreational boating activity within the Saguenay Fjord (Ménard et al., 2014). Although some commercial vessels navigated the fjord and thus passed through the observation area to reach either Grande-Anse or Port Alfred (342 vessels in 2017; (Turgeon, 2019)), only one whale-watching excursion company was operating in the area during our observations, with departures located upstream of our observation area (*Anse St. Jean*). This company passed through the observation zone four times a day, making two round trips, to reach the St. Lawrence Estuary. Few government and research vessels were observed, and, consequently, recreational boating emerged as the dominant activity within the observation area. In 2017, La Baie and Tadoussac marinas, located at the entrance and the end of the fjord, respectively, hosted the most seasonal boaters, with totals of 78 and 41 (Turgeon, 2019). Given their strategic locations at both ends of the fjord, many of these seasonal boaters are likely to navigate through the fjord, contributing to a significant presence of recreational boating within the area. Additionally, regarding overnight stays, Tadoussac marina recorded the highest number of visits, with 1,346 overnight stays in 2017 (Turgeon, 2019). Located at the mouth of the Saguenay, it provides easy access for boaters entering the fjord. According to the report by Conversano et al. (Conversano et al., 2017), between 2003 and 2016, recreational boating was the second most common type of vessel at the MSF, accounting for 29% of boat traffic, following whale-watching boats at 38%. Excluding ferries, which operate almost continuously and were outside the studied area, boats were present during 71% of the observation time at the MSF between June and August (Conversano et al., 2017). At SMB, however, recreational boats were the most prevalent, comprising 49% of boat traffic, with a 41% overall boat presence (Conversano et al., 2017). While the data from Conversano et al. (Conversano et al., 2017) include all types of boats, our study focuses exclusively on recreational boats that might involve the use of a motor; therefore, paddle boards and kayaks were not included.

Table 2.7 presents the number of recreational boat passages by type and year at ASE.

Table 2.7 Number of recreational boat passages by type and year at ASE.

Boat type	**2021**	**2022**	**Total**
Skiff boat	53	23	76 *(3.9%)*
Zodiac	76	35	111 *(5.6%)*
Speed boat	535	335	870 *(44.1%)*

Cruiser	194	95	289 *(14.6%)*
Sailboat	399	229	628 *(31.8%)*
Total	**1257**	**717**	**1974**

During our 2021-2022 observations, 1974 recreational boat passages were recorded through the observation area (1257 in 2021 and 717 in 2022). A "passage" refers to a recreational boat passing through the observational area. If the boat exits the area and later re-enters, each entry is counted as a separate passage. In addition, as soon as a recreational boat anchored within the bay, we considered the passage to be finished. If the boat later lifts anchor and departs, it is counted as a new passage. The majority of these boats' passages were speedboats (44.1%), followed by sailboats (31.8%), cruisers (14.6%), zodiacs (5.6%) and skiff boats (3.9%) (Table 2.7).

Table 2.8 presents the minimum, average, median, maximum, and standard deviation of presence times of recreational boats by type at ASE.

Table 2.8 Recreational boats' presence time by type at ASE.

Boat type	Min (hh:mm)	Mean (hh:mm)	Median (hh:mm)	Max (hh:mm)	SD (hh :mm)
Skiff boat	00:01	00:14	00:06	02:40	00:29
Zodiac	00:01	00:09	00:07	01:09	00:09
Speed boat	00:01	00:14	00:07	05:13	00:28
Cruiser	00:01	00:14	00:10	02:40	00:13
Sailboat	00:01	00:27	00:22	01:58	00:17

Skiff boats, speed boats, and cruisers spent a similar amount of time within the observation area (≈14 minutes on average), whereas zodiacs spent less time (≈9 minutes) and sailboats spent the most time (≈27 minutes) (Table 2.8). Maximum presence times reflected similar patterns, ranging from 1h09 for zodiacs to 5h13 for speed boats, and 1h58 for sailboats, with the latter largely due to slow movement caused by low wind speeds or meandering trajectories. Statistical analysis confirmed that these differences among vessel types were significant (Kruskal–Wallis $\chi^2 = 575$, df = 4, $p < 0.001$). Post-hoc tests revealed that sailboats remained in the area significantly longer than all other vessel types, cruisers had longer presence times than skiff boats and zodiacs, and speed boats were intermediate. Overall, these results indicate that sailboats tend to occupy the observation area the longest, while skiff boats and zodiacs spend the least time.

Table 2.9 presents the occupancy rates of recreational boats at ASE, overall and with engines running, by year, weekends, and holidays in 2021 and 2022.

Table 2.9 Occupancy rates of recreational boats at ASE, overall and with engines running, by year, weekends, and holidays (2021–2022)

Year	Category	Total presence (%)	Presence with engine (%)
2021	Overall	52.93 Min : 0.00 Max : 94.86	43.04 Min : 0.00 Max : 88.14
	Weekends	52.64 Min : 0.00 Max : 81.40	46.34 Min : 0.00 Max : 81.40
	Holidays*	57.26 Min : 21.71 Max : 82.75	47.31 Min : 0.00 Max : 81.40
2022	Overall	50.56 Min : 0.00 Max : 90.25	44.26 Min : 0.00 Max : 90.25
	Weekends	58.75 Min : 22.14 Max : 86.43	55.23 Min : 17.57 Max : 86.43

	Holidays*	56.31 Min : 33.40 Max : 75.35	49.97 Min : 25.40 Max : 67.54
2021 – 2022	Overall	52.05	43.50
	Weekends	54.68	49.30
	Holidays*	56.83	49.97

**It corresponds to Québec's annual two-week summer construction holiday.*

During our 2021-2022 observations, recreational boats were present for more than half of the observation time on average (52.05%), with boats with running engines present 43.97% of the time (Table 2.9). These occupancy rates were slightly higher on weekends and holidays. This indicates that recreational boating plays a significant role in boat traffic within the Saguenay Fjord, emphasizing its potential impact on the local environment and wildlife.

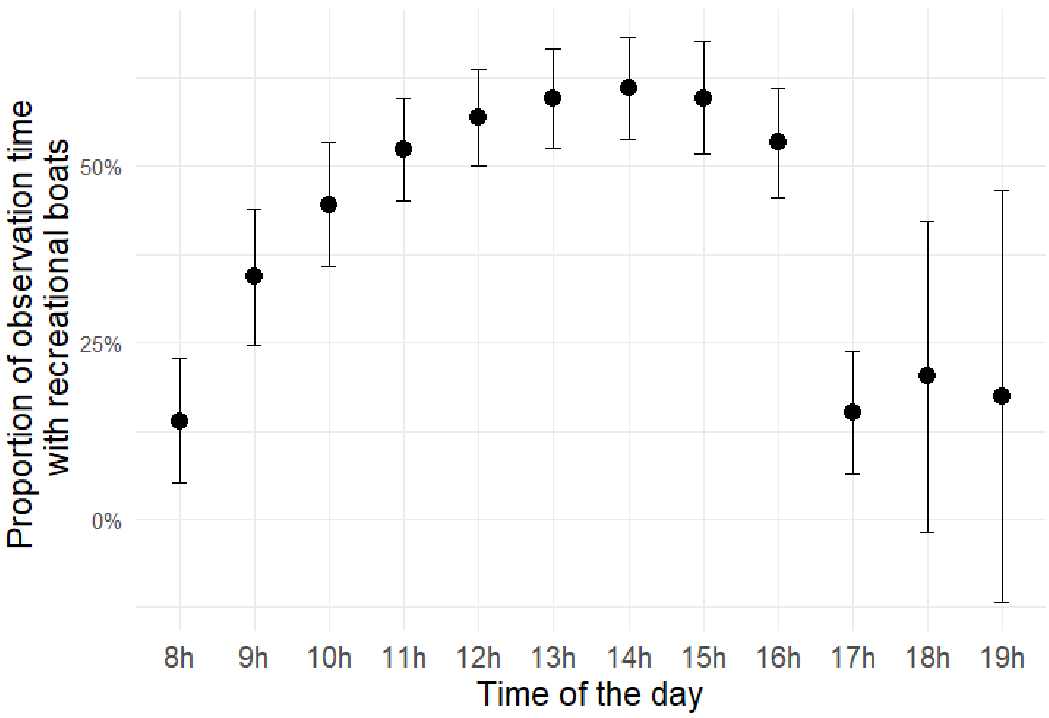


Figure 2.4 Proportion of observation time with recreational boats at ASE by time of day (mean ± 95% CI) for 2021 and 2022.

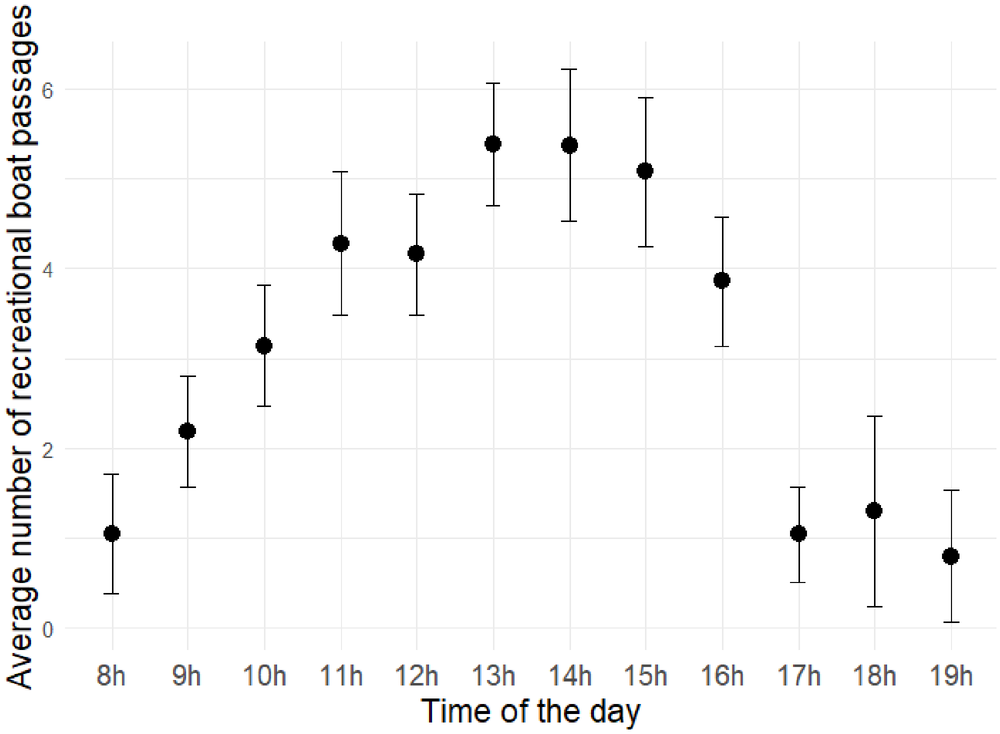


Figure 2.5 Average number of recreational boat passages binned per hour (mean ± 95% CI) for 2021 and 2022.

Between 2003 and 2016, the average number of recreational boats peaked at 2 p.m. at both SMB and MSF, with a more gradual increase at MSF compared to the sharper rise observed at SMB (Conversano et al., 2017). Similarly, Figures 2.4 and 2.5 show a gradual increase in recreational boat presence from 8 a.m. to 11 a.m., a peak during midday, and a clear drop after 5 p.m. This pattern likely reflects the time needed for recreational boats to travel to the observation area and then return to their home marinas. Given the locations of these three areas, these data suggest that significant boating activity occurs throughout the fjord during the middle of the day.

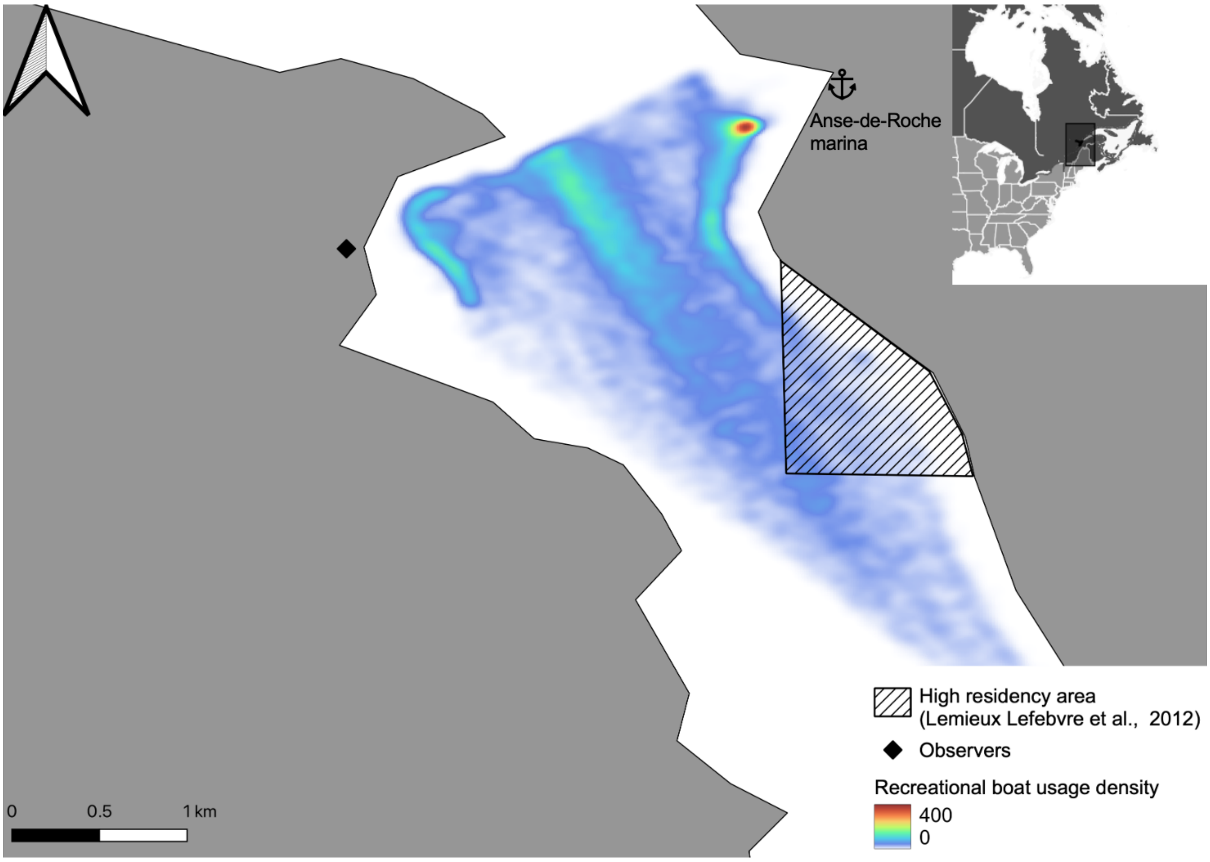


Figure 2.6 Recreational boats density map for ASE in 2021 and 2022.

A kernel density estimation was used to create the density map on Figure 2.6, visualizing the areas most frequently traversed by recreational boats over the study period. Each boat position influenced the density within a 100-meter radius, using a quartic kernel to emphasize local usage patterns. The map does not represent simultaneous boat presence but highlights high-use areas based on cumulative positions. A 10 x 10-meter pixel resolution was chosen to balance detail and clarity. The color gradient represents the cumulative density where higher values indicate areas more frequently used by recreational boats. Figure 2.6 highlights the three main zones used by recreational boats within the observation area. First, on the opposite shore from the observers, there is a marina (*Anse-de-Roche*) that contributes to a high concentration of boat positions in this area. Second, the centerline of the fjord is where the majority of recreational boats transit. Finally, the bay located adjacent to the observation area is another hotspot for recreational boating, particularly for fishers.

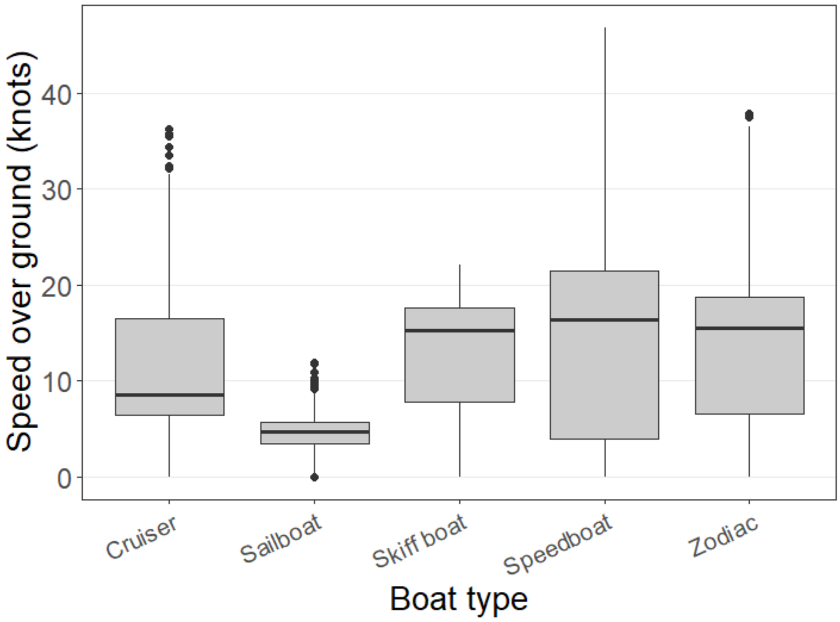


Figure 2.7 Distribution of recreational boat speeds by boat type at ASE in 2021 and 2022.

By using the theodolite, we quantified the speeds over ground of recreational boats within the observation area. Motorized vessels generally traveled at comparable speeds, with mean values ranging from 11.2 to 14 knots (Figure 2.7), and most remained well below the SSLMP speed limit of 25 knots. Nonetheless, some boats exceeded this limit, with maximum recorded speeds of 46.9 knots for a speedboat, 37.9 knots for a zodiac, and 36.3 knots for a cruiser. A Kruskal–Wallis test confirmed that speed distributions differed significantly among vessel types ($p < 0.001$). Dunn post-hoc comparisons showed that sailboats were significantly slower than all other types, while skiff boats, cruisers, and zodiacs exhibited broadly similar speed ranges. Speedboats, in contrast, traveled significantly faster than cruisers and zodiacs. Together, these results highlight substantial variability in boating speeds within the area, including instances of high-speed travel that may elevate the risk of disturbance to belugas.

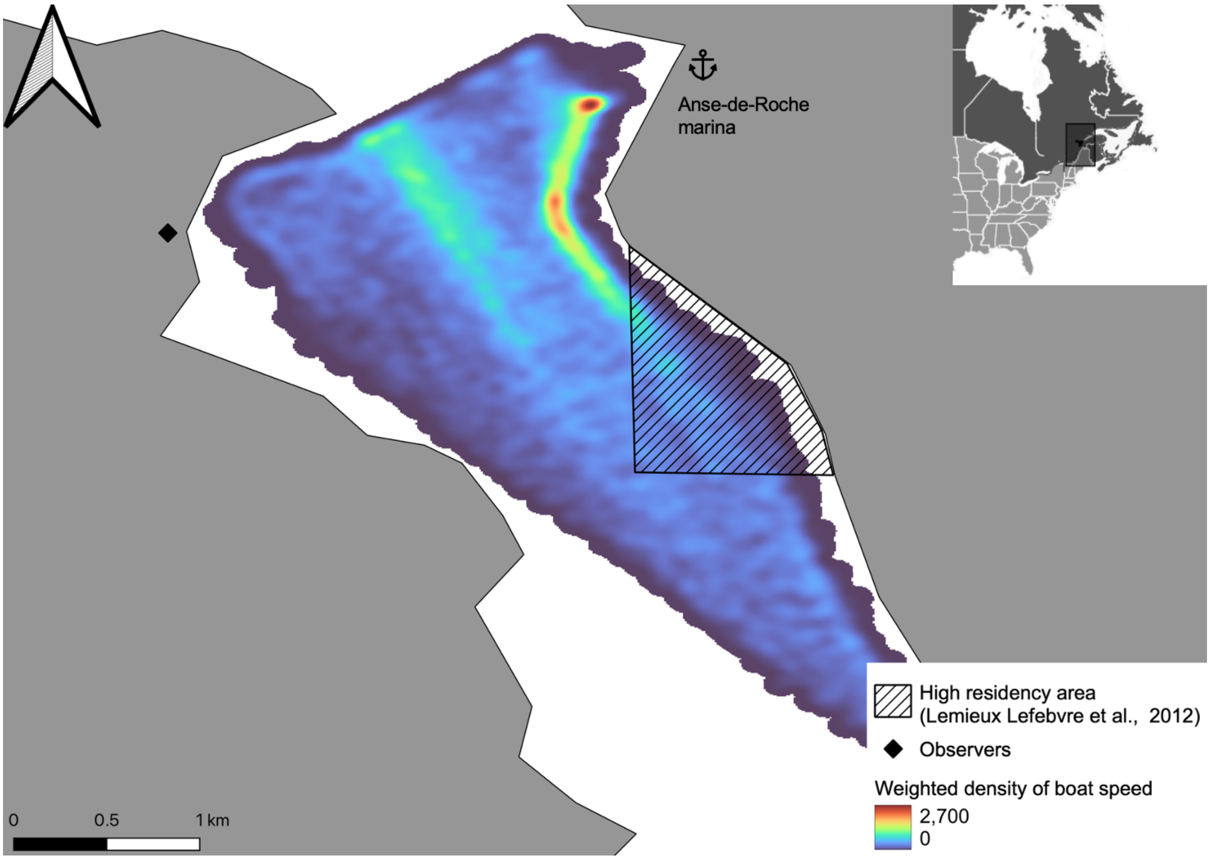


Figure 2.8 Density map of recreational boats at ASE in 2021 and 2022, weighted by vessel speed. The gradient transitions from blue to yellow to red, indicating increasing speed.

A kernel density estimation (KDE) was used to create the density map weighted by speed on Figure 2.8, visualizing the areas where recreational boats tended to navigate at higher speeds over the observation period. Each boat position influenced the density within a 100-meter radius, with speeds (in knots) used as weights to highlight zones of faster navigation. A quartic kernel was applied to emphasize local patterns, and a 10 x 10-meter pixel resolution was chosen for clarity. The color gradient reflects the weighted density of boat speeds, with higher values indicating areas where higher-speed navigation occurred more frequently. Figure 2.8 shows that boats navigating within the bay near the observation site predominantly travel at low speeds. This pattern confirms that the bay is primarily used for fishing activities.

2.3.4. Interactions

Co-occurrences

A total of 89 suspected co-occurrences were recorded during the summer seasons of 2021 and 2022 at ASE. Of these, 67 were confirmed as actual co-occurrences, with a distance of less than 400 meters, considered a regulatory violation within the SSLMP (29 in 2021 and 38 in 2022), occurring over 29 distinct days (with multiple co-occurrences recorded on some days). Table 2.12 presents the details regarding these 67 co-occurrences.

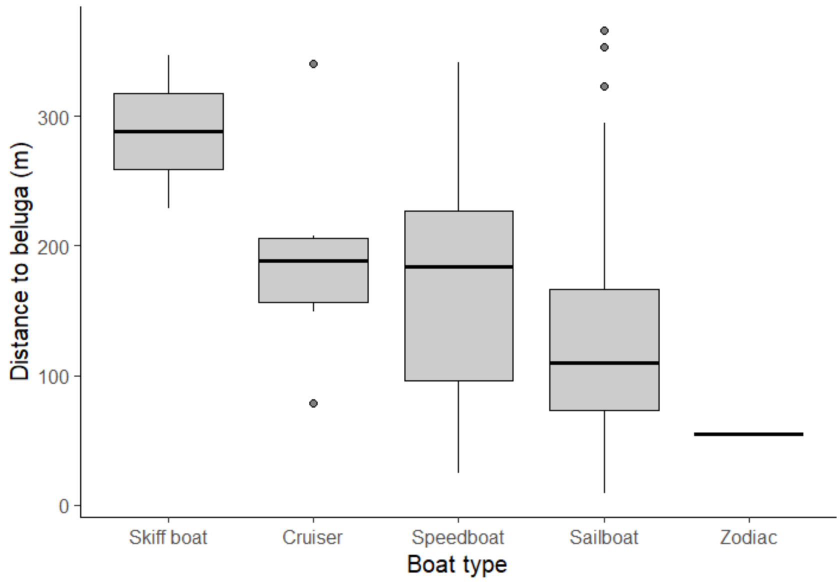


Figure 2.9 Distribution of minimum distances between recreational boats and beluga whales by boat type at ASE (2021–2022).

Figure 2.9 shows the distribution of minimum distances between recreational boats and beluga whales by boat type. A Kruskal–Wallis test indicated no significant differences in minimum distances to beluga whales among boat types ($\chi^2 = 9.33$, $df = 4$, $p = 0.053$). Subsequent pairwise comparisons confirmed that no differences were statistically significant. These results suggest that, although sailboats had more co-occurrences at close distances (Figure 2.9 and 2.10), differences among vessel types in proximity to belugas were not significant. Of the 42 sailboat co-occurrences, 26 occurred with sailboats navigating with deployed sails, which we assume are navigating without a running engine.

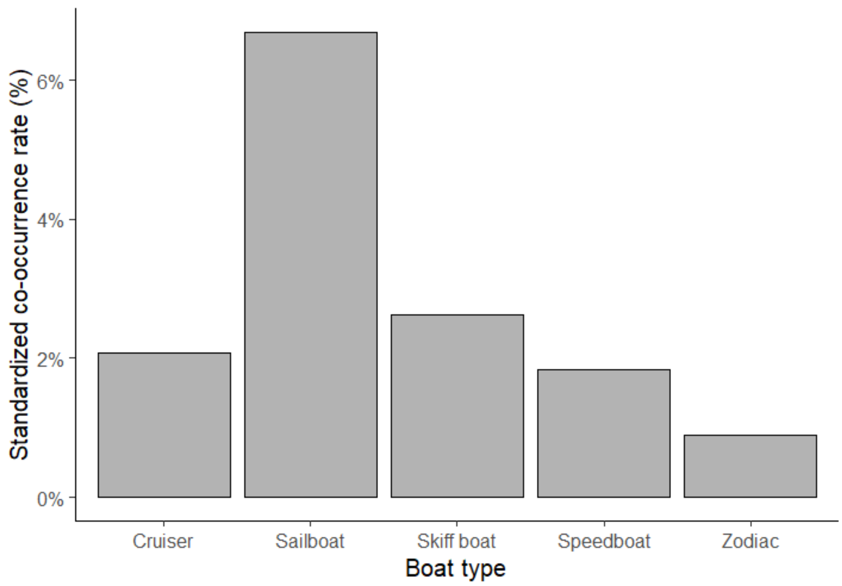


Figure 2.10 Standardized co-occurrence rate of recreational boats with beluga whales by boat type at ASE (2021–2022)

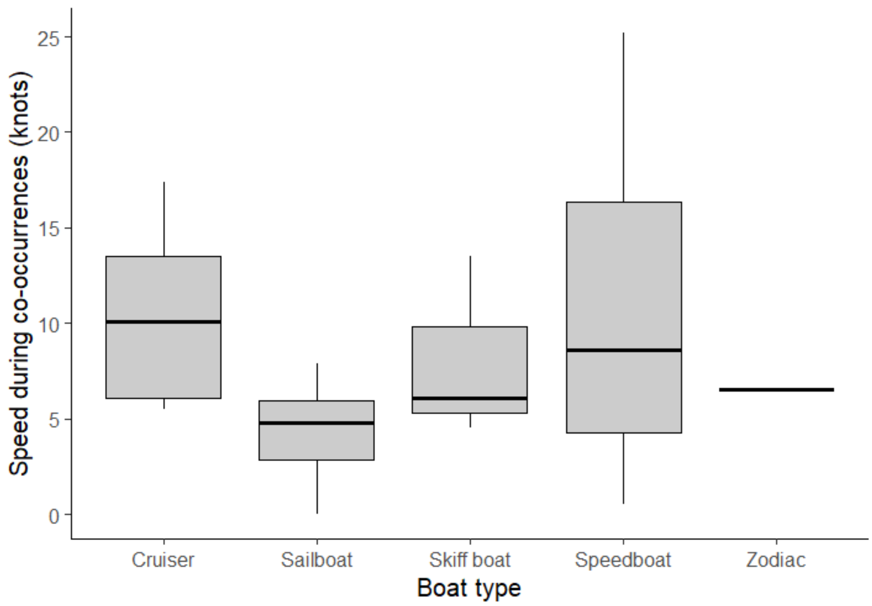


Figure 2.11 Distribution of recreational boat speeds during co-occurrences with beluga whales at ASE in 2021–2022, by boat type.

Figure 2.11 shows the distribution of recreational boat speeds during co-occurrences with beluga whales by boat type. A Kruskal–Wallis test indicated significant differences in boat speeds during co-occurrences among vessel types ($\chi^2 = 15.59$, df = 4, p = 0.0036). Dunn post-hoc tests revealed that sailboats were significantly slower than cruisers ($p = 0.031$) and speedboats ($p = 0.025$), while no other pairwise comparisons were statistically significant. These results suggest that, during co-occurrences with beluga whales, motorized boats generally traveled at similar speeds, whereas sailboats consistently moved slower.

During these co-occurrences, speed vessels, which are required to maintain a constant speed of between 5 and 10 knots, were generally within this range on average (Figure 2.11). However, some speeds exceeded these limits, reaching up to 25.2 knots for certain speed boats, which is even beyond the SSLMP speed limits. Although the beluga has highly directional hearing and can maneuver easily (Turl et al., 1987; Zahn et al., 2021), allowing it to avoid collisions with ships traveling in a straight line or at low speeds, it may still be vulnerable to collisions with vessels that make erratic movements or travel at high speeds (Lesage et al., 1999). Of these 67 co-occurrence events, 8 appeared to involve deliberate pursuits, where boat trajectories seemed to be adapted to approach belugas. These included 4 speedboats, 2 sailboats, 1 zodiac, and 1 cruiser. However, given the distance of the observations, these numbers should be interpreted cautiously, as it is challenging to accurately determine the intentions of recreational boaters from afar; there could be more or fewer instances than observed. From 2003 to 2012, when SMB was still open to recreational navigation, observers recorded co-occurrences of 400 meters or less. The percentage of days with reported co-occurrences at SMB averaged 32.3% over this period, with some years reaching up to 55% in 2010 and 64% in 2012, coinciding with a notable increase in calf mortalities during these two summers (Ménard et al., 2014). In comparison, during our 2021-2022 observations, the percentage of days with measured co-occurrences in our observation area was 45.45%.

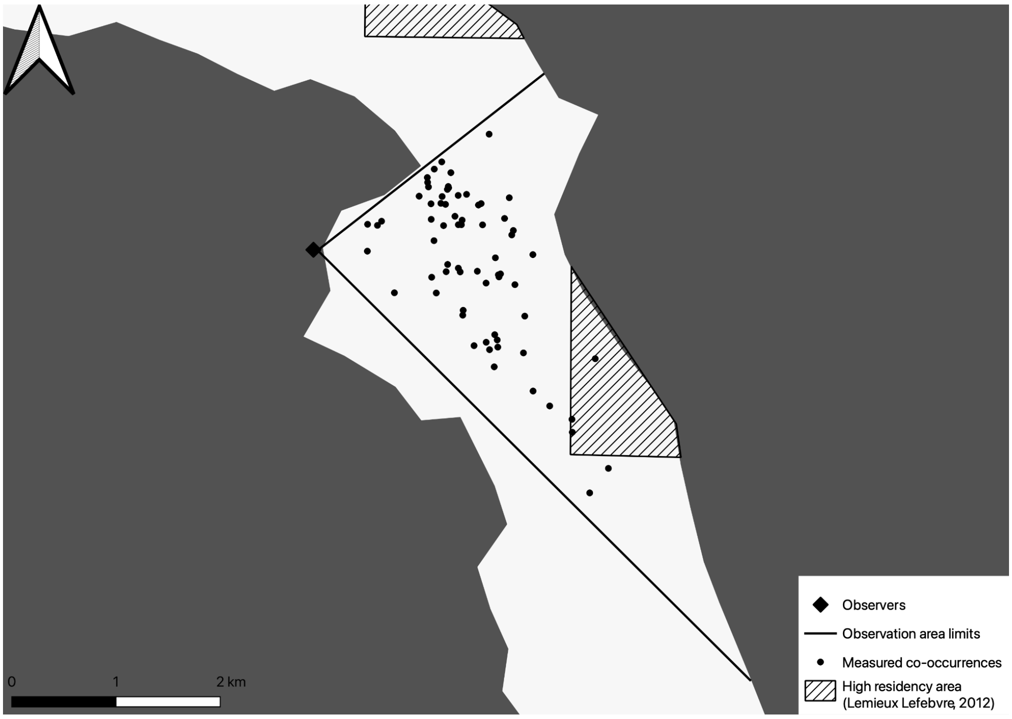


Figure 2.12 Location of recreational boat and beluga whale co-occurrences at ASE in 2021 and 2022.

Although the measured co-occurrences are distributed throughout the entire observation area (Figure 2.12), they tend to be more concentrated near the northern extent than the southern extent. This may be due to the layout of the observation area: the northern extent is much closer to the observers (approximately 2 km away) than the southern extent (approximately 5 km away). Since observers recorded the positions of beluga whales closest to a recreational boat when a co-occurrence was suspected, the distance to the observation point could have influenced the accuracy of the recordings. Estimating distances becomes more challenging with greater distances, which may have led to some co-occurrences near the southern extent being missed.

Trajectories comparison with and without belugas

The coefficient of variation in the speed of recreational boats was compared for trajectories when beluga whales were present in the observation area versus when they were not (Table 2.10).

Table 2.10 Variation in boat speeds at ASE: coefficient of variation by boat type and beluga presence (2021–2022).

Boat type	Beluga present in	Mean variance	Median variance

	the observation area	speed (%)	speed (%)
Cruiser	Yes	30.2	24.9
	No	20.7	7.60
Sailboat	Yes	21.1	16.0
	No	21.4	14.6
Skiff boat	Yes	53.9	37.5
	No	35.2	28.9
Speedboat	Yes	44.2	38.2
	No	45.3	36.2
Zodiac	Yes	47.6	46.6
	No	35.3	28.4

Across boat types, cruisers, skiff boats, and zodiacs tended to show higher speed variability when belugas were present (Table 2.10). However, statistical comparisons revealed that this difference was significant only for cruisers (Kruskal–Wallis test, $\chi^2 = 8.59$, $p = 0.003$). This behavior contrasts with the SSLMP regulations, which require maintaining a constant speed when belugas are detected. No significant differences were detected for sailboats, skiff boats, speedboats, or zodiacs ($p > 0.20$ for all).

In addition, the heading changes of recreational boats were compared for trajectories when beluga whales were present in the observation area versus when they were absent (Table 2.11).

Table 2.11 Heading changes of recreational boats at ASE by boat type in 2021 and 2022: comparison with and without beluga whales.

Boat type	Beluga present in the observation area	Mean heading change (°)	Median heading change (°)
Cruiser	Yes	10.3	3.49
	No	8.17	3.52
Sailboat	Yes	12.0	4.26
	No	9.59	3.72
Skiff boat	Yes	21.2	6.11
	No	15.2	5.27
Speedboat	Yes	21.0	8.05
	No	17.9	6.74
Zodiac	Yes	15.4	6.35
	No	12.5	4.59

Although the changes are slight, all types of recreational boats tend to exhibit greater heading variations when belugas are present (Table 2.11). Statistical comparisons indicate that these differences are significant for sailboats (Kruskal–Wallis test, $\chi^2 = 18.72$, $p < 0.001$), speedboats ($\chi^2 = 16.16$, $p < 0.001$), and zodiacs ($\chi^2 = 4.41$, $p = 0.036$), whereas no significant differences were detected for cruisers ($\chi^2 = 0.41$, $p = 0.52$) or skiff boats ($\chi^2 = 1.99$, $p = 0.16$). This may reflect adaptive trajectory behaviors by recreational boaters, either to approach or avoid the belugas. It is important to note that for both of these comparisons (speed variation and heading changes), the condition "*with beluga whales*" refers to the presence of beluga whales anywhere within the observation area. This does not necessarily imply that recreational boats were within 400 meters of beluga whales, nor that the boaters were aware of their presence. Further analysis incorporating vessel proximity to the whales (e.g., within 400 meters) could provide a more spatially explicit understanding of these interactions.

2.3.5. Non-compliance with regulations: Impacts and consequences

Our observations revealed instances of non-compliance with the SSLMP regulations, notably concerning boat speed and proximity to belugas. These violations underscore a significant gap in adherence to measures designed to minimize disturbances to the beluga population. The regulations aim to prevent disruptions to essential behaviors in beluga whales, and regardless of whether the vessel is motorized, the mere presence of boats can negatively impact the individuals.

Noise disturbance

Belugas have a highly varied vocal repertoire (Faucher, 1989; Sjare and Smith, 1986), requiring an acoustic environment that enables them to detect, discriminate and recognize signals to communicate effectively (Erbe et al., 2016). High noise levels from navigation reduce the acoustic space available to SSL belugas and can mask their vocalizations, leading to communication interference, reduced acoustic range, stress, and disruptions to critical activities like feeding and social interaction, ultimately threatening their well-being (Clark et al., 2009; Erbe et al., 2016; Gervaise et al., 2012; Lesage, 2021; Vergara et al., 2021). In some cases, such disturbances may even lead to the abandonment of areas, as was suspected in Tadoussac Bay after the construction of the marina, where the increase in maritime traffic and noise exposure likely caused the belugas to leave the area (Pippard, 1985). However, there is a lack of studies defining what constitutes an adequate acoustic environment, and the mechanisms linking noise to impacts on the health, reproduction, or survival of marine mammals are still poorly understood (Lesage et al., 2024). Observations from this study showed that recreational boats involved in co-occurrences often include motorized vessels (Figure 2.9 and 2.10), which emit sounds within the frequency range detectable by belugas (Castellote et al., 2014; Lagrois et al., 2023; Wladichuk et al., 2019). Moreover, some of these co-occurrences occurred at higher navigation speeds (Figure 2.11), potentially exacerbating the level of acoustic disturbance experienced by belugas.

Physical disturbance

Most of the measured co-occurrences involved sailboats (Figure 2.10), which are generally less maneuverable than other types of boats. Furthermore, 61.9% of these sailboat-beluga co-occurrences involved sailboats navigating under sail, which we assume means no engine power was used. This suggests that beluga whales may have approached the sailboats rather than the opposite. Field observations, reports from recreational boaters, and several studies (Ausen et al., 2022; Blane and Jaakson, 1994; Westdal et al., 2023) suggest that beluga whales may approach boats to investigate, which may in turn prompt boaters to actively seek out belugas, mistakenly interpreting this behavior as a sign of playful attraction to boats (Ménard et al., 2014). Recreational boating, whether motorized or not, can disrupt essential behaviors in marine mammals through both emitted noise and the mere physical presence of vessels (Pirotta et al., 2015). In fact, repeated avoidance reactions to vessel proximity or noise-induced reductions in foraging efficiency may lead to increased energy expenditure, which in turn can cause deterioration in body condition (Lusseau and Bejder, 2007; Senigaglia et al., 2016; Tennessen et al., 2024). Mother-calf pairs are particularly sensitive to these disturbances, which can induce stress and increase the risk of separation between mothers and their young (Vergara et al., 2021). Given the relatively small and vulnerable status of this beluga population, such disruptions, especially during calving season, may heighten mortality rates among young and contribute to the population's stagnation and limited recovery potential (Hammill, 2007; Ménard et al., 2014).

Patterns of non-compliance observed in this study align with findings from other marine protected areas worldwide, indicating that difficulties in enforcing boating regulations around marine mammals are not unique to the SSLMP. Similar violations of minimum approach distances or speed restrictions have been reported for humpback whales (*Megaptera novaeangliae*) and killer whales (*Orcinus orca*) in the Salish Sea (Fraser et al., 2020), for Burrunan dolphins (*Tursiops australis*) in Australia (Puszka et al., 2021), and for Florida manatees (*Trichechus manatus*) in United States (Jett et Thapa, 2010). The present study therefore reflects a broader pattern: compliance with marine mammal–related regulations in marine parks often remains low, reducing the effectiveness of conservation measures unless monitoring, enforcement, and education efforts are strengthened.

2.3.6. Innovative monitoring approach for beluga conservation in recreational boating areas

Instances of non-compliance with SSLMP regulations, particularly concerning speed limits and minimum distance requirements, have been observed and documented. The vast expanse of the marine park makes it challenging for patrols to monitor the entire area effectively. Additionally, enforcement officers often face difficulties in estimating distances and speeds while patrolling by boat, with their observations typically representing only a snapshot of recreational boating activities at a given moment. This limited monitoring approach allows boaters to claim that beluga whales appeared unexpectedly, when in reality, they may have been actively pursuing them. Given that the beluga population is classified as endangered and continues to decline, the lack of consistent adherence to protective regulations is of growing concern. While protective measures have been implemented, the diffuse nature of recreational boating activities across such a large area complicates monitoring efforts, particularly since boats are not required to have AIS. This situation underscores the need for more effective monitoring strategies.

The theodolite used in this study to collect data could help address some of these challenges. This non-invasive observation technique, undetectable by recreational boaters, allowed us to calculate distances and speeds retrospectively. However, systems now exist that enable real-time data collection by connecting the theodolite to a computer running appropriate software. Such systems can provide instantaneous information on distances and speeds. Additionally, the powerful zoom capability of the theodolite often allows for the identification of individual boats. When combined with actual enforcement patrols, land-based observers could relay real-time reports to park enforcement officers, describing the behavior of recreational boats and providing precise locations. This information could enable enforcement officers to either directly approach the boaters or document their details for follow-up actions. Furthermore, video recordings from the theodolite's perspective could serve as valuable evidence in the event of disputes with boaters denying non-compliance.

By implementing such methods and focusing on ecologically sensitive zones, such as high residency areas for belugas, it would be possible to significantly enhance the enforcement of SSLMP regulations. This, in turn, would contribute to the conservation of beluga whales in this critical habitat. To the best of the author's knowledge, this proposed method has not yet been implemented or documented in the scientific literature, highlighting its innovative potential for improving enforcement practices.

Although land-based theodolite tracking has been successfully used to document the movements and positions of recreational boats in several regions (e.g., Lo et al., 2022; Hermannsen et al., 2019; Kruse, 1991), its operational transposability across the entire habitat of the St. Lawrence Estuary beluga remains limited. First, from a methodological standpoint, the accuracy required to derive boat positions depends on access to elevated vantage points along the fjord and estuary, features that are not consistently available throughout the beluga's summer range. Second, technological and logistical constraints further challenge large-scale implementation, as deploying multiple total stations would require substantial financial investment as well as considerable personnel capacity to ensure continuous coverage. Consequently, although highly effective for targeted high-use areas, this method would need to be integrated into a broader, multi-method monitoring framework, consistent with existing coastal navigation inventories (e.g., Peuziat & Le Berre, 2015), combining land-based tracking with vessel-based patrols, automated sensors, or remote detection technologies to achieve comprehensive monitoring at the scale of the beluga habitat.

2.3.7. Limitations

This study also presents several limitations that should be considered when interpreting the results. First, analyses were restricted to an 8 km² observation area, representing less than 1 % of the St. Lawrence Estuary beluga's habitat, which limits the spatial generalizability of the patterns documented here.

Second, although recreational boats were consistently detectable under the observation conditions of this study, beluga detectability was inevitably imperfect and influenced by sea state, light conditions, distance, and observer experience. Because the objective was not to estimate abundance or density but to document presence and potential co-occurrence with recreational boats, this imperfect detection is unlikely to change the overall patterns described. Continuous monitoring from a fixed point and the exclusion of periods with poor visibility helped reduce variability in detection probability. Nevertheless, beluga detectability was not constant, and a systematic negative bias may have led to a slight underestimation of total passage events or time spent within the study area.

Finally, several environmental and contextual factors, including weather, tide, time of day, and human activity, may influence the behavior of both recreational boaters and belugas. These potential confounding variables were not explicitly accounted for in the analyses. As such, the patterns reported here should be interpreted as descriptive indicators rather than causal evidence of behavioral responses.

2.4. Conclusion

While anthropogenic disturbances from recreational boating are seasonal, they occur during the most critical period for belugas, coinciding with calving and the care of newborns. The presence of well-developed maritime infrastructures, such as marinas and boat ramps, facilitates easy access for recreational boats throughout the beluga's critical habitat, including high residency areas (Ménard et al., 2014). From June to October, the Saguenay Fjord serves as a crucial habitat for approximately 37% of the population, providing functions such as calving, nursing, feeding, rearing young, resting, socialization, habitat connectivity, communication, and navigation, supported by its warm, relatively shallow, and sheltered waters, which offer a suitable temperature range for these activities (Bonnell et al., 2024; Lesage et al., 2024; Ouellet et al., 2021). Additionally, due to the fjord's narrowness, close encounters between boats and beluga whales are more likely than in the broader St. Lawrence Estuary. Our observations at ASE, between the two main beluga study sites the MSF and SMB, have yielded unique insights into both beluga and recreational boat activity in the area, as well as the interactions between them. Notably, our approach allowed us to document instances of non-compliance with beluga protection measures, which have been underreported or insufficiently detailed in previous studies. These regulations aim to mitigate the risk of disturbance to belugas, as both vessel noise and physical presence can disrupt essential behaviors (Pirotta et al., 2015) and threaten the survival of the population (Hammill, 2007; Mosnier et al., 2015).

This underscores the value of our theodolite monitoring approach, which provides a precise method for detecting infractions and gaining a deeper understanding of boat-beluga interactions. Despite existing efforts to raise awareness and promote compliance with protective measures, additional actions are needed. Not all recreational boaters are fully informed about these regulations, and some may intentionally alter their routes to get closer views of the whales (Kowalski et al., 2024). While patrols and park enforcement contribute to raising awareness, effectively covering the entire beluga habitat remains a challenge. Moreover, distinguishing between intentional boat approaches and instances where belugas approach out of curiosity is difficult. In this context, the monitoring method we propose complements existing patrol strategies by enhancing the ability to detect non-compliance and better document interactions between boats and belugas. By integrating such a tool into monitoring and enforcement strategies, we can address key challenges and improve protection for this endangered beluga population. Our findings reinforce the importance of this approach and highlight its potential as a valuable tool for conservation efforts.

2.5. Acknowledgement

The authors express their appreciation to Maude Simard and Anne-Marie Blanchette for their roles as beluga observers during the 2021 and 2022 summer seasons, respectively. We would also like to thank Franck Turcotte for granting us permission to use the Petit-Saguenay's Village Vacances Belvedere as an observation site, Robert Michaud for his assistance with the beluga observation protocol, and Cristiane Martin Albuquerque for introducing us to the theodolite observation method.

Funding

The funding to support this research project was provided by the Ministère des Forêts, de la Faune et des Parcs du Québec and Secrétariat à la stratégie maritime du Québec. We also acknowledge the contribution of the Social Sciences and Humanities Research Council through the Canada Research Chair in Ecological Economics.

Chapitre 3 : Boating with whales: Exploring values, knowledge and behaviors of recreational boaters in the St. Lawrence Estuary and Saguenay Fjord using Q-methodology

Cet article a été publié dans Ocean and Coastal Management

Kowalski, C., Lévesque, A., Sénécal, J. F., Dupras, J., & Chion, C. (2024). Boating with whales: Exploring values, knowledge and behaviors of recreational boaters in the St. Lawrence Estuary and Saguenay Fjord using Q-methodology. *Ocean & Coastal Management*, *254*, 107170. https://doi.org/10.1016/j.ocecoaman.2024.107170

Contributions des auteurs

J'ai mené la collecte des données sur le terrain, réalisé les analyses et rédigé l'article. Ann Lévesque a contribué à la prise en main de la méthodologie Q et à l'interprétation des résultats. Jean-François Sénécal a apporté un soutien pour les analyses statistiques. Les autres co-auteurs, Jérôme Dupras et Clément Chion, ont supervisé le projet et participé à la révision du manuscrit.

Abstract

The whales of the St. Lawrence Estuary in Quebec, Canada, including the resident beluga (*Delphinapterus leucas*) population, classified as endangered and continuing to decline, face many threats of anthropogenic origins, in particular underwater noise generated by boat engines. In order to better understand the impact of recreational boating on the St. Lawrence region and the marine species that live there, we used the Q-methodology to identify perspectives of boaters based on their behaviors. Boaters were questioned about their habits, knowledge and values, which are considered to be linked to their behavior. Three distinct boater categories resulted from the analysis: the eco-responsible, the self-centered, and the altruist,

each named based on their prominent values. This study provides valuable insights into the motivations driving the behavior of recreational boaters, offering potential opportunities for government managers and NGOs to adjust their management strategies or awareness campaigns to encourage behavior that supports the conservation of whale species and the recovery of the beluga whale population.

3.1. Introduction

The St. Lawrence estuary and the Saguenay fjord: a place of interaction between whales and pleasure boats

During summer, various species of migratory whales travel to the St. Lawrence Estuary in Quebec, Canada to feed as they find an essential food source in this ecosystem (Cotté and Simard, 2005; Ramp et al., 2015; Truchon et al., 2013). In addition to these migratory species, the St. Lawrence Estuary beluga whale (*Delphinapterus leucas*) population resides there year-round and also uses the Saguenay Fjord as part of its summer habitat (Sergeant and Hoek, 1988). This population has been classified as endangered since 2014 (COSEWIC, 2014) and continues to decline, particularly due to high mortality rates among newborns (Mosnier et al., 2015), which poses challenges for its recovery (Hammill, 2007). It is therefore protected under Canada's Species at Risk Act (S.C. 2002, c. 29) (RLRQ, 2011). The Saguenay-St. Lawrence Marine Park (SSLMP) was created in 1998 with the aim of protecting the marine ecosystem of the St. Lawrence Estuary, in particular the area where the Saguenay Fjord flows into the estuary (Figure 3.1).

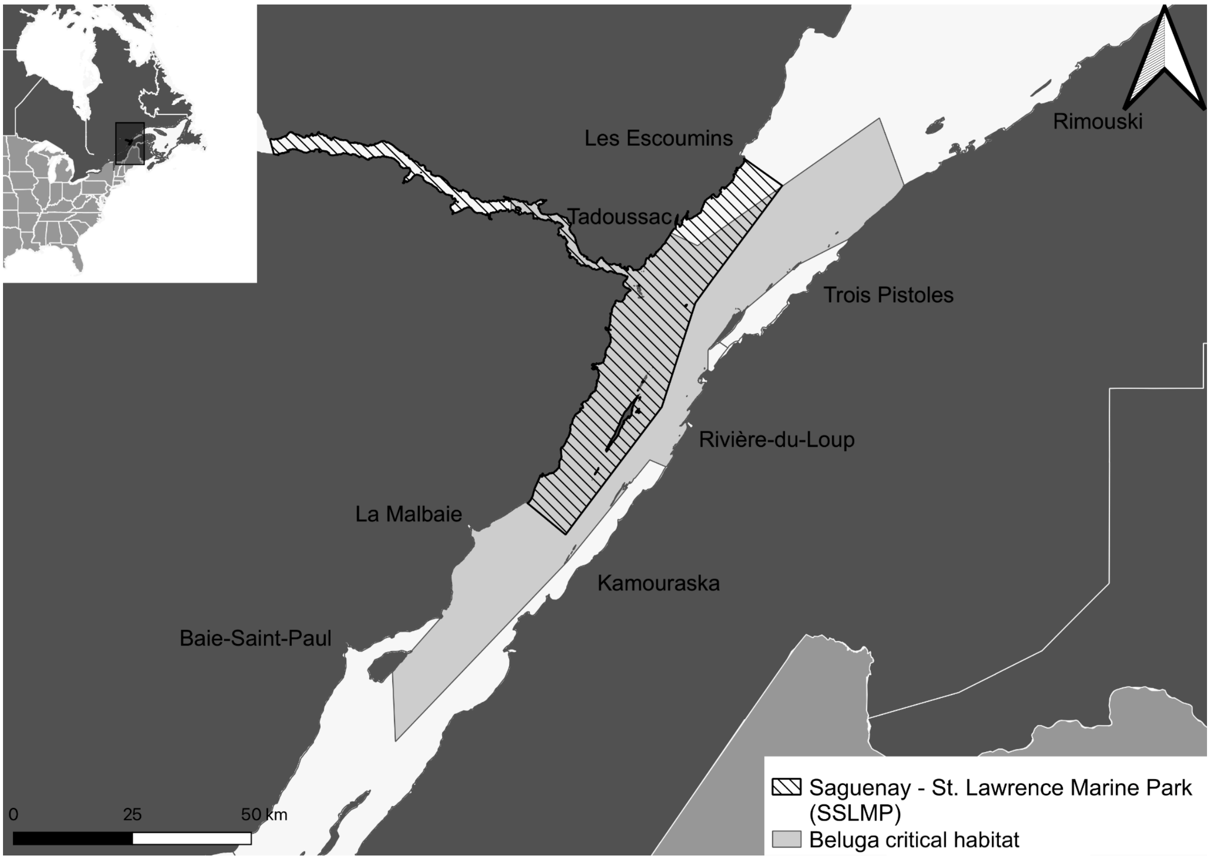


Figure 3.1 Study area (St. Lawrence Estuary and Saguenay Fjord, Québec, Canada) representing the Saguenay - St. Lawrence Marine Park as well as the beluga critical habitat.

Tourism is a crucial activity for some coastal communities along the Saguenay Fjord and the St. Lawrence Estuary (SSL), as it significantly boosts the local economy (Parrott et al., 2011). Indeed, the SSL is widely recognized as a popular and renowned destination for whale-watching. While whale-watching companies provide the opportunity to observe these marine mammals, some people navigating with their own boats seize the opportunity to discover this environment and sometimes encounter whales on their own. The peak of recreational activities happening within the critical habitat of the St. Lawrence Estuary beluga whale population is concentrated during the summer season, when females give birth and take care of newborns (Ménard et al., 2014). Between 2010 and 2012, the increase in recreational activities was correlated with the increase in calf mortality (Ménard et al., 2014), although no causality was demonstrated. These findings, along with numerous field observations, highlight the need to deepen knowledge about the impacts of recreational boating on the St. Lawrence Estuary beluga whale population. Indeed, the growing demand for high-quality leisure activities exerts considerable pressure on natural resources and their management (Romeril, 1989). Recreational activities in beluga whale habitat are poorly documented compared to other segments of navigation (Chion et al., 2007; Turgeon, 2019). Furthermore, the challenge in gathering data on recreational boats stems from the fact that they are not required to have an onboard automatic identification system (AIS) transponder. An AIS transponder is a device that transmits essential movement information, including the vessel's position, approximately every minute. This absence makes it difficult to obtain information about their visited locations, speeds, and other relevant details. In addition, no study has been conducted to understand the impacts of recreational boating around whales within the SSL. Like many marine mammals, beluga whales use sound cues to navigate through their environment, communicate and feed effectively (McQuinn et al., 2011). While recreational boating poses various threats to beluga whales, including collisions (accounting for 4% of overall mortality causes (Lair et al., 2013), although evidence regarding the types of boats involved is lacking) and disturbances due to human presence, underwater noise resulting from boat motors can be considered as the major threat affecting the entire St. Lawrence Estuary beluga whale population (DFO, 2020, 2012). Regulations outlining speed limits and mandatory distances for recreational boats have been established within the whales' habitat to ensure the protection and well-being of these marine mammals. Specifically, within the SSL, boats are required to maintain a distance of 400 meters from beluga, blue *(Balaenoptera musculus)*, and North Atlantic right *(Eubalaena glacialis)* whales, and 200 meters from other whale species. Additionally, a speed limit of 25 knots is imposed within the SSLMP boundaries. Activities that could potentially harm or disturb marine mammals, such as feeding, swimming near them, touching them, causing displacement, or separating them from their group, are strictly prohibited. Furthermore, in the presence of beluga whales, recreational boaters are advised by the SSLMP to continue navigating without stopping and to maintain a consistent course (DORS/2002-76).

Values as determinants of pro-environmental behavior

Values are general goals that people strive to achieve over their lifetime (Schwartz, 1992). They transcend specific situations, are relatively stable over time, and affect a wide range of behaviors (Rokeach, 1973; Schwartz, 1992). For several years, many attempts have been made to build models of human behavior that identify its determinants. Most of these models have considered that beliefs, attitudes and values of individuals are predictors of human behavior (Hargreaves, 2011). According to Dietz et al. (2003), values are the moral principles and standards that define what is important and valuable in life, and are generally accepted as a personal judgment of a person or situation. In the field of natural resource management, the notion of value is essential because it allows us to understand the fundamental motivations that underlie attitudes and behaviors, as pointed out by Schwartz (2006). Although social sciences have encountered difficulties in using values due to a lack of reliable empirical methods to measure them (Schwartz, 2006), in part due to the potential interference between discourse and action, as well as the complexity associated with quantifying subjective data (Amin, 2000), value analysis is often used to explain environmental behaviors (Steg and Vlek, 2009). Environmental behaviors include all types of behavior that modify the availability of materials or energy from the environment or modify the structure and dynamics of ecosystems (Stern, 2000). A so-called "pro-environmental" behavior is a behavior adopted by an individual who consciously decides to harm the environment as little as possible, or even to benefit it (Kollmuss and Agyeman, 2002; Steg and Vlek, 2009). Four types of values have been found to be the most relevant in predicting environmental behaviors (De Groot and Steg, 2008; Steg et al., 2014; Stern et al., 1998): biospheric, altruistic, egoistic and hedonic values (Table 3.1). While navigating within the SSL, recreational boaters interact with a fragile ecosystem that includes endangered whale species. Therefore, their navigation can be regarded as an environmental behavior, given its influence on these marine mammals through their mere presence. This rationale underlines our decision to incorporate these general values into this study.

This study aims to identify a typology of recreational boaters who navigate within the SSL and might interact with whales. By gaining a better understanding of their knowledge, behavior and value, this research will provide potential opportunities for government managers and NGOs to adjust their management strategies or awareness campaigns to encourage behavior that supports the recovery of the beluga whale population. This paper will begin by providing an overview of the Q-methodology and its general steps. Subsequently, we will demonstrate how we have applied this methodology to achieve our research objectives. We will present the categories that emerge from our analysis, highlighting both their convergences and divergences. Finally, we will discuss the values associated with these three categories, explore the implications for territorial management informed by these findings, and consider the potential application of these results for the representation of these behaviors in a simulation platform.

3.2. Method

3.2.1. Q-methodology

The Q-methodology, developed by William Stephenson in the 1930s, aims to investigate the subjectivity of the human mind: the individual point of view (Stephenson, 1935). This exploratory technique can provide some coherence to research questions for which there are multiple possible answers and which are socially controversial (Stainton Rogers, 1995). It is a self-directed approach combining qualitative and quantitative methods (Cross, 2004; Ellingsen et al., 2010; Ward, 2009). The Q-methodology is considered a novel approach because it involves factor analysis considering the viewpoints of individuals as variables (Stephenson, 1953), unlike regular factor analyses. The goal is then to identify correlations between participants' viewpoints on a specific subject. In order to extract all existing thoughts and/or behaviors on the subject, it is essential to survey various respondents so that they present contrasting perspectives (Bashatah, 2016). When applying the Q-methodology, data are collected qualitatively, using a smaller sample of participants than quantitative methods. However, these data are statistically analyzed with the same level of mathematical rigor as quantitative methods (Bashatah, 2016; Ellingsen et al., 2010). Basically, Q-methodology enables the analysis of individual perspectives to construct typologies that classify these perspectives into broader, understandable categories. Indeed, the perspective relates to the individual level while the typology corresponds to a categorization of perspectives that share varying degrees of similarity. Q-methodology can be applied in a multitude of fields such as health (Bang et al., 2016), social sciences (Yuan, 2010), education (Irie et al., 2018), environment (Forrester et al., 2015) or as a tool to help prioritize conservation actions (Levesque et al., 2023). Although other methods, such as semi-structured individual interviews (Ruhle and Süß, 2020), can be used to extract typologies of actors, the Q-method was chosen because of its ability to use qualitative statements while applying statistical analysis to identify meaningful groupings, which can provide a more robust and holistic approach for this research.

3.2.2. Application of the Q-methodology

To apply the Q-methodology, a series of sequential steps should be followed, as illustrated in Figure 3.2 below. It is essential to first identify the relevant topics of interest. Once these topics are defined, meaningful statements, called *Q-set* or *Q-sample*, are generated to encompass the entirety of the subject under investigation. The goal of this study is to identify the typology of recreational boaters who navigate within the summer habitat of the St.

Lawrence Estuary beluga whale population. To do so, we chose to base our statements (*Q-set*) on three axes: their behavior while navigating (habits, interactions with other boats and interactions with marine mammals), their knowledge (regarding marine mammals and the marine park) and their values as it can be considered to explain environmental behaviors. In order to produce meaningful statements, it is necessary to find out about navigation regulations in general, regulations related to the observation of marine mammals within the SSLMP as well as the navigation habits of boaters. To do so, several sources were consulted such as government laws, news media, popular texts as well as informal discussions. The 26 statements selected, focusing on navigation behaviors and knowledge, were then validated with a navigation professional in order to ensure full coverage of boaters behaviors observed on the water as well as the use of the appropriate terminology. They are presented in Table 3.2. The 12 statements regarding environmental values, adapted from those proposed by Steg et al. (2014) and Bouman et al. (2018), focusing on the four types of values that are considered as determinants of an environmental behavior are presented in Table 3.1. Then, the *Q-set*, composed of 38 statements, was presented to a small group of respondents as part of a *pilot test*, during which they were asked to rank the statements on a grid that takes the form of a quasi-normal distribution, with a rating scale ranging from strongly disagree to strongly agree, as illustrated in Figure 3.3. Following the successful pilot test, the finalized *Q-set* was then administered to the actual participants (*P-set*) in the study, recreational boaters navigating within the SSL. It is important to present participants with clear, single-idea statements so that they are unambiguous and easy to understand for all. The result of the statements ranked along this distribution is called a *Q-sort*. After all participants have completed their *Q-sort*, it is time to proceed with the analysis of the results. First, all *Q-sorts* are correlated with each other to generate a correlation matrix showing the degree of similarity between each respondent. Secondly, a principal component analysis (PCA) is performed to identify the axes that explain the most variation in the data, using the Kaiser-Guttman criterion (eigenvalues greater than 1). Then, based on the results of Horne's analysis, which involves comparing the obtained eigenvalues with those derived from random data, significant factors are retained (Watts and Stenner, 2012). Next, the centroid factor analysis is conducted in order to detect the highest correlations between the different *Q-sorts*. This analysis leads to a restructuring of the data to increase potential correlations (Ramlo, 2016). Finally, a varimax rotation is performed. By performing a factor rotation, the distribution of variances explained by the factors can be altered and examined from different perspectives, thus resulting in factors that group closely related individual viewpoints (Brown, 1993). The final factors, representing the different categories of respondents, are selected based on both quantitative criteria such as the Kaiser-Guttman criterion, Humphrey's rule, and the percentage of explained variance (Watts and Stenner, 2012) and qualitative criteria, considering their distinctive characteristics, coherence and relevance to the field of investigation (Brown, 1980; Lévesque et al., 2020; Ramlo and Newman, 2011). Throughout this process, associated Z-scores are computed. Z-scores are standardized scores, as defined by Watts and Stenner (2005). These scores represent the standard score or average assigned to each statement by the participants who performed the Q-sorts (Hutson et al., 2010). They indicate the level of agreement between each category and a specific statement (Zabala, 2014). It is essential to note that the factors resulting from a Q-methodology survey are the result of the sorting done by the participants themselves rather than integrated definitions (Cross, 2004). In fact, this factor analysis allows for the development of typologies that provide a condensed representation of the similarities among participants.

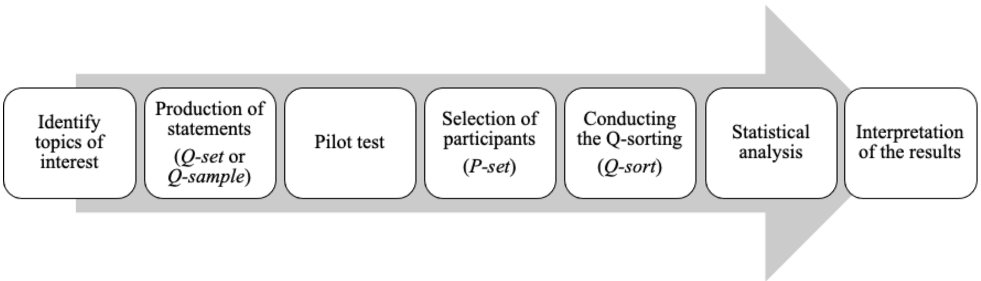


Figure 3.2 Q-methodology steps (adapted from Churruca et al., 2021).

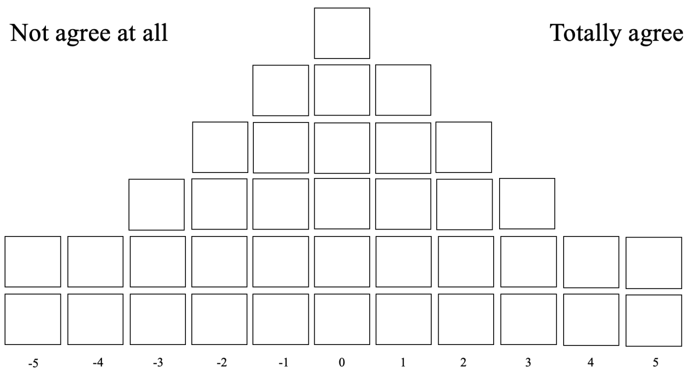


Figure 3.3 Empty Q-sort: Support on which the voluntary boaters placed the statements. In this context, the rating scale spans from 'strongly disagree' (-5) to 'strongly agree' (+5), with (0) indicating a neutral position.

3.2.3. Sampling strategy and data collection

Data collection was conducted during the 2022 summer season through in-person interviews in various marinas bordering the habitat of the St. Lawrence Estuary beluga whale population (Anse-Saint-Jean, Tadoussac, Rivière-du-Loup, Rimouski, Les Bergeronnes, Anse-de-Roche) (Figure 3.4). Participating boaters (*P-set)* were randomly approached directly on site (Ethics Certificate #2021-1210). The activity required between 25 to 45 minutes to complete. The oral comments of boaters were recorded during the sorting of the statements, which will further facilitate the interpretation of their point of view. In addition to applying the Q-method, participants answered a questionnaire on socio-demographic criteria, types of boats and navigation habits. It is essential to collect *Q-sorts* from a diversity of demographic groups, i.e. interview boaters from different areas, using various types of boats, etc. We determined the sample size based on the principle of data saturation, which means that we stopped acquiring more respondents once we assessed that no new information was being provided. Finally, all statistical processing was performed using the free software PQMethod version 2.35 (Schmolck, 2014).

In this study we consider a "*speed boat*" to be a small motor boat that can accommodate several passengers and is designed for trips of less than a day; a "*cruiser*" as a motor boat that can accommodate several passengers and is designed for trips of a day or more. In addition, a "*local*" is a boater holding a seasonal berth in a marina in the SSL region, while a "*visitor*" is a boater passing through for a limited time in the SSL region.

Table 3.1 Statements of the Q-set associated with the four types of values related to environmental behaviors, based on the methodology proposed by Steg et al. (2014).

Values	(Steg et al., 2014)	Statements (*Q-set*)
Biospheric	Prevent pollution	I systematically sort my waste.
	Unity with nature	I have already helped raise funds to protect nature.

(aiming at enhancing the environment)	Protection of the environment	I have already reduced my standard of living to protect the environment.
Altruistic (focusing on the well-being of both oneself and other human beings)	Equality	I think everyone should have the chance to navigate the Saguenay – St-Lawrence.
	Social justice	I have already volunteered to help people in need.
	Utility	I like to be useful to others.
Hedonic (aiming at valuing pleasure and comfort)	Pleasure	When out on the water, my main goal is to have fun.
	Satisfaction for oneself	The most important thing for me is to do what I love.
	Enjoying life	It is important for me to enjoy the pleasures of life.
Egoistic (favoring personal resources)	Social power	I like to control what is happening around me.
	Richness	It is important for me to have money and goods.
	Ambition	If I win a lot of money, I'll buy myself the boat of my dreams.

Table 3.2 Statements of the Q-set regarding recreational boaters behavior and knowledge.

Topic	Sub-theme	Statements (*Q-set*)

Behavior at sea	Habits	I precisely define a navigation route plan before navigating.
		I always know my destination before navigating.
		During navigation, I deviate from the itinerary defined beforehand.
		The majority of my navigation trips are similar (duration, trajectory, stopping points, destination).
		I always fish from my boat during my navigation trips.
		I drop the anchor at least once per navigation trip.
	Interactions with other boats	When I see a gathering of pleasure boats, I head towards them.
		I navigate alone (with no other boat but my own).
		When I see marine mammals, I broadcast the information via my radio/VHF or my phone.
		When I come across a whale, I approach it to contemplate it more closely.
		When I come across a whale, I turn off my engine.

		When I come across a whale, I feed it with what I have on board.
	Interactions with marine mammals	When I navigate, I listen to communications between whale-watching captains to find out where the marine mammals are.
		When I see a gathering of whale-watching boats, I approach them to enjoy the show.
		When I see a whale, I adapt my itinerary to observe it longer.
		I try to see several species of marine mammals during my navigation trip.
Knowledge	Knowledge on marine mammals	Beluga whales mainly use their eyesight to locate themselves underwater.
		The sound of my engine can disturb marine mammals.
		The St. Lawrence Estuary beluga whale population is in good health.
		There are more than 10 species of whales in the Saguenay Fjord.
		I know the Marine Park navigation rules.

		I know the geographical limits of the Marine Park.
		The Marine Park speed limits suit me.
	Knowledge and perceptions about the Saguenay-St. Lawrence Marine Park	I think that boats navigate too fast in the Marine Park.
		I find that the application of the regulations by the Marine Park's guard is insufficient.
		I think the Marine Park should be better known.

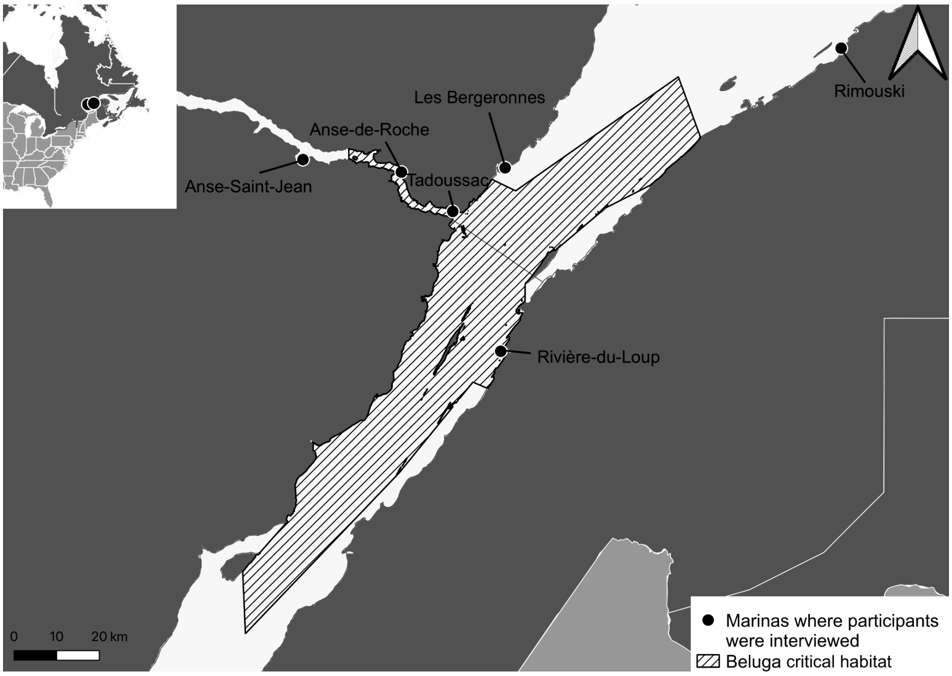


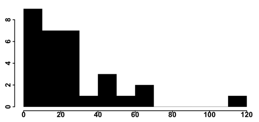
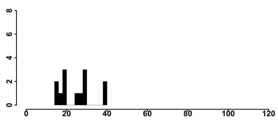
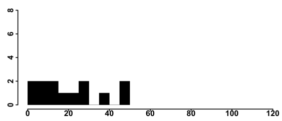
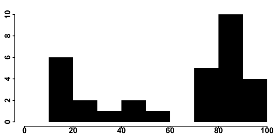
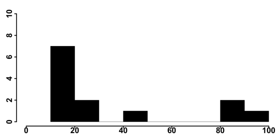
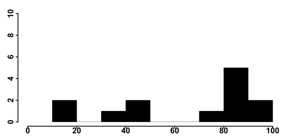
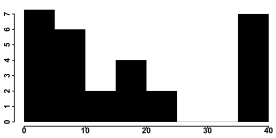
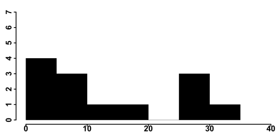
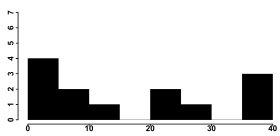
Figure 3.4 Study area (St. Lawrence Estuary and Saguenay Fjord, Québec, Canada) representing beluga critical habitat as well as marinas where boaters were surveyed.

3.3. Results

3.3.1. The emergence of 3 categories of boaters

A total of 60 boaters voluntarily participated in this study. The statistics regarding the respondents are presented in Table 3.3. Three categories have been identified: the eco-responsible, the self-centered and the altruist. They represent 50% of the explained variance. This indicates that these three groups encompass a substantial portion of the diverse opinions and viewpoints expressed by recreational boaters. Consequently, the retained categories hold significant value in reflecting the overall range of perspectives within the recreational boating community. According to Watts and Stenner (2012), an explained variance equal to 35% or more is satisfactory for the Q-methodology. However, the remaining 50% of the unexplained variance indicates that there are other opinions and perspectives that were not represented by the three retained categories. These unexplained perspectives may stem from specific subgroups of recreational boaters or factors that were not considered in this study. It is important to note that even if the three categories chosen explain 50% of the variance, this does not necessarily mean that the other perspectives are less important or negligible. They may simply reflect different aspects, less frequent points of view or additional nuances that were not captured in this specific analysis. In our study, three boaters were unassigned: one did not correspond to any profile, another corresponded equally to groups 2 and 3, and the last one loaded similarly in all three groups. When participants' Q-sorts load significantly on a given category, they are merged to produce a Q-sort illustrating that category, which allows it to be interpreted (Watts and Stenner, 2005). In Table 3.4, we can find the statements that received the highest scores: the statements with which boaters most agreed (+4 and +5) and those that received the lowest scores: the statements with which boaters most disagreed (-4 and -5) for each of the three extracted categories. However, it is important to consider the entire ranking of statements, not just those at the extremes of the distribution. Indeed, statements placed around the neutral zone can significantly help to illustrate a perspective (Watts and Stenner, 2005). Finally, the correlations between the discourses range from 0.62 to 0.75 (see the correlation matrix in Table 6.1, Annexes), indicating a certain similarity in the structure of the identified factors. These similarities can be attributed to the specificity of the subject studied (e.g., focus on pleasure boaters within the summer habitat of the St. Lawrence Estuary beluga whale population and not just navigation in general). Table 6.2, Appendices, provides the ranking of the statements and their associated Z-score.

Table 3.3 Key characteristics of recreational boaters interviewed at various marinas surrounding the SSL, who were subject to q-methodology categorization based on behavior, knowledge, and values.

	Category 1 : eco-responsible	**Category 2 : self-centered**	**Category 3 : altruist**
Number of participants	31	13	13
Boat type	Sailing boat: 61.3 % Cruiser: 16.1 % Zodiac: 16.1 % Speed boat: 6.5 %	Sailing boat: 69.2 % Cruiser: 30.8 % Zodiac: 0 % Speed boat : 0 %	Sailing boat: 30.8 % Cruiser: 23.1 % Zodiac: 7.6 % Speed boat : 38.5 %
Type of boater	Local: 58.1 % Visitor: 41.9 %	Local: 38.5 % Visitor: 61.5 %	Seasonal: 61.5 % Visitor: 38.5 %
Average number of trips per season	mean: 28.5 	mean: 25.5 	mean: 22.9 
Percentage of their trips taking place in beluga habitat	mean: 65.5 % 	mean: 36.2 % 	mean: 68.5 % 
Number of years of experience navigating SSL waters	mean: 16.45 years 	mean: 14.5 years 	mean: 18.6 years 

Order of preference for main interests during a trip	1- Pleasure to navigate 2- Beauty of the landscape 3- Tranquility 4- Marine mammals 5- Seabirds 6- Fishing 7- Diving	1- Pleasure to navigate 2- Beauty of the landscape 3- Marine mammals 4- Tranquility 5- Seabirds 6- Fishing 7- Diving	1- Pleasure to navigate 2- Beauty of the landscape 3- Fishing / Tranquility 5- Marine mammals 6- Seabirds 7- Diving

3.3.2. Participants

We observe that a majority of the boaters categorized in the first group are local boaters (58.1%). The home marina of local boaters is located within the summer habitat of the St. Lawrence Estuary beluga whale population. The boaters in this category perform the most navigation trips per season on average (28.5%), and the majority of these trips take place within the beluga habitat (65.5%), suggesting that they often encounter cetaceans. The boaters belonging to the second category are most likely to be visitors to the SSL; they all use boats suitable for day trips or longer, such as sailboats or cruisers and do not use fast or short range boats (Table 3.3). Since they are primarily visitors, it appears that these boaters have less experience navigating in waters populated by whales compared to the other two categories. Given the fact that the majority of these boaters have a home marina located outside the summer habitat of the St. Lawrence Estuary beluga whale population and that they spend the least time there (36.2%) compared to the two other categories, it is conceivable that these people are less informed about the risks faced by cetaceans, as well as the navigation regulations to be respected in the SSLMP. Nevertheless, generalizations should not be made, as there are many visiting boaters who navigate these waters for the primary purpose of observing the various species of whales. It is therefore evident that some of them find out beforehand about the rules to be followed. Finally, boaters belonging to the third category are mostly locals (61.5%) whose home marina is located inside the summer habitat of the St. Lawrence Estuary beluga whale population. Moreover, they spend the highest proportion of their navigation trips within this area (68.5%). They also have the longest average navigation experience within the SSL (18.6 years), supposing that they must be the boaters who have encountered the most whales during their lifetime. However, it appears that marine mammals are less of an interest to them compared to the other two categories. In fact, according to the average order of their main interests during a trip, marine mammals rank 5th, while they rank 3rd for the self-centered and 4th for the eco-responsibles. Finally, it is important to take into account that boaters navigating on zodiacs and speed boats are likely underrepresented. Indeed, boaters were approached on their boats, at the dock of the marinas, or during their visit of the marina reception, which led to questioning more boaters spending time in marinas, including overnight. Boaters who navigate on zodiacs or speed boats spend only one day at sea, leave the marina as soon as they return from navigation and therefore generally have less time to devote to the study. The following sections describe each category of boaters based on the Q-methodology results and the rationale behind their choice.

3.3.3. Category 1 : eco-responsible

This category explains 22% of the variability. 31 respondents (51.7%) belong to that group. These boaters demonstrate a good understanding of marine mammal ecology, being aware that beluga whales navigate without relying on sight and recognizing the real threat posed by engine noise. They are environmentally conscious, actively reducing their ecological footprint through waste sorting, conservation fundraising, and adjusting their lifestyle. They prioritize environmental issues, showing a strong commitment to protecting the planet. Material possessions hold little importance for them, as evidenced by their reluctance to pursue their dream boat even if they were to come into a large sum of money. This group is the best informed about the geographic boundaries of the SSLMP, likely because of their awareness of marine mammals and their tendency to inquire about regional measures. This explains why they are the only category to consider that boats are traveling too fast within the SSLMP. Additionally, they believe that the SSLMP should be better known, certainly to raise awareness among a larger number of people to prevent inappropriate behaviors. However, they are not entirely convinced that everyone should have the opportunity to navigate the SSL, as they fear it would result in an increase in the number of vessels and therefore have a greater impact on marine mammals. Regarding navigation, they sometimes fish on board, rarely anchor and leave their engine(s) on when encountering whales, thus respecting the rules of the SSLMP. Their route is not always clearly planned before departure, and their destination is not always known in advance. Finally, boaters in this category do not actively seek to observe multiple species of whales during their sea outings. While they enjoy contemplating whales, they believe that sightings occur at the whales' discretion.

3.3.4. Category 2 : self-centered

This category explains 13% of the variability. 13 respondents (21.7%) belong to that group. These boaters appear unaware that the noise from their engines can disturb marine mammals, likely due to their lack of knowledge regarding beluga whales' reliance on sound signals for navigation. Even though they claim to be in favor of stricter control on the water to enforce the rules of the SSLMP regarding marine mammals, they do not seem to be fully aware of these regulations, particularly on whether to turn off the engine when encountering a whale or not. These individuals prioritize material possessions over environmental protection, rarely altering their lifestyle to minimize their ecological footprint or engaging in fundraising for nature conservation. They exhibit a somewhat materialistic mindset, valuing ownership and self-preservation, as evidenced by their belief that not everyone should have the opportunity to navigate these waters due to concerns about overcrowding, preferring a more private experience at sea. They exhibit a pronounced desire for control, evident in both their approach to navigation and their broader outlook on life. This is reflected in their meticulous planning of destination and route before departure, as well as their need to control their surroundings. This behavior could be attributed to the fact that these boaters might be primarily visitors (Table 3.3) who come from afar and might have pre-booked their marina night stays. As a result, they want to have maximum control over their navigation experience. This could also explain the fact that they seek to see several whales during a navigation trip since their arrival in the waters of the SSL is often motivated by the presence of these mammals. In fact, they have occasionally adapted their itinerary in order to observe whales longer and have already headed towards a group of whale-watching cruises, often synonymous with the observation of one or more mammals, so that they can enjoy the scene too, without being aware that they are contributing to the pressure exerted on the animals Finally, they do not fish and anchor very rarely during their sea outings.

3.3.5. Category 3 : altruist

This category explains 15% of the variability. 13 respondents (21.7%) belong to that group. They possess knowledge about whales, being aware that beluga whales do not rely on sight to navigate their environment. When encountering a whale, they occasionally turn off their engine, which goes against the SSLMP's regulations. Despite them knowing the regulations, this action stems from a belief that it minimizes disturbance to marine mammals. This implies that their ecological understanding is not exhaustive, especially regarding the reasons why the SSLMP requires users to keep their engine running (*i.e. to facilitate the boat's location by whales*). They feel that there are too many marine park guards patrolling within the SSLMP, often encountering them to explain regulations. They believe these guards dictate what to do in an environment known for generations, lacking the depth of understanding they possess. They have seldom participated in fundraising for nature conservation, yet they have contributed more frequently to charitable causes for people in need. Their altruistic tendencies lead them to consider that everyone should have the opportunity to navigate these waters, without fully considering the potential increase in pressure on whales. If they were to come into a large sum of money, one of their priorities would be to buy the boat of their dreams. They don't demonstrate biospheric values, as they seldom reduce their standard of living to protect the environment and inconsistently sort their waste, preferring to prioritize their own well-being and that of others over environmental concerns. Similarly to boaters belonging to the first category, there is no clearly defined route plan and the destination is not always known before departure. They sometimes fish and anchor occasionally during their navigation trips. Finally, they do not adjust their route to better see one or more whales when they come across them. Seeing the most whale species during an outing is clearly not their goal. For them, it is unthinkable to approach a gathering of whale-watching cruise ships.

It is important to note that the percentages of respondents belonging to a category (i.e. 51.7% for group 1 and 21.7% for groups 2 and 3) do not accurately represent the distribution of boaters navigating within our study area.

3.3.6. Convergences and divergences

Even though the three boaters categories agree on some points, they differ on many others. The waste sorting methods differ according to the three categories: eco-responsible individuals sort systematically, while altruists do it sometimes and self-centered only rarely. If recreational fishing is conceivable for the third group during a sea trip, it is never practiced by the boaters from the second category and only rarely by the first. Regarding the approach to a group of whale-watching boats, each boater's categories seems to avoid it to varying degrees:

self-centered have approached on a few occasions, while eco-responsible boaters strive to further minimize such approaches. Additionally, altruists consistently refrain from approaching. Boaters' reactions to whales vary depending on their category. In fact, altruistic boaters tend to turn off their engine when crossing a whale, as opposed to eco-responsibles. Self-centered boaters adopt a rather neutral position on this question, maybe due to the fact that they are unsure on what to do. Finally, the different categories have divergent opinions about the effort put into enforcing the regulations within the SSLMP. Eco-responsibles consider the current effort sufficient, while the self-centered believe that more guards are needed to ensure regulation enforcement. Conversely, altruists feel that there is an excessive presence of guards. Table 3.4 highlights statements with the highest agreement and disagreement scores across the three categories.

Table 3.4 Statements with the highest agreement and disagreement scores across the three categories.

	Category 1: eco-responsible	Category 2: self-centered	Category 3: altruist
Strongly agree (+5)	I systematically sort my waste.	The most important thing for me is to do what I love.	I like to be useful to others.
	The sound produced by my engine can disturb marine mammals.	My destination is always known before departure.	The most important thing for me is to do what I love.
Agree (+4)	I like to be useful to others.	The route plan is clearly defined before departure.	I think everyone should have the chance to navigate the Saguenay – St.-Lawrence.
	It is important for me to enjoy the pleasures of life.	It is important for me to enjoy the pleasures of life.	I have already volunteered to help people in need

Disagree (-4)	Belugas mainly use their sight to locate themselves underwater.	When I come across a whale, I approach to contemplate it more closely.	When I come across a whale, I approach to contemplate it more closely.
	When I see marine mammals, I broadcast the information via my radio or my cell phone.	When I see marine mammals, I broadcast the information via my radio or my cell phone.	Belugas mainly use their sight to locate themselves underwater.
Strongly disagree (-5)	When I come across a whale, I approach to contemplate it more closely.	I fish every time I go out on my boat.	When I see a crowd of stationary whale-watching boats, I approach them to enjoy the show.
	When I come across a whale, I feed it with what I have on board.	When I come across a whale, I feed it with what I have on board.	When I come across a whale, I feed it with what I have on board.

3.4. Discussion

3.4.1. The values surrounding the three categories and potential biases

It is important to keep in mind that self-evaluation methods, such as the Q-method, are subject to biases related to social desirability. The social desirability bias refers to the tendency of research subjects to choose responses that they perceive as more socially acceptable rather than responses that reflect their true thoughts or feelings (Paulhus, 1991). Norms are important determinants of socially desirable behavior because they determine what constitutes a good impression in a given situation (Nederhof, 1985). It is a complex and multidimensional phenomenon and two factors seem to be involved in social desirability: self-deception - when a respondent actually believes in an overly positive self-presentation, even if it is inaccurate - and impression management - any distortion of the truth motivated by the desire to avoid judgment from others (Paulhus, 1984; Sackeim and Gur, 1978). Moreover, depending on individuals, social desirability may be considered as a stable personality trait, as a constant need for social approval, or as an item characteristic, considering that certain activities or attitudes are more or less socially undesirable (Jackson and Messick, 1958; Krumpal, 2013). In order to limit the effect of this bias during data collection, the study was presented to participants as solely focusing on pleasure boating, and at no point were the whales of the SSL mentioned as part of the project. In addition, participants' anonymity was guaranteed, and we emphasized several times the importance of responding as honestly as possible and that no one would judge their responses. The themes discussed in the Q-method statements allow us to associate navigation habits, interactions with other boats and with marine mammals, knowledge on marine mammals and on the SSLMP as well as their perception on the SSLMP, with each category of boaters. Moreover, collecting statements on values has helped to better understand what motivates the participants to adopt a certain behavior. All participants expressed significant hedonistic values, which is understandable as the activity in question was recreational and practiced for pleasure. This inclination is further evident in the participants' prioritization of their main interests during a trip, with the unanimous ranking of "pleasure to navigate" and "beauty of the landscape" as their top two preferences. However, it should be noted that each category exhibited tendencies associated with the three other types of values. Boaters belonging to the first group expressed important biospheric values, while those belonging to the second one showed a tendency towards egoïstic values, and finally, boaters belonging to the third group appear to be a bit more altruistic. Accordingly, we named the categories according to their values' tendency. It is important to keep in mind that each person is unique and has their own experiences, beliefs, needs, and desires that shape their values and behaviors. A person's values are often influenced by their social, cultural, economic, and political environment, as well as their personality and life experiences (Strauss, 2017). Therefore, it is normal for each individual to express different levels of each of the four types of values, as each has different priorities and motivations depending on their life context. In fact, each person is made up of a complex mix of values that can vary. Values are not fixed, immutable personality traits, but rather general orientations that guide a person's behaviors and attitudes (Gouveia et al., 2015). It is therefore unlikely that a person would be completely selfish or altruistic, as this would imply absolute constancy in that person's behaviors and attitudes. Rather, each individual is likely to make choices that reflect unique combinations of values, based on their personal experiences and motivations. For example, a person may be generally altruistic, but choose to make a self-centered decision in a particular situation where their personal interests are threatened. Similarly, a person who generally values fun and comfort may make biosphere choices in an outdoor activity that they particularly enjoy.

Ultimately, it's important to understand that values are tendencies rather than absolutes, and that each person has their own unique combination of these tendencies.

3.4.2. The need to protect the St. Lawrence Estuary population of beluga

After being classified as an endangered species, a recovery plan was implemented for the St. Lawrence Estuary beluga whale population, aiming to increase the current population size by a coefficient slightly greater than 7 by 2050 (DFO, 2012), bringing the population to approximately 6,300 individuals. As part of this plan, an action plan was devised to mitigate belugas' exposure to anthropogenic noise (DFO, 2020). One of the primary objectives of this action plan is to gather sufficient data on activities generating noise impacts within the SSL. As previously mentioned, there is a significant lack of information regarding SSL recreational boating. The extraction of this typology of boaters navigating through the beluga critical habitat enables a deeper understanding of recreational activities, their dynamics, and the motivations driving these dynamics. This understanding will not only facilitate comprehension of the impacts they generate but also aid in identifying areas where behavioral improvements are needed.

3.4.3. Territory management strategies

Awareness

Valuable resources, such as numerous websites, social media pages, and notably an online training program tailored for boaters and kayakers navigating whale habitats, offer insights into whale ecology, potential human impacts, and relevant regulations. This voluntary online training should definitely transition to a mandatory requirement to ensure that the majority of recreational boaters are equipped with the correct knowledge of appropriate behavior when encountering whales. It could potentially become a mandatory phase when obtaining a navigation license, taking sailing classes, renting a boat or booking a night stay in a marina within this environment for example. Additionally, considering that regulations may be subject to modification, a mandatory refresher of this training program should also be implemented. Additionally, thorough explanations of the reasons behind such regulations could be provided so that boaters understand the meaning of the regulations and do not simply perceive them as restrictions limiting their freedom. Key variables for determining the most suitable archetype for a boater can be identified, integrated into a brief questionnaire, and administered to a large sample of recreational boaters. This approach would enhance our understanding of the distribution of recreational boaters' typology. Indeed, while this study extracted three recreational boaters' perspectives, it did not provide insight into the distribution of these perspectives. The online training could be adjusted according to the user's perspective, prioritizing less familiar points for some perspectives and reducing explanations on topics better understood by others. Finally, this training could be complemented by a navigation simulator, enabling users to virtually navigate within whale habitats, encounter diverse scenarios involving marine mammals, and enhance their decision-making skills. This simulator could be accessible online immediately following the training or installed on screens, such as tablets or computers, in marinas bordering the whale habitats. Moreover, involving one or more recreational boaters, recognized within the community for their experience and/or affiliation with navigation clubs, in discussions on the implementation or modification of regulations within the SSL by the decision-makers could be beneficial. They could act as intermediaries between boaters who may not consistently support regulations, illustrating scenarios they often face that may contrast with decision-makers' perspectives. Furthermore, they could help in fostering acceptance of regulations among recreational boaters by providing a deeper understanding of the rationale behind these measures, and potentially garnering greater attention and respect from their peers.

Simulation modeling

The SSL constitutes a complex social-ecological system (Parrott et al., 2012) in which human activities interact with ecosystems. An agent-based model (ABM) of boat-whale interactions called 3MTSim (Marine Mammal and Maritime Traffic Simulator) has been used for more than a decade to support the sustainable management of navigation with regard to marine mammals within this environment (Chion et al., 2018, 2013). This simulator has previously been employed to assess management strategies for commercial shipping (Parrott et al., 2016; Chion et al., 2017, 2021) and to explore potential regulatory adjustments for whale watching vessels (Chion et al., 2013). Nonetheless, the simulation platform currently lacks representation of recreational boating activities. Consequently, there is a need to construct the ABM that captures the dynamics of recreational boating within the SSL and seamlessly incorporate it into the global simulator. Thus, the four main components of marine traffic will be included in 3MTSim (Turgeon et al. 2019; Chion et al. 2009), which will facilitate the understanding of their cumulative and relative impacts on the different whale species, allowing a test of mitigation scenarios. One of the greatest challenges in building an ABM such as 3MTSim is to gain a deeper understanding of the real actors' behaviors and be able to move from actors to agents (Chion et al., 2011; Rounsevell et al., 2012). The Q-methodology offers a promising avenue to achieve such a move, allowing to account for the diversity of the points of view from multiple actors into a tractable data-informed ABM. Moreover, it facilitates the understanding of the motivations, beliefs and values that influence the behaviors of the agents, thus providing valuable information for the construction of the model (Watts and Stenner, 2012). The identification of this boaters' typology will allow the development of the recreational boating ABM based on their distinct navigation habits in general but also when encountering whales. After incorporating their spatio-temporal behaviors into the 3MTSim simulation platform, it will be used to assess the impact of recreational boating and the cumulative effects of all navigation segments on whales within the SSL. Scenarios aimed at mitigating these impacts will be explored, such as examining how the enforcement of a new speed regulation or the closure of specific areas to recreational boats will affect whale populations. Also, a better understanding of this typology distribution would be highly beneficial for the simulation in 3MTSim, as it is crucial to accurately represent boaters' behavior. It would enable the testing of scenarios in which the proportions of perspectives, and thus behaviors, are altered, potentially reflecting increased awareness among boaters regarding whales. Ultimately, requiring the use of AIS transponders for recreational boaters would significantly improve our ability to gain a comprehensive understanding of high-pressure areas, accurately depict their spatio-temporal movement within the 3MTSim simulator, and assess more realistic management scenarios, providing a robust decision-making tool for policymakers.

3.5. Conclusion

To conclude, three main categories of recreational boaters who navigate in the waters of the SSL were identified: the eco-responsible, the self-centered, and the altruist. Individuals in each category possess distinct knowledge, habits, and values, which translates into different behaviors on the water. In addition to being an appropriate research approach to sensitive topics, the Q-methodology allows participants to freely classify all statements and explain their choices, which facilitates the overall understanding of categories. While the subjective input of the participant group shapes the interpretation of the Q-method, the aim of these interpretations is to represent a shared perspective rather than accurately capture each participant's individual opinion. To the best of the author's knowledge, there is a notable absence of Q-methodology studies that concentrate on the habits, knowledge and preferences related to a recreational activity, as opposed to solely examining perceptions. Moreover, the integration of Q-methodology and ABM, a relatively uncommon combination, has been previously applied to simulate an emergency situation (Oakes, 2014) or manage territorial aspects (Rasquinha, 2022) but never to model a leisure activity like recreational boating. Finally, by using this approach to identify the main categories of recreational navigation within the SSL, we can collaborate with stakeholders to address the necessary regulatory modifications and/or implement focused awareness campaigns. This collaborative effort holds the potential to make significant strides in enhancing whale protection within the SSL and ultimately contribute towards halting the decline of the beluga whale population.

3.6. Acknowledgement

The authors extend their gratitude to the 60 recreational boaters who graciously agreed to participate in this study. We would also like to express our appreciation to the marinas that allowed us to utilize their facilities and to the ROMM (Réseau d'Observation des Mammifères Marins) for providing us with boaters' contacts. We are also grateful to Michel Sacco for reviewing the navigation-related statements.

Funding

The funding to support this research project was provided by the Ministère des Forêts, de la Faune et des Parcs du Québec and Secrétariat à la stratégie maritime du Québec.
We also acknowledge the contribution of the Social Sciences and Humanities Research Council through the Canada Research Chair in Ecological Economics.

Chapitre 4 : Recreational boating and its impact on beluga herds configuration in the Saguenay Fjord

Cet article est en cours de préparation

Kowalski, C., Sénécal, J. F., Dupuch, A., Dupras, J., & Chion, C. Recreational boating and its impact on beluga herd configuration in the Saguenay Fjord.

Contributions des auteurs

J'ai conçu le protocole d'observation à partir de références méthodologiques existantes, en concertation ponctuelle avec des experts externes. J'ai effectué l'ensemble des observations de terrain, accompagnée de deux assistantes formées sur place, puis j'ai réalisé les analyses et rédigé l'article. Angélique Dupuch et Jean-François Sénécal ont contribué aux analyses statistiques. Jérôme Dupras et Clément Chion ont assuré la supervision scientifique du projet. L'ensemble des co-auteurs ont participé à la révision du manuscrit.

Abstract

There is limited knowledge about the presence of recreational boats in marine mammal habitats and their potential impacts. While numerous studies have examined the responses of marine mammals to commercial vessels, icebreakers, or whale-watching boats, the specific influence of private recreational boats remains understudied. This knowledge gap is particularly notable for the endangered St. Lawrence beluga whale population. In this study, we conducted land-based observations of recreational boats and beluga whales along the Saguenay Fjord. We first assessed how recreational boat presence related to temporal and environmental conditions, as well as to the proportion of time belugas were present in the observation area. We then examined whether recreational boats influenced beluga observations, specifically the number of belugas visible at the surface and their herd configuration. Our results indicate that recreational boat presence was associated with several temporal and environmental variables but was not related to beluga presence. The number of belugas observed at the surface showed no detectable systematic variation with the presence of recreational boats, although the limited sample size reduced the ability to detect subtle effects. However, a higher number of recreational boats was correlated with an increased likelihood of

observing changes in the distances between groups (i.e., dispersion) within beluga herds. Such changes in herd spacing likely reflect short-term behavioral adjustments of beluga groups to nearby recreational boats. These findings highlight the need to consider recreational boating activities in conservation strategies for the St. Lawrence beluga, particularly when managing human use of critical habitats during sensitive periods.

4.1. Introduction

Recreational boating represents a significant and growing sector of maritime traffic, particularly in coastal and ecologically sensitive areas (Boating Industry, 2024; ICOMIA, 2023; Smott et al., 2018). Unlike commercial shipping, ferries, or commercial whale-watching tours, which follow regulated routes and schedules, recreational boating activities are characterized by a greater spatial and temporal variability. While commercial vessels are required to be equipped with Automatic Identification System (AIS) transponders, providing continuous monitoring of their movements, recreational boats are not mandated to have such devices onboard in Canada, leading to a limited understanding of their distribution and behavior in marine environments (Hermannsen et al., 2019). Weather conditions, seasonality, short-term temporal factors, and proximity to recreational infrastructures all contribute to shaping boating patterns (Hunt et al., 2019; Kendall et al., 2021). Understanding these factors is crucial for predicting boat traffic and assessing its potential impact on marine wildlife. Although typically smaller than commercial vessels, recreational boats collectively exert significant pressure on marine ecosystems (Carreño and Lloret, 2021). Their impacts include the introduction of invasive species, physical disturbances such as propeller strikes and collisions, increased underwater noise, degradation of seabed habitats, pollution, and interactions with marine wildlife (Cole et al., 2019; Forrester, 2020; Gorzelany, 1998; Moreau et al., 2009; Ritter, 2012). Given the growing demand for leisure activities, these impacts require a closer examination, particularly in ecologically sensitive areas.

The marine biodiversity of the Saguenay Fjord and St. Lawrence Estuary makes the region a renowned whale-watching destination. Indeed, several migratory whale species, including the blue whale (*Balaenoptera musculus*), fin whale (*Balaenoptera physalus*), humpback whale (*Megaptera novaeangliae*), and minke whale (*Balaenoptera acutorostrata*), use these waters as feeding grounds during summer (Cotté and Simard, 2005; Ramp et al., 2015; Truchon et al., 2013). In addition to these migratory species, the St. Lawrence beluga

(*Delphinapterus leucas*) is a year-round resident of the region, with an increased presence in the Saguenay Fjord during summer (Lesage et al., 2024). Certain zones within this habitat are identified as high residency areas, characterized by slow net displacement speeds of beluga herds, indicating prolonged use likely due to the high ecological profitability of these areas (Lemieux Lefebvre et al., 2012). This population, classified as endangered (COSEWIC, 2014), faces numerous anthropogenic threats contributing to its continued decline. To address this, the Saguenay–St. Lawrence Marine Park, established in 1998, encompasses part of its critical habitat. Recreational boating activities primarily take place during summer, a critical period when females give birth and care for their newborns, which adds further stress to the population and hinders its recovery. Between 2010 and 2012, a correlation was observed between increased recreational boating and higher calf mortality (Ménard et al., 2014), although causality was not established. This highlights the urgent need to better understand how recreational boating affects beluga populations, especially given the growing recreational use of natural spaces.

Beluga whales rely on sound for navigation, communication, and foraging (Richardson et al., 2013). Consequently, underwater noise generated by boat engines poses a major threat to the St. Lawrence Estuary beluga population (DFO, 2020, 2012). Indeed, belugas are particularly sensitive to a broad range of frequencies (Castellote et al., 2014; Mooney et al., 2018), some of which overlap with the acoustic emissions of recreational boat engines (Wladichuk et al., 2019). Studies suggest that belugas can detect and be disturbed by these noise sources within a few hundred meters (Lagrois et al., 2023). Increased ambient noise can disrupt beluga vocalizations and echolocation abilities (Vergara, 2019), leading to compensatory behaviors such as increasing call amplitude and adjusting frequencies, responses that require additional energy expenditure (Au et al., 1985; Lesage et al., 1999; Scheifele et al., 2005).

Beluga whales exhibit a wide range of behavioral responses to vessel noise, which depend on factors such as vessel type, movement patterns, and proximity. Large commercial ships, for instance, tend to elicit minimal reactions from belugas, arguably due to their predictable movement patterns and the low-frequency range of their engine noise (Burns and Seaman, 1986; Fraker, 1977a; Macfarlane, 1981; Pippard, 1985; Sergeant, 1986, 1981). However, recent studies indicate that belugas may still increase their swim speed and adjust their bearing when ships are within a variable range, with effects detected up to ~79 km away

(Martin et al., 2023). Noise-intensive activities such as icebreaking and seismic surveys have been linked to significant behavioral disruptions. Icebreakers have been associated with decreased group cohesion and large-scale displacements, with disturbance radii reaching up to 32 km (Cosens and Dueck, 1988; Erbe and Farmer, 2000; Finley et al., 1990; Finley and Davis, 1984). Similarly, seismic operations have led to avoidance behaviors at distances of 10–20 km (Miller et al., 2005), suggesting substantial impacts on beluga habitat use. Smaller vessels, particularly those moving erratically or equipped with outboard motors, tend to provoke strong avoidance behaviors in belugas (Fraker, 1977b; Stewart et al., 1982). Studies have documented increased dive durations, tighter group formations, and faster swim speeds in response to whale-watching boats and recreational vessels (Blane and Jaakson, 1994; Krasnova et al., 2020). Some reports indicate that even stationary boats or vessels with engines turned off can elicit avoidance behaviors (Blevins, 2015). However, responses remain context-dependent, as some belugas have been observed showing no reaction (Ausen et al., 2022) or even displaying curiosity towards certain vessels (Westdal et al., 2023). These contrasting findings may be partially explained by differences in exposure history. Belugas inhabiting remote areas with low vessel traffic may be more reactive to boat presence, whereas populations like the St. Lawrence Estuary belugas, which are chronically exposed to vessel noise, may exhibit habituation to certain disturbances (Weilgart, 2007). This variability highlights the need for further research to better understand the complex interactions between belugas and boat traffic across different environments.

This study focuses on two main objectives to address the knowledge gap regarding recreational boating within a designated study area in the Saguenay Fjord and its potential interactions with beluga whales. The first objective is to examine the factors influencing the presence of recreational boats within that area, while the second objective is to investigate whether the presence of recreational boats affects St. Lawrence beluga herds during their passage through the study area.

4.2. Methods

4.2.1. Observation site

Located within the confines of the Saguenay-St. Lawrence Marine Park (SSLMP), the study area spans 8 km2 and predominantly features recreational navigation activities.

Observers were located at Anse de Saint-Etienne (ASE) (*latitude 48.2092°N, longitude 69.9082°W*), along the Saguenay Fjord as illustrated in Figure 4.1. The selection of this specific site was based on several considerations. Firstly, this section was recognized as a high residency area for St. Lawrence beluga whales (Lemieux Lefebvre et al., 2012). Additionally, the Saguenay Fjord was chosen due to its narrow width (~2 km), ensuring comprehensive coverage of observed activities within the designated section. Moreover, the upstream location of Baie Sainte-Marguerite, an important hotspot for beluga whales (Conversano et al., 2017; Ménard et al., 2018; Vergara et al., 2021), contributes to the frequent passage of beluga herds through the study area. Furthermore, the elevated observation site, positioned at an altitude of 50.51 meters above sea level, provided a panoramic view of the study area. Data were collected during the summer seasons of 2021 and 2022, with all observations conducted during daytime under suitable weather conditions when the opposite shore was visible. On average, each observation day lasted 6 hours and 38 minutes.

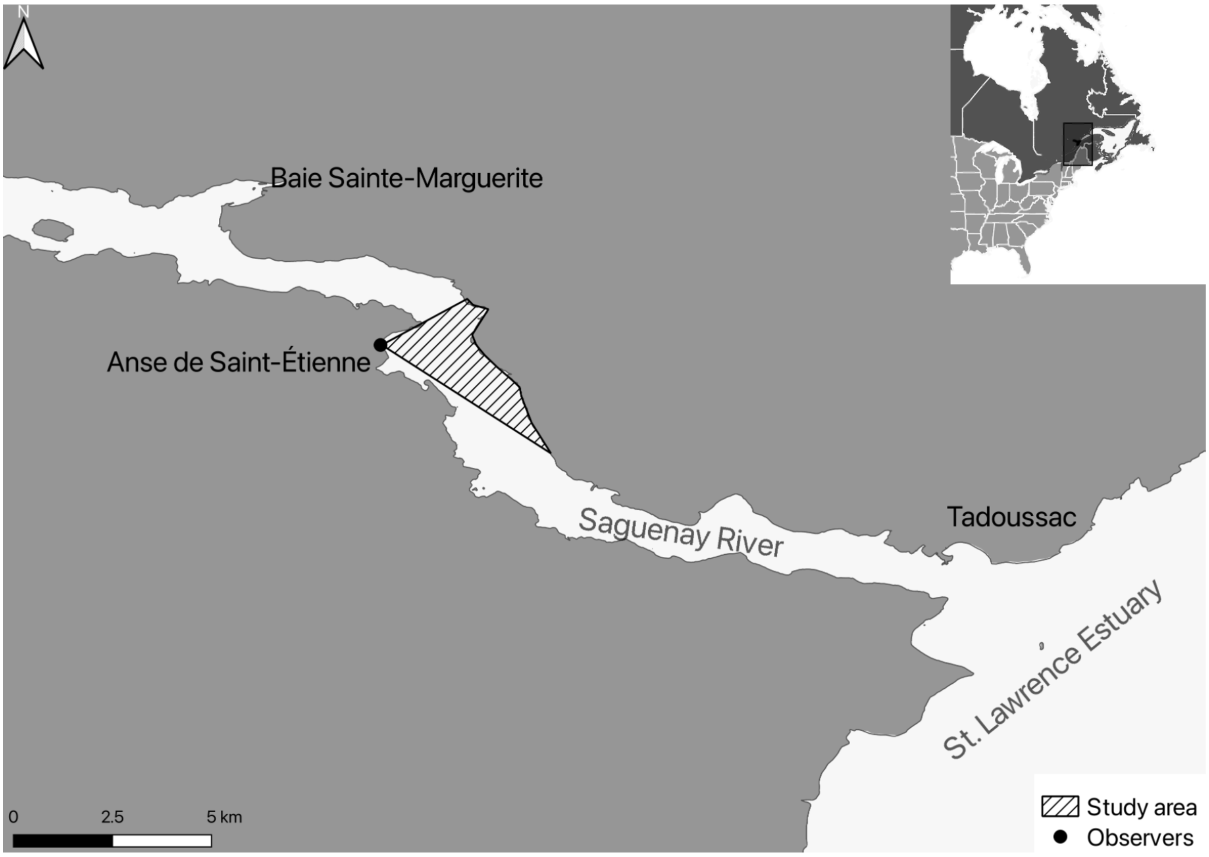
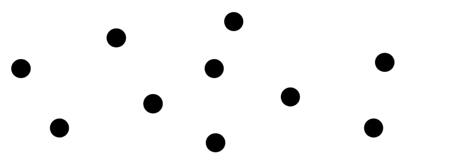


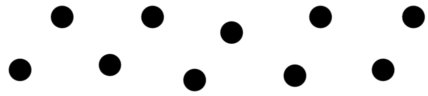
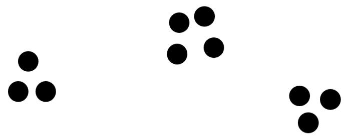
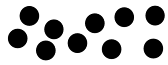
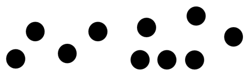
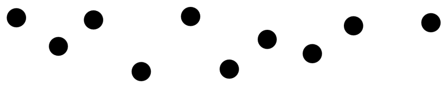
Figure 4.1 Map of the position of the observers and the viewshed that defines the study area (*dashed polygon).*

4.2.2. Data collection

The study area was scanned to record the presence of recreational boats. Binoculars (Bushnell 7x50) were used to describe the passages of beluga herds through the study area. Observations were conducted over 94 days (59 days in 2021 and 35 days in 2022). A passage refers to the movement of a beluga herd through the study area, either in an upstream or downstream direction. Observations were conducted using visual scan sampling (Mann, 1999) every 10 minutes whenever belugas were present. Each scan involved visually sweeping the study area to record the current state of the herd. We characterized a herd as a collection of groups separated by relatively short distances, typically a few tens to hundreds of meters, with each group consisting of animals swimming in close proximity (usually within one body length) and often displaying coordinated movements (Lemieux Lefebvre et al., 2012). The herd spatial configuration and number of individuals was recorded at each scan, and the highest count observed was retained to represent the size of the herd. Herd configuration was described based on three geometric aspects of groups' spatial organization within a herd: shape, structure, and dispersion (Table 4.1). The configurations of these aspects were systematically updated at each scan throughout the passage. A ΔConfiguration binary variable was created for each of the three geometric aspects (ΔDispersion, ΔShape, and ΔStructure) to indicate whether any change in that specific aspect occurred at least once during the herd's passage through the study area (presence or absence of configuration change: coded as "1" and "0" respectively). For ΔDispersion, a value of "1" indicates that the herd's dispersion either increased, decreased, or fluctuated during the passage.

Table 4.1 Description of the three geometric aspects used to characterize beluga herds spatial configuration (Lemieux Lefebvre et al., 2018). In the illustration column, each dot represents a group of beluga whales within a herd.

Aspect	Configuration	Description	Illustration
Shape *(factors with 2*	Broken	Groups do not show a precise configuration	

levels)	File	Groups are organized in a linear configuration	
Structure *(factors with 2 levels)*	Uniform	Groups are uniformly distributed within the herd	
	Clustered	Groups are distributed in a few distinct clusters	
Dispersion *(factors with 3 levels)*	Tight	Distance between groups <100m	
	Loose	Distance between groups = 100-300m	
	Dispersed	Distance between groups >300m	

4.2.3. Statistical analysis

Factors influencing recreational boating intensity

To explore the factors influencing the presence of recreational boats within the study area, observation data were organized into one-hour segments (n = 465, over 75 days). The response variable was the number of recreational boats present in the study area per hour. We examined a set of environmental and temporal predictors known to influence recreational boating activity (Kendall et al., 2021; Ménard et al., 2014; Turgeon, 2019), including sea conditions, tidal phase, wind speed and direction, temperature, time of day, weekday, and Julian day (see Table 6.3, Appendices, for more details). Additionally, we included the proportion of time belugas were observed within each segment to assess whether their presence attracted boaters, suggesting possible following behavior by boaters. Generalized additive models (GAMs) were fitted using the mgcv package (v.1.9.1; Wood, 2017), allowing for both linear and non-linear effects through the use of smooth functions. Julian day was modeled as a smooth term separately for each year to account for inter-annual variation. Wind direction and time of day were modeled using cyclic and cubic regression splines, respectively. Models were fitted using Maximum Likelihood (ML) estimation with a Gaussian family for the response variable. To identify the most influential predictors while accounting for model uncertainty, we employed model averaging using the *MuMIn* package. All possible combinations of explanatory variables were evaluated using the *dredge* function, and full model averaging was performed across the entire set of candidate models based on AICc weights (Burnham and Anderson, 2002).

Beluga herds responses to recreational boats

We examined whether the presence of recreational boats was associated with changes in either (1) the number of belugas observed during herd passages or (2) the geometrical configuration of herds. To isolate the potential effects of recreational boats, we retained only observations collected in the absence of cargo ships or whale-watching excursion boats.

To explore whether recreational boating activity affects the number of belugas observed at the surface, we used the scan-level dataset (513 observations) to calculate, for each herd passage, the average number of individuals observed during scans with at least one recreational boat and during scans without any boats. We then retained only the passages that included both types of scans (i.e., with and without recreational boats), resulting in a subset of 30 herds. For each of these 30 herds, we computed the mean number of belugas observed at the surface with and without recreational boats, and compared them with a paired t-test. This analysis aimed to assess whether the presence of recreational boats was associated with a lower number of belugas surfacing during passages.

To examine whether recreational boats were associated with changes in herd configuration (i.e., shape, structure, or dispersion), we created a passage-level dataset comprising 84 beluga herd passage through the observation area. Each of the three ΔConfiguration binary variables, ΔDispersion, ΔShape, and ΔStructure, was analyzed using Generalized Linear Mixed Models (GLMMs) with a binomial family implemented in the *glmmTMB* package (version 1.1.9). The main explanatory variable in all three models was the number of recreational boats observed during each herd passage. We also included control variables related to sampling effort (observer-herd distance, and observer evaluation, a confidence rating assigned by the observer and related to the quality of the data collected; see Table 6.4, Appendices). Herd passage duration was also included as longer passages increase the likelihood of encountering both a greater number of boats and observing changes in herd configuration. The herd's initial geometric configuration, recorded at the first scan of each passage, was included to account for its potential influence on the likelihood of changes during the passage. Non-significant control variables (observer-herd distance and observer evaluation) were removed based on AICc to adhere to the principle of parsimony. Since two observers collected data in a different year and observations spanned two years, observer identity was accounted for by including the sampling year as a random effect. All statistical analyses were performed in R version 4.4.0 (R Core Team, 2024).

4.3. Results

4.3.1. Factors influencing recreational boating intensity

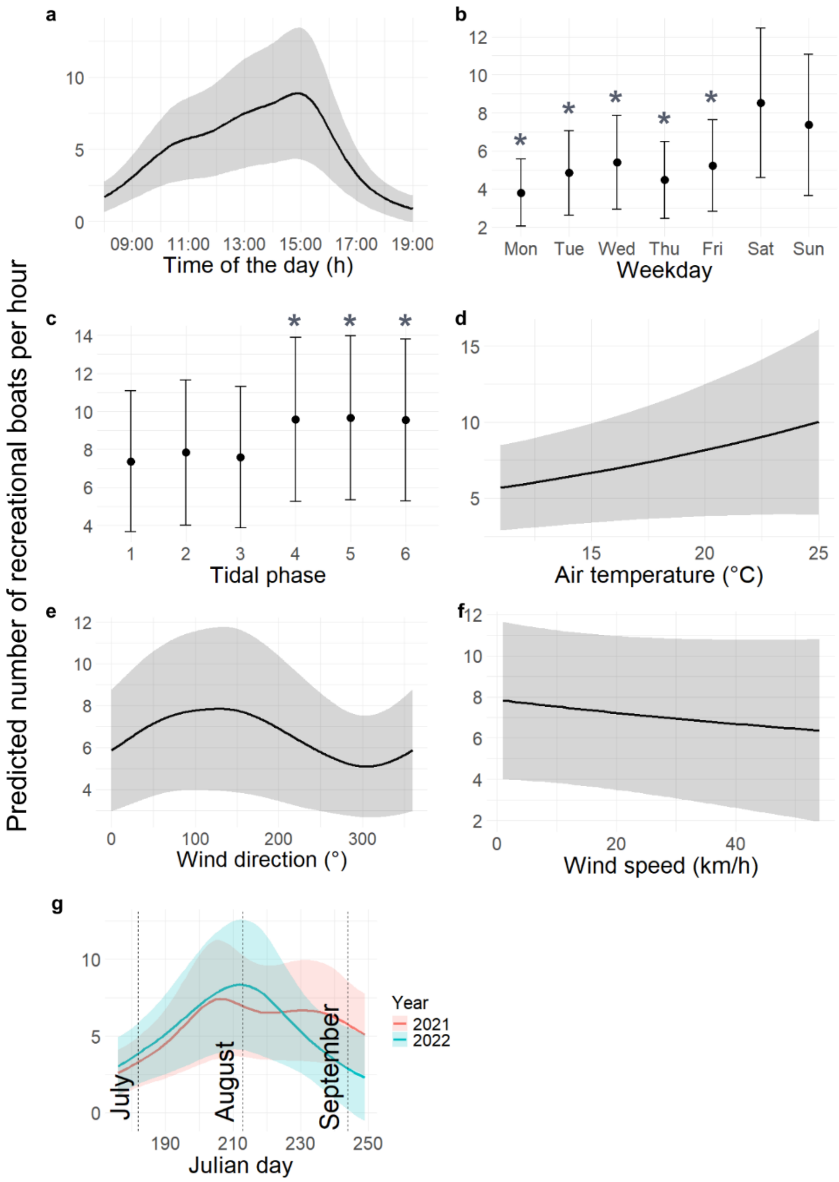


Figure 4.2 Predicted effects of significant environmental and temporal variables on recreational boat counts per hour. Predictions are based on model-averaged GAMs, with all other covariates held constant at representative values (e.g., time = 12:00, day = Sunday, Julian day = 208, wind direction = 178°, tidal phase = 1, proportion of observation time with belugas = 16.9%, sea condition = 0, year = 2021, wind speed = 15.26 km/h, temperature = 17.5°C).

The number of recreational boats per hour exhibited a clear daily pattern, gradually increasing throughout the day and peaking around 3 PM, before declining toward the evening (Figure 4.2a). Weekly patterns showed significantly lower numbers of boats on weekdays (Monday to Friday) compared to Sundays, while no significant difference was found between Saturdays and Sundays (Table 6.5, Appendices; see also Figure 4.2b). The number of recreational boats was significantly higher during low tide (phases 4 to 6) compared to high tide (phase 1), as shown by model results (Table 6.5, Appendices; see also Figure 4.2c). Air temperature was positively associated with boat presence: the predicted number of recreational boats per hour nearly doubled, increasing from just over 5 boats at 11 °C to about 10 boats at 25 °C (Figure 4.2d). In contrast, wind speed was negatively associated with boating activity, with fewer boats observed at higher wind speeds (Figure 4.2f). Wind direction also had a significant effect on the number of boats: the lowest numbers were predicted when the wind came from the West-North-West (~300°), while the highest numbers were observed when winds came from the South-East (~125°) (Figure 4.2e). Finally, seasonal patterns showed a sharp increase in the number of recreational boats per hour beginning in mid-July. In 2022, the peak was more pronounced, occurring in late July to early August, followed by a steep decline in mid-August. In contrast, the increase was more gradual in 2021, with a relatively stable plateau from late July through late August (Figure 4.2g). Sea conditions and the proportion of time with belugas had no significant effect on the number of boats per hour (Table 6.5, Appendices).

4.3.2. Beluga herds' behavioral response to recreational boats

The number of belugas observed did not vary systematically with the presence of recreational boats (paired t-test: $t = -0.62$, $df = 29$, $p = 0.54$). Post-hoc power analysis (one-sided paired t-test, $n = 30$, package *pwr*) revealed that the statistical power was low (≈ 15%), meaning that our ability to detect small effects is limited; larger datasets would be required to determine whether subtle changes in surfacing behavior occur in response to boat presence. Higher (in 50% of passages), lower (in 26.7% of passages), and similar (in 23.3% of passages) numbers of belugas were observed at the surface during herd passages with recreational boats.

Table 4.2 Results from the three GLMMs relating the herd configuration changes to the number of recreational boats and other control variables. The likelihood approach was used to estimate the significance of the odds ratios. The percentages within brackets in the Models column indicate the total variance explained by each model.

Models	**Variable**	**Odds Ratio (OR)**	**p-value (Likelihood Ratio Test)**
	Intercept	0.44	0.158

ΔDispersion (19.2%)	Number of boats	1.18	0.040*
	Herd transit time	1.00	0.991
	Dispersion (loose)	4.54	0.079
	Dispersion (dispersed)	2.15	
ΔShape (13.1%)	Intercept	0.13	<0.001 ***
	Number of boats	0.99	0.909
	Herd transit time	2.12	0.030*
	Shape	3.76	0.062
ΔStructure (21.9%)	Intercept	0.25	0.002*
	Number of boats	0.98	0.744
	Herd transit time	1.75	0.149
	Structure (clustered)	4.14	0.005*

** Statistically significant at $p < 0.05$*

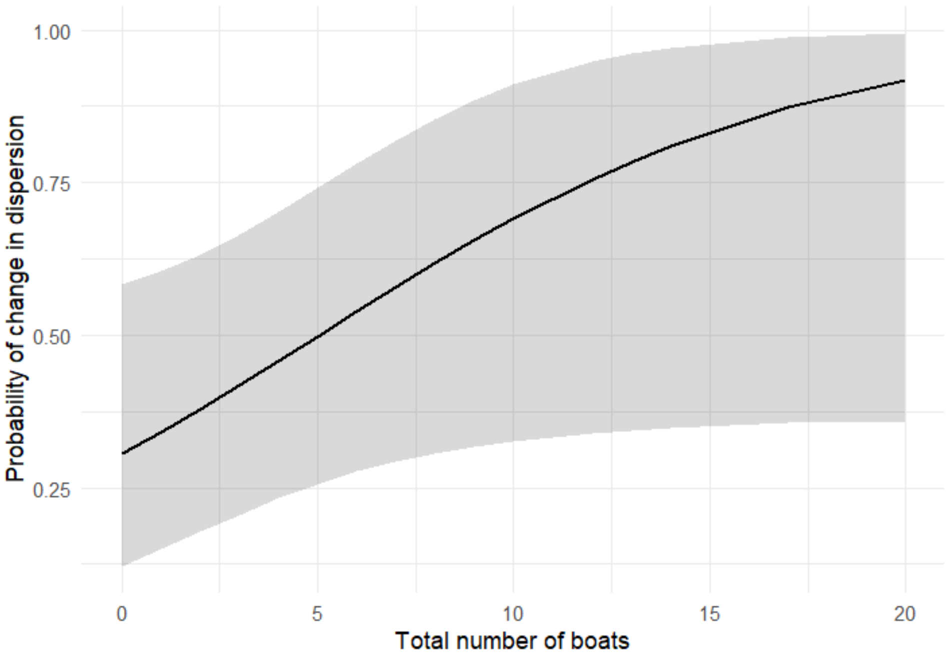


Figure 4.3 Model-predicted probability of ΔDispersion in beluga herds during passage as a function of the number of recreational boats. The solid black line represents the probability of ΔDispersion as the number of recreational boats increases. The shaded gray area around this line represents the confidence interval, indicating the uncertainty around the estimated probabilities.

The effect of the number of recreational boats was significant only in the ΔDispersion model ($p = 0.04$; Table 4.2). The odds ratio of 1.18 (Table 4.2) indicated that for each additional recreational boat present in the observation area, the odds of a change in herd dispersion increase by 18%, holding all other variables constant. The model explained 19.2% of the variance in changes in herd dispersion. When no recreational boats were present, the model predicted a 31% probability of change in the dispersion of beluga herds during their passage (Figure 4.3). These changes were characterized by similar proportions of increasing dispersion, decreasing dispersion and a mix of increasing/decreasing dispersion (Figure 4.4). However, when 20 recreational boats were present in the study area during the herd's passage, the probability of change in the herd's dispersion increased to 92% (Figure 4.3). These changes were mostly a mix of both an increase and a decrease in herds dispersion (Figure 4.4).

In the ΔShape model, only the herd transit time was significant ($p = 0.030$; Table 4.2). The odds ratio of 2.12 (Table 4.2) indicates that each additional hour of passage more than doubles the likelihood of a change in herd shape. This model explained 13.1% of the variance in changes in herd shape. For the ΔStructure model, only the initial structure of the herd was significant (p = 0.005; Table 4.2). Herds initially clustered were four times more likely to undergo structural changes compared to uniform herds (odds ratio = 4.14, Table 4.2). The model explained 21.9% of the variance in changes in herd structure.

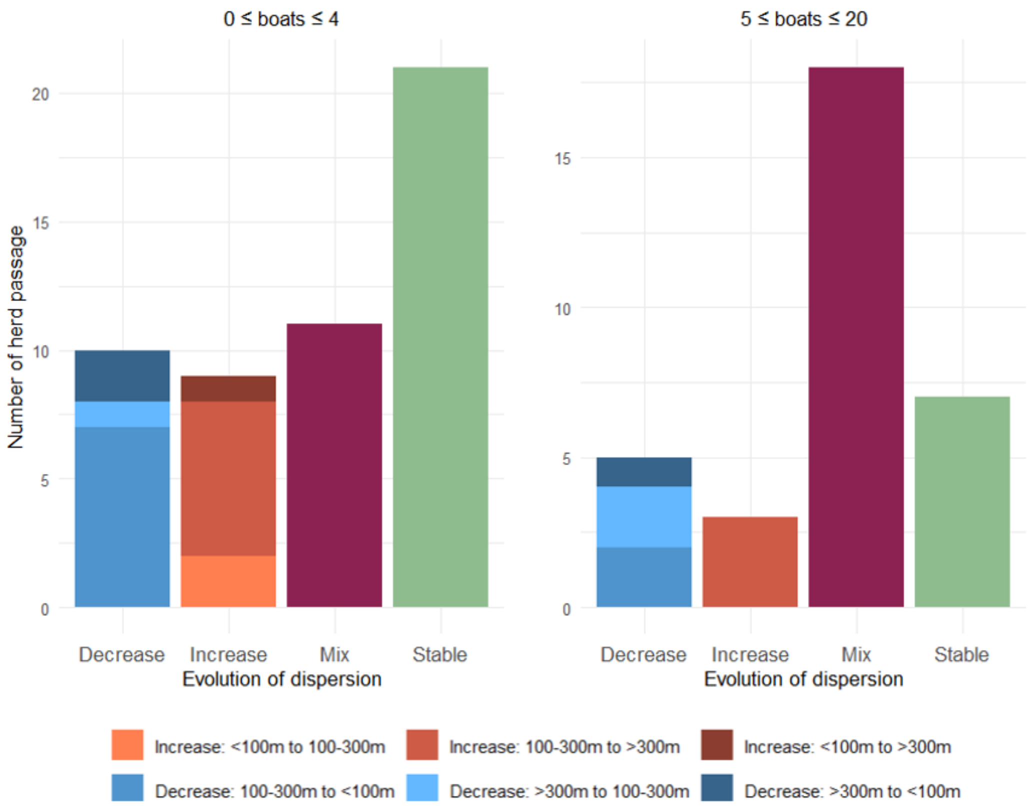


Figure 4.4 Histograms of observational data showing the number of herd passages categorized by dispersion change, with detailed classifications of increases and decreases.

To better understand the nature of the dispersion changes detected by the ΔDispersion model, we examined the observational data underlying these patterns. Figure 4.4 shows how herd dispersion evolved during passages under two levels of recreational boating activity (0–4 boats vs. 5–20 boats). For each herd passage, dispersion was classified into one of four categories based on the direction of change observed during sequential scans: Increase (groups moved farther apart), Decrease (groups moved closer together), Stable (no detectable change), or Mix (a combination of increasing and decreasing dispersion within the same passage). When recreational boating activity was low (0–4 boats), most herd passages showed no change in dispersion, with “stable” configurations being the most frequently observed outcome. However, when boating activity was higher (5–20 boats), the proportion of passages categorized as Mix increased noticeably, indicating that herds tended to alternate between tightening and spreading out during the same passage.

4.4. Discussion

4.4.1. Factors influencing recreational boating intensity

Temporal factors

The number of recreational boats within the study area displayed clear temporal trends. Specifically, it was significantly correlated with Julian day, day of the week, and time of day. Notably, recreational boating increased during the peak summer period (mid-July to mid-August), which coincides with the vacation season and best annual temperatures for boating in this region. Additionally, recreational boating occurred more often on weekends (Saturdays and Sundays), as local recreational boaters, even if not on vacation, typically navigate on these days. The daily trends further revealed that recreational boats numbers gradually increased throughout the day, reaching its peak around 3 PM. This peak is likely due to boats arriving in the observation area after traveling from marinas outside the study area, as the only marina within the area (*Anse-de-Roche*) was relatively small (28 local recreational boats and 79 overnight stays of visiting boats were recorded in 2017; Turgeon, 2019). After 4 PM, recreational boating decreased sharply, as boats usually began returning to their marinas before nightfall.

These temporal patterns are consistent with preliminary findings from a previous exploratory study conducted in various sectors of the SSLMP, including the mouth of the fjord, Anse-Saint-Jean, and Baie Sainte-Marguerite (Turgeon, 2019). Based on 30-minute observation segments, this study reported greater recreational boating activity during weekends and in the afternoon, with the highest boat counts recorded near the mouth of the fjord. Although the analysis was limited by small sample sizes in several sites and did not include the present study area, the trends identified align with our results and further highlight the importance of considering temporal variation when assessing boating pressure in this region.

Environmental factors

Environmental variables such as wind direction and speed, tidal phase, and temperature were significantly correlated with recreational boating activity.

Wind direction notably influenced the hourly count of recreational boats, with fewer boats observed when winds came from the West-North-West, and higher counts under South-East winds. This pattern likely reflects the effect of wind on navigability within the Saguenay Fjord. South-Easterly winds may facilitate upstream navigation from the St. Lawrence Estuary into the fjord, encouraging recreational boats to undertake day trips or longer excursions. Conversely, West-North-West winds might create more challenging conditions, especially for sailboats relying on engines against the wind or motorboats experiencing increased fuel consumption, thereby potentially deterring boaters and reducing vessel presence.

Wind speed exhibited a negative relationship with recreational boating activity, with about one less boat per hour observed as wind speeds increased. According to local recreational boaters, windier conditions, especially around 20 knots (approximately 37 km/h), can lead to choppier waters and more difficult navigation, particularly for smaller craft. These less favorable conditions may prompt some individuals to delay or cancel outings, contributing to the observed decrease in boating activity during windier periods.

Tidal phase also had a statistically significant effect, with more recreational boats observed near low tide compared to high tide. This pattern may reflect local navigation practices, as recreational boaters often align their trips with the tidal cycle to benefit from favorable currents. Specifically, entering the Saguenay Fjord from the St. Lawrence Estuary is generally easier during low tide or the flood tide, when currents are less intense or flow upstream (Turgeon, 2019). According to local boaters, timing travel with the tide is a commonly shared strategy, especially for longer journeys toward upstream destinations in the fjord, as it helps reduce travel time and fuel consumption. Similarly, boaters returning downstream toward the estuary may time their passage to coincide with the ebb tide. Given that ASE is located in the lower portion of the fjord, near the popular boating destination of Tadoussac (Figure 4.1), increased boat presence during low tide could reflect downstream movement from farther upstream. Additionally, tidal conditions may influence the attractiveness of the area for recreational fishing, which could also contribute to slightly higher boat counts during specific tidal phases.

Temperature was positively associated with boating activity, with predicted boat counts nearly doubling when comparing temperatures of 11 °C to those with 25 °C. This aligns with expectations that warmer weather encourages outdoor recreation, making boating more comfortable and enjoyable, and thus increasing the number of outings.

Finally, our results do not support the idea that beluga presence influences boater behavior, under the hypothesis that recreational boaters could be drawn to the area to observe whales, leading to an increase in the number of boats present.

4.4.2. Beluga herds' behavioral response to recreational boats

No detectable change in the number of belugas observed at the surface

Previous studies have shown that vessel traffic can influence both the surfacing behavior of cetaceans, potentially affecting the number of individuals observed at the surface, and their group structure. In our study, we did not detect a significant difference in the number of belugas observed during herd passages with versus without recreational boats. However, this result must be interpreted with caution. The post-hoc power analysis showed that, with our sample size ($n = 30$), we had only about a 15% chance of detecting a true effect of the magnitude observed. In other words, our ability to detect subtle effects was very limited. Achieving sufficient statistical power would require a much larger dataset. In this case, more than 600 herd passages containing both conditions (with and without boats) would be needed to reach a 90% chance of detecting a true effect. Collecting such a sample size was not feasible within the temporal and logistical constraints of the fieldwork conducted in this project. As a result, our study cannot conclusively determine whether boat presence affects surfacing numbers, and the absence of a significant effect should not be interpreted as evidence of no effect.

Despite these limitations, the observed trends are consistent with previous reports suggesting that belugas in areas with frequent vessel traffic, such as the St. Lawrence Estuary, may sometimes tolerate or habituate to certain boat disturbances (Weilgart, 2007; Ausen et al., 2022). At the same time, other studies have documented avoidance behaviors in response to small, erratic vessels or noise-intensive activities (Fraker, 1977b; Blane and Jaakson, 1994; Krasnova et al., 2020), highlighting that beluga responses to vessels are highly context-dependent. The upstream location of Baie Sainte-Marguerite (Figure 4.1), known as a key habitat hotspot for beluga whales (Conversano et al., 2017; Ménard et al., 2018; Vergara et al., 2021), likely contributes to the frequent passage of beluga herds through the study area. Despite the relatively narrow confines of the Saguenay River, which places belugas in close proximity to anthropogenic disturbances, their continued use of this important habitat suggests a strong ecological motivation to remain in the area. This may help explain the apparent absence of systematic avoidance behavior, although our ability to detect subtle changes was limited. Although no avoidance behavior was detected in terms of the number of individuals at the surface, we found that boat presence did influence the spatial organization of beluga herds.

Changes in group dispersion linked to boat presence

We observed that group dispersion within beluga herds during their passage through the study area was more likely to change as the number of recreational boats increased. These changes reflect alterations in the spacing between groups of individuals within the herds. Importantly, the nature of this dispersion change was not unidirectional; belugas exhibited both increased and decreased spacing between groups in response to boat presence (Figure 4.4). This variability suggests that beluga herds dynamically adjust their spatial organization when navigating areas with high boat traffic, rather than following a single consistent pattern of response.

This disruption could be attributed both to the noise and physical presence of boats, which may cause belugas to alter their initial movement patterns. In our observations, 81% of the boats present were navigating using a motor, including both motorboats and sailboats under engine power, while only 19% were sailing under wind power alone. An increase in the number of small vessels using motors in areas frequented by belugas is likely to interfere with their communication, as their engines generate noise at frequencies well above 1 kHz (Lesage et al., 1999), which are detectable by belugas. This disruption is particularly significant for socially bonded animals, such as belugas, that rely on vocalizations to locate specific individuals or maintain proximity within their social groups (Janik and Slater, 1998). Therefore, changes in the distance between individuals within the herd, combined with engine noise, could impact the quality of their communication.

The impact of recreational boats on beluga whales extends beyond noise pollution. While engine noise can mask essential vocal communication (Vergara et al., 2021), even the mere presence of boats without running engines can be disruptive (Blevins, 2015; Krasnova et al., 2020). Changes in herd dispersion do not necessarily indicate that beluga whales are attempting to escape from boats; they may also represent an attraction behavior. Indeed, field observations, reports from recreational boaters, and several studies (Ausen et al., 2022; Blane, 1990; Blane and Jaakson, 1994; Westdal et al., 2023) suggest that beluga whales may investigate boats. Regardless of whether belugas are attempting to escape or investigate recreational boats, these interactions result in human-induced displacement, which could alter their initial movement patterns.

Ecological implications

The changes in herd dispersion observed in this study raise important questions about their broader biological significance. According to Johnson & St-Laurent (2011), wildlife responses to disturbance occur across multiple, nested biological scales, from immediate behavioral reactions to potential long-term physiological, individual, and population-level consequences. In this framework, the dispersion adjustments documented here can be interpreted as early-stage behavioral responses within a broader disturbance cascade.

Short-term behavioral interruptions can interfere with essential activities such as feeding, socializing, or calf care, potentially leading to severe consequences for beluga growth, reproduction, and survival (Tyack, 2009; Vergara, 2019). If such behavioral changes are brief and isolated, their biological costs are likely limited. However, if they occur repeatedly, particularly during sensitive periods such as foraging or calf rearing, these disruptions may accumulate, contributing to chronic stress, reduced foraging efficiency or weakened social cohesion (Pirotta et al., 2015; Guerra et al., 2014; Wright et al., 2009).

Importantly, although recreational boat presence was significantly correlated with changes in herd dispersion, the model explained only 19.2% of the variance, indicating that vessel traffic represents just one component of a more complex suite of drivers. Environmental, social, and intrinsic factors likely play substantial roles in shaping herd spacing. Beluga responses to disturbance can vary with vessel speed and direction, habitat characteristics, ongoing behavioral state, individual noise tolerance and hearing sensitivity, age, sex, presence of calves, and prior experience with disturbance (Richardson et al., 2013; Vergara, 2019). Moreover, some individuals or groups may exhibit habituation to boat presence (Krasnova et al., 2020; Westdal et al., 2023), further contributing to the variability observed in dispersion responses.

4.4.3. Management implications

Although this study provides valuable insights into the environmental and temporal drivers of recreational boating activity, it is likely that additional factors contribute to boat presence in the study area. Complex and difficult-to-measure aspects such as boaters' personal preferences, availability, and spontaneous decisions probably explain part of the observed variability. Nonetheless, the identified key conditions leading to increased recreational boat presence in this section of the fjord are useful for management purposes. Temporal factors, such as weekends, remain important predictors of boating activity (Conversano et al., 2017; Ménard et al., 2014; Turgeon, 2019), but environmental variables also play a critical role. Additionally, recreational boat counts in our study area during peak periods (up to 8–9 boats per hour) were considerably higher than the mean values reported by Turgeon (2019), which were based on 30-minute observation segments, suggesting that ASE may experience particularly high levels of recreational use. A deeper understanding of these drivers can inform targeted conservation strategies; for instance, increasing patrol efforts during conditions favorable to boating could improve compliance with regulations and reduce disturbances, while land-based awareness campaigns in marinas may be more effective during less favorable conditions, when boaters are more likely to remain ashore. Given the significant correlation between the number of recreational boats and changes in beluga herd dispersion, management measures aimed at limiting the number of recreational vessels in sensitive areas could help reduce disturbance. Specifically, implementing a maximum vessel limit or carrying capacity in key sections of the fjord may contribute to preserving natural beluga behaviors and minimizing human-induced displacement. Such measures, combined with targeted surveillance during peak boating conditions, could enhance beluga protection while allowing for sustainable recreational use.

4.4.4. Limitations

This study presents several limitations that should be considered when interpreting the results. First, analyses were restricted to an 8 km² observation area, representing less than 1% of the St. Lawrence Estuary beluga habitat, which limits the spatial generalizability of the observed patterns. Moreover, the narrow and deep bathymetry of the Saguenay Fjord differs markedly from other parts of the habitat such as the estuary, potentially affecting sound propagation, current regimes, and beluga behavior, and thus constraining the extrapolation of behavioral responses to the entire habitat. Second, although recreational boats were consistently detectable under the study conditions, beluga detectability was inevitably imperfect and influenced by sea state, light conditions, distance, and observer experience, which may have slightly underestimated the number of individuals in the herds. Third, herd configuration was assessed visually and categorized into broad classes, which may not capture finer-scale variations in spatial organization. Fourth, models of herd configuration changes included only a subset of potential explanatory variables. Additional environmental, social, and biological factors likely contribute to variations in herd dispersion and structure, as reflected in the relatively low variance explained by the models (13.1–21.9%). Taken together, these limitations highlight that the results should be interpreted with caution. Additional data collection across different areas of the habitat, combined with more comprehensive analyses, would be necessary to draw general conclusions for the entire population.

4.5. Conclusion

This study is the first to specifically examine the interactions between recreational boating and beluga whales within the Saguenay Fjord. The results suggest that while no clear change in the number of belugas at the surface was detected, likely due in part to the limited sample size and low statistical power, belugas do adjust their herd spatial organization in the presence of boats. Such subtle but frequent behavioral responses may represent the first steps in a disturbance cascade that could, under certain conditions or over longer time scales, influence higher-level processes such as communication, energetic balance, and ultimately fitness. Future work should assess whether dispersion changes persist beyond the immediate passage event, whether they differ among social groups, and whether they translate into measurable acoustic, energetic, or physiological costs.

Beyond documenting beluga responses, this study also identifies the key temporal and environmental drivers shaping recreational boating activity in the area. This dual insight, on both whale behavior and human use of the habitat, provides an essential foundation for management. Knowing when boating pressure peaks creates opportunities for targeted and seasonally adapted mitigation, while the link between boat numbers and herd dispersion supports the implementation of measures such as vessel limits or capacity thresholds in sensitive zones.

Future work should extend these observations across the broader estuary, integrate more detailed information on boat–whale proximity, and examine how group composition and behavioral states mediate responses. High-resolution tracking or acoustic monitoring will be particularly important to assess whether the dispersion changes documented here translate into energetic, communicative, or social costs.

Overall, this study advances our understanding of how recreational boating shapes beluga spatial behavior and provides essential evidence to guide adaptive, context-specific management aimed at reducing cumulative disturbance in this endangered population.

4.6. Acknowledgement

We sincerely thank Maude Simard and Anne-Marie Blanchette for their contributions as beluga observers during the summer seasons of 2021 and 2022, respectively. Our gratitude also extends to Franck Turcotte for allowing us to use the Petit-Saguenay's Village Vacances Belvedere as an observation site, as well as to Robert Michaud for his valuable support in the beluga observation protocol.

Funding

The funding to support this research project was provided by the Ministère des Forêts, de la Faune et des Parcs du Québec and Secrétariat à la stratégie maritime du Québec. We also acknowledge the contribution of the Social Sciences and Humanities Research Council through the Canada Research Chair in Ecological Economics.

Chapitre 5 : Discussion générale

5.1. Principales contributions

Cette thèse vise à approfondir la compréhension de la navigation de plaisance au sein de l'habitat estival de la population de BESL. Pour ce faire, elle répond à quatre questions de recherche fondamentales : comment les plaisanciers utilisent-ils l'ASE et ajustent-ils leur navigation en présence de bélugas ? Quels profils de comportements et de valeurs gouvernent leurs décisions ? Quels facteurs environnementaux et contextuels conditionnent la présence des embarcations de plaisance ? Et enfin, comment la présence de ces embarcations influence-t-elle l'organisation des troupeaux de bélugas ? Ce segment de navigation, bien que largement présent dans certaines zones clés de l'ESL et du FS, demeure encore aujourd'hui le moins étudié parmi l'ensemble des segments de la navigation (Chion et al., 2007; Turgeon, 2019). Cette lacune est d'autant plus préoccupante que la région concernée constitue un secteur essentiel pour de nombreuses espèces de cétacés (Cotté and Simard, 2005; Ramp et al., 2015; Truchon et al., 2013), dont la population de BESL, une population résidente classée en voie de disparition (COSEWIC, 2014; Lesage et al., 2024). Documenter la navigation de plaisance représente un défi méthodologique important. Contrairement à d'autres types d'embarcations commerciales, les bateaux de plaisance ne sont pas tenus d'être équipés d'un système AIS au Canada. De plus, leurs déplacements sont caractérisés par une grande variabilité, tant dans les itinéraires empruntés que dans les intentions des plaisanciers, souvent spontanées ou récréatives. À l'inverse, les navires marchands suivent des corridors maritimes définis, les traversiers effectuent des trajets répétitifs et prévisibles, et les excursions aux baleines sont guidées par des objectifs commerciaux précis, consistant notamment à maximiser les opportunités d'observation de cétacés pour leur clientèle (Chion, 2011). Dans ce contexte, cette thèse apporte une contribution originale à l'étude de la navigation de plaisance dans l'habitat estival de la population du BESL, en constituant la première étude à documenter spécifiquement les interactions entre les plaisanciers et les bélugas de cette population résidente. Son caractère novateur réside dans l'approche interdisciplinaire adoptée, qui articule des analyses quantitatives écologiques fondées sur des observations de terrain et des analyses sociales basées sur l'étude des profils, valeurs et décisions des plaisanciers. Ce double regard permet de relier les usages humains et leurs comportements aux réponses observées chez les bélugas. En décrivant de manière détaillée *où, quand* et *comment* les plaisanciers naviguent dans l'ASE, en identifiant les profils de pratiques et de décisions qui structurent leurs comportements, et en documentant les ajustements spatiaux des troupeaux de bélugas en présence de bateaux, ce travail fournit une base empirique solide pour la gestion et la conservation. Ces résultats permettent d'orienter plus efficacement les mesures visant à limiter les impacts de la navigation de plaisance sur la faune marine.

Le premier chapitre introduit les fondements des MMA, présentés comme des outils particulièrement adaptés à la représentation de systèmes complexes et dynamiques tels que les SSÉ. Il s'appuie sur l'exemple du simulateur 3MTSim, un MMA déjà utilisé pour cette région, qui modélise certains segments de navigation ainsi que la présence de différentes espèces de baleines. Toutefois, 3MTSim ne prend pas encore en compte la navigation de plaisance, bien qu'elle constitue une composante majeure des usages maritimes dans ce territoire. Cette lacune justifie la pertinence d'une recherche centrée spécifiquement sur la navigation de plaisance dans l'ESL et le FS. En fournissant des bases empiriques et conceptuelles sur les plaisanciers, leurs comportements et leurs interactions avec les bélugas, cette thèse répond à un besoin de connaissances, tout en pouvant alimenter de futurs travaux de modélisation. Ce chapitre présente également les principales théories mobilisées pour appréhender les processus de prise de décision humaine dans les systèmes complexes, ainsi que les approches permettant leur intégration au sein de modèles multi-agents. En combinant ces dimensions, écologiques, sociales, théoriques et méthodologiques, il pose les fondements nécessaires à la compréhension des enjeux traités dans la thèse. Il en précise les orientations scientifiques, identifie les lacunes dans les connaissances actuelles, et définit les objectifs spécifiques poursuivis dans les chapitres suivants, en vue de contribuer à une modélisation plus intégrée et réaliste des interactions entre navigation de plaisance et faune marine dans l'ESL et le FS.

Le deuxième chapitre apporte une contribution empirique essentielle à la compréhension des interactions entre la navigation de plaisance et les bélugas dans une zone du FS: l'ASE. En s'appuyant sur une méthode d'observation fine à l'aide d'un théodolite (Piwetz et al., 2018), ce chapitre documente pour la première fois, avec une forte précision spatiale, la co-occurrence entre bélugas et embarcations de plaisance dans cette portion étroite du fjord, ainsi que le respect (ou non) des règlements du PMSSL. L'analyse révèle un usage intensif de la zone par les embarcations de plaisance, notamment durant les week-ends et les périodes de vacances estivales, avec des vitesses parfois élevées et des durées de présence prolongées. En parallèle, de nombreux passages de troupeaux de bélugas en transit ont été observés, souvent à proximité directe de ces embarcations. Ces observations ont permis de quantifier précisément la fréquence et les caractéristiques des cooccurrences à moins de 400 mètres entre bélugas et bateaux, mettant en lumière plusieurs types de perturbations potentielles. Les résultats mettent en évidence des infractions aux régulations du PMSSL: distances minimales non respectées, vitesses excessives, comportements potentiellement intrusifs de la part des plaisanciers. L'étude discute en détail les conséquences de ces perturbations, tant acoustiques que physiques, sur les comportements essentiels des bélugas (repos, communication, alimentation, etc.) (Erbe et al., 2016; Gervaise et al., 2012; Pirotta et al., 2015), en soulignant leur vulnérabilité accrue, en particulier pour les femelles accompagnées de jeunes (Vergara et al., 2021). Au-delà du constat, ce chapitre propose une approche novatrice pour améliorer la surveillance et l'application des règlements en milieu marin. L'utilisation du théodolite comme outil d'observation a permis de mesurer rétrospectivement les positions et vitesses des embarcations, et la mise en place potentielle d'un système connecté en temps réel est discutée. Une telle approche fournirait aux patrouilles du Parc Marin des données objectives et localisées, utiles tant pour cibler les interventions que pour documenter d'éventuels litiges, tout en appuyant des recommandations concrètes en faveur de la protection d'une espèce menacée dans un contexte de forte fréquentation touristique.

Le troisième chapitre vise à identifier les profils types de plaisanciers naviguant dans l'habitat estival de la population de BESL, en s'appuyant sur une approche semi-qualitative, la méthode-Q (Stephenson, 1953). À partir de 60 entretiens réalisés auprès de plaisanciers utilisant divers types d'embarcations, l'analyse explore leurs connaissances du milieu, leurs pratiques de navigation, leurs valeurs et motivations, ainsi que leur rapport aux baleines du SSL. Pour structurer l'interprétation des données, l'approche mobilise la théorie des valeurs de Schwartz (Schwartz, 2006) ainsi que des éléments de la théorie VBN (Stern, 2000). L'analyse a permis d'identifier trois archétypes principaux : les plaisanciers biosphériques, motivés par la préservation de la nature et sensibles à la cohabitation avec les espèces sauvages ; les plaisanciers égocentriques, davantage centrés sur leur plaisir personnel et leur liberté de mouvement, avec une sensibilité environnementale plus variable et les plaisanciers altruistes, attachés à la liberté de navigation et au bien-être d'autrui, qui font preuve d'une compréhension partielle des enjeux écologiques et interprètent parfois les règlements selon leur propre sens moral. Ces archétypes ne sont ni rigides ni exhaustifs, mais offrent un cadre analytique pertinent pour représenter la diversité des profils de plaisanciers et leurs logiques d'action dans le futur MMA. Ce cadre typologique permet d'agréger les comportements selon des tendances observées, plutôt que de modéliser chaque individu de manière isolée. Il constitue également un levier pour affiner les stratégies de gestion du territoire et les campagnes de sensibilisation, en tenant compte de la diversité des motivations et des représentations des usagers du milieu marin. Ces résultats ouvrent ainsi la voie à des actions plus ciblées, tant sur le plan éducatif que réglementaire, pour encourager des comportements plus compatibles avec les objectifs de conservation du béluga.

Le quatrième chapitre repose sur les observations terrestres menées à l'ASE. Il vise à mieux comprendre les interactions entre les plaisanciers et les bélugas. Alors que les effets des navires commerciaux et des bateaux d'excursion ont été relativement bien documentés (Burns and Seaman, 1986; Fraker, 1977; Krasnova et al., 2020; Macfarlane, 1981; Martin et al., 2023; Pippard, 1985), l'impact des embarcations de plaisance demeurent peu étudiées, malgré leur présence dans les habitats critiques. Dans une première série d'analyses, les observations ont été divisées en segments horaires afin d'examiner les facteurs influençant le nombre de bateaux de plaisance dans la zone d'étude. Les analyses ont également mis en évidence des effets significatifs de certaines variables environnementales et temporelles sur la présence des plaisanciers à l'ASE (conditions météorologiques, jour de la semaine, etc.). Ce chapitre fournit des données empiriques essentielles pour orienter la gestion de la navigation de plaisance dans les habitats critiques du Saint-Laurent, en envisageant, par exemple, des mesures basées sur le regroupement ou la limitation du nombre de plaisanciers dans les zones sensibles. En plus de fournir les éléments nécessaires à l'évaluation de différents scénarios de gestion, les résultats permettent également d'identifier les périodes et conditions environnementales associées à une forte ou faible fréquentation de l'ASE par les plaisanciers, ce qui peut guider la planification de patrouilles de sensibilisation ciblées, sur l'eau lorsque les conditions sont favorables à la navigation, et à terre lorsque l'achalandage est moindre. Dans une deuxième série d'analyses, le chapitre se penche sur les réactions comportementales des troupeaux de bélugas en présence de bateaux de plaisance, à partir d'un sous-ensemble de données ne contenant aucune autre perturbation anthropique (navires commerciaux ou bateaux d'excursion). Le nombre d'individus ainsi que trois aspects géométriques des troupeaux ont été analysés : la forme, la structure et la dispersion. Si la taille des troupeaux ne semble pas être affectée par la présence de plaisanciers, les analyses montrent que le nombre de bateaux est positivement associé à la probabilité d'un changement dans la dispersion des groupes composant les troupeaux. Cela suggère que les bélugas modifient leurs distances interindividuelles en réponse à la présence de plusieurs embarcations. Toutefois, ces changements ne sont pas systématiquement orientés dans une seule direction (éloignement ou rapprochement), ce qui indique une flexibilité dans l'organisation spatiale des troupeaux lorsqu'ils traversent des zones de trafic nautique. Cette flexibilité n'est toutefois pas sans implications : les ajustements de dispersion constituent des réponses comportementales précoces qui peuvent, s'ils sont répétés ou surviennent durant des périodes sensibles, perturber des activités essentielles telles que la communication, la socialisation, l'alimentation ou le soin aux jeunes (Pirotta et al., 2015; Guerra et al., 2014; Wright et al., 2009). Ils s'inscrivent ainsi dans les premières étapes d'un possible continuum de perturbation dont les effets cumulés pourraient, à terme, influencer la cohésion sociale, l'efficacité de recherche alimentaire ou même la condition physique des individus (Johnson et St-Laurent, 2011). Ces résultats soulignent que, même si les plaisanciers ne provoquent pas nécessairement des fuites massives, ils peuvent perturber subtilement l'organisation des troupeaux, notamment en modifiant la proximité nécessaire au maintien des échanges sociaux et vocaux.

Au-delà de ces contributions propres à chacun des chapitres, cette thèse offre également des avancées transversales majeures pour l'étude et la gestion du SSÉ du SSL. Elle fournit d'abord des données inédites sur les activités de plaisance dans un habitat essentiel d'une population de béluga en voie de disparition, comblant une lacune importante dans la connaissance des pressions humaines qui s'y exercent. Ces résultats empiriques, produits pour la première fois dans cette région, constituent un socle essentiel pour appuyer les efforts de conservation et alimenter un simulateur déjà en développement, ouvrant la voie à une gestion plus informée et durable des usages maritimes. Sur le plan méthodologique, ce travail démontre également la pertinence d'une approche interdisciplinaire, combinant observations écologiques et méthodes issues des sciences sociales pour représenter de manière cohérente les interactions entre humains et faune. L'articulation entre données comportementales, méthodes qualitatives et cadres théoriques issus de la psychologie environnementale offre un modèle exportable à d'autres systèmes socio-écologiques. La démarche proposée, mêlant typologie des usagers fondée sur leurs connaissances, habitudes et valeurs, et analyse fine des interactions observées sur le terrain, peut en effet être transposée à d'autres contextes marins ou terrestres, en adaptant les énoncés et les référents locaux. Ce travail montre ainsi qu'une meilleure compréhension des dynamiques humain–faune passe par l'intégration des dimensions sociales et écologiques au sein d'un cadre commun, et ouvre la voie à des applications plus larges en conservation et en modélisation des socio-écosystèmes.

5.2. Vers l'intégration de la navigation de plaisance dans le simulateur global 3MTSim

Les résultats présentés dans cette thèse apportent des connaissances inédites sur les dynamiques de la navigation de plaisance dans l'habitat estival des bélugas de l'estuaire du

Saint-Laurent, les profils et comportements des plaisanciers, ainsi que les effets potentiels de leur présence sur les troupeaux de cétacés. Ces contributions, bien qu'ayant une portée propre et autonome, peuvent également être mobilisées pour enrichir des outils existants de simulation tels que 3MTSim, un modèle multi-agents développé pour représenter les interactions spatio-temporelles entre cétacés et les principaux segments du trafic maritime dans l'ESL et le FS (Parrott et al., 2011 ; Chion et al., 2011). Actuellement, 3MTSim intègre quatre grands segments de navigation : le trafic commercial, les croisières, les traversiers, et les bateaux d'excursion pour l'observation des baleines. Toutefois, la navigation de plaisance, bien que largement présente dans certaines zones clés de l'habitat estival de la population de BESL, n'est pas encore représentée dans le modèle. Les connaissances issues de cette thèse ouvrent ainsi la possibilité d'intégrer ce segment dans le simulateur, à travers deux composantes complémentaires :

- Un modèle de génération de trajectoires (TLM, pour *Trajectory Level Model*), développé dans une étude antérieure, qui simule des trajectoires réalistes de plaisanciers à partir de données AIS, sans tenir compte de la présence des cétacés (Barde, 2025).
- Un modèle d'interactions (ILM, pour *Interaction Level Model*) qui vise à représenter les décisions des plaisanciers lorsqu'ils rencontrent une ou plusieurs baleines.

Le fonctionnement combiné de ces deux modèles dans 3MTSim peut être décrit ainsi : les trajectoires de plaisanciers sont d'abord générées par TLM, sur la base de plans de navigation et de conditions environnementales. Dès qu'une cooccurrence spatio-temporelle entre un plaisancier et une baleine est détectée dans la simulation, ILM est activé pour simuler le comportement du plaisancier durant l'interaction. Une fois la situation d'interaction terminée (en raison d'un éloignement suffisant entre les agents ou d'un seuil temporel atteint), TLM reprend le contrôle et génère une trajectoire optimisée vers la destination initialement prévue.

La contribution spécifique de cette thèse porte principalement sur la conceptualisation du module ILM, notamment grâce à l'identification d'archétypes de plaisanciers dont les comportements varient selon leurs valeurs, motivations et connaissances. Cette typologie fournit une première base pour représenter des logiques décisionnelles différenciées dans un futur modèle comportemental.

Bien que les autres chapitres de la thèse ne soient pas directement orientés vers la modélisation, ils renforcent néanmoins la validité empirique du futur module. Par exemple : Le chapitre 2 met en évidence des situations de non-respect de la réglementation, ce qui souligne l'importance de représenter aussi des comportements déviants. Les chapitres 2 et 4 décrivent de manière fine les interactions plaisanciers-bélugas ainsi que les contextes temporels et environnementaux associés, apportant des données précieuses pour la calibration ou la validation du modèle. Le chapitre 4 met en lumière une association entre le nombre d'embarcations et la probabilité de dispersion des bélugas, ce qui ouvre la voie à une réflexion sur l'évolution des sous-modèles cétacés dans 3MTSim, notamment pour mieux simuler leurs réponses comportementales. En somme, si l'objectif central de la thèse demeure de comprendre et documenter les dynamiques de la navigation de plaisance dans l'habitat du béluga, ses résultats s'avèrent également transférables et mobilisables dans le cadre d'approches de modélisation intégrée, dont 3MTSim constitue un exemple prometteur.

5.3. Conceptualisation du modèle d'interaction plaisanciers–baleines

5.3.1 Contexte de simulation et entités mobilisées

Le modèle conceptuel de la navigation de plaisance s'intègre dans l'environnement de simulation global du modèle 3MTSim, qui couvre l'ensemble de la surface du PMSSL ainsi que l'habitat essentiel de la population de BESL. Dans le cadre de la présente conceptualisation, seules deux entités spatialisées sont prises en compte : les agents plaisanciers naviguant à bord de leur embarcation, et les cétacés présents dans la zone. Les déplacements des cinq espèces de baleines du Saint-Laurent sont déjà pris en compte dans 3MTSim grâce à un modèle comportemental individuel validé (Lamontagne, 2009) simulant leurs déplacements en trois dimensions. L'ensemble du modèle opère à une résolution temporelle d'une minute et repose sur une grille spatiale de 100 m × 100 m, toutefois, les positions des entités, qu'il s'agisse des embarcations ou des cétacés, sont continues, ce qui leur permet d'occuper n'importe quel point à l'intérieur d'une cellule.

5.3.2 Variables d'état des agents plaisanciers

Les agents plaisanciers sont générés automatiquement en début de simulation par TLM et demeurent actifs tout au long de la simulation. Chaque agent plaisancier est défini par un ensemble de variables d'état qui déterminent ses caractéristiques, son comportement et sa trajectoire au cours de la simulation. Ces variables incluent :

- L'itinéraire planifié, comprenant les lieux et horaires de départ et d'arrivée du plaisancier.

- Le type d'embarcation, parmi cinq catégories représentées dans le modèle : voilier, bateau à moteur rapide (speedboat), bateau de croisière (cruiser), chaloupe et zodiac.
- L'archétype du plaisancier, biosphérique, égocentrique ou altruiste, défini dans le chapitre 3.
- L'état comportemental, qui reflète l'activité en cours du plaisancier, notamment s'il est en navigation ou en observation de cétacés.
- La mémoire, qui stocke les rencontres et expériences passées du plaisancier avec des baleines au cours de son trajet.
- Un compteur temporel, mis à jour à chaque minute, permettant de suivre le temps restant dans l'excursion. Ce temps restant peut influencer certaines décisions comportementales du plaisancier.

Ces variables permettent de représenter la diversité des comportements humains dans le cadre de la navigation de plaisance et d'analyser leur influence potentielle sur la cohabitation avec les cétacés dans le SSL.

5.3.3 Aperçu des processus

La figure 5.1 illustre le schéma conceptuel du processus décisionnel des plaisanciers (ILM) lors des rencontres avec les baleines du Saint-Laurent, tel qu'il s'intègre à l'architecture globale du modèle avec le module de génération de trajectoires (TLM).

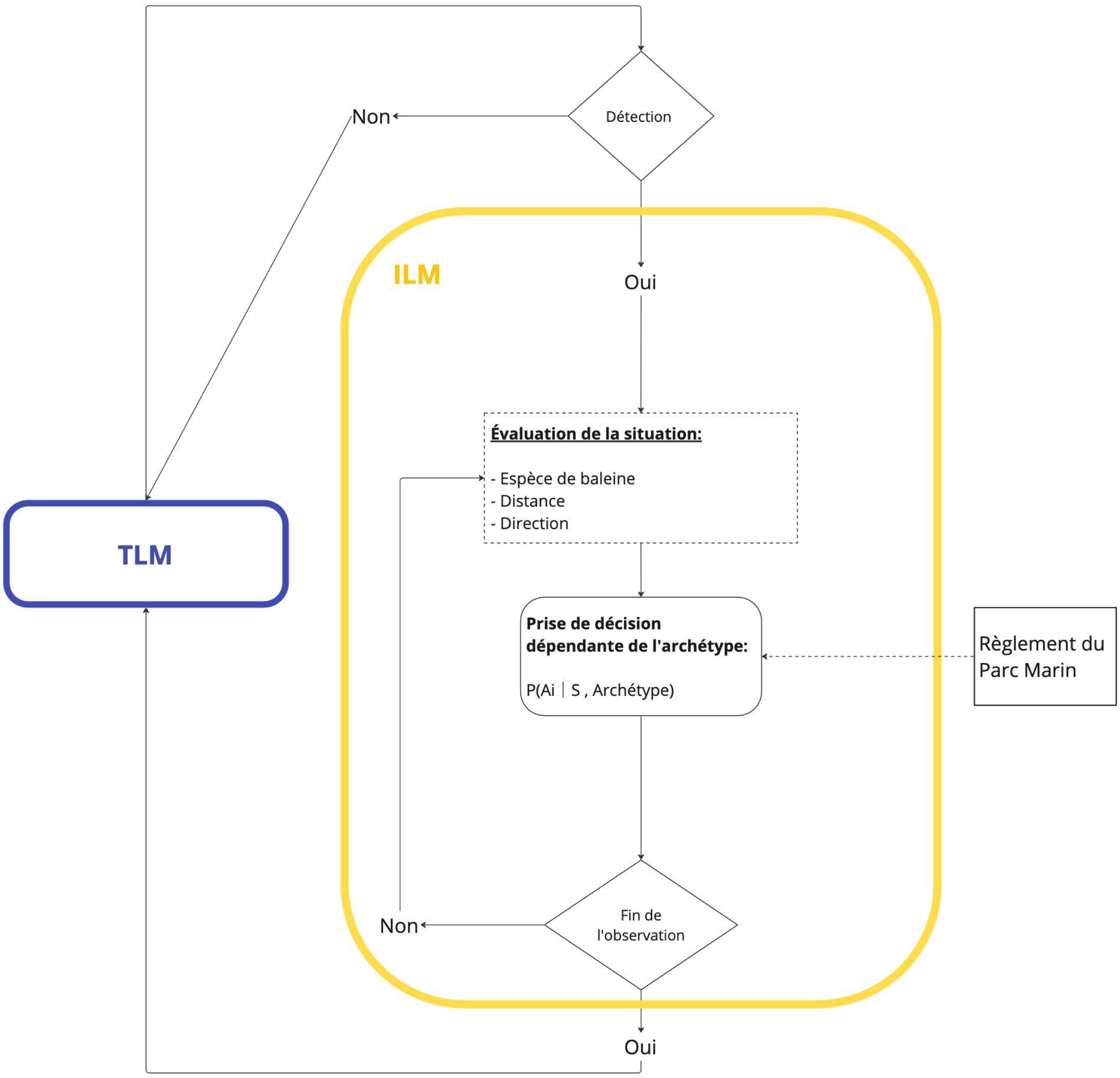


Figure 5.1 Schéma conceptuel du processus décisionnel des plaisanciers face aux baleines du SSL (ILM), intégré dans l'architecture globale avec le module de génération de trajectoires (TLM).

Le fonctionnement du modèle s'inscrit dans une simulation dynamique, où, à chaque pas de temps, une vérification est effectuée pour déterminer si une baleine est détectable dans l'environnement du plaisancier. La probabilité de détection dépend de la distance entre le bateau et l'animal, mais également de l'espèce rencontrée et de la position relative de la baleine par rapport au bateau. Les distances de détection varient selon l'espèce, certaines étant plus visibles ou reconnaissables que d'autres. À ce stade, ces distances sont estimées à partir d'un tableau de référence basé sur les déclarations de capitaines d'excursion (professionnels), en fonction des conditions de visibilité (Tableau 6.6, Annexes). Bien que ces valeurs ne reflètent pas directement les capacités de détection des plaisanciers, qui possèdent généralement moins d'expérience dans l'identification des cétacés, elles fournissent une première approximation utile en attendant une collecte de données plus spécifique.

Si aucune baleine n'est détectée, le bateau poursuit sa trajectoire générée par TLM et demeure "en état de navigation" (Figure 5.2). En revanche, lorsqu'un cétacé est détecté, le modèle ILM est activé et le plaisancier bascule "en état d'observation" (Figure 5.2).

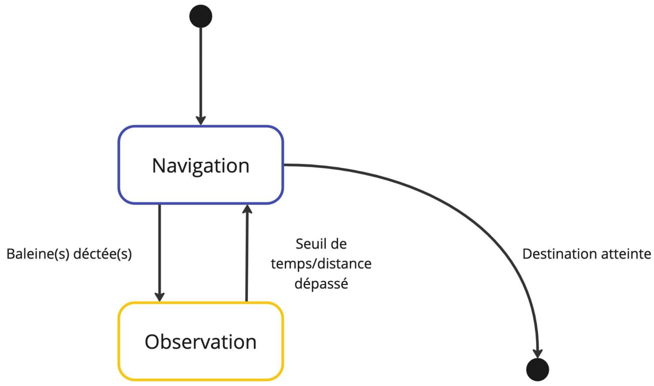


Figure 5.2 Diagramme d'état UML des plaisanciers.

L'agent évalue alors la situation S_j en tenant compte de trois paramètres fondamentaux : l'espèce de la baleine observée, la distance entre le bateau et l'animal, ainsi que la position relative de la baleine par rapport à l'embarcation. L'espèce constitue un facteur particulièrement déterminant, certaines étant perçues comme plus impressionnantes, rares ou attractives par les plaisanciers (Tableau 6.7, Annexes), ce qui influence directement leur volonté d'interagir. Lorsque le plaisancier passe en état d'observation, une interaction simulée débute. La mémoire de l'agent est alors mise à jour pour conserver une trace structurée de cette rencontre. Elle inclut notamment le nombre total d'interactions avec des baleines, la liste des espèces observées, le temps total passé en observation, ainsi que le temps passé en observation pour chaque espèce. Ces informations pourront ensuite être mobilisées pour moduler les décisions futures de l'agent. Par exemple, un agent pourrait être moins enclin à s'arrêter de nouveau s'il a récemment observé la même espèce (effet de familiarité), ou au contraire être plus susceptible d'initier une nouvelle observation si la durée ou la proximité de l'interaction précédente était limitée.

La décision du plaisancier à ce stade est modélisée comme une probabilité conditionnelle de l'action A_i dans la situation S_j et de l'archétype auquel il appartient : P(A_i | S_j, Archétype). Les actions possibles incluent une modification de la vitesse, du cap et/ou le changement d'état du moteur (éteint ou en marche) (Figure 5.3). Cette formulation permet de représenter une variabilité interindividuelle fondée sur les profils de plaisanciers identifiés, lesquels se distinguent par leurs motivations, leurs valeurs, et leur degré de connaissance ou de sensibilité à la réglementation. Le règlement en vigueur dans le Parc marin est modélisé dans un module distinct, qui décrit l'ensemble des actions attendues des plaisanciers selon les règles actuelles (vitesse, distances d'approche, etc.). Ce module n'impose pas de manière automatique le comportement des agents, mais interagit avec le processus décisionnel en modulant la probabilité de conformité en fonction de l'archétype. Certains profils, par exemple, ignorent le règlement ou choisissent de ne pas le respecter, tandis que d'autres y adhèrent davantage en raison de leur sensibilité ou de leur niveau de connaissance. Ce couplage entre le module réglementaire et la prise de décision, représenté par une connexion dirigée dans le schéma conceptuel, permet de simuler une diversité de comportements face aux mêmes contraintes réglementaires, tout en préservant une architecture souple et évolutive.

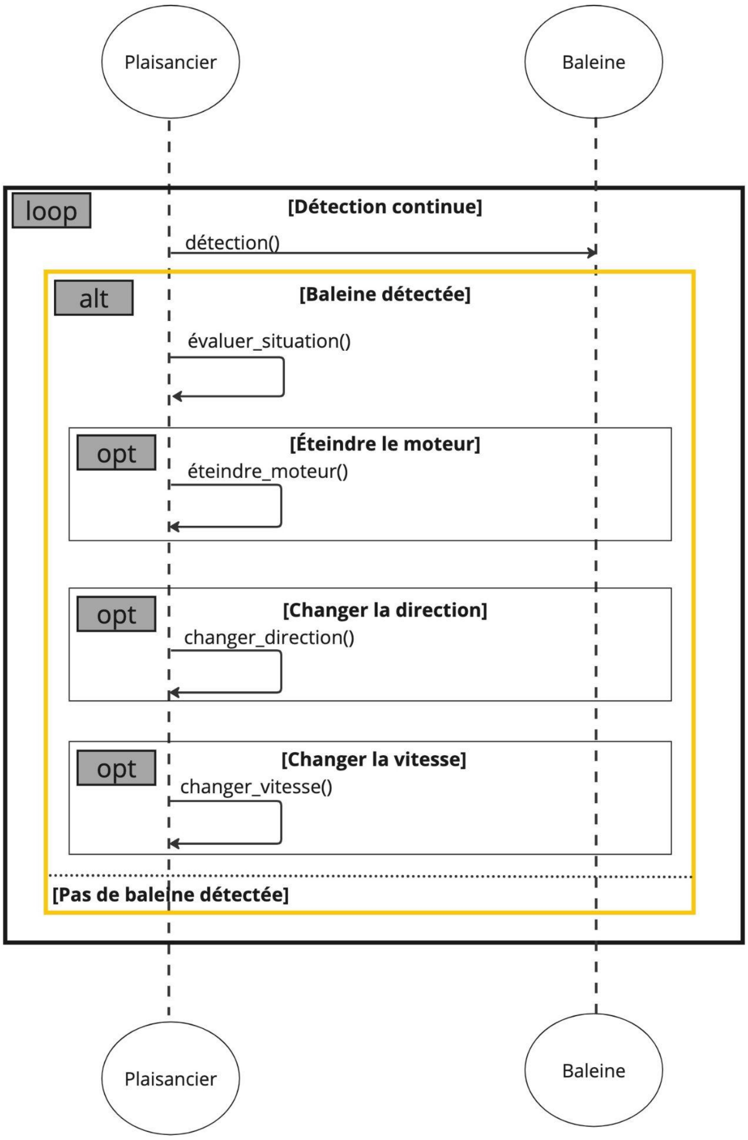


Figure 5.3 Diagramme de séquence UML pendant les interactions entre les plaisanciers, les baleines et les bateaux.

Une fois en état d'observation, l'agent poursuit l'interaction tant que les conditions sont réunies : la baleine est toujours détectable (i.e. sous le seuil de détection défini selon l'espèce et la configuration spatiale) et le temps d'observation maximal autorisé n'est pas dépassé. Ce temps est lui-même fonction de l'archétype du plaisancier et de son horaire de navigation. À chaque pas de temps, la situation est réévaluée ; si les conditions de l'observation ne sont plus remplies, l'agent revient en état de navigation. Une nouvelle trajectoire optimisée vers la destination finale est alors calculée par TLM, prenant en compte les éventuels ajustements induits par l'interaction précédente.

Ce fonctionnement par boucle décisionnelle, bien que simplifiée à ce stade, ouvre la voie à des développements futurs permettant de représenter des ajustements continus des décisions des plaisanciers au cours de l'interaction, par exemple en cas de changement de configuration (apparition d'un deuxième cétacé, variation de distance, modification du cap de la baleine, etc.). Une telle logique permettrait d'affiner encore davantage le réalisme comportemental du modèle.

5.3.4 Données de sortie issues de la simulation

Le modèle conceptuel a pour objectif de produire, une fois implémenté dans le simulateur géoréférencé 3MTSim, un ensemble de données de sortie utiles à l'analyse des interactions entre plaisanciers et cétacés, ainsi qu'à l'évaluation de divers scénarios de gestion.

La mémoire individuelle des agents jouera un rôle clé dans la production d'indicateurs comportementaux dynamiques, tels que le nombre total d'observations réalisées, les espèces privilégiées, la durée moyenne des interactions, ou encore la distance moyenne d'approche. Ces données permettront d'analyser l'évolution dynamique des comportements selon le profil d'archétype et les expériences passées.

L'intégration du modèle dans 3MTSim permettra également d'extraire des données spatio-temporelles détaillées, notamment : l'identification des zones à forte fréquence d'interactions (hotspots), les temps passés dans des zones de proximité critique avec les cétacés, les ajustements de trajectoire, ainsi que l'exposition sonore générée par les embarcations. L'exposition des cétacés au bruit généré par les embarcations pourra être estimée à plusieurs échelles : selon le niveau sonore émis par chaque bateau individuellement, selon l'intensité sonore ambiante lorsque plusieurs embarcations se trouvent simultanément à proximité de cétacés, et de manière cumulative, en évaluant le bruit total perçu par un cétacé au cours d'une journée ou d'une saison. Puisque 3MTSim intègre déjà des modèles de déplacement pour d'autres segments de la navigation (navires marchands, traversiers, bateaux de croisière et excursions aux baleines), l'ajout du modèle de plaisanciers viendra compléter ce panorama, en permettant une estimation plus fine du niveau de bruit cumulé reçu par les cétacés à l'échelle du système dans son ensemble.

5.4. Simuler pour mieux gérer : potentialités du modèle

5.4.1 Un outil de soutien à la gestion

La gestion durable des systèmes socio-écologiques tels que celui du SSL représente un défi complexe. À la croisée des usages humains et de l'habitat des cétacés, ce territoire est un espace d'interactions constantes entre navigation et faune marine. Ces interactions soulèvent des enjeux de conservation, de cohabitation et de gouvernance. Dans ce contexte, la prise de décision s'appuie souvent sur des données incomplètes, des effets à long terme difficiles à anticiper, et des compromis entre les besoins des usagers et la protection de la faune. Le simulateur 3MTSim, en tant que MMA géoréférencé intégrant à la fois les mouvements de plusieurs espèces de cétacés et les comportements des différents segments de navigation, constitue un outil puissant pour éclairer ces décisions (Chion et al., 2017; Parrott et al., 2011). Il permet non seulement de générer des données inaccessibles par les moyens classiques d'observation – telles que l'exposition cumulée d'un individu au bruit ou la fréquence d'interactions à l'échelle d'une saison –, mais aussi de servir de laboratoire virtuel. En effet, dans cet environnement contrôlé, il devient possible de simuler différents scénarios réglementaires, d'en observer les effets à court et long terme, et de comparer leur efficacité avant leur mise en œuvre réelle sur le terrain. Ce type de démarche représente un gain précieux pour les gestionnaires.

5.4.2 Évaluation de scénarios de gestion et leviers d'intervention

Grâce à l'architecture modulaire du modèle, les règles de navigation sont représentées comme un composant autonome, distinct du reste du processus décisionnel des plaisanciers. Cette séparation offre une grande flexibilité dans la mise en œuvre et l'évaluation de scénarios de gestion. Il est ainsi possible de modifier indépendamment les règles applicables (p. ex. distances minimales d'approche, limitations de vitesse, zones d'exclusion temporaire ou permanente) sans devoir altérer les autres mécanismes internes au modèle. Par exemple, un scénario peut consister à imposer une vitesse maximale réduite dans certaines zones sensibles, à étendre les distances d'approche obligatoires, ou à instaurer des limites sur le nombre d'embarcations simultanément présentes autour d'un groupe de cétacés. Ce dernier levier est particulièrement pertinent au regard des résultats empiriques présentés dans le chapitre 4, qui indiquent une association entre le nombre de plaisanciers présents et une probabilité accrue de changement de dispersion au sein des troupeaux de bélugas. En réduisant la densité d'embarcations autour des groupes de cétacés, il serait donc envisageable de limiter les perturbations comportementales. De par son architecture, le modèle permet également de simuler des plaisanciers dits « idéaux », c'est-à-dire des agents qui respectent systématiquement les règles en vigueur. En neutralisant l'effet des variables comportementales associées aux différents archétypes, ce type de simulation permet d'isoler l'efficacité intrinsèque d'une mesure réglementaire, indépendamment de son niveau d'adoption ou d'adhésion par les usagers.

Inversement, le modèle permet aussi de manipuler les proportions d'archétypes de plaisanciers dans la population simulée. Chaque archétype adopte des comportements différents en situation d'interaction avec des cétacés. En augmentant, par exemple, la proportion d'un archétype plus respectueux de la faune, on peut simuler les effets attendus d'une campagne de sensibilisation efficace, et ainsi estimer son impact potentiel sur les dynamiques d'interaction et la réduction des perturbations.

En combinant ces leviers (modification des règles, changement de proportions d'archétypes, etc.), le modèle devient un outil d'exploration fine, permettant d'évaluer à la fois l'impact écologique des mesures (exposition au bruit, temps passé en zone critique, etc.) et leurs effets sur les dynamiques d'usage (redistribution spatiale des plaisanciers, modification de trajectoires, concentration dans certaines zones, etc.).

5.5. Limites et travaux futurs

5.5.1 Limites

Comme toute recherche menée dans un contexte socio-écologique complexe, ce travail présente certaines limites qu'il convient de souligner.

Tout d'abord, en ce qui concerne la caractérisation des archétypes de plaisanciers (chapitre 3), celle-ci repose sur une méthode qualitative ayant permis d'identifier des profils types selon leurs valeurs, leurs connaissances et leur rapport à la réglementation. Bien que cette approche offre une compréhension riche et nuancée des différentes perspectives existantes, elle ne permet pas de quantifier la proportion de chaque archétype au sein de la population de plaisanciers. L'absence de données quantitatives limite donc, à ce stade, l'ancrage empirique de la distribution des archétypes dans le modèle conceptuel. De plus, les entretiens menés dans le cadre de cette étude portaient sur des aspects larges des pratiques de navigation de plaisance ainsi que sur les valeurs et perceptions générales des plaisanciers. Cette approche, bien que précieuse pour identifier des profils d'acteurs selon leurs intentions et rapports au monde, ne permet pas de distinguer finement les comportements concrets adoptés en situation d'interaction avec les cétacés. Il en résulte que les règles comportementales intégrées au modèle conceptuel reposent sur une interprétation générale des archétypes, plutôt que sur une observation directe de leurs actions spécifiques sur l'eau. Ces comportements gagneraient à être affinés par des méthodes complémentaires (voir section 5.5.2).

Les chapitres 2 et 4, qui reposent sur des données d'observation collectées sur le terrain, comportent également certaines limites. Une première collecte de données exploratoire avait été envisagée avec deux stations totales afin de pouvoir suivre les déplacements des bélugas de manière plus fine. Cependant, cette approche s'est révélée difficilement applicable en raison du comportement dynamique et collectif de cette espèce. Les bélugas se déplacent souvent en grands troupeaux, avec des structures de fusion/fission fréquentes, ce qui rendait impossible le suivi individuel ou même groupé sur la durée. En conséquence, les données disponibles ne permettent pas d'estimer précisément la position des bélugas, ni leur trajectoire ou leur vitesse, ce qui limite les analyses comportementales croisées, notamment sur les distances exactes entre plaisanciers et bélugas. Seules les cooccurrences rapprochées (<400 m) observées ponctuellement ont pu être considérées (chapitre 2). De plus, les observations ont été réalisées dans une zone relativement restreinte d'environ 8 km². Cette zone ne représente qu'une fraction de l'aire estivale de cette population de béluga et elle se situe dans le fjord du Saguenay, un secteur dont les caractéristiques bathymétriques et environnementales diffèrent sensiblement de celles de l'estuaire. Ces spécificités limitent la possibilité d'extrapoler nos résultats à l'ensemble de l'habitat de la population. Néanmoins, il est raisonnable de considérer que certaines tendances décrites, notamment celles liées aux interactions dans le fjord, pourraient être représentatives d'autres portions du Saguenay où des conditions similaires prévalent.

Par ailleurs, d'autres sources d'incertitudes subsistent dans la modélisation elle-même: les comportements sont schématisés, les réactions des cétacés aux perturbations humaines sont encore imparfaitement connues, et l'environnement modélisé reste une simplification du réel. Ces limites sont cependant inhérentes à tout modèle de simulation et peuvent être progressivement réduites par des itérations entre modélisation, collecte de données et validation.

5.5.2 Travaux futurs

Plusieurs pistes de recherche et de développement peuvent être envisagées pour prolonger ce travail. La priorité est de poursuivre le développement du modèle conceptuel en vue de son implémentation dans le simulateur 3MTSim. Cette étape implique une formalisation informatique des règles de comportement, un calibrage des paramètres, ainsi qu'une validation du modèle à l'aide des données disponibles.

Une fois implémenté, le modèle offrira la possibilité de simuler divers scénarios de gestion, en testant l'effet de nouveaux règlements (vitesse, distances d'approche, création de zones interdites à la navigation, limitation du nombre d'embarcations dans un périmètre donné autour des cétacés, etc.). Ces scénarios permettront d'anticiper les effets potentiels de différentes mesures de gestion à la fois sur les comportements des plaisanciers et sur le niveau de pression exercée sur les bélugas. Ils offriront également un cadre pour évaluer l'efficacité de ces mesures dans la réduction des perturbations et dans l'encadrement des pratiques de navigation.

Pour améliorer la robustesse du modèle, des efforts devront être entrepris pour affiner les connaissances sur la plaisance dans le PMSSL. Cela pourrait passer par :

- L'estimation des proportions d'archétypes de plaisanciers, à l'aide d'un questionnaire ciblé, basé sur les caractéristiques clés identifiées dans le chapitre 3. Distribué à un large échantillon de plaisanciers, ce questionnaire, conçu pour être rapide et accessible, permettrait de classer les répondants dans un archétype donné et de disposer ainsi d'une base quantitative solide pour calibrer la population simulée.
- L'analyse des comportements en situation simulée, via un jeu sérieux (*serious game*). Ce type d'outil immersif permettrait de présenter une série de situations réalistes aux plaisanciers participants (rencontres avec différentes espèces, distances variables, angles d'approche, etc.). Bien qu'imparfait, un tel dispositif offrirait l'opportunité de collecter des données comportementales plus fines et contextualisées. Avec un jeu géoréférencé, ces données pourraient également être spatialisées avec une grande résolution, renforçant ainsi la qualité des informations disponibles pour améliorer et calibrer le modèle.

5.6. Conclusion

Dans un contexte de pressions croissantes sur les écosystèmes marins, une compréhension fine des interactions entre les activités humaines et la faune s'avère essentielle pour concevoir des stratégies de gestion adaptées. Cette thèse s'inscrit dans cette perspective, en explorant de manière interdisciplinaire les dynamiques de la navigation de plaisance au sein de l'habitat estival de la population de BESL, une population en voie de disparition particulièrement sensible aux perturbations anthropiques.

Ce travail propose plusieurs contributions originales. Il établit d'abord les bases théoriques et méthodologiques nécessaires à la représentation des interactions humain–faune dans des systèmes socio-écologiques complexes, en mobilisant les principes de la modélisation multi-agent, ainsi que plusieurs cadres issus des sciences du comportement et de la psychologie environnementale. Il identifie ensuite, à partir d'une enquête qualitative, différents archétypes de plaisanciers en fonction de leurs valeurs, de leurs connaissances et leurs comportements. Cette typologie offre un cadre précieux pour mieux comprendre la diversité des pratiques en mer, ainsi que les motivations qui les sous-tendent.

Par ailleurs, une série d'analyses empiriques fondées sur des observations de terrain a permis de caractériser les conditions d'occurrence de la plaisance dans une zone spécifique de l'habitat estival du béluga, ainsi que les effets potentiels de cette présence sur les configurations spatiales des troupeaux. Ces résultats apportent des éléments concrets pour soutenir les efforts de gestion, notamment en matière de sensibilisation et de régulation.

En intégrant ces différents volets – conceptuels, qualitatifs et quantitatifs – la thèse propose une conceptualisation détaillée d'un modèle d'interaction entre plaisanciers et bélugas, qui tient compte des profils de plaisanciers, du cadre réglementaire, et du contexte environnemental. Cette étape a permis de développer le module d'interaction (ILM), constituant un préalable essentiel pour intégrer ultérieurement ce segment de navigation dans 3MTSim et nourrir le développement d'un MMA plus global représentant le SSÉ du SSL.

Elle met également en lumière les défis associés à la collecte de données empiriques sur le terrain et à la formalisation des comportements humains dans un cadre de simulation. Enfin, elle propose des pistes concrètes pour enrichir et affiner la modélisation future, notamment par le recours à des outils complémentaires tels que des questionnaires à large diffusion et des jeux sérieux géoréférencés.

Chapitre 6 : Annexes

Table 6.1 The correlation matrix regarding the three categories.

	Category 1	Category 2	Category 3
Category 1	1.0000	0.6504	0.7525
Category 2	0.6504	1.0000	0.6209
Category 3	0.7525	0.6209	1.0000

Table 6.2 The statements ranking (Q-Sort Value*) and their Z-scores** for each statement.

#	Statements	P1		P2		P3	
		Z-score	Q-sort value	Z-score	Q-sort value	Z-score	Q-sort value
1	I precisely define a navigation route plan before navigating.	0.471	0	1.403	4	-0.007	0
2	I always know my destination before navigating.	0.858	2	1.957	5	0.616	2
3	During navigation, I deviate from the itinerary defined beforehand.	-0.338	-1	-0.679	-2	-1.117	-3

4	The majority of my navigation trips are similar (duration, trajectory, stopping points, destination).	-0.198	-1	-0.495	-1	0.011	0
5	I always fish from my boat during my navigation trips.	-1.008	-2	-1.711	-5	0.376	1
6	I drop the anchor at least once per navigation trip.	-1.079	-3	-0.730	-2	0.117	0
7	When I see a gathering of pleasure boats, I head towards them.	-1.297	-3	-0.912	-3	-0.681	-2
8	I navigate alone (with no other boat but my own).	0.134	0	0.744	2	-0.176	-1
9	When I see marine mammals, I broadcast the information via my radio/VHF or my phone.	-1.366	-4	-1.678	-4	-1.081	-3
10	When I come across a whale, I approach it to contemplate it more closely	-1.640	-5	-1.428	-4	-1.508	-4
11	When I come across a whale, I turn off my engine.	-0.412	-1	-0.286	0	0.782	2

12	When I come across a whale, I feed it with what I have on board.	-2.248	-5	-2.245	-5	-2.165	-5
13	When I navigate, I listen to communications between whale-watching captains to find out where the marine mammals are.	-0.918	-2	-0.609	-2	-0.882	-2
14	When I see a gathering of whale-watching boats, I approach them to enjoy the show.	-1.310	-3	-0.177	0	-1.511	-5
15	When I see a whale, I adapt my itinerary to observe it longer.	-0.716	-2	0.208	0	-0.812	-2
16	I try to see several species of marine mammals during my navigation trip.	0.009	0	0.397	1	-0.553	-1
17	Beluga whales mainly use their eyesight to locate themselves underwater.	-1.596	-4	-0.501	-1	-1.475	-4
18	The sound of my engine can disturb marine mammals.	1.454	5	0.301	0	0.562	1

19	The St. Lawrence Estuary beluga whale population is in good health.	-0.889	-2	-0.874	-3	-1.461	-3
20	There are more than 10 species of whales in the Saguenay Fjord.	-0.365	-1	-0.361	-1	-0.009	0
21	I know the Marine Park navigation rules.	1.033	3	0.686	2	0.957	3
22	I know the geographical limits of the Marine Park.	0.686	2	0.199	0	0.137	0
23	The Marine Park speed limits suit me.	0.981	3	0.940	3	0.465	1
24	I think that boats navigate too fast in the Marine Park.	0.599	1	-0.538	-1	-0.056	-1
25	I find that the application of the regulations by the Marine Park's guard is insufficient.	0.140	0	0.309	1	-0.765	-2
26	I think the Marine Park should be better known.	0.985	3	0.481	1	0.270	1
27	I systematically sort my waste.	1.820	5	-0.502	-1	0.585	2

28	I have already helped raise funds to protect nature.	0.540	1	-1.262	-3	0.179	0
29	I have already reduced my standard of living to protect the environment.	0.555	1	-0.593	-2	-0.561	-1
30	I think everyone should have the chance to navigate the Saguenay – St-Lawrence.	0.517	1	0.517	1	1.543	4
31	I have already volunteered to help people in need.	0.857	2	0.012	0	1.345	4
32	I like to be useful to others.	1.441	4	0.669	2	1.547	5
33	When out on the water, my main goal is to have fun.	0.717	2	1.034	3	1.010	3
34	The most important thing for me is to do what I love.	0.520	1	1.710	5	2.199	5
35	It is important for me to enjoy the pleasures of life.	1.354	4	1.653	4	1.224	3

36	I like to control what is happening around me.	0.105	0	1.211	3	0.311	1
37	It is important for me to have money and goods.	-0.307	-1	0.750	2	-0.268	-1
38	If I win a lot of money, I'll buy myself the boat of my dreams.	-0.092	0	0.400	1	0.851	2

**Q-Sort value meaning : +5 = totally agree; +4 = very agree; +3 = agree; +2 = moderately agree; +1 = rather agree; 0 = neutral; -1 = rather disagree; -2 = moderately disagree; -3 = disagree; -4 = very disagree; -5 = extremely disagree.*

***Z-scores are standardized scores, as defined by Watts and Stenner (2005). These scores represent the "standard score or average" assigned to each statement by the participants who performed the Q-sorts. Zabala (2014, p. 166) summarizes that Z-scores indicate the level of agreement between each factor and a specific statement.*

Table 6.3 Hourly environmental variables used in the model exploring the factors that influence the number of recreational boats present in the study area per hour.

Sea conditions according to the Beaufort Scale (collected in the field and updated	0: Sea like a mirror
	1: Ripples with appearance of scales are formed, without foam crests
	2: Small wavelets still short but more pronounced; crests have a glassy appearance but do not break

every hour)	3: Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses
Tidal phases (Data obtained from Canadian Hydrographic Service) (See Figure 6.1, Annexes, for more details)	1: High tide: ± 1h high tide
	2: Ebb tide: first half between high and low tide
	3: Mid-ebb tide: second half between high and low tide
	4: Low tide: ± 1h low tide
	5: Flood tide: first half between low and high tide
	6: Mid-flood tide: second half between low and high tide
Wind speed *	in km/h
Wind direction *	from 0 to 360°
Air temperature *	in °C

* Obtained from Environment Canada (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html), last accessed on August 16, 2024.

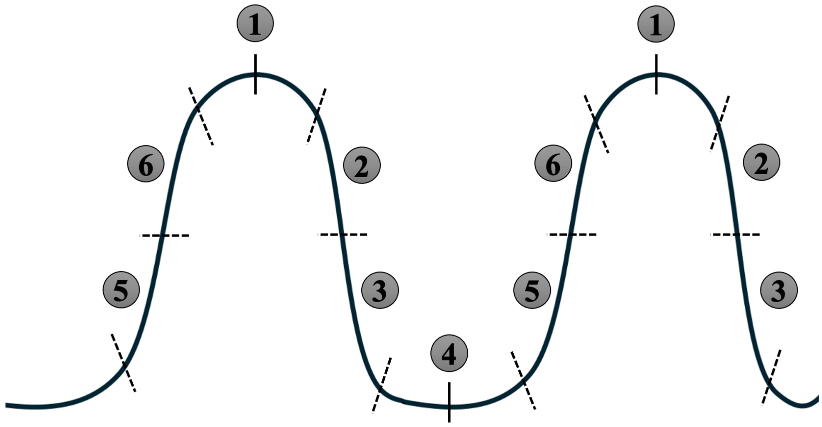


Figure 6.1 Tide phases used for the analysis. 1: ± 1h high tide phase (high tide), 2: first half between high tide phase and low tide phase (ebb tide), 3: second half between high tide phase and low tide phase (mid-ebb tide), 4: ± 1h low tide phase (low tide phase (low tide), 5: first half between low tide phase and high tide phase (flood tide) and 6: second half between low tide phase and high tide phase (mid-flood tide).

Table 6.4 Control variables related to sampling effort.

Observer-herd distance (details in Figure 6.2, Annexes) *(factors with 3 levels)*	1: The majority of the beluga herd is located within the area closest to the observer (Zone 1 in Figure 6.1)
	2: The majority of the beluga herd is located within the middle area of the fjord (Zone 2 in Figure 6.1).
	3: The majority of the beluga herd is located within the area opposite the observer (Zone 3 in Figure 6.1)
Evaluation of data collected by the observer *(factors with 4 levels)*	1: Difficult
	2: Average
	3: Good

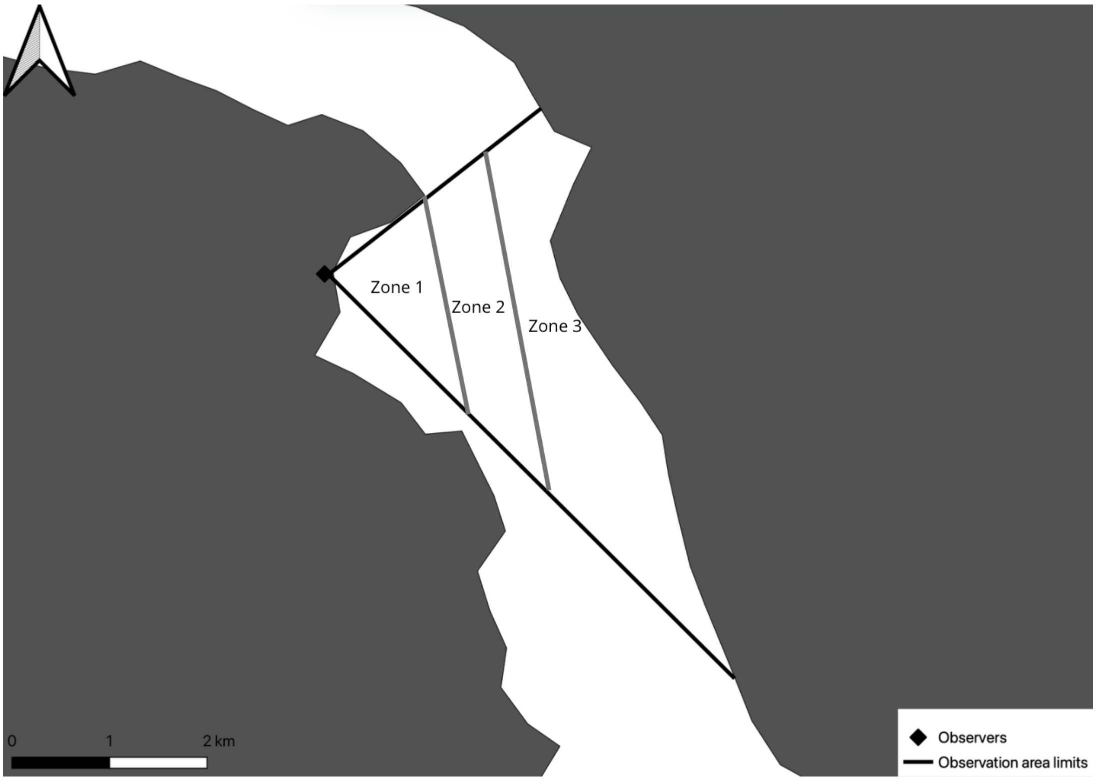


Figure 6.2 Spatial division of the observation area by observer-beluga herd distance.

Table 6.5 Model-averaged parameter estimates for predictors of the number of recreational boats per hour in the study area.

Term	Estimate	Std. Error	z-value	p-value
Parametric coefficient				
Intercept	0.690	0.328	2.103	0.036 *
Sea condition (1)	0.124	0.164	1.753	0.451
Sea condition (2)	-0.193	0.171	-1.128	0.259
Sea condition (3)	-0.364	0.191	-1.902	0.057
Weekday (Monday)	-0.660	0.141	-4.682	<0.001 ***
Weekday (Tuesday)	-0.417	0.129	-3.240	0.001 **
Weekday (Wednesday)	-0.310	0.134	-2.317	0.020 *

Weekday (Thursday)	-0.498	0.133	-3.755	<0.001 ***
Weekday (Friday)	-0.340	0.130	-2.618	0.009 **
Weekday (Saturday)	0.148	0.112	1.328	0.184
Proportion of time with belugas	0.002	0.001	1.720	0.085
Tidal phase (2)	0.074	0.129	0.573	0.567
Tidal phase (3)	0.038	0.128	0.294	0.769
Tidal phase (4)	0.305	0.116	2.628	0.009 **
Tidal phase (5)	0.314	0.112	2.799	0.005 **
Tidal phase (6)	0.301	0.110	2.734	0.006 **
Temperature	0.042	0.014	2.970	0.003 **
Wind speed	-0.008	0.004	-2.044	0.041 *
Smooth terms	**edf**	**Ref.df**	**Chi.sq**	**p-value**
s(Wind direction)	2.368	8.000	22.48	<0.001 ***
s(Time of the day)	5.747	6.872	106.91	<0.001 ***
s(Julian day:Year 2021)	3.474	4.302	29.33	<0.001 ***
s(Julian day:Year 2022)	2.891	3.594	28.75	<0.001 ***

** Statistically significant at $p < 0.05$*

Statistics for the smooth terms involving Julian day by year are derived from the global GAM model.

Tableau 6.6 Distance de détection approximative en fonction de l'espèce dans des conditions météorologiques idéales et moyennes (Chion, 2011).

	Distance de détection à l'œil nu (m)	
Espèce	Conditions météorologiques	Conditions météorologiques

	idéales	moyennes
Petit rorqual	2000	1500
Rorqual commun	4500-5000	3000
Rorqual bleue	6000	4000-4500
Rorqual à bosse	4500-5000	3000
Béluga	3000	1500-2000

Tableau 6.7 Classement des espèces de baleines selon leur attractivité perçue par les plaisanciers, par archétype.

"Quelle espèce de baleine vous attire le plus ?"		
Archétype 1 - Éco-responsable	Archétype 2 - Égocentré	Archétype 3 - Altruiste
- 38% : Pas de préférence - 26% : Béluga - 19% : Rorqual à bosse - 18% : Rorqual bleu - 3% : Rorqual commun - 3% : Petit rorqual	- 31% : Pas de préférence - 25% : Béluga - 19% : Rorqual bleu - 19% : Rorqual à bosse - 6% : Rorqual commun - 0% : Petit rorqual	- 54% : Pas de préférence - 31% : Béluga - 8% : Rorqual bleu - 8% : Rorqual à bosse - 0% : Rorqual commun - 0% : Petit rorqual

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