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BY
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AN AGENT-BASED MODEL FOR THE SUSTAINABLE MANAGEMENT OF NAVIGATION ACTIVITIES IN THE SAINT LAWRENCE ESTUARY

MONTREAL, MAY 5 2011

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FOREWORD

When I decided to engage in my PhD project, I had thankfully no idea about what was lying ahead. At approximately the same time, I decided to practice seriously for long-distance runs. I had the brilliant feeling that training for long-distance races would lead me to improve some skills also needed to complete a PhD, including endurance, mental strength, perseverance, humility, toughness, and love for pasta. In fact, a marathon is a breeze! Running is a lonesome experience with performance on race day relying on one's own preparation and pre-race meal. My PhD had the added social dimension, if not a true human experience of success depending on communication abilities, tact, extreme patience (I was not equipped with this one), regular questioning, and psychological resilience. Eventually, the value of the gained experience has no parallel.

Despite not having anticipated all these differences with a PhD when I started my physical workout, after a few years I discovered another similitude between these two kinds of *races*, worth mentioning. At approximately ¾ of the *race*, hitting a wall while running out of *vital resources* (food in one case, money to buy food in the other), a demon came whispering to me "What are you doing here?" During a marathon, you are lucky if a roadside spectator, noticing you are whiter than your T-shirt and understanding you are probably about to faint, in which case he would feel guilty, starts cheering, allowing you to limp away. On the other hand, when the completion of your PhD appears to be within the realm of fiction, relatives and friends come into play to support and carry you until you cross the finish line.

To conclude this foreword, which appears to be the only section without red-penciling, I would like to mention several principles that have been driving me all along this five-year project. These can be seen as a personal code of conduct. I tried to stimulate the collaboration between researchers, promoting the sharing of high-quality data for the benefit of knowledge discovery. I also tried to bridge the gap between some isolated research areas since I strongly believe in multidisciplinarity (which may sound like a cliché or obviousness for someone studying complex systems but is far from easy in practice). In the context of an applied project, I paid a lot of attention to the concrete needs and constraints of project partners, while trying to generalize my contributions and make them useful to a larger community of researchers. Finally, I exerted much effort and awareness to be collaborative and transparent in all situations, sharing unpublished analyses with researchers to reduce the delays inherent to the scientific publication process and promote knowledge diffusion. Not claiming that I've always succeeded in sticking to these principles, I certainly tried with all my might and will continue to keep them in mind as a line of conduct.

REMERCIEMENTS

J’exprime mes profonds remerciements à mon directeur de recherche, Pr Jacques-André Landry, et ma co-directrice, Pre Lael Parrott, pour leur encadrement et leur soutien tout au long de ma thèse.

Ma thèse de doctorat s’inscrit dans le cadre d’un projet collaboratif, impliquant un nombre important de personnes et d’institutions. Je tiens à remercier toutes les personnes qui en collaborant, de quelque façon que ce soit, ont favorisé la réalisation du travail présenté ici. Nombre d’entre elles sont mentionnées dans cette dissertation et comme il serait impossible de toutes les nommer sans omission, je ne me risquerai pas à l’exercice. À vous qui vous reconnaîtrez, ma reconnaissance est immense. Sans vous, il est évident que ce projet aurait achoppé sur de nombreux obstacles. Je tiens bien sûr à remercier mes collègues du LIVIA (ÉTS) et ceux du laboratoire de systèmes complexes (Université de Montréal) pour l’atmosphère agréable qu’ils ont su créer tout au long de ces cinq années.

Mes remerciements vont également aux organismes subventionnaires qui ont permis à ce projet d’exister, à savoir le Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG) et le Fonds québécois de la recherche sur la nature et les technologies (FQRNT).

Finalement, j’ai une gratitude sans borne pour ma famille, particulièrement mon frère Cédric et ma mère Joëlle, mes amis et ma douce Anne. Votre soutien de tous les instants et vos encouragements sont une richesse et une source d’inspiration sans pareil.

UN SYSTÈME MULTI-AGENTS POUR FAVORISER L'UTILISATION DURABLE DE L'ESTUAIRE DU SAINT-LAURENT PAR LES ACTIVITÉS DE NAVIGATION

Clément CHION

RÉSUMÉ

Les gestionnaires de ressources naturelles dans les aires protégées se doivent d'encadrer les activités humaines susceptibles de menacer la santé et/ou l'intégrité des écosystèmes à protéger. Ces systèmes physiques où des humains interagissent avec des ressources naturelles sont appelés systèmes socio-écologiques (SSE) et possèdent les caractéristiques de systèmes complexes adaptatifs (p. ex. coévolution). L'investigation du SSE constitué des activités de navigation et des baleines interagissant dans le parc marin du Saguenay–Saint-Laurent (PMSSL) et la zone de protection marine Estuaire du Saint-Laurent au Québec, Canada, ainsi que sa représentation sous forme d'un système multi-agents sont présentées dans cette thèse. Le simulateur implémenté, appelé 3MTSim (pour *Marine Mammal and Maritime Traffic Simulator*), est conçu pour aider les gestionnaires des aires marines protégées dans leur objectif de réduire la fréquence et l'intensité des cooccurrences bateau-baleine dans le Saint-Laurent et incidemment les risques de collision.

Les connaissances extraites des analyses de données (relatives aux activités de navigation à moteur et à voile), existantes ou recueillies dans le cadre de ce projet, ont justifié de concentrer l'effort de modélisation sur les excursions commerciales (incluant les excursions d'observation de baleines), les navires de la marine marchande et les paquebots de croisière. Les analyses ont permis pour la première fois de dresser un portrait complet des activités de navigation sur l'ensemble de la région où les baleines se rassemblent en grand nombre pendant la saison estivale. Entre autres résultats, une analyse quantitative a abouti sur une estimation précise du temps total de navigation dans chaque écosystème marin de la région. Cette étude a permis d'identifier les zones utilisées intensivement par les activités de navigation, telles que l'embouchure de la rivière Saguenay et le secteur au large de Les Escoumins.

Plusieurs campagnes d'acquisition de données menées dans le cadre de ce projet ont permis d'identifier des facteurs (p. ex. abondance et distribution des espèces de baleines, lacunes de gestion, décisions des compagnies et des capitaines) favorisant une dynamique collective des « croisières aux baleines » indésirable, tant du point de vue de la conservation que de l'expérience des visiteurs du PMSSL. La rationalité limitée a été choisie comme cadre conceptuel pour étudier la prise de décision des capitaines, et plus généralement comprendre la dynamique du SSE des « croisières aux baleines » au complet. L'éventail des stratégies utilisées par les capitaines de « croisières aux baleines » a été décrit et les résultats de cette investigation vont conduire à un ensemble de recommandations relatives à la gestion durable de ces activités à l'intérieur et aux alentours du PMSSL.

Les résultats des investigations de terrain et de l’analyse des données sur la navigation ont alimenté le processus de construction du modèle, incluant une représentation explicite de la prise de décision des capitaines de « croisières aux baleines ». Les analyses ont démontré que les navires de la marine marchande et les paquebots de croisière suivent des routes prévisibles avec peu de variabilité. Par conséquent, une approche de modélisation complexe basée sur le comportement des pilotes a été écartée au profit d’une approche statistique, justifiée par la quantité importante de données historiques de grande qualité disponibles pour ces deux composantes.

L’approche de modélisation par patrons (« *pattern-oriented modelling* ») s’est avérée performante pour sélectionner un modèle valide des excursions d’observation des baleines lorsque couplé à un modèle à l’échelle de l’individu des mouvements de baleines. Les simulations effectuées ont confirmé que les capitaines d’excursion privilégient l’observation de quelques rares espèces de rorquals (p. ex. baleines à bosse), boudant l’espèce la plus abondante, à savoir le petit rorqual. Par conséquent, des simulations ont été effectuées avec 3MTSim visant à quantifier l’impact d’un changement de stratégie décisionnelle des capitaines d’excursions, tant sur la nature de l’exposition des baleines aux bateaux (intérêt pour la conservation) que sur le contenu des excursions (intérêt commercial). Les résultats ont montré que des capitaines virtuels soucieux d’éviter les zones d’observation surencombrées et/ou cherchant à augmenter la diversité des espèces observées entraînait des gains statistiquement significatifs relativement aux aspects de conservation sans affecter les caractéristiques importantes des excursions. Enfin, les bonnes performances du modèle des déplacements de bateaux assurent une utilisation sécuritaire de 3MTSim comme un outil d’aide à la décision pour la gestion, dans la mesure où ses limites sont comprises et considérées dans l’interprétation des résultats.

Mots-clés : système multi-agents, trafic maritime, système socio-écologique, aires marines protégées, conservation, mammifères marins, fleuve Saint-Laurent, rationalité limitée, prise de décision, modélisation orientée par patrons, interactions bateau-baleine.

AN AGENT-BASED MODEL FOR THE SUSTAINABLE MANAGEMENT OF NAVIGATION ACTIVITIES IN THE SAINT LAWRENCE ESTUARY

Clément CHION

ABSTRACT

Natural resource managers of protected areas are concerned with the management of human activities potentially harmful to ecosystems' health and/or integrity. These systems where human interact with natural resources are called social-ecological systems (SES) and possess the characteristics of complex adaptive systems (e.g. co-evolution). The SES of navigation activities and whales interacting within the Saguenay–St. Lawrence Marine Park (SSLMP) and the projected St. Lawrence Estuary Marine Protected Area in Quebec, Canada, has been investigated and modelled using the agent-based modelling (ABM) technology: The resulting *Marine Mammal and Maritime Traffic Simulator* (3MTSim) is designed to support marine protected area managers in their effort to reduce the frequency and intensity of boat-whale co-occurrences within the St Lawrence Estuary and mitigate the risks of vessel strikes. This dissertation presents the building process of the 3MTSim's boat ABM.

The knowledge extracted from analyses of gathered and collected data relative to all forms of sailing and motorized navigation supported the decision to first focus on the modelling of commercial excursions (including whale-watching trips), cargo ships, and cruise liners. Data analyses allowed, for the first time, to draw a comprehensive portrait of navigation activities throughout the region where whales congregate in great numbers during the summer season. Among others, a quantitative analysis led to an accurate estimate of the total navigation time within each separate ecosystem of the region. This study identified areas intensively used by maritime traffic such as the mouth of the Saguenay River and offshore Les Escoumins.

Several field campaigns carried out in the context of this project allowed to link some undesirable collective patterns of whale-watching excursions (regarding both whale conservation and SSLMP visitors' experience) with contextual factors including whale species' abundance and distribution, management gaps, and companies and captains' decisions. The bounded rationality framework was chosen to investigate captains' decision making and more generally the dynamics of the whole whale-watching SES. A portrait of the decision strategies followed by whale-watching captains has been drawn. The results will lead to a set of recommendations regarding the sustainable management of whale-watching excursions in and around the SSLMP.

Results from field investigations and data analyses have fed the model building process, including an explicit representation of the whale-watching captains' decision making. Data analyses revealed that cargo ships and ocean liners tend to follow predictable routes with low variability. Consequently, a complex behavioural modelling approach was deemed unnecessary in favour of a statistical approach, justified by the large volume of high-quality historical data available for both components.

The pattern-oriented modelling approach proved appropriate for selecting a valid model of whale-watching excursions. Model simulations confirmed that whale-watching captains do favour the observation of a few rare rorqual species (e.g. humpback whales), leaving aside the most abundant one, namely the minke whales. Therefore, 3MTSim was run to quantify the impact that whale-watching captains changing their decision strategy could have on both whale exposure to boats (conservation concern) and excursion content (commercial concern). It was found that captains willing to avoid crowded observation sites and/or seeking to increase the diversity of species observed could have statistically significant benefits regarding conservation issues without affecting important features of their excursions. Finally, the convincing performance of the 3MTSim's boat ABM ensures its safe use as a decision-support tool for management insofar as model limitations are understood and accounted for in the results and discussion.

Keywords: agent-based model, maritime traffic, social-ecological system, marine protected area, conservation, marine mammals, St. Lawrence river, bounded rationality, decision making, pattern-oriented modelling, boat-whale interactions.

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LIST OF ABBREVIATIONS

3MT-SES	Marine mammal and maritime traffic social-ecological system
3MTSim	Marine mammal and maritime traffic simulator
ABM	Agent-based model(ing)
ACCOBAMS	Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea, and contiguous Atlantic area
AI	Artificial intelligence
AIS	Automatic identification system
AOM	Activités d'observation en mer (i.e. o*bservation activities at sea*)
CLSLP	Corporation of Lower St. Lawrence Pilots
COSEWIC	Committee on the status of endangered wildlife in Canada
DAI	Distributed artificial intelligence
DPS	Distributed problem solving
CCG	Canadian coast guard
COLREGS	Collision avoidance regulations
DFO	Department of Fisheries and Oceans
GIS	Geographic information system
GREMM	Group for research and education on marine mammals
IBM	Individual-based model(ling)
IDE	Integrated Development Environment
IMO	International Maritime Organization
INNAV	Information on navigation system
IWC	International Whaling Commission

MAS	Multiagent system
MCTS	Marine Communication and Traffic Services
MPA	Marine protected area
NDM	Naturalistic decision making
NMAE	Normalized mean average error
NME	Normalized mean error
POM	Pattern oriented modelling
RQUMM	Réseau québécois d’urgence pour les mammifères marins
SDE	Software development environment
SES	Social-ecological system
SLEMPA	St. Lawrence Estuary marine protected area
SSLMP	Saguenay–St. Lawrence marine park

INTRODUCTION

0.1 Context

0.1.1 Human impact on ecosystems

Whether it be on the ground, underwater, or up in the air, humans have colonized all dimensions of our living environment (Vitousek *et al.*, 1997). Human expansion comes with a variety of problems for ecosystems exposed to anthropogenic activities. Deforestation, overfishing, and overgrazing are some of the visible consequences of human over-consumption or mismanagement of natural resources observed worldwide (Dietz, Ostrom and Stern, 2003; Halpern *et al.*, 2008; Rapport, Costanza and McMichael, 1998; Vitousek *et al.*, 1997).

The human impact on ecosystems is easily detectable in the case of harvest activities (e.g. clearcutting in forestry). However, some apparently non-consumptive activities have proved to have insidious impacts on ecosystems in the long-term, invisible in the short-term. Widely known examples of such long-term costs include watercourse slow poisoning by poorly treated wastewater, ozone layer depletion caused by aerosols, and global warming induced by greenhouse gas emissions. At a more local scale, this is also the case of negative impacts of human-wildlife interactions, either deliberate (e.g. wildlife viewing activities) or fortuitous (e.g. roadkills). Effects of repeated interaction between human beings and wildlife have proved deleterious for numerous exposed populations (e.g. Bejder *et al.*, 2006; Bugoni, Krause and Petry, 2001; Forman and Alexander, 1998; Wilson *et al.*, 2006) leading some conservation biologists to argue that human disturbance should be considered a part of the predation risk (Frid and Dill, 2002).

The context of the present project is precisely related to the study of human-wildlife interaction, specifically the case of boat-whale encounters within the St Lawrence River Estuary and the Saguenay River in Québec, Canada. Thereafter, details about this specific issue are considered.

0.1.2 Boat-whale interactions

Human impact on marine ecosystems is occurring worldwide in many forms (Halpern *et al.*, 2008). In this section, the issue of boat-whale fortuitous (i.e. collisions and noise) and deliberate (i.e. whale-watching) interactions potentially harmful to marine ecosystems are discussed.

0.1.2.1 Collisions

Ship strikes are the first type of interactions that come to mind due to their visible, dramatic outcomes (Jensen and Silber, 2004; Laist *et al.*, 2001). Accurately quantifying the number of collisions with whales and the impact at the population level is challenging. Ship strikes are not systematically reported or even noticed by mariners and several factors certainly lead to an underestimation of these events (Laist *et al.*, 2001). For instance, 40% of the endangered North Atlantic right whale (*Eubalaena glacialis*) mortality is attributable to collisions with boats, with a detection rate of carcasses as low as 17% for this population (Kraus *et al.*, 2005). This suggests that ship strikes are more common than previously thought, which could compromise the long-term recovery of some exposed endangered whale populations (Kraus *et al.*, 2005; Laist *et al.*, 2001). Serious and lethal injuries mostly imply ships longer than 80 m (Laist *et al.*, 2001), with approximately 80% of mortality at speeds greater than 15 knots (Vanderlaan and Taggart, 2007). Among the 11 whale species involved in collisions, the most reported are fin (*Balaenoptera physalus*), right, and humpback whales (*Megaptera novaeangliae*), although several biases apply to this portrait (Laist *et al.*, 2001).

Mitigation measures to decrease the risk of lethal injuries have been proposed (Vanderlaan and Taggart, 2007) and successfully implemented worldwide to reduce human induced mortality of the North Atlantic right whales (Vanderlaan and Taggart, 2009) and other marine mammal populations (e.g. Laist and Shaw, 2006). Ongoing scientific efforts occur in several regions to better characterize the collision issue and address it through mitigation measures (e.g. Betz *et al.*, 2010; Panigada and Leaper, (in press); Williams and O'Hara, 2010). The recent holding of a workshop dedicated to the reduction of the risk of collisions between vessels and cetaceans (International Whaling Commission and ACCOBAMS, 2010) along with the guidance document recently published by IMO to minimize the risk of ship strikes (International Maritime Organization (IMO), 2009) demonstrate the importance of this issue worldwide.

0.1.2.2 Noise

Collisions do not represent the only navigation-related deleterious side effect on whale populations. Ship noise, one of the top-most contributors in background ocean noise with seismic exploration and sonars (Nowacek *et al.*, 2007), is also a stressor for marine wildlife. Noise is of special concern for cetaceans that strongly rely on sound for communication and echolocation (Weilgart, 2007). Typically, large mysticetes (i.e. baleen whales such as blue, fin, minke, and humpback whales) use low frequencies (infrasonics) ranging from 10 to 2000 Hz, whereas odontocetes (i.e. tooth whales such as belugas and sperm whales) use mid to high frequencies ranging from 1 to 150 kHz (Richardson *et al.*, 1995).

Boat noise is mostly generated by propellers and by hull vibration induced by inside machinery. Noise frequencies mostly depend on the size of the boat with the general rule that larger (resp. smaller) boats produce more sounds in low (resp. high) frequencies (Richardson *et al.*, 1995).

The response of whales to noise falls into three categories (Nowacek *et al.*, 2007):

1) Behavioural: change in surfacing, diving, and heading patterns, as well as abandonment/disruption of an activity.
2) Acoustic: change of type or timing of vocalization, masking effect.
3) Physiological: increased stress level, change in heart rate, temporary and permanent threshold shifts (i.e. hearing damage).

Whale exposure to noise has been shown to be related to other long-term effects such as stranding and habitat abandonment in some cases (Weilgart, 2007).

Whale-watching activities have also been associated with noise disturbance. Erbe (2002) studied the impact of whale-watching proximity to killer whales and found that a zodiac with twin 150-hp engines (low-average power) at 51 km/h (~27.5 knots) in a calm sea is audible at 16 km underwater and has the potential to mask whale calls at up to 14 km, inducing behavioural changes at 200 m and provoking temporary and in some cases permanent hearing damages after sufficiently long expositions. Despite evidence that noise can cause major damage to whales, it is not yet possible to establish acceptable levels of noise exposure for each of the 84 species of whales (Nowacek *et al.*, 2007), of interest for management purpose.

0.1.2.3 Whale-watching

According to Hoyt (2007), "Whale watching is defined as tours by boat or air or from land, with some commercial aspect, to see or listen to any of the 84 species of whale, dolphin, or porpoise". Whereas the first commercial whale-watching excursions can be traced back to 1955 in San Diego, its dramatic rise coincides with the post-1986 moratorium on commercial whaling by the International Whaling Commission (IWC). From an economic point of view, whale-watching is a non-consumptive alternative to whaling bringing in more than US$1.25 billion a year to more than 500 local communities of some 87 countries all around the world, getting more than 10 million tourists closer to marine mammals (Hoyt, 2001; 2007). A study requested by the Australian government, released in 2009, concluded that "whales are worth more alive than dead" (Syneca Consulting Pty Ltd, 2009).

Despite the interesting nature of whale-watching as an alternative to commercial whaling, two decades of research have begun to reveal the hidden cost of this non-consumptive activity (Baker and Herman, 1989; Lusseau and Bejder, 2007). Although short-term behavioural changes (e.g. change in diving pattern) have been noticed in targeted marine mammal populations in many places all around the world due to whale-watching (e.g. Constantine, Brunton and Dennis, 2004; Corkeron, 1995), establishing a link between short-term individual effects and long-term population-wide impact is challenging (Corkeron, 2004). However, several researches already came up with conclusions of long-term deleterious effects of boat-based whale-watching activities on targeted populations (Bejder *et al.*, 2006; Lusseau, Slooten and Currey, 2006; Williams, Lusseau and Hammond, 2006). Long-term effects on marine mammal populations include habitat abandonment (Lusseau, Slooten and Currey, 2006), changes in the whales' energetic budget (Williams, Lusseau and Hammond, 2006), and decrease in their reproductive success (Bejder *et al.*, 2006). These results have crucial implications: Sustainability of whale-watching can no longer be taken for granted and management efforts must be done to identify and minimize its impact (e.g. whale disturbance) while maximizing its benefits (e.g. tourist educative experience, payoff for local communities) (Higham, Bejder and Lusseau, 2009; Hoyt, 2007).

0.1.3 Study area

0.1.3.1 Portrait

The study area encompasses the portion of the St Lawrence River Estuary from Baie-Saint-Paul to Betsiamites on the North shore, and from Saint-Roch-des-Aulnaies to Métis-sur-Mer on the South shore along with the Saguenay Fjord (cf. Figure 0.1). An exceptional oceanographic phenomenon occurs in the region: The upwelling of cold salty water driven by tides in the Laurentian channel meets with the fresh and warmer waters from the Saguenay River at its mouth, between Tadoussac and Baie-Sainte-Catherine (Simard, Lavoie and Saucier, 2002). This favours the primary productivity of plankton, leading to high concentrations of pelagic fish (e.g. capelin) and euphosiids (e.g. krill), making it an attractive summer feeding ground for marine mammals (Simard and Lavoie, 1999; Simard, Lavoie and Saucier, 2002).

This region is an important habitat for several whale species of critical status according to the Committee on the Status of Endangered Wildlife in Canada (COSEWIC): The resident St. Lawrence beluga (*Delphinapterus leucas*) is "threatened" (COSEWIC, 2010), and the migratory species North Atlantic blue whale (*Balaenoptera musculus*) and fin whale (*Balaenoptera physalus*) are respectively listed "endangered" (Beauchamp *et al.*, 2009) and of "special concern" (COSEWIC, 2010). In total, up to 13 marine mammal species can be found in the St. Lawrence Estuary which is known to be a summer feeding ground for migratory species (Saguenay–St. Lawrence Marine Park, 2010). Apart from the blue, fin, and beluga whales, two whale species, namely the minke whale (*Balaenoptera acutorostrata*) and humpback whale (*Megaptera novaeangliae*), complete the list of the regular visitors: The present study is solely concerned with these five species. Therefore, the generic term *whales* used in the context of this project will refer to any or all of these five species, if no other mention. Several species of seals, porpoises and dolphins add to the impressive biodiversity of marine mammals present in the area but will not be considered in the current project, either because navigation does not represent an identified threat to them or because of a lack of data.

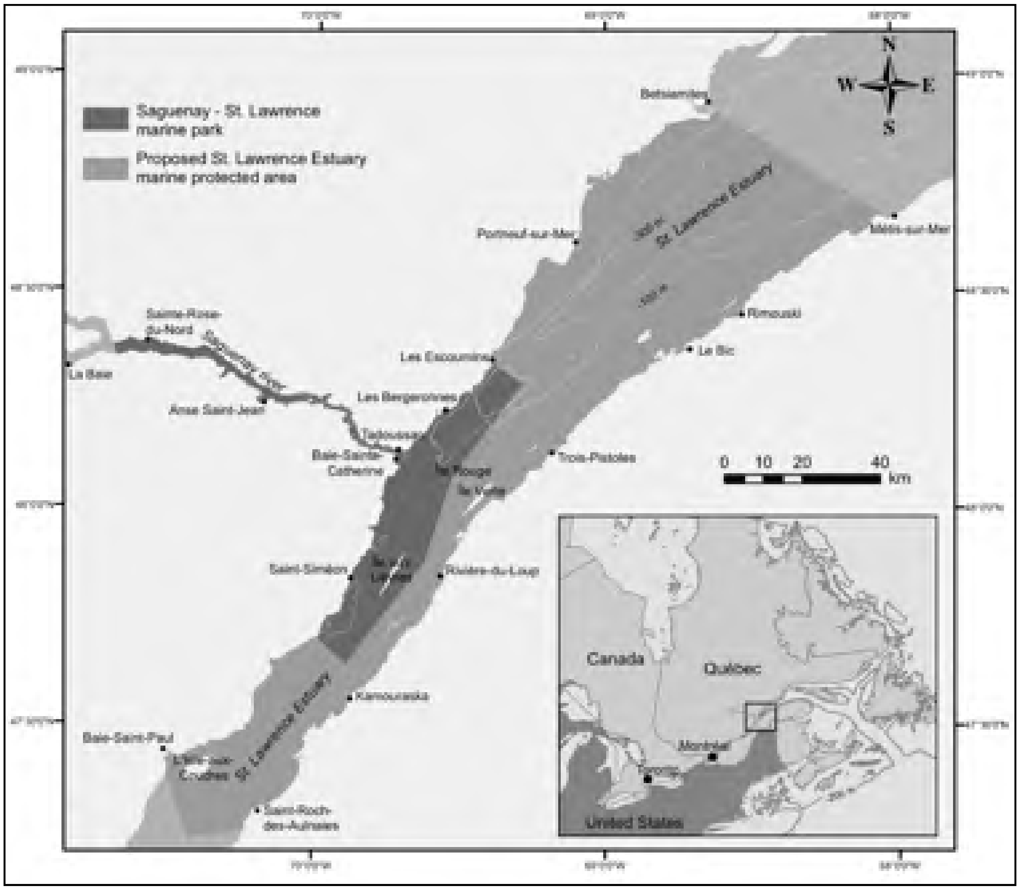


Figure 0.1 Study area.
Map produced in collaboration with Samuel Turgeon (Univ. de Montréal)

The St. Lawrence River is a major commercial seaway linking the Atlantic Ocean with the Great Lakes with approximately 6000 ships taking this route every year, thus passing through the study area. During the *summer season* (May to October) when whales are abundant in the Estuary, some 23 000 ferry trips, 13 000 commercial excursions, 9200 pleasure craft outings, and 3100 shipping trips take place in the study area for a total of more than 51 000 movements in locations where whale mostly congregate (see Chion *et al.*, 2009 in APPENDIX I for a complete description). The region attracts more than 1 million tourists a year (Gosselin and Priskin, 2009; Gosselin, 2006), being considered by specialists as one of the best places in the world to observe whales in the wild (Scarapaci, Parsons and Lück, 2008).

Added to other environmental issues such as water pollution (e.g. Lebeuf *et al.*, 2004; Martineau *et al.*, 2002; Michaud and Pelletier, 2006), maritime traffic is posing serious threats to the conservation of marine ecosystems. To address the urgent need to protect the St. Lawrence beluga whale population now reduced to approximately 1000 individuals, a long process of public pressure followed by consultations by Parks Canada and Parcs Québec led to the creation of the Saguenay–St. Lawrence Marine Park (SSLMP) in 1998. This national park is jointly managed by the governments of Canada (jurisdiction related to body of water) and of Quebec (jurisdiction related to lands) (Guénette and Alder, 2007), and covers more than 1245 km^2 (Figure 0.1). In 2002, based on scientific studies (Michaud and Giard, 1997; 1998), the first version of the Marine Activities in the Saguenay–St. Lawrence Marine Park Regulations was adopted with law enforcement by a team of park wardens (Parks Canada, 2002). In 2004, the Department of Fisheries and Oceans (DFO) identified a 6000 km^2 area buffering the SSLMP as a priority for the establishment of a Marine Protected Area (MPA) (Savaria *et al.*, 2003; Tecsult Environnement Inc., 2000) under the Oceans Act (*Oceans Act*, 1996). The establishment of the proposed St. Lawrence Estuary Marine Protected Area (SLEMPA), identified in Figure 0.1, is still a work in progress.

0.1.3.2 A social-ecological system

The complex system composed of boats, whales, and institutions in the study area falls into the category of social-ecological systems (SESs) (Ostrom, 2009) sometimes referred to as coupled human and natural systems (CHAN) (Liu *et al.*, 2007) or human-environment systems (Clarke, 2002). This section presents the concepts related to the study of SESs along with a description of the studied system according to Ostrom's framework (Ostrom, 2007; 2009).

Figure 0.2 is an illustration of the core components that make up SESs, after Ostrom's general framework developed to study the sustainability issue of such systems (Ostrom, 2009). In the rest of this dissertation, the SES of navigation, whales, and related institutions in both the SSLMP and the SLEMPA will be labelled the 3MT-SES standing for *marine mammal and maritime traffic social-ecological system*.

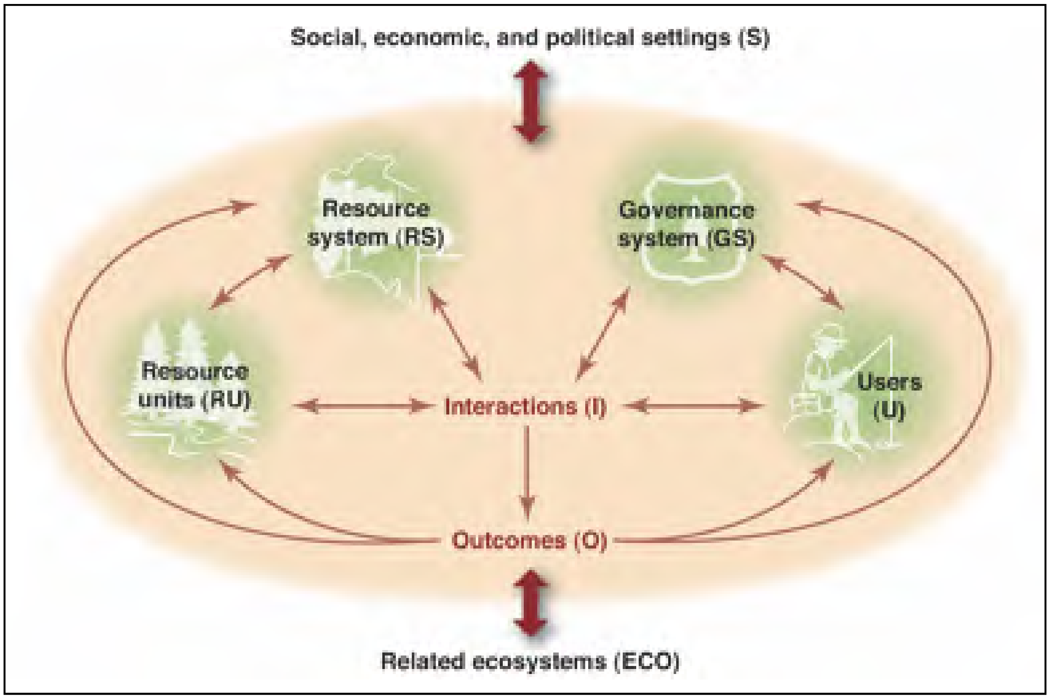


Figure 0.2 Core subsystems in a social-ecological system.
Reproduced from Ostrom (2009)

Using the terminology presented in Figure 0.2, the 3MT-SES can be described as follows:

- Resource system (RS): Two contiguous MPAs (SSLMP + SLEMPA).
- Resource units (RU): Marine mammals including the five whales species of interest (cf. section 0.1.3).
- Governance systems (GS): Parks Canada and Fisheries and Oceans Canada federal institutions propose the regulations (after public consultations) and ensure law enforcement over the body of water.
- Users (U): All navigation activities interacting with whales either deliberately (i.e. whale-watching activities, commercial or private) or fortuitously (e.g. shipping industry, ferries, service boats…). Fishing activities, whether recreational or commercial, are marginal in the area so they are not considered in this study.

These four subsystems affect and can be affected by smaller and larger socioeconomic and political settings (S) and ecosystems (ECO). The following examples for the 3MT-SES can be given:

- S: For instance whale-watching tourism demand can be influenced by the international economic context (e.g. the 2008 economic crisis). National-level laws (e.g. Oceans Act), fundamental principles (e.g. free-enterprise principle), and government guidelines (e.g. in 2007, due to poaching issues in Northern national parks, all Parks Canada's wardens and rangers were temporarily relieved of law enforcement duties) can also interfere with (favour or impede) conservation efforts at the local level.
- ECO: The downstream Gulf of St. Lawrence ecosystem is directly connected to the Estuary. All whales present in the area went through the Gulf at one point in time. Some of the whale's preys found in the Estuary (e.g. krill) partly come from the Gulf's primary productivity, influencing in turn the abundance of whale species feeding on them (e.g. blue whale). Moreover, since many whale species feeding in the area are migratory, the recovery of certain stocks may have an impact on the number of individuals visiting the region. For instance, the recovery of the North Atlantic humpback whale population coincides with an increase in the number of observations of this species in the area since the early 2000's (Stevick *et al.*, 2003).

The four subsystems (RS, RU, GS, and U) are interconnected with each other via such interactions (I) as, for instance, whale disturbance by boats, information exchange between whale-watching captains, or water use conflict between shipping and whale-watching industries. Outcomes (O) either social (e.g. mariners' compliance level to the regulations) or ecological (e.g. collisions with whales) resulting from these interactions can be measured or tracked to a certain extent.

There exist numerous feedback loops that can affect the dynamics of SESs, identified in Figure 0.2 by unidirectional arrows stemming from O towards the four subsystems. For instance, the recurrence of undesirable behaviours (O) from whale-watching captains (U) in the 1990's partly contributed to the justification of the SSLMP creation in 1998 (GS) and to regulations in 2002 (Parks Canada, 2002) to limit abuses. Resource-wise, habitat abandonment could hypothetically be observed in whale populations exposed to disturbance if energetic costs would reveal greater than the energetic benefits drawn from foraging preys in the area. The complex set of feedback loops driving the dynamics of an SES must be understood to diagnose correctly some undesirable outcomes (Liu *et al.*, 2007).

0.1.3.3 Special concerns

Both SSLMP and SLEMPA aim to ensure the conservation of marine mammals including their habitat. Several sources of concern have been identified in relation with the maritime traffic in the area. The threatened St. Lawrence beluga (~1000 individuals) and endangered Northwest Atlantic blue whale (~250 mature individuals) populations do not show any sign of recovery despite 30 years of conservation efforts (Beauchamp *et al.*, 2009; Hammill *et al.*, 2007). It is challenging and perhaps futile to try identifying a sole factor responsible for the stagnation or decrease in whale populations since cumulative impacts apply. Noise, collisions, entanglement in fishing gears, and water pollution are commonly identified as major threats for the St Lawrence whales (Beauchamp *et al.*, 2009; Hammill *et al.*, 2007; Savaria *et al.*, 2003).

Currently, the only speed restricted area within the study region is 25 knots in the SSLMP (no limit elsewhere). However, at 25 knots, any collision would be lethal for a struck whale (Vanderlaan and Taggart, 2007). In the St. Lawrence Estuary, at least 46 collisions (including non-lethal) have been recorded (reports and carcass necropsies) between 1993 and 2009 (Parks Canada, Group for Research and Education on Marine Mammals-GREMM, Réseau québécois d'urgences pour les mammifères marins-RQUMM, unpublished data) with an average of approximately 3 detected collisions a year: Fin whales account for 43% of the collisions, beluga whales for 23%, with 28% for the other rorqual species altogether. Moreover, collision scars have been observed on at least 5% of the individual blue whales observed in the St Lawrence waters (Beauchamp *et al.*, 2009). Since evidence suggest that these data reflect only a fraction of all collision events, mitigation measures are needed to protect whale populations for which the loss of any individual is critical to their recovery (Beauchamp *et al.*, 2009; Kraus *et al.*, 2005) and to prevent healthy populations from becoming impacted critically.

Regarding the St. Lawrence beluga, whereas specialists consider that a major factor explaining the lack of recovery in the population is related to their polluted habitat (16% primary cause of death due to carcinoma vs. 6% for collisions) (Hammill *et al.*, 2007, p. 6), they agree that collisions, boat noise and disturbance are actual threats that must be mitigated (Demers, Bouchard and Beauchamp, 2010). However, several studies have highlighted the need to mitigate whale disturbance by boats in the St. Lawrence (Lesage *et al.*, 1999; Michaud and Giard, 1997; 1998). Other studies on anthropogenic noise within the St. Lawrence led to the identification of zones where whales are subject to high levels of such noise (Simard, Lepage and Gervaise, 2010; Simard, Roy and Gervaise, 2008). Despite the regulations enforced by the SSLMP wardens (Parks Canada, 2002), the high number of whale-watching excursions in the region (Chion *et al.*, 2009; Michaud *et al.*, 1997) and the frequency of their close encounters with belugas are adding to the list of stressors exerted on targeted populations (Beauchamp *et al.*, 2009).

In summary, large ship strikes seem to occur mainly with large whales (rorquals) and to a lesser extent with belugas (possibly due to the difficulty to detect them) in the study area. Detected collisions with belugas have been reported mostly for small commercial fast-moving vessels in areas where they congregate. Marine protected area managers from both Parks Canada Agency and DFO came to the conclusion that, whether or not collisions affect belugas in a major way, the number of co-occurrences should be reduced and boat speed lowered to decrease whale exposure, whatever the species. They expressed some needs regarding the management of navigation activities, detailed thereafter.

0.1.3.4 Management needs

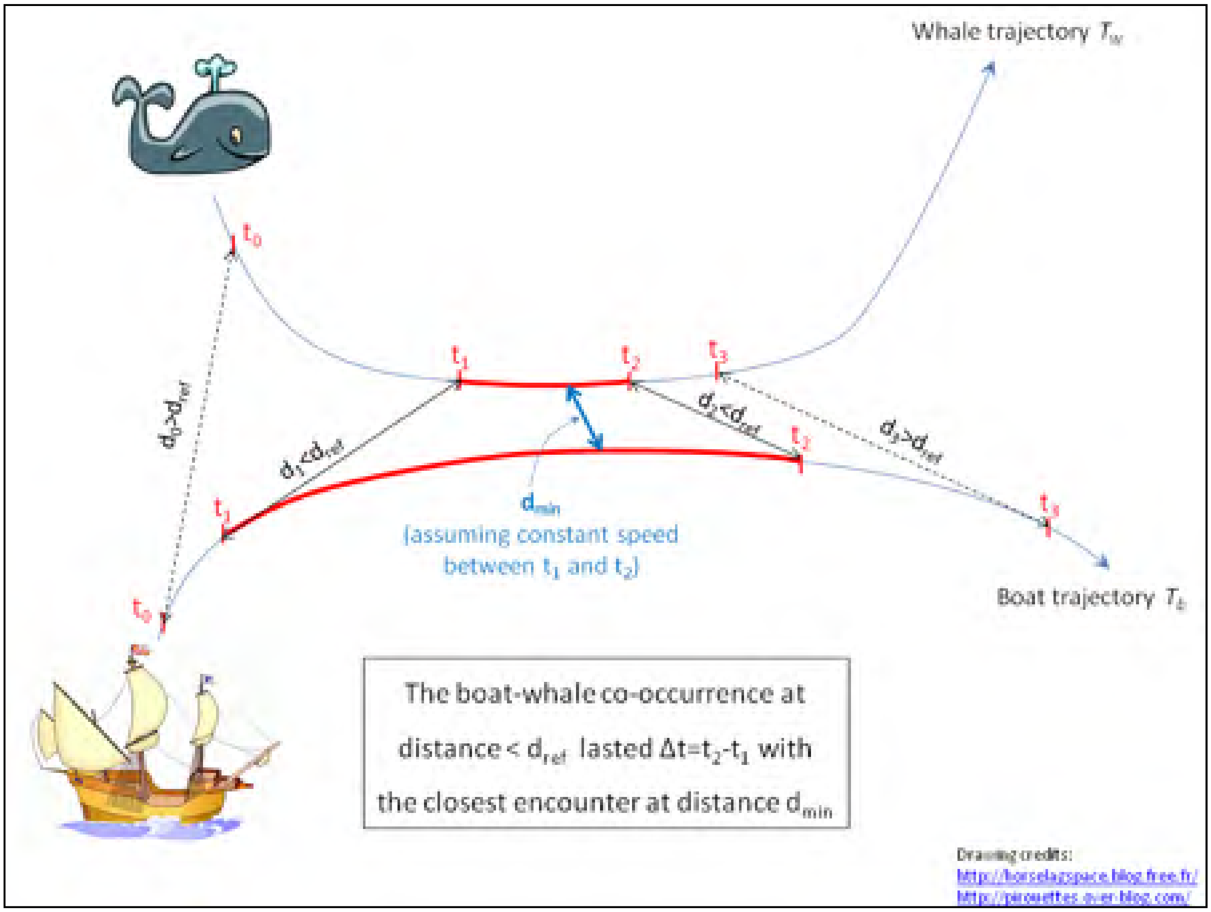
Canadian marine protected areas (MPAs) function under the adaptive management paradigm obliging managers to update their policy according to the most recent scientific advancements and knowledge. Incidentally, SSLMP managers are updating the 2002 regulations on marine activities at sea (Parks Canada, 2002), with the revised version expected in 2012. For their part, SLEMPA managers aim to gain a better understanding of the risk of ship strikes with marine mammals within the proposed MPA, in preparation of their upcoming policymaking agenda.

These management concerns have resulted in the following four explicit needs expressed by the managers of both MPAs:

1) Assess the effects of increased whale-watching boat traffic, particularly expanding the capacity of the Tadoussac marina, at the mouth of the Saguenay.
2) Assess the effects of rerouting maritime shipping vessels to the southern channel (i.e. southeast of Île Rouge) in the St. Lawrence so as to avoid the SSLMP area where rorquals congregate in large numbers to feed.
3) Assess the effects of the proposed zoning plan on traffic in the SSLMP and on the collisions potential between boats and whales.
4) Evaluate the effects of different shipping vessel speed scenarios and changes in maritime traffic lanes on the probability of collisions with whales.

For each of these four questions, several scenarios need to be tested; therefore the tool developed in this project should offer this functionality. Moreover, to assess correctly the performance of alternative management scenarios, some metrics need to be developed to facilitate comparisons. According to the concerns expressed about whale conservation, the exposure of whales to boats in the area must be measurable. Whale exposure to boat is illustrated in Figure 0.3 with the concept of spatiotemporal co-occurrence between a boat and a whale (co-occurrence and encounter will be used interchangeably to refer to this concept). Several variables can be tracked to characterize such interactions in space and time, including the following:

- Type of boat involved in the encounter.
- Whale species involved in the encounter.
- Minimal distance between the boat and the whale during the encounter.
- Boat speed at the minimal distance during the encounter.
- Duration of the encounter closer than a given distance.
- Localization of the encounter.
- Overall risk of whale mortality in case a collision occurs (by species).
- Overall number or/and total time of encounters.
- Distribution of encounter durations by whale individual.



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http://pirouettes.over-blog.com/

Figure 0.3 Illustration of the concept of boat-whale spatiotemporal co-occurrence (or encounter) at a distance $d < d_{ref}$, with d_{ref} a reference distance fixed for a given analysis.

Therefore, the development of a spatially-explicit simulator of boat and whale movements and interactions has been proposed to address the needs expressed by MPA managers. The present thesis is part of this modelling endeavour.

0.2 Thesis goal

SESs can be modelled using the agent-based modelling (ABM) technique (Bonabeau, 2002; Janssen and Ostrom, 2006b; Parrott, 2008). A prototype of whale-watching activities in the SSLMP was developed using this approach prior to the current project (Anwar *et al.*, 2007). This prototype was a proof of concept addressing the issue of cooperative vs non-cooperative behaviour of whale-watching captains with related impacts on whales. The prototype was not based on behavioural data either for whales or for captains, nor was it validated: hence, it could not be used to address the above-mentioned management needs.

Incidentally, the ultimate purpose of this thesis project is to implement a spatially explicit agent-based model (ABM) of the critical maritime traffic components coupled with an individual-based model (IBM) of the St. Lawrence whales (Lamontagne, 2009), suitable to support MPA managers by shedding light on the four aforementioned issues (section 0.1.3.4). The larger project of which this work is a part is named the *Marine Mammals and Maritime Traffic Simulator* (3MTSim) project, described in CHAPTER 1.

The development of any simulation model (such as an ABM) of a real system dedicated to a real-life application is much more than programming (Sargent, 2005). It requires acquiring an in-depth understanding of the system to be modelled as illustrated by the modelling process in Figure 0.4.

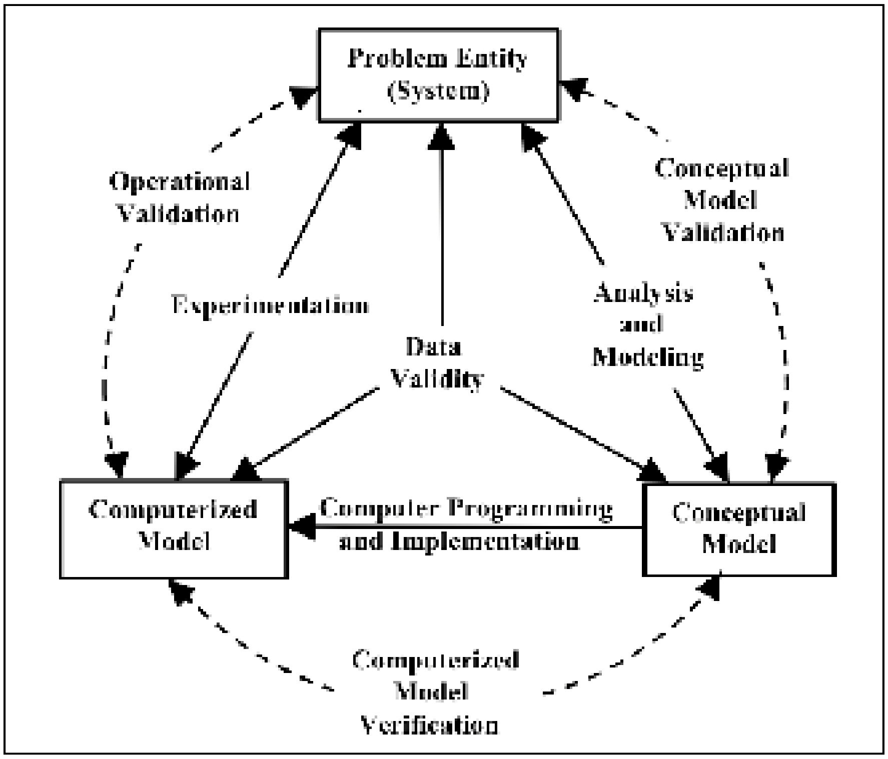

Figure 0.4 Overview of the modelling process.
Reproduced from Sargent (2005)

The development of the ABM of boat movements presented thereafter followed the process presented in Figure 0.4 (Sargent, 2005). Valid data lie at the center of the modelling process.

Analyses of valid data about the system to model (i.e. the 3MT-SES) lead to the development of a conceptual model that must be valid (i.e. relying on reasonable theories and assumptions). Then, the model can be implemented from the conceptual model according to a set of specifications. Model verification must lead to the correspondence between the conceptual model and the effective computerized model. Finally, the operational validity related to the modelling purpose is checked through analyses made on the simulation results. An overview of the problematic and methodology associated with these different steps is presented thereafter with an in-depth discussion in section 1.3 (in CHAPTER 1).

0.3 ABM problematic and methodology

Several challenges underlie the building process of an ABM dedicated to the management of a SES. These challenges belong to one of the following three broad categories:

1) Build a valid model.
2) Ensure model acceptance and trust by the future end-users.
3) Technology transfer.

Each of these issues must be dealt with appropriately to give the model/simulator the opportunity to be used for management purposes. Conversely, a failure to tackle one of them may jeopardize the final application of the model. A description of general objectives and methodology to follow in order to tackle these issues is presented in Table 0.1. The specific challenges and the methodology followed to build the 3MTSim's boat model are discussed later on in section 1.3 (CHAPTER 1).

Table 0.1 Overview of the objective and methodology relative to the building process of a model useful for management

Problematic	Objectives (challenges)	Methodology
Building a valid model	**UNDERSTAND THE SYSTEM** 1) Gain an in-depth understanding of the system's dynamics. 2) Elicit major interactions between system's entities, driving the dynamics. 3) Identify important factors affecting the system's dynamics.	• Identify key people and institutions. • Gather existing knowledge about the studied system. • Gather existing and available data. • Conduct appropriate analyses. • Identify missing data, plan field campaigns complying with ethical rules, and extract needed knowledge.
	IMPLEMENT THE MODEL 1) Build a valid conceptual model Acquire modelling skills. 2) Represent adequately human decision making in the model. 3) Use an appropriate validation framework.	• Ensure that the level of complexity induced by the conceptual model is manageable (appropriate level of abstraction). • Identify patterns of the system's dynamics through data analysis.
Ensuring model acceptance by the future end-users	1) Work in collaboration to develop a common understanding of the system's dynamics. 2) Stimulate end-users' active participation in modelling decisions (including interface). 3) Ensure that end-users' needs are well understood and accounted for.	• Communication and agreement of the concepts underlying the model (through regular meetings). • Communication and transparency about model's limitations. • Avoid modelling's technical details and jargon. • Share a common vocabulary.
Technology transfer	**DELIVER A USABLE SOFTWARE** 1) Design a user-friendly and ergonomic model interface. 2) Ensure cross-platform compatibility on basic operating systems. 3) Build easily runnable installers. 4) Maintenance and debugging.	• Favour a cross-platform programming language (e.g. Java, Lisp). • Clean all unnecessary details from the model's interface. • Use a versioning system to facilitate the management of model updates. • Organize training sessions with end-users.

Some of the challenges presented in Table 0.1 must be tackled simultaneously during the whole process. The first objective is to build a valid model able to address managers' needs. As previously discussed, data play a prominent role in the modelling process (cf. Figure 0.4). Collaborations for data sharing may take a while to be effective and should not be taken for granted until an agreement has been reached. Most of time, available data have not been collected for modelling purposes. Moreover, there could be some issues never investigated so far but crucial to address the management needs. Consequently, additional data may have to be collected in the field to meet this need. Once a fairly good understanding of the target system has been gained via data analyses, a conceptual model can be built followed by the programming phase.

The best model could be useless if managers do not feel comfortable with the idea of using it. This highlights the importance of information sharing with end-users during regular meetings. The degree of end-users' involvement in the modelling process will have an impact on their willingness to use it.

Finally, if the model is to be hosted on the end-users' systems, attention should be paid to technology transfer early in the process. Some software-related aspects such as the compatibility with various operating systems, visualization aesthetics, and a user-friendly and ergonomic interface could be necessary.

0.4 Outline

The 3MTSim simulator has been jointly developed by Philippe Lamontagne (whale model) (Lamontagne, 2009) and the author, Clément Chion, (boat model) with the contribution of several professors and students from École de techonologie supérieure (Montréal), Université de Montréal, University of Calgary, and non-academic partners: An updated list of contributors can be found in (Parrott, 2010). This manuscript-based thesis dissertation presents the key steps leading to the implementation of the 3MTSim's boat model as part of the 3MTSim project, fully described in CHAPTER 1. This dissertation is organized as follows. CHAPTER 1 is a description of the 3MTSim project with a focus on the 3MTSim simulator itself. CHAPTER 1 also presents the specific objectives, problematic, methodology, and contributions relative to the work presented within this dissertation. CHAPTER 2 is a literature review on agent-based modelling (ABM) and human decision making in cognitive sciences. The integration of cognitive science results for ABM building is one of the challenging tasks addressed in this work. CHAPTER 3 (manuscript submitted to the peer-reviewed journal *Ecology and Society*) presents an in-depth analysis of the social-ecological system of whale-watching activities in the SSLMP using an original framework, namely bounded rationality. More details on maritime traffic in the SSLMP region can be found in APPENDIX I (report submitted to Parks Canada). CHAPTER 4 (to be submitted to the peer-reviewed journal *Journal of Cognitive Engineering and Decision making*) presents some key elements of whale-watching captains' decision making resulting from an interview campaign led in 2007; these findings served to fuel both the whale-watching model development and its validation (cf. CHAPTER 6). CHAPTER 5 (conditional acceptance subject to revisions in the peer-reviewed journal *International Journal of Geographic Information Science*) presents an original path-planning algorithm called RayBaPP (standing for Ray-Based Path-Planning algorithm) developed to solve the pathfinding problem of captain agents. RayBaPP is a faster and more capable alternative to the classical A^* (Hart, Nilsson and Raphael, 1968) that was used within the prototype ABM (Anwar *et al.*, 2007). CHAPTER 6 (accepted in the peer-reviewed journal *Ecological Modelling*) presents the selection process of a valid model of whale-watching excursions based on the comparison of patterns (real vs. simulated). CHAPTER 7 (accepted for publication in the peer-reviewed book entitled *Whale-watching, Sustainable Tourism, and Ecological Management*) is an example of how the 3MTSim simulator can be used. CHAPTER 8 presents the details relative to the building of the shipping model. Finally, a conclusion and a description of limitations and future works end this dissertation.

CHAPTER 1

THE 3MTSIM PROJECT

This chapter is aimed at giving a description of the global 3MTSim project of which the work presented in this dissertation is an important component. Since the work presented in this dissertation is entirely related to the 3MTSim project, the specific problematic and methodology underlying this thesis along with author's contributions to the 3MTSim project are also presented herein.

1.1 Partners and contributors

The 3MTSim project has been partially funded by the NSERC strategic project program (2006-2009). It is a collaborative project mainly involving the following institutions:

- Three universities in charge of developing the simulator:
  1. École de technologie supérieure (Montreal).
  2. Université de Montréal.
  3. University of Calgary.
- Two federal department/agency, for whom the simulator is designed for management purposes, interchangeably referred to as partners and end-users:
  1. The Canadian department of Fisheries and Oceans (DFO): In charge of the proposed St. Lawrence Estuary marine protected area (SLE-MPA) whose limits are given in Figure 0.1.
  2. Parks Canada agency: Managing the Saguenay–St. Lawrence marine park (SSLMP) whose limits are given in Figure 0.1.
- Two non-governmental organizations (NGOs) interested in the simulator and data analysis are also referred to as partners and end-users:
  1. The Group for research and education on marine mammals (GREMM): The GREMM "is dedicated to scientific research on the St. Lawrence marine mammals and education for the conservation of the marine environment".

2. The Mériscope Marine Science Centre: The Mériscope “is a registered non-profit organization dedicated to research on marine mammals and conservation of the marine environment”. Its goal “is to promote field research and education in marine science and to raise public awareness about the effects of climate change and other human impacts on the marine environment”.

For the complete up-to-date list of people and institutions involved in the 3MTSim project along with their detailed contributions, visit the website at the following URL: http://www.geog.umontreal.ca/syscomplex/3MTSim/.

1.2 General description

1.2.1 Deliverables

The acronym 3MTSim, standing for marine mammals and maritime traffic simulator, is the name of the whole system presented in Figure 1.1. The *3MTSim system* encompasses two main components and additional sub-components delivered to partners, which are:

1) A spatially explicit ABM of maritime traffic and marine mammals’ movements occurring in the study area called the *3MTSim simulator* or *3MTSim (global) model*. It was implemented using Java 1.5 with Repast Simphony ABM libraries.
2) A georeferenced database (topmost box in Figure 1.1) integrating the available and acquired data on maritime traffic, whale movements, and spatial characteristics of the environment (e.g. bathymetry). This geospatial database served for the 3MTSim model calibration and validation, along with various additional analyses. It was set up using the ArcGIS’s Personal GeoDatabase (.mdb) database structure.

Additionally, two post-treatment sub-components were also built to process 3MTSim model output:

1) A toolbox designed for ArcGIS software v.9.2 called *3MTSim ArcToolbox*: This toolbox encompasses several functionalities to map model’s raw output, compute densities, and

create histograms relative to whales, boats, and their co-occurrences (cf. Figure 0.3). It was implemented using Python 2.4.

2) A java-based stand-alone module for data visualization and basic analyses.

For the sake of clarity, it is important to mention that the term 3MTSim alone refers to the global model (i.e. 3MTSim simulator).

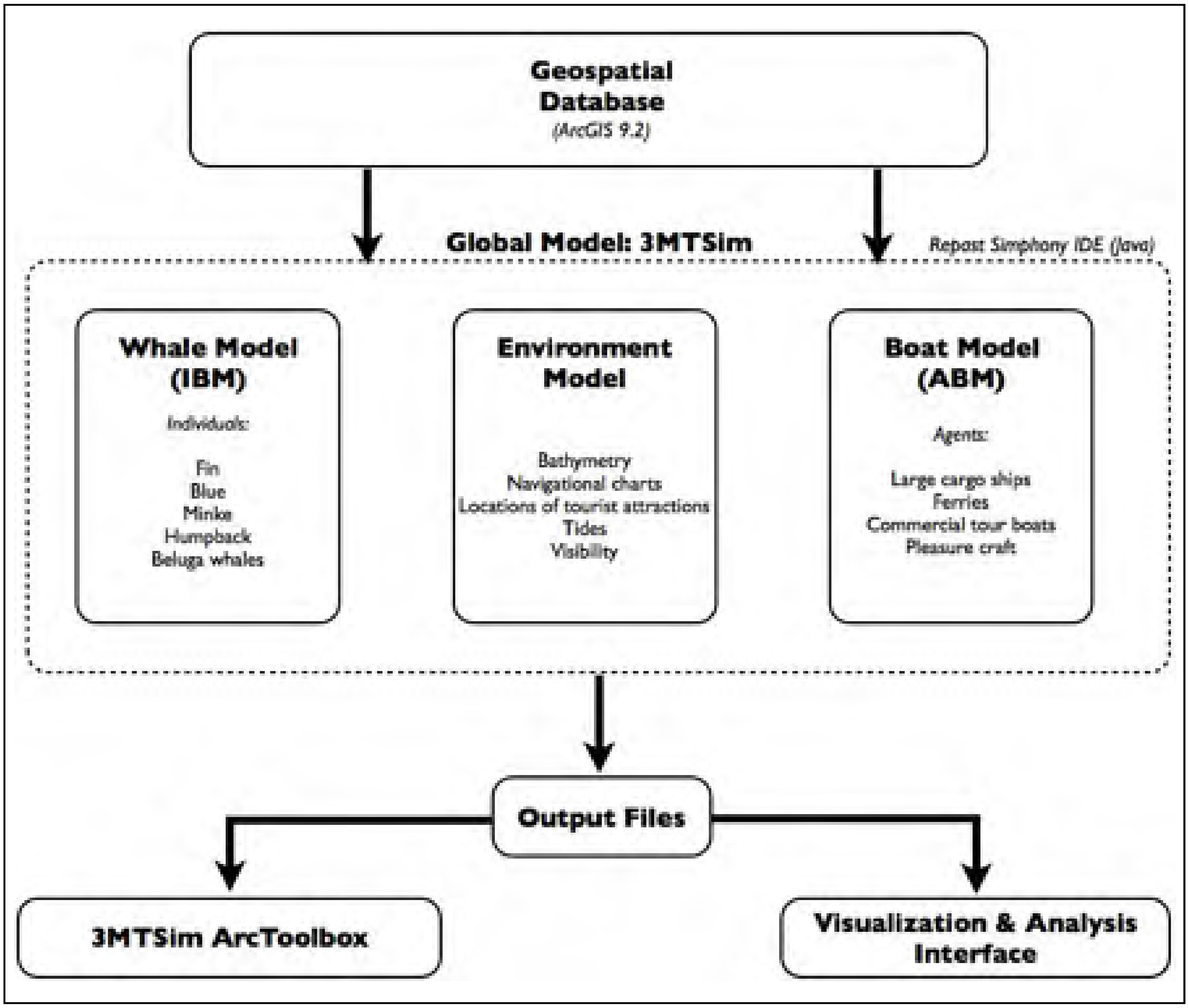

Figure 1.1 The 3MTSim system.
Reproduced from Parrott et al. (2010)

1.2.2 Data

As for any ABM dedicated to management, data are the cornerstone of the 3MTSim project. They are summarised in Table 1.1. Only the main datasets related to maritime traffic are discussed thereafter. For a further description, the interested reader will be referred to (Parrott *et al.*, 2010).

Table 1.1 Summary of data used in the 3MTSim project.
Adapted from (Parrott *et al.*, 2010)

Description	Year	Source
ENVIRONMENTAL DATA		
> Bathymetric and navigational charts	-	Canadian Hydrographic Service
MARINE MAMMAL DATA		
> 32 000 marine mammal sightings from whale watching boats (AOM database)	1994-09	GREMM, Parks Canada, DFO
> 80 whales (fin, blue and beluga) tracked by VHF (~ 380 hours)	1994- 08	GREMM, Parks Canada, DFO
> 140 focal follows (fin, blue, minke & humpback whales) tracked from land based stations (~100 hours of tracking for individuals followed for more than 30 minutes)	2008-09	C.C.A. Martins (Ph.D candidate,
> Areas of high residency (AHR) of the St. Lawrence beluga whales	2001-05	GREMM, modified from (Lemieux Lefebvre, 2009)
> 547 baleen whales sightings from transect surveys	2006-09	GREMM, Parks Canada, DFO
> Marine mammal habitat limits (from the Fish Habitat Management Information System)	-	DFO
MARITIME TRAFFIC DATA		
> AOM database: 2100 whale-watching excursions tracked by GPS (1-minute resolution) with contents sampling including the nature of activities (10-minute resolution)	1994-09	GREMM, Parks Canada, DFO

Description	Year	Source
> Monitoring of arrival/departure from the Baie-Sainte-Catherine quay	2007	Parks Canada
> PREVISION_INNAV database: Predicted trips of maritime traffic	2003-07	Canadian Coast Guard
> AIS_INNAV database: Real-time automatic information system tracking of maritime traffic (1-minute resolution)	2007	Canadian Coast Guard
> Seven semi-structured interviews with whale watching captains (following an excursion with the interviewee)	2007	Clément Chion (thesis author)
> One semi-structured interview with two St. Lawrence pilots (commercial shipping)	2008	Clément Chion (thesis author)
> Interviews and patrols with park wardens	2008-09	Clément Chion (thesis author)
> 15 hours of VHF radio monitoring	2008	Clément Chion (thesis author)
> AOM-transect dataset (15 excursions of small boats departing from Tadoussac): a systematic sampling of marine mammal observation integrated within the AOM protocol.	2009	GREMM, Parks Canada, DFO
> 180 questionnaires filled out by pleasure craft captains	2006	Daniel Gosselin (Parks Canada)
> 26 track sticks (GPS coordinates with a 1-minute resolution) of pleasure craft excursions	2006	Daniel Gosselin (Parks Canada)

1.2.2.1 Maritime traffic

Information about maritime traffic in Canadian waters is managed by the Canadian Coast Guard (CCG) via the INNAV system (Information on Navigation System). INNAV is a powerful integrated system that centralizes and archives real-time (e.g. radar) and prevision data about ship trips in Canadian waters. As illustrated in Figure 1.2, INNAV classifies vessels in 14 broad classes (first code letter in Figure 1.2) for a total of 78 subcategories, according to their main activity at sea. Two separate datasets extracted from INNAV's archives were available:

1) The PREVISION dataset: This dataset contains all planned trips of ships greater than 20 meters in transit in Canadian waters. The CCG has created a mesh of control points covering all Canadian waters, including ports, anchorages, and numerous key offshore locations. For each planned ship trip in the PREVISION dataset, the estimated time of arrival (ETA) and estimated time of departure (ETD) at each control point lying on the planned course along with boat activity (e.g. cargo unloading, transiting upbound) at these points are available; ETA and ETD at each mesh point are updated up to 6 hours before ship passage near the next CCG's Marine Communication and Traffic Services (MCTS) centre on its route. Information such as the ship ID, company, type, size, maximum speed, draught, and cargo are also available in the PREVISION dataset. This dataset will be referred to as PREVISION_INNAV.
2) Automatic Identification System (AIS) dataset: AIS system transmits data about the equipped ship to all AIS receivers at a given detection distance on every minute. CCG's INNAV system receives these data and keeps them archived for 3 months, or more upon request (Daniel-André Delisle, INNAV manager, CCG, personal communication). Since May 2005, most ships (over 500 ton gross tonnage for non-international trips, and 150 ton gross tonnage carrying at least 12 passengers or over 300 ton gross tonnage for international trips) navigating in Canadian waters have to be equipped with AIS transponders. AIS data contain such dynamic information as ship position with related time and speed at a 1-minute resolution, along with static information including the ship ID, company, type, cargo, length, draught, port of departure, and country flag transmitted every 10 minutes. This dataset will be referred to as AIS_INNAV.

PREVISION_INNAV is an almost exhaustive count of the ship trips throughout the study area, from 2002 to 2007. AIS_INNAV is not exhaustive but contains the great majority of shipping-related trajectories in the St. Lawrence part of the study area, from March to November 2007. However, data are virtually absent in the Saguenay Fjord since the AIS signal is blocked by steep cliffs along the river. This is not a major flaw since the narrowness of the navigation corridor in the Saguenay induces a low spatial variability of ship routes. Moreover, ship speeds are estimated in the PREVISION_INNAV.

These two datasets were extensively used to draw an accurate portrait of navigation activities within the St. Lawrence Estuary (cf. APPENDIX I) and build the shipping model component of the 3MTSim simulator (cf. CHAPTER 8).

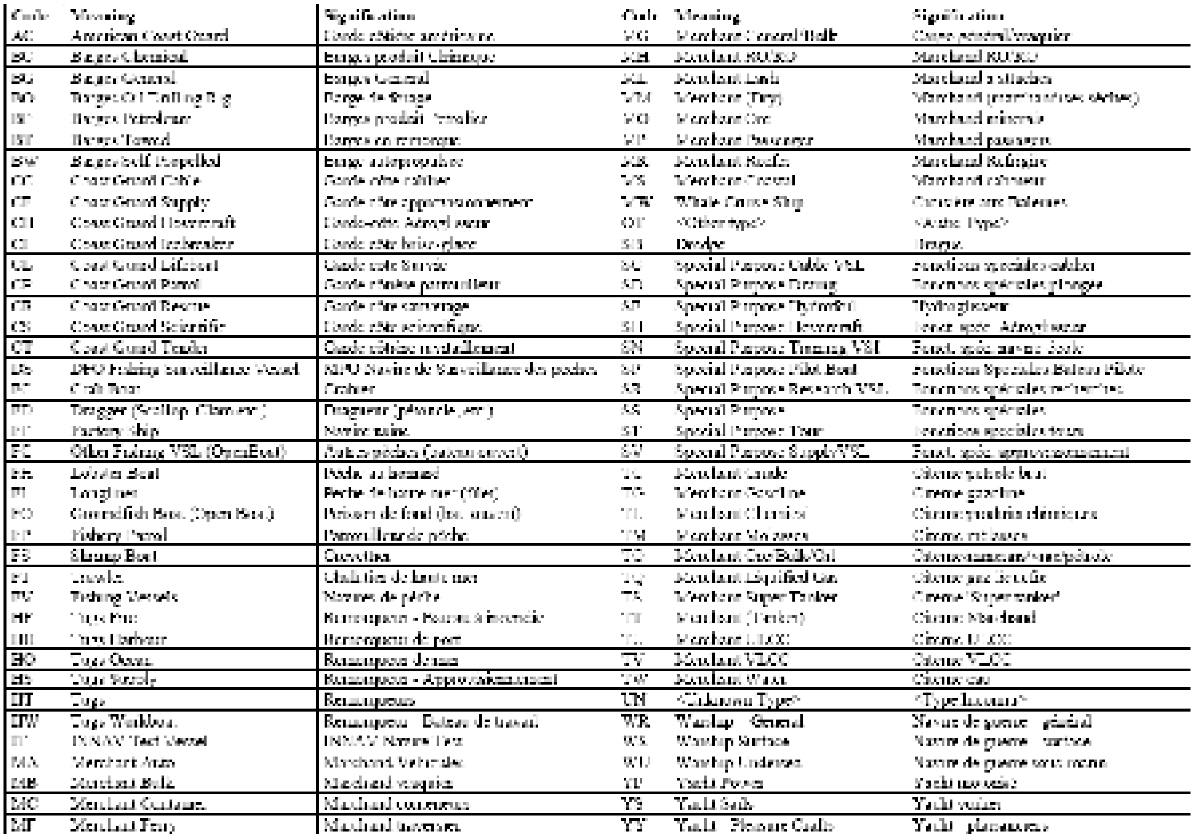

Figure 1.2 INNAV list of codes used for vessel type.

1.2.2.2 Commercial excursions

Commercial excursions are mostly dedicated to whale-watching in the study area. These activities have been monitored since the mid-80s via the ongoing AOM project (Michaud *et al.*, 1997). The current protocol used by the AOM monitoring program is in place since 1994. An overall description is given below. See (Michaud *et al.*, 1997) for further details about the AOM protocol.

Each excursion is tracked by GPS (including position, speed, and bearing) with a 1-minute resolution. Additionally, the excursion content is sampled with a 10-minute resolution, with recordings including the following features:

- Excursion activity: This mainly includes travelling, observing a pod of whale, observing landscape feature, observing pinnipeds or birds.
- Species observed: This includes targeted animals (focal) and surrounding ones.
- Number of animals by species in the surrounding (within 400m and 2000m).
- Number of boats by category in the surrounding (within 400m and 2000m).
- Visibility (distance) and sea state (wave height).
- Comments relative to specific events.

These data have been extensively analyzed during the investigation phase of the 3MT-SES (CHAPTER 3) and the building of the whale-watching model (CHAPTER 6).

1.2.2.3 Ferries

Data about ferry trips come from companies' schedules available online, and from the INNAV system (cf. section 1.2.2.1).

1.2.2.4 Yachting

Among the major navigation activities in the area (with commercial excursions, maritime traffic, and ferries), yachting is the least monitored with few spatiotemporal data. The source of data available for the 3MTSim project comes from a survey conducted in 2007 by the firm SOM[1] and Parks Canada (Gosselin, 2006). This survey was aimed at estimating the number of visitors in the SSLMP, thus including a special part dedicated to boater visitors (Gosselin *et al.*, 2007). Pleasure crafts' owners were joined in marinas where they were asked to fill in

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[1] http://www.som.ca/

a questionnaire on their sailing habits. They were also proposed to use a track stick (similar to a GPS recorder) during there next outing. In total, 26 track sticks have been matched with a filled questionnaire.

1.2.2.5 Data acquisition campaigns

Several field campaigns were carried out to gain an understanding of human decisions underlying the navigation's spatiotemporal patterns. Semi-structured interviews were always favoured since this format allows flexibility during the interview, along with the setting of a relaxed atmosphere. Finally, the monitoring of the public VHF radio channel allowed validating hypotheses regarding information sharing between boat operators. Additional shore- and boat-based (~30 excursions) observations with reports were made to construct and validate hypotheses.

Seven interviews (for a total of 7 hours and 51 minutes) were conducted in summer 2007 with whale-watching captains from seven different companies (out of nine approached) covering the main ports of the SSLMP with the goal of understanding how they make decisions at sea. All but one interview was conducted right after having taken part in an excursion operated by the interviewed captain: This gave the opportunity to clarify some abstract questions with concrete events having occurred during the excursion. After profiling questions (e.g. name, experience as a whale-watching captain, past companies), the main topics discussed during the interview were relative to goals and objectives, excursion planning, interactions with other boats, attitude in relation to the regulations, and influence of several factors such as weather conditions, species context (abundance and distribution), boat operated, and excursion time and duration.

Regarding the maritime traffic (mostly shipping and cruise ships), as described later in section 8.1 (CHAPTER 8), expert pilots are in charge of large ships' safe navigation upstream Les Escoumins (cf. Figure 0.1). In 2008, a 2-hour interview was then conducted with two pilots from the Corporation of Lower St. Lawrence Pilots (CLSLP) to understand the key aspects of their decision making process along with the rules governing their interaction with boats and whales in the area.

1.3 Problematic and methodology relative to the 3MTSim project

According to the thesis goal stated in section 0.2, the problem entity (or system in Figure 0.4) to be modelled here is the 3MT-SES, so the development of the boat model has been fuelled by the literature on SESs (e.g. Janssen and Ostrom, 2006b). The problematic of this study along with the methodology followed to carry out the development of the ABM of boat movements are presented below.

The simulator of maritime traffic to be built is the boat model subpart of the global 3MTSim simulator. An overview of the 3MTSim simulator is given in Figure 1.1 (dotted box in the middle). The boat model is connected to an IBM of whale movements (whale model in Figure 1.1) developed by Philippe Lamontagne (2009). As previously mentioned, the 3MTSim model is spatially explicit, thus containing a representation of the environment structured in layers of information, similar to a Geographic Information System (GIS). In its current form, only boats react to whale presence but whales' reaction to boats is expected to be introduced in the model at a subsequent development stage according to new data availability (Cristiane Albuquerque Martins, personal communication).

The actual problematic of this project is to move from a proof of concept to an ABM that could be an informative tool for management issues. To do so, an ABM must be empirically based on accurate data (Janssen and Ostrom, 2006a). Adequate data must be used at different stages during the development of the maritime traffic simulator, as illustrated in Figure 0.4. In summary, data are necessary to:

- Guide the modelling choices related to ABM implementation and calibration.
- Elicit the critical drivers of system's dynamics with suitable analyses.
- Represent relevant human decisions.
- Account for the determinants of critical human agents' decisions.

- Elicit agents' decision processes that produce observed outcomes, where relevant.
- Validate the simulation outcomes with patterns (i.e. non-random variations of the system's variables characterizing some aspect of its dynamics).

According to the general modelling process presented in Figure 0.4, intermediary steps (along with challenges) leading to the building of the 3MTSim's boat ABM are discussed below.

1.3.1 Gathering maritime traffic data

The maritime traffic in the study area has been classified into eight categories of activity, namely 1) commercial shipping of goods also called shipping (e.g. tankers, bulk carriers); 2) commercial cruise boats carrying passengers who spend at least one night onboard (e.g. The Queen Mary 2 ocean liner); 3) commercial excursions with no overnight stay (i.e. whale-watching excursions and coastal tours); 4) private yachting; 5) service boats (e.g. coast guard, pilot boats, dredge, research); 6) ferries; 7) kayaks; and 8) other rare activities (e.g. commercial fishing, military).

Spatiotemporal data are crucial to quantify maritime traffic and understand the patterns of use in space and time. No comprehensive database previously existed on maritime traffic in the region so that it had to be set up jointly with Samuel Turgeon, a research assistant in geography at Université de Montréal. Data were widespread among researchers and institutions so the first step was to locate them for acquisition either by collaboration or purchasing.

1.3.2 Characterization of navigation activities

This step is aimed at drawing an accurate portrait of the maritime traffic in the study area. For each navigation component, the characterization step encompasses the quantification of trips along with the identification of spatial patterns of use and temporal variability. Given the lack of data for the SLEMPA area and the predominance of documented boat-whale co-occurrences (cf. Figure 0.3) in the SSLMP, the investigation was mostly focused on this later area (cf. APPENDIX I).

1.3.3 Conceptual models

Model conceptualization is a mandatory step in modelling (cf. Figure 0.4). Given the results of maritime traffic data analyses and the availability of resources (time and money) for a field campaign dedicated to knowledge acquisition on navigation in the area, some conceptual choices had to be made in accordance with the MPAs management priorities (cf. section 0.1.3.4). Practically, the focus has been placed on three major components representing different modelling challenges, namely 1) commercial shipping; 2) commercial cruise boats; and 3) commercial excursions, including two distinct categories namely whale-watching and coastal tours. A specific conceptual model is built for each of these components. Other components of the regional maritime traffic will be added in a subsequent phase of development, beyond the scope of the work presented herein.

Analyses made on PREVISION_INNAV and AIS_INNAV 2007 datasets revealed little spatiotemporal variability for commercial shipping and cruises, as presented in APPENDIX I. Consequently, the modelling approach for these two components has been chosen to be purely statistical, as detailed later in CHAPTER 8.

For commercial excursions in the SSLMP, the analyses revealed an important spatiotemporal variability for whale-watching trips as a result of the captains' complex decision making processes (cf. APPENDIX I). It justified the need for an alternative modelling approach to that followed for the commercial shipping model. Therefore, a behavioural modelling approach based on captains' decisions was chosen for the whale-watching category of commercial excursions (cf. CHAPTER 6). Commercial excursions devoted to coastal tours and landscape viewing revealed to be mostly planned trips with predictable spatiotemporal patterns. Consequently, the modelling approach for landscape viewing excursions is similar to that of shipping and cruise boats.

1.3.4 Elicitation of captains' decision making

The spatiotemporal dynamics of maritime traffic is the footprint of boat operators' decision processes and outcomes. As mentioned in the previous paragraph, information about the decision making process of whale-watching captains is needed to build an accurate model of these excursions. To do so, as discussed in section 1.2.2.5, a survey campaign has been prepared following these steps:

1) *Define the key elements of the survey*. This step includes the identification of the targeted population, the choice of the survey method, the justification of the approach, and the building of the survey material, in compliance with the goals of the campaign and the state-of-the-art in survey research.
2) *Ensure that the survey campaign complies with the rules of ethics in research*. Preparation of an application for approval of the fieldwork campaign by both Research Ethics Committees of ÉTS and U. Montréal (cf. APPENDIX II).
3) *Plan the survey*. This includes all the logistic from planning of the fieldwork in the region, to making contact with the target population by mail.
4) *Conduct the survey*. Once authorizations are obtained from Universities and contacts with the population have been established successfully, the survey is ready to start.
5) *Interview transcription and analyses of verbatim.* Qualitative analyses can finally be performed to extract the knowledge for which the field campaign was designed.

Pilots from the CLSLP had to be met as well and an interview was obtained in summer 2008, following exactly the same process as for whale-watching captains.

1.3.5 Dynamics of the 3MT-SES

Whale-watching captains operating excursions in the study area are part of the 3MT-SES. Their decisions and actions at sea both affect and are affected by the other components of the system they are a part of. An in-depth investigation of the 3MT-SES components and their relations driving the observed dynamics is thus necessary to understand key elements of captains' decisions and model them adequately.

On the other hand, pilots from the CLSLP in charge of shipping have the priority in the majority of interactions at sea. Consequently, they rarely need to change their behaviour in reaction to smaller boats. Interaction rules with other ships are regulated by the International Regulations for Preventing Collisions at Sea 1972 (COLREGS) (International Maritime Organization (IMO), 1972).

1.3.6 Model implementation

The technical specifications about model implementation are summarized below:

- The model is implemented in Java language (1.5) as it enables cross-platform programming.
- The Repast Simphony libraries (Argonne National Laboratory, 2008) are used to implement the ABM since performance for supporting spatially explicit models are good (Railsback, Lytinen and Jackson, 2006) and repast developers are actively providing online supports to a growing community of users (Argonne National Laboratory, 2008). The somewhat steep learning curve (i.e. initially low then increasing without bound) of Repast Simphony is counterbalanced by the high modelling flexibility.
- Eclipse is used as the software development environment (SDE) as it already comprises an integrated development environment (IDE) and can come bundled with Repast Simphony libraries.
- The ABM of maritime traffic must be merged with the IBM of whale movements developed by Philippe Lamontagne (2009) in a similar environment (Java 1.5+Eclipse+Repast).
- The global simulator 3MTSim should ideally be executable on a standard desktop.

1.3.7 Model verification

Verification is part of the developer’s job. This step is aimed at verifying that the code actually produces what it is intended to, according to the valid conceptual model (Sargent, 2005). It is a continuous process, which is done simultaneously as the code is growing. This is referred to as *Computerized model verification* within the modelling process illustrated in Figure 0.4 (Sargent, 2005).

1.3.8 Model validation

Validating an ABM is a challenging task (Janssen and Ostrom, 2006a). Data validity lies at the center of the modelling process (cf. Figure 0.4): It is defined as "ensuring that the data necessary for model building, evaluation and testing, and conducting the model experiments to solve the problem are adequate and correct" (Sargent, 2005). However, data are rarely perfect and flaws need to be identified to take the best advantage of available datasets.

Validation can take other forms. For instance, it was decided to put some important knowledge implemented within the model to the test of partner judgment, when their expertise was relevant (e.g. phase 3 in Table 4.1). This has the dual benefit of validating important model components while reinforcing end-users' trust in the model.

1.3.9 Model testing

Although the completion of simulations relevant for management is beyond the scope of this thesis, an application of the simulator is proposed in CHAPTER 7. The model's suitability to perform analyses for which it was built are also presented in (Parrott *et al.*, 2010).

1.4 Contributions to the 3MTSim project

The author's contributions to the 3MTSim project can be broadly split into technical, organizational, and communicational accounts.

The main technical contributions of the author to the 3MTSim project are mostly related to the stages leading to the implementation of the 3MTSim's boat ABM and the delivery of debugged system to end-users:

- Acquire the relevant knowledge to build an accurate model of boats (field campaigns, data identification, collection, and analyses).
- Implementation of the 3MTSim's boat ABM.
- Finishing touches to the global 3MTSim simulator, including overall debugging.
- Finishing of the post-processing 3MTSim ArcToolbox developed by Philippe Lamontagne.
- Delivery of the 3MTSim simulator in the form of a software: This includes all stages leading to the building of the installers with compatibility ensured for Windows 7, Windows XP, and Mac OS X operating systems.
- Delivery of the debugged version of the 3MTSim ArcToolbox.

Contributions related to organization/coordination within the "team" of contributors include:

- Coordination of the technical work.
- Supervision of several students in their work related to the 3MTSim project.

Finally, communication played a crucial role in this project, particularly with partners which had to be kept informed on a regular basis of advancements. This also includes public lectures to inform local people of the ongoing 3MTSim project:

- Coordination of regular meetings between partners and collaborators.
- Ensure partners' implication.
- Stimulate the data sharing effort.
- Scientific and public communications.

1.5 Description of the 3MTSim simulator

1.5.1 Visualization modes

Two visualization modes are currently available in the 3MTSim model:

1) 3D visualization mode (cf. Figure 1.3).
2) NASA World Wind embedded visualization mode (cf. Figure 1.4).

Visualization proved to be useful during model development where it allowed identifying flagrant bugs. It was also useful for communication purposes.

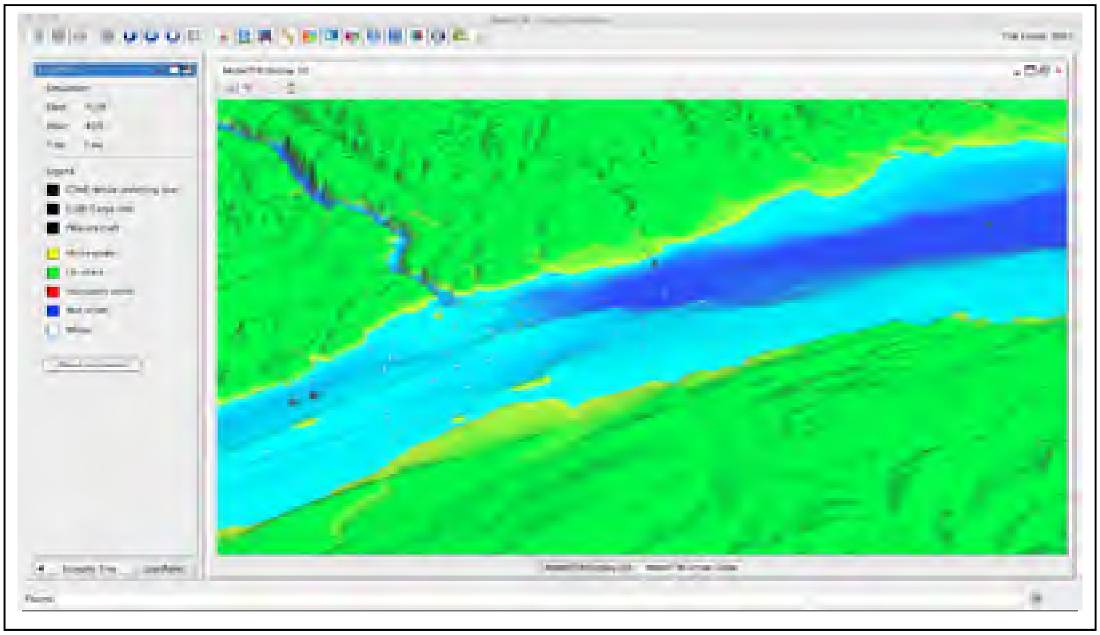

Figure 1.3 Snapshot of the 3D visualization mode
showing 3MTSim agents and environment.

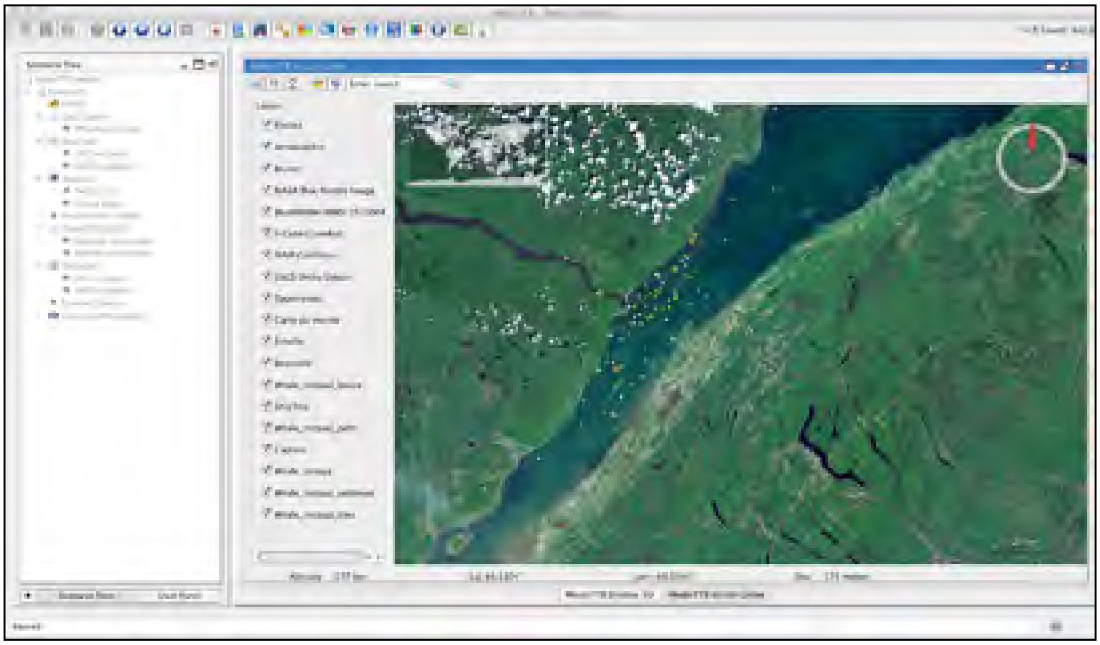

Figure 1.4 Snapshot of the NASA World Wind based visualization mode
showing agents and environment.

1.5.2 Model parameters

3MTSim's users have access to various parameters related to the management needs identified in section 0.1.3.4. These parameters are accessible via the parameters panel in 3MTSim's interface (cf. Figure 1.5). The following list of parameters is available to end-users:

- Maximum duration of an observation.
- Homeport for each company.
- A map of speed limits for each component of the maritime traffic.
- A map of restricted areas (zoning) for each component of the maritime traffic.
- Start date of the simulation.
- Duration of the simulation run.
- Number of individuals for each whale species in a given simulation run.
- Distribution map for each whale species in a given simulation run.

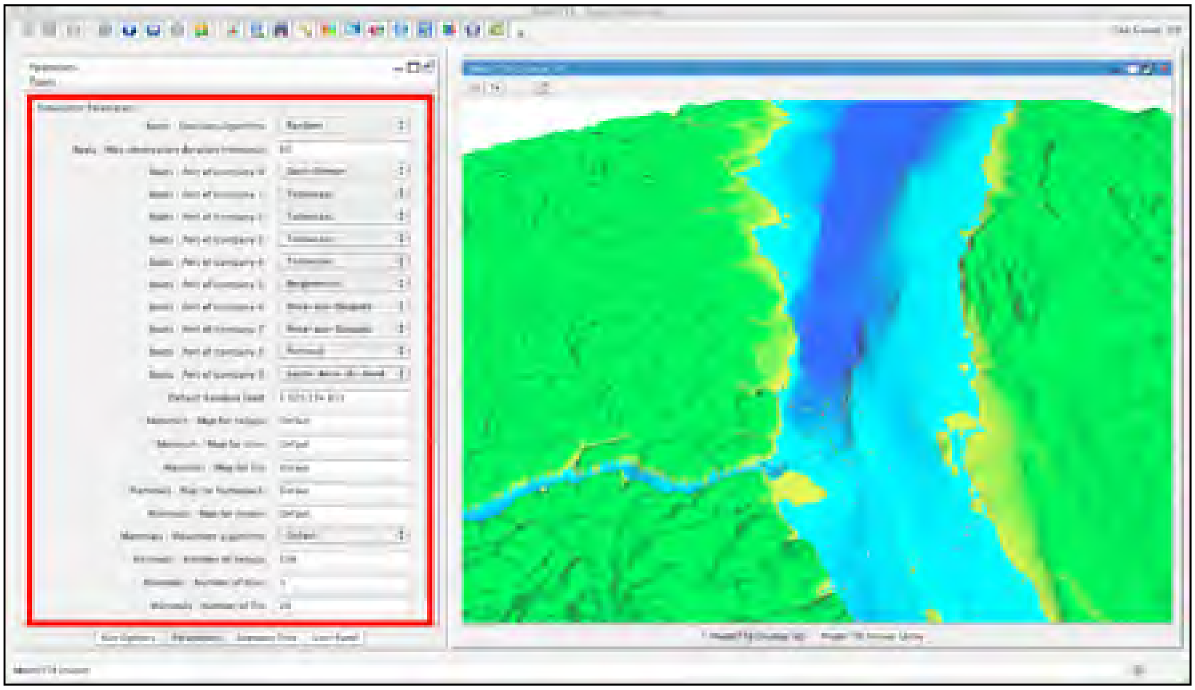

Figure 1.5 Snapshot showing the parameters panel (red box) within the 3MTSim's interface.

1.5.3 Post-treatment modules

The 3MTSim simulator returns ASCII files that need to be analyzed using some post-treatment modules. A first version of the 3MTSim ArcToolbox has been developed by Philippe Lamontagne after his master thesis. This toolbox is developed in Python with database operations processed with the AWK (originally UNIX-based) data-driven programming language. Debugging and finishing of the 3MTSim ArcToolbox have been carried out before its final delivery to end-users (cf. section 1.4). The interface of the 3MTSim ArcToolbox is shown in Figure 1.6. Data post-processing functionalities include:

- Maps of boat distribution by component or aggregated.
- Maps of whale distribution by component or aggregated.
- Maps of boat-whale co-occurrences for different distances and boat speeds.
- Map of whale observations.
- Histogram of the distribution for several variables of interest (duration of observation sequences, duration of whale exposure at different distances,…).

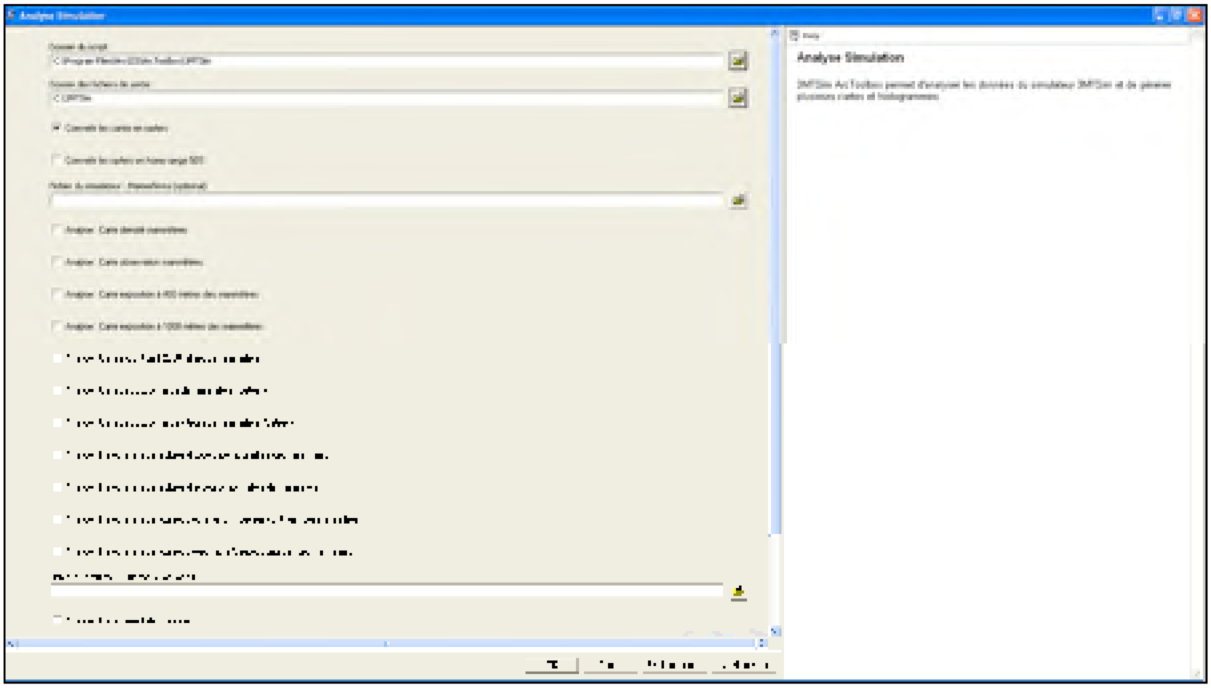

Figure 1.6 Interface of the 3MTSim ArcToolbox.

Some concrete illustrations of 3MTSim's post-treatment modules' capabilities are presented in CHAPTER 7, with more findable in (Parrott *et al.*, 2010).

The stand-alone visualization module has been developed in Java as part of Botao Zhens's Master thesis at the University of Calgary. All relevant information about this module can be found in (Zhens *et al.*, to be submitted in February 2011).

CHAPTER 2

LITERATURE REVIEW

2.1 Agent-based modelling

Agent-based modelling (ABM) is a simulation technique suitable to model complex systems made of autonomous entities (Bonabeau, 2002). The underpinning postulate is that the dynamics of the whole system to be modelled is an emergent property of interactions and decisions made by the components that make it up, without the intervention of centralized control. Accordingly, ABM focuses on the representation of agents' decisions and interactions and is labelled a bottom-up modelling approach. First, an overview of the historical milestones and terminology of the bottom-up modelling paradigm will be given. Then, the notion of software agents and the agreed properties of ABMs are presented. After an overview of ABM's applications, the section endswith a discussion on the current challenges of this modelling paradigm.

2.1.1 History and terminology

One can trace back the idea to model a system in a disaggregated manner to Boltzmann's contribution to the kinetic theory of gases in which it is postulated that gas macroscopic properties (e.g. temperature, pressure, volume) are the resultant of the microscopic molecular composition and motion (Boltzmann, 1909). Some people attribute ABM's roots to the 1940's with John von Neumann's cellular automata (von Neumann, 1947; von Neumann and Burks, 1966). Other influential contributors should also be cited when referring to the early developments of disaggregated modelling. First of all, John Conway's cellular automaton called Game of Life, or simply Life (Gardner, 1970), became famous by illustrating how complex patterns can emerge at the macroscopic level from a limited number of simple rules. In this game, each cell of a 2D lattice can have two states, alive or dead. The state of each cell evolves deterministically at each discrete time step (birth, survival, or death) by following four simple rules solely based on the neighbour cells' state. The emergence of a variety of spatiotemporal patterns has been paralleled with some fundamental biological patterns of living systems (e.g. Beer, 2004) and other natural phenomena (e.g. Bak, Chen and Creutz, 1989).

Schelling (Schelling, 1971) developed a cellular automaton-based model in an effort to study the issue of racial segregation in the United States of America's cities. He showed how a systematic local preference (even weak) for some "similar" neighbours can lead to the observed racial segregation in space at the global (city) level.

Axelrod (Axelrod and Hamilton, 1981) studied the importance of the cooperation strategy in human relations with his famous experimental tournament on the two-players iterated prisoner's dilemma problem (IPD). In this IPD tournament, he asked contenders to devise computer programs of the strategy to play at each round of the game. Interestingly, the most rewarding strategy called *tit for tat*, proposed by Anatol Rapoport, was also the simplest one (Axelrod and Hamilton, 1981). This strategy is simply to cooperate on the first round and then imitate his opponent's previous strategy on each subsequent round. Axelrod developed numerous agent-based models to study the questions of cooperation and altruism, culture dissemination, and other topics related to political and social sciences (Axelrod, 1997).

It was not until the late 1980's that the paradigm of disaggregated modelling took a place of choice in the research agenda, notably in ecology (Huston, DeAngelis and Post, 1988) where this paradigm took the name of individual-based modelling (IBM) (Grimm, 1999). The growing accessibility of powerful computers made possible the resurgence of the disaggregated paradigm (Marty Anderies, 2000), challenging the dominance of classical aggregated ecological models (Lotka, 1925; Volterra, 1931).

Many fields concurrently built on the disaggregated paradigm in their own way and only the most significant will be mentioned thereafter. Artificial life (A-life) (C. Langton (ed.), 1989) evolved simulation models to explain the origin of such essential biological phenomena as multicellularity, cellular self-organization, and the evolution of the genetic code (Bedau, 2003). Distributed artificial intelligence (DAI), a subfield of artificial intelligence (AI), focuses both on the collective resolution of problems by cooperating entities (distributed problem solving, DPS) and the study of autonomous agents and their individual functions within a system of interacting entities (multiagent systems–MAS– or multiagent-based simulation–MABS) (Hewitt and Inman, 1991; Stone and Veloso, 2000; Wooldridge and Jennings, 1997). The development of ABMs in social sciences built on DAI. An overview of ABM and social simulation history in social sciences can be found in (Macy and Willer, 2002).

Inspired by developments in DAI and A-life, environmental scientists developed ABMs under a great variety of names (Hare and Deadman, 2004) such as multiagent-based simulation (MABS), agent-based simulation modelling (ABSM), agent-based social simulation (ABSS), multi-agent simulation (MAS), agent-based simulation (ABS), or else individual-based configuration modelling (IBCM). All these terms coined by different groups of researchers are variations of the same broader concept of disaggregated modelling. This lack of consensus about terminology seems to reflect a non-mature technology still trying to get its bearings. For the sake of clarity, we will use agent-based model (ABM) as a general term to refer to these models. Recent developments have revealed a growing acceptance of ABM as the general term used to designate disaggregate models. The term IBM will be sometimes used to refer to ecological models representing non-human entities.

Following this presentation of the bottom-up paradigm's history and terminology, the notion of software agent underpinning any development in ABM is now discussed.

2.1.2 Agent

The central component of any ABM is the agent. In this section I focus exclusively on the notion of software agents, leaving aside the various meanings the agency concept bears in many fields (e.g. sociology, psychology, economics, or politics). Philosophical discussions about human agency can be found in the seminal work of Albert Bandura (1989; 2001).

Many definitions of what a software agent or autonomous agent is, or should be, have been proposed so far. Instead of enumerating all the variations on the theme of software agent, I will simply reuse the definition stemming from Franklin and Graesser’s comprehensive review (1997) who define an autonomous agent as “a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future”.

Synthesizing agents’ properties found in (Bousquet and Le Page, 2004; Ferber, 1999; Hare and Deadman, 2004; Jennings, Sycara and Wooldridge, 1998; Russell and Norvig, 1995; Stone and Veloso, 2000; Wooldridge, 1999; Wooldridge and Jennings, 1997) software agents should have the following properties:

- Autonomy: Control over its actions.
- Orientation toward a goal.
- Perception: Ability to get information.
- Communication: Ability to pass on information.
- Cognition: Ability to process information.
- Action: Ability to modify the state of the world (of other agents, itself and/or of the environment).

Franklin and Graesser (1997) made a review on agents and proposed a series of properties reused by several researchers (e.g. Jiang and Gimblett, 2002). According to this review, to differentiate agents from a generic program, an agent must possess some of the above characteristics:

- Reactivity.
- Autonomy.
- Orientation toward a goal.
- Continuously active across time.
- Communicative ability.
- Learning and/or adaptation ability.
- Mobility.

- Flexibility in actions.
- Character (exhibit some form of personality and emotional state).

Each of these properties can be more or less developed depending on the problem at hand. For instance, the cognition of an agent can be as simple as reactions to stimuli (Camazine *et al.*, 2001) or a more elaborated information-processing algorithms (Manson, 2006). This skeleton of a typical software agent can be enhanced by additional properties if necessary such as memory (Bennett and Tang, 2006) and adaptation and learning abilities (Weiss, 1996). For the modelling of humans, emotions (Prietula and Carley, 2001), belief, desire, and intention (BDI) (Dia, 2002; Rao and Georgeff, 1995), and negotiation skills (Courdier *et al.*, 2002) are sometimes also explicitly considered as software agents' properties. In summary, as long as an entity's property appears to be worth accounting for modelling purpose, if sufficient knowledge is available this property should therefore be included in the corresponding agent's description.

2.1.3 ABM properties

Bonabeau (2002) gives the three following reasons to use ABM instead of alternative modelling tools:

1) ABM captures emergent phenomena.
2) ABM provides a natural description of a system.
3) ABM is flexible.

According to Goldstone and Janssen (2005), ABMs possess the four following characteristics:

1) Computational description at the agent level: This characterises bottom-up modelling where the system's dynamics results from the description of agents and their interactions.
2) Stigmergic interactions: Stigmergy is a form of indirect communication between agents who modify their common environment and act upon it as a function of the past modifications (from all agents and external factors).

3) Autonomy of agents: Agents are autonomous and generally have their own goals, desires, beliefs and other psychological traits driving their actions. They can change their behaviour during a simulation through such processes as learning or adaptation.
4) Spatially distributed populations of agents: Most of ABMs consist of agents spatially distributed within a 2D or 3D representation of an environment.

Macy and Willer (2002) talking about applications in sociology attribute three similar properties to ABMs as Goldstone and Janssen (2005), but substituted the notion of spatiality for the assumption that agents must follow simple rules. This difference is inherent to the domains of application where the goals pursued are somewhat distinct.

According to Bousquet and Le Page (2004), a meaningful definition of ABMs (referred to as MAS in their review) for ecology and environmental sciences can be drawn from Ferber (1999), and is illustrated in Figure 2.1. Accordingly, an ABM must be composed of:

- An environment E (usually space).
- A set of objects O situated in E.
- A set of agents A (subset of O) which are active entities of the ABM.
- A set of relations R between objects (including agents).
- A set of operations Op that can be performed by agents.
- A set of operators (rules) designating the modifications induced by agents' actions.

As stated earlier, a software agent is situated within an environment (Franklin and Graesser, 1997). Accordingly, an ABM must include some representation of agents' environment, implicit or explicit. In its simplest form, an agent's environment is made of another agent with which it interacts as for the two-players IPD game (Axelrod and Hamilton, 1981). However, in many ABMs the environment is more elaborated with its own explicit representation (Parker *et al.*, 2003).

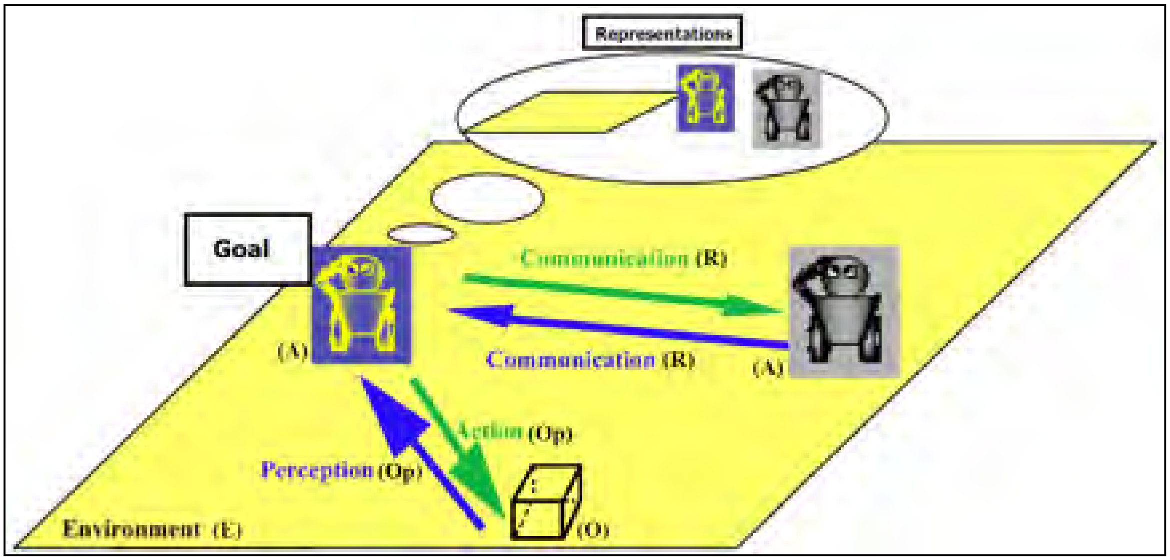

Figure 2.1 Components and properties of an ABM.
Adapted from Ferber (1999)

2.1.4 Applications

Brown and Xie (2006) make the distinction between two broad classes of ABMs (involving software agents only) according to their purpose:

1) *Representational* mode: In such ABMs, each agent must behave in a similar manner as a real entity (e.g. human, animal, institution, cell…). The ultimate purpose of these ABMs is generally to support decision makers in the resolution of complex problems related to the management of the modelled system, by means of simulations.
2) *Instrumental* mode: Here, the goal is to support a software user by reducing the cognitive and/or attention demand associated to certain tasks to be performed. Tasks processed by such agents can be the partial resolution of subproblems, real-time identification of missing information, and information search and retrieval (common in online applications). An example of such an ABM is proposed by Sengupta and Benett (2003) with the DIGME agent-based environment: this spatial decision support system assists the user to locate and retrieve spatial data and analytical models distributed on Internet, and transforms these spatial data for input in analytical models via the use of a GIS software.

Bousquet and Le Page (2004, p. 314) make the same distinction by simply distinguishing multi-agent simulations (*representational*) from other applications involving software agents (*instrumental*) such as in telecommunications and network management applications (e.g. Bieszczad, Pagurek and White, 1998).

Models belonging to the *representational mode* can be dedicated to address real-world issues or to explore theoretical questions. The maritime traffic simulator to build unarguably belongs to this class since it is devoted to simulations for management purpose. Consequently, the forthcoming section will focus on ABM of social-ecological systems devoted to support natural resource management. A brief discussion is proposed about the abundant literature on ABM relating to theoretical questions.

2.1.4.1 Theoretical use

The use of ABMs is not restricted to real-world applications. Numerous ABMs have been developed to address theoretical questions in various domains such as sociology (Axtell, Epstein and Young, 1999; Macy and Willer, 2002), computational economics (Testfatsion, 2006), organization theory (Prietula, Carley and Glasser, 1998), politics (Cederman, 2001), and psychology (Smith and Conrey, 2007). The vast number of studies using ABM to address theoretical issues will not be discussed further owing to the applied nature of the project presented in this dissertation. Rather, ABM applications involving human-nature interactions are discussed thereafter.

2.1.4.2 Management of human activities in SESs

ABMs have been applied to support the management of SESs mainly to mitigate human impact on natural resources (Bah *et al.*, 2005; Becu *et al.*, 2003; Mathevet *et al.*, 2003) or to increase the satisfaction of parks visitors (Gimblett, Richards and Itami, 2002). The first domain where ABMs have been widely used is the study of land-use and land-cover change (LUCC) (Matthews *et al.*, 2007; Parker *et al.*, 2003). Generally, ABMs for the study of

LUCC aim to elicit how contextual factors (environmental and institutional) influence landowners' decisions regarding the exploitation of their land properties (Deadman *et al.*, 2004) with the consequences on the environment (Manson and Evans, 2007). Many of these models involve farmers and agricultural systems (e.g. Berger, 2001; Manson, 2005). Reviews of ABMs use in LUCC studies can be found in (Matthews *et al.*, 2007; Parker *et al.*, 2003).

Fisheries management is also a field where ABMs are frequently used. Many of these ABMs have been developed to explore the effects of fishermen's strategy on the exploited resource (BenDor, Scheffran and Hannon, 2009; Cabral *et al.*, 2010; Dreyfus-Leon, 1999). Some of these models are designed to support the establishment of management policies dedicated to the conservation of fish stocks (Little *et al.*, 2008; Little *et al.*, 2009).

Gimblett and colleagues were pioneers in applying the ABM technology to support the management of recreational use, including parks (Gimblett, 2002; Gimblett, Richards and Itami, 2002; Gimblett, Durnota and Itami, 1996; Itami and Gimblett, 2001; Itami *et al.*, 2003; Roberts, Stallman and Bieri, 2002). The RBSim simulator has been developed to support the management of the Broken Arrow Canyon park near Sedona, Arizona. Numerous ABMs have been adapted from RBSim for the management of other terrestrial parks in the United States of America (Cole, 2005). Among these models, one can cite the GCRTSim which simulates river trips along the Colorado River (Roberts, Stallman and Bieri, 2002).

ABMs have also been used extensively in pedestrian modelling (Jiang, 1999; Torrens, 2007; Zhu and Timmermans, 2010b) and crowd behaviour (Pan *et al.*, 2007). These models usually involve human agents moving within urban environments with no direct link with any natural resource. However, the kind of decisions made by these agents is similar to that of human agents within 3MTSim (repeated spatial decisions with short time interval). Consequently, despite the absence of a natural resource to manage, the study of these models is relevant for the building of 3MTSim's agents.

Additionally, without being exhaustive, one can mention other ABM applications such as water management (Becu *et al.*, 2003; Schlüter and Pahl-Wostl, 2007), management of lake eutrophication (Janssen and Carpenter, 1999), urban planning (Baynes and Heckbert, 2009), the study of urban development and its implication on the surrounding environment (Monticino *et al.*, 2007), management of hunting activities (Bousquet, 2001; Mathevet *et al.*, 2003), and the development of management strategy to reduce the number of moose-vehicle interactions in the province of Quebec, Canada (Grosman *et al.*, 2009).

Reviewing ABMs of human-nature interactions developed for management purposes, it appears clearly that the involvement of stakeholders early in the building process is a key for a model's eventual use as a decision-support tool (Voinov and Bousquet, 2010). However, the participation of stakeholders during the whole process does not guarantee model utilization: A sine qua non is some form of model validation implying an accurate reproduction of humans' decision making within the software agents (Janssen and Ostrom, 2006a; Manson, 2002). These challenges are discussed within the next section.

2.1.5 Challenges in ABM

2.1.5.1 Representation of human decision making

The most widespread theory underlying the representation of agents' decision making under uncertainty is certainly the expected utility theory (EUT). For a good presentation of the EUT, the reader may refer to (Baron, 2004). Let us consider a decision problem where an option A yields X with a probability p_1 and Y with a probability p_2, the expected utility of the option A is $(p_1 \cdot X + p_2 \cdot Y)$. Therefore, in problems where the yielded return should be the highest, according to EUT, the decision maker needs to compare the expected utilities of all candidate options and choose the most rewarding one. Despite the mathematical convenience of EUT and other optimization methods, increasing evidence from applied psychology in real-world settings has demonstrated that humans' decision outcomes are rarely well described by what the theory of optimal choice is prescribing (e.g. Deadman and Schlager, 2002, p. 143; Kahneman, Slovic and Tversky, 1982; Klein, 2001; Tversky and Kahneman, 1981). Consequently, following researchers in psychology, ABM developers have begun to explore alternative theories to better represent humans' cognitive processes and decision outcomes.

Jager and colleagues proposed the consumat model (Jager *et al.*, 2000). In this model, an agent uses one of the four following behavioural strategies (cognitive processes) to make decisions, depending on the level of satisfaction expected and the uncertainty of the decision task:

1) Deliberation: the level of need satisfaction is low and the degree of uncertainty is low.
2) Social comparison: the level of need satisfaction is low and the degree of uncertainty is high.
3) Imitation: the level of need satisfaction is high and the degree of uncertainty is high.
4) Repetition: the level of need satisfaction is high and the degree of uncertainty is low.

The consumat model is interesting in that it is an alternative to classical models of *Homo economicus* (i.e. rational agents considered in economics) whose sole cognitive capability is the deliberation process, often assuming the maximization of expected utility from the EUT.

ABMs are widely used to model land-use/land cover change, particularly in agriculture (see Parker *et al.*, 2003, for a review). In these models, agents (typically households, farmers) make decisions about what to grow on each plot of land, on a yearly basis. The most commonly used theories underlying the representation of such decisions are the rational choice theory and a variant called the perfect rationality (Berger, 2001; Manson, 2006). Models such as statistical regression and maximization of expected utility are frequently used, with the assumption that agents have perfect cognitive abilities and have access to complete information (Myers and Papageoregiou, 1991). Manson explored genetic programming to determine the importance of a set of contextual factors in landowners' decision about land use in the Yucatan, Mexico (Manson, 2005). Using multiple years of data about land use and contextual factors (environmental and institutional), Manson fitted regression models based on historical data (training dataset) and tested them on data not used for the training stage. Manson later claimed that the genetic programming approach developed to represent agents' decision making matches the precepts underpinning the bounded rationality theory (Manson, 2006).

In LUCITA, a model of land-use/land-cover change in the Altamira region, Brazil, developers used non-evolving genetic algorithms to represent the decision of households (Lim *et al.*, 2002). The classifier system took into account labour force and capital availability to make a decision.

Itami used a fuzzy approach to model hikers' decisions arriving at trail junctions (Itami, 2002). Park visitors were divided into distinct groups with their own preferences. Using the analytical hierarchy process (AHP) (Saaty, 1987; Saaty, 1995), agents compute a score for each candidate trail according to a set of weightings which characterizes the group they belong to. Accordingly, agents from different groups can make different decisions, but agents within a given group will behave the same way.

The GCRTSim simulator represents the dynamics of rafting trips along the Colorado River (Roberts, Stallman and Bieri, 2002). The decision making of rafting guides is modelled using a hybrid approach involving expert knowledge and fuzzy logic among others; however, few details are available on this approach. The tendency to give only limited details or fuzzy information about the decision making models of human agents is frequent in the ABM literature.

Urban pedestrian modelling is another field where ABMs have been used extensively in recent years (e.g. Benenson and Torrens, 2004). Here again, the most widely used theory used to represent human agents' decision making is the rational choice theory with agents assumed to be utility-maximizers (Zhu and Timmermans, 2010b). However, similarly as for models of land-use/land cover change, new paradigms are now penetrating the field competing with the classical models. Zhu and Timmermans (2010a) used heuristics from the bounded rationality literature to model the *go-home* decision of pedestrians shopping in the city center of Beijing, China. They also proposed a framework in an effort to overcome three shortcomings of decision heuristics in bounded rationality, namely:

1) Dynamic selection of cues for decision;
2) Explicit modelling of the heuristic selection mechanism.
3) Modelling of individual differences (preferences).

The work conducted by Zhu and Timmermans (2010a; 2010b) appears to be one of the most advanced studies in terms of identifying and proposing solutions to the weaknesses of the bounded rationality theory for ABM.

2.1.5.2 Model verification and validation

Verification and validation are key steps for models devoted to aid decision makers (Sargent, 2005). In particular, they are mandatory steps in the building process of ABMs, notably in the context of SESs (Janssen and Ostrom, 2006a).

Manson defines *model verification* as the step where the software model is tested to ensure that the underlying programs are working normally (Manson, 2002). According to Manson (2002), *model validation* comes in two varieties which are:

1) Structural validation: the extent to which the model implemented represents the conceptual model. This is what Sargent (Sargent, 2005) called *computerized model verification* (cf. Figure 0.4).
2) Outcome validation: the extent to which model outcomes match representative observations of the real system. This is what Sargent (Sargent, 2005) called *operational validation* (cf. Figure 0.4).

It is not clear how *structural validation* and *model verification* refer to different concepts. On the other hand, Sargent (2005) proposes a preliminary step called *conceptual model* *validation*, which refers to the validation of theories used to conceptualize the target system (cf. Figure 0.4).

A valid model should ideally satisfy the following criteria, all related to verification and validation (Kwasnicki, 1999):

- Correctness: Match between structure and outcomes of the model and the target system. This relates directly to the concept of validation.
- Consistency: Match between the conceptual model and its implemented version. It also refers to the relevance of the theories underlying the conceptual model. This relates directly to the verification step.
- Universality: Model's ability to be applicable in contexts different from those defined by the calibration data. This concept is related to generalization.
- Simplicity: The simplest model should be preferred, all other things being equal. However, there is a trade-off between a useless oversimplified and an intractable overcomplexified model, called "the Medawar Zone" by some agent-based modellers (Grimm *et al.*, 2005).
- Novelty: Model's ability to create new knowledge about the system represented.

Valid data (i.e. adequate quality, representative sampling, and meet modellers' needs) are the centerpiece of all verification/validation stages (Sargent, 2005). This idea of solid data on which any simulation model should be grounded is also highlighted by Janssen and Ostrom in the particular case of ABMs representing SESs (Janssen and Ostrom, 2006a).

Relying on representative observations of the target system, Grimm et al. (2005) proposed the pattern-oriented modelling (POM) approach to build valid models. Patterns are defined as "observations of any kind showing non-random structure and therefore containing information on the mechanisms from which they emerge" (Grimm *et al.*, 2005). Using the POM approach and comparing model outputs with a set of observed patterns, a modeller can:

1) Determine an appropriate model structure. This is related to the notion of *structural validation*.

2) Choose among alternative theories. This is equivalent to *model selection*.
3) Choose values for the model's parameters. This can be referred to *model calibration*.

For the validation of spatial phenomena, there are several pitfalls that should be avoided (Parker *et al.*, 2003). Among them, the choice of the spatial resolution used for spatial comparison must be consistent with the resolution at which the model operates and data spatial resolution. Authors also mention the spatial autocorrelation issue and the required adequacy between the assumptions underpinning the verification/validation process and system's complexity. Abrupt changes observed in the system's behaviour should be explained by the conceptual framework implemented in the model, rather than linked to some model artefact. Finally, a great challenge lies in the validation of so-called abstract outcomes stemming from human interaction (e.g. trust, learning) since they are difficult to measure.

2.2 Insight into human decision making in cognitive psychology

Modelling human decision-making is central to ABMs involving human-nature interaction. Therefore, this second part of this literature review is an overview of the main streams of thought about human decision making in cognitive psychology.

2.2.1 Formalism

In this section, the focus is on multi-alternative/multi-attribute decision problems *P*. An alternative *S*, candidate solution of *P*, is characterized by a set of attributes $\{a_i\}$, also referred to as cues. The validity v_i of cue a_i, related to a decision problem *P* is defined by equation (2.1) below.

$$v_i = \frac{R_i}{R_i + W_i} \tag{2.1}$$

Where R_i represents the number of right (correct) inferences and W_i, the number of wrong (incorrect) inferences considering the cue a_i only.

2.2.2 Human decision making

A decisions is often referred to as a judgment about what to do (Baron, 2004). Decision making refers to the cognitive mental process resulting in the choice of a course of action.

2.2.3 Metaphors of the mind

Most cognitive psychology researchers of the last decades have focused on a widely accepted conception of the mind as a computer-like information-processing system. Newel and Simon (1972) were the pioneer of the new paradigm called the information-processing model of mind (Gigerenzer, 2000, p.31-47). This metaphor of the computer dates back to the early 60's *cognitive revolution* in the American psychology; it succeeded to the Enlightenment' view of rationality (i.e. intelligence) as a combinatorial calculus assuming *homo economicus* inhabited by a homunculus or demon. The acceptance of this theory of mind is observable in the computer science vocabulary used by cognitive scientists such as *encoding, retrieval, storage, executive processes, algorithms and computational cost.* The previously accepted metaphor of mind was the mind as an "intuitive statistician", stemming from the emergence and acceptance of another scientific tool, inferential statistics (Gigerenzer, 2000, p. 6-14). Brunswik was the first to coin the term "intuitive statistician" to describe cognitive processes in the mid 40's (Brunswik, 1943), but his vision only came to be accepted after inferential statistics had entered the field of psychology as a widely accepted analytic tool in the 60's (Gigerenzer, 2000).

2.2.4 Normative and descriptive models of decision making

The study of judgment and decision making is traditionally concerned with the comparison of judgments to standard rules coming from what are called normative theories (Baron, 2004). Normative theories for cognition aim to tell us how we ideally should or ought to reason, make judgments and decisions (Over, 2004). Theories such as formal logic, probability theory, utility theory (Baron, 2004), statistics, and decision theory are supposed to dictate the rules that we should follow in order to act in a *rational* way. In contrast, descriptive theories try to describe how people actually think. Discrepancies between descriptive results and the projections of normative theories are sometimes taken as the basis to conclude that people's reasoning is fallacious or biased (Kahneman, Slovic and Tversky, 1982). But the real question risen by Over (2004) could be summed up like this: "To what extent do normative rules really serve people's objectives in specific contexts?"

A third class of models are called the prescriptive rules (e.g. Baron, 2004). Prescriptive rules are sets of procedures that can be used to improve the compliance of observed behaviours with the normative theories when these theories can help us achieve our goals. According to Over (2004), Research in cognitive psychology and in judgment and decision making should not only tell us how close, or far apart, the outcomes of normative and descriptive models can be in human thought and decision making. It should also find prescriptions for transparent representations that enable people to be consistent with normative theories.

According to Over (2004), whether a theory, or one of its rules, is truly "normative" or relevant in some contexts depends on the definition of *rationality*. Since the study of decision making requires a definition of rationality, the next section presents the instrumental rationality, presupposed in most studies in judgment and decision making (Over, 2004).

2.2.5 Instrumental rationality

The definition of rationality used in this dissertation is the instrumental rationality, underpinning the works of such researchers as Herbert Alexander Simon (Simon, 1983), and Gerd Gigerenzer. In this view, rationality is seen as an instrument that helps us to achieve our goals. This perception of rationality can be traced back to Hume (1978) who wrote that "Reason is, and ought to be the slave of the passions, and can never pretend to any other office than to serve and obey them".

According to Over (2004, p. 5), "Instrumental rationality is presupposed in almost all discussions in cognitive psychology about normative rules and their proper application".

Rational action is a primary notion, from which *rational belief* and *rational inference* are derived (Over, 2004). People have goals as a result of their subjective desires, which are expressed in preferences that vary from person to person. According to Simon (1983, p. 7-8), the father of bounded rationality, "Reason is wholly instrumental. It cannot tell us where to go; at best it can tell us how to get there. It is a gun for hire that can be employed in the service of any goal we have, good or bad". Accordingly, reason cannot tell us to prefer an objective or another, but can help us to derive a relevant course of action to achieve our current goal. Baron (2000, p. 53) defined rational thinking as:

"…whatever kind of thinking best helps people to achieve their goals. If it should turn out that following the rules of logic leads to eternal happiness, then it is "rational thinking" to follow the rules of logic (assuming that we all want eternal happiness). If it should turn out, on the other hand, that carefully violating the laws of logic at every turn leads to eternal happiness, then it is these violations that should be called rational."

Having defined what rationality is standing for in this dissertation, the next section proposes an overview of alternative theories of human rationality.

2.2.6 Alternative theories of human rationality

According to Gigerenzer and Selten (2001a), the different visions of rationality can be split into two streams of thought, perfect rationality and bounded rationality, as illustrated in Figure 2.2.

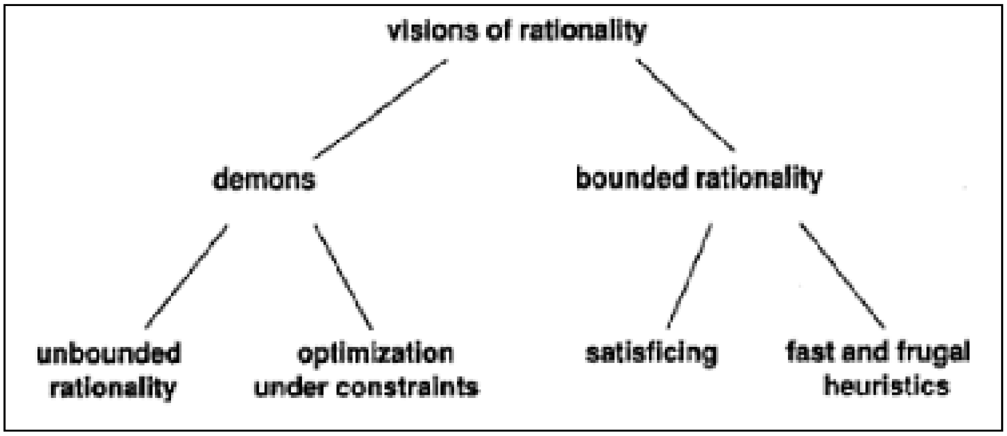

Figure 2.2 Different views of rationality.
Reproduced from Gigerenzer (2001, p. 39)

Models of "perfect rationality" are referred to as demons in Figure 2.2. From the two streams of thought, four different views of rationality are currently considered by researchers on decision making. These four paradigms (bottom of Figure 2.2) are described below:

1) *Unbounded Rationality*: This is the classical view of rationality with no consideration on time and computation limitations. Theories such as the maximization of expected utility or Bayesian calculation provide models currently used by advocates of this vision of human rationality.
2) *Optimization under constraints*: Similar to unbounded rationality but it is considered that the information search is limited by a stopping rule (i.e. stop when the searching cost exceeds the benefits that could be yield by continuing the search).
3) *Satisficing*: This has been proposed by Simon (1955) and belongs to the bounded rationality stream of thought. Satisficing consists of searching for alternatives until one satisfies some levels of requirement.
4) *Fast and frugal heuristics:* These heuristics consist of searching for cues to decide between alternatives (Gigerenzer and Todd, 1999). These heuristics are different from those proposed in the prospect theory (Kahneman and Tversky, 1979). Whereas the prospect theory describes heuristics as imperfect and humans' weaknesses (usually demonstrated in well controlled laboratory experiments), fast and frugal heuristics are described as adaptive shortcuts evolved by humans to deal with the real-world complexity (Gigerenzer and Selten, 2001b).

Gary Klein, a renowned researcher working on decision making in natural settings (e.g. experts), described the models of perfect rationality as fictions (Klein, 2001). In most real-world settings, it is virtually impossible to assess whether or not a choice is optimal because of time pressure, uncertainty or ill-defined goals (Klein, 2001, p. 103).

Whereas the perfect rationality paradigm has proved to perform poorly to describe human reasoning, researchers mostly agree that it provides acceptable normative models in situations where resources are not bounded. The distinction between normative models (how people *should* make decisions) and descriptive models (how people *do* make decisions) has been addressed by many researchers (Baron, 2004; Over, 2004; Wu, Zhang and Gonzalez, 2004) and was shortly discussed previously.

The emergence of bounded rationality as a direct alternative to classical decision theories motivates the presentation of models associated with this theory, the subject of the next section.

2.2.7 Models of bounded rationality: Cognitive heuristics

Logic, probability, and heuristics correspond to three periods in the history of the development of decision theories (Gigerenzer, 2008). The laws of Logic depict the mind as an "intuitive logician" focusing on truth preservation. This is the theory underlying most of Piaget's work (e.g. Inhelder and Piaget, 1999) and still advocated by contemporary cognitive scientists (e.g. Rips, 1994). The paradigm of the "intuitive statistician" underpinned by the laws of probability succeeded to the "intuitive logician". Finally, with the cognitive revolution, the emergence of the computer metaphor of the mind came with its new models describing human decision making. Cognitive heuristics were first described as a way to explain the discrepancies observed between what was still considered the normative laws of decision making and what was actually observed (Kahneman, Slovic and Tversky, 1982). Recent developments of some researchers have been challenging this negative view of cognitive heuristics as imperfect and fallacious mechanisms of the mind (e.g. Gigerenzer and

Todd, 1999). Several researchers in bounded rationality have been claiming that the decision maker has at his disposal a collection of heuristics in an adaptive toolbox (Gigerenzer and Selten, 2001a). This Darwinian-inspired theory claims that the heuristics contained within this adaptive toolbox may have been evolved through past experiences to solve real-world problems where decisions must generally be made in situations of time pressure, given incomplete information and bounded computational abilities.

Gigerenzer (2004) defines a model of cognitive heuristic as "a rule whose purpose is to describe the actual process – not merely the outcome – of problem solving". Heuristics exploit evolved capacities and structures of the environment, are distinct from as-if optimization models, and are simple compared to the learned capacities of the organism.

Several models of cognitive heuristic with their domain of application are now described. They can all be used to represent decisions in multi-attribute/multi-alternative problems and are all considered to be part of the adaptive toolbox proposed by researchers in bounded rationality from the Max Planck Institute (Gigerenzer, 2008).

The first well-known model of cognitive heuristic is the *satisficing* heuristic (Simon, 1955). Using satisficing, a decision maker selects the first alternative whose cues values satisfy given expectation levels (cf. APPENDIX VII). This heuristic is alternative-based, selective, and noncompensatory (all attributes do not have the same importance). It is an alternative to the optimization theory for high-stake decisions with no optimal solution.

The recognition heuristic (Goldstein and Gigerenzer, 2002) is defined as follows: "if one of two objects is recognized and the other is not, then infer that the recognized object has the higher value with respect to the criterion". The recognition is alternative-based, selective, and performs when the ignorance is correlated with the criterion considered. An instance of a decision problem where this heuristic works well is the case where someone is asked to tell which one of two cities in a given country has the largest population. If the decision maker knows only one of the two cities, he is expected to choose the known city, since the probability is low to ignore a populated city.

The lexicographic heuristic, also known as the take-the-best heuristic (Gigerenzer and Goldstein, 1996) starts by assessing the cue validities (i.e. to which extent a given cue value is correlated to a good decision). This step is a learning phase evolved with experiences by decision makers. After having ordered cues in decreasing order of their validity, a decision is made by comparing cue values of each alternative. This heuristic performs well in noncompensatory environments (Gigerenzer, 2004, p. 77) when cue validities vary highly, information is scarce, and redundancy is moderate to high (Gigerenzer, 2008). This heuristic is described in APPENDIX VII.

The minimalist heuristic is similar to the lexicographic heuristic, except that cues are picked randomly, with no regard on their validity. This approach is compensatory contrary to the lexicographic heuristic. It is used when time is extremely limited by considering cues as they come making the best of it (Martignon, 2001).

Other heuristics can be related to social behaviours. For instance, such imitation heuristics as *do-what-others-do*, *do-what-the-majority-do*, and *do-what-the-successful-do* are commonly considered to belong to the adaptive toolbox of decision strategies (Gigerenzer, 2008).

Some heuristics are considered to be part of the adaptive toolbox while not being frugal. For instance the Dawes' rule (also known as tallying) is a unit-weight linear model which simply computes the sum of binary cues favourable to the expected outcome (Dawes, 1979). This strategy performs well in environments where cue validities vary little (i.e. compensatory environments) with a low cue redundancy. This heuristic is described in APPENDIX VII.

Advocates of the adaptive toolbox claim that their heuristics are faster, more frugal and more psychologically plausible than their counterparts from the rational choice theory. However, such researchers as Newell oppose two major criticisms to the fast and frugal heuristic and adaptive toolbox theories (Newell, 2005):

1) The correct ordering of cues according to their validity (e.g. in the lexicographic heuristic) is not that fast and frugal since it presupposed a lot of processing.
2) The System 1 which is supposed to host those heuristics has supposedly a parallel architecture (Evans, 2008), meaning that it can process a lot of information simultaneously, making speed and amount of information unrelated (Chater, 2000). The interested reader may refer to (Evans, 2008; Sloman, 1996) to gain an insight into the various theories of dual-processing accounts of the human mind's functioning.

Moreover, Lee and Cummins (2004) highlight the fact that the frequentist approach used to compute cues' validity does not accurately account for the major importance of a cue that gave 150/150 times the good choice on all pairwise comparisons, over a cue that gave 1/1 time the good one (other cases being unable to discriminate). They both have a validity of 1 and would be considered equally by the lexicographic heuristic.

A vigorous debate is still underway between cognitive psychologists aiming to impose their decision models and theories as the main stream of thought (e.g. Lee and Cummins, 2004; Newell, 2005; Todd and Gigerenzer, 2000). A common strategy used by researchers is to consider others' performing models as instances of their own theory (Lee and Cummins, 2004; Newell, 2005). However, it is important to keep in mind that researchers usually admit that no unique theory is able to provide the best models for all decision problems (Gigerenzer, 2008, p. 20). Even regarding low-level theories of the mind, by relying on heuristics in general, we can more or less implicitly conform to the normative rules of logic, probability theory, or decision theory. But this does not mean that we are explicitly following those rules. There is a distinction between implicitly conforming to, or complying with, rules and explicitly following them (Smith, Langston and Nisbett, 1992).

2.2.8 Experts and professional decision making

There is a separation that has recently been drawn between on one hand the study of mechanisms involved in everyday's decision making and those of professionals in action. Traditionally, the study aiming at identify basic mechanisms underlying common decisions has been occurring in controlled setting (laboratories), with puzzles and problems sometimes designed to highlight failure in human judgment (Kahneman, Slovic and Tversky, 1982). Opposed to this approach, for more than 25 years, researchers have studied more deeply human decision making in action, giving birth to the field called Naturalistic Decision Making (NDM) (Endsley *et al.*, 2007; Klein, 2008).

There are eight factors commonly accepted as standards to characterize decision making in naturalistic settings (Montgomery, Lipshitz and Brehmer, 2005):
1) Ill-constructed problems.
2) Uncertain dynamic environments.
3) Shifting, ill-defined, or competing goals.
4) Action/feedback loops.
5) Time stress.
6) High stakes.
7) Multiple players.
8) Organizational goals and norms.

NDM researchers have proposed models and theories to describe cognitive mechanisms involved into real-world related decision making. Among them, one can mention macrognition (Klein *et al.*, 2003), recognition-primed decision model (Klein *et al.*, 1993), situation awareness (Endsley, 1995; Wickens, 2008), or mental models (Rouse and Morris, 1986). Although these theories have not been deeply explored for 3MTSim development, they provide research avenues both to investigate and model professionals' and experts' decision making.

CHAPTER 3

UNDERSTANDING SOCIAL-ECOLOGICAL SYSTEMS DYNAMICS THROUGH THE BOUNDED RATIONALITY LENS: INSIGHT FOR THE MANAGEMENT OF WHALE-WATCHING IN THE ST. LAWRENCE ESTUARY REGION, QUÉBEC, CANADA

3.1 Manuscript submission information

This article has been submitted to the journal Ecology and Society. Its status when this dissertation was submitted was 'in review'. The ordered list of authors who contributed to this manuscript is:

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2) Benoit Dubeau, M. Sc., Supervisor for resource conservation in the SSLMP, Parks Canada.
3) Robert Michaud, M. Sc., President of the GREMM.
4) Samuel Turgeon, Research assistant in geography at Université de Montréal.
5) Lael Parrott, Ph.D., Associate Professor and Director of the Complex Systems Laboratory in the Department of Geography, Université de Montréal.
6) Jacques-André Landry, Ph.D., Professor in the Department of Automated Production Engineering, École de technologie supérieure.
7) Danielle Marceau, Ph.D., Professor in the Department of Geomatics Engineering, University of Calgary.
8) Nadia Ménard, M. Sc., Ecosystem scientist in the SSLMP, Parks Canada.
9) Suzan Dionne, Expert in marine ecosystem management, Parks Canada.
10) Guy Cantin M. Sc., Oceans conservation, Fisheries and Oceans Canada.

Thesis author's main contributions to this work include the following:

- Elaboration of the methodology.
- Field data collection.
- Data analyses.

- Writing of the manuscript.

3.2 Abstract

Understanding the dynamics of social-ecological systems (SESs) for natural resource management is a challenging task which requires a broad range of competences from natural, social, and management sciences. Ostrom proposed a framework (Ostrom, 2009) to study SESs' sustainability. Re-using this framework, we propose an approach to investigate SESs' dynamics through the resource user's standpoint, based on the bounded rationality concept from Cognitive Sciences. Bounded rationality portrays humans' decisions as being determined by the combined effects of the problem's structure to deal with and the actor's cognitive limitations. The case study presented is related to wildlife-watching tourism, which is non-consumptive by nature but may threaten the targeted animals. We used the bounded rationality approach to investigate the SES of whale-watching excursions in the St. Lawrence Estuary, Canada. Excursions are the key link connecting the social and ecological subsystems. We focused our investigation on whale-watching captains' decisions since the dynamics of excursions are the footprints of these decisions. We started by identifying a set of critical patterns of whale-watching activities. Then, relying on analyses of multiple sources of data, we went backward through the causal chain of relations to identify mechanisms leading to potentially adverse decisions by captains. Our investigation revealed several relations between the core subsystems identified in Ostrom's framework, which could be considered to mitigate the identified issues. We showed that merging the bounded rationality concept with Ostrom's general framework can be insightful to support the sustainable management of SESs when resource users have little incentive to self-regulate. Interestingly, the bounded rationality concept taken as an investigation framework naturally fosters the unification of social and natural sciences for the study of SESs.

3.3 Introduction

Natural resource misuse is threatening a variety of ecosystems worldwide (Vitousek *et al.*, 1997). Elinor Ostrom (2009) proposed a general framework to analyze the sustainability of social-ecological systems (SESs). This framework (cf. Figure 3.1) identifies four first-level core subsystems (RS, RU, GS, and U) in interaction (I) producing a set of outcomes (O) with possible feedback effects, that may affect or be affected by other related socioeconomic, political (S), and ecological (ECO) settings. Each first-level subsystem is composed of multiple second-level variables such as the size of the resource system or the number of users (Ostrom, 2009).

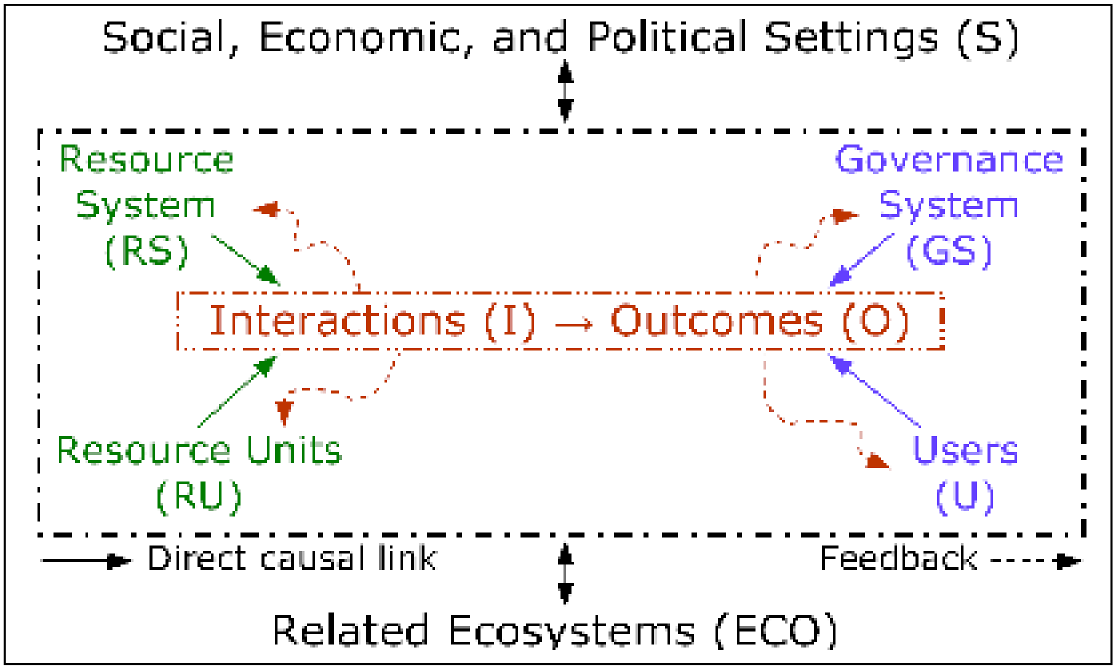


Figure 3.1 Ostrom’s general framework for the analysis of SESs’ sustainability. Reproduced from Ostrom (2007)

Ostrom’s general framework is an effort toward the development of an interdisciplinary approach to diagnose problems within SESs and propose adapted governance arrangements (Ostrom, 2007). There exist examples of SESs where resource users have developed self-organized systems of governance to ensure the sustainability of their practice (Berkes *et al.*, 2006; Dietz, Ostrom and Stern, 2003; Ostrom, 1990; 2009; Ostrom *et al.*, 1999). An example is the self-design of fishing rules by lobstermen in Maine. Following a critical drop in lobster stocks, co-management involving the small community of lobster fishers allowed to reach the goals set by government scientists leading to the population recovery (Wilson *et al.*, 1994; Wilson, Yan and Wilson, 2007). In other contexts, however, the implication of external management institutions in designing rules is required to restrict users' practices and avoid the Tragedy of the Commons (Hardin, 1968). For instance, the Community Natural Resource Management (CNRM) approach implemented in some nature reserves including Kenya and Nepal proved to focus mainly on socioeconomic benefits for local communities, failing to address adequately biodiversity protection (Kellert *et al.*, 2000). For SESs in which the achievement of sustainable practices is out of reach through users' self-regulation, resorting to top-down management does not guarantee the achievement of sustainability. Drawing on Ostrom's general framework and terminology (Ostrom, 2009), we propose an approach to identify the mechanisms leading to the deterioration of a natural resource by users' practices and ultimately support managing institutions in their conservation efforts.

Since users are the last link of the chain in any SES who act directly upon resource units, understanding their decision process can provide avenues to reduce negative impacts on ecosystems. Accordingly, the proposed approach is centered on the resource end-users, focusing on their interactions with the subsystems making up the whole SES they are part of (Ostrom, 2009). This approach is an extension of the bounded rationality concept drawn from the branch of cognitive psychology studying human decision making proposed by Simon (1990). According to Simon, considered the founding father of bounded rationality, *human rational behavior is shaped by a scissors whose two blades are the structure of the task environment and the computational capabilities of the actor* (Simon, 1990, p.7).

The widely used rational choice theory of human decision making postulates that a *demonic homunculus* located in the human brain ensures the delivery of optimal answers to complex real-life problems, complying with the normative rules of Logic, Bayesian reasoning or maximization of expected utility (Gigerenzer, 2001). Conversely, bounded rationality claims that, when a decision problem is complex, humans facing choices rarely use optimization procedures (i.e. find the best solution, assuming that one exists) but rather rely on a collection of heuristics that *satisfice* (i.e. find a good-enough solution) (Gigerenzer, 2008). These heuristics evolve through past experiences to provide the decision-maker with satisfying solutions according to his goal, expectations, limited cognitive abilities, and partial understanding of the complexity of the decision task at hand (Simon, 1955). We illustrate the concept of bounded rationality in Figure 3.2, showing the role it can play in analyzing an SES. The figure conceptualizes how the behaviours (i.e. decisions and actions) of natural resource users (e.g. fishermen) are simplified responses (but functional according to their goals) coarsely adapted to the complexity of the subsystems' characteristics they interact with (e.g. fish location, market demand, fishing quotas). Starting from critical patterns of use (i.e. outcomes) at the SES level, the bounded rationality approach is proposed as a general investigation canvas to backtrack the causal chain of relations down to the root causes. Given that interpreting the dynamics of complex SESs is challenging, we argue that the bounded rationality approach can be integrated into Ostrom's general framework to support such an investigation process.

In this article, focusing on resource users, we illustrate the suitability of the bounded rationality lens to complement Ostrom's framework (Ostrom, 2009) in the effort to identify the mechanisms that lead users to degrade ecosystems. To do so, we use the case study of the whale-watching SES in the Saguenay–Saint Lawrence Marine Park (SSLMP) in Québec, Canada. Thus, our work is in line with the idea to study SESs in light of human decisions (Beratan, 2007). We place the focus at the closest level to the natural resource, referred to as the micro-level in the terminology on the sustainable management of whale-watching activities (Higham, Bejder and Lusseau, 2009).

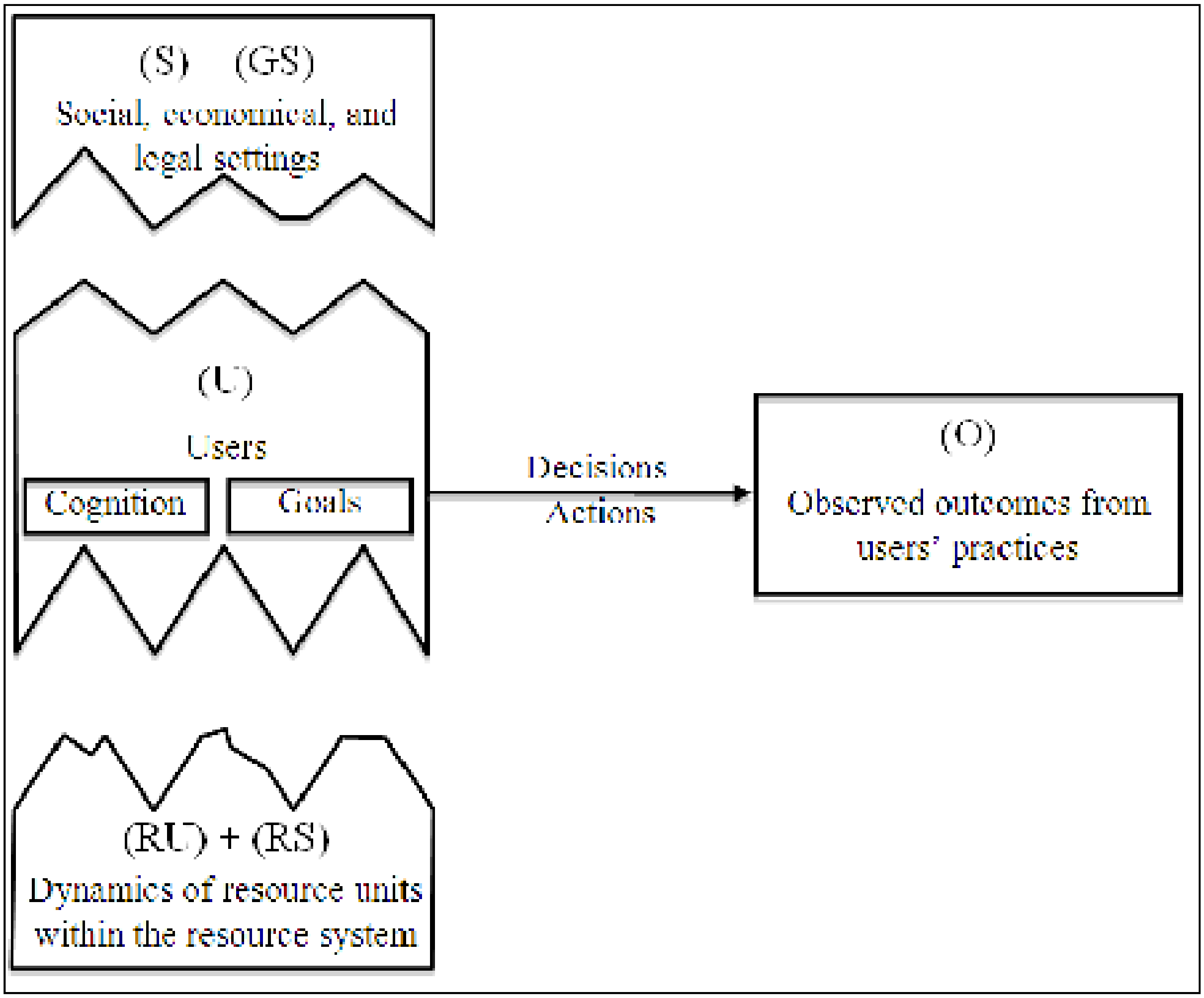


Figure 3.2 A conceptualization of bounded rationality applied to the study of SESs centered on natural resource users (U). This schema symbolizes the coarse adaptation of users (U) to the complex decision task defined by external subsystems (RU+RS+S+GS), producing the observed outcomes (O). The terminology used for the description of SES's subsystems is drawn from Ostrom (2009).

After a description of the studied SES, we detail our methodology. After an identification of critical issues associated with whale-watching activities, re-using the terminology presented in Figure 3.1 we apply the bounded rationality lens on the investigated SES and follow the trail from the known issues back to the causal interactions and characteristics of the constituent subsystems. We finish with a discussion of the results and general implications for the study of SESs.

3.4 Case study

Our case study is focused on whale-watching excursions operating in a marine park situated in the St. Lawrence estuary located in Québec, Canada. The estuary is an important summer feeding ground for up to 13 marine mammal species. One threatened resident population (COSEWIC, 2010), the St. Lawrence beluga (*Delphinapterus leucas*) inhabits this ecosystem with several migratory species including the endangered blue whale (*Balaenoptera musculus*), the fin whale (*Balaenoptera physalus*) listed as 'of special concern' under the Canadian species at risk act (COSEWIC, 2010), the humpback whale (*Megaptera novaeangliae*), and the minke whale (*Balaenoptera acutorostrata*). The regular presence of marine mammals have made the area renowned as one of the best places in the world for whale-watching (Scarapaci, Parsons and Lück, 2008). From May to October, around 10 000 commercial excursions get tourists closer to the whales, mainly between Tadoussac and Les Escoumins (Chion *et al.*, 2009). Added to this are about 40 000 kayak-based visit-days and 9000 trips of private pleasure crafts mainly concentrated within the Saguenay River, encompassing key habitats for the threatened beluga whale population (Michaud, 1993; Pippard, 1985).

In response to a long process of public pressure and subsequent consultations, Parks Canada (government of Canada) and Parcs Québec (government of Quebec) created the Saguenay–St. Lawrence Marine Park (SSLMP) in 1998 (Guénette and Alder, 2007), an area covering more than 1245 km^2 (Figure 3.3). In 2002, the Marine Activities in the Saguenay–St. Lawrence Marine Park Regulations was adopted, to be enforced by the Parks Canada team of wardens (Parks Canada, 2002). In 2004, the Department of Fisheries and Oceans (DFO) proposed a 6000 km^2 St. Lawrence Estuary Marine Protected Area project under the Oceans Act (*Oceans Act*, 1996), a proposal still in progress. Both marine protected areas aim to ensure marine mammal conservation including the protection of their habitat. Accordingly, the management of human activities including whale-watching is among their priorities.

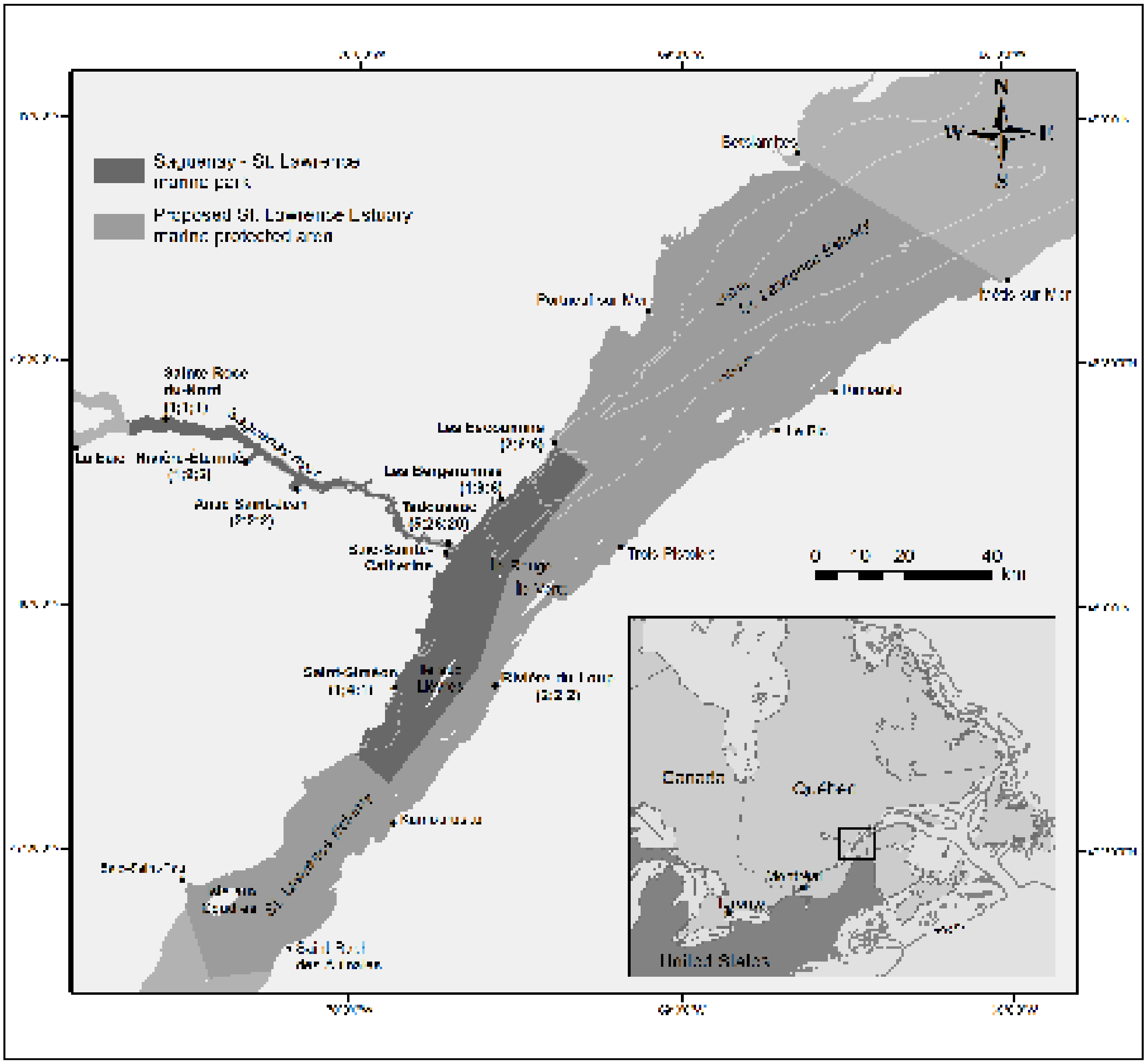
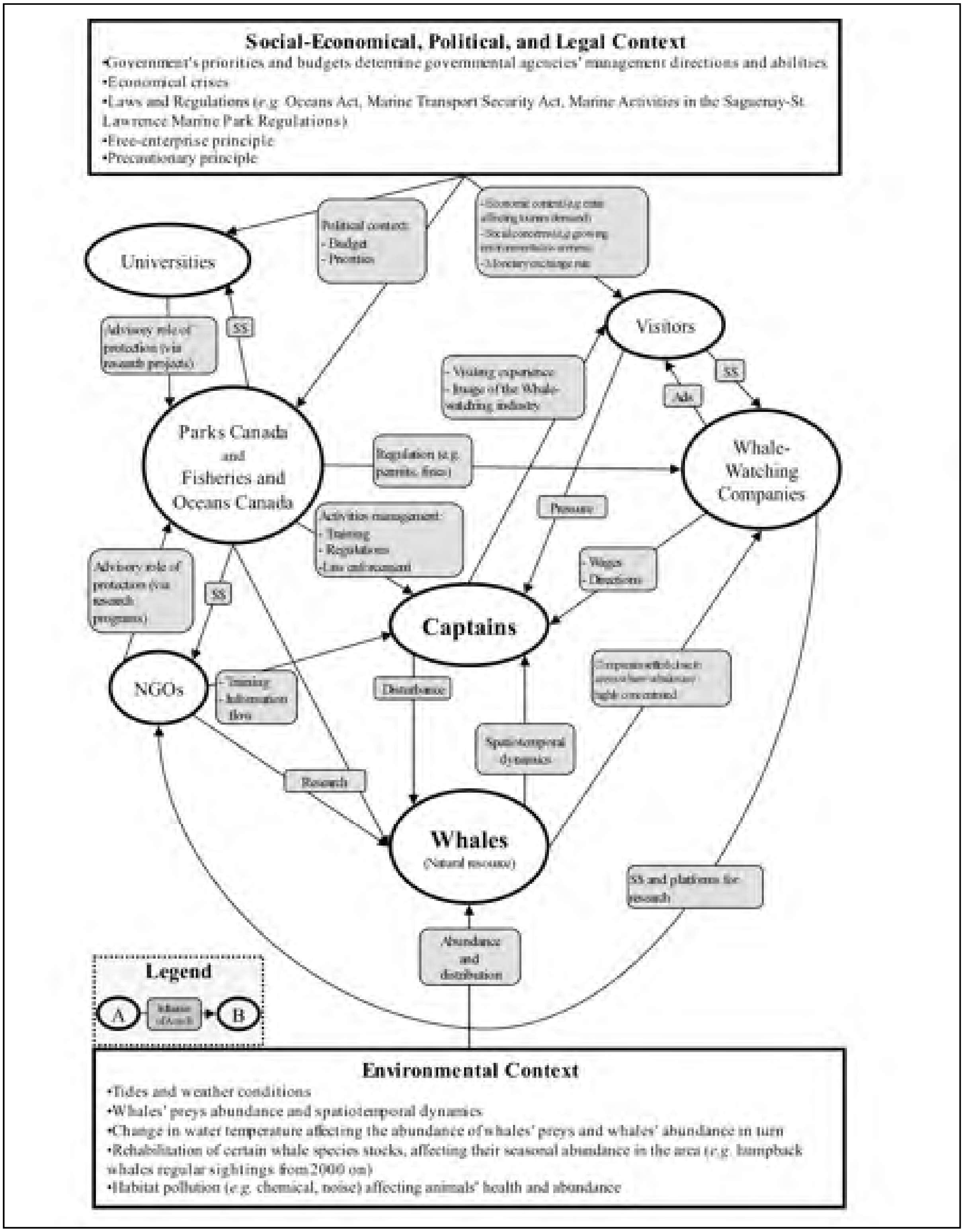


Figure 3.3 Study area. The toponyms in bold are towns serviced by whale-watching companies. The triplet (a;b;c) under toponyms stands for the number of a: companies; b: commercial excursion permits; and c: active boats in 2010.

In 2010, twelve operators were authorized to commercialize whale-watching excursions in the SSLMP for a total of 59 permits (Parks Canada, 2002). Forty-one boats operated in 2010 with capacities extending from 7 up to 800 passengers (cf. Figure 3.3). They generated an economic impact of US$ 98 million in 2009 (Gosselin and Priskin, 2009). While being a non-consumptive alternative to whaling and a potentially good way to increase the greater public's awareness of the importance of conserving marine ecosystems, a growing number of studies report on the negative impacts of whale-watching activities on targeted marine mammals populations. Short-term behavioural impacts include noise disturbance (Erbe, 2002), change in respiratory patterns (Stamation *et al.*, 2010), activity budget (Michaud and Giard, 1998), vocalization behaviour (Lesage *et al.*, 1999), or reduction in resting and socialization (Constantine, Brunton and Dennis, 2004; Lusseau, 2004). Long-term biological impacts include increase in energetic demand (Williams, Lusseau and Hammond, 2006), decrease in reproduction rates (Bejder *et al.*, 2006), and area avoidance (Lusseau, 2004). From the perspective of a precautionary approach, the ecological cost of whale-watching must be mitigated to satisfy standards of ecotourism and achieve sustainability (Corkeron, 2004; Hoyt, 2007; Lien, 2001). Our motivation is thus to better understand the SSLMP social-ecological system (SES) so that ways to reduce the pressure exerted by whale-watching excursions on the targeted marine mammals can be found.

Natural resource management in Canada must involve the implication and consensus of all stakeholders. While more and more legislations try to impose the ecosystem-based management balancing the three spheres of sustainable management (social, ecological, and economic), the private sector's interests often prevail when the precautionary principle cannot be supported by scientific evidence (Higham, Bejder and Lusseau, 2009). Consequently, in the St. Lawrence Estuary, regulations based on the precautionary principle and/or worldwide examples (jurisprudence or precedents) are very difficult to implement if they are potentially interfering with the touristic demand. In this context, we argue that efforts to reduce human impact on the ecosystem may be effective if they operate at the bottom-most level of the excursion by directly influencing the critical decisions of captains at sea.

The SES of whale-watching activities in the St. Lawrence Estuary has a complex structure characterized by heterogeneous interconnected stakeholders (Figure 3.4).



Social-Economical, Political, and Legal Context

- •Government's priorities and budgets determine governmental agencies' management directions and abilities
- •Economical crises
- •Laws and Regulations (*e.g.* Oceans Act, Marine Transport Security Act, Marine Activities in the Saguenay-St. Lawrence Marine Park Regulations)
- •Free-enterprise principle
- •Precautionary principle

Environmental Context

- •Tides and weather conditions
- •Whales' preys abundance and spatiotemporal dynamics
- •Change in water temperature affecting the abundance of whales' preys and whales' abundance in turn
- •Rehabilitation of certain whale species stocks, affecting their seasonal abundance in the area (*e.g.* humpback whales regular sightings from 2000 on)
- •Habitat pollution (*e.g.* chemical, noise) affecting animals' health and abundance

Figure 3.4 Overview of the major stakeholders and their interactions in the social-ecological system of whale-watching in and around the Saguenay–Saint Lawrence Marine Park (SSLMP).

Whale-watching companies respond to tourism demand by offering trips within the marine park. Only accredited companies can operate commercial excursions. Park managers partly rely on universities and NGOs for scientific research and consulting, supporting them in the creation of regulations regarding observation activities, enforced by park wardens. The emergence of such an interconnected human and institution system results from the regular presence of marine mammals (i.e. natural resource) in the area. Whale-watching excursions thus serve as the key link connecting the social and ecological subsystems in the estuary. Their observed dynamics is the footprint of captains' decisions at sea resulting from these interactions. These important decisions include 1) whether to *explore* space or *exploit* the knowledge of where whales are currently being observed; 2) which whale to target in *exploitation* mode; 3) where to search when in *exploration* mode; 4) when to interrupt an observation sequence of a given pod of whales; and 5) whether or not to diversify excursion activities (e.g. lighthouse viewing, coastal touring) to enrich visitors' experience. Understanding how captains address these specific decision problems and how their decision outcomes relate to exposure of whales to human activities are subsequently addressed following the bounded rationality framework.

3.5 Methods

Following Simon's scissors metaphor of bounded rationality (Simon, 1990) conceptualized in Figure 3.2, the dynamics of whale-watching excursions in the SSLMP is the footprint of a captain's sequence of decisions that reflects his cognitive adaptation (*cognitive blade*) to achieve his goals in a given task environment (*environmental blade*). In Figure 3.4, the *environmental blade* is described by a set of interconnected ecological, social, economical, and legal factors, with captains and their *cognitive blade* lying at the crossroad of these subsystems. Re-using Ostrom's terminology, the different interconnected subsystems of our case study are identified in Table 3.1.

Table 3.1 Description of the SSLMP whale-watching SES using Ostrom's terminology (Ostrom 2009)

Ostrom's terminology of SESs	SSLMP case study
Social, economic, and political settings (S)	cf. top box in Figure 3.4
Users (U)	Whale-watching captains
Resource unit (RU)	Whales
Resource system (RS)	Saguenay-St Lawrence Marine Park
Governance system (GS)	Parks Canada and Dept. of Fisheries and Oceans
Interactions (I)	cf. links in Figure 3.4
Outcomes (O)	Issues of whale-watching excursions

Our methodology involved three phases:

1) Phase 1: Identify excursions' key characteristics, elicit important features of whales' movement patterns and use of the study area, and draw hypotheses about captains' decision processes through quantitative analyses of available excursions datasets, and qualitative analysis of collected observational data.
2) Phase 2: Characterize captains' decision process (*cognitive blade*) with qualitative analyses of semi-structured interviews and observations, and establish a link with contextual factors (*environmental blade*).
3) Phase 3: Validation of the results with park wardens and expert scientists.

Whale-watching activities have been extensively studied in the SSLMP for more than 16 years via the ongoing AOM[2] monitoring program funded by Parks Canada and Fisheries and Oceans Canada and led by an NGO, the Group for Research and Education on Marine Mammals (GREMM) (Michaud *et al.*, 1997). AOM data are fully described in (Michaud *et*

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[2] AOM: *Activités d'Observation en Mer* (Observation activities at sea)

al., 1997). Statistical and spatial analyses were conducted on this database to describe excursions' dynamics and identify their key features. This process allowed the elicitation of hypotheses about the mechanisms driving captains' decision making responsible for observed excursions' dynamics. Since this database could only give limited insights into captain's choices and behaviours, additional data were collected. Onboard observations made during 30 outings with all operators offering excursions in the area gave us a rich point of view from inside the system. Patrols and interviews with park wardens and scientific outings with GREMM researchers were also conducted. Finally, we completed this first phase by compiling knowledge about the dynamics of whale species in the area.

Relying on the knowledge extracted from the first phase, we conducted an interview campaign with whale-watching captains to start the second phase. We chose the semi-structured interview format for its flexibility in exploring avenues not initially foreseen by the interviewer. Conversational interviews are suitable to the creation of an informal and relaxed atmosphere, priceless in the context of the project. Seven interviews (~8 hours) were conducted in 2007. All but one interview was conducted right after the interviewer took part in an excursion with the captain. In line with the Critical Decision Method (Klein, Calderwood and MacGregor, 1989), this approach allows the interviewer to refer to real events to clarify some questions and go further into detail about decision processes and motivation. Captains rely heavily on VHF radio communication as a medium for passing on information about whale locations. We thus monitored the public "whale channel" for a total of 10 hours spread over seven days to characterize the nature and analyze the content of information flowing through it. We completed this second phase of investigation by conducting qualitative analyses over the transcribed data (Paillé and Mucchelli, 2003; Silverman, 2005).

Finally, we validated the extracted knowledge about captains' behaviours with park wardens. Marine mammal specialists were also involved to validate information extracted about whales' dynamics. More details on data collection and analyses are presented in the appendices.

3.6 Results

3.6.1 Outcomes (O): Dynamics of users (U)' activities and critical issues for the resource (RU)

We carried out several specific analyses and develop indices from the AOM database for the purpose of this study. Here we report on the results of analyses about the dynamics of whale-watching excursions, presented in APPENDIX III. In the SSLMP area, 98.89 % of mid-day whale-watching motorboat excursions observed at least one whale from 1994 to 2009. The abundance and reliable presence of whales in relatively easily accessible areas make this high success possible. This supports some cetacean-watching specialists' claims that the SSLMP area is one of the best regions worldwide to observe whales (Scarapaci, Parsons and Lück, 2008), which explains the high tourist demand.

Four migratory rorqual species, namely blue, fin, humpback, and minke whales, along with the resident beluga population account for more than 98% of the targeted animals for observations. The discrepancy between species' relative abundances and their contribution to total observations highlights a ranking in their attractiveness for observation (statistically significant, alpha=2%). This ranking is confirmed by the distributions of boat numbers in the vicinity of the targeted pods. Humpback whales generate the greatest boat aggregations, followed by fin, blue and minke whales. Blue whales tend to concentrate in the eastern end of the SSLMP, far from Tadoussac, the busiest port (cf. Figure 3.3). When blue whales have been observed in the vicinity of Tadoussac, boat concentrations were significantly higher than values presented for the whole area.

Although high aggregations of boats are frequently observed in the SSLMP, excursions departing from the four main ports first try to keep their activities close to their respective homeport (cf. APPENDIX III). However, some situations (e.g. attractive species spatially clustered, captains' limited search effort), generated locally high aggregations of boats, which proved to be detrimental for exposed whales in the SSLMP (Michaud and Giard, 1998).

For mid-day excursions (from 10:00AM to 4:00PM), a whale-watching vessel is alone with the targeted pod during only 14.5% of total observation time, whereas 21.9% of this time there are at least 10 boats surrounding within 2 km (~55% of which lie within 400m), exceeding most of the levels enforced or recommended by worldwide regulations and guidelines (Carlson, 2010). For zodiac-based excursions from Tadoussac, our analyses show that 80% of the time, an observation sequence begins with other boats already observing the targeted pod. Boats taking their turn to observe the same pod is undesirable for targeted whales since this implies that they are continuously exposed for long periods of time without respite (pers. comm. C. C. A. Martins); this is also undesirable for tourists' visiting experience (Giroul, Ouellet and Soubrier, 2000) and the whale-watching industry's image, but is favoured by the busy excursion timetable (cf. Figure III.1 in APPENDIX III).

Finally, increasing the time allocated to other activities such as sea floor viewing and coastal tours has been highly encouraged by park managers to highlight the unique beauty of the region while decreasing the pressure exerted on whales. Despite improvements, except for companies totally dedicated to landscape viewing or some excursions onboard large boats, the proportion of these activities remains low especially for small vessels.

In summary, three issues (not totally independent) have been identified to increase whale exposure to boats, namely 1) large aggregations of boats around whales; 2) the ranking in species value for observation, the most valuable being the most spectacular (incidentally the scarcest); and 3) long-lasting continuous observations of the same pods by boats following one after another. We now present some major interactions underpinning these issues.

3.6.2 Interactions (I): Elicitation of users (U)' interactions with subsystems contributing to critical outcomes (O)

Following the bounded rationality approach, we describe both the *task environment* and *cognitive blades* from the whale-watching captain's standpoint in order to identify the mechanisms favouring the three abovementioned issues related to whale exposure.

3.6.2.1 The task environment blade

Resource units (RU) and resource system (RS) dynamics: Whale species' dynamics

Analyses have been carried out on the AOM database (Michaud *et al.*, 1997) and indices developed for the purpose of this study. Here we present the summary of analyses on the spatiotemporal patterns of whale species' dynamics detailed in APPENDIX IV. The SSLMP area is a summer feeding ground for the migratory fin, minke, blue and humpback whales, whereas the St Lawrence beluga population is resident. From mid-June to the end of September, fin, minke, and beluga whales have almost always been present in the SSLMP area since the AOM monitoring program has been in place (1994). Conversely, blue and humpback whales' summer residence have proved to be unpredictable in the area, being present 55.4% and 63.9% of the time respectively.

The abundance of the four rorqual species in the area is highly variable across different time scales. From year to year, species' abundance can vary a lot depending on changes in prey availability in the region (Giard *et al.*, 2001). Sudden changes in abundance may also occur on a day-to-day basis: the home range of these foraging whale populations being considerably larger than the SSLMP area, their abundance is contingent upon the density of their preys whose short-term spatiotemporal dynamics is largely driven by complex oceanographic phenomena (Simard and Lavoie, 1999; Simard, Lavoie and Saucier, 2002). On average, the minke whale is unarguably the most abundant rorqual species, followed by fin, humpback, and blue whales.

When present in the area, minke, fin, and to a lesser extent humpback whales' spatiotemporal residency tends to be stable (thus predictable) from day to day. Despite the fact that blue whales display little spatiotemporal stability and are relatively scarce, their spouts can be located up to four times farther than those of the smaller minke whales, making this species easy to detect in favourable weather conditions.

Whales’ surface behaviour is a determinant for observation and is variable among species (and individuals). Surfacing whales mostly show the top of their head and their back. Only humpback and few individual blue whales do “fluke-up dives” on a regular basis. Fin and beluga whales are highly gregarious whereas minke are mostly solitary. In the presence of boats, humpback and fin whales rarely exhibit long-distance fleeing behaviours compared to blue whales, known to be harder to approach. Minke and humpback whales occasionally breach out of the surface, offering a dramatic show for observers. However, spectacular surface displays tend to be exceptions in such feeding grounds as the SSLMP region.

Governance System (GS) and social, economic, and political setting (S)

A set of constraints are exerted on whale-watching captains. These constraints may affect captains’ subgoals, strategies and thus decision outcomes. The main constraints are the regulations (Parks Canada, 2002), the guidelines coming from their company (e.g. minimize fuel consumption; reimbursement of unsuccessful excursions), the competitive context (e.g. show at least the same whales as if not more than direct concurrent operators’ excursion), the characteristics of the product sold (e.g. duration of the excursion, discovery of landscape and historical features), and mechanical limitations (e.g. boat speed, large deck boats’ ability to reach offshore areas that small boats will avoid in heavy sea, maneuverability, deck height).

Implicit ethical and social rules apply within the small whale-watching captains’ community, due to their repeated interactions during the season. This is sometimes observed for such decisions as restricting observation duration when several boats target the same pod. Another cooperative behaviour is observed when captains summarize the knowledge about whales’ current locations on the VHF radio to inform departing excursions.

Generally speaking, the enforcement by park wardens of the current regulations on marine wildlife observation (Parks Canada, 2002) is constrained by the low ratio patrol/whale-watching fleet (2/41), with whale-watching excursions spreading over the whole park.

3.6.2.2 Users (U): Captains' cognitive blade

In this section we synthesize the key features extracted from the analyses of the multiple data sources presented earlier. We only detail elements of captains' decision making directly related to critical whale exposure.

Our investigation centered on whale-watching captains revealed several key features of their decisions at sea. Several collective strategies have been evolved by captains to ensure they keep track of attractive whales throughout the day. A fundamental mechanism underlying excursion dynamics is the total cooperation between captains who help each other by passing on information about whale locations on the open VHF radio "whale channel", no matter the company. Cooperation also occurs when captains having explored some areas without success report it to advise other captains to search for whales elsewhere. The uncertainty about whale location could virtually affect anybody anytime, thus justifying cooperation in the community. Moreover, this apparent socioeconomic paradox (i.e. captain cooperation in a context of competition between companies) is rewarding on the long-run for the numerous captains who conduct several excursions a day, since cooperation ensures that their task of locating whales will get easier as the day goes on. Some captains even claimed in interviews that "After 10 AM, all large rorquals (i.e most attractive species, namely humpback, fin and blue whales) are located in the SSLMP", suggesting the efficacy of this collective strategy.

In a context of heavy competition where 54.7% of whale-watching tourists select a company on the spot by word of mouth (Giroul, Ouellet and Soubrier, 2000), some operators have a refund (or raincheck) policy in case of empty-handed excursions, to avoid negative comments from unsatisfied tourists. The pressure of success is on captains to satisfy onboard tourists' expectations. This context of heavy competition between companies favors at least two phenomena: 1) risk aversion (fear of failure) pushes captains to prefer the convenient *exploitation* of discovered whales over the more risky space *exploration* in search of new ones (illustrated earlier); and 2) captains try to show at least the same whales as competing companies, leading to boats following one after another around a limited number of targeted pods.

As illustrated earlier, all species are not equally attractive to captains. In interview, some captains revealed that they believe tourists want to witness spectacular whale displays. The vast majority of companies' advertising material exhibits pictures or movies of whales showing their tail fluke, shaping tourists' expectations. However, this behaviour tends to be exceptional in the region and mostly seen in the humpback whale and in rare blue whales, namely the two scarcest species in the region. Images of whales breaching out of the water are also used to attract tourists although this behaviour is even rarer than fluke-up dives, observed mostly in humpback and minke whales. Consequently, to run the chance to be consistent with the content of advertising material, captains will tend to overly observe humpback whales when present in the area. Fin whales are gigantic animals (2nd largest animal ever lived on Earth after the blue whale), occasionally hunting in large groups, and present on a regular basis in the region making them excellent candidates for observation. Blue whales being hard to approach, mostly distributed far from busy ports, and subject to a 400-meter minimal observation distance (Parks Canada, 2002), they are not the first choice for captains. Minke whales are fast, small and abundant relative to other rorqual species, and observable from the shore making them less attractive despite their spectacular surface behaviours. Finally, endangered beluga whales are also subject to a 400-meter minimal observation distance (Parks Canada, 2002) so that they are observed mostly opportunistically. These are some of the reasons why few whales attract many boats. The summary of the mechanisms responsible for critical whale exposure to boats is given in Table 3.2 and discussed thereafter along with their broader implications.

Table 3.2 Mechanisms favoring the three issues of whale exposure to whale-watching boats and their links with subsystems. For U, we differentiate captains from companies

Critical issue	Underlying mechanisms	Subsystem					
		U		RU	S	GS	RS
		captain	company				
(1) High boat aggregations	No restriction on the number of daily departures/permit + busy timetable		x			x	
	High proportion of small boats (<48 passengers) in the whale-watching fleet		x			x	
	High tourist demand			x	x		x
	Cooperation and information sharing between captains (non-rival activity)	x					x
	Existence of numerous collective strategies to facilitate whale observation	x					
	Exploitation of discovered whales prevails upon space *exploration* (more risky)	x					
	Attractive (dramatic) species are scarce			x			x
	Dramatic species tend to aggregate close to busy ports			x			x
	Companies tend to homogenize excursion content (competition)		x		x		
	Permissive regulation (no restriction on boat number at d > 400 m of a whale)					x	
	Lack of awareness of collective and cumulative effects of whale exposure	x	x			x	
	Ignorance that visitors dislike boat aggregations (conflicting with the feeling of wilderness experience)	x	x				
	Difficult navigational conditions are frequent						x

Critical issue	Underlying mechanisms	Subsystem					
		U		RU	S	GS	RS
		captain	company				
(2) Unbalanced species attractiveness	Search for dramatic behaviours (competition)	x	x		x		
	Fashionable species (herding effect, social convergence)	x					
	Competition between companies		x		x		
	Tourist expectations influenced by advertisement material (e.g. pictures of dramatic whale displays)		x			x	
	Abundant species (e.g. Minke whales) can be observed from the shore, decreasing their observation value offshore.			x			x
	Humpback whales species display spatiotemporal stability (predictability)			x			x
	Rare naturalist guides onboard small boats to mitigate the quest for dramatic behaviours.		x		x	x	
(3) Long-lasting continuous observations	Captains' inexperience (low retention rate)	x	x				
	Ignorance of visitors' satisfaction criteria (prone to increase boat aggregations)	x	x				
	Permissive regulation (max 60 minutes on the same observation site)					x	
	Risk aversion of captains	x					
	Busy timetable of excursions (captains take their turns on observation sites)		x				
(1)+(2)+(3)	Lack of activity diversification	x	x				
	No guide of good practices for whale-watching captains	x	x				

Critical issue	**Underlying mechanisms**	**Subsystem**					
		U		RU	S	GS	RS
		captain	company				
	○ Weak social recognition for the whale-watching captain profession		x		x	x	
	○ Not enough information/interpretation provided to visitors before, during, and after the excursion		x			x	
	○ Tourists are mostly passive and uninvolved during excursion (few activities related to conservation onboard small boats)		x			x	

3.7 Discussion

Whale selection is often well explained by a one-reason decision making process based solely on the species attribute, humpback, fin, and blue whales being the most valuable in the eyes of captains. The repetition of long-lasting observation sequences by boats following one after another around these attractive whales throughout the day increases the chances for a captain to witness dramatic behaviours on the long-run. However, this results in large aggregations of boats around a few targeted whales in the region. This could potentially lead to the tarnishing of the whale-watching industry's image (Finkler and Higham, 2004; Giroul, Ouellet and Soubrier, 2000) while being harmful for overly targeted whales (Michaud and Giard, 1997; 1998).

Large aggregations of boats around fashionable species is a feature of convergent social behaviour called herding (Raafat, Chater and Frith, 2009). Herd behaviour is self-reinforced by captains' risk aversion. In addition to putting excessive pressure on few animals, this collective behaviour decreases both the captain's job interest (stagnation of the pool of discovered whales) and visitors' experience (risk of a "boat-watching" experience). This emergent herd behaviour is a self-defeating strategy (Batten, 2007) in the sense that carried to extremes, captains losing the only discovered whale will not have any alternative to exploit. Whether large aggregations of boats around attractive species are due to real visitors' preferences, captains' preferences, misunderstanding of tourists' expectations, or a combination of these reasons, captains' herd behaviour could ultimately turn out to be a self-defeating strategy for the local whale-watching industry as a whole.

Members of small communities must share a common representation of the system in which they operate to cooperate effectively and achieve their goals (Hoc and Carlier, 2002; Salas *et al.*, 1995). We argue that misconceptions can remain strongly anchored in a local mindset; all the more if they conveniently justify that any change is unnecessary. This is the case when some captains deny or minimize the fact that their activities disturb whales despite scientific evidence. This is also the case for captains who believe that a good excursion should necessarily contain the observation of spectacular displays. The fact that most of companies exhibit whale tails on their advertising material reinforces and justifies the quest for spectacular behaviours in this direction by influencing visitors' expectations. However, only some animals from the least abundant species occasionally do fluke-up dives, making them overly observed when present in the area. The presence of the sought-after humpback whales in easily accessible areas reinforces their exaggerated attractiveness, promoting in turn large aggregations of boats in their surroundings.

Finally, analyses revealed that captains tend to overly *exploit* existing information rather than *exploring* the space for new whales. Risk aversion and the prevalence of inexperienced captains (due to low employee retention) certainly contribute to explain this preference for less risky strategies, which ultimately favours large aggregations of boats and extended presence on the observation sites.

The regulatory body carries the burden of proof to assess the long-term effects of whale-watching activities on targeted populations. We therefore believe that intervening with captains to increase their awareness is a major lever that can be used to mitigate ecological (whale disturbance) and social (visitors' experience) costs of whale-watching activities and achieve sustainability. The guarantee to meet and maintain the standards of sustainability for the SSLMP whale-watching SES requires a synergy between natural resource managers, NGOs, researchers, and the tourism industry. The undergoing development of a guide of good practices for whale-watching activities is precisely an effort in this direction. Agreement on a common vision, transparency in decisions, regular exchanges of information, and acknowledgment of past mistakes are necessary to ensure the success of such an approach.

Tourists' fidelity to a destination is an objective of sustainable whale-watching (Hoyt, 2007), contributing to the prosperity of local tourism. This is all the more true for the SSLMP where approximately half of the visitors come from the province of Québec. This loyalty is contingent upon the post-experience satisfaction of tourists' expectations (del Bosque and

San Martin, 2008; Okello and Yerian, 2009). Therefore, a failure in providing an educative and wilderness experience desired by visitors (Giroul, Ouellet and Soubrier, 2000) could likely make them reluctant to repeat an experience in the region, and prone to spread unfavourable comments by word of mouth. The local emergence of alternative whale-watching destinations in the surrounding region should stimulate the industry to meet ecotourism standards in demand, a sector growing three times faster than the whole tourism industry (The International Ecotourism Society, 2006; Wearing and Neil, 2009). The quest for true sustainable whale-watching in the St Lawrence Estuary should be paid careful attention in order for local stakeholders not to miss the boat.

3.8 Conclusion

For SESs where the precautionary principle can hardly compete with the free-enterprise principle, focusing on the closest level of the human-nature interface might be a key to improving natural resource management en route towards sustainability. In the present case study, relying on Ostrom's general framework (Ostrom, 2009), we showed how the bounded rationality concept can allow to connect undesirable outcomes at the SES level with some of its subsystems' interactions by focusing on the bottom-most level of the system, the users. From a philosophical standpoint, observing SESs through the bounded rationality lens forces the unification of the all too distinct social and ecological spheres of scientific research (Liu *et al.*, 2007; Norgaard, 2008; Ostrom, 2009).

According to the classification of ecosystem goods and services proposed in Brown et al. (2007) and Costanza (2008), we presented a SES where users are non-consumptively exploiting an exclusive ecosystem where commercial whale-watching is subject to restricted permits. However, the studied SES can switch from a non-rival (mostly uncongested activity in a vast territory) to a rival status when the number of boats around the observed whales increases due to the scarcity of attractive species and herd effect in captains behaviour. We believe that the switch to a rival system (i.e. numerous boats surrounding the same pod of whales) can be deleterious both for the ecological and social components of the system.

The social system of users (whale-watching captains and companies) proved to be reluctant to change. Ostrom argues that self-organization of users is rare when no scarcity (feedback on past actions) is observed due to bad practices (Ostrom, 2009). Accordingly, several elements can be put forward to explain the resistance to change observed in our system, mostly related to the absence of feedback-related negative effects of bad practices in the past. First of all, the consequences of cumulative whale exposure to boats are very hard to assess (Corkeron, 2004; Higham, Bejder and Lusseau, 2009). Second, establishing any causal effect between whale disturbance, species abundance, and the number of whale-watching tourists is in the realm of speculation. For example, the number of whale-watching tourists has decreased by ~20% between 2001 and 2005 (D. Gosselin, personal communications), coinciding with an overall decrease in whale abundance revealed by interviewed captains and local scientists. From 2005 to 2009, the number of whale-watching tourists has stagnated, coinciding with an apparent increase in whale abundance. However, even if the effect of bad practices would lead some whales to abandon the St Lawrence Estuary habitat, and if there could be some causal effect between whale abundance and tourist frequentation, the causal relation would be hard to elicit so as to convince operators to change their practices using economic arguments. Thirdly, a great proportion of whale-watching tourists are first-time participants (Giroul, Ouellet and Soubrier, 2000) so that many do not have any reference on what a sustainable whale-watching experience is, restraining them from providing post-experience constructive positive or negative feedbacks to operators. In the broader context of non-consumptive activities where some private companies are in competition, if unsustainable practices do not lead to significant negative economic consequences by feedback (i.e. scarcity), there is only little incentive for users to self-organize and call into question their practices (Ostrom, 2009). In such contexts, bounded rationality can be a powerful framework to guide an in-depth investigation of users' activities and draw recommendations regarding management agencies, private companies, and end-user training. Interestingly, the bounded rationality concept taken as an investigation framework naturally fosters the unification of social and natural sciences for the study of SESs.

CHAPTER 4

ELEMENTS OF WHALE-WATCHING CAPTAINS' DECISION MAKING: COLLECTIVE STRATEGIES AND DECISION HEURISTICS

The bounded rationality theory underlies all the results presented thereafter. As discussed in CHAPTER 3, the spatiotemporal dynamics of whale-watching excursions in the SSLMP is the footprint of captains' decisions at sea. According to the bounded rationality theory, captains' decision making processes can be seen as simple heuristics evolved across time and past experiences to fit the requirements of the complex task environment given such cognitive bounds as memory (Ebbinghaus, 1964) and computation limitations (Simon, 1990), as schematized in Figure 3.2. Captains' decisions which have been studied are related to the problem of localization and observation of whales.

An important characteristic of the SSLMP whale-watching system is that captains often make decisions as part of a collective. As a matter of fact, most of time several excursions are simultaneously active and captains can take advantage of this situation in various ways in order to locate and observe whales. Thus, the present chapter presents the knowledge acquired about whale-watching captains' decision making processes and outcomes, both individual and collective, related to the problem of localizing and observing whales during excursions. In CHAPTER 3, the focus was solely on captains' decisions leading to undesirable outcomes (cf. section 3.6.2.2). In this chapter, all the captains' decision heuristics and collective strategies elicited during field campaigns are presented. Whale-watching excursions have been investigated both quantitatively with spatial and statistical analyses, and qualitatively through various observations made on captains. The next section presents an overview of these investigations. The rest of this chapter is an in-depth description of individual and collective decision making strategies used by captains to observe whales.

4.1 Summary of field campaigns and data analyses

The data used to study whale-watching captains' decision making processes are given in Table 4.1 in the column 'data source'.

Table 4.1 Summary of data collection, analyses, and extracted knowledge about whale-watching captains' decision making

Phase	Data source	Characteristics of the data	Analyses	Information extracted	
1	Excursions content sampling (AOM^2)	• 15 years of sampled excursions (10 minute resolution) • Trajectories (1-minute resolution)	• Spatial analysis • Statistical analysis	• Impact of the context (species abundance) • Spatial characteristics of species dynamics (spatial correlation corresponding to tide cycles) ➔ relative predictability of species distribution on a day to day basis • Whale group size pattern with the tide ➔ defines the relative spatial clustering of animals	• Companies' operating areas • Difference between companies' practices (e.g., lower distance traveled for small companies) • Daily variations in captains' strategies (morning vs. evening)
	Compilation of existing information	• Companies' excursion schedules • Reports on species abundances • Environmental characteristics • Interviews with the park warden	• Compilation • Summaries • Synthesis	• Species preferences ➔ suggests a non-compensatory task environment • Scheduling strategies • Task environment characteristics	• Products sold by different companies ▪ observe the "blue whale" ▪ visit the Fjord Saguenay experience, ▪ present images from a submarine camera ▪ observe the biodiversity
	Personal observations	• 30 whale-watching excursions • 100h of shore-based observations • Outings with researchers for animal censuses • Outings with the warden	• Readings • Summaries • Meaning interpretation	• Exploration strategy in squadron • Exchange of observation sites between captains • Repetition of earlier excursion of the day • Species attractiveness	• Preference for close locations • Spatial clustering tendency around star whales • Group size tends to increase with high tide
2	Conversational interviews	• 7 interviews with different companies from the 5 major ports • ~9h of discussions	• Meaning condensation • Meaning categorization • Meaning interpretation	• Building dynamic expectations based on ▪ past observations ▪ other active excursions • Homogeneity in same company's excursion content • Exploration vs. exploitation strategy • Determined captains' motivation • Influence of boat type on decision making process	• Companies' preferences and constraints • Non respect of the regulation • Conditions for exploration (e.g., avoidance of crowded sites) • Differences between captains • Repetition of the "same" excursion for subsequent excursions by the same captain
	VHF radio monitoring	• ~15h of monitoring	• Meaning categorization • Content analysis	• Cooperation (information sharing between all captains) • Identification of hubs • Collective coordination • Flag strategy • Exploration vs. exploitation	• Recurrence of information summary • Spatial responsibility in exploration • Territoriality • Conditions for exploration (e.g., expected species not found) • Effect of bad visibility conditions
	AOM transects protocol data	• 15 excursions, same boat, same company, same time of the day, inexperienced captains • Report on all boats and whales sighted and observed in the vicinity • Report on all survey-boat's activities • Report on relevant contextual factors	• Statistical analysis • Spatial analysis	• Minimum time on observation sites (2 exploratory sequences) • Strategy (imitation, follower, exploration…), as a function of captain's experience and species context	• Species choice in given contexts and captain's characteristics
3	Validation with the warden	• Presentation interview • 2 patrolling outings • Validation interview		Critics, improvements, generalization and categorization	

The field campaigns, which have been described in sections 1.2.2.5 and 1.3.4, were approved by Parks Canada (permit #SAGMP-2007-1203) and by both Research Ethics Committees of École de technologie supérieure and Université de Montréal (cf. APPENDIX II).

An overview of information extracted from the different datasets is given in Table 4.1. This knowledge has been used to fuel the development of several modules of the 3MTSim's whale-watching excursion component (cf. Figure 6.2). Elements of whale-watching captains' cognition intervening in their decision making process are presented in the next section.

4.2 Whale-watching captains' cognition

The main components that have been identified to influence captains' decisions at sea are presented in Figure 4.1. Figure 4.1 is not an exhaustive description of all interleaved contextual, environmental, and psychological factors, mechanisms, and relationships between them leading to the observed behaviours; it is rather a summary of influential and salient elements identified as major drivers of captains' decisions after the field campaigns. These elements are described thereafter.

According to the bounded rationality theory, the captains' decision making system is a functional (non-optimal) adaptation to the task environment structure and its inherent uncertainty that must be dealt with to achieve their goals (cf. Figure 3.2). *Beliefs* about tourists' expectations, *knowledge* acquired by past experiences, and captains' own *preferences* define their *desires* of achievement and *fears* about what to avoid in the broad sense. The *information* about which whales are currently or have been recently seen defines captains' *expectations* of what can and should be observed during the current excursion. In order to satisfy their *desires* and avoid their *fears*, according to the possible future courses of actions, captains derive goals and pursue them (explicitly or implicitly) by implementing *collective strategies* or using *cognitive heuristics* that have proved successful in the past.

In this section we present the knowledge extracted from observations, interviews and analyses of VHF monitoring about the way captains make decisions to locate and observe whales. Figure 4.1 presents our conceptualization of this process.

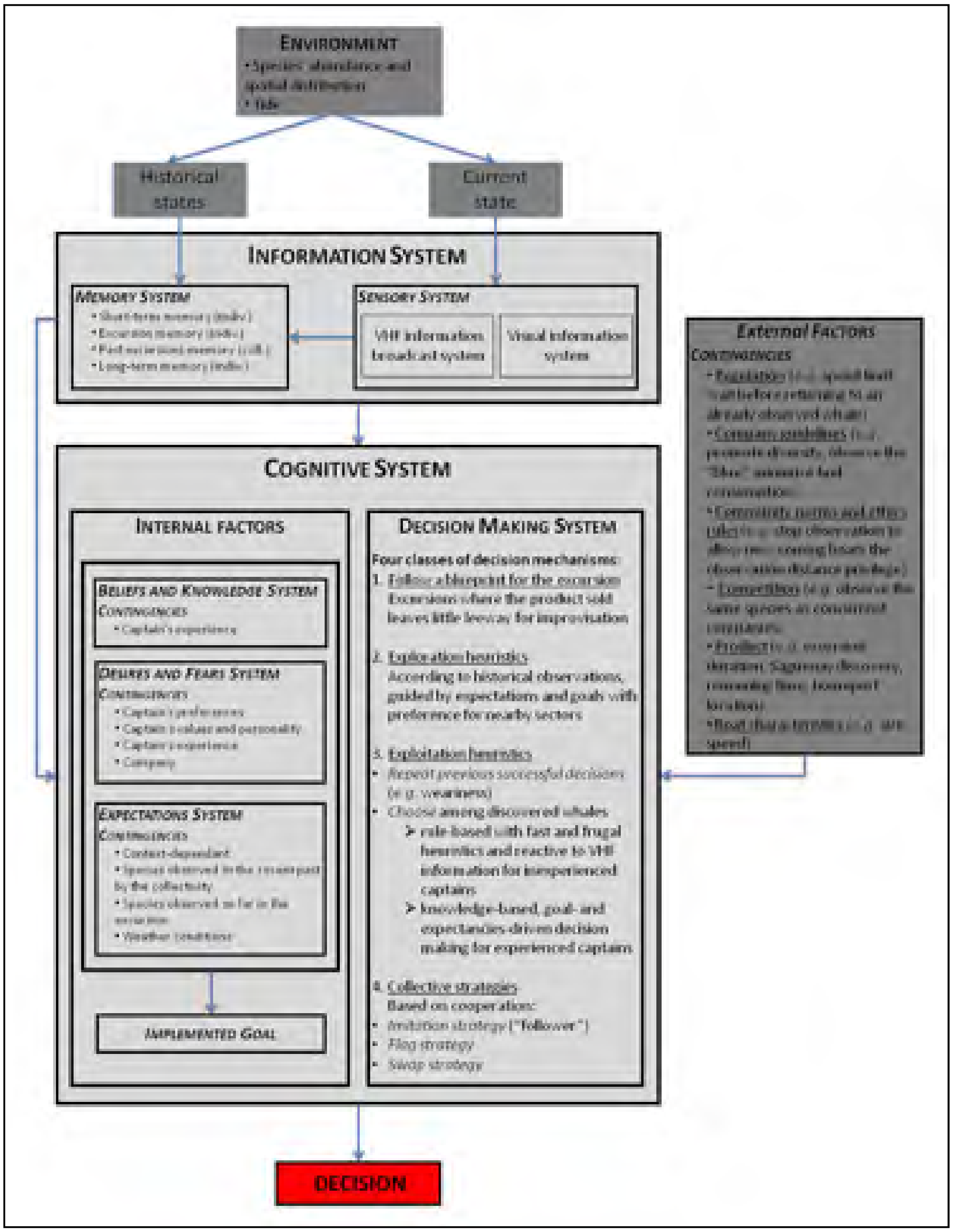

Figure 4.1 Conceptual model of factors influencing whale-watching captains' decisions relative to the task of whale localization. Dark grey boxes relate to the external environment, whereas light grey boxes relate to the captain's inner environment including his sensory and cognitive abilities.

4.2.1 External factors

These factors have already been presented in the previous chapter in section 3.6.2.1.

4.2.2 Information

Information is crucial for any relevant decision to be made. The *Information System* described on top of Figure 4.1 is the interface between the state of the environment and the captains' representation of it (incomplete by nature).

4.2.2.1 Sensory system

The best tool available to captains to locate whales in normal weather conditions is vision. Surfacing whales can be located either via direct visual cues (e.g. tail, back) or indirect clues (e.g. blow condensing in the air up to 8-meters high, sound made by the blow useful to locate whales on foggy days). Another indirect indicator of whales' underwater presence is the aggregation of sea birds feeding at the water surface. Sea birds and whales have some preys in common so that they can be observed simultaneously in food-rich areas. Surface current fronts are also sometimes used by captains as a proxy to locate whales. The visual detection distance varies according to whale species and weather conditions (i.e. visibility, sea state, wind). Table 4.2 presents an overview of detection distances as a function of whale species and weather conditions (Sarah Duquette, GREMM, personal communication).

Table 4.2 Approximate species-dependant detection distance under ideal and average weather conditions (Sarah Duquette, GREMM, personal communication)

	Detection distance to the naked eye (meters)	
Target species	Ideal weather conditions	Average weather conditions
Minke whale	2000	1500
Fin whale	4500-5000	3000
Blue whale	6000	4000-4500
Humpback whale	4500-5000	3000
Beluga	3000	1500-2000

4.2.2.2 Communication

As soon as some whales are observed within the marine park, communication via the radio VHF channel becomes the main vehicle for information flow between captains. Somehow paradoxically, despite a strong competition between whale-watching operators (i.e. companies), captains extensively cooperate at sea, regardless of their company. Some captains carry out specific roles in the communication systems such as hubs (very informative with any captain) and relays (regularly summarizing the available information). Given that the territory cannot be entirely explored by a sole captain during an excursion and that whales can occupy virtually any location in the area, nobody has the assurance to locate whales easily day after day. Consequently, cooperation is the best alternative on the long run to minimize the risk of coming back empty-handed from an excursion.

4.2.2.3 Memory system

Whatever the whale context, captains can only capture some signals of it. Historical states of whales' dynamics experienced by captains play an important role since they make up the base of knowledge stored on different memory systems, spanning from the short-term working memory accessed for rapid decisions to the long-term memory shaping hard-coded patterns considered as the bases of expertise.

In the absence of up-to-date information about the whales' setting (*i.e.* species' abundance and distribution), memory provides input to chose which locations to favour for space exploration. Particularly, over a short period of time (typically a few hours), past locations of observed whales are usually efficient clues to predict with a meaningful probability areas where whale species can be found. Whales' preys are pelagic fish and plankton species whose distribution is related to tide cycles. Due to the bathymetry of the area, at high tide preys tend to congregate and be trapped in features of the underwater relief, attracting pods of predating whales in these food-rich zones. Conversely, at low tides, preys tend to disperse, causing whales to spread in a less predictable way. Several captains rely on this pattern which is particularly valid for the fin whale.

Four different types of memory have been found to have an impact on captains' decisions:

1) Long-term memory: Shapes captains' individual experience. It mostly allows captains to develop causal links between contextual and historical factors and most likely whale locations, and to make correct inferences in critical situations.
2) Past-excursions memory: Characterizes the recent context (past day at most) giving the broad picture of the likely species abundance and distribution. This memory tends to be a shared by the captains' community owing to their cooperative behaviour. It mostly influences the choice of spatial locations to explore first.
3) Excursion memory: Keeps track of the areas explored (successfully or not) and observation made so far in the excursion. It mostly influences the decision of species to observe (e.g. captains willing to maximize the diversity of observed species).
4) Short-term memory: Keeps track of whales detected opportunistically during the excursion while already engaged in an activity (e.g. a fin whale surfacing nearby while observing a humpback). It mostly influences the decision of the next whale to observe.

Memory and sensory systems supply the cognitive system with information. The next section describes elements of captains' cognitive system found to influence their decisions at sea.

4.2.3 Cognitive system

Beliefs (including expectation) and knowledge have an impact on desires and fears. Desires and fears are emotional and motivational states which play an important role in goal selection (Bratman, 1988; Rao and Georgeff, 1995). Preferences as well have an impact on goals (Over, 2004). Whereas discovering how these emotional and psychological features precisely articulate to generate observed decisions is beyond the scope of this work, their identification is insightful to understand excursions dynamics.

4.2.3.1 Beliefs and knowledge

Beliefs are distinguished from knowledge to account for the fundamental difference between unfounded ideas (sometimes self-reinforced misconceptions within small communities) and solid knowledge based on evidence (learned by experience or scientifically based).

Several captains believe that they do not have any negative impact when observing whales. Other captains claim that whale-watching is better than whaling arguing that whales must adapt to their presence. Frequently encountered beliefs are that a successful excursion (i.e. meeting onboard tourists' expectations) must absolutely contain the observation of whales' dramatic behaviours or at least fluke-up dives, and close encounters.

Some operators occasionally record animals' positions into their GPS and infer their most probable location across time. Inevitably, past observations are stored unconsciously within captains' memory, creating their knowledge base. Experienced captains apparently are efficient at locating whales in the absence of current information, making them good candidates for the risky early morning excursions.

4.2.3.2 Desires, fears and preferences

Unequivocally, what captains declare desiring the most is to satisfy onboard tourists. Accordingly, they derive and implement goals to satisfy this desire, according to their beliefs. Their predominant fear is to come back empty-handed from their excursion because dealing with unsatisfied tourists is unpleasant. Moreover, some operators adopt a refund policy for such excursions putting pressure on captains' shoulders. However, captains frequently conduct several excursions a day. Most of the time tourists do not formulate explicit requests or desires, relying entirely on the captain's experience. In such contexts, captains' personal preferences can play an important role in decision making. For instance, from a captain's perspective, the decision to observe the occasionally spectacular humpback whale during his four daily excursions increases his chance of witnessing a dramatic behaviour, even if the overall probability of such an event is very low in the area. Captains' preferences can also lead to decisions that may reduce their impact on whales, for instance captains may deliberately avoid crowded areas, preferring to observe whales alone.

4.2.3.3 Expectations

Captains have expectations about which whales they could observe based on the current and recent context of observations made in and around the marine park. If a given species has not been seen for weeks in the area, nobody will expect nor struggle to observe it. Conversely, species that are currently observed by excursions at a given moment have an impact on expectations of the captains who communicate on the VHF radio. In a context of competition, captains departing from the same port try to homogenize their excursions' content (in terms of species observed) to avoid the spread by word of mouth of unsatisfied tourists' comments. Additionally, captains from the same company leading simultaneous excursions also try to observe the same species in order to avoid disappointments emerging from discussions on the way back to the quay.

4.2.3.4 Goals and subgoals

In addition to ensuring that passengers have a safe and enjoyable experience, the main goal of a whale-watching captain is to locate and observe whales. The derivation of goals and subgoals to satisfy their main desire (i.e. satisfy onboard tourists) stems from captains' beliefs and knowledge regarding tourists' expectations. Captains sometimes make their decisions of which species to observe by surveying tourists' preferences, opting for the majority's choice. Some captains try to achieve more elaborated goals than simply showing whales. Several criteria can affect the quality of an excursion such as the number of observed species, the size of whales' pods (large groups are more dramatic), or the whale's behaviour (e.g. breaching, tail slapping, and fluke-up dives). These subgoals pursued by some captains can be influenced by their own preference system (personal values, personal interest, and experience of what tourists have shown to appreciate in the past) and by internal rules imposed by their company. Observations suggest that experienced captains tend to plan their excursion and to pursue more elaborate goals compared to younger captains who appear to be more reactive and opportunistic.

4.2.3.5 Decision making system: heuristics and strategies to deal with uncertainty

Quantitative statistical analyses along with qualitative observations and interviews revealed several individual heuristics and collective strategies developed by captains to tackle the uncertainty of whales' locations. Thereafter, individual *heuristics* refer to mostly unconscious cognitive functions shaped by experience and learning, and collective *strategies* relate to deliberate plans of action followed by captains acting in coordination. Both *heuristics* and *strategies* presented here are used to solve the whale localization/observation problem.

The socio-economic paradox of *cooperation* between captains from companies in *competition* is an example of a collective adaptation evolved to tackle the uncertainty related to the localization of whales. Put in general terms, we elicited four categories of decision mechanisms employed by captains which are the use of 1) rigid predetermined blueprints, 2) exploration heuristics, 3) exploitation heuristics, and 4) coordinated collective strategies.

An excursion is a commercial product so that some companies (mostly owners of large boats) integrate activities other than whale-watching to diversify their offer (e.g. lighthouse viewing, coastal tour, submarine camera). To conduct these excursions in a timely fashion, captains often rely on predetermined spatial blueprints where there is very little leeway for improvisation.

Two categories of heuristics can be used by captains: *exploration* or *exploitation*. *Exploration* relates to the action of mining space, searching for whales without any certainty of making an observation. Conversely, *exploitation* characterizes the behaviour of taking advantage of the available information on current observations to pick a pod to target. Individually, *exploration* is risky but may lead to high-quality observations (no other boats around the whale); collectively, *exploitation* leads to the stagnation of discovered whales, limiting the value of excursions' content (stagnation of the pool of potential observations). *Exploration* is guided by past observations, with the priority given to the closest areas where favourite species have recently been observed. Typically, captains operating the first excursions of the day use this heuristic that can be called the *go-to-most-recent-and-close-rewarding-area* heuristic, suggesting a trade-off between *recent* and *close* along with an interpretation of what *rewarding* means for a given captain. Some experienced captains tend to explore more often than other captains, aware of the advantage of observing a whale with no other boat around. When several excursions start simultaneously in an area where no whales have been discovered, captains tend to coordinate their *exploration* effort and spread over the space (minimizing the detection distance overlap between search areas) to increase their chance of detecting whales.

Although there are counter-examples, captains operating large boats tend to *exploit* existing information and rarely take the risk of *exploring*. Two reasons can be put forward to explain this fact: 1) the risk of making hundreds of customers unsatisfied due to an unsuccessful risky exploration must be avoided at all costs; and 2) most large boats are not very manoeuvrable, are slower than small vessels and consume more fuel, so exploring the area with such boats is economically suboptimal. Conversely, small vessels are fast and numerous in different parts of the marine park. The two reasons stated above for large vessels can be reused to explain why this strategy is viable for small ones. Accordingly, excursions onboard large boats are always scheduled after the departure of some small vessels' excursions, allowing them to take advantage of small vessels' searching effort. However, when attractive whales are far from a large boat's homeport, the captain may decide to explore a closer area because if his inability to exploit the discovered observation sites.

Knowledge *exploitation* can be done using several heuristics. Captains can use the *satisficing* heuristic (Simon, 1955) by choosing to observe the first whale whose "important" attributes (e.g. location and species) satisfy given thresholds. Most of time, captains face a multi-alternative/multi-attribute decision problem. Exploitation heuristics used in such cases rely on comparison rules applied on available attributes relative to each alternative to choose from such as *take-the-best* (Gigerenzer and Goldstein, 1996) or *tallying* (Payne, Bettman and Johnson, 1993) heuristics. Finally, in the case of captains conducting several excursions a day, when the spatiotemporal dynamics of whales is known to be stable in the area, some captains simply repeat the pattern of a previous successful excursion, thus applying the *repeat-previous-successful-excursion* heuristic. This strategy is not cognitively demanding and can be rewarding if the environmental context remains stable.

Individually, the pressure of the first observation of an excursion on a captain can be high. In cases where the company reimburses customers if no whales are observed during the excursion, or in critical context (e.g. when whales are scarce, hard to access, or hard to detect), a captain tends to individually satisfy himself with almost any species for his first observation, regardless of what his *preferences* and *expectations* are prescribing. That is to say, a captain willing to make his first observation at all costs will choose any whale easily visible, whatever the species or the conditions of observation, thus using a *satisficing* heuristic (Simon, 1955).

Most observed collective strategies are related to *exploitation*, except for coordinated *exploration* where captains explore areas not overlapping with other captains. Imitation is observed when a captain simply makes the same decisions as another, applying the *follow-this-captain* rule. This dynamics mainly occurs within a given company when inexperienced captains follow more experienced ones. This strategy can also be used when whales are in low abundance or hard to locate (e.g. due to weather conditions).

To keep track of “interesting whales” (i.e. species with a high observational value) over time and avoid the need to locate a whale again in successive excursions, captains sometimes adopt what we called the collective *flag* strategy; to perform it, at least one boat has to stay around a whale (or group of whales) of particular interest until a new boat has arrived to observe it. Doing so, captains maximize the chance that whales remain easily observable throughout the day. This strategy can be labelled the *do-not-leave-a-pod-if-alone* rule.

Finally, the *swap* strategy allows captains to control the number of boats around observed whales, in order to take advantage of the distance privilege defined in the regulation (Parks Canada, 2002), allowing boats to get closer to whales when there are strictly less than five boats on an observation site. This strategy is typically used by two captains who coordinate to simultaneously swap their observation site, leaving unchanged the number of boats on each observation site; it is observed almost exclusively in the presence of patrolling wardens. This strategy can be labelled the *swap-pod-with-another-captain* strategy.

4.3 Conclusion and future works

Captains use several strategies and decision heuristics to achieve the task of locating and observing whales. Those presented in this chapter were revealed by a combination of investigations including interviews, observations, and data analyses. One of the most important characteristic that appeared to drive the whale-watching excursions’ dynamics is the active information sharing between operating captains and their overall cooperation. To a certain extent, their organization at sea could be regarded as a group of entities working in collaboration to discover a variety of whales while trying to reduce collectively the effort allocated to this task. Captains demonstrate a form of collective intelligence in the space search process while sharing a collective memory of past observations, with certain specialization: For instance, small boats which are fast can explore remote areas to find new whales while large boats which tend to be slower serve as a flag to keep track of the discovered whales.

There remain several open questions to draw an accurate portrait of captains' decisions underlying the observed dynamics of whale-watching excursions. These questions can be formulated as follows:

1) Some strategies and heuristics used by captains have been linked to some combinations of contextual factors. However, further investigations could be led to improve our understanding of how internal (e.g. captain's values, preferences, experience) and external factors (e.g. number of boats at sea, whale species' abundance and distribution, company's guideline) combine to trigger specific behaviours.
2) The decision to *stop an observation* has been barely investigated. Basically, the minimum duration of an observation was found to be the time needed to observe two respiratory sequences of the focal animal whereas the maximum duration tends to be the maximum authorized according to the Regulations, that is 60 minutes (Parks Canada, 2002): Eliciting the factors affecting the time allocated to an observation is critical to understand the variability in the distribution of durations found in data and improve the description of excursions' dynamics.

CHAPTER 5

RAYBAPP—A RAY-BASED PATH-PLANNING ALGORITHM FOR AUTONOMOUS MOBILE OBJECTS IN LARGE 2D RASTER-BASED ENVIRONMENTS

Following the presentation of the results of investigations conducted on the 3MT-SES, this chapter presents a path-planning algorithm developed to reproduce realistic movements of boat agents within 3MTSim.

5.1 Manuscript submission information

This article has been submitted to the journal International Journal of Geographical Information Science. Its status when this dissertation was submitted was 'accepted with major revisions'. The ordered list of authors who contributed to this manuscript is:

1) Clément Chion, M. Eng., (thesis author).
2) Alex d'Auteuil Charest, B. Eng.
3) Jacques-André Landry, Ph.D., Professor in the Department of Automated Production Engineering, École de technologie supérieure.
4) Lael Parrott, Ph.D., Associate Professor and Director of the Complex Systems Laboratory in the Department of Geography, Université de Montréal.

Thesis author's main contributions to this work include the following:

- Development of the algorithm concept.
- Methodology.
- Tests and results analyses.
- Writing of the manuscript.

5.2 Abstract

We present RayBaPP, an original path-planning algorithm designed to allow autonomous agents to find their route within large raster environments with binary states. In agent-based models, classical graph-search algorithms are commonly used for path-planning or pathfinding purposes. Thus, we compared the performance of RayBaPP with the classical A* and Dijkstra graph traversal algorithms in several environments for which we varied both structure and dimension. Regarding computational speed, we found that RayBaPP is the fastest to return a solution whatever the environment‘s structure and dimension, outperforming A* by up to 1000 times and Dijkstra by up to 10^9 times. The relative speed improvement was greatest for large environments with simple obstacles. On the basis of memory usage, no algorithm was found to considerably outperform the two others, except in obstacle-free environments for which RayBaPP requires a very low amount of memory, whatever the spatial extent. Complexity wise, A* was the least demanding algorithm and RayBaPP's relative performance tended to decrease with the environment's structural complexity. Next, we tested RayBaPP's capability to produce realistic routes in a spatially explicit agent-based model of marine traffic. For this application, the environment is a 1983x2205 raster with two states (navigable versus obstacle). Realism was assessed by means of two metrics which are 1) the one-way distance, and 2) the length of the simulated trajectory compared to the real reference trajectory. Since Dijkstra proved to be unable to deal with large environments in a tractable time, we compared RayBaPP with A* implemented with the Manhattan distance heuristic, known to be the fastest to compute. We found that RayBaPP outperforms A* in terms of realism for an application involving agents familiar with their environment. For modelling applications where users have to deal with large environments, covering extended geographical areas for example, the use of a fast processing path-planning algorithm is crucial to satisfy common modelling constraints (e.g. numerous agents acting simultaneously, numerous simulations to run). We believe that the lack of efficient path-planning algorithms able to deal with large environments can deter modellers from building agent-based models coupled with growingly available fine-scale geographical information. When the environment can be defined with binary cells, graph-

search algorithms are uselessly too powerful to tackle the path-planning problem, unlike dedicated algorithms such as RayBaPP which are specifically designed for this kind of situation.

5.3 Introduction

Spatially-explicit agent-based models (SEABMs) can represent autonomous mobile objects also called *agents* that move across an explicit representation of a physical environment. Here, we define an *autonomous mobile object* or *autonomous agent* as an entity being situated in, and part of, an environment, sensing and acting on that environment over time, with the goal of satisfying its own objectives. Different kinds of representations exist for agent's environments, the most commonly used being networks (Gimblett, Durnota and Itami, 1996; Roberts, Stallman and Bieri, 2002) and 2D-grids (Anwar *et al.*, 2007; Torrens, 2007). Recent advances in spatial data collection tools (*e.g.* satellite imagery, LIDAR, sonar) coupled with the growing number of data-sharing programs have democratized the use of fine-scale geographical data describing physical environments. For modellers, this is an opportunity to model spatial processes occurring across large raster environments. In such cases, autonomous agents (*e.g.* boat captains (Anwar *et al.*, 2007), elk (Bennett and Tang, 2006), or pedestrians (Torrens, 2007)) need to find their routes through a possibly large amount of cells.

In the video game industry, path-planning is known to be one of the most resource-consuming computational tasks (Botea, Müller and Scaeffer, 2004; Graham, McCabe and Sheridan, 2003). The same is true for SEABMs where an accurate representation of agents' movements must be achieved. Modellers intending to build SEABMs require the use of efficient and fast-processing path-planning algorithms, which is a challenging task if the following model characteristics are encountered: 1) the model has a small *temporal grain* (*i.e.* fine-scale resolution) along with large *temporal extent* (*i.e.* simulation over large periods of time); 2) the model has a small *spatial grain* (*i.e.* fine-scale resolution) along with a large *spatial extent* (*i.e.* large environment); and/or 3) numerous (typically hundreds) autonomous agents move simultaneously. Additionally, critical simulation constraints include: 1) large number of simulations (numerous alternate candidate modules for calibration, replications for model performance assessment, or scenarios for model application) need to be run; 2) the realism of agents' movements matters; 3) environment can potentially be dynamic, making pre-processing of the environment undesirable; and/or 4) real-time visualization must be fluid, potentially on a standard workstation. If any of these cases applies, it is imperative to have a computationally efficient path-planning module to model agent movements.

In this article we propose a path-planning algorithm based on a geometrical approach called RayBaPP. We use the term *path-planning* in lieu of *pathfinding* to describe the mechanism of totally computing an agent's path prior to any movement. RayBaPP is intended to find a short and smooth path across a large raster-based environment made of binary-state cells (passable cells *vs.* obstacle cells) faster than classical methods so as to satisfy the above mentioned simulation constraints when the above mentioned model characteristics are met. We focus on applications where the environment is familiar to the agents and we can thus take advantage of their knowledge to anticipate obstacle avoidance during the route planning step. We do not deal with collision avoidance mechanisms between agents; this particular problem could be tackled by a higher-level pathfinding module that would re-compute a new local avoidance path in case of collision risk detection (Mors, Belle and Witteveen, 2009; Silver, 2005). This kind of problem is known as cooperative pathfinding.

We first introduce the classical algorithms used for path-planning. Then, we present the proposed RayBaPP algorithm. In order to assess RayBaPP's performance (speed, memory and complexity), we present the results of a benchmark led on classical environments (e.g. U-shape obstacle, spiral) with classical algorithms (A* and Dijkstra). We illustrate the use of RayBaPP by presenting an application where it has been successfully implemented within a SEABM. We finish with a general discussion about RayBaPP's strengths and limitations along with suggestions for potential improvements.

5.4 Classical algorithms used for pathfinding

Dijskstra (Dijkstra, 1971) and A* (Hart, Nilsson and Raphael, 1968) are graph traversal algorithms frequently adapted to the solving of pathfinding problems in 2D-environments. They are optimal (quasi-optimal for A* used with an admissible heuristic, that is a rule overestimating the distance to destination) and ensure the user to find a solution if one exists. They are particularly powerful when the cost associated with cell traversal is not uniform (*e.g.* for an agent moving with a car, using a tarred road cell is faster than using a gravel road cell, affecting their respective traversal cost). Moreover, transforming a 2D-grid into a graph is very simple and can be done during the algorithm execution. Unfortunately, these algorithms tend to be very time-consuming, which is particularly critical when used on large environments. This poses problems when one has to deal with the above-mentioned simulation constraints requiring fast-processing pathfinding.

Both Dijkstra and A* are local graph search algorithms. Dijkstra works with two lists *open* and *close* and proceeds by *expanding* the least costly node at each iteration. The action of *expanding a node* consists in inserting in *open* each node connected to the one being developed as a triplet made of 1) the connected node, 2) the cumulative cost to get to this node, and a pointer to the parent node (i.e. the node being expanded). Note the two following cases: 1) if a node is already in *close* (*i.e.* already expanded), it is not considered anymore. If a node is already in *open*, if its newly computed cumulative cost is lesser than the old one, the old cost is replaced with the new one and the parent node is updated. Once a node has been *expanded*, it is removed from *open* and placed into *close* as a triplet (*i.e.* with its associated cost and its parent node). The next node to be expanded is the one with the lowest cost in *open*. The search stops when *open* is empty and the least cost path is found by tracing back the parent node, starting from the destination to the origin. A* is very similar to Dijkstra with modifications allowing a faster convergence. A* prioritizes the expansion of nodes that bring the search closer to the destination, using an underestimation of the distance to destination called an admissible heuristic (*e.g.* distance as the crow flies). By accounting for the distance to destination in the search process, A* ensures a more rapid convergence by leaving aside from the expansion process the nodes that keep the search away from the destination.

In numerous multi-agent applications including pedestrian simulation or video games, programmers use classical powerful and resource-consuming graph-search algorithms such as Dijkstra, A*, and its variants (HPA*, D*, LRA*, CA*) to solve spatial pathfinding problems in *binary environments* (*e.g.* (Anwar *et al.*, 2007; Kumar *et al.*, 2004; Peng, Ruihua and Xiaolei, 2007)). Variants of A* along with a great amount of simplification tricks such as navigation meshes (O'neill, 2004) have been proposed to improve performance, especially computational time and memory requirement. Handling a binary environment (*i.e.* cell's crossing cost is solely related to the distance), a programmer willing to use A* or its variants without any simplification of the environment must consider it as a specific instance of a graph where the costs associated with a cell-to-cell displacement are calculated as follows:

- Straight displacements (in the 4-cell Von Neumann neighbourhood) have a cost of 1 unit.
- Diagonal displacements have a cost of √2 units.

Regarding the realism of generated trajectories, A* and its variants do not allow taking advantage of the *a priori* knowledge that some modelled agents may have about the structure of the whole environment (*e.g.* pedestrians walking in their home town (Torrens, 2007), commercial boat captains navigating several times a day in the same area (Anwar *et al.*, 2007), or animals moving within their familiar living environment (Bennett and Tang, 2006)). Local graph-search algorithms act as if an agent could only check the status of its closest neighbourhood, forcing it to turn back if its past decision had led it toward a dead-end location. We propose a geometrical algorithm called RayBaPP which addresses the problem of computational time in large environments as well as the issue of trajectory realism in familiar environments.

5.5 Ray-Based Path-planning algorithm (RayBaPP)

RayBaPP algorithm, standing for Ray-Based Path-Planning, is a purely geometrical approach that aims at finding a short and straight path within large familiar environments, faster than classical algorithms. It is not a graph-traversal algorithm and thus cannot be used to find a least-cost path within a graph. Its application is restricted to 2D rasters with binary states cells (passable vs. obstacle).

5.5.1 General principles of RayBaPP

Overall, the construction of the planned trajectory with RayBaPP is divided into 2 steps:

1) Creation of a coarse waypoints list L_w between origin O and destination D cells.
2) Smoothing of L_w to get rid of superfluous waypoints.

Once the waypoints list has been found, the agent must then interpolate its new position at each time step during the simulation run.

RayBaPP is inspired by the ray tracing method in 3D graphics. The general concept is to cast a ray between two points, say from O to D and see what happens. If the ray can reach the target D without striking any obstacle, this means that the straight line (shortest path between O and D) can be followed by the agent without having recourse to any intermediary waypoint. Thus, the returned path is composed of only 2 points, O and D, and the agent will have to interpolate its position according to its speed along the straight line joining O to D.

On the other hand, if the ray cast from O to D crosses some obstacle, we must give the agent the capability to find the relevant intermediary waypoints in order to plan its route. The geometric approach that we propose is detailed in the next subsection. This approach allows the agent to determine a list of intermediary waypoints to reach its final destination; however, some of these points may prove superfluous, especially if they force the agent to change its heading uselessly. A smoothing algorithm is employed to deal with this issue as described below.

5.5.2 Creation of a coarse waypoints list

As stated by Torrens (Torrens, 2007), “people use waypoints to develop a general sense of how to get somewhere”. Accordingly, the purpose of this first step is to build a list of points containing at least all the key locations that will shape the skeleton of the final trajectory. First, we present the general concept with an example. Figure 5.1 illustrates the geometric concept of how the algorithm generates the coarse waypoints list L_w.

Typically, moving agents probe a raster where a cells’ value is stored (passable vs. obstacle). In Figure 5.1, the agent starts at location *O* and wishes to move to *D*. The way RayBaPP converges to the solution path is entirely described in the caption of Figure 5.1.

During the first step of the algorithm, the action “cast a ray” is called several times. This basic operation is executed using the well-known Bresenham’s algorithm (Bresenham 1965) which is easily available in its very optimized form. Drawing a line between two points is analogous to ray tracing except that rays do not bounce when they hit an obstacle, but instead go through the obstacle keeping track of the entering (e.g., A and C, Figure 5.1) and exiting points (e.g., B and E, Figure 5.1). The pseudo-code of this first step is available in APPENDIX V.

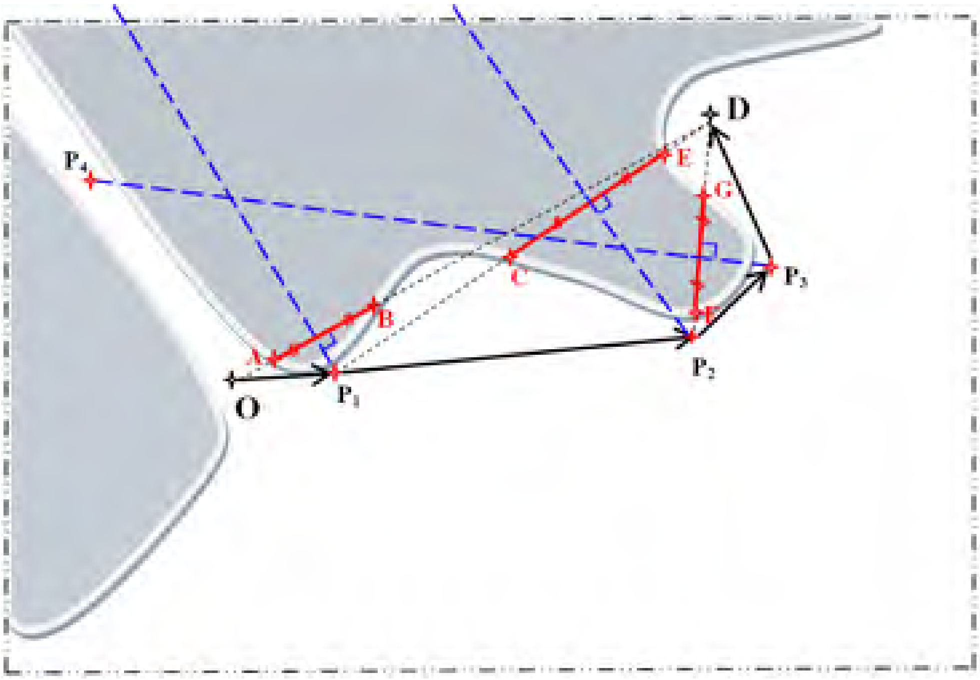

Figure 5.1 Example (sketch) of the creation of the coarse waypoints list. Starting from point O, the agent's goal is to reach D avoiding the grey dotted area (non passable zones). A first ray is cast from O to D (thin black dashed line) keeping track of the first segment [AB] that crosses the obstacle (thick plain line). From the midpoint of [AB] a ray is cast perpendicularly in each direction (thick dashed line), and only the attainable point P_1 is recorded since no passable point is found in the alternate direction. Then P_1 is inserted in a waypoints list L_w between O and D. Then from P_1 the same procedure is repeated between P_1 and D and P_2 is found and introduced within L_w between P_1 and D. Finally, the ray cast between P_2 and D crosses the obstacle between F and G, giving two alternate points P_4 and P_3 and therefore two alternate paths $L_w=\{O;P_1;P_2;P_3;D\}$ and $L_w'=\{O;P_1;P_2;P_4;D\}$. Since L_w is complete and allows the agent to join O to D, the algorithm stops and returns L_w as the final coarse waypoints list of the planned trajectory.

5.5.3 Smoothing the coarse path

In some situations, unneeded points can be generated during the creation of the coarse waypoints list. A waypoint is nonessential if its previous and subsequent points in the waypoints list L_w can be linked together with a straight line without crossing any obstacle. In such a case, this point must be removed from L_w. In the example drawn in a continuous space and presented in Figure 5.1, smoothing would be useful if a ray cast between O and P_2 would not cross any obstacle. In this case, P_1 would be removed from L_w. This smoothing algorithm is very simple and consists once again in several calls of the optimized Bresenham's algorithm. The pseudo-code of the smoothing algorithm is given in APPENDIX VI.

After calling this smoothing function, the list of waypoints is reduced to its shortest form, ensuring that the trajectory has a minimum number of heading changes for the moving agent.

5.5.4 Position interpolation during the simulation

The previous two steps allow any agent to determine the list of locations it will go through to reach its destination; this is a planning stage which occurs prior to any move. In the context of a discrete-time simulation, the agent will have to calculate its new position at each time step depending on its velocity. If the destination changes during the movement (due to any event), the agent will have to refresh its waypoints list L_w by calling the path-planning algorithm and the smoothing function again.

5.5.5 Optimization of the solution path search

Despite its apparent simplicity, the driving concept of RayBaPP can lead to complications if the search process is not carefully examined. Two strategies were used to adjust the search process in order to ensure it will unfold successfully. They are detailed below.

5.5.5.1 Removal of useless candidate paths to prevent their exponential growth

The structure of the RayBaPP algorithm may lead the search to produce a huge number of candidate paths in the case of complex environments. Indeed, each obstacle encountered generates a sub-problem to be solved leading to the production of up to two new concurrent paths (*cf.* Figure 5.1 with P_3 and P_4). In a more complex environment, this can lead to a demanding computational effort, as the search must be performed among an exponentially growing number of candidate paths. To avoid this problem, we considered that each time a cast ray crosses an obstacle, it creates a sub-problem of the same kind as the general problem.

Therefore, each time a specific sub-problem has been resolved, all concurrent paths that had been generated to solve that specific sub-problem can be removed from the set of candidate paths. Consequently, only the candidate paths generated and grown to deal with unsolved sub-problems co-exist in the dynamic set of concurrent candidate paths. This strategy proved successful in all of our experiments.

5.5.5.2 Best-first search approach to promote the shortest paths

The set of candidate concurrent paths is sorted by length at each new path creation. This way, the first path selected to be processed by the main "while" loop of the RayBaPP algorithm (see APPENDIX V) is always the shortest (in total distance) in the list. The best-first search ensures that priority is given to plausible paths since aberrant concurrent paths tend to grow rapidly in terms of their total length. More importantly, this strategy promotes the shortest path, which is the most likely to be selected by an agent moving into a familiar environment.

5.6 Results and discussion

5.6.1 Methods

We designed a benchmark test in order to compare RayBaPP's performance with classical graph-search algorithms, namely A* and Dijkstra. The A* algorithm is implemented with the Manhattan distance heuristic (admissible), known as the fastest to compute (Patel, 2001). Implementations of A* and Dijkstra used the lightest data structure in Java, namely *Hashmap*. A complete description of these algorithms can be found in LaValle ((LaValle, 2006); also available online[3]).

We varied two environmental characteristics, namely 1) *structure*: no obstacle, square-shaped obstacles (cf. Figure 5.5), U-shape (cf.

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[3] http://planning.cs.uiuc.edu/

Figure 5.6), spiral (cf. Figure 5.7); and 2) *dimension* (from 10*10 up to 2000*2000 grids) in order to assess the influence of these parameters on algorithm performance

For each algorithm, the observed computational variables are total *processing time* (milliseconds), *memory requirement* to complete the search (Kilobytes) and *search effort* (number of cells explored during the search process). We end our assessment by visually comparing output paths in order to highlight differences between the algorithms. RayBaPP's smoothing step is considered in all tests.

All experiments have been conducted on a computer equipped with a standard processor *Intel® Core™ 2 Duo CPU T7300 @ 2.00GHz*.

5.6.2 Computational results

5.6.2.1 Computational time

Figure 5.2 illustrates the fact that RayBaPP is almost always faster than A* and Dijkstra, whatever the environment's structure and dimension and Dijkstra is always the slowest. In large environments, RayBaPP's gain over A* in terms of processing time ranges from approximately 10 times for the spiral to up to 1000 times for obstacle-free paths. Overall, we observe that the simpler the structure of the environment, the greater RayBaPP outperforms Dijkstra and A* in terms of convergence time.

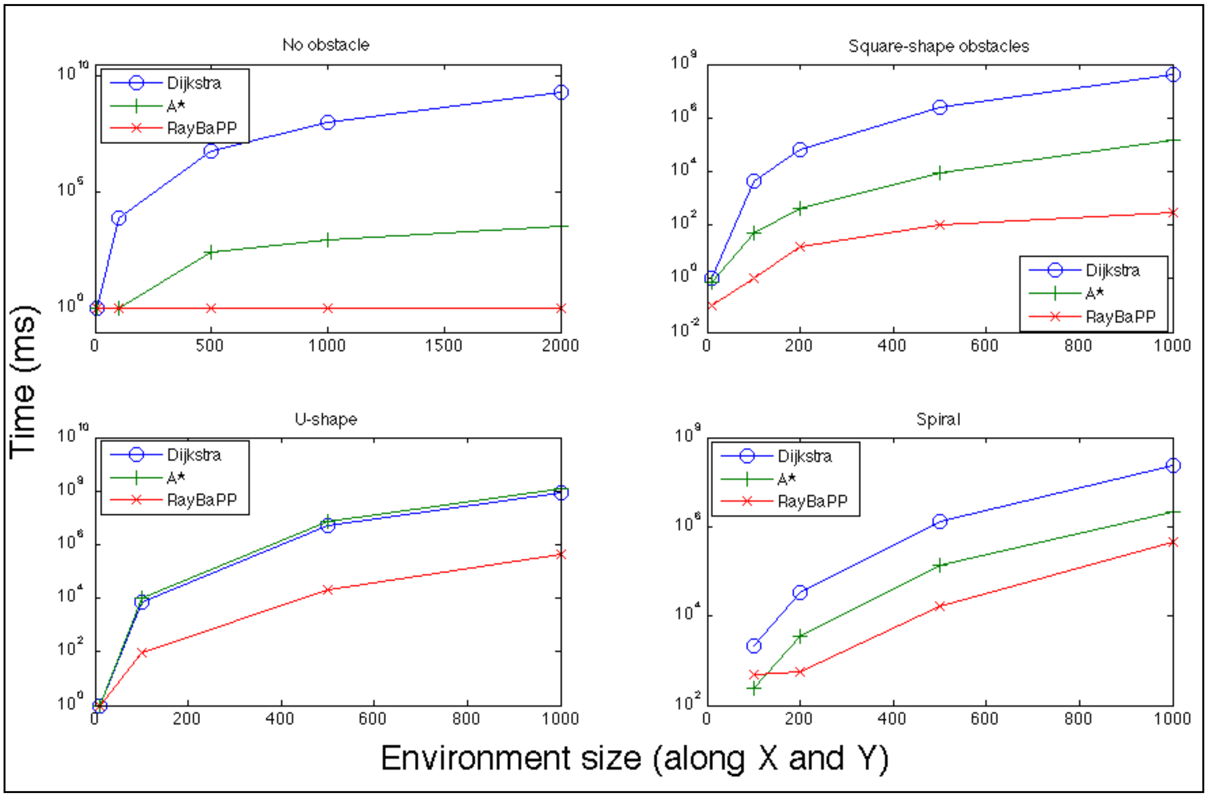

Figure 5.2 Computational time in milliseconds (ms) for different environment structures and dimensions. Time assessment accuracy is approximate for durations less than 1 ms.

5.6.2.2 Memory requirement

As illustrated by Figure 5.3, Disjkstra's search process is the greediest whereas A* and RayBaPP are generally the most efficient in terms of memory usage. In the obstacle-free environment, RayBaPP greatly outperforms both A* and Dijkstra whereas as the complexity of the environment increases, A* and RayBaPP tend to perform similarly. Relative performances of algorithms tend to be constant as the environment's dimension increases, some fluctuations and inconsistencies being possibly related to java's memory allocation management.

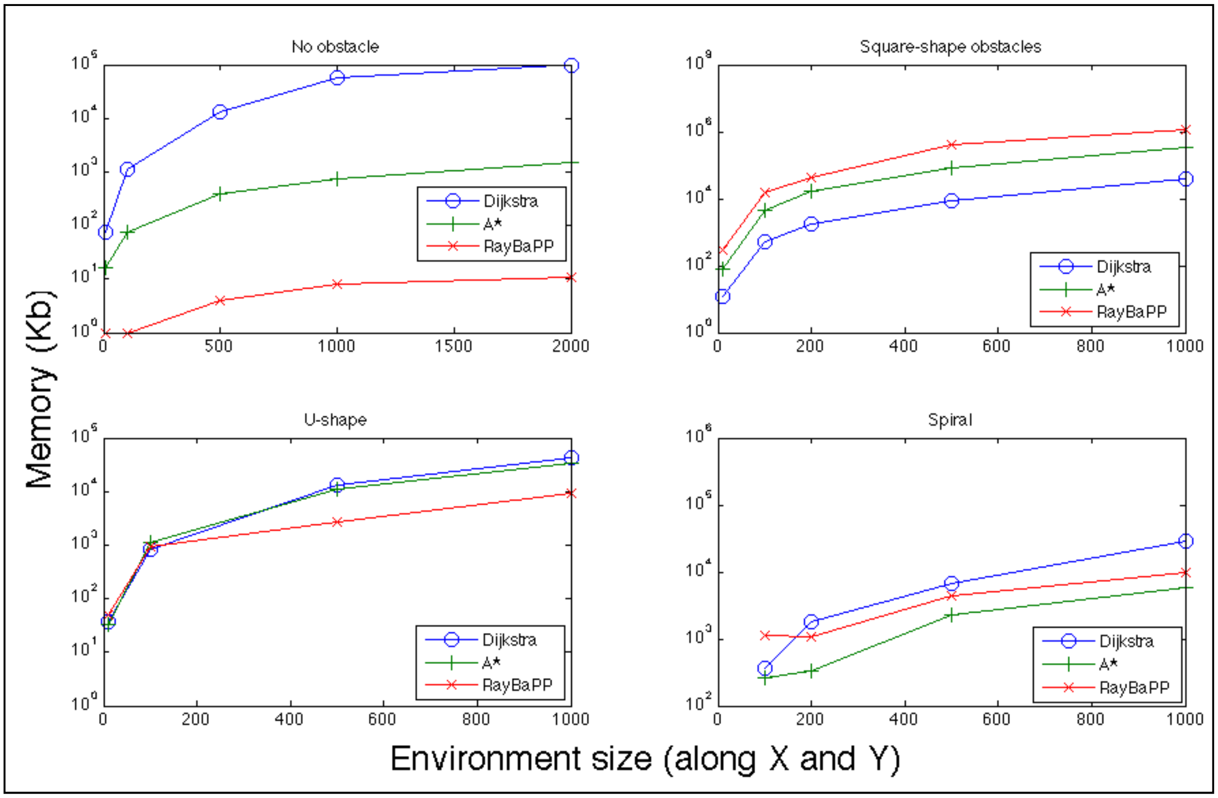

Figure 5.3 Memory requirement for different environment structures and dimensions. The memory is computed as the difference between the maximum and minimum free memory available during the path search process.

5.6.2.3 Spatial exploration

The spatial exploration process is characterized by the number of cells probed by the algorithms during the search. In Figure 5.4, we observe that A* is the most efficient in terms of spatial exploration, regardless of the environment's structure and dimension. As the environment's complexity varies from obstacle-free to spiral, RayBaPP shifts from being the most efficient to the greediest algorithm relative to A* and Dijkstra in terms of spatial exploration. RayBaPP's extensive search is partly due to the smoothing stage (cf. section 5.5.3 and APPENDIX VI), inexistent for A* and Dijkstra algorithms.

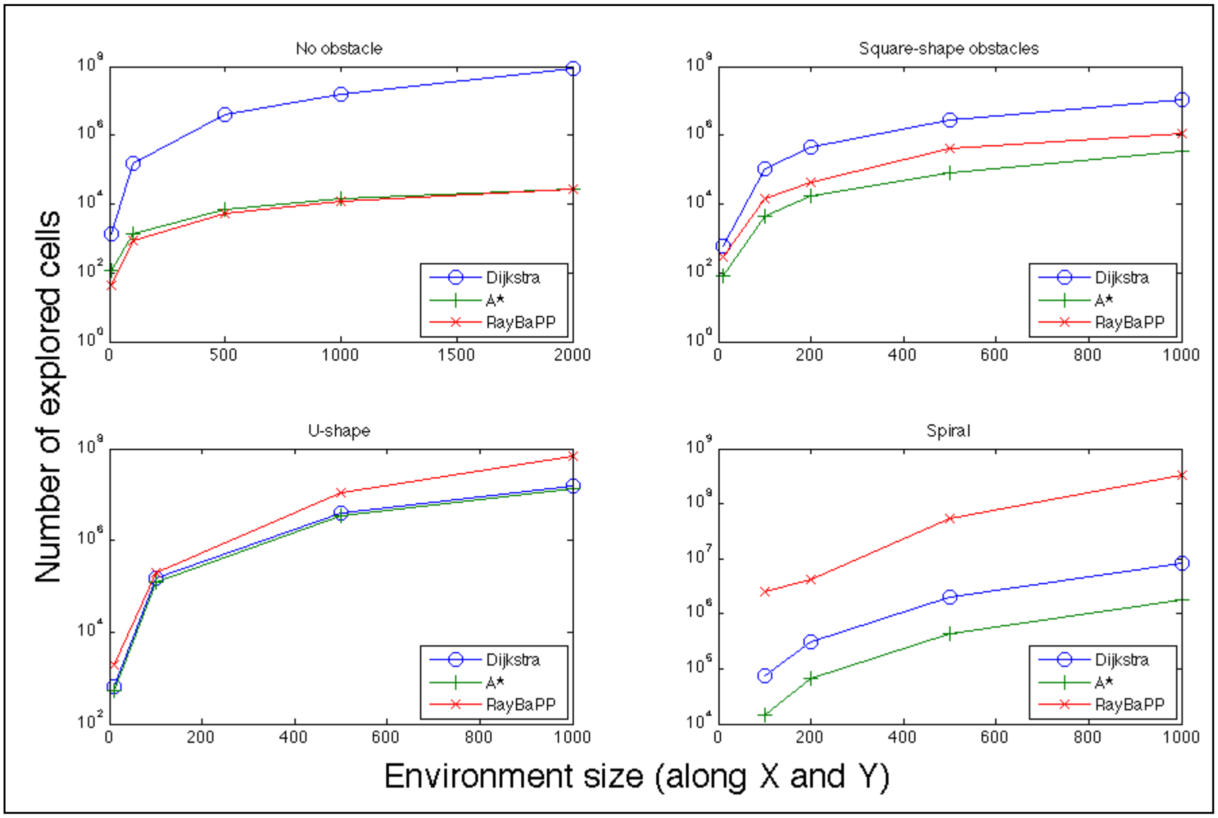

Figure 5.4 Number of cells explored during the path search for different environment structures and dimensions.

5.6.3 Spatial results

Only the results with obstacles are shown since trajectories in the obstacle-free environment are straightforward lines linking together origin and destination. It should be noted that the trajectories' shapes generated by the three algorithms are independent of the environment's dimension.

5.6.3.1 Square-shaped obstacles

Figure 5.3 illustrates the differences between trajectories returned by the three tested algorithms. For situations where agents move across a familiar environment, the trajectory generated by RayBaPP is intuitively the most realistic. A common default displayed both by A* and Dijkstra is their tendency to generate routes that stick to obstacles when skirting around them. In terms of distance traveled, all three algorithms tend to perform equally well on this spatial configuration.

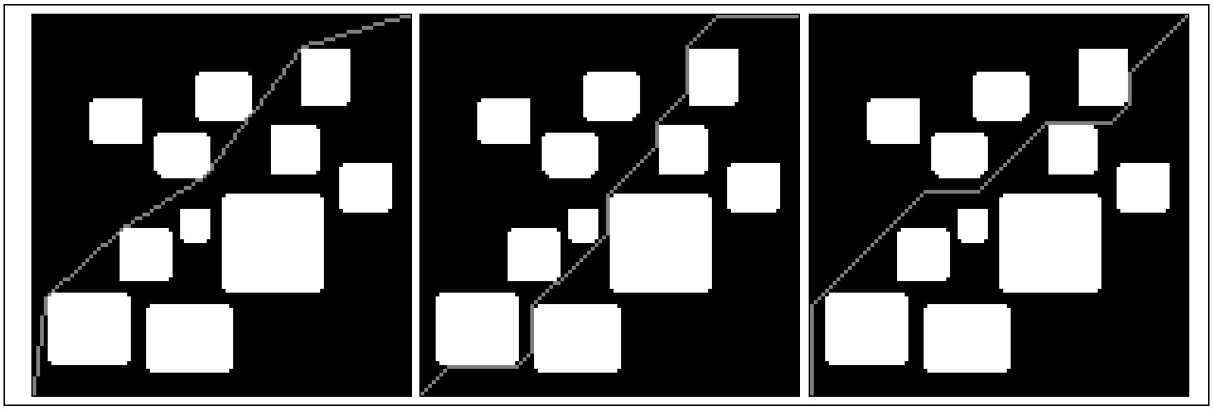

Figure 5.5 RayBaPP (left), A* (center) and Dijkstra (right) trajectories returned for an environment with square-shaped obstacles. Obstacles are white, traversable cells are black and the output path is grey.

5.6.3.2 U-shaped obstacle

Figure 5.6 does not show major differences between the output of the three algorithms for a U-shaped obstacle. However, an artefact appears in A*'s route since some oscillations emerge on the upper part of the path; this artefact could be discarded by using an alternate heuristic such as the Euclidian distance, at the expense of processing time.

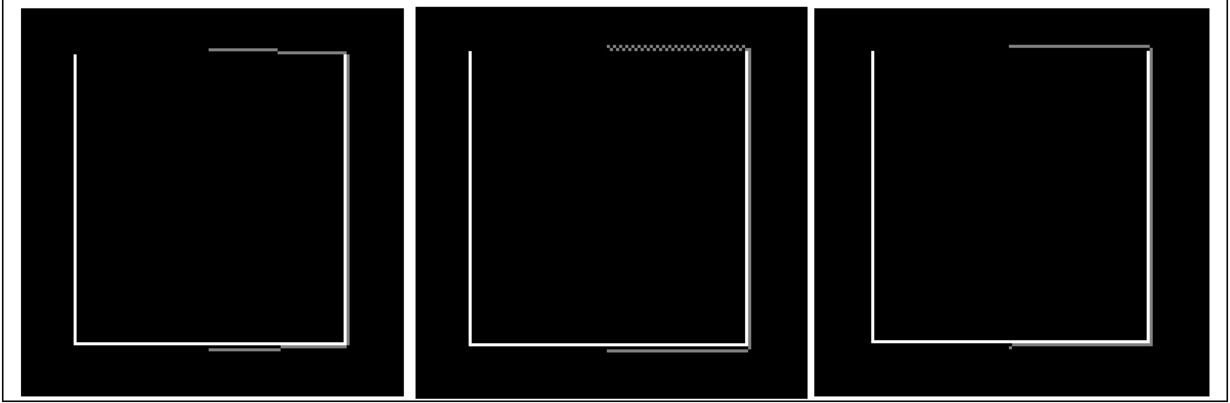

Figure 5.6 RayBaPP (left), A* (center) and Dijkstra (right) trajectories returned for a U-shaped environment. Obstacles are white, traversable cells are black and the output path is grey.

5.6.3.3 Spiral

Finally, results for the spiral environment are shown in Figure 5.7. Here again, we notice that RayBaPP heads more rapidly towards the obstacle's corner than A* and Dijkstra that tend to stick to obstacle' borders, resulting in a longer path. This advantage presented by RayBaPP is partly due to the smoothing step which tends to remove unnecessary waypoints from the output path.

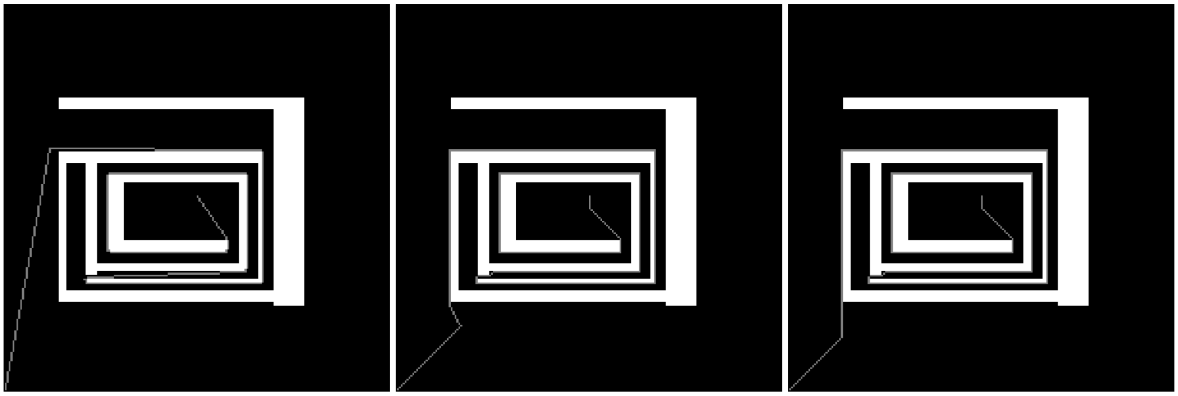

Figure 5.7 RayBaPP (left), A* (center) and Dijkstra (right) trajectories returned for a spiral environment. Obstacles are white, traversable cells are black and the output path is grey.

5.6.4 Discussion

5.6.4.1 Algorithms performance

For the great majority of tested environmental configurations, RayBaPP solved the problem faster than A* and Dijkstra. Because of its search mechanism based on systematic ray-casting, RayBaPP tends to explore more cells than A*, but almost always less than Dijkstra. However, since RayBaPP does not systematically compute the cost for each evaluated cell (contrary to A* and Dijkstra), its computational time remains far below that of its competitors.

Even if Dijkstra is designed to return the optimal least-cost path, it does so at the expense of speed and memory usage, making it the greediest of the tested algorithms, regardless of the environment. Within large environments, under such constraints as those presented in the introduction, one cannot consider using Dijsktra unless considerable computational power is available. Alternatively, A* used with an admissible heuristic guarantees that a quasi-optimal path be returned in a more tractable time.

5.6.4.2 Path shape

For all three algorithms, the shape of the returned path was found to be independent of environment dimension. By visual inspection, we see that RayBaPP produces straighter paths than both A* and Dijkstra. RayBaPP's output paths tend to be more plausible from what we intuitively expect from an agent moving into a familiar environment since obstacle avoidance is anticipated by RayBaPP, which is consistent with the searching strategy. Moreover, contrary to RayBaPP, A* and Dijkstra tend to produce paths that stick to obstacles when skirting around them.

5.6.4.3 General points

The three algorithms displayed some asymmetry in the resolution of the path-planning problems. In some situations, finding a path between an origin and a destination location can be much harder than the reverse problem (from destination to origin). Most notably, in the spiral environment, going out from the inside proved much more difficult than reaching the center from the outside for RayBaPP, whereas the opposite was true for A* and Dijkstra.

5.6.4.4 RayBaPP limitations and potential improvements

RayBaPP is most efficient in environments with large spatial extents and few obstacles. For environments with a complex obstacle geometry, several improvements can be specified to allow RayBaPP to converge more rapidly. First of all, as proposed in (Chen *et al.*, 2006), one can identify and compute obstacle geometry in order to extract the skirting path when the search process crosses its border. Another solution for some environments could be to build the minimum polygon convex hull containing the origin, the destination, and the obstacles lying between the two points. However, to pursue the convex hull approach, one has to solve the problem emerging from obstacles whose convex hull would overlap, potentially blocking off the opening to destination.

An artefact of RayBaPP's search is that when a ray is cast in a specific direction, depending on the nature of the environment, the ray may reach an isolated non-obstacle area, disconnected from the main zone (*e.g.*, donut-shape obstacle); in that case, the algorithm could fail to find its way out of this isolated area. There are two simple ways to overcome this problem involving pre-processing. One can either compute a pre-treatment on the raster containing the spatial information, in order to remove all the problematical cells (cells that achieve the criterion of reachable cells but are disconnected from the true spatial domain of agents). Another way is to add a binary layer of information where reachable cells that are connected to the main agent's spatial domain are identified and assigned a specific value. Doing so requires the RayBaPP algorithm to query two layers (the basic DEM and the supplementary layer) in order to conclude that a given location is or is not reachable. Another efficient solution without any pre-processing step is to set a threshold value corresponding to the maximum number of iterations that should never be exceeded when attempting to solve a given sub-problem during the first step of RayBaPP after the discovery of a new waypoint. Reaching this threshold means that RayBaPP has failed to solve the sub-problem in a reasonable number of tries, between a previously found point and its following one in the waypoints list. We are then allowed to conclude that this point is not connected to the navigable area and the search for another navigable point must be resumed to replace this isolated one. The iteration threshold value depends on the structure of the environment.

Finally, in its present form, RayBaPP stops its search process as soon as the first solution path has been found. For many reasons, this path may not be the fittest one. Modifications to the path-search stopping rule could be brought to RayBaPP to allow the discovery of more than one solution and use a specific criterion to pick the best one according to a given context.

5.7 Example application of RayBaPP

The application project consisted in the creation of a SEABM called 3MTSim which represents interactions between marine mammals and maritime traffic in the St. Lawrence Estuary, Québec, Canada (Parrott *et al.*, (submitted)). This model is intended to be used by marine protected area (MPA) managers as a decision-support system for the management of navigation in the MPAs of the region. For additional information on the 3MTSIM project, we refer the interested reader to the project website (http://www.geog.umontreal.ca/syscomplex/3MTSim/index.htm).

3MTSim represents the movements of four types of boats and five species of marine mammals. There can be up to 1200 autonomous agents moving simultaneously in the environment represented by a 2205×1983 raster.

5.7.1 Datasets

We used 3 different databases containing spatiotemporal trajectories of boats. For ferries and cargo ships, the database was supplied by the Canadian Coast Guard. These data come from the INNAV system (http://www.innav.gc.ca) that acquires and stores information about ships navigating in Canadian waters (*e.g.,* position, time, speed, ship type). For commercial whale watching excursions, the database was provided by the GREMM (Group for Research and Education on Marine Mammals, http://www.gremm.org). Finally, the database of yacht trajectories was provided by Parks Canada (http://www.pc.gc.ca); these data were acquired as part of a project aiming at quantifying the number of visitors and characterizing their visits within the Saguenay–St. Lawrence Marine Park. All datasets were acquired between 2005 and 2007 with a temporal resolution of 1 minute.

5.7.2 Experiments

Since the Dijkstra algorithm has proved not to be suitable for path-planning in large environments, we assess RayBaPP and A*'s ability to reproduce some real boat trajectories given the origin and destination. In this experiment, performance concerns realism and this has been tested by comparing both the *length* and the *shape* of the trajectories returned by RayBaPP and A* with the real one.

In order to compare the relative capabilities of the RayBaPP and A* algorithms to produce realistic trajectories, we selected a number of prototypical trajectories representative of moves observed within the study area, for each category of power-operated boats (*cf.* Figure 5.8). All trajectories are polylines linearly extrapolated from actual sets of GPS positions sampled at each minute. We selected trajectories that satisfy the following constraints:

1) Origin and destination are clearly derivable from a visual study of trajectory. The operator's purpose can be almost undoubtedly deducted from trajectory shape, given the knowledge of both local constraints and boat characteristics (mainly draught, speed and activity).
2) No major event disrupted the normal route (*i.e.* speed remained almost constant during the movement, and turning angles remained close to 0 in the absence of obstacle avoidance).

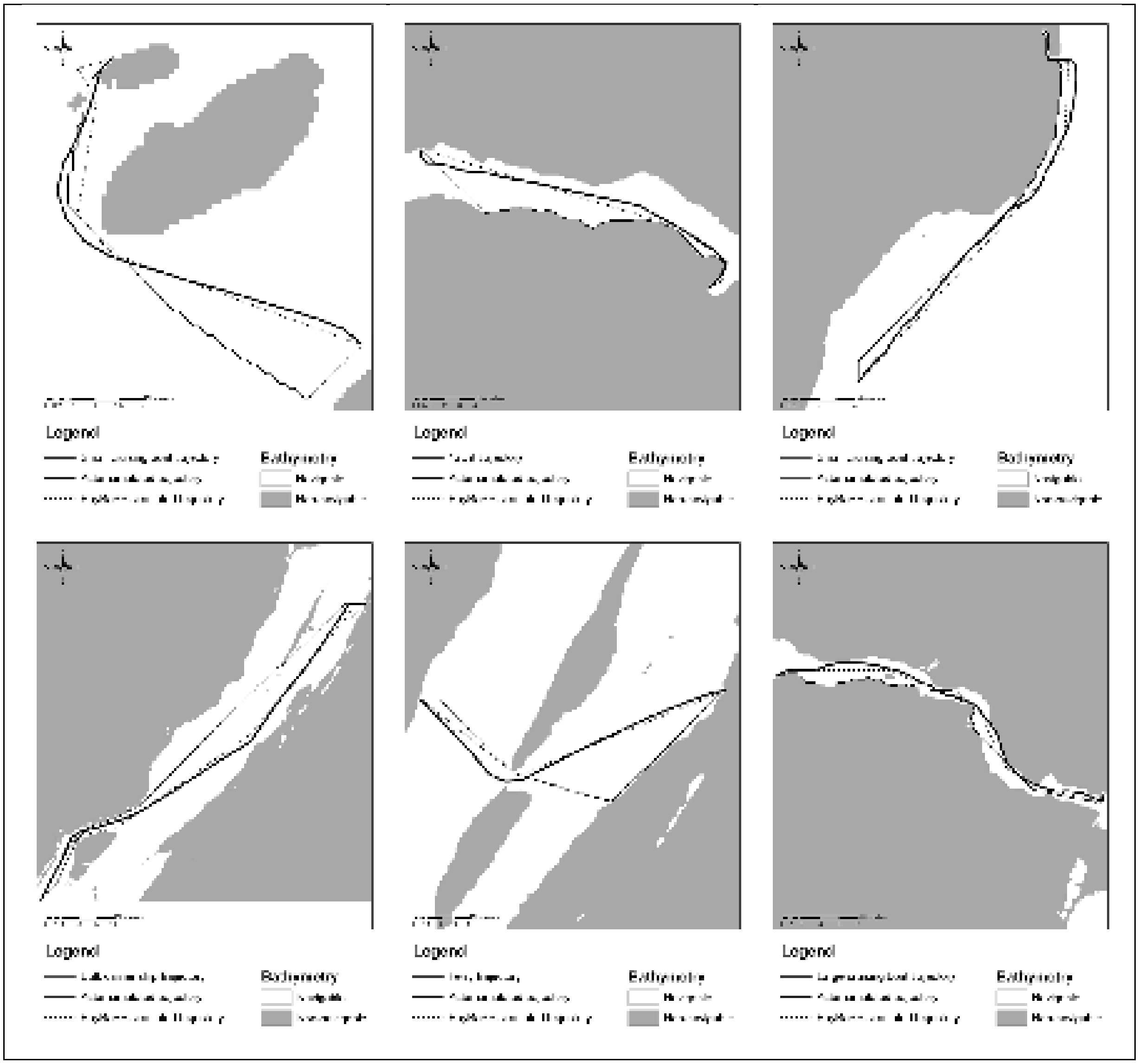

Figure 5.8 The six maps above present real boat trajectories (black thick lines) extracted from one of the three independent datasets at hand. For each real trajectory, the corresponding one returned by A* is plotted with a black thin line whereas a dashed line represents the one produced by RayBaPP. The binary back ground is white when navigable, and grey otherwise (the threshold value is chosen according to the draught of the vessel).

A good knowledge of landscape attractions in the region supported the interpretation of trajectories and the identification of captain's intentions with a reasonable degree of confidence. The selection of trajectories presenting only one intention (going from actual location *O* to a destination *D*) was important in our case. In our application, we need to call a path-planning module immediately after an agent has picked a destination (via a decision-making module). We propose two measures to assess the goodness-of-fit of simulated trajectories with the corresponding real one:

1) *Trajectory length*: this is simply computed by summing the length of the segments formed by each two consecutive GPS points that compose the whole trajectory.
2) *Trajectory similarity:* this is assessed using an approximation of the average of the two one-way-distances (OWD) between the simulated and the real trajectories (see (Lin and Su, 2008) for a complete description of the OWD). For a given real trajectory T_r, both A* (T_{A*}) and RayBaPP ($T_{RayBaPP}$) simulated trajectories start and finish at the same locations O and D. Consequently, each pair of polylines $\{T_r; T_{sim}\}_{(sim=A* \text{ or } RayBaPP)}$ defines a closed polygon. We then approximate the distance $d_{r \Leftrightarrow sim}$ between two trajectories as the polygon area divided by the average of the two trajectories' lengths (*cf.* equation (5.3)).

The OWD $D_{owd}(T_1, T_2)$ between two trajectories T_1 and T_2 proposed in (Lin and Su, 2008) is given in equation (5.1).

$$D_{owd}(T_1, T_2) = \frac{1}{|T_1|} \cdot \left\{ \int_{p \in T_1} D_{point}(p, T_2)\, dp \right\} \tag{5.1}$$

This definition suggests that the distance $D_{owd}(T_1, T_2)$ is different from $D_{owd}(T_2, T_1)$ since the lengths of the two trajectories are different (affecting the first factor), and since their shapes are different (affecting mainly the integral part). Our simplification is that both integrals are equal and can be approximated by the area between the two trajectories. This is supported by the fact that the two trajectories start and finish at the same points, and that their shapes should not be too dissimilar in most cases.

$$\overline{D}_{owd}(T_1, T_2) = \frac{1}{2} \cdot \left[D_{owd}(T_1, T_2) + D_{owd}(T_2, T_1) \right] \tag{5.2}$$

Consequently, the definition of the average OWD given in equation (5.2) can be approximated by a new definition of the modified average OWD proposed in equation (5.3), stemming from the previously stated assumptions.

$$\tilde{\tilde{D}}_{owd}(T_1,T_2)=\frac{|T_1|+|T_2|}{2\cdot|T_1|\cdot|T_2|}\cdot Area\left[polygon\,(T_1,T_2)\right] \qquad (5.3)$$

5.7.3 Results and discussion

Fourteen real trajectories were selected from the three datasets to take into account all categories of power-operated boats namely small (less than 50 places) and large cruise boats, private yachts, cargo ships and ferries. For simplicity, only six of the trajectories are presented here. Data storage, analysis and cartography were carried out using ESRI software ArcMap version 9.2. Figure 5.8 presents the six real trajectories with the corresponding A* and RayBaPP simulated ones. The simulated agent's environment is a 2205×1983 grid, where navigable cells have a connectivity of 8 nearest neighbours.

The first observation from Figure 5.8 is the systematic spatial proximity between RayBaPP simulated trajectories and real boat routes, whatever the boat type. On the other hand, A* trajectories are characterized by space exploration, which was predictable since this pathfinding algorithm does not take advantage of the *a priori* knowledge that agents have about the structure of the environment (bathymetry here). This results in the generation of trajectories that follow the coastline or navigational borders.

Regarding the length of the simulated trajectories, in 5/6 cases, RayBaPP simulated trajectories were the shortest or the closest in length to the real reference trajectory (1/6 in both cases for A*) (Table 5.1). Simulated trajectories generated by RayBaPP tend to slightly underestimate real length.

Table 5.1 Summary of A* and RayBaPP performances for the six selected trajectories shown in Figure 5.8. The values in bold identify the algorithm that produced the most realistic trajectory in terms of total length, whereas underlined values identify the shortest simulated trajectory

Boat type	**Trajectory length (m)**			**Average OWD (m)**	
	Real	Astar	RayBaPP	Astar	RayBaPP
Yacht (a)	24472.98	26214.93	24025.53	1010.07	262.71
Small cruising boat (b)	25239.33	24553.41	24660.64	371.41	224.65
Bulk carrier ship (c)	111801.16	110765.30	108268.15	3209.21	578.42
Ferry (d)	26570.65	28613.20	25393.49	1738.73	383.34
Large cruising boat (e)	41179.64	43900.21	40657.06	479.90	284.98
Small cruising boat (f)	10377.08	11443.86	10481.49	508.24	166.33

The estimation of the average OWD presented in Table 5.1 shows the superiority of RayBaPP over A*. For the six selected trajectories, RayBaPP produced the most spatially similar trajectory in 6/6 cases with an average OWD of 316 meters, while A* produced trajectories with an average OWD of approximately 1220 meters. Obviously, these values could vary according to the tested trajectories; however, what is noticeable is that RayBaPP produces the most similar trajectories both in terms of length and closeness to the reference trajectory in comparison to A*. These results are confirmed by additional tests conducted over another subset of trajectories (not presented here).

The addition of environmental information related to the surface currents would certainly reduce these values since currents may account for most of the variability not explainable by deliberate captains' decisions.

Obviously, the A* trajectories could be smoothed to produce more realistic shapes. However, considering the large number of waypoints stored by this algorithm (in fact all connected cells that lead from the origin to the destination), such an exercise could result in a critical computation cost since hundreds of agents may potentially call the algorithm at each time step. This is not desirable for the purposes of our application.

5.8 Conclusion

Developers of spatially explicit agent-based models (SEABM) in some respects face the same challenges as video game developers. In dealing with the representation of *autonomous agents'* behaviour in large environments, decision-making related to path-planning remains a critical issue, both in terms of realism of followed routes and in computational demands. We argue that despite the greater availability of fine-scale geographical data for large areas, the lack of dedicated path-planning algorithms able to deal with large environments in a tractable time impedes the development of SEABMs involving numerous autonomous mobile objects without using a simplified version of the agents' space.

We illustrated the ability of RayBaPP to reproduce real-world boat trajectories. For the tested application we demonstrated that RayBaPP produced trajectories similar to the real one observed, both in terms of shape and length, outperforming A* on those criteria.

In several applications, the problem of finding the "best" path between two given locations can be approached as a simple geometrical problem where a good path is simply the shortest one in terms of distance traveled, with no regard to other factors (kind of surface, dangerous area…). For such applications, the use of graph-traversal algorithms such as A* and Dijkstra proved to be computationally inefficient in the context of constraints commonly encountered in spatially explicit agent-based modelling. In order to deal with the constraint of fast path computation within large environments, we proposed the RayBaPP algorithm which proved to be faster than both A* and Dijkstra for all tested environment structures and dimensions. For long-distance obstacle-free movements (greater than 1000 cells), RayBaPP converges more than 1000 times faster than A* and one billion times faster than Dijkstra for the same result. Thus, for applications where the environment is large and made of obstacle-free areas, RaybaPP is an appropriate computationally efficient solution.

CHAPTER 6

ELICITING COGNITIVE PROCESSES UNDERLYING PATTERNS OF HUMAN-WILDLIFE INTERACTIONS FOR AGENT-BASED MODELLING

Using the knowledge extracted from the field campaign presented in CHAPTER 3 and CHAPTER 4, and the path-planning algorithm presented in CHAPTER 5, this chapter presents the approach followed to select a valid model of whale-watching captains' decision making process in 3MTSim.

6.1 Manuscript submission information

This article has been submitted to the journal Ecological Modelling. Its status when this dissertation was submitted was 'accepted after minor revision'. The ordered list of authors who contributed to this manuscript is:

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Thesis author's main contributions to this work include the following:

- Elaboration of the methodology.
- Model programming.
- Results analyses.
- Writing of the manuscript.

6.2 Abstract

Integrating humans in our perception of ecosystems is of critical importance to adequately protect natural resources. This poses the challenge of understanding human decision making in the context of decisions potentially threatening nature's integrity. In this study, we developed a spatially explicit agent-based model that simulates commercial whale-watching vessel movements based on a representation of the captains' decision making process when observing marine mammals in and around the Saguenay–St. Lawrence Marine Park in Québec, Canada. We focus here on the human part of the global model, the submodel of whale movements having been developed and validated independently. Following the pattern-oriented modelling approach (POM), we selected and validated a whale-watching captains' decision making model based on a set of primary patterns. Three models of cognitive heuristics (satisficing, tallying and Take The Best) along with a null model (random choice) were tested to represent the captains' decision making process. These concurrent decision making models were built upon knowledge extracted from data collected during field investigations, including interviews with whale-watching captains and park wardens, onboard and shore-based observations, and analyses of a multi-year dataset of sampled whale-watching excursions. Model selection is performed by statistically comparing simulated and real patterns of boat trajectories (excursion length), spatial hotspots (kernel home range 50%), and excursion content (species observed, time allocated to different activities). The selection process revealed that the Take The Best heuristic was the best performing model. We used the distribution of the number of whale-watching boats in the vicinity (2000 m) of each vessel as a secondary pattern to validate the ability of each decision making model to reproduce real observations. Given the prevalence of the species attribute in the choice of which whale to observe, the Take The Best heuristic's ability to deal with non-

compensatory information partly explains its overall best performance. Moreover, implementation of communication abilities between modelled captains led to the emergence of persistent *observation sites* in the park, which is a well-known collective spatiotemporal characteristic of the whale-watching industry; thus validating the fundamental assumption that cooperation is an important mechanism behind the pattern of whale-watching boat dynamics. The relatively good performance of the satisficing and tallying heuristics supports both field evidence and literature on bounded rationality in that humans likely use collections of heuristics (adaptive toolbox) to solve decision problems in different contexts. The POM strategy appears suitable to build up an informative ABM regarding the management of human activities in a natural environment so that further developments will be assessed following the same approach.

6.3 Introduction

The degradation of ecosystems, including the marine environment, is a reality all around the world (Dietz, Ostrom and Stern, 2003; Halpern *et al.*, 2008; Rapport, Costanza and McMichael, 1998; Vitousek *et al.*, 1997; York, Rosa and Dietz, 2003). The consequences of natural resource depletion such as overfishing (Jackson *et al.*, 2001), or pasture overgrazing (Gilles and Jamtgaard, 2008) are generally measurable so that specific management policies can be set out. Conversely, impacts of non-consumptive human activities on ecosystems such as wildlife disturbance by encroachment upon natural habitats and wildlife-watching tourism can be more difficult to detect for several reasons. The monitoring of impacted populations is hard or expensive (e.g. species with large home ranges), cumulative biological impacts are only observable over long time scales (e.g. animals with a long life span), and disentanglement of mixed effects coming from multiple sources of disturbance is challenging, making the identification of the major threat intractable (e.g. pollution in the food chain plus habitat loss plus habitat degradation plus climate change plus…). Therefore, it can be challenging to draw on a precautionary approach for efficient policy-making regarding the impacts of such non-consumptive activities’ on ecosystems (Duffus and Dearden, 1993).

Canada's protected areas, including marine parks, function under the ecosystem-based management paradigm (Guénette and Alder, 2007). Accordingly, managers have the mandate to keep intact ecosystems of species naturally occurring in their limits (Parks Canada, 2009). In the context of wildlife-watching tourism in Canada, understanding the complex interactions between humans and animals is key to preserving the integrity of ecosystems over the long-term (Musiani *et al.*, 2010). Accordingly, ecologists, biologists, and managers involved in the management of human activities for wildlife conservation will benefit from understanding users' decisions underlying human-wildlife interactions. Whale-watching is a mature branch of the tourism industry in Canada (Hoyt, 2001). It has the potential to create greater awareness about marine ecosystems amongst the general public while offering an economically viable alternative to whaling (Corkeron, 2004). However, long-term biological impacts on targeted populations are beginning to be demonstrated for this non-consumptive anthropogenic activity (Bejder *et al.*, 2006; Lusseau, 2004; Williams, Lusseau and Hammond, 2006). The pressure exerted by whale-watching vessels on targeted animals is an ecological cost that should be mitigated to satisfy ecotourism standards and achieve sustainability (Corkeron, 2004; Hoyt, 2007; Lien, 2001).

Social-ecological systems (SESs), also known as coupled human and natural systems (Liu *et al.*, 2007), can be studied as complex systems (New England Complex System Institute, 2010) insofar as global dynamics emerges from a set of interactions occurring locally between heterogeneous components (e.g. humans, institutions, and animal populations)(Janssen and Ostrom, 2006a; 2006b). Therefore, a whale-watching system involving whale species, whale-watching companies, governmental agencies (e.g. marine park) and NGOs is a typical example of a complex SES. Agent-based models (ABMs) are particularly well suited to account for the specificity of complex systems making them a tool of choice for their study (Marceau, 2008; Parrott, 2008). ABMs have been extensively used over the past decade to deal with various natural resource management related issues such as agriculture in the Yucatan region of Mexico (Manson, 2005), fishing activities on the Great Barrier Reef in Australia (Little *et al.*, 2004), sailing activities on the Colorado River (Roberts, Stallman and Bieri, 2002), water management in Thailand (Becu *et al.*, 2003), or pasture management in the Sahel (Bah *et al.*, 2005). ABMs may help to provide a deeper insight into such systems' dynamics under variable circumstances, such as changing environmental conditions, climate change (Janssen and de Vries, 1998; Patt and Siebenhüner, 2005), or different management policies (Gimblett, 2002; Ligmann-Zielinska and Jankowski, 2007). However, sufficient empirical data and knowledge about components (attributes and interactions) are crucial for an ABM to go beyond a simple "proof of concept" (Janssen and Ostrom, 2006a). In the context of natural resource management, validated ABMs can be seen as virtual laboratories to test hypotheses with the aim of avoiding the Tragedy of the Commons (Hardin, 1968).

Ecology has been contributing significantly to the development of disaggregated models called individual-based models (IBMs) (Grimm, 1999; Grimm and Railsback, 2005; Hudson, 1994), widely used to represent species' population dynamics at the individual level (Grimm, 1999). Ecologists have also been making efforts to build standard protocols both for the development of IBMs, with the pattern-oriented modelling (POM) approach (Grimm *et al.*, 2005; Wiegand *et al.*, 2003) and their description, with the Overview-Design concept-Details (ODD) protocol (Grimm *et al.*, 2006; Grimm *et al.*, 2010). These protocols have been further extended to address the case of ABMs where human beings are involved (Grimm *et al.*, 2010; Polhill *et al.*, 2008). Both the concepts of ODD and POM are reused later in this study.

Modellers building human-centered ABMs for management purposes must tackle numerous challenges (Bonabeau, 2002; Janssen and Ostrom, 2006a). In this article, we focus on two of them, namely: 1) the accurate representation of humans' complex behaviours and decisions; and 2) the selection of a valid model grounded on empirical data. The case study presented here is the implementation of a spatially explicit ABM of whale-watching tours and whale movements in and around the Saguenay–Saint-Lawrence Marine Park, in Québec, Canada referred to as the Marine Mammal and Maritime Traffic Simulator (3MTSim). This region is known as one of the best places in the world for the observation of marine mammals (Scarapaci, Parsons and Lück, 2008). The study of human decision making is a major focus for cognitive science research. Our work is a contribution to bridge a gap between the recent theories and models developed by cognitive scientists and the representation of humans' decision making in ABMs. After a description of the study area, we give an overview of the global simulator 3MTSim. Thereafter, we focus exclusively on the human part of the whale-watching submodel of 3MTSim, described following the ODD protocol. We present simulation experiments carried out following the POM approach to fit an accurate model of whale-watching captains' decision making. We finish with a discussion of the results in light of the existing literature before concluding.

6.4 Material and methods

6.4.1 Study area

The St. Lawrence Estuary located in Québec, Canada is the world's largest estuary. The study area, which extends over more than 7000 km^2, from Betsiamites to Baie-Saint-Paul on the North shore, and from Métis-sur-Mer to Saint-Roch-des-Aulnaies on the South shore, including a large portion of the Saguenay River (cf. Figure 6.1), is centered around the Saguenay–St. Lawrence Marine Park. It is an unavoidable transit area for more than 5000 cargo ships that annually convey merchandise between the Atlantic Ocean and the Great Lakes (Chion *et al.*, 2009). The estuary also contains several ferry routes crossing the river in the transversal direction, as well as some secondary routes linking islands to the mainland, totaling more than 40 000 trips per year. Due to extraordinary oceanographic phenomena with the highly productive St. Lawrence ecosystem, zooplankton and forage fish are concentrated in an area of the estuary located in proximity to the mouth of the Saguenay River; thus making the area a summer feeding ground for up to 13 marine mammal species. The relative predictability of marine mammals in a small area and easy access has made it renowned as one of the best areas in the world for whale-watching (Scarapaci, Parsons and Lück, 2008) where a major marine tourism industry was developed as of the late 1980's. One threatened resident population (COSEWIC, 2010), the St. Lawrence beluga whale (*Delphinapterus leucas*), populates this ecosystem with several migratory species from the Atlantic Ocean including the endangered blue whale (*Balaenoptera musculus*) and the finback whale (*Balaenoptera physalus*) listed as *special concern* by the Committee on the

Status of Endangered Wildlife in Canada. Abundance of marine mammals in this region attracts about 1 million visitors/year (Gosselin, 2006), roughly half of which practice activities at sea such as commercial whale-watching excursions, scenery viewing aboard cruise ships, pleasure boating or kayaking. From May to October, more than 10 000 commercial excursions get tourists closer to large marine mammals mainly between Tadoussac and Les Escoumins (Chion *et al.*, 2009). In addition to this mature whale-watching industry, there are about 9000 trips per season of private pleasure crafts mainly concentrated within the narrow Saguenay River (Gosselin *et al.*, 2007), a portion of which represents a critical habitat for the resident population of threatened beluga whales (Pippard, 1985).

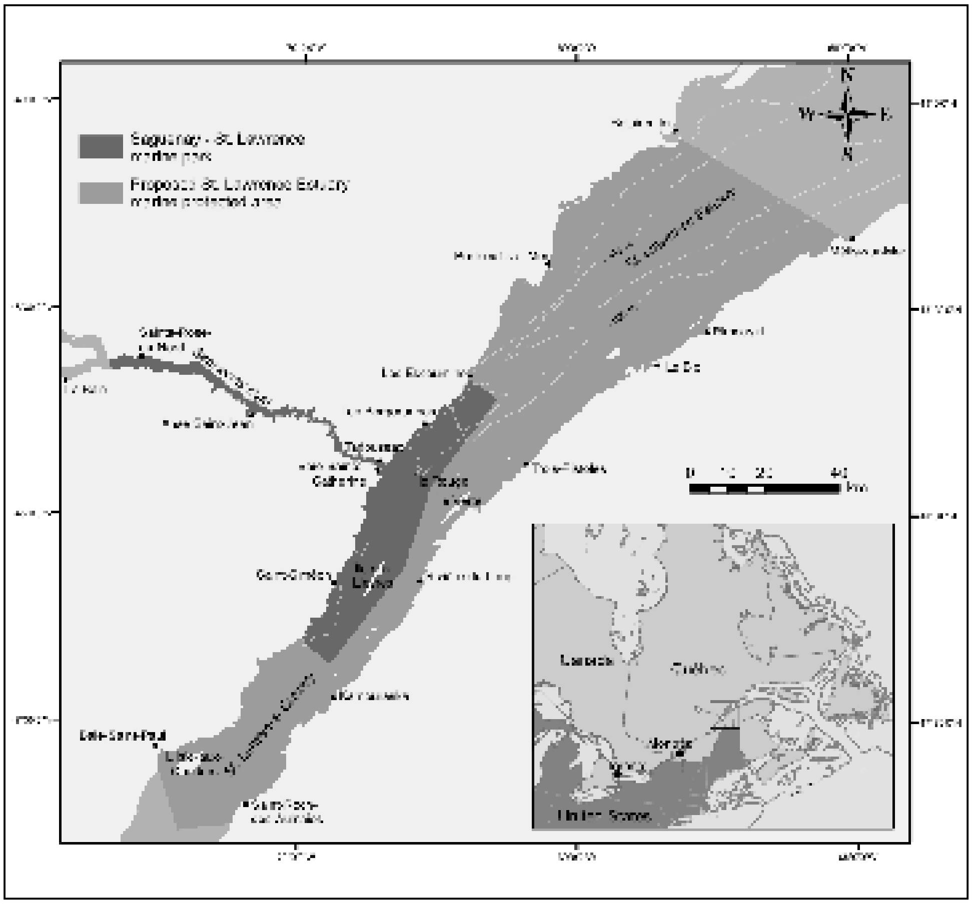

Figure 6.1 Study area.

In order to deal with the urgent need to protect the beluga whale population subject to such intensive anthropogenic activities occurring throughout the St. Lawrence watershed, following a long process of public pressure and subsequent consultations led by Parks Canada and Parcs Québec, the governments of Canada and of Québec created the Saguenay–St. Lawrence Marine Park (marine park hereafter) in 1998 (Guénette and Alder, 2007), covering more than 1245 km^2 (cf. Figure 6.1). Amongst the numerous studies initiated in the context of one of Canada's first marine protected areas' establishment, a multi-year research and monitoring program (1994-ongoing) was launched to study whale distribution and the interactions between whale-watching boats and whales in the park (Michaud *et al.*, 1997). In 2002, the first version of the Marine Activities in the Saguenay–St. Lawrence Marine Park Regulations was adopted to be enforced by the team of park wardens (Parks Canada, 2002). In 2004, the Department of Fisheries and Oceans proposed the 6000 km^2 St. Lawrence Estuary Marine Protected Area (MPA) project under the Ocean Act (*Oceans Act*, 1996), a proposal still in progress. Both marine protected areas aim to ensure marine mammal conservation including the protection of their habitat. Functioning under the adaptive management paradigm, protected area managers must regularly update their policy according to the most recent scientific advancements and new knowledge. Incidentally, marine park managers are in the process of updating the current regulation while MPA managers aim to gain a better understanding of the risk of ship strikes on marine mammals within the proposed MPA. In support of these management goals, we have developed 3MTSim, a spatially explicit simulator of whale–boat interactions over the whole extent of the marine park and adjacent MPA. An overview of 3MTSim is given thereafter.

6.4.2 The Marine Mammal and Maritime Traffic Simulator (3MTSim)

The simulator named 3MTSim puts together an IBM of five whale species, along with an ABM of five types of boats; both the IBM and ABM are spatially explicit and the environment is a mix of spatial and static components (Parrott *et al.*, 2010). Before describing the whale-watching ABM, we present an overview of 3MTSim's submodels, illustrated by Figure 6.2.

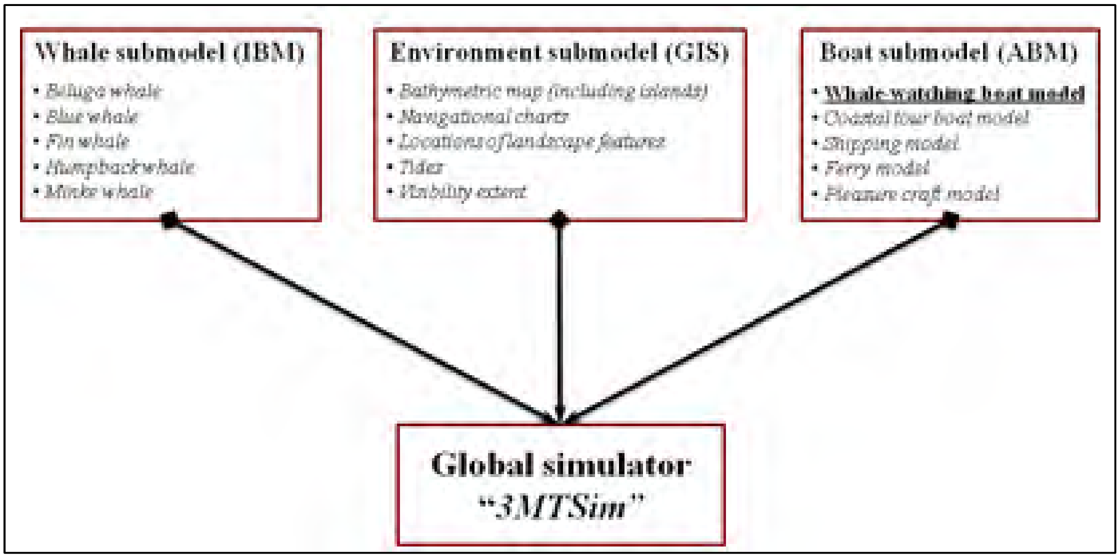

Figure 6.2 Simulator overview. 3MTSim is made of three distinct blocks that are an individual-based model (IBM) of whale movements, a geographical information system (GIS) of the physical environment, and an agent-based model (ABM) of boat movements guided by operators' decision making; the boat model itself is made of five submodels, the whale-watching ABM being the one described here.

6.4.2.1 Environment: Geographical Information System (GIS)-based model

The environment model has the layered structure of a Geographical Information System (GIS). It is made of a digital elevation model of the bathymetry including islands and shoals, critical information contained within navigational charts (e.g. ports, speed limits, navigation channels for cargo ships), landscape features of touristic value and whale species' distribution maps (Michaud *et al.*, 2008). The environmental model also includes non-spatial characteristics such as tide cycles (dynamic) and visibility extent (fixed for a simulation). These retained environmental attributes stem from a selection process made according to field observations, data analyses and expert consultations. Attributes that have proved to play a driving role in whales' and boats' spatial dynamics were kept in the model.

6.4.2.2 Whale movements: Individual-Based Model (IBM)

The whale model is a spatially explicit IBM of the five most targeted species found in the study area, namely the beluga, blue, minke, finback, and humpback whales. It has been developed and calibrated following the POM approach (Grimm *et al.*, 2005; Wiegand *et al.*, 2003). The IBM was built upon several datasets (Michaud and Giard, 1997; 1998; Michaud *et al.*, 2008) from which knowledge and rules about whale movements were extracted (Lamontagne, 2009). Eventually, simulated whales reproduce accurately 95% of the real movement patterns characterized by movement parameters (turning angle, travelled distance, and speed), aggregation size (*i.e.* number of whales in a 400 m radius), and spatial distribution over the study area (kernel home range). A limitation of the current whale model is the absence of whale's response to the presence of boats; however, this response behaviour is likely to affect only whale's small-scale movements (unpublished data), certainly beyond the scope of our accuracy expectancies. Another limitation is that the distribution, movement, and abundance of preys (e.g. krill, capelin) are not represented within the whale model despite their major role in marine mammals' spatial dynamics in the study area; the unavailability of data about preys explains this choice. Moreover, since the goal of the global model is not to investigate nor explain anything about whales' dynamics, the great amount of data at hand describing whales' distribution, movement, and aggregation patterns sufficed to overcome this limitation and accurately reproduce the best of our knowledge about their spatiotemporal displacements within the study area.

6.4.2.3 Boat movements: Agent-Based Model (ABM)

The boat model is made of five main submodels dedicated to the five main categories of navigational activities within the study area (around 98% of total boat traffic in terms of time at sea). Each submodel is grounded on original data collected in the field, including interviews with boat captains, ship pilots, park wardens and other local experts, onboard and shore-based observations, radio VHF monitoring and analyses of multiple datasets on boat and whale presence and activities in the study area. The processes of selection and validation of the ABM representing whale-watching activities will be described in the rest of this article. The POM approach is used for determining an adequate representation of the whale-watching captains' decision making.

6.4.3 Description of the whale-watching ABM with the ODD protocol

The ABM of whale-watching activities in the marine park is described following the ODD protocol (Grimm *et al.*, 2006) which consists of seven elements. The first three provide an overview, the fourth element explains general concepts underlying the model's design, and the remaining three elements provide details.

6.4.3.1 Overview

Purpose

The model is aimed at simulating whale-watching excursions' dynamics according to whales' distribution and abundance over short time periods in the St. Lawrence Estuary covering the Saguenay–St. Lawrence Marine Park and the proposed St. Lawrence Estuary Marine Protected Area in Quebec, Canada. The main purpose of the model is to test alternative scenarios of regulations for whale-watching activities in order to support the marine park managers in the process of updating the current regulation on whale-watching activities in the marine park. The model is also intended to guide the identification of zones with high risks of ship strikes and to support discussions during multipartite meetings involving local stakeholders.

A secondary purpose is to generate simulated data that quantify several aspects of the interactions between boats and whales that are difficult (or intractable) to collect exhaustively in the field. These data include for instance the cumulative exposure of an individual whale to fast-moving boats, or the frequency of whale/boat encounters at a certain distance for a given period of time.

Finally, 3MTSim can be used as an educative tool available to the public in interpretation centers.

State variables and scales

The whale-watching ABM contains two kinds of spatially-explicit entities: captain agents operating whale-watching excursions and whale individuals (IBM). Although whales are individual entities, since the whale IBM has been fully developed and validated independently, whales are considered as biotic elements of the whale-watching excursions' environment.

Whale-watching excursions are created according to companies' schedules. Twelve distinct companies offer whale-watching trips in the marine park. Boats can be of either of three categories, depending on their passenger capacity (type 1: ≤12; type 2: >12 and ≤48; type 3: >48). Other real boats' static variables introduced in the model are the maximum speed and cruising speed.

Individual captains at sea have the following attributes: captain ID, company ID, excursion ID, homeport, position, speed, boat ID, goal, activity, excursion clock, excursion memory. All captain agents and boats are created at the beginning of the simulation and their instances remain active during the whole simulation duration. Excursions have a planned duration and the remaining time is updated as long as the simulation is running. The remaining time in the excursion affects the decisions made by the captain.

The temporal resolution is 1 minute since it is the sampling interval of most of the data used to develop the model. The spatial resolution of the GIS model (environment) is 100m×100m; this was chosen according to spatial data accuracy. However, an entity's position (whale or boat) is continuous so that it can occupy any location within a 100m×100m cell. Finally, the model extent covers exactly the entire surface of both the marine park and the MPA.

The whale-watching ABM's environment is spatially explicit and can be decomposed into an abiotic and a biotic part:

1) Spatial abiotic characteristics of the environment are the bathymetry, the location of attractive features, and zoning management restrictions (speed). Non-spatial abiotic characteristics are the visibility extent, tide, date, and time. Spatial characteristics are structured within a GIS. The date and time controls both the schedule of excursion departures and tide dynamics.
2) The biotic elements of the environment are the whales. Whale movements are described by an autonomous IBM developed following the POM approach (Lamontagne, 2009). This model simulates the 3D movements of five different species (cf. Figure 6.2). It reproduces real diving cycles, social aggregation, movement parameters (speed, turning angles and travelled distance), and spatial distribution, with no regard to population dynamics (irrelevant considering the model purpose and time scale).

Process overview and scheduling

A typical simulation lasts from a few days up to 6 months (i.e. the duration of a touristic season). The model proceeds in 1-minute time steps. The goal of the model, as stated before, is to explore the impact of regulations in terms of whales' cumulative exposure to boats during the summer (migratory species mostly occupy the study area from May to October). Accordingly, longer simulations which are common in the study of population dynamics are not justified here.

As shown in Figure 6.3, first of all a whale-watching captain agent in an excursion starts by updating his information about the environment. This encompasses a visual update of its neighbourhood according to the visual extent (whales visible at the surface), an update of the remaining time in the excursion, a memory update of its own past actions (observations) and the collective memory of past observations, and a list of whales currently under observation obtained by mimicking the VHF communication channel used by captains. Once the information is up-to-date, the captain updates its goal to pursue. Whale-watching captain agents have four different goals which are 1) observe whale; 2) observe a landscape feature; 3) go to an alternate port to embark or disembark tourists; and 4) go back to the homeport.

The adoption of a specific goal by a captain is driven by transition rules, as a function of the remaining time and the location of whales.

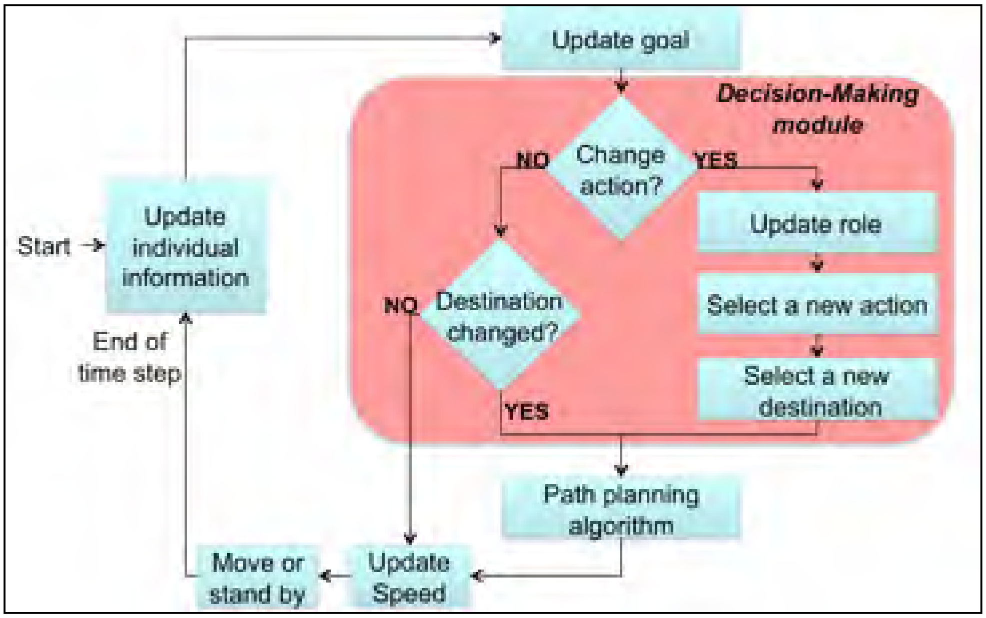

Figure 6.3 Conceptual model of whale-watching captains' sensing-objective-decision-action process. This Figure shows the sequence of operations performed by each whale-watching captain at each time step during the simulation.

If the current action (e.g. follow a given whale to observe it) has changed (e.g. go back to homeport), then the captain has to select a new goal to which is attached a corresponding destination. On the contrary, if the action has not changed (e.g. follow a given whale), then the captain has to check whether its destination has changed. The planned trajectory is updated via a path-planning algorithm developed for the model (Chion *et al.*, 2010a). Once the planned trajectory is computed, the boat's speed is updated before executing the move if any.

The scheduling is basic since at each time step, each captain goes through the whole process described in Figure 6.3. At each time step, information about the state-of-the-world is kept in memory; doing so, each captain agent updates its internal status according to the same information, thus reproducing simultaneous behaviours despite the serial nature of the updating process. Moreover, the order in which captains' actions are updated is shuffled at each time step.

6.4.3.2 Design concepts

Emergence

When a captain agent's goal is to observe whales (the main goal of whale-watching excursions) its expectations, in terms of which species to observe during the excursion, are an emergent property of the system; actually, because of competition between whale-watching companies, captains try to observe at least the same whale species as those observed by the other active captains (Chion *et al.*, 2010b) (cf. CHAPTER 3). Other emergent properties of the system (patterns) are 1) the average distance travelled by boats as a function of their homeport, labelled “length”; 2) the proportion of time spent in different activities (whale observation, landscape feature observation, and travelling/searching), labelled “activity”; 3) the percentage of time spent in observation of each species, labelled “species”; 4) the spatial hotspots of residence, labelled “home range”; 5) the group size distribution of whale-watching boats around observed whales, labelled “boat density”, and 6) the appearance of persistent *observation sites* resulting from several whale-watching boats around a group of whales. The first four quantitative properties are incidentally the primary patterns used in the selection step of the POM process described in the next section. The fifth quantitative property characterizes whale-watching collective behaviour; it is the secondary pattern used to validate the selected model. The last emergent property is used as a qualitative secondary pattern since it reproduces a well-known characteristic of the whale-watching boats' spatiotemporal dynamics.

Adaptation

Communication between captains and constant updates of observed whales' spatial distributions allows them to adapt their expectations that drive their subsequent decisions of which species to observe.

Fitness

In our model, whale-watching captain's expectations emerge from observations made by other captains from the same port. In general, competition pushes captains from different companies to observe at least the same species, especially the attractive ones (humpback, fin, and blue whales). For excursions leaving simultaneously from the same port, the pressure for matching each other's observations is even stronger. Actually, when tourists embark simultaneously on different boats, they may complain on the way back if they did not see as many species as people on other boats.

Prediction

Captain agents use historical knowledge on whale distribution (collective memory) to predict where to head in the area to increase their chance of observation. This simple prediction heuristic was revealed during interviews with whale-watching captains, and subsequently validated by studying the data on whale and boat locations.

Sensing

Whale-watching captain agents are aware of other agents (whales or other boats) lying within their surroundings, in the limit of the visibility extent. Captains have the capability to communicate and share information about whale locations. This capability is modelled via a blackboard approach where all captains have access to the information on all current observations. In the real system, captains communicate with each other via VHF radio channel; the regulations of marine activities (Parks Canada, 2002) forces captains to share all their observations; moreover, cooperation is the best strategy in such a collectivity of workers where the resource (i.e. whales) can be scarce, dynamic, and uncertain. Captains are professionals who have a good knowledge of the environment’s structure (navigable areas, landscape features of touristic value). Accordingly we modelled them as completely aware of where to navigate safely and optimally.

Finally, captain agents have four kinds of memory which are 1) memory of past observation sites in the area up to one day in the past (collective memory); 2) memory of the current excursion's visited locations to avoid exploring unsuccessfully the same spots (individual memory); 3) memory of whales observed during the excursion to avoid observing twice the same whale, which is forbidden by the regulation (individual memory); and 4) visible memory of surrounding whales that could have been sighted but not observed for any reason (e.g. the captain was already observing a whale) (individual memory).

Interaction

The main interaction is the communication between whale-watching captains. A second type of interactions is dictated by the regulation on the maximum number of boats on an observation site at a given distance from a group of whales.

Interactions between components of the maritime traffic exist although they do not have any major impact on large-scale spatiotemporal dynamics. For this reason, we separately developed the different submodels of the maritime traffic and did not take into account interactions between those components.

Stochasticity

Whale-watching captains are used to making decisions under uncertainty since whale locations are not perfectly predictable. Consequently, stochasticity is introduced in the model to describe whale movements that in turn affect the movements of whale-watching boats.

Stochasticity is generated by the algorithm driving whales' movement in the IBM (Lamontagne, 2009).

Collectives

Captains are regrouped by ports and by companies. Captains coming from the same port will provide each other with more relevant information than those coming from remote ports, since they will tend to operate within the same area.

In a more general sense, a whale-watching captains' community is a concrete example of collective intelligence. Captains may follow one of two strategies when pursuing the goal to observe whales. If no excursion is currently observing whales, and there are no visible whales in the surroundings, then a captain cannot exploit any information helping him to make an observation. In this case, captains need to explore the space searching for whales. Locations explored in priority are those where recent observations have been made, with preference given to the nearest spots. Field observations revealed that the less risky exploitation strategy was the dominant one, thus explaining the choice to give priority to exploitation over exploration in captains' decision process within the whale-watching ABM.

The exploitation strategy relies heavily on cooperation and information sharing between captains. Despite the heavy competition between companies, captains have a real advantage to share information in order to minimize the risk of coming back empty-handed on the long run (i.e. several excursions). According to field observations, total cooperation amongst captains is the norm; this is reproduced in the model.

Observation

The model has been developed in Java 1.6 with the Repast libraries[4]. The data are collected within the runtime of Repast for calibration, validation and analysis purposes. The calibration and validation phases are presented in the following section.

6.4.3.3 Details

Initialization

At the beginning of a simulation, for each species the number of whales is input and individuals are distributed within the environment according to probabilities derived from their known spatial distribution maps. The simulation starts at the date specified by the user.

At the beginning of the simulation, captains start without any knowledge about the system, which is obviously not true in reality. Consequently, there exists a transient state of less than one day that should be omitted for data analysis. For the analyses presented thereafter, the first day was systematically removed.

Input

In addition to the bathymetric map and visibility extent value, three inputs are necessary for any simulation to be run, namely 1) the scenario of whales' abundance (integers) and spatial distribution (maps) for each species; 2) the schedule of excursions as a function of the seasonal period drawn from companies' historical schedules; and 3) the management policies (regulations, speed limitations, area closures).

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[4] http://repast.sourceforge.net/

Submodels

The submodel of whale movements has been fully described by Lamontagne (2009). It has been discussed within the global overview of the simulator 3MTSim at the beginning of this article.

The tidal cycles affecting the feeding and aggregation behaviour of certain whale species are reproduced within the model. At flood tide, large concentrations of plankton and small pelagic fish, which make up the diet of some large cetaceans, tend to concentrate along bathymetric features. As a consequence, marine mammals tend to congregate at these prey concentrations, increasing locally whale group size.

6.4.4 Model selection and validation: Pattern-oriented modelling (POM)

The POM approach for the selection and validation of the whale-watching ABM is presented in this section; four candidate models of multi-alternative/multi-attribute decision-making have been tested.

6.4.4.1 POM process

In this section we detail the different steps of the POM process, illustrated in Figure 6.4.

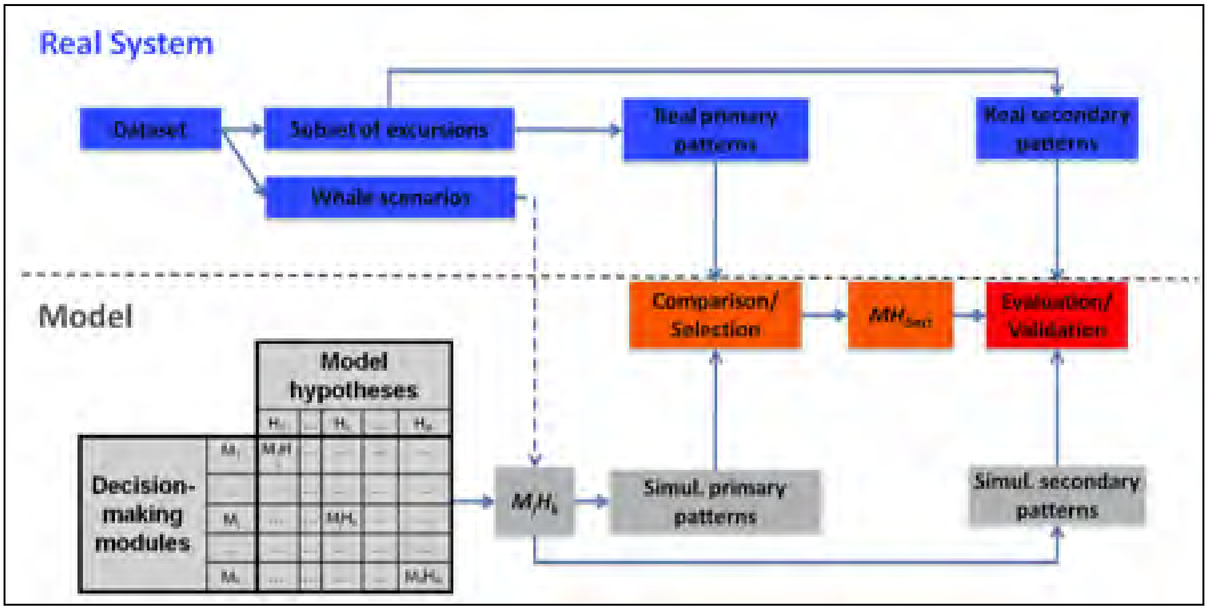

Figure 6.4 POM approach for the selection and validation of the whale-watching ABM.

Dataset

The dataset is made of whale observation locations, GPS tracks of the excursions (at 1 minute interval), weather conditions (waves, visibility) and excursion contents (at every 10 minutes) such as whale observations (species, group size), and boat density. See (Michaud *et al.*, 1997) for more details on the data collection protocol. From this dataset, both whale scenario and whale-watching excursion patterns were extracted as illustrated in the upper part of Figure 6.4.

Whale scenario

The current implementation of the model does not allow varying whales' abundance and spatial distribution during a simulation run; both are inputs of the model fixed by the user prior to each run. Consequently, for selection and validation purposes, we extracted a whale scenario (cf. upper part of Figure 6.4) from the dataset where the context of species present in the area was constant, and where the spatial distribution of whales exhibited a minimal level of uniformity. We picked the period from July 1st to 25th in 2007. For this period, abundance in the area was estimated at 25 minke whales, [1 to 8] fin whales and [1 to 3] humpback whales. Values were validated with the analysis of transect data gathered during that period. Beluga whales were exceptionally removed from these simulations. Currently, within the limits of the marine park, any observation directed towards this species is illegal from a distance less than 400 m. This restriction decreases their interest value according to whale-watching captains; therefore, captains tend to avoid belugas most of the time, which despite their relatively high abundance within the study area compared to other species, makes them almost absent from the dataset as a target species.

Subset of excursions

For the selected period of 25 days in July 2007, a subset of 30 excursions (with an average duration of 2h30) is available (cf. Figure 6.4, upper part). These excursions originated from three different homeports from the north shore of the St. Lawrence River, namely Tadoussac, Bergeronnes, and Les Escoumins. Also, two different boat types were sampled, which are large boats (>48 passengers) and small boats (≤12 passengers). Therefore, subsequent pattern analyses were disaggregated according to the homeport and boat type.

Pattern choice

A pattern can be defined as *any display of order above random variation* (Grimm and Railsback, 2005). POM is a process that explores a space of plausible modelling alternatives by comparing simulated patterns with real ones (cf. figure 1 in (Wiegand *et al.*, 2003)). As much as possible, patterns should represent important features of the studied system and not be redundant. A set of primary patterns extracted from field investigations are used to assess the performances of candidate models and select the best-performing one. Then, secondary patterns outputted by the simulations of the best model are used to validate the model selection according to its ability to reproduce a reliable dynamics.

A total of five different quantitative patterns were extracted to characterize whale-watching excursions. These patterns have been previously detailed in the ODD protocol (Design Concept/Emergence).

Alternative models tested

We tested four different models, differing according to the captain agents' decision making models (lower left part of Figure 6.4). The satisficing, tallying, and Take The Best models of cognitive heuristics are fully described in APPENDIX VII, whereas the fourth one, random choice, was taken as the reference decision making model (i.e. null model). These heuristics are used when a captain, in the exploitation mode, needs to pick a whale to observe among a set of candidates. All decision making models are presented in Table 6.1.

The set of attributes used for the Take The Best and tallying heuristics were elicited for the most part during interviews with whale-watching captains. Only those cues (attributes) that appear major in decisions (as determined through observations and interviews) were retained for the satisficing heuristic. The Take The Best heuristic processes non-compensatory information, so retained cues were ordered according to their importance in the final decision. On the contrary, tallying exploits compensatory information since all cues have the same weight in the decision process.

Table 6.1 Details of the tested decision making models

Decision making models	**Cues (attributes)**
Take The Best	1. Select whale species absent from the current context of observations. 2. Select whales from species never observed in this excursion. 3. Select whales from the most attractive species (blue, fin, and humpback whales). 4. Select whales which are about to be lost (last boats about to stop observing them). 5. Select whales observed by less than 4 boats (limit for the distance privilege according to the marine park regulations). 6. Select whales that leave enough time for at least one subsequent observation. 7. Select the closest whale in case of a tie.
Tallying	Same as Take The Best, without ordering.
Satisficing	The whale is from an attractive species. OR The whale is about to be lost from the pool of discovered whales. OR The whale belongs to a new species regarding the current context of all excursions. OR The whale increases the diversity of species observed in the excursion.
Random	Choice is made randomly among candidate whales.

For a given simulation, all captain agents make decisions with the same decision making model. Since a captains' context (e.g. surrounding whales, expectations) and constraints (e.g. boat speed, excursion duration) are different, decision outputs will differ despite the similitude of their decision making model.

Comparison of patterns

The metrics used to compare the five quantitative simulated and observed patterns depend on the nature of the patterns. For the patterns of activity, species and boat density, the cumulative distributions were compared using Kolmogorov-Smirnov statistics (KS) to determine whether they come from the same population. The error is given by [(1-KS) × 100]. The values were computed in R (R Development Core Team, 2009).

For the excursion length pattern, since we do not have enough observations to consider data dispersion, we compare the average excursion length (by port and boat type) with the Normalized Mean Absolute Error (NMAE). The values were computed in R.

Finally, for the spatial distribution (home range pattern), since the number of observations is small compared to the simulated data, we estimated the home range (50% core area) based on kernel density maps. The percentage of overlapping area between observed and simulated hotspots for each homeport is the metric used for selection; consequently, the error is given by (100 - %overlap). This test was conducted in ArcGis 9.2 using a Python script.

Model selection and validation

Model selection was conducted on the set of four primary patterns, keeping the boat density as a secondary pattern for the validation phase (see section 2.3.2.1 for description). This pattern characterizes a strictly collective phenomenon since each density value implicitly contains information about several whale-watching captains' decisions. This choice was also made since the number of boats around whales is considered an important variable for managers of the area. So, instead of forcing a model to fit this important pattern (with a risk of overfitting), confidence in the model is greater with this pattern reproduced based on other system's characteristics.

We used "global ranking" to select the best model. This is simply the sum of the ranks computed according to the statistically significant difference between the results generated by the concurrent decision making model for each pattern.

6.4.4.2 Simulation experiments

The simulations are based on a 3½-week scenario of whales' distribution and abundance, extracted from real data (described in the whale scenario). To cope with the uncertainty on the exact species abundances for that period, we conducted 45 simulations with variable combinations of abundances for each of the three present species, picked within their confidence intervals, for each decision making model; thus 180 simulations were performed. The results of these simulations are described below.

6.5 Results

Figure 6.5 presents the error (%) of the four tested models for each primary pattern, as discussed above, and Table 6.2 summarizes these results for the primary patterns. For each pattern, a ranking of the four models was made according to the statistical significance of the pairwise difference between model results.

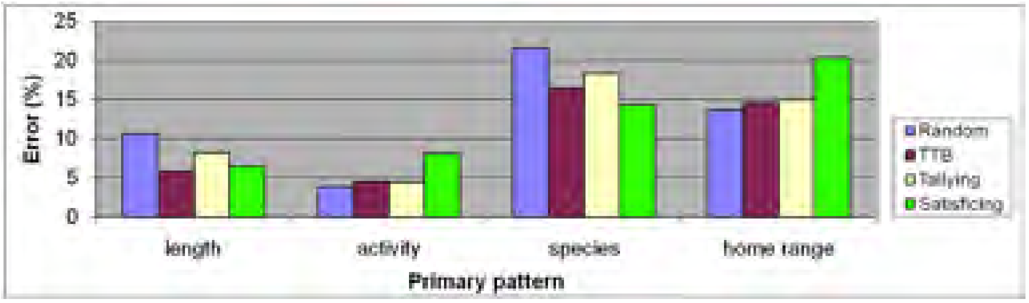

Figure 6.5 Performance of the four decision making models on the set of primary patterns for the ABM selection process. For each pattern, the error (%) is based on a metric (KS statistics for activity and species, NMAE for length, and % overlap for home range).

Table 6.2 “Global ranking” approach for the selection of the best-performing decision making model

	Primary patterns				**Global ranking (∑)**
Decision Making Models	Length	Activity	Species	Home Range	
Take The Best	1	1	2	1	5
Tallying	3	1	3	1	8
Satisficing	1	4	1	4	10
Random	4	1	4	1	10

Simulations revealed that Take The Best outperformed the other decision making models on the selected set of primary patterns, followed by the tallying heuristic. Given the non-compensatory nature of information processed by the captains at sea (the species attribute being the most important one in the decision), Take The Best corresponds closely with captains’ decision making process. The decision making model determines which whale a captain agent will observe, explaining that the most affected pattern is the species that is directly related to that decision. The species pattern is also the pattern with the greatest error for all decision making models except for satisficing. It appeared that too much weight was given to the observation of minke whales in the four models as compared to other attractive species (fin and humpback whales). One reason could be that virtual captains have been programmed to comply with the regulations (Parks Canada, 2002), allowing a maximum of 60 minutes in observation of the same whale during an excursion. In reality, the time spent in observation of a minke whale rarely reaches 60 minutes when more attractive species (even already observed) are accessible. Accounting for this species-dependant reality in specific contexts would certainly lead to an improvement of the results obtained along the species pattern.

Spatially, Take The Best appears to produce a good spatial match with real observations (Figure 6.6). The discrepancies in hotspot areas at the mouth of the Saguenay River can be partially explained by the fact that GPS tracks of excursions departing from Tadoussac going to Baie-Sainte-Catherine begin recording data when leaving Baie-Sainte-Catherine, therefore missing this portion of the route. These systematic breaks in the recording protocol tend to stretch hotspots over a larger surface in this area. Moreover, let us note that the number of real observations (30 excursions) is quite low compared to the number of simulated excursions. Consequently, the risk of giving too much weight to an outlier excursion in the real observations is relatively high. Conversely, the kernel computed for model outputs is based on all available simulated excursions (several hundred) having the same characteristics as the real ones (same ports, boat types and departure times); consequently, the risk of outliers distorting the results is very small since we consider all the outputted data. This partially explains why the dispersion of spatial home range in the simulated excursions (Figure 6.6, right) is lower than the one in real observations (Figure 6.6, left).

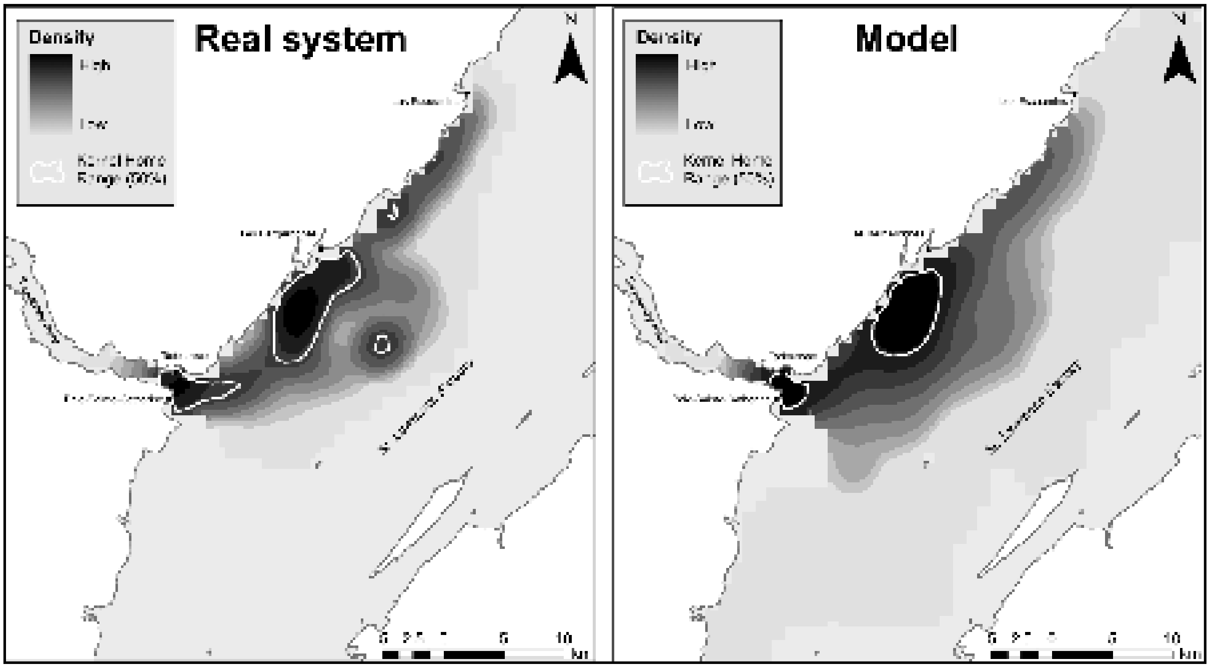

Figure 6.6 Comparison between the real whale-watching spatial distribution (left) and the aggregated outputs of 45 replications of the whale-watching model with the Take The Best decision making heuristic (right). The whales' distribution and abundance scenario is from July 1st to 25th in 2007. The kernel is created with a 3 km radius and a resolution of 1 km, based on GPS tracking of real excursions (left) and model output (right), with a 1-minute resolution.

Regarding secondary patterns, Table 6.3 presents a summary of models' performance along the quantitative boat density pattern around observed whales for the four decision making models. Both the KS statistic and NMAE are computed for each of the three homeports (Tadoussac, Bergeronnes, and Les Escoumins). We observe that Take The Best performs relatively well at reproducing this pattern but is outperformed by satisficing. Unlike other decision making models, Take The Best's performance regarding the boat density pattern (KS and NMAE) is rather similar for the three major ports.

Table 6.3 Decision making models' performance on the boat density pattern (Kolmogorov-Smirnov statistics, KS; Normalized Mean Absolute Error, NMAE). Values in boldface indicate the best performance amongst models

Decision Making Models	**Boat density (secondary pattern)**					
	Port 1		Port 2		Port 3	
	NMAE (%)	KS	NMAE (%)	KS	NMAE (%)	KS
Random	15	0.14	29	0.26	17	0.17
Take The Best	17	0.14	15	0.14	12	0.14
Tallying	15	0.13	19	0.19	7	0.12
Satisficing	6	0.08	15	0.15	12	0.14

Figure 6.7 displays a well-known secondary pattern emerging from simulations (independently of the decision making model), called *observation sites* in the real system. By exploiting the existing information about the current locations of whales, whale-watching captains congregate in space and time, creating local temporary hotspots circled in black in the Figure 6.7. The emergence of this secondary pattern confirms the importance of cooperation via VHF radio communication between captains in the whale-watching excursions' dynamics.

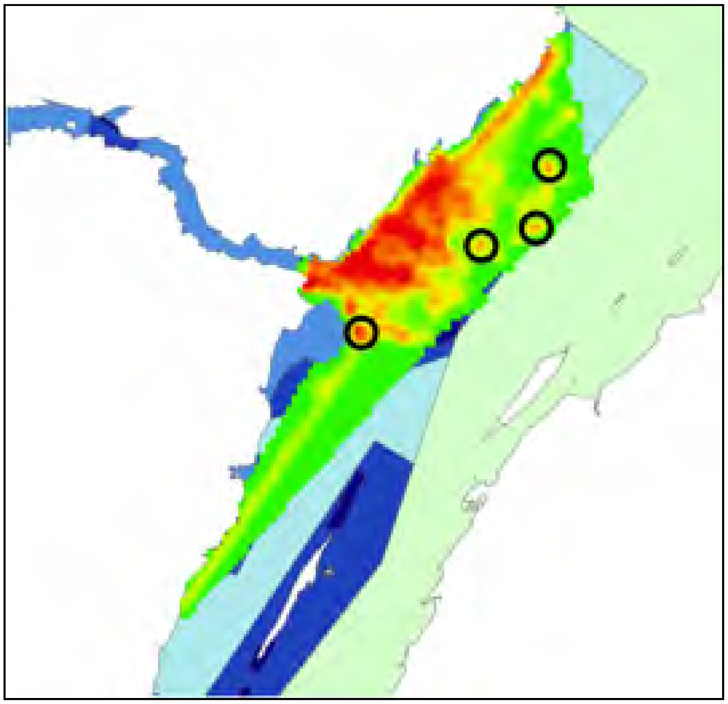

Figure 6.7 Emergent observation sites (circled in black) for a 1-day simulation with Take The Best. This secondary pattern is consistent with field observations.

6.6 Discussion

Modelling human decisions in ABMs is challenging (Janssen and Ostrom, 2006a). Many modellers have opted for the Expected Utility Theory for such a task (e.g. Berger, 2001; Little *et al.*, 2009; Monticino *et al.*, 2007). However, for more than three decades, psychologists have been demonstrating that the Expected Utility Theory can merely be used as a suitable normative model of human decisions but by no means as a descriptive model (Kahneman and Tversky, 1979). Considering the systematic violations and inconsistencies of this theory, we chose to resort to models of heuristics based on a bounded view of rationality to describe the way humans process information to output decisions.

Simulations revealed that the Take The Best heuristic outperformed the three other tested models regarding the decision of which whale to observe. This suggests that whale-watching captains tend to use non-compensatory strategies, emphasizing attributes related to the whale species. However, with an exception for the reference (null) model of decision making (random choice), which is almost systematically dominated, the differences between the three cognitive heuristics are not clear-cut enough to completely eliminate tallying and satisficing. In reality, humans likely have at their disposal a collection of heuristics (adaptive toolbox) that they choose from according to their past success in solving different classes of problems(Gigerenzer and Selten, 2001a; Gigerenzer, 2008). Accordingly, interviews led with whale-watching captains revealed that when whales' abundance is scarce in the area, they tend to go observing "whatever they can find" to "save their excursion". In such circumstances, captains tend to use a satisficing heuristic with a very low level of expectation, picking the first observable whale regardless of its species. Other known heuristics such as repetition or imitation (Gigerenzer, 2008; Jager *et al.*, 2000) have been identified in the field. Regarding repetition, captains conducting several excursions a day tend to repeat their previously successful sequence of decisions when the whale context remains stable. Imitation-wise, we regularly observe some young captains following more experienced ones during simultaneous excursions, thus imitating all their decisions.

Lastly, the good performance of the three tested cognitive heuristics compared to the null model validates 1) the identification of relevant factors (cues) intervening in decisions, and 2) other mechanisms implemented in the model such as cooperation via communication, the use of collective memory in space exploration, and the prevalence of current knowledge exploitation over space exploration to observe whales.

In the current implementation of the model, all captains from companies behave the same way when the goal pursued is to observe whales. However, it appears that all whale-watching companies do not have exactly the same philosophy nor ethics regarding their activities at sea, neither do they put the same constraints on captains (e.g. maximizing diversity of observations, minimizing fuel consumption). An accurate portrait of whale-watching companies would allow to take into account this relevant characteristic to refine the model.

As stated earlier, Gigerenzer and colleagues claim that people adapt their strategy depending on the structure of the decision problem at hand, referring to the collection of available heuristics as an adaptive toolbox (Gigerenzer and Selten, 2001a). Accordingly, since the context of whale species' accessibility (abundance and distribution) directly affects the ease of observing whales (and thus the structure of the problem to be solved), a special investigation of how this context influences captains' strategy would be valuable. Moreover, further investigation of captains' ethical values, preferences, and subgoals are needed to discover whether captains belong to natural classes according to their observed behaviours (Berger, 2001; Cabral *et al.*, 2010; Mathevet *et al.*, 2003; Musiani *et al.*, 2010). This could translate into different cue ordering using the Take The Best strategy, selecting different heuristics facing the same situations, or pursuing different subgoals (e.g. avoid boat aggregations, favour the observation of diverse species). Some researchers developing ABMs for pedestrian simulations have begun to address some shortcomings of bounded rationality models such as the description of the process leading to the selection of attributes used in decisions, heuristic choice to solve a given decision problem and how context influences it (ecological rationality), and how individual differences influence heuristic selection (Zhu and Timmermans, 2010a; 2010b). This kind of approach show promise for making models of bounded rationality competitive compared to classical theories.

In addition, there are some well-known experienced whale-watching captains in the collectivity. Field observations suggested that these experts tend to operate like explorers rather than followers. They have the capacity to anticipate other captains' collective behaviour (e.g. herd effect around very attractive species such as the humpback whale) and conduct their excursion in accordance. These captains are important drivers of the system dynamics and a different modelling approach based on situation awareness (Endsley, 1995) or naturalistic decision making (Klein, 2008) could be more effective than a heuristic-based approach.

6.7 Conclusion

Two challenging tasks for the building of ABMs involving humans are the representation of humans' decision making, and the selection of a valid model based on empirical data. We presented the pattern-oriented selection process of an ABM of whale-watching activities within the St. Lawrence Estuary in Québec, Canada. ABM has proven to be a suitable tool to synthesize existing knowledge about the whale-watching SES under study. Its implementation has also motivated the collection of new data to better understand these activities. In an effort to bridge the gap between recent developments in cognitive sciences and ABM, we investigated the literature on the bounded rationality paradigm to build plausible decision making models. Models of heuristics from bounded rationality proposed by cognitive scientists managed to faithfully reproduce whale-watching captains' decisions at sea. Simulations following the POM approach revealed that the Take The Best heuristic generally outperformed other tested decision making representations, suggesting that captains deal with non-compensatory information when they seek to observe whales (mostly grounding their decisions on the whale species attribute). However, the relatively good performance of the satisficing and tallying heuristics shed light on the likelihood that captains use different decision strategies in different situations, which is consistent with results in cognitive science (Gigerenzer and Selten, 2001a). These good results also confirm that the collective mechanisms (e.g. cooperation via communication, memory) implemented in the model are important drivers of the system's dynamics and suggest that they have been adequately accounted for. However, more developments are needed to address such open questions as "how to select the correct heuristic in a given context?" and "how does individual difference drive both attribute and heuristic selection?". These questions highlight the need to collect additional data to deepen our understanding of context-dependant strategy selection, elicit how individual differences influence observed behaviours, and also to characterize the role of experience on expert whale-watching captains. Since POM offered a robust framework for comparing model performances, upcoming field investigations leading to the refinement of decision making models will be tested and compared reusing this approach.

6.8 Acknowledgments

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CHAPTER 7

INSIGHTS FROM AGENT-BASED MODELLING TO SIMULATE WHALE-WATCHING TOURS: INFLUENCE OF CAPTAINS' STRATEGY ON WHALE EXPOSURE AND EXCURSION CONTENTS

This chapter presents an example of application of the model of whale-watching excursions whose simulation results have been presented in CHAPTER 6. Since the decision making process of whale-watching captains has been modelled explicitly in 3MTSim, the application presented thereafter describes an example of the kind of knowledge which can be drawn from the model's simulations.

7.1 Manuscript submission information

This article has been submitted for a review process to be published as chapter of the forthcoming book entitled *Whale-Watching, Sustainable Tourism and Ecological Management*, edited by James Higham, Lars Bejder, and David Lusseau to be published by Cambridge University Press (Cambridge, UK). Its status when this dissertation was submitted was 'submitted'. The ordered list of authors who contributed to this manuscript is:

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7) Robert Michaud, M. Sc., President of the GREMM.
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Thesis author's main contributions to this work include the following:

- Elaboration of the methodology.
- Model programming.
- Simulations.
- Result analyses.
- Writing of the manuscript.

7.2 Introduction

Multi-agent models can bear several names depending on the field they were initially developed in (e.g. agent-based model in social science, individual-based model in ecology). Agent- and individual-based models (ABMs and IBMs) are becoming tools of choice to simulate complex social-ecological systems (Bennett and McGinnis, 2008; Gimblett, 2002; Monticino *et al.*, 2007). The recent development of dedicated programming platforms and libraries has also contributed to the expansion of multi-agent models coupled with GIS-based environments (Railsback, Lytinen and Jackson, 2006). Such models have been applied in a wide variety of natural resource management contexts where heterogeneous actors interact, including rangeland management in arid zones (Gross *et al.*, 2006), management of water use and access in river basins (Schlüter and Pahl-Wostl, 2007), control of irrigation channels (van Oel *et al.*, 2010), agriculture management (Manson, 2005), and forest clearing for agriculture (Moreno *et al.*, 2007). ABMs have also been used to support national parks and recreation areas managers by simulating visitor movements to predict over-crowded areas along vehicular routes and hiking trails (Itami *et al.*, 2003), or along riverside rest areas and attraction sites for rafting trips on the Colorado River (Roberts, Stallman and Bieri, 2002).

ABMs of social-ecological systems where natural resource management is at stake are frequently used to explore outcomes of *what-if* scenarios of policy rules (Gimblett, Richards and Itami, 2002). Apart from testing policy rules, such models involving humans can also be used to explore the effects of alternative behaviours on the status of the natural resource. In this study, we developed a spatially explicit multi-agent model named 3MTSim (Marine Mammals and Maritime Traffic Simulator) to investigate whale-watching activities in the Saint-Lawrence Estuary and the Saguenay River, Québec, Canada. Whale-watching activities in this area have increased dramatically since the 1990's, raising concerns about the impact of intensive navigation on targeted whale populations, some of which were, and still are, endangered or threatened. Public pressure on governments led to the creation of the Saguenay–Saint-Lawrence Marine Park (referred to as park later) in 1998 (Guénette and Alder, 2007) whose limits are shown in Figure 7.1. The implementation of regulations on marine activities followed in 2002 (Parks Canada, 2002), with law enforcement ensured by Parks Canada wardens. On top of a series of rules regulating observation activities (e.g. maximum observation duration), the regulations also fixed at 59 the maximum number of permits for commercial boats operating in the park (53 dedicated to whale-watching) (Parks Canada, 2002). Whale-watching activities in the park area rely on the relatively predictable presence of several whale species, five of which represent 98.5% of the total number of observations (Michaud *et al.*, 2008). In 2007, we estimated that approximately 13 000 commercial excursions went to sea, 80% of which were dedicated to whale-watching within the park (Chion *et al.*, 2009). The proposed Saint Lawrence Estuary Marine Protected Area (MPA), managed by Fisheries and Oceans Canada, is expected to extend the protection of marine ecosystems beyond the park limits (Figure 7.1). Since whale-watching activities are significantly less dense and abundant in the MPA than in the park, we decided to focus our study on park's excursions only.

3MTSim combines an ABM of navigation activities with an IBM of whale movements into a GIS-based representation of the geographic area. An asset of 3MTSim is that it allows the collection of exhaustive data of phenomena difficult or expensive to sample in the real system, such as the total time of exposure for each individual whale to observation boats. Major components of local marine activities are considered in 3MTSim with a special focus on whale-watching excursions. A great deal of effort was made to understand whale-watching captains' decision making in order to reproduce realistically their behaviour in 3MTSim. Whale-watching excursions data analysis and investigation of captains' decision-making processes through cognitive interviews revealed that they often do favour *sure observations* of *potentially dramatic species* (Chion *et al.*, 2010b). Captains achieve *sure observations* mainly by exploiting the knowledge of current observations made by other whale-watching boats; a high level of cooperation at sea being the fundamental behavioural mechanism allowing the flow of information via the radio VHF communication channel. *Potentially dramatic species* are those well known for their spectacular displays (e.g. humpback whales' breaches or tail-slapping, fin whales hunting in large groups) or having notable characteristics (e.g. blue whale is the largest animal ever on Earth, adult belugas are all white). Similarly, a vast collection of multiplatform observation data (enumerated later) was used to simulate the movements and distribution of the whales.

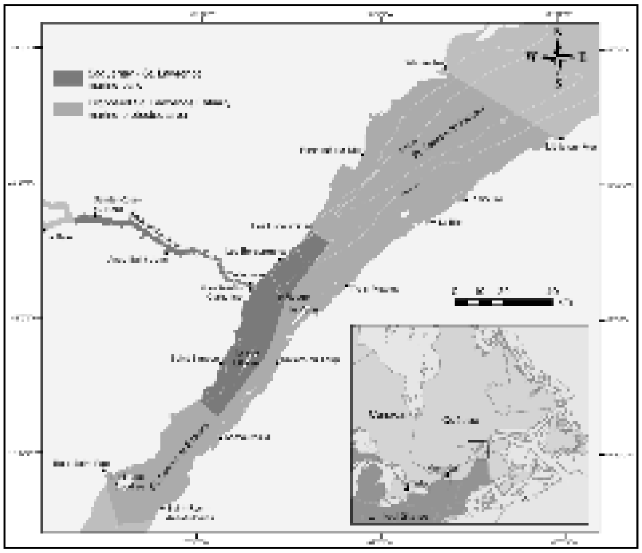


Figure 7.1 The study area encompassing the Saguenay–Saint-Lawrence Marine Park and the projected Saint-Lawrence Estuary marine protected area.

In this chapter, we investigate the effect of different captains' decision making strategies on targeted whale's exposure to observation vessels. Our investigation is aimed at demonstrating the feasibility of using an ABM for advisory purposes. After an overview of 3MTSim, we use the model to explore how alternative decision-making strategies, which could be suggested to whale-watching captains via a code of conduct or training sessions, might decrease whales' exposure to boats. We then discuss some lessons and insights that can be learned about the dynamics of whale-watching excursions using multi-agent modelling.

7.3 Overview of 3MTSim

3MTSim was developed as a decision-support tool for marine protected area managers. It integrates features dedicated to test the potential effects of alternative zoning and regulation plans (e.g., introducing speed limits, altering shipping routes, adding restricted access zones) on the patterns of traffic in and around the park and thus on the characteristics of whale-vessel encounters (e.g. rate, location). An overview of the model and its functionality is provided in (Parrott *et al.*, 2010).

The model combines a raster-based spatial environment (GIS) with an individual-based model (IBM) of whale movements and an agent-based model (ABM) of boats. During simulation runs, the movement of each individual whale and each boat is determined by algorithms and rules calibrated to reproduce observed patterns of behaviours (Grimm *et al.*, 2005). Simulations are run for short periods of time, based on existing environmental conditions and known scenarios of whale abundances and patterns of habitat selection. The time step currently used for simulations is 1 minute.

7.3.1 Spatial environment

The spatial environment of 3MTSim is represented by raster data stored in an embedded GIS. The bathymetry is considered in the displacement and diving routines of whales, as well as for navigation. The state of the tide is modelled according to a simple daily cycle that selects the tide condition (flood, high, ebb, and low tide) according to the date and time of day.

While weather conditions are not explicitly modelled, visibility extent is represented by a single parameter for the whole area. This value remains constant for the duration of a simulation, mainly affecting whale-watching captains' ability to locate whales in their vicinity.

7.3.2 Whale individuals

The IBM of whale movements is described in detail in (Lamontagne, 2009). It includes the five most common species in the estuary: beluga (*Delphinapterus leucas)*, minke (*Balaenoptera acutorostrata)*, fin (*Balaenoptera physalus)*, humpback (*Megaptera novaeangliae)*, and blue whales (*Balaenoptera musculus)*. Since insufficient data were available on whales' food sources and on individuals' activity budgets, no attempt was made to devise a behavioural model. Instead, movement patterns were extracted from:

- Tracking VHF data: 80 tracks for more than 380 hours, for beluga (Lemieux Lefebvre, 2009), fin and blue whales (Giard and Michaud, 1997; Michaud and Giard, 1997; 1998).
- Land-based theodolite tracks of the four rorqual species: 140 focal follows with ~100 hours of tracking of individuals followed for more than 30 min (C. C. A. Martins, unpublished data).

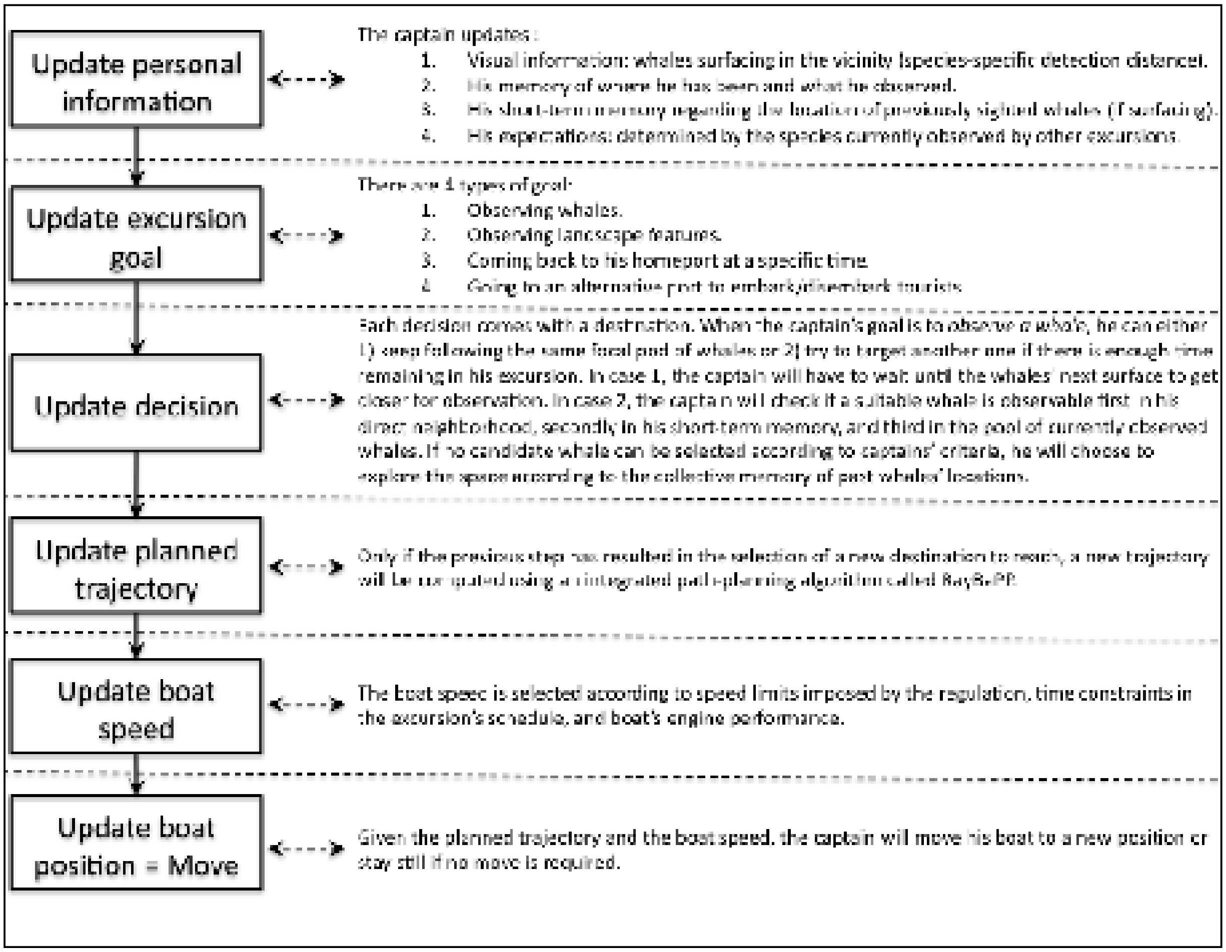
Spatial distribution and aggregation patterns were derived from:

- Sightings made from research vessels: ~550 baleen whales sightings from transect surveys (Groupe de recherche et d'éducation sur les mammifères marins (GREMM), 2007).
- Sightings made from whale-watching vessels: 32 000 marine mammal sightings from more than 2 100 sampled whale-watching excursions (Michaud *et al.*, 1997; Michaud *et al.*, 2008).

The model combines a simple diving routine with a displacement algorithm to determine each individual whale's depth, direction and speed at each time step. Diving and surface sequences durations are randomly selected from an empirically derived Weibull distribution computed for each species from land-based tracking data. The diving routine uses a simple deterministic function to calculate the amount of remaining oxygen as a function of the whale's depth and diving time; thus forcing the whale to surface regularly for breathing. Several displacement algorithms were implemented and tested, starting from a simple random walk and increasing in complexity to include residence indexes (Turchin, 1998) and social interaction between whales (Couzin *et al.*, 2005). The ability of each algorithm to successfully match the (often conflicting) patterns for each species was assessed. The algorithm MMNB (for "minimization of the mean normalized bias"), a modification of the correlated random walk (Turchin, 1998), proved the most successful at reproducing the desired patterns, and is currently implemented in the model. For each species, MMNB randomly selects an individual's speed and move duration from the empirical distribution and then adjusts the turning angle to reduce the normalized mean difference between the real and simulated group size (animal density within a 2km radius), turning angle and spatial distribution patterns (Lamontagne, 2009).

7.3.3 Whale-watching boat captain agents

Whale-watching excursions are challenging to model. Their dynamics, which is driven by captains' decisions, is highly dependent on several factors such as whales' spatiotemporal distribution, species' abundance, and contextual factors (e.g. regulations, current observations made by concurrent companies, companies' guidelines and directions). These boat captains are goal-oriented and have to find a way to achieve their goal in a dynamic environment. Interviews with boat captains and park wardens conducted after excursions at sea, as well as VHF radio monitoring, revealed a number of attributes of their decision making, and were included in the model. In particular, whale-watching boat captains: 1) take advantage of information on the most recent observations to explore space when no other information is available; 2) share information about whale locations; 3) give priority to more dramatic species such as the humpback whale; 4) try to adjust the content of their excursion according to that of their direct competitors; and 5) must respect navigational limits related to currents and bathymetry. In the model, at each time step the virtual captain agents follow a series of steps from information acquisition to movement execution (Figure 7.2).



The captain updates :

1. Visual information: whales surfacing in the vicinity (species-specific detection distance).
2. His memory of where he has been and what he observed.
3. His short-term memory regarding the location of previously sighted whales (if surfacing).
4. His expectations: determined by the species currently observed by other excursions.

There are 4 types of goal:

1. Observing whales.
2. Observing landscape features.
3. Coming back to his homeport at a specific time.
4. Going to an alternative port to embark/disembark tourists.

Each decision comes with a destination. When the captain's goal is to *observe a whale*, he can either 1) keep following the same focal pod of whales or 2) try to target another one if there is enough time remaining in his excursion. In case 1, the captain will have to wait until the whales' next surface to get closer for observation. In case 2, the captain will check if a suitable whale is observable first in his direct neighborhood, secondly in his short-term memory, and third in the pool of currently observed whales. If no candidate whale can be selected according to captains' criteria, he will choose to explore the space according to the collective memory of past whales' locations.

Only if the previous step has resulted in the selection of a new destination to reach, a new trajectory will be computed using an integrated path-planning algorithm called RayBePP.

The boat speed is selected according to speed limits imposed by the regulation, time constraints in the excursion's schedule, and boat's engine performance.

Given the planned trajectory and the boat speed, the captain will move his boat to a new position or stay still if no move is required.

Figure 7.2 Sequence of actions (from top to bottom) that each captain agent goes through at each time step during the simulation.

A whale-watching captains' main objective is to observe whales during an excursion (although some also have sub-objectives related to sightseeing, for example). In the model, excursions leave port according to planned schedules. Captains navigate using a path-planning algorithm to select the shortest path to their destination. Captains choose which whale to observe using a cognitive heuristic decision-making module (Chion *et al.*, in revision) according to their preferences and constraints. The captains must make use of existing information (either from current data on whale locations if available, or retrieving from the memory of previous day's observations) to select where to head their excursion to observe whales. This type of decision is rapid, based on limited information, with no optimal universal solution, and is repeated several times during an excursion. We assume, therefore, that the captains are operating in a context of bounded rationality, where they will select what appears to be the best choice given currently available information and the contextual setting both in time (e.g. what species they have already observed during the excursion will affect their choice of the next pod to target) and in space. The validation of the whale-watching vessel captain model is described in further detail in (Chion *et al.*, in revision).

Other whale-watching captains' cognitive and sensory capabilities are implemented within the model. Past observations are aggregated in a collective spatial memory according to a simple clustering algorithm that groups those past observations in clusters where the maximum pairwise distance does not exceed the visibility extent. This approach was chosen to represent the way captains aggregate past unique observations in broader regions where the action took place, rather than in precise locations where each given observation occurred.

The distance of whale detection by a captain's visual module is species dependant. For each species, the detection distance was calibrated using the knowledge of observers working at counting whales on the Saint-Lawrence during sea-based transects.

7.4 Methods

7.4.1 Rules considered by whale-watching captains to choose a whale to observe

Our investigation of whale-watching captains' decision making revealed several notable characteristics and mechanisms which were subsequently implemented within the model (Figure 7.2). The following decision rules were elicited from field work mainly consisting in 1) 7 semi-structured interviews (~10 hours) conducted with whale-watching captains after an excursion, 2) 15 hours of VHF radio monitoring, and 3) observations made during 30 excursions onboard all boats and ports in the park area. Extracted decision rules serve as the reference model for whale-watching captains' decision making about which pod to target for observation. Within the sequence of actions detailed in Figure 7.2, these rules intervene at the step "update decision", when the goal is "observing whales" and a new pod of whales has to be targeted among a set of candidate animals. Given a set of candidate whales, the captain agent jumps to the next rule until only one whale remains in the list. Rules are ranked as follows:

1) Captains try to find species that are not currently observed by any captain at sea. If such a species appears opportunistically in their surroundings, the captain will target it. This will give the captain an edge over his competitors.
2) Captains favour species not already observed in their own excursion that have been observed in other excursions.
3) Captains prioritize the whales belonging to the overall top-ranking species in their decision (i.e. humpback, fin and blue whales). In fact, species' attractiveness is not the same for all species. When present in the area, data from sampled excursions show that humpback whales are responsible for the largest aggregations of boats followed by the fin, blue, minke, and beluga whales (all pairwise differences statistically significant). Several characteristics have an impact on species' attractiveness, such as their potential spectacular displays, ease of observation (no fleeing behaviour), predictability of individual distribution, core habitat areas (e.g. proximity from departure ports), abundance, and species-specific regulations.
4) Captains prefer whales that are about to be lost from the pool of discovered ones (i.e. no boat observing them anymore). This is all the more true for individuals from species standing high in the preference ranking such as humpback whales.
5) The next criterion is the preference for whales with the lowest number of boats in their surrounding. Some captains, often those with more experience, give a higher priority to non-crowded sites.
6) Captains favour observations allowing subsequent observations in the area. This ability to anticipate and build an excursion in advance and adjust it as a function of upcoming information is expected to be more prevalent with experienced captains.
7) In case of a tie between candidate whales, captains will break the tie by choosing the closest whale.

We followed a naturalistic decision making approach to investigate captains' decisions in action (Klein, 2008; Klein, Calderwood and MacGregor, 1989) and modelled it following the bounded rationality framework (Gigerenzer and Selten, 2001a; Simon, 1957). Being aware that all captains neither have the same experience nor the same values, using a single model to represent all captains' decision processes is a current limitation of the model. However, the validation process proved that this approach allowed the faithful reproduction of some key individual (total length, activity budget, and contribution of species in observations) and collective (core areas of activity and boat aggregations) patterns of excursions (Chion *et al.*, in revision). This suggests that from the collective perspective, which is of particular interest, individual differences influence less critically the global dynamics than individual similarities (e.g. overall preference ranking for given species) and shared collective mechanisms (e.g. cooperation via communication, prevalence of knowledge exploitation over space exploration).

The rules described above were implemented as cues within the *take-the-best* heuristic structure (Gigerenzer and Goldstein, 1996) that has proved to best reproduce excursion patterns (Chion *et al.*, in revision) amongst several cognitive heuristics taken from the bounded rationality literature (Gigerenzer and Selten, 2001a). The prevalence of a non-compensatory heuristic such as *take-the-best* over compensatory ones (e.g. Tallying) suggests that whales' characteristics do not have the same weight in captains' decisions.

7.4.2 Alternative decision making strategies

To study how the decision-making process of captains can influence the dynamics of whale-watching excursions and ultimately affect the global dynamics of the system, we implemented two alternative decision making strategies in 3MTSim that virtual captains follow when deciding which whale to observe. Our objective is to foresee how such alternative behaviours could affect both whales' exposure and excursions' dynamics and content. This type of application could lead to a series of recommendations passed on to captains during seasonal training sessions. The simulations run with each alternative decision making model (DMM) aim at demonstrating the feasibility of such a utilization of ABM for advisory purposes.

We present hereafter the two alternative DMMs that were implemented and tested within 3MTSim. Rules contained within the two alternative models were implemented within the *take-the-best* heuristic structure. The alternatives are expected to mitigate whales' exposure without significantly affecting observation activities (e.g. time spent in observation).

7.4.2.1 Preference for less crowded observation sites (DMM-1)

The idea of this DMM is to favour whales with fewer boats in observation. Taking into account this criterion in the process of selecting whales to observe is expected to decrease the aggregation of boats on observation sites, which is a goal pursued by parks managers regarding the management of whale-watching activities. Captains using this decision strategy will apply the following rules:

1) Captains try to find species that are not currently observed by any captain at sea. If such a species is visible in their surroundings, it will be targeted.
2) Captains favour species not already observed in their own excursion.
3) Captains will pick the observation site with the fewest boats on it, with a coordination mechanism allowing captains to account for others' intentions (i.e. captains heading to observe a whale but not currently observing it).
4) In case of a tie, captains will chose the closest site regardless of species.

7.4.2.2 No preference ranking of whale species (DMM-2)

This DMM gives the same weight to all species in captains' selection process of which pod of whales to target. The idea to test this DMM comes from an issue noticed repeatedly in the past, when some whales belonging to scarce species attract numerous boats in their vicinity, via a domino effect. Captains using this decision strategy will consider the cues as follows:

1) Captains try to find species that are not currently observed by any captain at sea. If such a species appears in their surroundings, it will be targeted.
2) Captains favour species not already observed in their own excursion.
3) Captains will not ground their decision based on a species preference ranking.
4) In case of a tie, captains will pick the closest whale between remaining candidates.

7.4.3 Design of experiment and simulation parameters

For the reference model and both alternative DMMs described above, we ran 10 replications of a 1-week simulation. We fixed the number of runs to 10 by monitoring the inter-runs' variability.

The data from the first day of each simulation (transient state) were systematically discarded to keep only the model's steady state. The visibility parameter was set to 4 km for all simulations. The period of the year simulated is the peak tourist season (between mid-July and mid-August); this is the most critical time of the year in terms of the number of boats at sea. Excursion schedules and zodiac departures reach a peak at this time of the year in response to the maximum touristic demand.

All simulations were run with the same whale species' abundance and spatial distribution settings (Table 7.1). Except for belugas, abundances were selected to reflect the approximate proportion of each species compared to the others, as observed during recent seasons. For belugas, since they are often excluded from observation activities due to the minimum observation distance restriction (400 meters), we lowered their number (from ~1000 in the real system to 100) to speed up simulations.

Table 7.1 Whale species' setting used for simulations

Species	**Abundance**	**Years of spatial distribution data used**
Minke	40	2007
Fin	20	2007
Blue	3	2007
Humpback	3	2007
Beluga	100	1994-2007

7.4.4 Variables observed

In order to assess the impact of a given DMM strategy on the system, we observed several variables output by the model during the simulations. We distinguish variables characterizing the impact on whales' exposure from those impacting excursions' dynamics.

7.4.4.1 Variables characterizing whales' exposure to whale-watching boats

We chose four variables to characterize whale exposure to observation boats. We made the distinction between individuals, species, and overall exposure.

- Exposure of individual whales:
    - *Percentage of individual whales observed*. This variable provides insight on the proportion of individual whales that have been exposed to observation activities.
    - *Duration of continuous sequences of observatio*n. This variable allows monitoring the duration of the continuous sequences of observation that animals are subject to. For instance, if two boats observe the same whale during 30 minutes successively (the first boat leaving when the other arrives), the duration of the continuous observation sequence will be 60 minutes.
- Exposure of species:
    - *Species' contribution to observation activities*. This variable tells us the contribution of each species to the budget of all whale-watching activities.

  - Overall exposure of whales present in the area:
  - *Time spent in observation activity*. This variable allows computing the total time whale-watching boats have been observing whales.

We are aware that some of these variables should be regarded cautiously since the level of knowledge introduced in the model may not be sufficient to consider them with high confidence. For instance, the percentage of individuals observed partially depends on the spatial location of individual whales; however, in reality some specific individuals may display some site fidelity, which is not fully known nor modelled within 3MTSim.

7.4.4.2 Variables characterizing excursions' dynamics

Modifying a captain's strategy affects excursions' dynamics. We monitor changes by recording and analyzing the following variables:

- *Success of* the excursions. This variable informs us about the percentage of excursions that made at least one observation during the outing.
- Time spent in observation activity.
- Proportion of time boats are alone with the targeted pod. This variable is an indicator of the quality of observations. Since the large number of boats at sea is one of top-most sources of concern about whales' protection and the most negative element experienced by whale-watching tourists during their excursion (see (Giroul, Ouellet and Soubrier, 2000), p. 53-54), it can be reasonably inferred that decreasing boat concentrations would contribute to the enhancement of the visitors' experience.
- Boat aggregations around observed pods of whales. This is a critical variable for managers who wish to decrease boat aggregations at sea.

More variables could be added to this analysis framework. However, the set of variables presented above are intended to give an insight into 3MTSim's capability to monitor effects induced by captains' changes of behaviour.

7.5 Results and discussion

We now present and discuss the simulation results for both alternative models (DMM-1 and DMM-2) and compare them to the reference model's outputs characterizing the current situation at sea.

7.5.1 Whale exposure

Simulations revealed that DMM-1 and DMM-2 both increase the total number of individual whales observed during a day compared to the current situation (modelled by the reference DMM). The strategy where captains favour observation sites with fewer boats leads to a 15% increase in the number of individuals observed whereas the strategy where no preference ranking of species exists leads to a 1.5% increase in the number of observed individuals (Table 7.2). These relative increases are significant with both p-values < 0.01 (Wilcoxon rank sum test).

We compared the distributions of the duration of observation sequences produced by DMM-1 and DMM-2 (cf. Figure 7.3). Neither DMM-1 nor DMM-2 affected this metric significantly compared to the reference model (Wilcoxon rank sum test). This is a consistent result since the rule that controls the decision to leave the observation site remained the same for all tested models (a function of the number of the targeted whale's surfaces observed, the maximum time allowed by the marine park regulations for observing the same pod, the presence of other whales observable in the vicinity, and the remaining time in the excursion).

Table 7.2 Increase in the total number of individual whales observed each simulated day for both alternative DMM in comparison to the reference model

DMM-1 (compared to reference)	**DMM-2 (compared to reference)**
+15%	+1.5%

Several ways could be envisioned to reduce the duration of observation sequences in the real system: giving incentives to explore space to search for new whales instead of taking advantage of discovered whales; reducing the maximum authorized time in observation of the same pod (currently 60 minutes); or giving incentives to diversify activities at sea leading to more time spent discovering landscape features (e.g. lighthouse, sand dunes). Such strategies could be tested in the model to predict the effects on the duration of observation sequences.

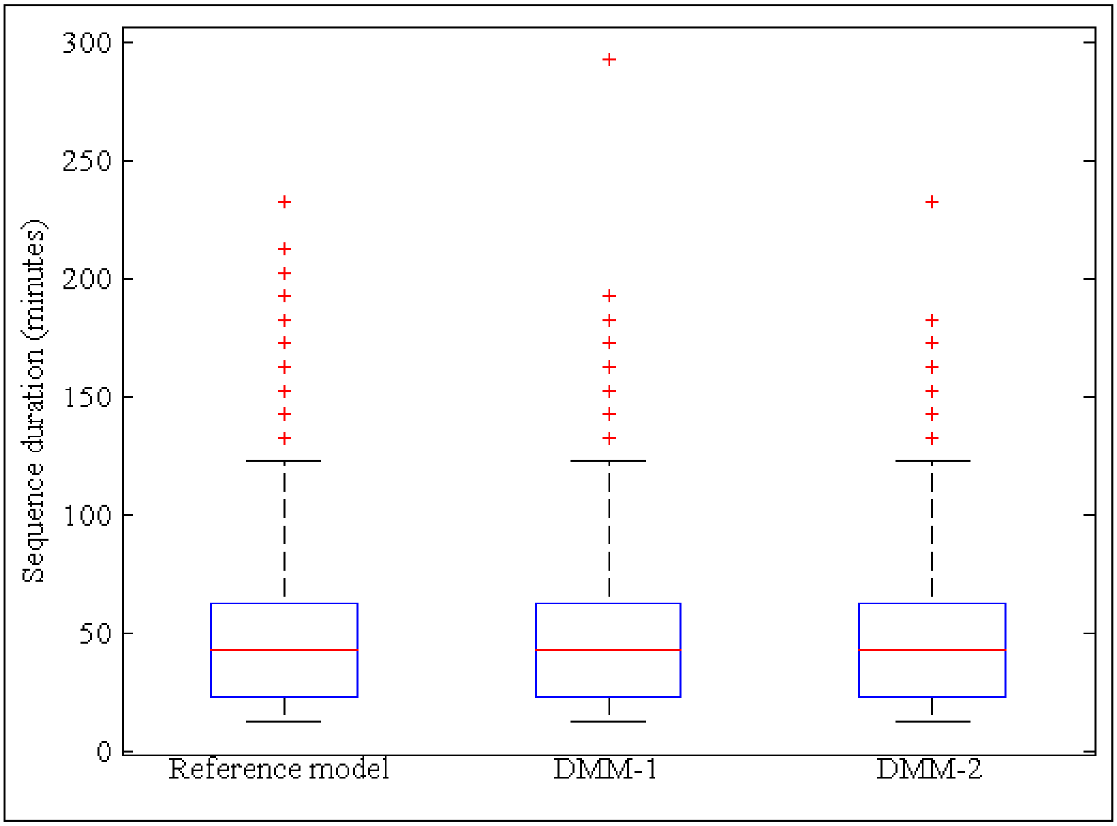


Figure 7.3 Boxplots of observation sequence durations for the three tested DMMs. No statistical difference was noticed between the distributions.

Table 7.3 shows the repartition of observation effort on the four rorqual species. Both DMM-1 and DMM-2 led to a significant reduction of the proportion of time devoted to humpback whales observation. Attractiveness of this species is particularly high in the area for several reasons including its occasional spectacular behaviours, stability of individual locations, and core habitat located in the vicinity of main ports of excursion departure. In contrast, despite having the same abundance in simulation runs (3), blue whales always account for a smaller part of observation, especially because their home range is located more downstream, farther from the most active homeports.

Table 7.3 Contribution of each species to overall observation of activities

	Minke whale	**Fin whale**	**Blue whale**	**Humpback whale**
Reference model	33%	31%	4%	32%
DMM-1	44%	36%	4%	16%
DMM-2	34%	38%	8%	20%

7.5.2 Excursion dynamics

The percentage of empty-handed excursions is similar for all tested models at approximately 3%. Again this is consistent since for all simulations captains favour (when possible) exploitation of discovered whales rather than the more risky exploration of space. Consequently the success rate is not affected.

Conversely, we found a slight change in the total amount of observation activities. Both DMM-1 and DMM-2 strategies lead to more observations than the reference model (Table 7.4).

Table 7.4 Average and standard deviation of proportion of time spent in observation during excursions

Reference model	**DMM-1**	**DMM-2**
49% +/- 2 %	54% +/- 1%	53% +/- 2%

The increase in time spent in observation is due to the fact that captains promote opportunistic observations for both DMM-1 and DMM-2. In the case of DMM-1, this is due to the fact that a whale surfacing opportunistically in the vicinity can be the best choice since there is no boat observing it. In the case of DMM-2, since the species is no longer a criterion for whale selection, whales surfacing in the vicinity of a boat will have more chance to be selected for observation. Observing close whales opportunistically reduces the travel time needed to reach a more distant site, thus explaining the increase in observation activities.

Reducing boat aggregations around pods of whales is positive both for whales and visitors' experience. Table 7.5 shows the proportion of time one or two boats are observing the same pod simultaneously. As expected, using the DMM-1 strategy, captains significantly increase by ~11% the proportion of time they spend alone or with only another boat observing a pod when compared to the reference model. In contrast, DMM-2 does not affect those metrics significantly. Let us point out that these figures take into account all excursions in a day, including early and late excursions where most of observations occur alone since few boats are at sea at these times (compared to busier mid-day schedules).

Table 7.5 Proportion of the total observation time an excursion is alone (1) or with another boat (2) observing a pod

	Reference Model	**DMM-1**	**DMM-2**
1-Alone with the pod	26.3%	32.2%	25.7%
2-Two boats observing the same pod	22.8%	27.7%	23.6%
Sum (1+2)	49.1%	59.9%	49.3%

Figure 7.4 shows the boxplots of the boat number distributions on observation sites. Only DMM-1 significantly reduces boat densities around whales, including median and maxima (Wilcoxon rank sum test).

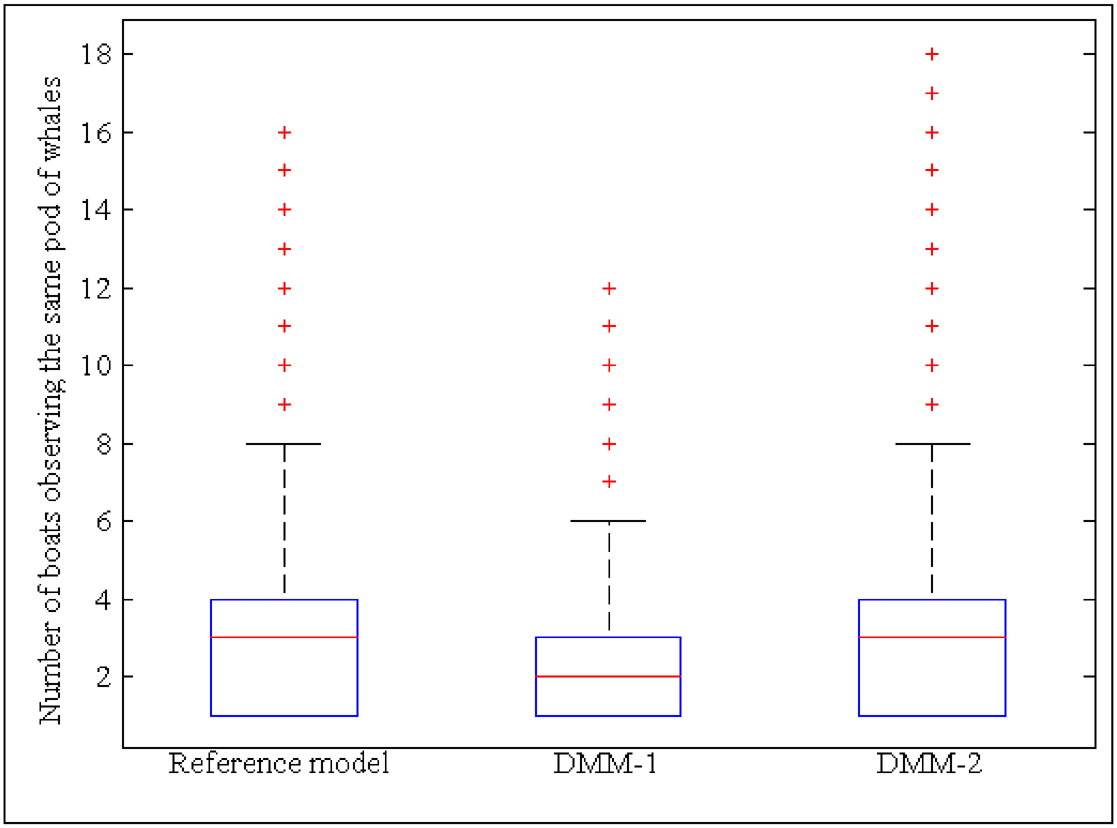


Figure 7.4 Boxplots representing the number of boats on observation sites for each tested DMM.

7.6 Conclusion

Our goal was to provide insights on the use of multi-agent modelling to better understand the nature of interactions between whale-watching excursions and whales. 3MTSim is a spatially explicit multi-agent model representing whale movements and navigation activities within the Saint-Lawrence Estuary, Québec, Canada. This model was primarily developed to test alternative navigation-related management scenarios, including observation activities. Since the whale-watching captains' decision process was modelled in detail, 3MTSim can also be used to predict outcomes from changes in captains' strategies to locate and observe whales, which was presented here.

Currently, whale-watching captains mostly ground their decisions on which whale to observe based on species, proximity, and competitor excursions' content. We demonstrated that taking into account other criteria such as boat aggregation could help to decrease the overall density of boats in the vicinity of whales, without affecting some excursion's performance (e.g. time spent in observation). Additional decision strategies can be expected to improve the situation at sea. For instance, captains could engage in more space *exploration* (by opposition to the currently widespread *exploitation* of discovered whales) or else could systematically present some landscape or historical features as part of their excursion instead of overly focusing on whale observation.

By testing alternative decision strategies that could be followed by captains, it is possible to devise a set of recommendations that park managers could communicate to whale-watching captains during training sessions. As a decision-support tool, 3MTSim has the advantage of being able to illustrate the whole picture of the collective impact of navigation and observation activities on whales. Appreciation of their collective impact on targeted whales was particularly absent from captains' discourses during interviews, suggesting that multi-agent models could also help in providing further captain awareness at this level.

As new knowledge about the system's dynamics becomes available, it is possible to integrate it in the multi-agent model. Future improvements expected are a model of noise emission (by boats) and 3D propagation in the area, whales' reaction to the presence of boats, along with captains' individual differences (e.g. values, preferences). Finally, other variables could be observed to achieve a more complete impact analysis such as spatial variations of boat-whale co-occurrences, or whales' cumulative exposure to noise sources.

7.7 Acknowledgments

This project was made possible by a strategic project research grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). Thanks to: Benoit Dubeau, Daniel Gosselin, Jeannie Giard, Veronique Lesage, and Michel Moisan for contributing to discussions and data analysis. We are grateful to the following tour companies for their participation in the project: Croisières AML Inc., Croisière 2001 Inc., Groupe Dufour Inc.,

Croisières Charlevoix Inc., Les Croisières Essipit Inc., Croisières du Grand Héron, Les Écumeurs du Saint-Laurent, Société Duvetnor Ltée.

CHAPTER 8

THE SHIPPING MODEL

After the presentation of the work related to the development of the component of 3MTSim related to whale-watching excursions, this chapter is devoted to the development and validation of the shipping model (cf. Figure 6.2). The term *shipping* refers to all maritime activities conducted by boats carrying commercial goods or passengers with overnight stays, thus excluding most of ferry trips and commercial excursions (e.g. whale-watching excursions).

Most geospatial analyses were carried out with the technical support of Samuel Turgeon, research assistant in geography at Université de Montréal.

8.1 Compulsory pilotage

Any ship registered in Canada measuring over 80 meters in length and weighing over 3300 tons gross tonnage, as well as any ship not registered in Canada measuring over 35 meters in length are subject to compulsory pilotage in the St Lawrence waters upstream of Les Escoumins including the Saguenay River (cf. Figure 0.1) referred to as the pilotage District No. 2 (Department of Justice Canada, 2010). Since the great majority of ships with commercial cargos exceed these limits, almost all ship transits are assisted by experts pilots. In the District covering the study area, pilotage service is provided by the Corporation of Lower St. Lawrence Pilots (CLSLP). Ship transits in the study area are ensured by expert pilots thus contributing to the low level of spatial variability observed in their trajectories (cf. APPENDIX I).

8.2 Data

The databases used to develop the shipping model are PREVISION_INNAV and AIS_INNAV, fully described in section 1.2.2.1.

8.3 Shipping model description

8.3.1 General characteristics of 3MTSim

The following characteristics stand for all submodels of 3MTSim (Figure 1.1):

- Spatial extent: The model area is given in Figure 8.1. It encompasses the study area described in Figure 0.1.

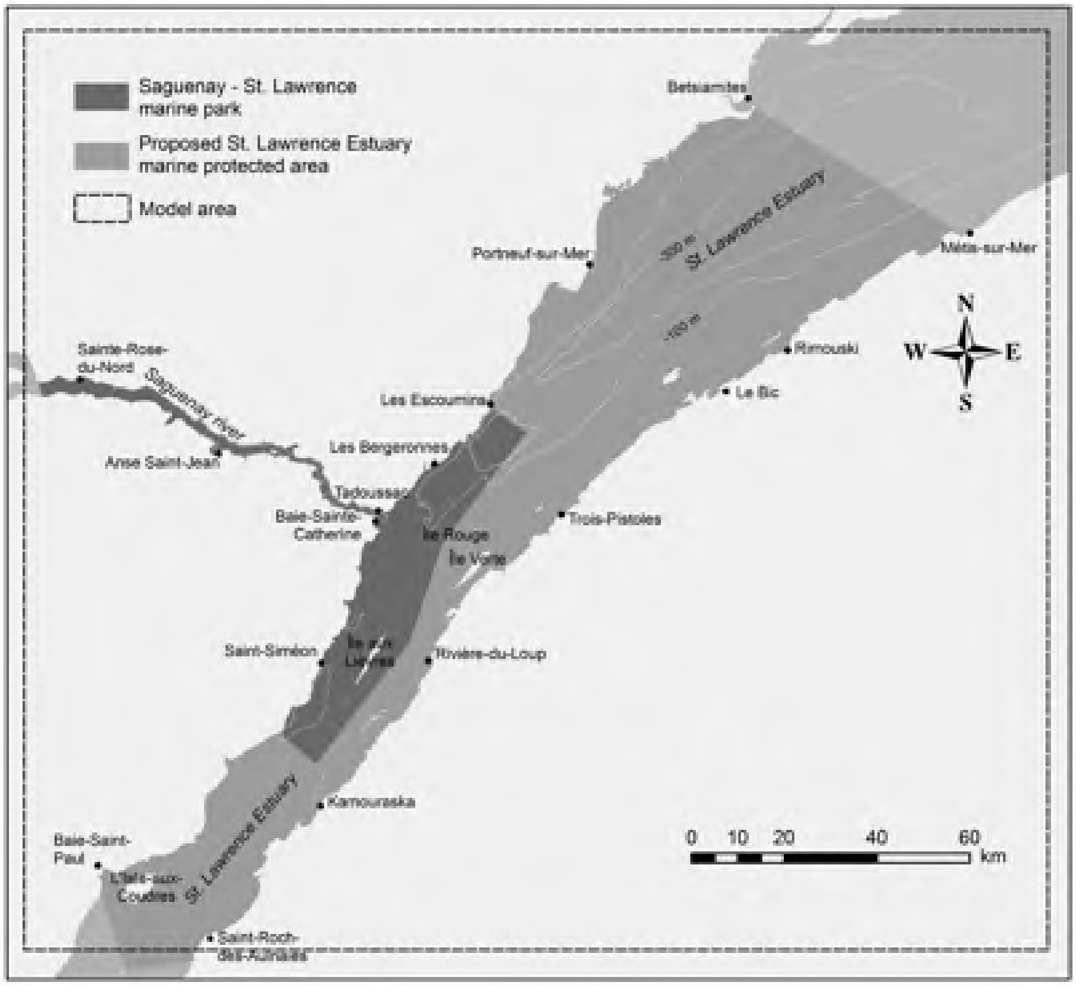


Figure 8.1 Model area.

- Spatial resolution: continuous for agent position; 100m×100m for environment information (e.g. bathymetry).
- Temporal extent: May to October (i.e. period of whale presence in the study area).

- Temporal resolution: 1 minute. This was chosen since most of spatiotemporal datasets have a temporal resolution of 1 minute.

The conceptual model of shipping activities is now presented following Sargent's modelling process illustrated in Figure 0.4 (Sargent, 2005).

8.3.2 Ship interactions with other agents

In 2008, an interview was conducted with two expert pilots from the CLSLP to gain knowledge about their decision making process in the study area. Information extracted from this interview and those conducted with whale-watching captains, along with personal observations revealed several interaction patterns between ships and their environment.

First of all, encounters between ships (e.g. overtaking, head-on situation) are regulated by the International Maritime Organisation (IMO) with the Collision Avoidance Regulations (COLREGS) (1972). Considering the low (and local) impact of such avoidance behaviours on ship trajectories, in order to keep model complexity as low as possible and stay in the Medawar zone (Grimm *et al.*, 2005), no collision avoidance module have been implemented in the current version of the shipping model.

Commercial ships tend to get the priority over other activities at sea. Given their low manoeuvrability, any smaller boat (e.g. excursions boats, yachts) should give way in the area. From a ship's wheelhouse, the detection of a small boat on the path might be too late for an avoidance manoeuvre. As a matter of fact, commanding officers operating large ships only engage in such manoeuvres in case of an emergency which tends to be exception. Some informal arrangements exist between whale-watching companies and the CLSLP, leading some pilots to deliberately anticipate the avoidance of whale observation areas. However, not all pilots respect this rule, nor does it apply in all situations. Considering that the spatial impact on ship trajectories induced by such local avoidance is very low, this occasional behaviour is ignored in the current version of the shipping model with presumably minor impact on the model results.

Finally, avoidance behaviour towards whales is not considered since no data exist about such pilots' behaviours. In the same way as for the avoidance of smaller boats, this modelling simplification does not affect model applicability since collision events between whales and ships are not explicitly simulated within 3MTSim (due to a lack of understanding of the very circumstances leading to ship strikes); only statistics related to boat-whale spatiotemporal encounters (concept illustrated in Figure 0.3) are computed from 3MTSim's output.

8.3.3 Conceptual model

PREVISION_INNAV is an almost exhaustive count of commercial trips transiting in the area so it gives a reliable statistical portrait of ship trips' characteristics (ship type, cargo, maximum speed, length, and draught) along with their temporal variability in 2007. AIS_INNAV is not complete but represents a significant part of the ship trips in the area in 2007. Consequently, the model was developed based on 2007 historical data. Two thousand seven was also taken as the reference year to build the model of commercial excursions (cf. CHAPTER 6) so that this choice is consistent for these two submodels.

Given the great quality of the data at hand and the spatial regularity of ship trips (cf. APPENDIX I), the chosen modelling approach was a purely statistical one based on 2007 PREVISION_INNAV and AIS_INNAV historical datasets. Before the presentation of the shipping model dynamics in the next section, some details about the Monte-Carlo approach are given since the stochastic selection of most of simulated ship trips' parameters from historical data rely on it.

To be consistent with Philippe Lamontagne's whale model implemented in 3MTSim (Lamontagne, 2009), the definition of the Monte-Carlo method used to develop the shipping model is similar to that proposed by Judson (1994) in the context of IBM: The Monte-Carlo method refers to the use of a probability distribution of a variable X and a random number generator used to draw values from X's distribution stochastically.

Practically, let us consider a continuous variable X, its known cumulative distribution function cdf_x, and a random number generator that draws values v_i uniformly on the interval $[0,1)$. The stochastic selection of X_i following cdf_x given v_i is given by $X_i=cdf_x^{-1}(v_i)$ with cdf_x^{-1} the inverse function of cdf_x, as illustrated in Figure 8.2.

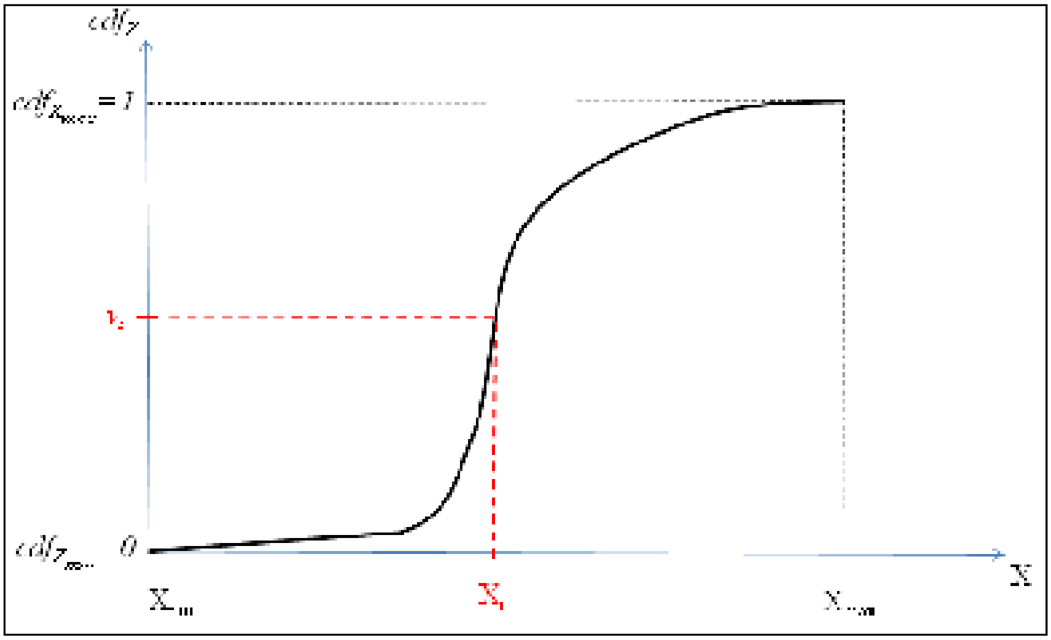


Figure 8.2 Monte-Carlo method for the stochastic selection of values from a continuous variable X given its cumulative distribution function cdf_x, and a random number v_i uniformly drawn on $[0,1)$.

All parameters (discussed in the next section) of the 3MTSim's ship trips agents are discrete because only the finite set of values appearing in INNAV datasets are considered. Consequently a discrete version of the Monte-Carlo method is needed, illustrated in Figure 8.3.

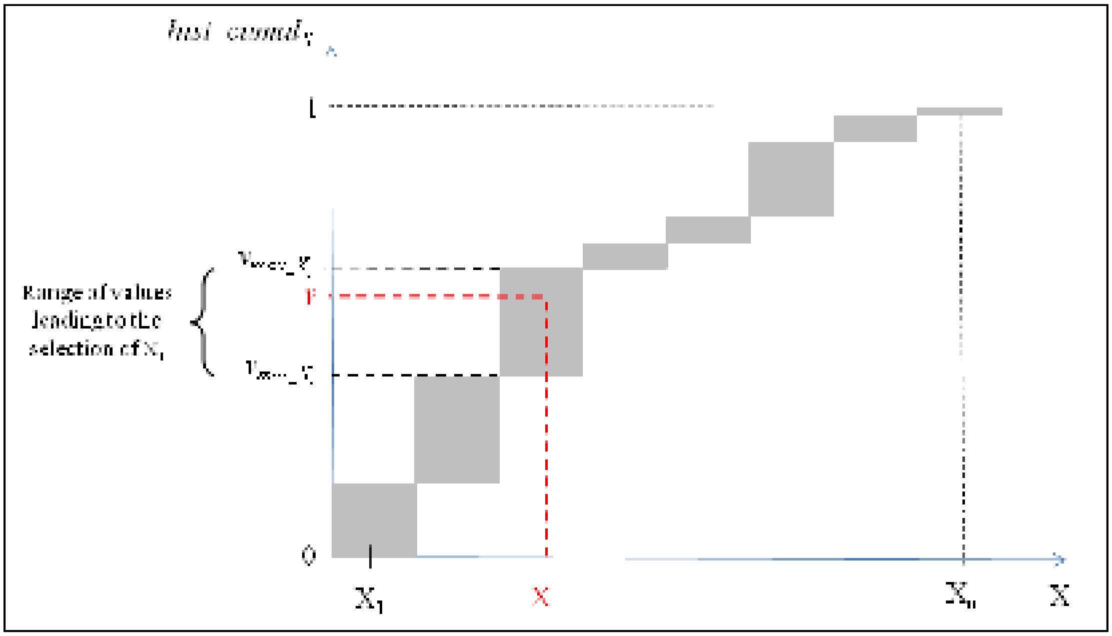


Figure 8.3 Monte-Carlo method for the stochastic selection of values from a discrete variable X given its cumulative histogram *hist_cumul*$_x$, and a random number v_i uniformly drawn on $[0,1)$.

Using this discrete version of the Monte-Carlo method on successive random draws, each discrete value of $X=\{X_1, X_2, \ldots, X_n\}$ is selected with a probability $P(X_i)$ given by equation (8.1), using notations of Figure 8.3.

$$P(X_i) = frequency\ (X_i) = (v_{max\_X_i} - v_{min\_X_i}) \qquad (8.1)$$

Now that the general conceptual model has been set, the shipping model dynamics is presented.

8.3.4 Shipping model dynamics

The flowchart of the shipping model presented in Figure 8.4 is detailed step by step thereafter.

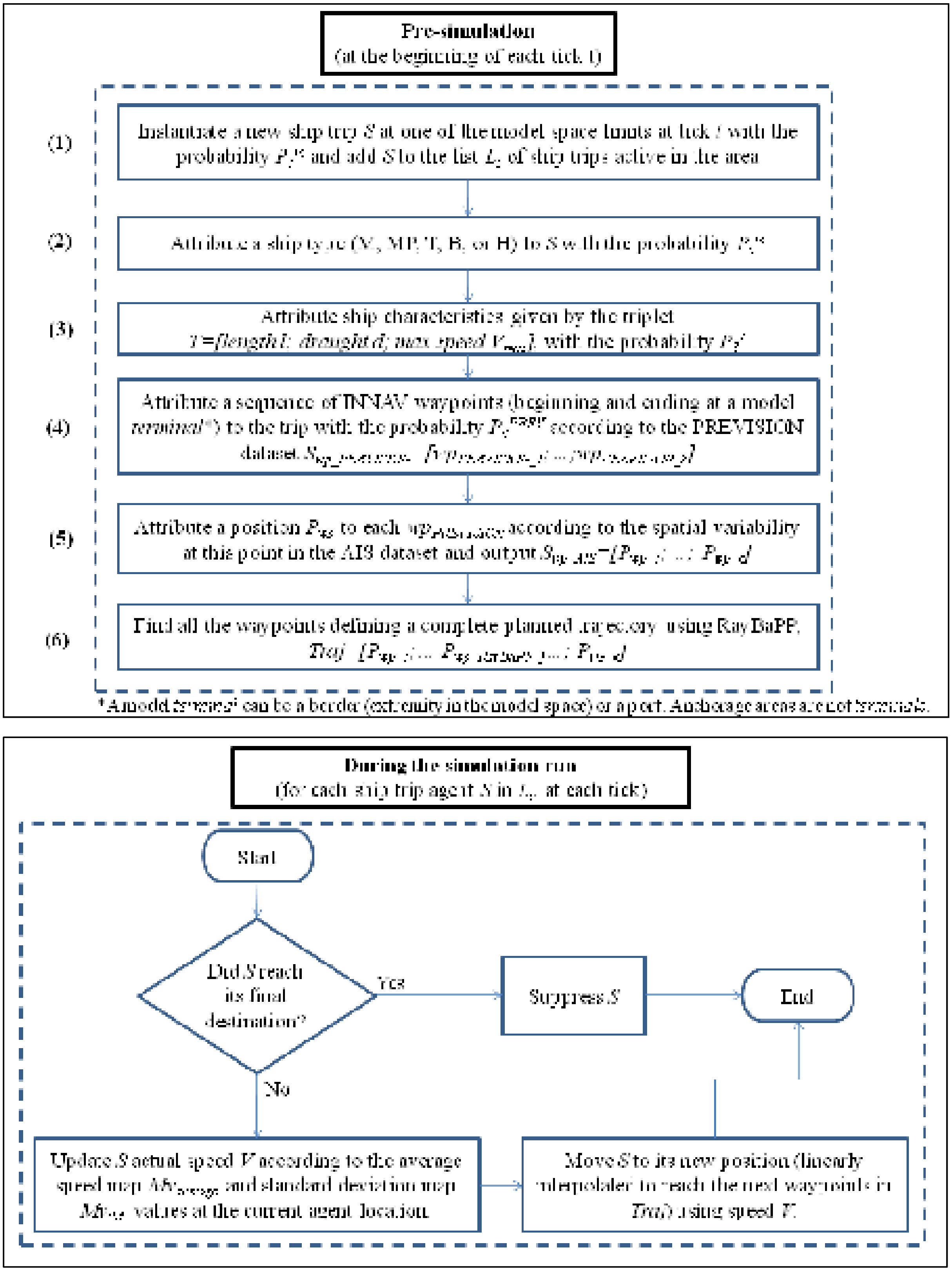


Figure 8.4 Flowchart of the shipping model dynamics.

The overall dynamics of the shipping model is divided into a pre-simulation and a simulation phase as described in Figure 8.4. During the pre-simulation phase (top part of Figure 8.4), six steps (the numbering 1 to 6 in Figure 8.4 is reused below) are necessary to create a planned ship trip *S* in the model space, detailed below.

1) First, at each time step (1-minute) during a simulation, a new ship trip *S* is instantiated at one of the three borders (upstream and downstream the St. Lawrence, and the north-west end of the Saguenay fjord) with a probability P_1^m defined by equation (8.2).

$$P_1^m = \frac{Number\ of\ ship\ trips\ in\ month\ m}{Number\ of\ minutes\ in\ month\ m} \tag{8.2}$$

   Given that there exists a non-random seasonal variability in the number of ship trips in transit in the area (cf. figure 1 in APPENDIX I), P_1^m varies monthly.

2) Once *S* has been instantiated, re-using the CCG's INNAV class codes (Figure 1.2), one of the five commercial classes $C_S=\{M,MP,T,B,H\}$ is attributed to *S* with a probability P_c^m defined by equation (8.3).

$$P_c^m = \frac{Number\ of\ trips\ from\ vessel\ class\ c\ in\ month\ m}{Number\ of\ ship\ trips\ in\ month\ m} \tag{8.3}$$

   The description of the five vessel class codes designing commercial trips retained for the shipping model purposes is given below:

   - Merchant ships (M): All commercial ships carrying solid cargoes (e.g. bulk carriers, containers).
   - Merchant ships for passengers (MP): National and international cruise boats (e.g. ocean liners).
   - Tankers (T): All commercial ships carrying fluid cargoes (e.g. chemicals, oil, LNG).
   - Barges (B): All barges including self-propelled.

- Tugs (H): Tugboats.

The remaining categories were not considered because 1) they do not designate commercial shipping or cruising activities (A, C, D, I, S, W); 2) the number of their trips is marginal in the area (F, O, U); or 3) they are already (or will be) accounted for in another submodel (MF, MW, Y). Any of the classes left aside could be added to 3MTSim as a new component of the boat submodel (cf. Figure 6.2) if its inclusion would become justified. Discrete values of ship classes are selected using the discrete version of the Monte-Carlo method described in Figure 8.3.

3) Three static characteristics were retained to characterize a ship:
   - Ship length l (in meters): given in PREVISION_INNAV.
   - Ship draught d (in meters): given in PREVISION_INNAV.
   - Ship maximum speed in the study area V_{max} (in knots): extracted from AIS_INNAV.

   For each ship trip S having transited in the area from May to October 2007, the triplet $T=[l, d, V_{max}]$ was recorded to calculate the frequency of occurrence of each triplet. The probability P_3^T of selecting the triplet T appearing n_T times given the total number of ship trips is determined using the following basic formula (8.4):

$$P_3^T = \frac{n_T}{Total\ number\ of\ ship\ trips} \tag{8.4}$$

   No evidence of monthly variation in triplet values was found so this probability was not made monthly. Triplets T are selected using the discrete version of the Monte-Carlo method described in Figure 8.3.

4) For each trip transiting in the study area, the planned sequence of INNAV waypoints $S_{wp\_PREVISION}$ was extracted from PREVISION_INNAV. For a given S, $S_{wp\_PREVISION}$ represents the skeleton of its planned trajectory, starting and finishing at a model terminal

(*i.e.* one of the three model space borders or any ports, excluding anchorage areas). After a pre-processing step to get rid of incomplete and aberrant sequences, the correct sequences were compiled and their frequencies computed. The selection of a $S_{wp\_PREVISION}$ is given by a probability P_4^{PREV} following the exact same procedure as for triplet T (i.e. discrete version of the Monte-Carlo method).

5) For each INNAV waypoint $wp_{PREVISION}$ in the sequence $S_{wp\_PREVISION}$, a corresponding real position P_{wp} is attributed according to the real spatial variability around this point in AIS_INNAV (only for trips planning to go through $wp_{PREVISION}$). To do so, an algorithm was built to extract the closest points from a ship trip's AIS trajectory to the set of $wp_{PREVISION}$ contained in its sequence $S_{wp\_PREVISION}$, such as illustrated in Figure 8.5 with the simple case of two trip trajectories and two INNAV waypoints.

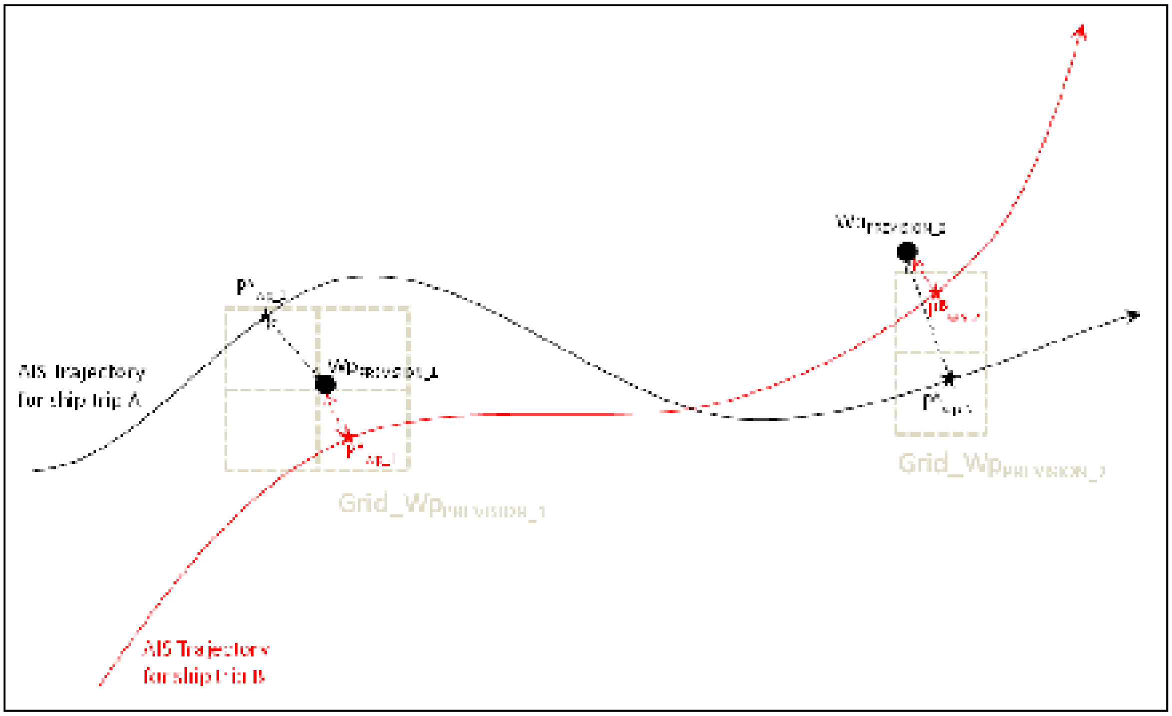


Figure 8.5 Extraction procedure of the closest AIS points to PREVISION waypoints.

Therefore, for each waypoint $wp_{PREVISION}$ of the INNAV spatial mesh (hundreds of points), the set of all corresponding AIS_INNAV points from ship trips containing it in their sequence is mapped on a 100m×100m grid such as described in Figure 8.5. The proportion of AIS points falling into each grid cell thus determines the probability of selecting the cell's centre as the corresponding P_{wp} for a given ship trip containing $wp_{PREVISION}$ in its sequence $S_{wp\_PREVISION}$. The new sequence of real waypoints P_{wp} that the ship trip is planned to go through is labelled S_{wp_AIS}.

6) To finish the pre-simulation phase, a complete planned trajectory needs to be computed using the path-planning algorithm RayBaPP described in CHAPTER 5. During the simulation a ship agent needs to go through all waypoints in S_{wp_AIS} successively, without colliding with any obstacle in between (i.e. islands, shoals, or mainland). Since there is no assurance that joining in straight line each waypoint would allow such a collision-free outcome, additional waypoints $P_{wp\_RayBaPP}$ computed by the RayBaPP algorithm (cf. CHAPTER 5) may need to be inserted into S_{wp_AIS}, resulting in the final planned trajectory *Traj*.

During the simulation, at each time step (i.e. model tick) the status of each ship trip *S* is updated (in random order), according to the bottom part of the flowchart presented in Figure 8.4. Accordingly, the first action is to check whether *S* has reached the final destination of its planned trajectory *Traj*: if yes, *S* is suppressed from the model's list of active agents. If *S* is still active after its last move (previous tick) then its current speed must be updated. For this purpose, the following two maps (1000m×1000m resolution) have been computed:

- $Mv_{average}$: Each cell value is the average of all AIS point speeds divided by ship's maximal speed in the study area, Vmax. Therefore, each cell value is in the range [0,1] and represents the average percentage of maximum speed of ships having gone through it in AIS_INNAV.
- Mvstd: Each cell value is the standard deviation associated to the distribution of ships' percentage of maximum speed going through it, according to AIS_INNAV.

Before computing these maps, the normality of these relative speed distributions has been verified in a randomly selected set of cells.

Therefore, the actual speed of S is updated according to the values contained in both maps $Mv_{average}$ and Mv_{std} at current S position (x_s, y_s), using a random number drawn from the Gaussian distribution (mean $\mu = Mv_{average}(x_s, y_s)$ and standard deviation $\sigma = Mv_{std}(x_s, y_s)$): a new percentage of maximum speed value is then output and multiplied by V_{max} to get S actual speed V. Therefore, S can execute its movement by linearly interpolating its new position based on V, its current position (x_s, y_s), and the next waypoints to reach in *Traj*. This terminates the description of the dynamics of ship trip agents implemented in the current version of 3MTSim. The next section is devoted to the validation of the shipping model.

8.4 Model validation

Several validation steps were carried out to assess model performance. Performance was assessed on 2440 simulated trips against 2007 historical data. Three validation steps are presented below. First, static characteristics (class code, and triplet T) are validated, along with the frequency of their transits. Second, the spatial characteristics of the trips generated are compared with real data. Finally, ship speed during transit is analysed and validated.

8.4.1 Static attributes and transit frequency verification

8.4.1.1 Total number of trips instantiated

The first step is to validate the correct use of P_1^m. For the 4-month period June to September, 2440 ship trips were instantiated whereas 2412 real trips transited in the region during this period (~1% difference). The monthly variability was also reproduced adequately.

8.4.1.2 Number of trips by month and vessel type (frequency)

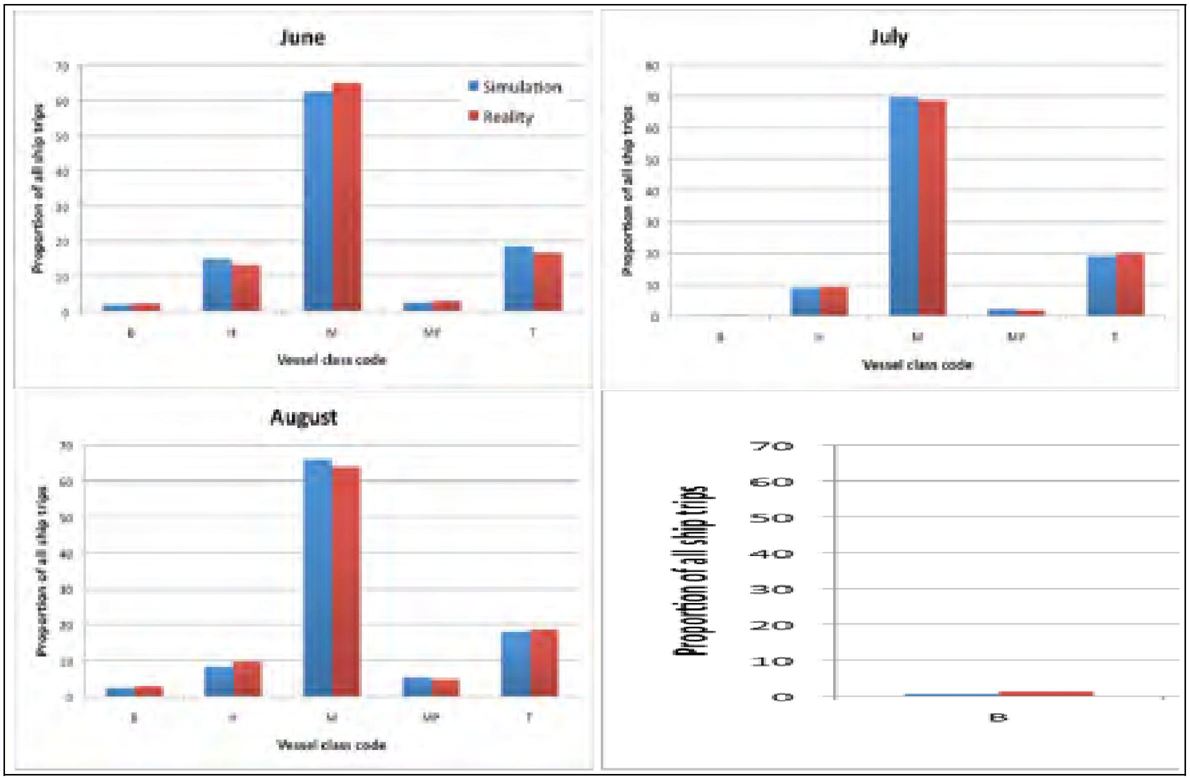


Figure 8.6 Proportion of trips from each class for the four months (simulation vs. reality).

Figure 8.6 illustrates the good match between the real flow of ships in the study area and the simulated ones. This validates the correct use of the probability P_c^m.

8.4.1.3 Ships' characteristics

The objective here is to validate that the ship trips modelled have statistically the same characteristics (triplet T) as the real ones. This is equivalent to validating the correct use of the probability P_3^T.

Here only the results of the V_{max} attribute vessel class code M and T (80% of the ship trips in the area) are given in order to alleviate this section. Results for the other characteristics of the triplet (l, d) are exactly similar as for V_{max}.

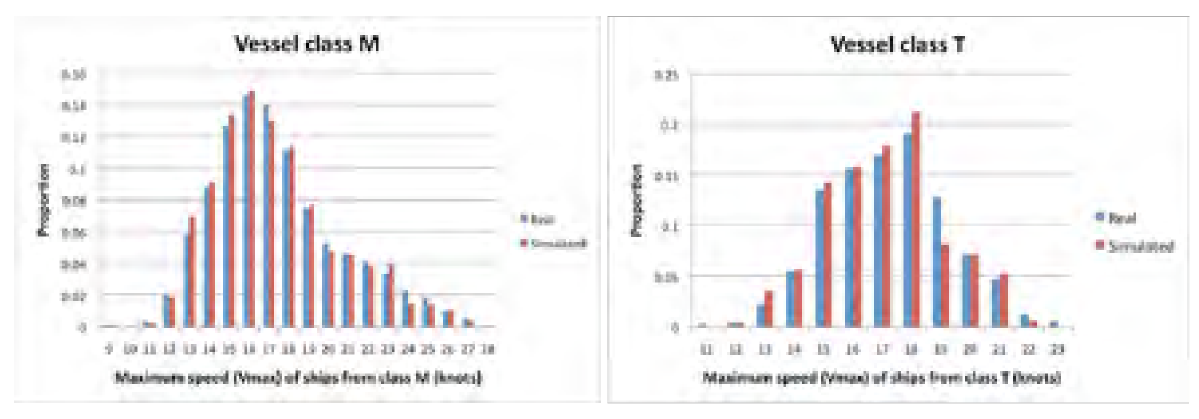


Figure 8.7 Results for the V_{max} attribute of ship trips for classes M and T only, for the June to September period.

Figure 8.7 shows a good match between real and simulated ship characteristics.

8.4.2 Spatial validation

In this section, we assess the spatial validity of the ship trip model for different resolutions. This step is performed by using trajectories computed from points (AIS for real observations, and 3MTSim output for simulations). Overall performances are presented first. Then, the spatial variability of the error is mapped and discussed. Finally, a special analysis is conducted in order to assess the shipping model's spatial accuracy as a function of the spatial resolution.

8.4.2.1 Overall performance

The overall spatial performance is assessed using the Jaccard index *J*. This simple index measures the similarity between two sets A and B by dividing the size of their intersection by the size of their union, as given by equation (8.5). The value returned by *J* is in the range *[0,1]*.

$$J(A,B) = \frac{|A \cap B|}{|A \cup B|} \tag{8.5}$$

We propose a spatialised version of the Jaccard index for two polygons where the numerator in equation (8.5) is the area of polygons intersection divided by the area of their union.

We computed the density of trajectory for both real and simulated data, and extracted the polygons covering 75% of core activities. For the home ranges 75%, the Jaccard index between simulated and real observations is *J = 0.69*. In the next section, we propose a spatial analysis and discuss the nature of the errors.

8.4.2.2 Error map

Figure 8.8 shows the kernel density computed from real observations and model output.

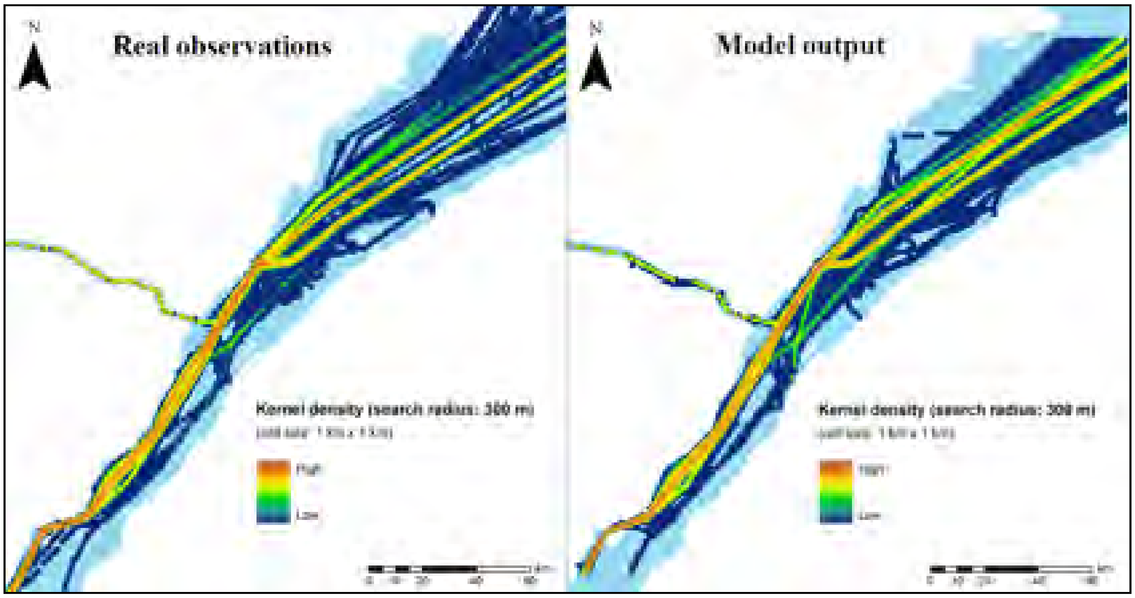


Figure 8.8 Comparison between the kernel density of real observations of maritime traffic (left) and model output (right). Results are presented qualitatively but the colour scale established from density values is the same for both maps.

Observed and real densities of densities are similar over most of the model area and the error map is presented in Figure 8.9.

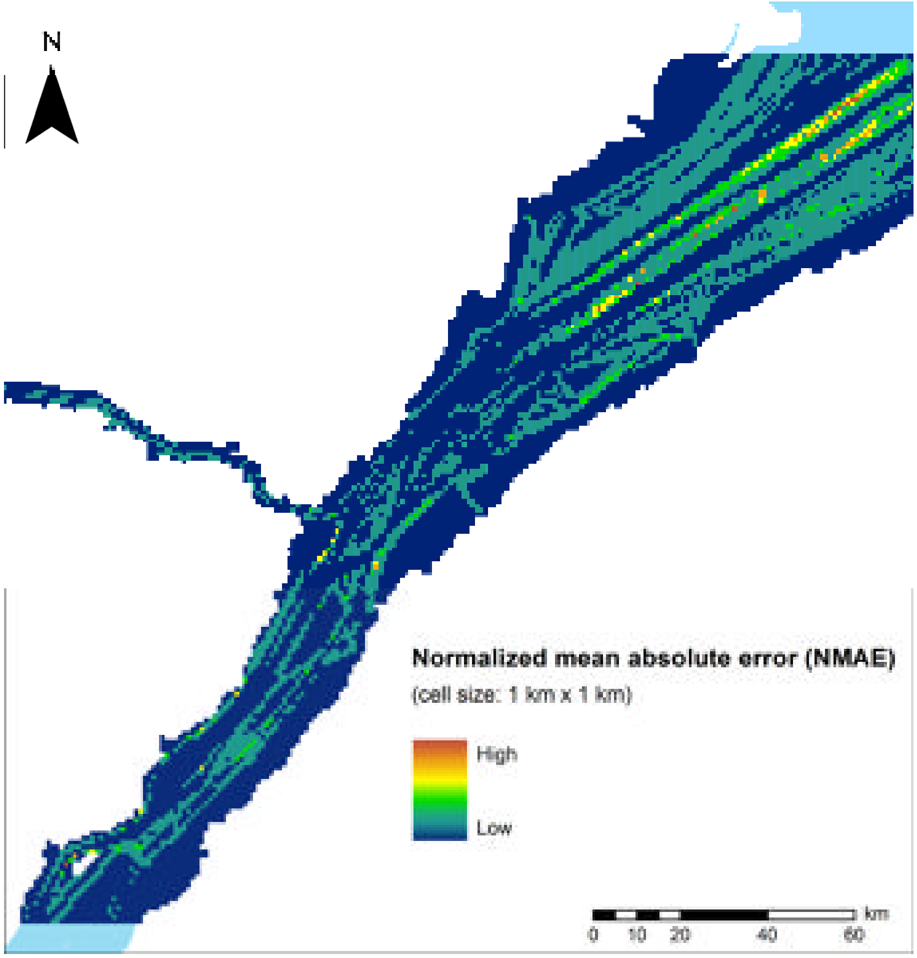


Figure 8.9 Error map computed from name maps.

Regions of high spatial error are located in the section downstream from Les Escoumins where ships sail mostly in straight line. In this area, a local offset may propagate and increase the overall error. The sources of error are discussed in the last section of this chapter.

8.4.3 Speed validation

Speed analyses were conducted at a 1000m×1000m resolution, which is the resolution of the input speed maps $Mv_{average}$ and Mv_{std}. First the overall performances are presented, followed by the spatial repartition of error.

8.4.3.1 Overall performance

Two error measures are used to assess model ability to reproduce ship speeds. They are the Normalized Mean Absolute Error (NMAE), and the Normalized Mean Error (NME) given by equations (8.6) and (8.7).

$$NMAE = \left| \frac{\overline{X_i^{sim}} - \overline{X_i^{real}}}{\overline{X_i^{real}}} \right| \tag{8.6}$$

$$NME = \frac{\overline{X_i^{sim}} - \overline{X_i^{real}}}{\overline{X_i^{real}}} \tag{8.7}$$

The overall error has been computed for all model cells, and also weighted to account for the number of points in cells. The results are given in Table 8.1.

Table 8.1 Overall NMAE and NME for ships' speed values, for model's cells only or weighted by the number of points in cells

	Cells	Points
NMAE	8.5%	7%
NME	-7%	-7%

8.4.3.2 Histogram of errors

Figure 8.10 shows that more than 70% of model cells have an NMAE on ship speed lower than 10%. To account for the variable number of points in each cell, Figure 8.11 shows that these 70% of model's spatial cells represent around 80% of the total number of points (observed and simulated). Finally, Figure 8.12 shows simulated speeds tend to underestimate real ships' speed since most of the cells' NME is negative.

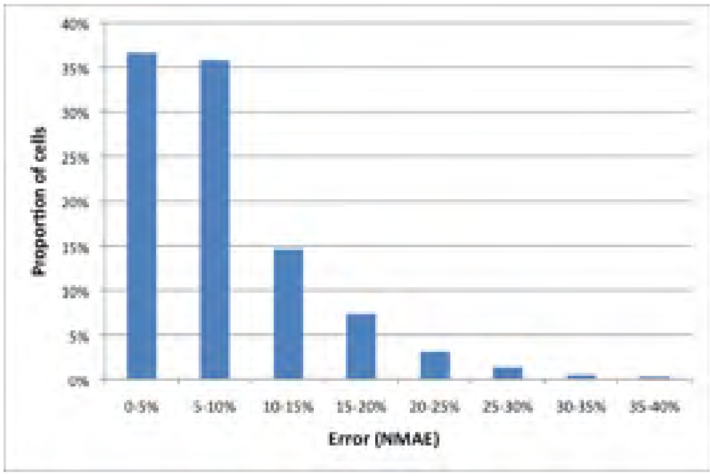


Figure 8.10 Histogram of NMAE for the 1000m×1000m cells.

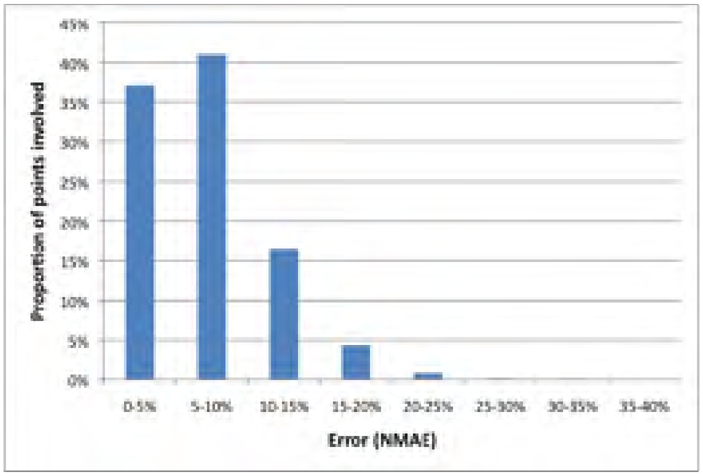


Figure 8.11 Histogram of NMAE weighted by the number of points in each cell.

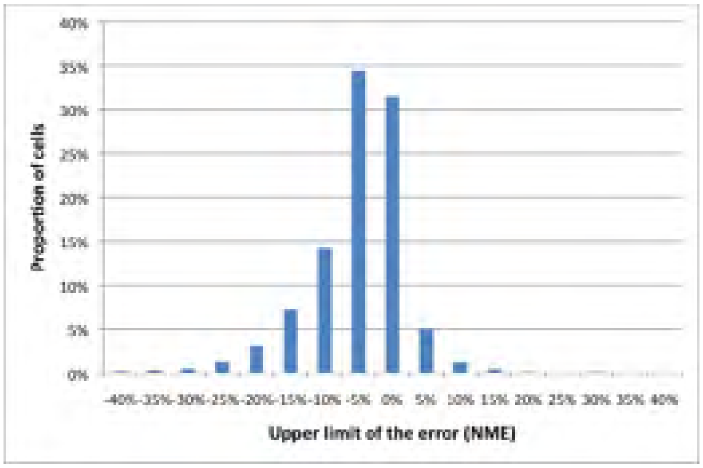


Figure 8.12 Histogram of NME for the 1000m×1000m cells.

8.4.3.3 Error map

Figure 8.13 illustrates the spatial distribution of ship speed error. The largest speed errors are mostly found in areas where the traffic density is low.

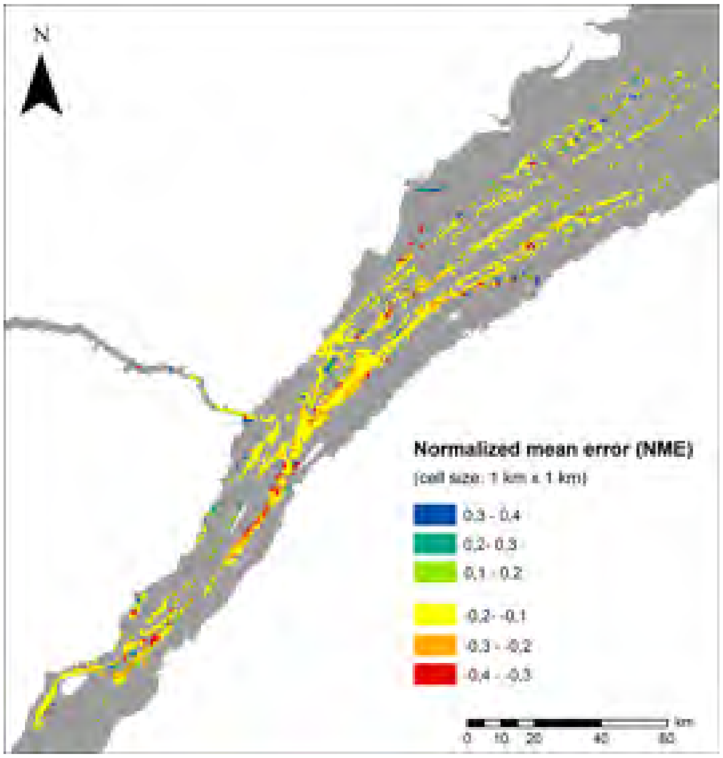


Figure 8.13 Error map (NME) for ship speed (1000m×1000m cells).

8.5 Discussion and future work

The results of the shipping model validation process revealed an overall ability of the model to match the key features of maritime traffic in the area (cf. Figure 8.6, Figure 8.7, Figure 8.8, and Table 8.1). Simulated ship characteristics (i.e. triplet *T*) along with simulated speeds gave good performance. Model improvement lies in reducing the spatial error. Eliciting the sources of error is key to improving for the ship model. Consequently, the following discussion explores the sources of spatial discrepancy between the real and simulated trajectories.

The first source of spatial mismatch elicited is due to a weakness in the AIS_INNAV dataset which contains only 21% of tug trips (type H). Since this component represents up to 15% of ship trips in the area, the underrepresentation of some highly occurring sequences lead to biased real trajectories. Consequently, the real trajectories available should be weighted to represent the frequency of INNAV sequences in the AIS_INNAV dataset to adequately match the real observations. Whereas this source of error is the most important for H type ships, it is also true for other ship types which are not completely accounted for.

Another source of spatial error inherent to the modelling approach is that the points in S_{wp_AIS} (cf. Figure 8.4) are attributed independently for a given sequence $S_{wp\_PREVISION}$, whereas they are spatially correlated in reality. In the real system, ships that pass north of a given $wp_{PREVISION\_i}$ will tend to pass north of the next INNAV waypoint $wp_{PREVISION\_i+1}$. Since this spatial correlation is not accounted for in the model (each point is drawn independently with a probability determined by overall spatial variation around the INNAV waypoint), the resulting simulated trajectories will tend deviate from real ones.

Finally, spatial errors due to ships sailing too close from the shore have been noticed at several locations over the model area. No criterion has been set in the RayBaPP algorithm to keep the ship at a minimal distance from obstacles when computing intermediary points in *Traj*. Since the minimal distance from the coast is location-dependant, a solution to solve this problem is to add waypoints (in addition to INNAV $wp_{PREVISION}$) in the regions where the spatial error is affected by this phenomenon.

Reducing the spatial discrepancy by above-mentioned adjustments will also have an impact on speed results (spatially). Although this impact is expected to be minor, this will need to be verified following the same procedure as presented. In its present form, simulated ship speeds tend to slightly underestimate real ship speeds. Therefore, the duration of ship residency in the area is slightly overestimated and the risk of lethal collision with whales, which depends on ship speed (Vanderlaan and Taggart, 2007), is underestimated; these considerations should be accounted for when using the model for management purposes.

CONCLUSION

The building process of the 3MTSim's boat agent-based model (ABM) involved several data campaigns (cf. section 1.2.2.5 and APPENDIX II) and analyses (e.g. APPENDIX I, APPENDIX III, APPENDIX IV) that provided new knowledge about the 3MT-SES. In some way, this building process can be considered to be at least as important as the model itself, having fostered the investigation of some important aspects of the real system left aside so far. To conclude the work presented in this dissertation, a summary of the contributions and how they link to the problematic enunciated in section 1.3 is proposed.

Summary of the contributions

- Development of a novel ABM dedicated to natural resource management involving agents moving in a spatially explicit environment along relatively unconstrained paths. This is one of the first ABM of boats, and among the most detailed and well validated models dedicated to decision-support in marine protected areas.
- Portrait (quantitative, spatial, and temporal) of the maritime traffic in the SSLMP where whales mostly congregate (APPENDIX I). This first exhaustive study of navigation activities in the region is of particular interest for local scientists and for model parameterization. The study report (Chion *et al.*, 2009) served as a reference in the building process of the new SSLMP 2010-2017 management plan (Foisy, Désaulniers and Balej, 2010).
- Introduction of an original investigation framework to study the dynamics of social-ecological systems (CHAPTER 3). This framework fosters the unification of both natural and social sciences to investigate SESs' sustainability. Whereas this contribution is relevant for researchers working on SESs, the results of its application on to the 3MT-SES are insightful for local MPA managers.
- Elicitation of whale-watching captains' main strategies (individual and collective) used to locate and observe whales (CHAPTER 4). This investigation proved informative for local managers, while representing an original application for researchers on naturalistic decision making (Klein, 2008).

- Development of an original path-planning algorithm RayBaPP, functional for 3MTSim simulator's requirements, and significantly faster than classical algorithms on large environments. RayBaPP proved to produce realistic boat trajectories, and allows a real-time visualization of simulations with rare slow-downs (CHAPTER 5). This contribution is particularly interesting for the growing number of agent-based modellers dealing with mobile agents moving along unconstraint paths across large environments.
- Application of the pattern-oriented modelling framework to elicit the nature of whale-watching captains' dominant decision making process (CHAPTER 6). POM allowed to select a valid model of captains' decision-making, thus confirming the non-compensatory nature the whale location/observation problem, and to validate the assumption that cooperation and communication were major drivers of the dynamics of whale-watching excursions. This contribution is of interest for the community of SES modellers, concerned with both challenges of representing human decision making in ABMs and by the model selection/validation issue.
- Application of the whale-watching submodel presented in CHAPTER 7 to explore impacts of captains' decisions. This is a relevant contribution for the whale-watching community, including researchers, managers, and policy-makers. It shows some expected consequences (regarding both whale conservation and excursions' content) of alternative whale-watching captains behaviours. Results could be useful to advise captains during their regular training sessions in order to reduce the intensity of whale exposure to boats.

Link between the problematic and the results

The problematic of this project was to move from a proof of concept (Anwar *et al.*, 2007) to an ABM that could be informative to address the management issues expressed by SSLMP and SLEMPA managers (cf. section 0.1.3.4). In summary, the road toward this goal has been mostly covered and the convincing performance of the 3MTSim ensures its safe use as a management tool insofar as model limitations are understood and accounted for in the interpretation of results. A collaborative work with MPA managers and other stakeholders is in progress to complete the final steps by the end of 2011. The involvement of stakeholders during the whole building process of 3MTSim with frequent consultations and transparency about important modelling choices certainly contributed to the interest and trust expressed by MPA managers regarding the simulator.

The challenge of building a suitable validation framework for 3MTSim has been met (cf. CHAPTER 6). The challenge of understanding and representing captains' complex decision making processes and outcomes has been cleared (cf. CHAPTER 3 and CHAPTER 4) even if it could still be improved via additional investigations, as discussed in the next chapter. Describing and modelling human behaviour is one of the daunting tasks that a modeller must tackle when dealing with ABM and SESs (Janssen and Ostrom, 2006a; 2006b). The choice to ground the investigation and modelling of captains' decision making on recently emerged cognitive science theories was ambitious and necessitated a large amount of work upstream. Despite the demanding nature of this approach and the shortcomings of the bounded rationality theory compared to well-established decision theories (i.e. expected utility theory), the direction of this research is believed to be a promising one and the contribution presented in this dissertation will contribute to the dissemination of the bounded rationality paradigm in ABM.

FUTURE WORK

A lot of work has been done to build 3MTSim from scratch en route toward a decision support tool devoted to the management of navigation activities in the study area (Figure 0.1). In order to refine the 3MTSim simulator for management purposes, both the whale and boat submodels (cf. Figure 1.1) can be enhanced. The discussion below identifies areas for improvement regarding the 3MTSim's boat ABM only.

Whale-watching excursions model

Whale-watching captains face several decision problems during their excursion, two of which are recurrent and determinant in the study of whale-watching dynamics, namely the "*locate-and-observe-whale*" and the *"stop-an-observation"* problems. The first one has been investigated in the field and knowledge has been elicited through data analyses (cf. CHAPTER 3, CHAPTER 4, and CHAPTER 6) but the later has only been touched upon.

- The *"locate and observe whale*" problem: Our understanding of contextual circumstances favouring the use of identified strategies by whale-watching captains, along with the individual variability among captains could be deepened. Habituation, bandwagon effect, use of individual heuristics or collective strategies, along with captains' preferences, experience, knowledge, and values are known to influence the choice of a given course of action: A complete portrait could be drawn.
- The "*stop-an-observation*" problem: No investigation has been made on this decision problem which is determinant regarding excursions dynamics. Data analyses showed that the *minimum duration* of a given observation by an excursion boat (i.e. time spent observing the same pod of whales) is two surfacing sequences from the focal animal. The *maximum duration* of a given observation has been considered to be the maximum permitted in the Regulations (Parks Canada, 2002), which is 60 minutes. However, the variability of the observation duration should be understood by studying this specific decision problem in order to improve the whale-watching model.

Whatever the decision problem, the duration of an observation is expected to depend on several contextual factors such as:

- Whale context factors: the availability of other whales in the vicinity, abundance and distribution of species.
- Excursion factors: the remaining time in the excursion, species and size of the pods observed so far in the excursion, products (additional activities such as coastal tours) sold to onboard tourists.
- Observation site factors: the number of boats observing the same pod, the attractiveness of the targeted pod.
- Captain related factors: experience, preferences, knowledge and beliefs, information available to the captain at the time of the decision.
- Weather factors: visibility, sea state.

Finally, a role-playing game (Barreteau, Bousquet and Attonaty, 2001) could be built to complete the data-driven validation made with POM (cf. CHAPTER 6) and the validation of captains' decision strategies carried out with the park warden (cf. CHAPTER 4).

Shipping model

For the shipping model, areas for improvement have been proposed in section 8.5.

Other components of the 3MTSim's boat ABM

Two components are planned to be integrated to the 3MTSim simulator to account for the great majority of motorized maritime traffic in the study area. These components are the ferry and the pleasure craft activities. Although they are not necessary to address the current management needs (cf. section 0.1.3.4), they could prove useful for future uses of the model (e.g. assessment of the underwater boat noise).

1) Ferry model: Several ferry lines are in operation throughout the study area. All the lines operate according to a preset schedule available online. The routes followed by each ferry line display very low variability (cf. APPENDIX I) and ferries tend to be given the

priority by other boats, except with cargo ships. Consequently, the modelling of ferry movements does not present particular challenges.

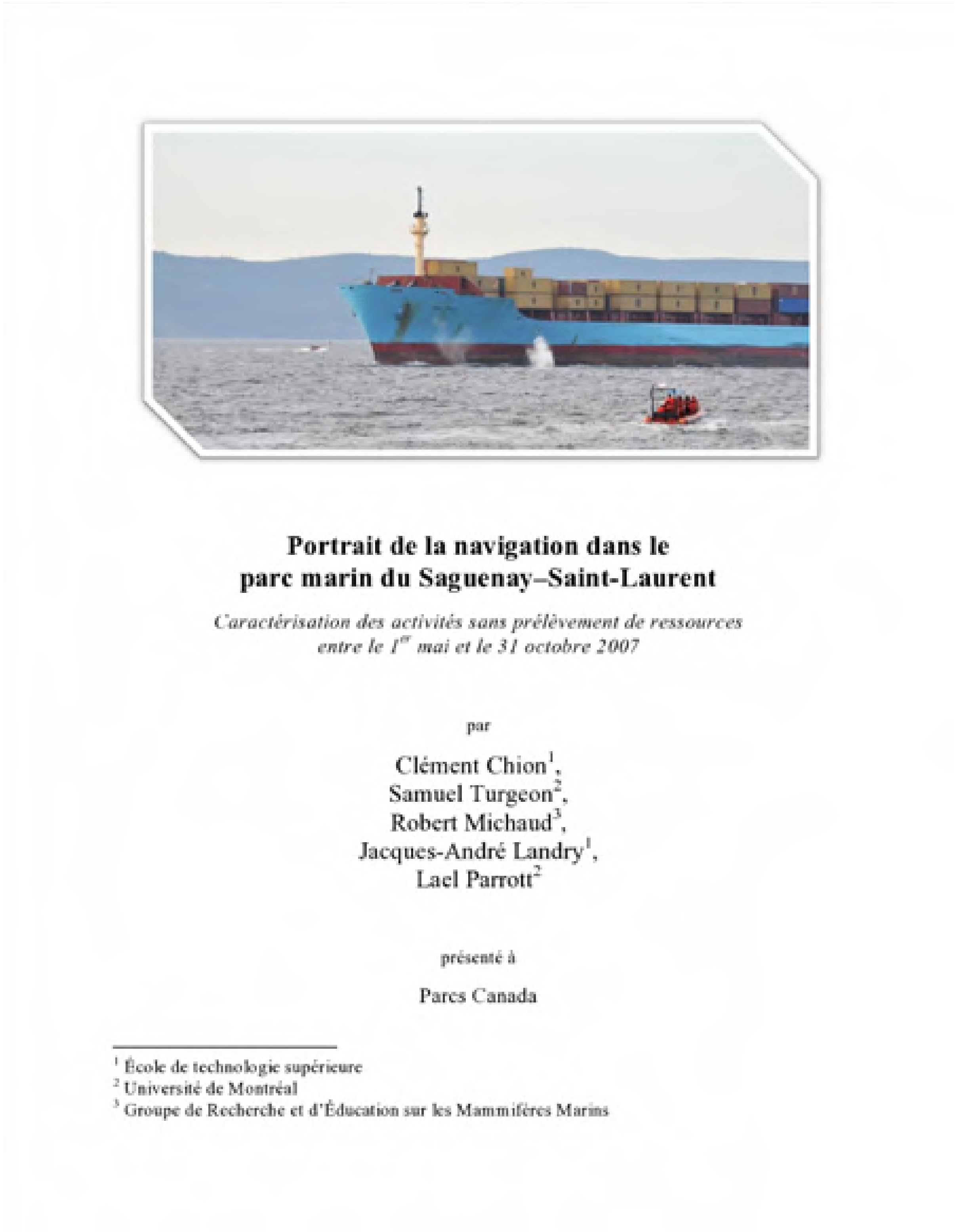
2) Pleasure craft model: Few spatiotemporal trajectories (26) of pleasure crafts are available in the SSLMP but they appeared to represent fairly well the characteristics of pleasure trips revealed by 186 questionnaires filled out by boaters (cf. APPENDIX I). In the SSLMP, yachting activities are mainly concentrated within the Saguenay River (72% of the total time at sea), and in the Upper Estuary of the St. Lawrence (24% of time). Yachting activities appear to be marginal in the SLEMPA. Additional knowledge should be gained on boaters' motivations and behaviours in order to build an accurate model of this component that could be useful for further possible management needs.

Finally, the case of pilot boats (used to transport pilots between land and ships they are piloting) has been left aside in most modelling discussions. However, in the area offshore Les Escoumins, which is one of the busiest in terms of traffic density (cf. APPENDIX I), they account for a significant part of total movements. In this sensitive area where several whale species congregate (including the endangered blue whale), their contribution to overall disturbance and risk of collisions with whales should not be overlooked.

APPENDIX I

PORTRAIT DE LA NAVIGATION DANS LE PARC MARIN DU SAGUENAY–SAINT-LAURENT—CARACTÉRISATION DES ACTIVITÉS SANS PRÉLÈVEMENT DE RESSOURCES ENTRE LE 1ER MAI ET LE 31 OCTOBRE 2007

An Acrobat PDF version of this report with all colour figures is available online via the following hyperlink (date of last access, February 20, 2011): http://www.geog.umontreal.ca/syscomplex/docs/Rapport%20sur%20le%20trafic%20maritime%20dans%20le%20PMSSL%20en%202007_Chion%20et%20al_version%20finale.pdf



Portrait de la navigation dans le parc marin du Saguenay–Saint-Laurent

Caractérisation des activités sans prélèvement de ressources entre le 1er mai et le 31 octobre 2007

par

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présenté à

Parcs Canada

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Cristiane C. Albuquerque Martins (U. de Montréal), Guy Cantin (MPO), Manuela Conversano (ISMER), Suzan Dionne (Parcs Canada), Benoit Dubeau (Parcs Canada), Luc Foisy (Consultant), Daniel Gosselin (Parcs Canada), Pierre Grégoire (CPBSL), Marie-Claude Martel (MPO), Nadia Ménard (Parcs Canada), Michel Moisan (GREMM). L'équipe du GREMM. La Garde côtière canadienne. SCTM Les Escoumins.

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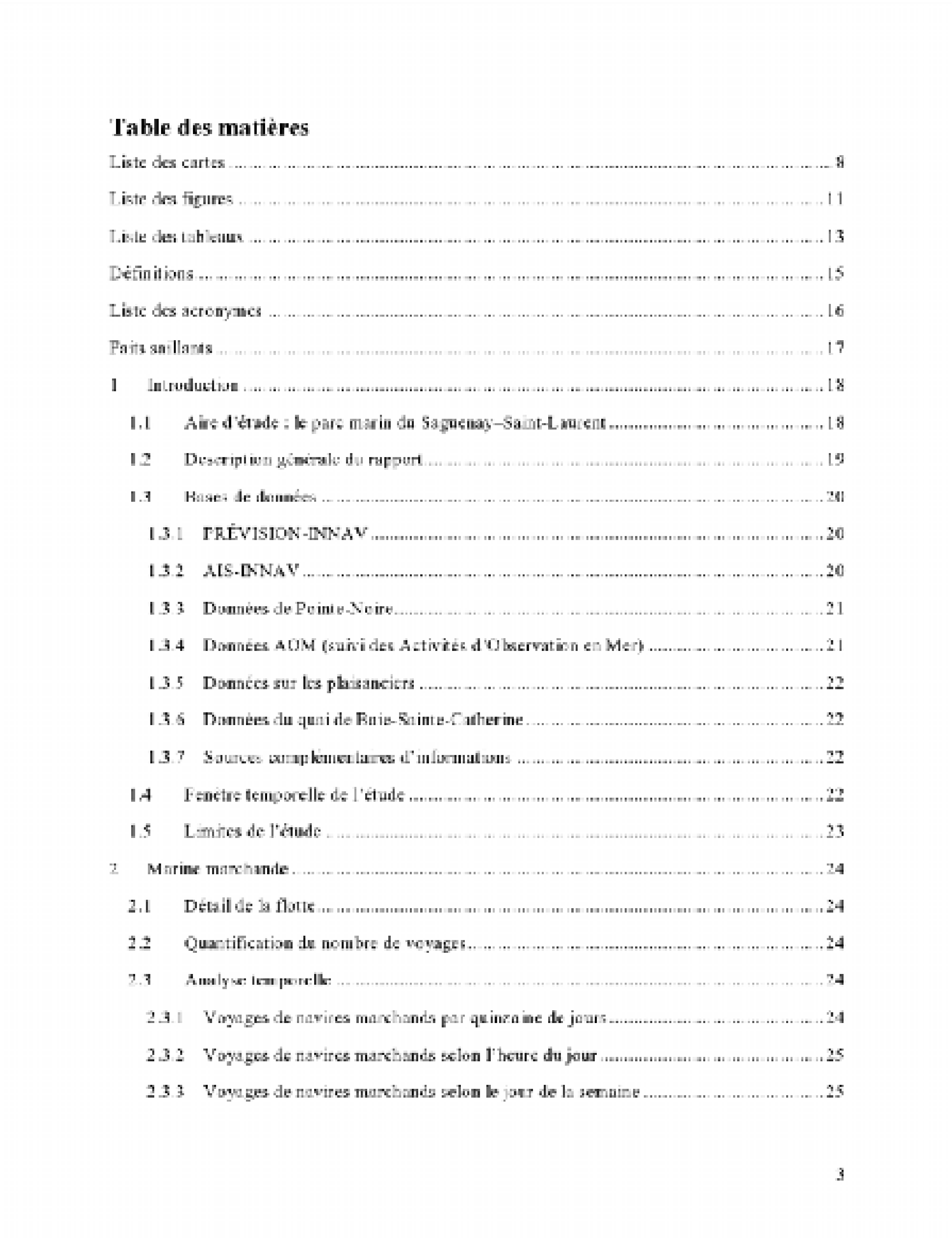

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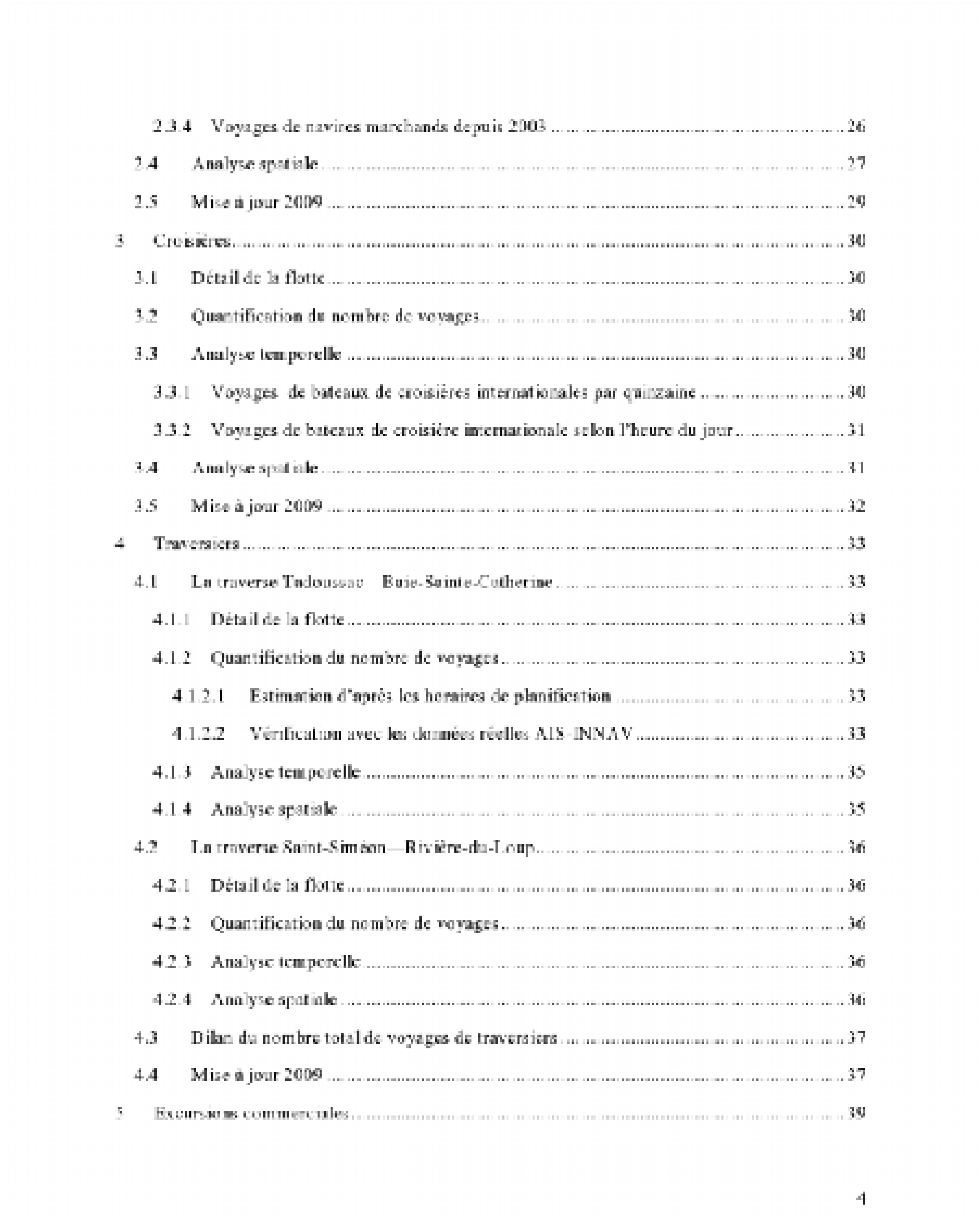

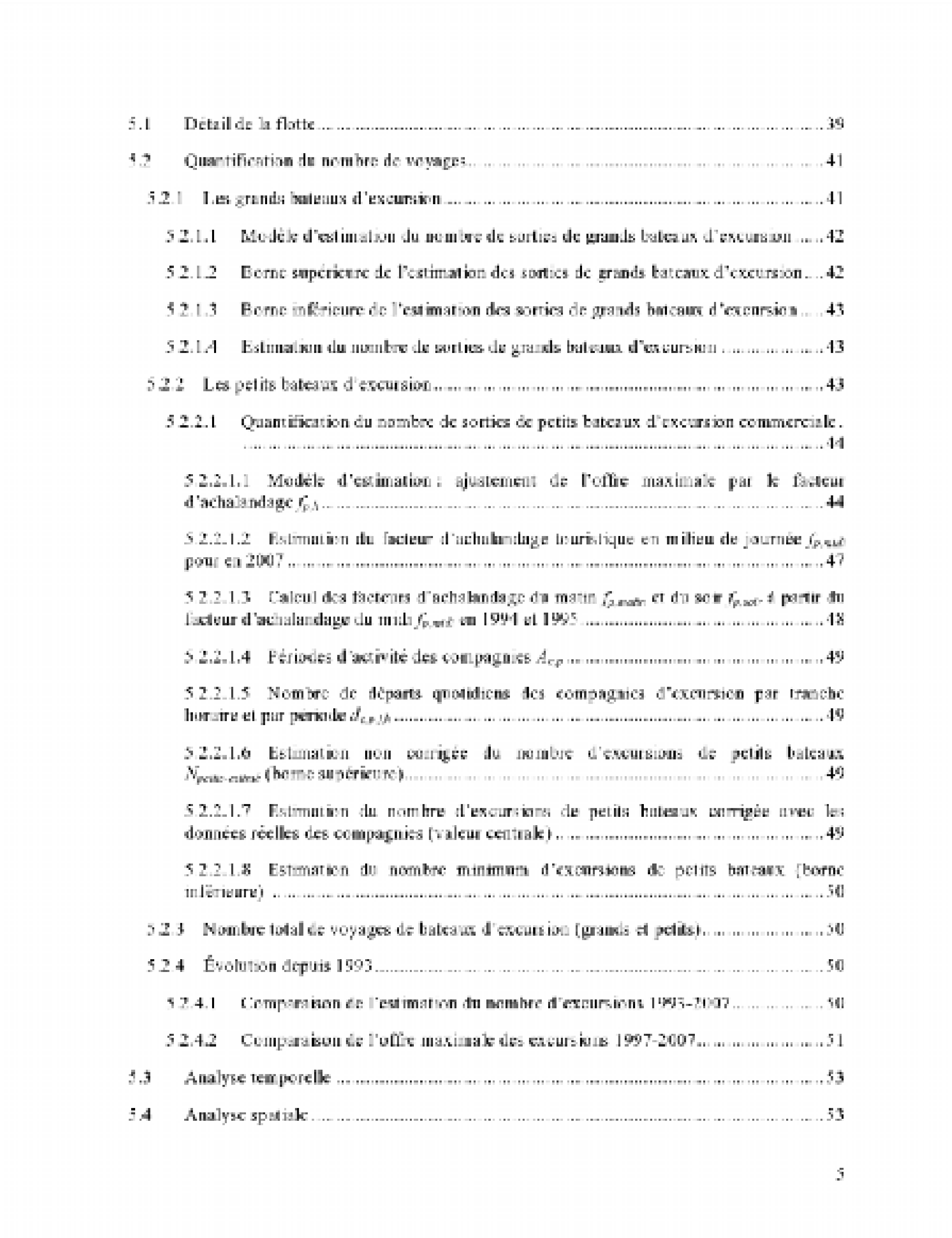

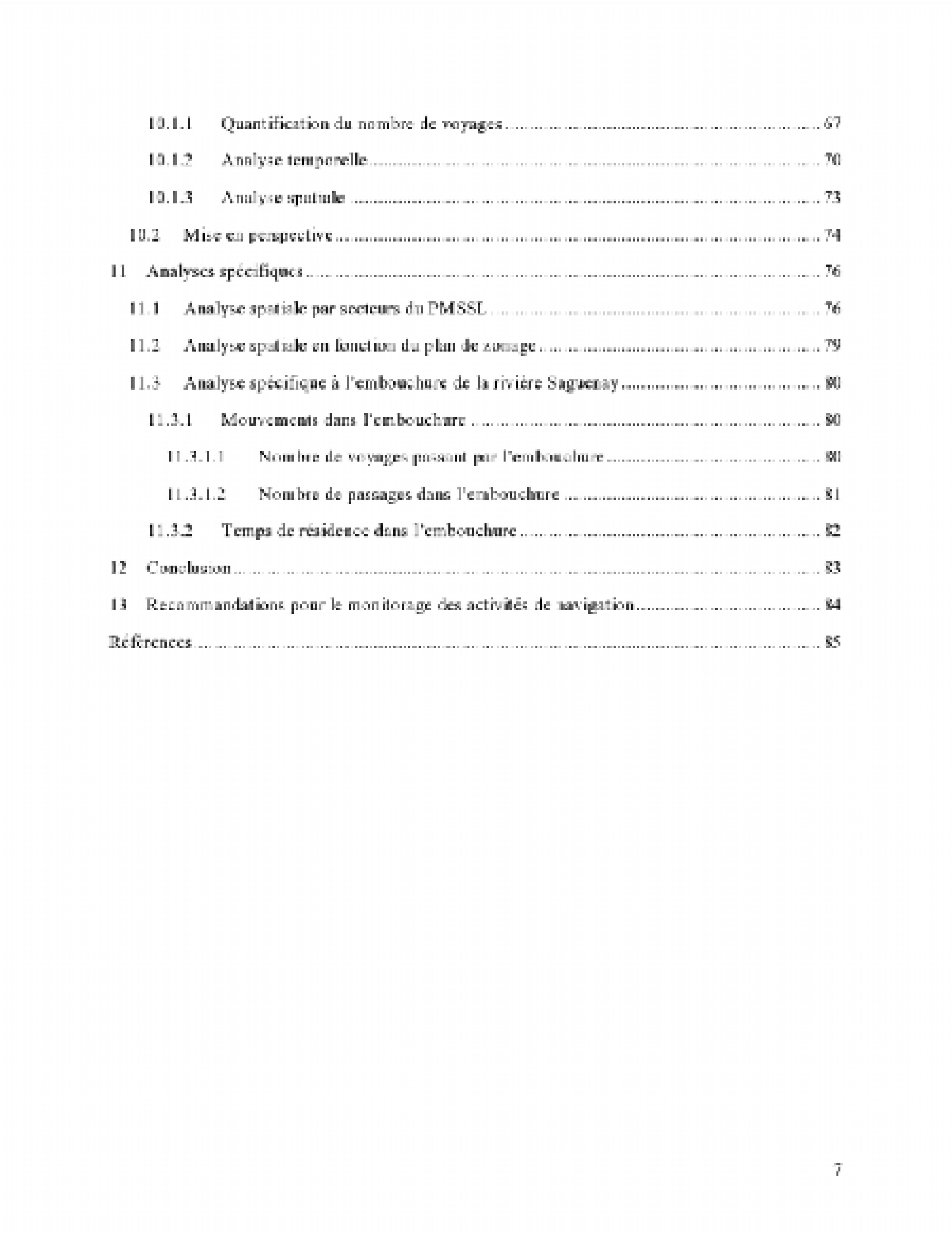

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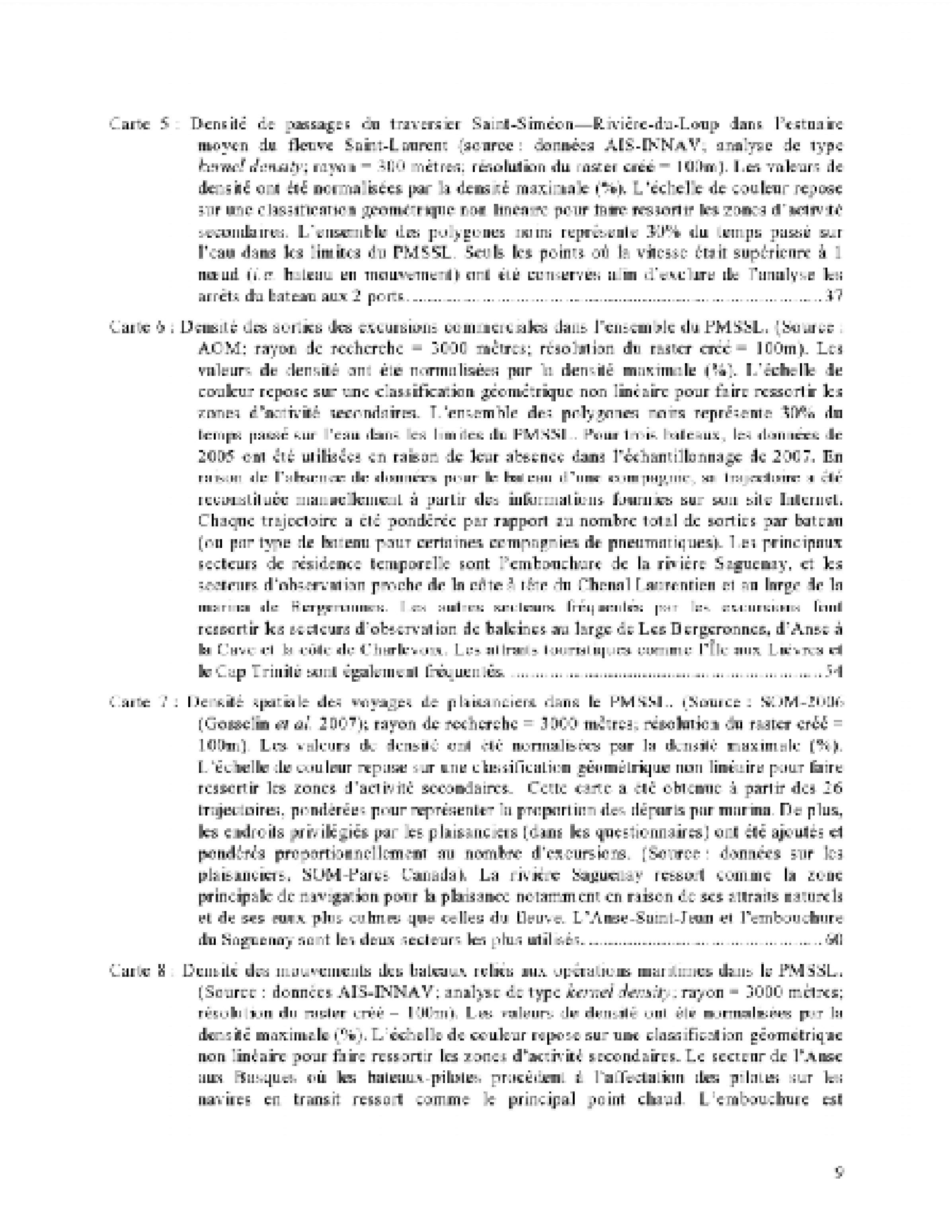

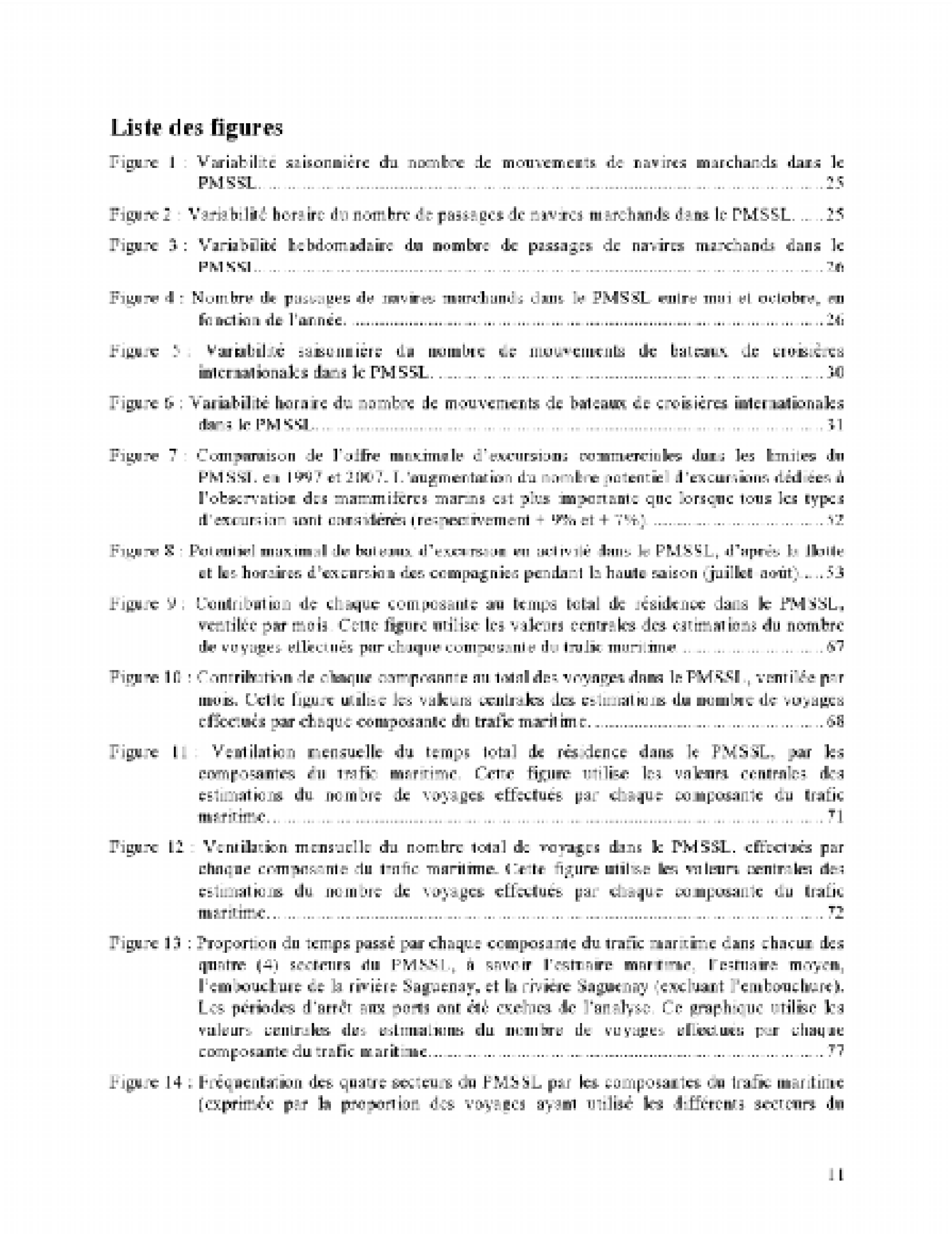

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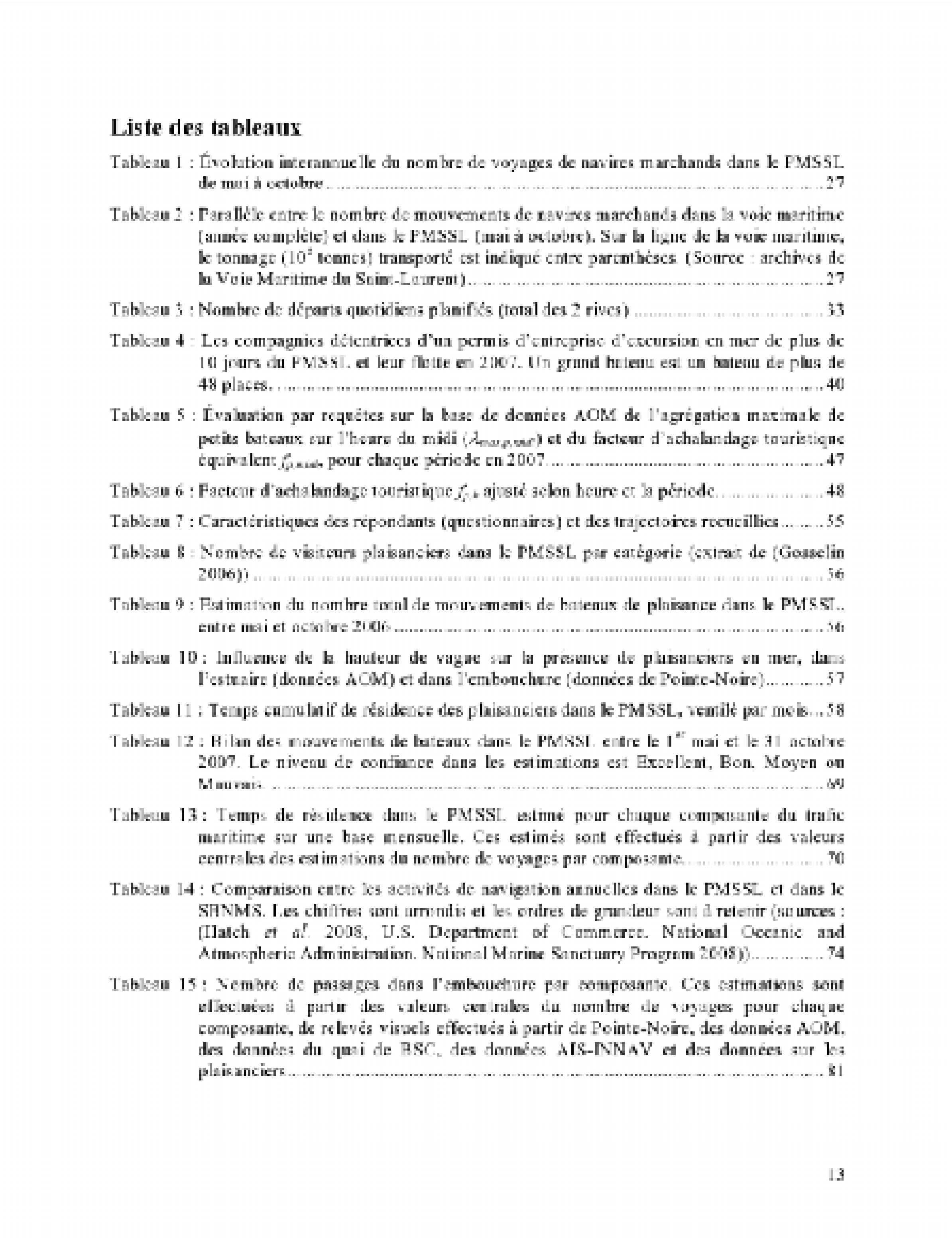

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Définitions

Croisière : par opposition à l'*excursion*, au cours d'une *croisière* les passagers vont passer au moins une (1) nuit à bord du bateau.

Embouchure : le terme « embouchure » désigne l'embouchure de la rivière Saguenay, telle que définie par la Carte 11.

Excursion : une *excursion* fait référence à une sortie en mer effectuée à bord d'un bateau exploité par une compagnie commerciale. Dans le PMSSL, seules les compagnies détentrices d'un permis délivré par Parcs Canada ont le droit d'effectuer des *excursions* commerciales. La distinction entre une *excursion* et une *croisière* est la durée de la sortie : à l'instar d'une *croisière*, lors d'une *excursion*, les clients ne passent aucune nuitée à bord du bateau.

Mouvement, Sortie, Voyage : désigne l'ensemble des activités d'un bateau en mer entre deux arrêts successifs à un port, une marina ou plus généralement un quai (excluant les zones d'ancrage). Dans le cas des *excursions* commerciales, une *excursion* est comptabilisée comme un seul mouvement par convention, y compris pour les *sorties* en mer qui desservent plusieurs ports. Ce choix a été effectué puisque c'est de cette façon que sont compilées les données des compagnies d'*excursions* pour quantifier leurs *sorties* en mer; de plus, la majorité des *excursions* ne dessert qu'un seul port.

Les termes *mouvement*, *sortie* et *voyage* sont employés indifféremment dans le rapport. Il ne faut toutefois pas les confondre avec le terme *passage* qui désigne une autre notion (*cf.* définition).

Offre maximale : pour une compagnie offrant des excursions commerciales, ce terme désigne (dans ce rapport) le nombre maximal de départs de bateaux pour une période donnée. Pour une compagnie et une période données, l'*offre maximale* est obtenue en multipliant le nombre de départs prévus à l'horaire par la taille de la flotte active.

Passage : un *passage* dans un secteur correspond à une incursion du bateau dans ce secteur donné du PMSSL. Au cours d'un même *voyage*, un bateau peut effectuer plusieurs incursions dans un secteur donné, ce qui sera alors comptabilisé comme autant de *passages* dans ce secteur. Pour le secteur enclavé de l'embouchure du Saguenay, la notion de *passage* apporte une information supplémentaire à la notion de *voyage*, en ce sens qu'elle permet de dénombrer les utilisations de ce secteur.

Sortie : *cf.* définition de *Mouvement*.

Temps de mer, temps de navigation, temps de résidence : ces termes désignent la durée du *mouvement* d'un bateau en activité de navigation ou à l'ancrage.

Voyage : *cf.* définition de *Mouvement*.

Liste des acronymes

AIS :	Automatic Identification System.
AOM :	Activités d'Observation en Mer.
CPBSL :	Corporation des Pilotes du Bas Saint-Laurent.
GCC :	Garde Côtière Canadienne.
GPS :	Global Positionning System (Système de Positionnement Global, SPG).
GREMM :	Groupe de Recherche et d'Éducation sur les Mammifères Marins.
INNAV :	système d'INformation sur la NAVigation maritime.
ISMER :	Institut des Sciences de la MER.
MPO :	Ministère des Pêches et des Océans du Canada.
OM :	Offre Maximale.
ONG :	Organisation Non-Gouvernementale.
PMSSL :	Parc Marin du Saguenay–Saint-Laurent.
SBNMS :	Stellwagen Bank National Marine Sanctuary.
SCTM :	Services de Communications et de Trafic Maritimes.
SÉPAQ :	Société des Établissements de Plein Air du Québec.
ULCC :	« Ultra Large Crude Carrier » (ultra gros porteur). Désigne les navires pétroliers d'une contenance de 350 000 tonnes et plus.
VLCC :	« Very Large Crude Carrier » (très gros porteur). Désigne les navires pétroliers d'une contenance de 200 000 tonnes et plus.

Faits saillants

Sauf autre mention, tous les chiffres sont donnés pour le PMSSL pour la période du 1er mai au 31 octobre 2007. De même, les chiffres ci-dessous sont les valeurs centrales estimées ou les décomptes.

- Le nombre de voyages de bateaux dans le PMSSL est estimé à **51 796 ± 11%** (section 10).
  - Les traversiers font le plus grand nombre de voyages avec **22 541** (section 4).
  - Les excursions sont la deuxième composante avec **13 073** sorties (section 5).
  - **24.8%** des voyages ont eu lieu au mois d'août (section 10).
- Le temps total de résidence associé à la navigation est estimé à partir de la valeur centrale du nombre de voyages à **88 149 heures** (section 10).
  - Les plaisanciers passent le plus de temps sur l'eau avec **38 871 heures** (section 6).
  - Les excursions sont la deuxième composante avec **32 129 heures** (section 10).
  - **31.8%** du temps de navigation a eu lieu au mois d'août (section 10).
- Les aires d'utilisation intensives sont l'embouchure, la tête du Chenal Laurentien, les abords du quai des pilotes (Les Escoumins) et le secteur de l'Anse-Saint-Jean (Carte 10).
- L'embouchure supporte **13.24%** du temps total de résidence dans le PMSSL pour une superficie de **1.09%** du parc (section 11).
  - **51%** du temps de résidence dans l'embouchure est attribuable aux excursions.
  - Les traversiers comptent pour **25%** du temps de résidence dans l'embouchure.
- Le nombre total de passages dans l'embouchure est **48 902** (section 11).
  - Les excursions comptent pour **21 348 passages** dans l'embouchure.
  - Le traversier Baie-Sainte-Catherine/Tadoussac suit avec **21 247**.
  - Les deux axes de transits les plus utilisés dans l'embouchure sont quai de l'Anse du Portage/quai de l'Anse à l'Eau (**21 247**) et Saguenay/Estuaire (7331).
- Les excursions sont la principale composante utilisant les zones de niveau 1 définies dans le plan de zonage 2008 du PMSSL (section 11.2).

1 Introduction

1.1 Aire d'étude : le parc marin du Saguenay–Saint-Laurent

Le parc marin du Saguenay–Saint-Laurent (PMSSL) s'étend sur environ 1245 km² jusqu'à la ligne des hautes marées ordinaires, incluant la colonne d'eau et les fonds marins (Gareau *et al.* 2009). Il se compose de trois écosystèmes : le Fjord du Saguenay en aval du cap de l'Est, l'estuaire moyen du Saint-Laurent à partir de Gros cap à l'Aigle en amont et l'estuaire maritime jusqu'à la pointe Rouge (Les Escoumins) en aval (cf. Carte 1).

Carte 1 : Parc marin du Saguenay–Saint-Laurent (PMSSL)

Faisant suite à une prise de conscience collective de la pression exercée par les activités humaines sur les écosystèmes marins incluant jusqu'à 13 espèces de mammifères marins, avec l'appui des acteurs socio-économiques de la région, les gouvernements du Canada (Agence Parcs Canada) et du Québec (Ministère du développement durable, de l'environnement et des parcs) ont créé le PMSSL en 1998. Pour accroître le niveau de protection des mammifères marins résidents ou migrateurs dont certaines espèces comme le béluga du Saint-Laurent, le rorqual bleu ou encore le rorqual commun ont des statuts critiques (Savaria *et al.* 2003, COSEWIC 2005), le PMSSL s'est doté en 2002 d'un règlement sur les activités d'observation en mer (Règlement sur les activités en mer dans le parc marin du Saguenay–Saint-Laurent 2002) visant à réduire la pression sur ces populations.

Suivant les principes de la gestion adaptative, le PMSSL entre dans un processus d'élaboration d'un plan de gestion et de révision de la réglementation des activités en mer (Règlement sur les activités en mer dans le parc marin du Saguenay Saint-Laurent 2002); l'aboutissement de ce processus est prévu pour 2010. Le plan de gestion doit être basé sur les meilleures connaissances existantes sur les activités en mer. Le rapport sur l'état du parc marin en 2007 mentionnait un manque de connaissance sur les activités de navigation (Ménard *et al.* 2007). L'objectif du présent rapport est précisément de caractériser les *activités sans prélèvement de ressources*, incluant toutes les activités de navigation à l'exception de la pêche (*activité avec prélèvement de ressources*).

Le contenu de ce rapport est présenté ci-dessous.

1.2 Description générale du rapport

Ce document présente le portrait des activités de navigation dans le PMSSL pour la période allant du **1er mai au 31 octobre 2007**. Cette caractérisation repose sur quatre types d'analyses distinctes :

1. **Détail de la flotte :** description de la flotte à laquelle les analyses se rapportent.
2. **Quantification :** décompte ou estimation du nombre de mouvements de bateaux dans le PMSSL. Lorsqu'il s'agit d'un décompte (base de données complète ou données des opérateurs), aucune marge d'erreur n'est proposée. Lorsqu'il s'agit d'une quantification issue d'un modèle d'estimation, une marge d'erreur est calculée.
3. **Analyse temporelle :** identification de la variabilité temporelle des activités sur plusieurs échelles de temps (heure du jour, jour de la semaine, mois de l'année). Lorsque pertinent, le temps total de navigation est également présenté.
4. **Analyse spatiale :** distribution spatiale des activités, identification des zones d'utilisation intensive dans le PMSSL et des secteurs majeurs de résidence;

Pour ces analyses, le trafic maritime dans le PMSSL est désagrégé en huit classes distinctes :

1. Marine marchande;
2. Navires de croisières nationales et internationales;
3. Traversiers;
4. Bateaux d'excursion commerciale;
5. Bateaux de services (bateaux de ministères ou d'agences gouvernementales, bateaux d'organisme de service spécial-OSS-, bateaux de recherche…);
6. Plaisanciers;
7. Kayaks;
8. Autres (e.g. navires militaires, yachts de grande taille).

Les analyses ont été faites sur la base de l'année 2007, année pour laquelle les données disponibles sont les plus complètes. Lorsqu'indisponibles pour 2007, des données d'autres années rapprochées ont pu être exceptionnellement utilisées. Une brève mise à jour pour 2009 est proposée pour chacune des composantes lorsque de l'information pertinente est disponible.

Chacune de ces composantes est caractérisée individuellement selon la disponibilité des données la concernant. Ces analyses individuelles sont ensuite regroupées pour dresser le portrait global des activités de navigation dans le parc. Par la suite, la navigation dans le PMSSL est comparée avec celle dans le Sanctuaire Marin de Stellwagen Bank (Massachusetts, États-Unis) pour mettre en perspective la situation du PMSSL à ce chapitre dans le contexte des aires marines protégées. Des études spécifiques plus fines terminent nos analyses; elles visent à mettre en relief les enjeux de gestion dans des secteurs critiques du PMSSL comme l'embouchure du Saguenay. Pour finir, une série de recommandations est proposée ayant pour but de faciliter le monitorage des activités de navigation dans le PMSSL dans les années à venir.

1.3 Bases de données

1.3.1 PRÉVISION-INNAV

Ces données proviennent du système INNAV de la Garde côtière canadienne (GCC). Il s'agit de données de prévision et non de données historiques effectives. La GCC a établi un réseau de points de contrôle (maillage) dans les eaux canadiennes incluant le PMSSL; selon la trajectoire prévue d'un voyage dans les eaux canadiennes (pour tous les bateaux de 20 mètres et plus), une série de points de contrôle lui est associée; un ensemble de caractéristiques du voyage est attaché à chaque point de contrôle associé à la trajectoire prévue (*e.g.* heure de passage prévue à ce point de contrôle, nom du bateau, type de bateau, année de construction, port d'attache…). Tous les navires requérant le service d'un ou plusieurs pilotes de la Corporation de Pilotage du Bas Saint-Laurent (CPBSL) doivent s'annoncer au centre de communication des Escoumins, service de communications et trafic maritimes (SCTM), 24 h, 12 h et 6 h avant l'arrivée au quai des pilotes des Escoumins. D'une façon générale, les navires canadiens de plus de 80 mètres ayant une jauge brute de plus de 3300 tonneaux et les navires étrangers de plus de 35 mètres sont soumis au pilotage obligatoire à partir des Escoumins, en remontant le fleuve ainsi que dans la rivière Saguenay. À ces navires s'ajoutent les barges et les gabarres canadiennes qui transportent des produits polluants. Pour les exceptions, se référer au Règlement de l'Administration de pilotage des Laurentides (Règlement de l'Administration de pilotage des Laurentides 1985).

Il faut noter que certains bateaux de plus de 20 mètres qui font des sorties sur une base régulière dans le PMSSL ne se rapportent pas de façon systématique au SCTM (*e.g.* grands bateaux d'excursion de Tadoussac). Ainsi, cette base de données ne peut pas être utilisée seule pour dénombrer de façon exhaustive les mouvements effectués par de tels bateaux.

1.3.2 AIS-INNAV

Depuis le 10 mai 2005, Transport Canada a rendu obligatoire le système automatique d'identification (AIS : Automatic Identification System) pour les bateaux de 500 tonnes et plus (autres que les bateaux de pêche) construits après le 1er juillet 2002, non-engagés dans un voyage international, navigant dans les eaux canadiennes. Depuis le 1er juillet 2008, la restriction sur la date de construction du bateau ne s'applique plus. Par ailleurs, les bateaux impliqués dans des voyages internationaux de plus de 150 tonnes ou transportant plus de 12 passagers, ainsi que ceux (autre que les bateaux de pêche) de 300 tonnes ou plus doivent être équipés du système AIS (Transport Canada 2007).

Le système AIS permet la transmission automatique, toutes les minutes, des informations du bateau en route (identité, type, position, vitesse, cap, etc.). Cette transmission s'effectue par ondes VHF et est destinée aux autres navires et autres stations terrestres à proximité. Le centre INNAV capte et stocke ces données dans une base de données.

La base de données AIS-INNAV contient donc des données relatives aux bateaux décrits au début de ce paragraphe, pour les mois de mars à décembre 2007, couvrant donc la période d'intérêt de cette étude. Les informations ci-dessus indiquent que cette base de données n'est pas exhaustive et ne permet donc pas le dénombrement direct du nombre de mouvements. De plus, quelques dysfonctionnements ponctuels lors de l'enregistrement/sauvegarde de ces données ne permettent pas de les utiliser à de telles fins (communication personnelle, D.-A. Delisle, Garde côtière canadienne). Toutefois, cette base de données fournit de l'information spatiale précise sur l'utilisation du territoire. Compte tenu du fait que le manque de données dues aux erreurs durant le processus d'enregistrement/sauvegarde est occasionnel (certaines zones spatiales, certaines périodes temporelles), la représentativité des données pour caractériser l'utilisation du territoire est excellente pour de nombreux types de bateaux. En effet, pour les types de bateaux de la marine marchande et ceux des croisières internationales, le pourcentage des voyages figurant dans la base PRÉVISION-INNAV et dans AIS-INNAV pour la période considérée dépasse 95%. Pour d'autres types comme les bateaux d'excursion, les données AIS ne permettent pas de dresser un portrait précis de l'utilisation du territoire du PMSSL puisque très peu sont équipés du système AIS. De plus, en 2007, les bateaux d'excursion ne se rapportaient pas de façon systématique au SCTM Escoumins, ce qui implique une apparition irrégulière de leurs voyages dans la base PRÉVISION-INNAV, ne permettant pas leur analyse à partir de cette base de données.

1.3.3 Données de Pointe-Noire

Depuis 1998, un observateur effectue des relevés sur la présence des bateaux et des bélugas dans l'embouchure du Saguenay au moyen d'un ensemble trépied–tête–socle–jumelle, à partir du site de Pointe-Noire dans la municipalité de Baie-Sainte-Catherine, Charlevoix. En 2007, l'observatrice était Manuela Conversano, étudiante à la maîtrise en océanographie à l'Institut de la Mer, Rimouski sous la direction du Pr Yvan Simard, supervisée par Mme Nadia Ménard (Parcs Canada). Les relevés systématiques concernent principalement le dénombrement et la localisation de bélugas, ceux d'espèces de rorquals ainsi que ceux de tout le trafic maritime dans l'embouchure de la rivière Saguenay. La période couverte par ces données s'étend de fin juin à fin août 2007. Ainsi, pour cette période, il est possible d'obtenir de l'information complémentaire sur la fréquentation de ce secteur critique du PMSSL par les différents types de bateaux. Ce projet est financé par Parcs Canada. En 2009, des données plus détaillées sur les mouvements des bateaux d'excursion commerciale ont été recueillies.

1.3.4 Données AOM (suivi des Activités d'Observation en Mer)

Depuis 1984, le Groupe de Recherche et d'Éducation sur les Mammifères Marins (GREMM) en collaboration avec Parcs Canada procède à une campagne de collecte de données destinée à caractériser les activités d'observation en mer (AOM) dans le PMSSL. Chaque été, des techniciens échantillonnent les activités des bateaux d'excursion dans le PMSSL et notent leurs activités toutes les 10 minutes (*e.g.* espèces observées, densité du trafic maritime) (Michaud *et al.* 2008). Depuis 2005, la trajectoire de ces bateaux d'excursion est également enregistrée au moyen d'un GPS portatif. Les données récoltées nous renseignent sur les activités des bateaux d'excursion et nous permettent d'élaborer un modèle d'estimation du nombre d'excursions commerciales effectuées à bord de petites embarcations, tel que détaillé dans la section relative à ces activités. Ce projet est financé par Parcs Canada et le MPO.

La période d'échantillonnage pour la saison 2007 s'étend du 17 juin au 29 septembre 2007.

1.3.5 Données sur les plaisanciers

En 2006, M. Daniel Gosselin (Parcs Canada) a effectué un travail de recensement des activités de plaisance au sein des marinas d'importance bordant le PMSSL. Environ 30 trajectoires de plaisanciers ont pu ainsi être enregistrées et plus de 150 questionnaires ont été remplis par les plaisanciers, caractérisant le type d'utilisateur du PMSSL et identifiant leurs habitudes, attentes, connaissances et degrés de satisfaction. Les données couvrent la totalité de notre période d'intérêt. Cette étude a été réalisée par la firme SOM et financée par l'agence Parcs Canada.

1.3.6 Données du quai de Baie-Sainte-Catherine

Des agents de Parcs Canada ont compilé les données de tous les mouvements de bateaux d'excursion commerciale effectués au quai de Baie-Sainte-Catherine, de mai à septembre 2007.

1.3.7 Sources complémentaires d'informations

Toutes les sources d'informations jugées pertinentes sont utilisées pour corriger, raffiner les informations extraites des différentes bases de données. Il s'agit de documentations mises à disposition par les compagnies d'excursion, les horaires des traversiers, les différents sites Internet des compagnies ou encore les communications personnelles recueillies auprès de personnes-ressources et d'experts (*e.g.* Parcs Canada, Garde côtière canadienne). Ces sources sont brièvement détaillées lorsqu'elles sont utilisées dans les analyses suivantes. Plusieurs techniciens et observateurs réguliers du trafic maritime du secteur ont également été consultés pour valider des hypothèses et confirmer la validité de certains résultats du rapport.

1.4 Fenêtre temporelle de l'étude

La période considérée s'étend du **1er mai au 31 octobre 2007**. C'est au cours de cette période que les activités de navigation culminent (en termes de mouvements) dans le secteur du parc marin du Saguenay–Saint-Laurent. Les raisons principales pour le choix de cette période sont :

- L'année 2007 est l'année récente pour laquelle le volume de données sur la navigation est maximal;

- Les activités de navigation atteignent leur maximum dans le PMSSL entre le **1er mai et le 31 octobre** en raison de l'affluence touristique dans la région;

L'année 2007 et particulièrement la fenêtre de six mois choisie (mai à octobre) servira donc de référence pour l'élaboration du plan de gestion des activités en mer du PMSSL (communication personnelle, *Comité de travail pour la révision du plan de gestion des activités en mer dans le PMSSL, 25 septembre 2008*).

1.5 Limites de l'étude

Pour diverses raisons, les données réelles exhaustives concernant certaines composantes du trafic maritime dans le PMSSL n'ont pu être obtenues. Pour ces composantes, des modèles d'estimation ont dû être développés dans cette étude (excursions commerciales) ou dans d'autres études (plaisanciers, (Gosselin *et al.* 2007)). Le modèle développé pour les excursions commerciales a pu être calibré et validé au moyen de bases de données présentées précédemment et de données transmises par des compagnies.

Afin d'assurer la confidentialité des estimations du nombre de départs des compagnies d'excursion commerciale, aucun détail (autres que ceux accessibles par le grand public) ne sera fourni permettant d'associer un nombre de départs à une compagnie précise. Les compagnies nous ayant transmis leurs données ne seront pas nommées et les estimations du nombre de départs d'excursion effectués ne seront présentées que dans leur globalité (*i.e.* pas de ventilation par port ni par compagnie). Le but de cette étude étant de caractériser les activités de navigation dans le PMSSL par composante puis dans leur globalité, cette approche est justifiée.

L'analyse des kayaks présentée dans ce rapport est très limitée et reflète la disponibilité des données pour cette composante de la navigation. Cette analyse ne faisait pas partie de l'étude initialement (limitée à la navigation à moteur et à voile), ce qui explique le faible effort consenti à l'obtention de données sur ces activités. Les kayaks sont donc exclus du bilan global et des analyses spécifiques.

Concernant les bateaux de pêche commerciale ou récréative, ces activités faisant partie des *activités avec prélèvement de ressources*, elles ont été exclues des analyses. Les déplacements dans le PMSSL associés à ces activités sont marginaux et leur absence n'altère évidemment pas les résultats de la présente étude de façon significative.

2 Marine marchande

2.1 Détail de la flotte

Dans cette catégorie se trouvent tous les navires marchands à l'exception des navires transportant des passagers (croisières, excursions et traversiers). Les catégories de navires prises en considération dans cette composante sont :

- **Barge** (de produits chimiques, généraliste, de forage, de produits pétroliers, en remorque et autopropulsée);
- **Citerne** (de pétrole brut, gazoline, de produits chimiques, mélasses, de minerai/vrac/pétrole, de gaz liquéfié, « super tanker », marchand, ULCC, VLCC, d'eau);
- **Marchand** (vraquier/généraliste, porte-conteneurs, roulier, à attaches, transporteur de marchandise sèche, minerai, réfrigéré, caboteur, transporteur de véhicules, vraquier);
- **Remorqueur** (à incendie, de port, de mer, d'approvisionnement, général, de travail);

Au total, ce sont plus de 650 navires distincts dans cette catégorie qui avaient un voyage prévu dans le PMSSL entre le 1er mai et le 31 octobre 2007. Chaque année, 25% de nouveaux navires (c'est-à-dire jamais vus auparavant dans l'estuaire du Saint-Laurent) effectuent des voyages dans le secteur.

2.2 Quantification du nombre de voyages

Le décompte des voyages est fait à partir des données de PRÉVISION-INNAV. La confiance dans ce décompte du nombre de voyages des navires marchands est excellent compte tenu de la fiabilité de cette base de données. Le type de bateau est clairement identifié par un champ dans PRÉVISION-INNAV. En effectuant une requête spatiale (*i.e.* tous les voyages de navires qui ont au moins un point de passage prévu dans le PMSSL) et temporelle (pour la période allant du 1er mai au 31 octobre), il est possible d'isoler les voyages qui nous intéressent. Pour l'ensemble des types de navires considérés, le nombre de voyages enregistrés dans la base PRÉVISION-INNAV est **3135**. Ce nombre correspond toutefois à un minimum, compte tenu de l'absence possible de certains voyages dans la base de données. En raison de l'absence d'autres informations et de la fiabilité de la base de données, aucune marge d'erreur n'est associée au nombre de voyages reporté dans le Tableau 12.

Il y a donc **3135** voyages de navires marchands qui ont transité dans le PMSSL entre mai et octobre 2007.

2.3 Analyse temporelle

2.3.1 Voyages de navires marchands par quinzaine de jours

La répartition des voyages de navires dans le PMSSL pendant la période d'intérêt est relativement constante tel qu'illustré à la Figure 1. Le maximum est atteint entre le 15 août et le 15 septembre 2007.

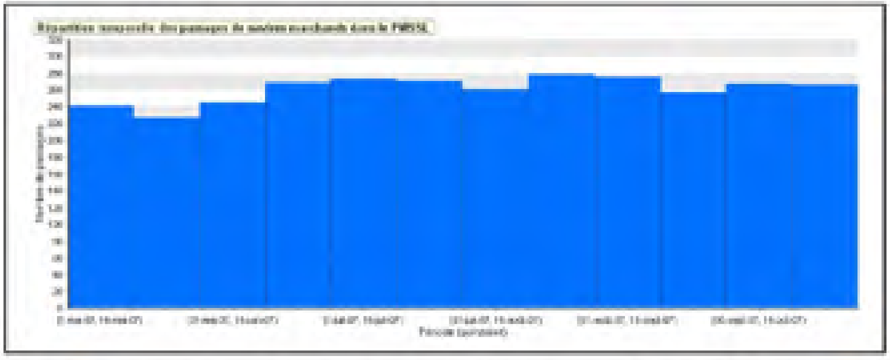

Figure 1 : Variabilité saisonnière du nombre de mouvements de navires marchands dans le PMSSL.

2.3.2 Voyages de navires marchands selon l'heure du jour

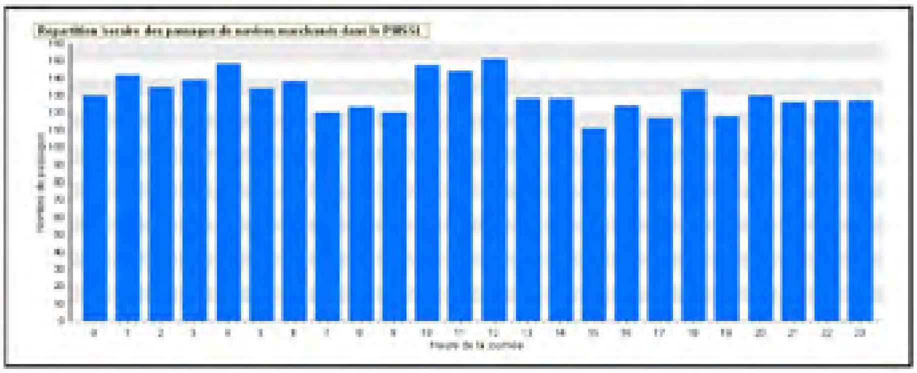

Figure 2 : Variabilité horaire du nombre de passages de navires marchands dans le PMSSL.

La distribution des voyages de navires marchands selon l'heure de la journée est relativement uniforme, comme l'indique la Figure 2. On distingue toutefois deux « crêtes d'activité » dans le PMSSL en 2007 sur les créneaux [10 h -12 h] et [1 h - 6 h].

2.3.3 Voyages de navires marchands selon le jour de la semaine

La Figure 3 indique que les voyages de navires marchands étaient plus importants le vendredi que les autres jours de la semaine, bien que la différence avec les autres jours de la semaine soit faible.

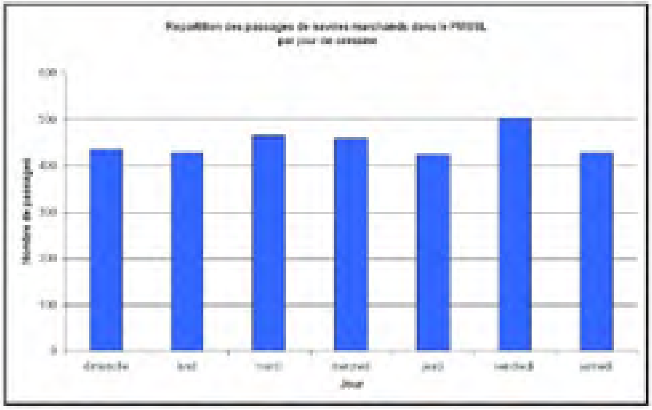

Figure 3 : Variabilité hebdomadaire du nombre de passages de navires marchands dans le PMSSL

2.3.4 Voyages de navires marchands depuis 2003

La base de données INNAV-PRÉVISION permet de faire le comparatif interannuel depuis 2003 du nombre de voyages de navires marchands dans le PMSSL.

Figure 4 : Nombre de passages de navires marchands dans le PMSSL entre mai et octobre, en fonction de l'année.

Le Tableau 1 et la Figure 4 présentent l'évolution du nombre de mouvements de navires marchands dans les limites du PMSSL. On une légère hausse (+9.2%) de 2003 à 2007 pour les six mois d'intérêt (mai à octobre) avec une stabilisation amorcée en 2006. En faisant un parallèle avec les transits de navires dans la voie maritime depuis 1999, on obtient la tendance à plus long terme présentée dans le Tableau 2. On constate que le trafic était en baisse jusqu'en 2003 avant d'amorcer la hausse notée dans la Figure 4.

Tableau 1 :
Évolution interannuelle du nombre de voyages de navires marchands dans le PMSSL de mai à octobre

Année	2003	2004	2005	2006	2007
Nombre de voyages de navires marchands	*2870*	*2885*	*3016*	*3120*	*3135*

Tableau 2 :
Parallèle entre le nombre de mouvements de navires marchands dans la voie maritime (année complète) et dans le PMSSL (mai à octobre). Sur la ligne de la voie maritime, le tonnage (10^6 tonnes) transporté est indiqué entre parenthèses. (Source : archives de la Voie Maritime du Saint-Laurent[4])

Année / Secteur	1999	2000	2001	2002	2003	2004	2005	2006	2007
Voie maritime (10^6 tonnes)	4656 (47.9)	4185 (46.6)	4085 (41.7)	3891 (41.4)	3886 (40.8)	4090 (43.5)	4361 (43.3)	4613 (47.2)	4450 (43.0)
PMSSL	?	?	?	?	*2870*	*2885*	*3016*	*3120*	*3135*

Les archives de la voie maritime nous informent également que le nombre de voyages de navires était d'environ 10 000 dans les années 1960, diminuant constamment au fil des années en lien avec l'augmentation progressive du tonnage des navires marchands. Le tonnage transporté est resté stable en dessous de la barre des 50 000 000 tonnes depuis 1989, indiquant une stagnation pour la voie maritime depuis ces années. On constate donc que de 2003 à 2007, la tendance du nombre de mouvements de navires marchands dans le PMSSL suit sensiblement la même tendance que les transits dans la Voie Maritime du Saint-Laurent. Il est donc probable que le nombre de transits dans le PMSSL ait également subi une baisse de 1999 à 2002 avant de remonter jusqu'au nombre actuel. La conclusion est que le nombre de voyages de navires marchands fluctue légèrement depuis plusieurs années, restant malgré tout en deçà des valeurs atteintes dans les années 1960. La tendance des 5 dernières années montre une légère hausse constante des mouvements dans le PMSSL.

2.4 Analyse spatiale

La Carte 2 nous renseigne sur plusieurs phénomènes relatifs au pilotage des navires dans la région. Les trajectoires des navires marchands sont très régulières; hormis les navires possédant leur propre pilote à bord, tous les navires requérant les services d'un expert de la Corporation des Pilotes du Bas Saint-Laurent (CPBSL) transitent dans la portion du PMSSL située dans l'estuaire maritime pour rallier la zone d'embarquement/débarquement située proche de l'Anse aux Basques. Les bateaux devant faire escale au port de Cacouna (Rive-Sud) évitent parfois le PMSSL. Pour tous les autres bateaux, le passage par le Chenal du Nord (traversant le PMSSL) constitue l'option la plus courte en distance (et en temps) et la plus sécuritaire puisque le Chenal Sud (extérieur au PMSSL) autrefois entretenu ne l'est plus ; il ne permet le passage que des

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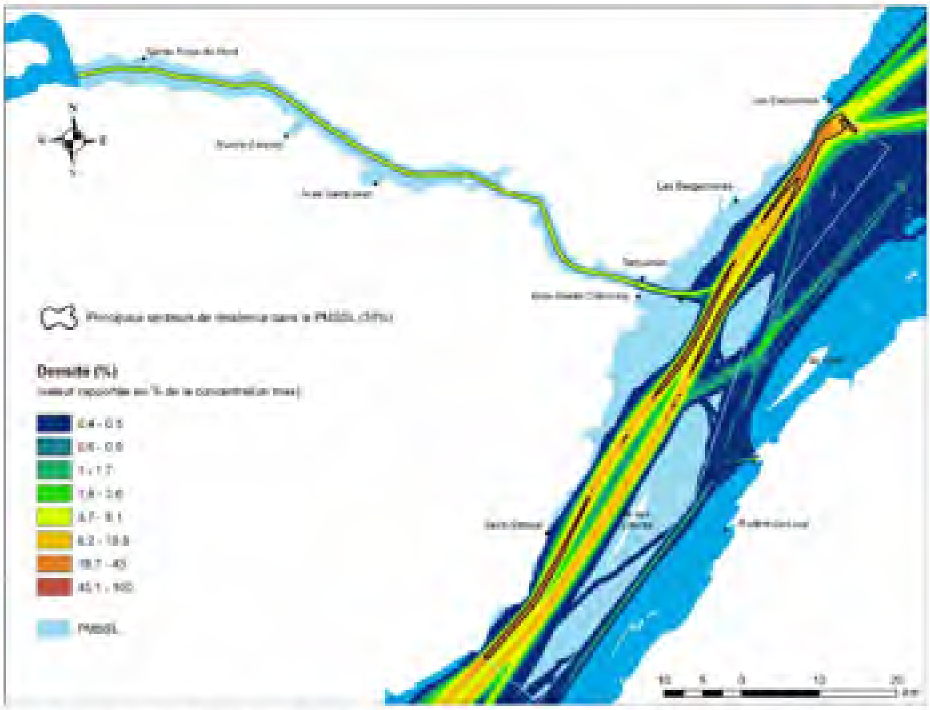
[4] http://www.greatlakes-seaway.com/fr/voie-maritime/faits/traffic/index.html

navires tirant moins de 7 mètres d'eau (communication personnelle, Pierre Grégoire, président de la CPBSL).



Carte 2 : Densité des trajectoires de navires marchands dans le PMSSL (source : données AIS-INNAV; analyse de type *kernel density*; rayon = 300 mètres; résolution du raster créé = 100m). Les valeurs de densité ont été normalisées par la densité maximale (%). L'échelle de couleur repose sur une classification géométrique non linéaire pour faire ressortir les zones d'activité secondaires. Le signal AIS des navires dans le Saguenay est perdu en amont de l'Anse-de-Roche, la station la plus proche étant à Rivière-du-Loup. La portion prolongée en amont de ce point est une trajectoire prototype reconstituée à partir des informations de la base PRÉVISION-INNAV. Les polygones noirs représentent 30% du temps passé sur l'eau dans les limites du PMSSL. Étant donnée la très grande régularité des trajectoires des navires, les secteurs de forte présence temporelle des navires (polygones) correspondent aux zones de ralentissement. Il s'agit des abords de la station de pilotage, du passage de la batture aux Alouettes et de l'extrémité Sud du PMSSL. On constate que ces secteurs sont ceux où les navires montants et descendants suivent des routes rapprochées.

Proche de l'extrémité Nord-Est du PMSSL (extérieur du parc), la zone d'ancrage des Rasades se distingue. Plusieurs facteurs peuvent inciter certains capitaines de navires à placer leur bateau à l'ancrage dans ce secteur. Les Rasades se situent à la limite externe de la zone de pilotage obligatoire et l'attente à ce site n'entraîne donc pas de coût de pilotage. Les deux raisons principales de patienter à l'ancre sont l'attente d'un quai libre au port de destination et l'attente d'une marée favorable pour le passage d'un secteur critique (*e.g.* la Traverse Nord dans le secteur de l'Île d'Orléans).

Les zones de plus forte résidence temporelle sont cerclées dans la Carte 2 par des lignes noires. Compte tenu de la régularité des routes suivies par les navires, ces zones font ressortir les secteurs de ralentissement. La zone d'embarquement/débarquement de pilotes dans le secteur de l'Anse aux Basques est une zone de ralentissement, expliquant les cercles noirs. Le contournement de la batture aux Alouettes est également un secteur de ralentissement et enfin dans l'extrême Sud du PMSSL, le passage dans le secteur de Cap à l'Aigle en montant seulement est une zone de ralentissement. Les abords de l'Île aux Lièvres et de l'Île Rouge sont peu profonds donc les pilotes les évitent la plupart du temps.

L'entrée et la sortie de la rivière Saguenay s'effectuent à très basse vitesse compte tenu des risques associés à cette manœuvre (étroitesse du chenal associée aux forts courants de marée pouvant atteindre 7 nœuds au jusant). La bathymétrie accidentée dans cette zone ne laisse qu'un mince corridor de moins de 650 mètres de large entre les bouées S7 et S8 pour les navires entrants et sortants dans le Saguenay. Ceci explique la régularité des trajectoires dans ce secteur.

Enfin, sur l'ensemble du chenal Nord, il est possible de distinguer deux routes principales correspondant aux routes des navires montants et descendants le fleuve. En effet, lors des situations de croisement entre plusieurs navires, les pilotes observent la règle simple (identique à la circulation routière en Amérique du Nord) de conserver l'autre navire à son bâbord. Ainsi, deux voies se démarquent. Ces voies sont beaucoup plus espacées en aval des Escoumins (zone sans pilotage obligatoire) en raison d'un système de séparation du trafic (deux corridors distincts) recommandé pour les navires montants et descendants.

2.5 Mise à jour 2009

Le trafic de navires marchands a subi une légère baisse en 2009, possiblement reliée au ralentissement économique mondial (communication personnelle, SCTM Escoumins).

S'il est difficile de prédire l'évolution future du trafic de navires marchands relié aux échanges commerciaux internationaux, le transport maritime de courte distance (TMCD), communément dénommé cabotage, est un secteur qui pourrait connaître un essor important dans les prochaines années au Québec, comme alternative au camionnage. La Table du Québec sur le TMCD travaille sur plusieurs projets tels que le rétablissement du service d'approvisionnement du Saguenay–Lac Saint-Jean en produits pétroliers au moyen de navires-citernes à partir de la raffinerie de Lévis (*cf.* Journée maritime québécoise, 27 octobre 2009). Compte tenu des avantages énergétiques du TMCD sur ses concurrents directs (ferroviaire et camionnage essentiellement) et de la problématique grandissante des émissions de gaz à effets de serre, le TMCD dans le secteur du PMSSL pourrait connaître une croissance dans les prochaines années.

3 Croisières

3.1 Détail de la flotte

À l'intérieur de la fenêtre temporelle d'intérêt, un seul bateau a été identifié dans la catégorie des croisières nationales dans le PMSSL. Compte tenu du très petit nombre de voyages (**13 voyages**, dont deux allers et deux retours dans le Saguenay), aucune analyse approfondie n'est jugée pertinente ici. Les analyses spatiale et temporelle présentées ici concernent donc les croisières internationales. À l'intérieur de la fenêtre temporelle d'intérêt, les voyages de navires de croisières internationales se concentrent principalement à la fin de l'été et à l'automne. Il y a 17 bateaux distincts qui ont effectué des voyages dans le PMSSL en 2007. Le transit de ces navires dans le PMSSL est assuré par les pilotes de la CPBSL, conformément au règlement sur le pilotage dans la région (Règlement de l'Administration de pilotage des Laurentides 1985). Les activités de croisières dans le PMSSL doivent être autorisées par Parcs Canada au moyen de l'émission d'un permis de moins de 10 jours (Règlement sur les activités en mer dans le parc marin du Saguenay–Saint-Laurent 2002).

3.2 Quantification du nombre de voyages

Le nombre de voyages effectués par des bateaux de croisières internationales présents dans la base de données PREVISION-INNAV est validé par le nombre de trajectoires disponibles dans la base AIS-INNAV. Ce nombre est **95 voyages**; parmi ces voyages, plus de 30 sont entrés dans le Fjord du Saguenay. Le Tableau 12 contient le détail de ces chiffres. Lorsqu'additionnés aux 13 voyages effectués par des croisières nationales, on arrive à un décompte total de **108** voyages de bateaux de croisières dans le PMSSL en 2007.

3.3 Analyse temporelle

3.3.1 Voyages de bateaux de croisières internationales par quinzaine

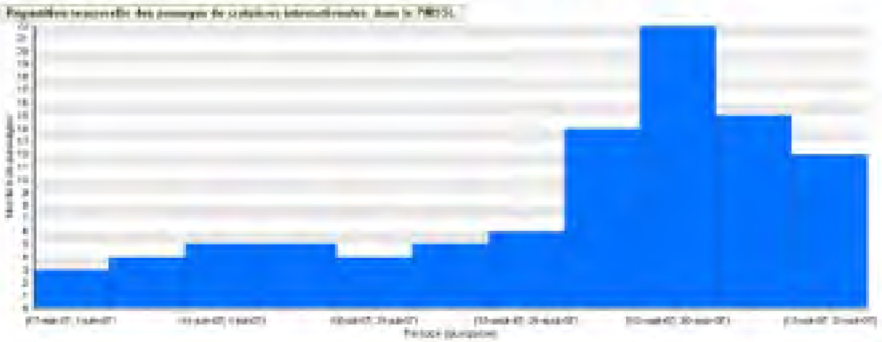


Figure 5 : Variabilité saisonnière du nombre de mouvements de bateaux de croisières internationales dans le PMSSL.

Au cours de la saison, la crête d'activités pour les croisières internationales dans le PMSSL se concentre sur la période automnale en septembre et octobre. Ceci s'explique en grande partie par l'attrait touristique que représente la coloration du feuillage du couvert forestier bordant les littoraux du fleuve Saint-Laurent et de la rivière Saguenay à cette saison.

3.3.2 Voyages de bateaux de croisière internationale selon l'heure du jour

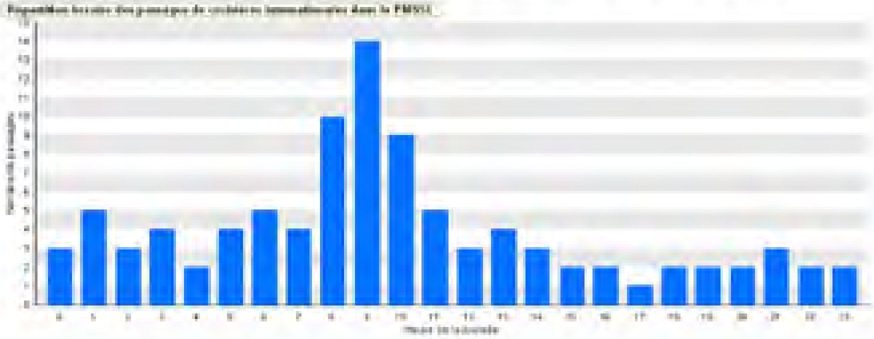


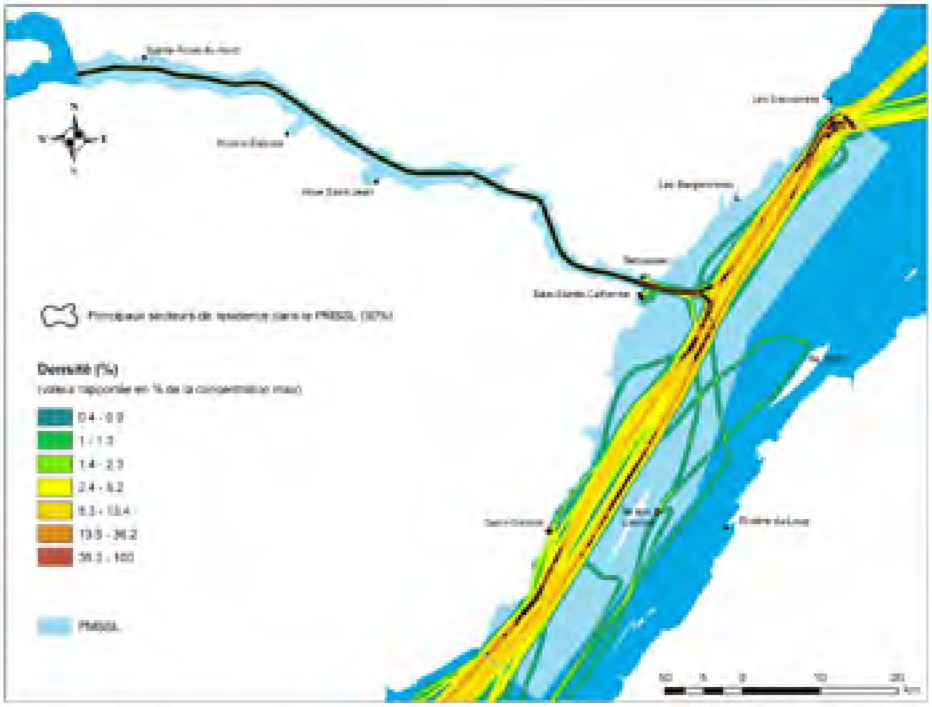
Figure 6 : Variabilité horaire du nombre de mouvements de bateaux de croisières internationales dans le PMSSL.

Les croisières internationales visitent majoritairement le PMSSL le matin sur le créneau horaire [8h–11h]. En dehors de cette plage, il ne semble pas y avoir de préférence pour un autre moment particulier de la journée. La raison de cette hausse d'activité reste à confirmer, mais elle peut être due au choix de présenter la région aux touristes avec les lumières et le calme du matin. Cela peut aussi être dû à des contraintes horaires.

3.4 Analyse spatiale

La Carte 3 permet de constater que le Fjord du Saguenay est visité dans une grande proportion par les croisières internationales. Les zones de forte résidence temporelle (cerclées de noir dans la Carte 3) sont les goulots d'étranglement, provoqués par des contraintes de navigation (l'entrée/sortie de la rivière Saguenay avec le chenal formé par les bouées S7 et S8, le contournement de la batture aux Alouettes), ou encore la zone d'embarquement des pilotes aux Escoumins. Le Saguenay est une zone de résidence importante pour les navires de croisière puisqu'il s'agit d'un attrait touristique important.

De façon générale, l'occupation du territoire du PMSSL est similaire à celle des navires de la marine marchande. L'échouement du Norwegian Sky en septembre 1999 sur le banc de l'Île Rouge a incité les compagnies à ne pas dévier des routes prévues sécuritaires pour s'adonner à l'observation opportuniste de mammifères marins. Le secteur étant parsemé de hauts-fonds, de battures et sujet à de forts courants, les routes sécuritaires sont connues et privilégiées par les pilotes de la CPBSL.



Carte 3 : Densité des trajectoires des bateaux de croisière internationale dans les limites du PMSSL (source : données AIS-INNAV; analyse de type *kernel density*; rayon = 300 mètres; résolution du raster créé = 100m). Les valeurs de densité ont été normalisées par la densité maximale (%). L'échelle de couleur repose sur une classification géométrique non linéaire pour faire ressortir les zones d'activité secondaires. Comme le signal AIS est perdu en amont de l'Anse-de-Roche, une trajectoire prototype a été rajoutée manuellement en tenant compte des données de PRÉVISION-INNAV et en se basant sur la vitesse moyenne prévue des bateaux de croisière pour la traversée de la rivière Saguenay. Les polygones noirs représentent 30% du temps passé sur l'eau, à savoir les secteurs principaux de résidence temporelle dans les limites du PMSSL. Pour les bateaux de croisière internationale, le secteur de résidence principale dans le PMSSL est le Saguenay ainsi que les zones de ralentissement proche de la station de pilotage, dans le contournement de la batture aux Alouettes ainsi que dans le secteur de l'Île aux Lièvres.

3.5 Mise à jour 2009

En septembre 2008, le nouveau quai d'escale de Ville Saguenay (La Baie) dans la Baie des Ha! Ha! a été inauguré. Il permet l'accostage de paquebots de grande taille, ce qui affirme la volonté de promouvoir ce type de tourisme dans le Saint-Laurent et le Saguenay. Par conséquent, une augmentation du trafic relié aux croisières dans le PMSSL est à prévoir dans les prochaines années.

4 Traversiers

Deux services de traversier étaient actifs en 2007 sur le territoire du PMSSL :

1. Tadoussac—Baie-Sainte-Catherine;
2. Saint-Siméon—Rivière-du-Loup.

Le service de traversier entre les Escoumins et Trois-Pistoles a repris en 2008 après trois ans d'interruption de service, en raison de l'attente d'une décision concernant la cession des deux quais par Transport Canada à la Régie intermunicipale des infrastructures portuaires de Trois-Pistoles et des Escoumins et de subventions nécessaires pour leur réfection.

4.1 La traverse Tadoussac—Baie-Sainte-Catherine

4.1.1 Détail de la flotte

Deux bateaux ont effectué la traversée Baie-Sainte-Catherine—Tadoussac sur une base régulière au cours de la saison 2007 : le N.M. Armand-Imbeau et le N.M. Jos-Deschênes. Pour la période allant du 22 juin au 3 septembre, un troisième traversier le N.M. Félix-Antoine-Savard vient prêter main-forte aux deux autres bateaux, offrant alors entre 11 h et 17 h 30 un départ de chaque rive toutes les 13 minutes.

4.1.2 Quantification du nombre de voyages

4.1.2.1 Estimation d'après les horaires de planification

Les horaires et le nombre de départs sont variables selon le jour de la semaine et la période de l'année, tels que présenté dans le Tableau 3. En se basant sur les horaires planifiés des départs en 2007, l'estimé du nombre de traversées est de **21 131**.

Tableau 3 :
Nombre de départs quotidiens planifiés (total des 2 rives)

Jour / Période	Lundi au vendredi	samedi	dimanche
1 mai au 3 mai	**108**	**85**	**88**
4 mai au 21 juin	**108**	**106**	**106**
22 juin au 3 septembre	**128**	**126**	**126**
4 septembre au 12 octobre	**108**	**106**	**106**
13 octobre au 31 octobre	**108**	**85**	**88**

4.1.2.2 Vérification avec les données réelles AIS-INNAV

En prenant plusieurs jours témoins pour le mois d'août (seul mois où la base de données AIS-INNAV contient des voyages des 3 traversiers simultanément), le nombre de traversées total est estimé pour corriger l'estimation effectuée à partir des horaires planifiés. Compte tenu du manque de données AIS pour toute la période d'étude, l'intégralité des traversées n'est pas estimable par une requête directe.

La Société des traversiers du Québec a fait paraître en 2008 son rapport d'activités et il y est mentionné que sur la totalité de l'exercice 2006-2007 (fin le 31 mars 2007), 98.8% des voyages planifiés ont été effectués (soit 40 364/40 726). Ce rapport ne concerne pas la période d'intérêt, mais donne toutefois une indication de la fiabilité du service de traversiers Tadoussac—Baie-Sainte-Catherine.

Sur la période témoin du mois d'août 2007 (12 jours choisis au hasard parmi ceux où les données AIS pour les 3 bateaux sont disponibles), il apparaît que le nombre de passages effectués entre les deux rives a été supérieur à ceux planifiés. Lorsque les 3 traversiers sont en fonctionnement simultanément, le nombre de traversées moyen mesuré dans AIS-INNAV est de 130.3/j alors que l'horaire indique un nombre moyen de 127.4/j (plus 2.3%). Le nombre de traversées effectuées en août 2007 dépasse celui prévu mais reste toutefois très proche. Le manque de données exhaustives pour les autres mois ne permet pas de juger de la situation sur l'ensemble de la période d'intérêt.

Ainsi, deux estimés sont possibles à partir de l'ensemble de ces données, un estimé conservateur (borne inférieure) et un estimé majorant (borne supérieure). En supposant que le taux d'efficacité de 2006 (nombre de traversées effectuées/nombre de traversées prévues) est le même qu'en 2007, l'estimé conservateur est obtenu en multipliant le nombre de traversées prévues en 2007 par ce taux d'efficacité :

Estimé conservateur = 98.8% × 21 131 = 20 877 voyages

La borne supérieure de l'estimé, est calculée en supposant que pendant la période considérée, il y a 2.3% de traversées supplémentaires, tel qu'identifié pendant le mois d'août 2007. Dans ce cas, l'estimé majorant est obtenu comme suit :

Estimé majorant = 102.3% × 21 131 = 21 617 voyages

Certains événements ponctuels ont perturbé le service de traversier en 2007 parmi lesquels on peut en citer 2 :

- Un individu s'est barricadé dans son véhicule le 12 juin 2007, provoquant l'arrêt complet du service de traversier pendant quelques heures. Un troisième navire a été ajouté pendant les heures qui ont suivi l'incident pour permettre de résorber les problèmes d'attentes qui en ont découlé.
- En raison du bris d'une rampe d'accès sur un traversier, le 30 juillet 2007, le service est assuré par 2 navires au lieu de 3 pendant quelques heures (une traversée toutes les 20 minutes au lieu de 13 minutes).

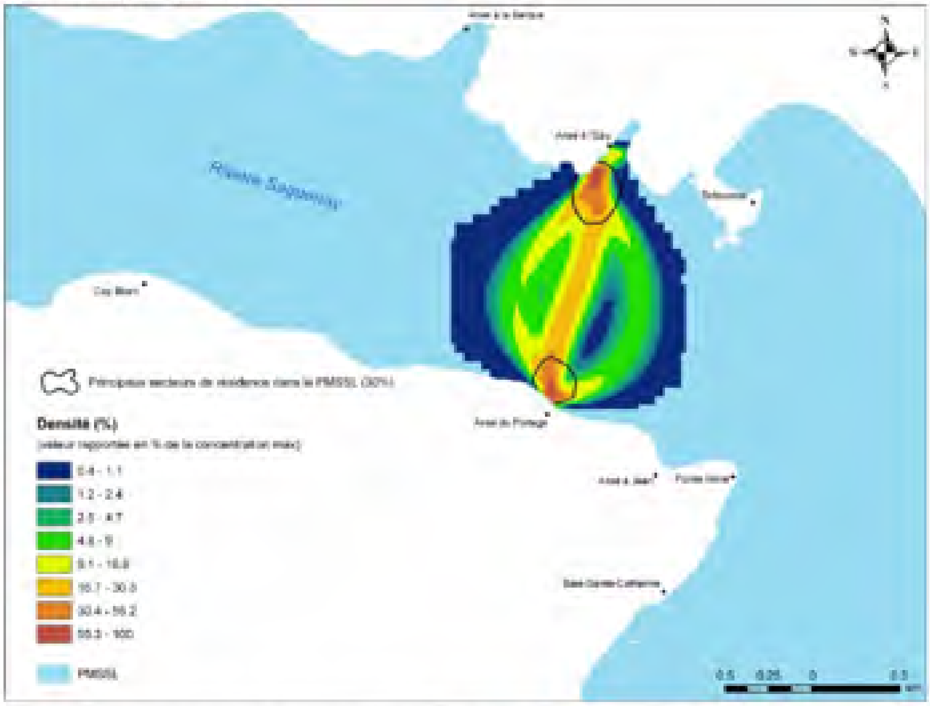
Ces modifications momentanées confirment qu'une marge d'erreur doit être appliquée pour l'estimation du nombre de traversées. La valeur centrale du nombre de voyages de traversiers entre Baie-Sainte-Catherine et Tadoussac pour la période d'intérêt est 21 247.

Ces chiffres sont consignés dans le Tableau 12.

4.1.3 Analyse temporelle

Les traversées ont lieu toute la journée, avec un maximum d'activité pendant les heures du jour. Les fins de semaines, les traversées sont moins fréquentes qu'en semaine, et cette différence est maximale pendant la basse saison. Le nombre maximal de mouvements de traversiers entre Tadoussac et Baie-Sainte-Catherine a été atteint entre le 22 juin et le 3 septembre 2007, lorsque les trois bateaux étaient en service simultanément, offrant alors une traversée des deux rives toutes les 13 minutes aux heures de pointe. L'heure de pointe est située entre 8 h 20 et 20 h 40 pendant la période d'intérêt et de 10 h 30 à 16 h 30 entre le 22 juin et le 3 septembre 2007.

4.1.4 Analyse spatiale



Carte 4 : Densité des passages de traversiers entre Tadoussac et Baie-Sainte-Catherine, dans l'embouchure et le Fjord du Saguenay (source : données AIS-INNAV; analyse de type *kernel density*; rayon = 50 mètres; résolution du raster créé = 50m). Les valeurs de densité ont été normalisées par la densité maximale (%). L'échelle de couleur repose sur une classification géométrique non linéaire pour faire ressortir les zones d'activité secondaires. Cette carte a été pondérée pour représenter le nombre total de traversées (valeur centrale de l'estimation). L'ensemble des polygones noirs représente 30% du temps passé sur l'eau dans les limites du PMSSL. Pour cette analyse, seuls les points AIS où la vitesse est supérieure à 1 nœud (bateaux en mouvement) ont été conservés afin d'exclure de l'analyse les arrêts du bateau aux deux ports. Compte tenu du fort ralentissement à l'abord des zones d'embarquement/débarquement, les principaux secteurs d'activités sont tout de même situés proche des quais.

La trajectoire préférentielle des traversiers est la ligne droite entre les quais de l'Anse du Portage et de l'Anse à l'Eau. Toutefois, deux autres trajectoires curvilignes se distinguent aisément sur la Carte 4. Ces trajectoires secondaires sont le fait de l'adaptation de la route aux forts courants de travers ainsi qu'à l'évitement des autres bateaux en service.

Les fortes périodes de résidence temporelle sont les zones de ralentissement aux abords des deux quais de l'Anse du Portage et de l'Anse à l'Eau, tel qu'illustré par les polygones noirs dans la Carte 4.

4.2 La traverse Saint-Siméon—Rivière-du-Loup

4.2.1 Détail de la flotte

Un seul bateau offre ce service; il s'agit du N.M. Trans-Saint-Laurent.

4.2.2 Quantification du nombre de voyages

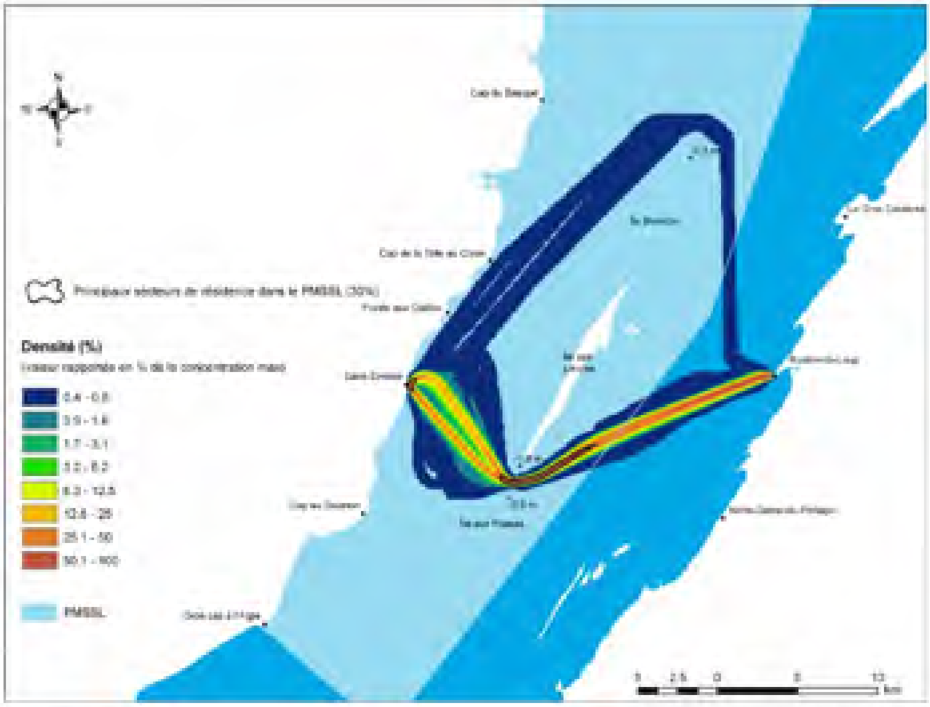
Le nombre de traversées extrait par requêtes sur la base de données PRÉVISION est de **1 286**. Ce nombre est appuyé par les analyses effectuées sur la base AIS-INNAV qui couvrent sans interruption la période d'intérêt. Les horaires prévoyaient un total de 1 302 départs pour cette même période, ce qui impliquerait un taux d'efficacité de **98.7%**, comparable à celui de la traverse Tadoussac—Baie-Sainte-Catherine en 2006. Compte tenu des manques possibles à la base de données PRÉVISION, ces deux valeurs sont prises comme les bornes inférieure et supérieure de l'estimation du nombre de voyages, tel que reporté dans le Tableau 12. La valeur centrale du nombre de voyages effectués par le traversier entre Rivière-du-Loup et Saint-Siméon est **1 294**.

4.2.3 Analyse temporelle

Au cours de la saison, les traversées se répartissent entre 7 h du matin et 21 h 45 en période touristique. Aucune activité n'a donc lieu normalement entre 23 h et 7 h du matin.

4.2.4 Analyse spatiale

La Carte 5 caractérise spatialement les trajets effectués par le traversier entre Saint-Siméon et Rivière-du-Loup. Cette carte met en évidence la répétitivité des routes suivies par le N.M. Trans-Saint-Laurent, notamment en ce qui a trait au choix de contournement de l'Île aux Lièvres par la passe de l'Île aux Lièvres, au Sud de celle-ci. On remarque toutefois que quelques traversées (8 sur 1286 = 0.6%) ont été effectuées en contournant la bouée K59 au Nord de la batture de l'Île Blanche. Bien que non identifiées de façon certaine, une des raisons peut être le manque d'eau dans la passe de l'Île aux Lièvres déjà assez peu profonde (entre 3.8 mètres et 4.1 mètres au zéro des cartes) puisque le N.M. Trans-Saint-Laurent tire au maximum 4.27 mètres d'eau (source : base de données INNAV). Hormis cette variabilité, l'autre variation notable est la présence très nette de deux routes distinctes à l'Ouest de l'Île aux Lièvres : elles correspondent aux deux trajectoires distinctes suivies selon que le bateau arrive ou repart de Saint-Siméon.



Carte 5 : Densité de passages du traversier Saint-Siméon—Rivière-du-Loup dans l'estuaire moyen du fleuve Saint-Laurent (source : données AIS-INNAV; analyse de type *kernel density*; rayon = 300 mètres; résolution du raster créé = 100m). Les valeurs de densité ont été normalisées par la densité maximale (%). L'échelle de couleur repose sur une classification géométrique non linéaire pour faire ressortir les zones d'activité secondaires. L'ensemble des polygones noirs représente 30% du temps passé sur l'eau dans les limites du PMSSL. Seuls les points où la vitesse était supérieure à 1 nœud (*i.e.* bateau en mouvement) ont été conservés afin d'exclure de l'analyse les arrêts du bateau aux 2 ports.

Les zones de forte résidence temporelle sont encore une fois les zones de ralentissement, identifiées dans la Carte 5 par les lignes noires. Il s'agit des abords des ports de Saint-Siméon et de Rivière-du-Loup. L'autre secteur notable de ralentissement est la passe de l'Île aux Lièvres qui représente une zone à risque compte tenu de la faible profondeur d'eau.

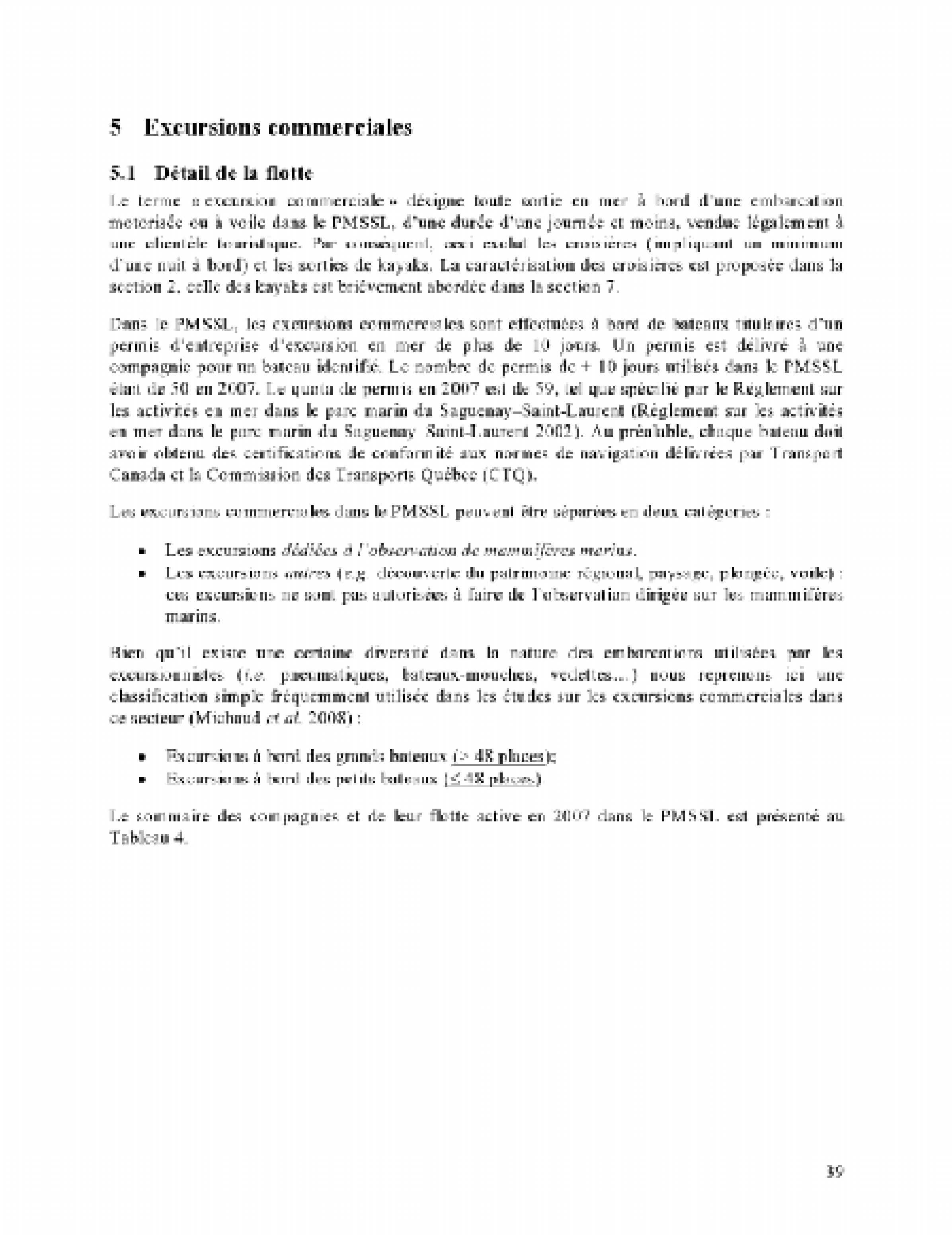
4.3 Bilan du nombre total de voyages de traversiers

Le bilan du nombre total de voyages de traversiers dans le PMSSL pour la période considérée est dans l'intervalle [22 163; 22 919], pour une valeur centrale de **22 541**.

4.4 Mise à jour 2009

Le changement principal depuis 2007 concerne la reprise du service de traversier entre Les Escoumins et Trois-Pistoles en 2008. Ce traversier a planifié approximativement **560 voyages** entre mai et octobre 2009. La route de ce traversier coupe l'extrémité Nord dans l'estuaire maritime du PMSSL.

L'autre information à retenir est l'annonce de la construction de trois nouveaux traversiers subventionnée à hauteur de 400 millions de $ par le gouvernement du Québec. Deux de ces traversiers sont dédiés à la traverse entre Baie-Sainte-Catherine et Tadoussac, suggérant que le projet d'un pont au-dessus de la rivière Saguenay n'est pas une priorité du gouvernement.



5 Excursions commerciales

5.1 Détail de la flotte

Le terme « excursion commerciale » désigne toute sortie en mer à bord d'une embarcation motorisée ou à voile dans le PMSSL, d'une durée d'une journée et moins, vendue légalement à une clientèle touristique. Par conséquent, ceci exclut les croisières (impliquant un minimum d'une nuit à bord) et les sorties de kayaks. La caractérisation des croisières est proposée dans la section 2, celle des kayaks est brièvement abordée dans la section 7.

Dans le PMSSL, les excursions commerciales sont effectuées à bord de bateaux titulaires d'un permis d'entreprise d'excursion en mer de plus de 10 jours. Un permis est délivré à une compagnie pour un bateau identifié. Le nombre de permis de + 10 jours utilisés dans le PMSSL était de 50 en 2007. Le quota de permis en 2007 est de 59, tel que spécifié par le Règlement sur les activités en mer dans le parc marin du Saguenay–Saint-Laurent (Règlement sur les activités en mer dans le parc marin du Saguenay–Saint-Laurent 2002). Au préalable, chaque bateau doit avoir obtenu des certifications de conformité aux normes de navigation délivrées par Transport Canada et la Commission des Transports Québec (CTQ).

Les excursions commerciales dans le PMSSL peuvent être séparées en deux catégories :

- Les excursions *dédiées à l'observation de mammifères marins*.
- Les excursions *autres* (e.g. découverte du patrimoine régional, paysage, plongée, voile) : ces excursions ne sont pas autorisées à faire de l'observation dirigée sur les mammifères marins.

Bien qu'il existe une certaine diversité dans la nature des embarcations utilisées par les excursionnistes (*i.e.* pneumatiques, bateaux-mouches, vedettes...) nous reprenons ici une classification simple fréquemment utilisée dans les études sur les excursions commerciales dans ce secteur (Michaud *et al.* 2008) :

- Excursions à bord des grands bateaux (> 48 places);
- Excursions à bord des petits bateaux (≤ 48 places)

Le sommaire des compagnies et de leur flotte active en 2007 dans le PMSSL est présenté au Tableau 4.

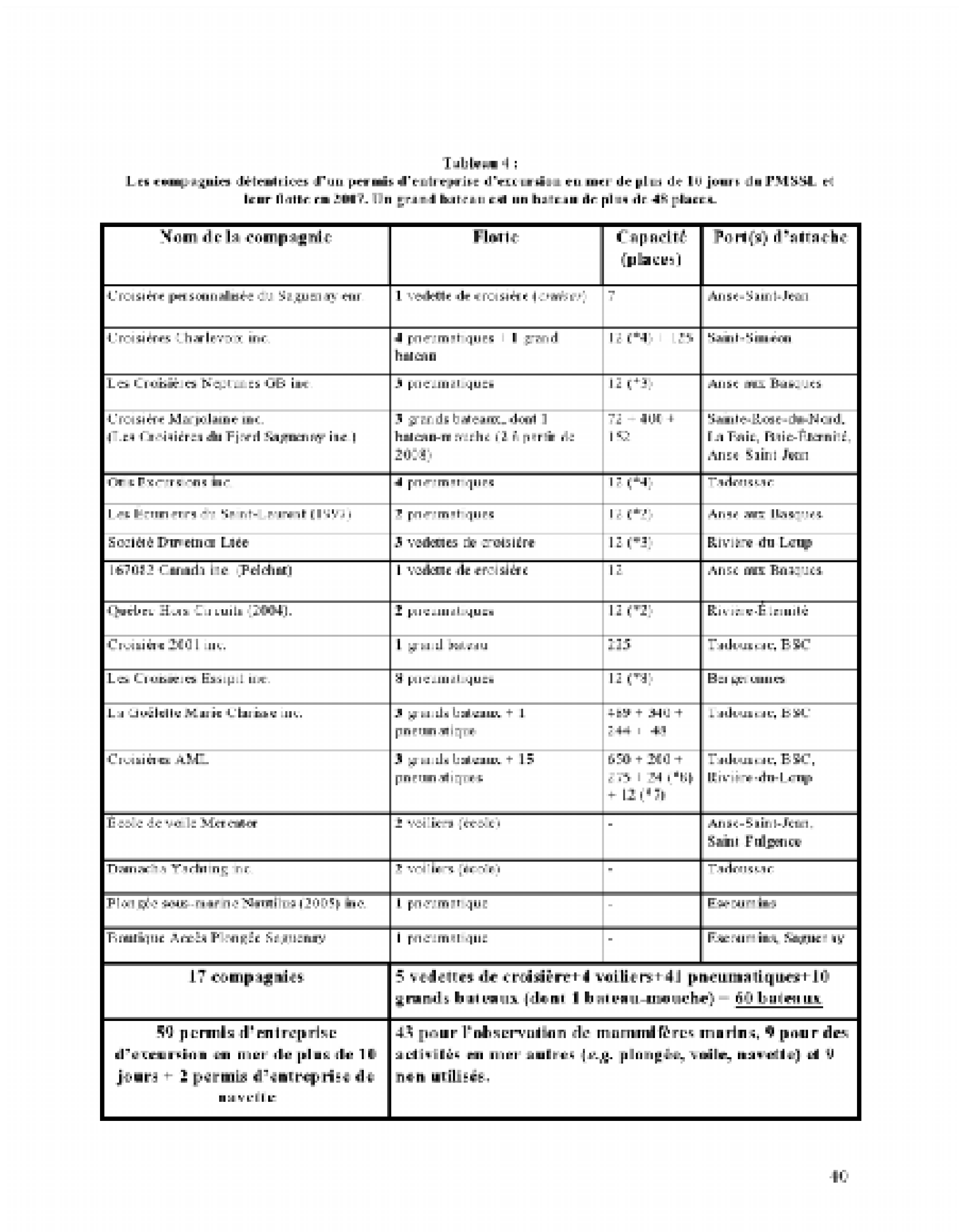
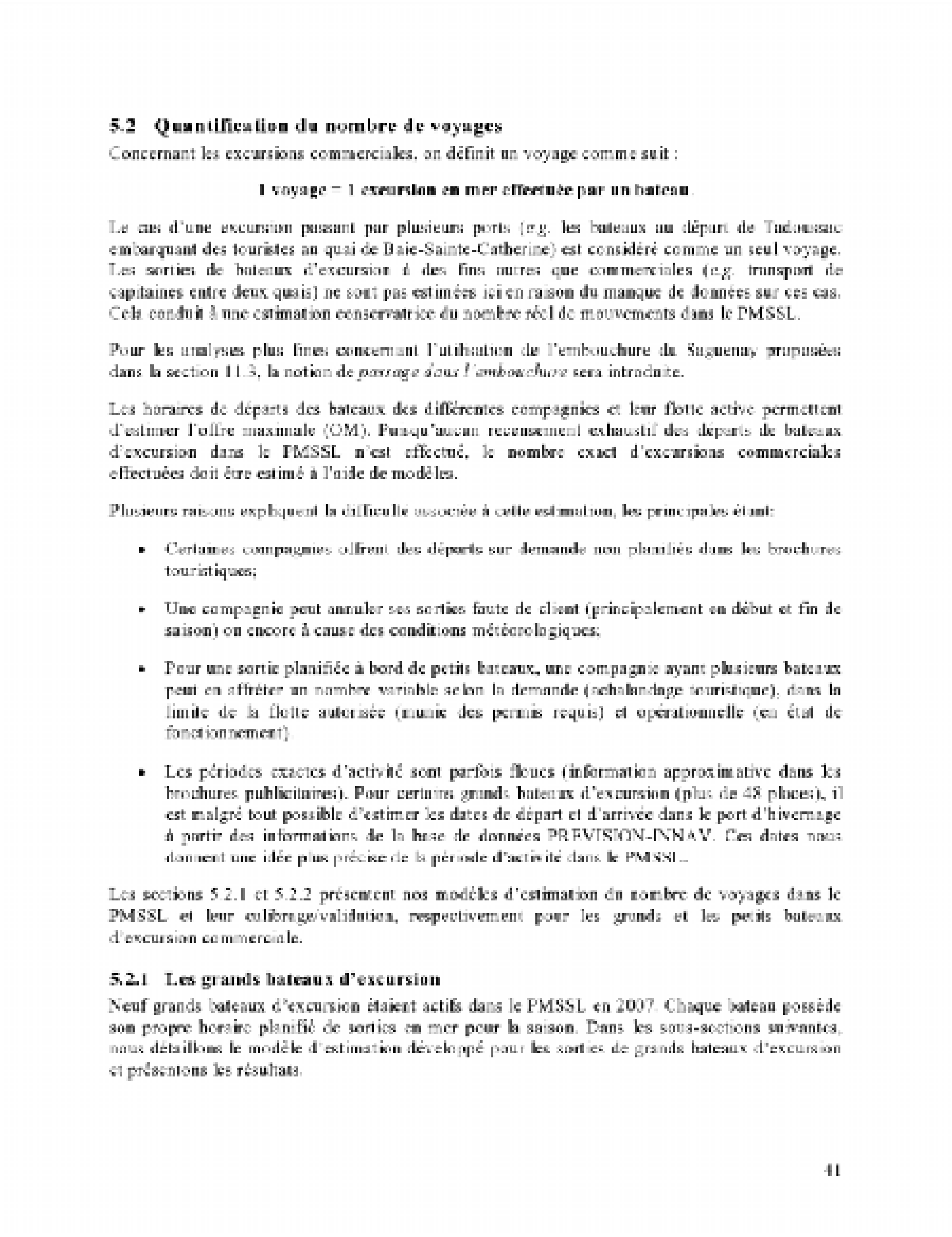


Tableau 4 :
Les compagnies détentrices d'un permis d'entreprise d'excursion en mer de plus de 10 jours du PMSSL et leur flotte en 2007. Un grand bateau est un bateau de plus de 48 places.

Nom de la compagnie	Flotte	Capacité (places)	Port(s) d'attache
Croisière personnalisée du Saguenay enr.	1 vedette de croisière (cruiser)	7	Anse-Saint-Jean
Croisières Charlevoix inc.	4 pneumatiques + 1 grand bateau	12 (*4) + 125	Saint-Siméon
Les Croisières Neptune GB inc.	3 pneumatiques	12 (*3)	Anse aux Basques
Croisière Marjolaine inc. (Les Croisières du Fjord Saguenay inc.)	3 grands bateaux, dont 1 bateau-mouche (2 à partir de 2008)	72 + 400 + 152	Sainte-Rose-du-Nord, La Baie, Baie-Éternité, Anse Saint Jean
Otis Excursions inc.	4 pneumatiques	12 (*4)	Tadoussac
Les Écumeurs du Saint-Laurent (1993)	2 pneumatiques	12 (*2)	Anse aux Basques
Société Duvetnor Ltée	3 vedettes de croisière	12 (*3)	Rivière du Loup
167082 Canada inc. (Pelchat)	1 vedette de croisière	12	Anse aux Basques
Québec Hors Circuits (2004).	2 pneumatiques	12 (*2)	Rivière-Éternité
Croisière 2001 inc.	1 grand bateau	225	Tadoussac, BSC
Les Croisières Essipit inc.	8 pneumatiques	12 (*8)	Bergeronnes
La Goélette Marie Clarisse inc.	3 grands bateaux + 1 pneumatique	469 + 340 + 244 + 48	Tadoussac, BSC
Croisières AML	3 grands bateaux + 15 pneumatiques	650 + 200 + 275 + 24 (*8) + 12 (*7)	Tadoussac, BSC, Rivière-du-Loup
École de voile Mercator	2 voiliers (école)	-	Anse-Saint-Jean, Saint Fulgence
Damacha Yachting inc.	2 voiliers (école)	-	Tadoussac
Plongée sous-marine Nautilus (2005) inc.	1 pneumatique	-	Escoumins
Boutique Accès Plongée Saguenay	1 pneumatique	-	Escoumins, Saguenay
17 compagnies	**5 vedettes de croisière+4 voiliers+41 pneumatiques+10 grands bateaux (dont 1 bateau-mouche) = 60 bateaux**		
50 permis d'entreprise d'excursion en mer de plus de 10 jours + 2 permis d'entreprise de navette	**43 pour l'observation de mammifères marins, 9 pour des activités en mer autres (*e.g.* plongée, voile, navette) et 9 non utilisés.**		



5.2 Quantification du nombre de voyages

Concernant les excursions commerciales, on définit un voyage comme suit :

1 voyage = 1 excursion en mer effectuée par un bateau.

Le cas d'une excursion passant par plusieurs ports (*e.g.* les bateaux au départ de Tadoussac embarquant des touristes au quai de Baie-Sainte-Catherine) est considéré comme un seul voyage. Les sorties de bateaux d'excursion à des fins autres que commerciales (*e.g.* transport de capitaines entre deux quais) ne sont pas estimées ici en raison du manque de données sur ces cas. Cela conduit à une estimation conservatrice du nombre réel de mouvements dans le PMSSL.

Pour les analyses plus fines concernant l'utilisation de l'embouchure du Saguenay proposées dans la section 11.3, la notion de *passage dans l'embouchure* sera introduite.

Les horaires de départs des bateaux des différentes compagnies et leur flotte active permettent d'estimer l'offre maximale (OM). Puisqu'aucun recensement exhaustif des départs de bateaux d'excursion dans le PMSSL n'est effectué, le nombre exact d'excursions commerciales effectuées doit être estimé à l'aide de modèles.

Plusieurs raisons expliquent la difficulté associée à cette estimation, les principales étant:

- Certaines compagnies offrent des départs sur demande non planifiés dans les brochures touristiques;
- Une compagnie peut annuler ses sorties faute de client (principalement en début et fin de saison) ou encore à cause des conditions météorologiques;
- Pour une sortie planifiée à bord de petits bateaux, une compagnie ayant plusieurs bateaux peut en affréter un nombre variable selon la demande (achalandage touristique), dans la limite de la flotte autorisée (munie des permis requis) et opérationnelle (en état de fonctionnement);
- Les périodes exactes d'activité sont parfois floues (information approximative dans les brochures publicitaires). Pour certains grands bateaux d'excursion (plus de 48 places), il est malgré tout possible d'estimer les dates de départ et d'arrivée dans le port d'hivernage à partir des informations de la base de données PREVISION-INNAV. Ces dates nous donnent une idée plus précise de la période d'activité dans le PMSSL.

Les sections 5.2.1 et 5.2.2 présentent nos modèles d'estimation du nombre de voyages dans le PMSSL et leur calibrage/validation, respectivement pour les grands et les petits bateaux d'excursion commerciale.

5.2.1 Les grands bateaux d'excursion

Neuf grands bateaux d'excursion étaient actifs dans le PMSSL en 2007. Chaque bateau possède son propre horaire planifié de sorties en mer pour la saison. Dans les sous-sections suivantes, nous détaillons le modèle d'estimation développé pour les sorties de grands bateaux d'excursion et présentons les résultats.

5.2.1.1 Modèle d'estimation du nombre de sorties de grands bateaux d'excursion

Les chiffres des compagnies pour les grands bateaux n'étant pas disponibles pour 2007, un modèle d'estimation doit être développé. Les hypothèses de ce modèle d'estimation sont:

- Le nombre de sorties a pour borne supérieure la somme sur la période d'activité de l'offre maximale journalière (OM) de chaque grand bateau.
- Le nombre de sorties des grands bateaux desservant Tadoussac et Baie-Sainte-Catherine a pour borne inférieure conservatrice le ratio *r* du nombre de départs effectués à partir du quai de Baie-Sainte-Catherine (données du quai de Baie-Sainte-Catherine) avec le nombre de départs prévus dans les horaires pour les mêmes périodes, multiplié par l'OM totale de ces bateaux. Ce ratio *r* est mensualisé en ratios r_m.
- Le ratio *r* estimé pour les grands bateaux desservant à la fois Tadoussac et Baie-Sainte-Catherine est transposable aux autres grands bateaux du PMSSL.

Plusieurs grands bateaux offrent des départs à partir du quai de Baie-Sainte-Catherine, et la (quasi-)totalité de ces excursions dessert également le quai de Tadoussac. Les données exhaustives de l'utilisation du quai de Baie-Sainte-Catherine de cette année compilées par Parcs Canada sont utilisées pour estimer la borne inférieure de l'estimé du nombre de sorties des grands bateaux. Tadoussac étant le pôle touristique majeur et la marina et le quai étant les points de départs principaux de ces excursions, il arrive (hors période touristique de pointe) que des départs aient lieu à partir de Tadoussac mais ne desservent pas Baie-Sainte-Catherine, faute de touristes. Ces situations seront interprétées dans la borne inférieure de notre estimation comme une absence d'excursion. Ainsi, la borne inférieure est dite conservatrice.

Ce modèle d'estimation simple peut être répété pour des années futures à l'aide des brochures publicitaires des compagnies et des données d'utilisation du quai de Baie-Sainte-Catherine.

5.2.1.2 Borne supérieure de l'estimation des sorties de grands bateaux d'excursion

Tel que discuté, la borne supérieure N_{sup} de l'estimation est donnée par l'offre maximale (OM). L'OM de chaque bateau peut être calculé à partir des brochures publicitaires, permettant de connaître la variabilité saisonnière des départs. La période d'activité est extraite des brochures publicitaires et corrigée si possible avec les données PREVISION-INNAV. Ainsi, l'offre maximale saisonnière de chaque grand bateau est calculée comme suit :

$$OM(bateau_i) = \sum_{j=1}^{j=\text{Nbre de jours en opération}} N_{départs_j}$$

Par conséquent, la borne supérieure de l'estimation égale à l'OM de tous les grands bateaux d'excursion dans le PMSSL en 2007 est :

$$N_{sup} = OM_{tot} = \sum_{i=1}^{i=9} OM(bateau_i)$$

La borne supérieure *Nsup* du nombre de sorties en mer effectuées par des grands bateaux d'excursion en 2007 est donc N_{sup} = **<u>3 205</u>** sorties.

5.2.1.3 Borne inférieure de l'estimation des sorties de grands bateaux d'excursion

Le ratio r_m décrit précédemment a été extrait des données du quai de Baie-Sainte-Catherine pour chaque mois.

Ainsi, la borne inférieure conservatrice N_{inf} du nombre d'excursions de grands bateaux dans le PMSSL en 2007 est :

$$N_{inf} = \sum_{m} (r_m \times OM_m) = 2\,582 \text{ sorties}$$

5.2.1.4 Estimation du nombre de sorties de grands bateaux d'excursion

Selon notre modèle d'estimation, le nombre de sorties N_{grands} en mer dans le PMSSL en 2007 effectuées par des grands bateaux d'excursion (>48 places) est situé dans l'intervalle :

$$N_{grands} \in [2\,582 ; 3\,205]$$

La valeur la plus probable pour N_{grands} est donc la valeur centrale de cet intervalle, à savoir $N_{grands} = \underline{2\,893}$ sorties de grands bateaux d'excursion.

5.2.2 Les petits bateaux d'excursion

Compte tenu du caractère « sportif » des excursions en pneumatique (exposition importante aux intempéries, secousses…), celles-ci sont plus prisées par les jeunes adultes que celles à bord des grands bateaux, extrêmement plus confortables. Or, puisque située après la fin des vacances scolaires, les touristes de la période 3 (fin août à fin septembre) sont généralement plus âgés que ceux des périodes 1 (jusqu'à mi-juillet) et 2 (mi-juillet à fin août) (Giroul *et al.* 2000). Par le fait même, la période 3, en plus d'être moins achalandée que la période 2, voit le nombre de pneumatiques sur l'eau baisser de façon plus abrupte que la simple baisse d'achalandage, en raison du changement de type de clientèle et de la météo moins clémente. Un grand bateau d'excursion (~340 places en moyenne) ayant une capacité d'accueil de passagers bien supérieure à celle d'un pneumatique standard (12 à 48 places), le nombre de ses sorties est beaucoup moins affecté par cette baisse d'achalandage, d'autant que leur clientèle cible est moins touchée par cette baisse globale du nombre de touristes. De plus, la visibilité de ces grands bateaux sur l'eau est une stratégie publicitaire non négligeable dans un contexte de compétition entre les compagnies, impliquant des sorties avec peu de clients à bord notamment aux extrémités de la saison touristique (avril-mai et octobre-novembre).

À l'inverse, les compagnies de pneumatiques peuvent faire sortir plus ou moins de bateaux sur un même créneau horaire pour répondre aux fluctuations de la demande touristique. Certaines compagnies font également des départs sur demande pendant la saison. Ainsi, l'achalandage touristique a une influence directe sur le nombre de bateaux qui sortent en mer sur un créneau horaire. La plupart des compagnies de petits bateaux effectuent une sortie en mer à partir de trois clients (~25% de remplissage pour un bateau de 12 places) et certaines moins. Les compagnies d'excursion proposant des sorties à partir de plusieurs petits bateaux dans le PMSSL affichent globalement un taux d'occupation situé aux alentours de 30%.

Dans cette section, nous présentons les excursions commerciales effectuées à bord de pneumatiques, vedettes de croisière (*cruiser*), bateaux-mouches et voiliers, de 48 places et moins.

Nous détaillons d'abord le modèle d'estimation développé pour quantifier le nombre de sorties des bateaux de cette catégorie. Les données réelles de plusieurs compagnies servent à calibrer les estimés finaux.

5.2.2.1 Quantification du nombre de sorties de petits bateaux d'excursion commerciale

Certaines compagnies offrant des excursions dans le PMSSL ont transmis les chiffres de leurs sorties en mer ventilés par mois pour l'année 2007. Toutefois, comme cette information réelle est inconnue pour plusieurs compagnies, nous devons développer un modèle d'estimation reposant sur les meilleures données disponibles concernant les petits bateaux d'excursion commerciale. Les données AOM (*cf.* section 1.3.4) et les informations commerciales relatives aux planifications des départs des compagnies servent de base au développement du modèle d'estimation. Les informations fournies par les experts et observateurs réguliers des activités d'excursion permettent de valider certaines données et de réduire l'incertitude sur les termes utilisés par le modèle.

Afin d'assurer la confidentialité des estimations du nombre de départs des compagnies d'excursion commerciale, aucun détail (autres que ceux accessibles par le grand public) ne sera fourni permettant d'associer un nombre de départs à une compagnie précise. Ainsi, les compagnies nous ayant transmis leurs données ne seront pas nommées et les estimations du nombre de départs d'excursion effectués ne seront présentées que dans leur globalité (*i.e.* pas de ventilation par port ni par compagnie).

5.2.2.1.1 Modèle d'estimation : ajustement de l'offre maximale par le facteur d'achalandage $f_{p,h}$

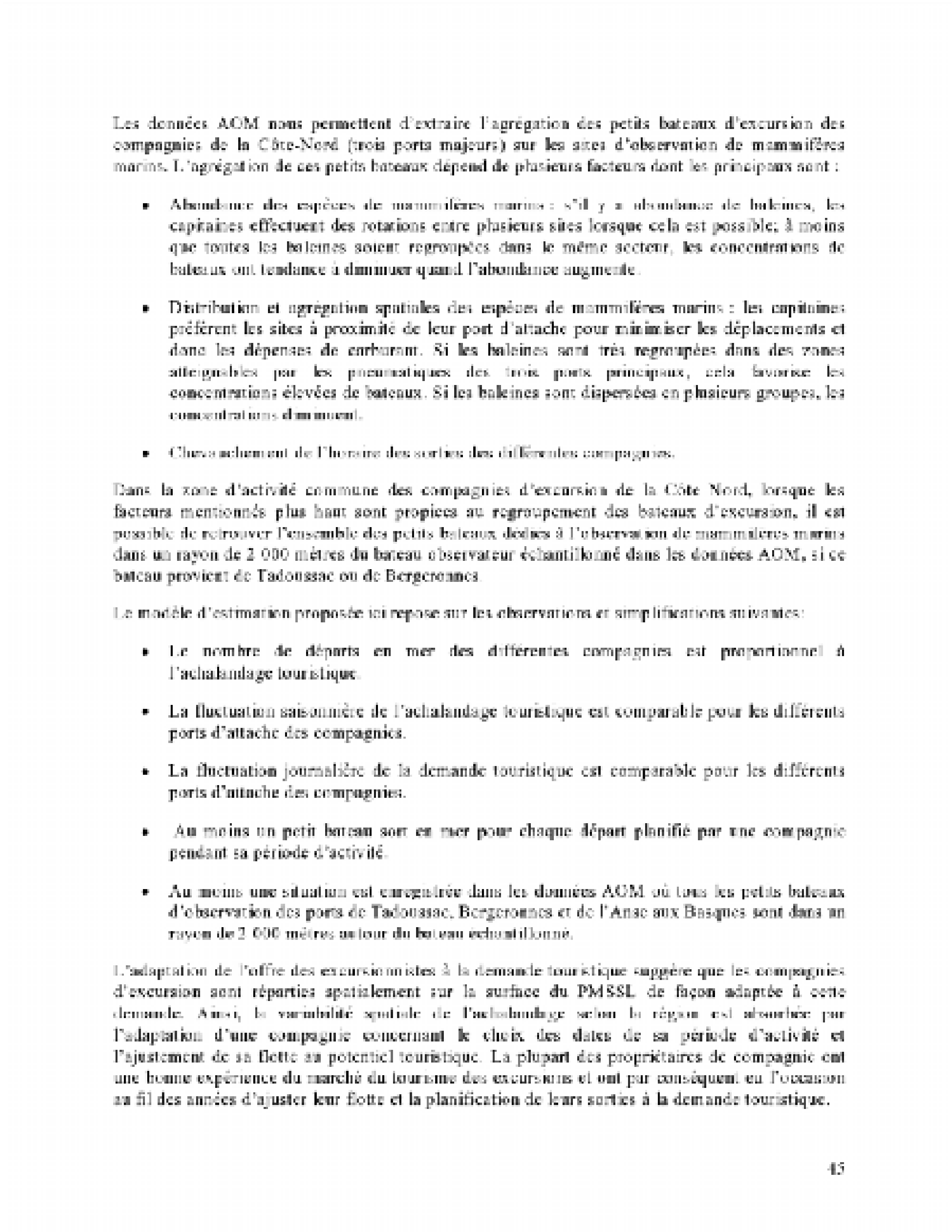
Le modèle d'estimation proposé ici vise à quantifier les excursions en mer effectuées par des petits bateaux en 2007 dans le PMSSL. L'offre maximale $OM_{c,p,j,h}$ d'une compagnie c offrant un nombre $d_{c,p,j,h}$ de départs d'excursion le jour j de la période p à la plage horaire h à bord de F_c petits bateaux (flotte de la compagnie) est donnée par :

$$OM_{c,p,j,h} = d_{c,p,j,h} \times F_c$$

Nous définissons trois plages horaires pour h (*matin* – avant 10 h; *midi* – entre 10 h et 16 h; et *soir* – après 16 h) pour lesquelles l'achalandage touristique et donc le nombre de départs fluctuent. De plus, la saison (de mai à octobre) est découpée en périodes p de 15 ou 16 jours pendant lesquelles l'achalandage touristique est supposé constant. Une compagnie c ayant $A_{c,p}$ jours d'activité dans la période p a une offre maximale saisonnière OM_c donnée par :

$$OM_c = \sum_{p} \left(\sum_{j=1}^{j=A_{c,p}} \sum_{h=1}^{h=3} OM_{c,p,j,h} \right)$$

Les meilleures données caractérisant ces activités sont les données AOM (décrites dans l'introduction); le modèle d'estimation est donc développé pour la composante des *excursions dédiées à l'observation des mammifères marins*. Comme ce type d'excursion compose la grande majorité des excursions commerciales dans le PMSSL (88% des permis utilisés), cette approche est justifiée.



Les données AOM nous permettent d'extraire l'agrégation des petits bateaux d'excursion des compagnies de la Côte-Nord (trois ports majeurs) sur les sites d'observation de mammifères marins. L'agrégation de ces petits bateaux dépend de plusieurs facteurs dont les principaux sont :

- Abondance des espèces de mammifères marins : s'il y a abondance de baleines, les capitaines effectuent des rotations entre plusieurs sites lorsque cela est possible; à moins que toutes les baleines soient regroupées dans le même secteur, les concentrations de bateaux ont tendance à diminuer quand l'abondance augmente.

- Distribution et agrégation spatiales des espèces de mammifères marins : les capitaines préfèrent les sites à proximité de leur port d'attache pour minimiser les déplacements et donc les dépenses de carburant. Si les baleines sont très regroupées dans des zones atteignables par les pneumatiques des trois ports principaux, cela favorise les concentrations élevées de bateaux. Si les baleines sont dispersées en plusieurs groupes, les concentrations diminuent.

- Chevauchement de l'horaire des sorties des différentes compagnies.

Dans la zone d'activité commune des compagnies d'excursion de la Côte Nord, lorsque les facteurs mentionnés plus haut sont propices au regroupement des bateaux d'excursion, il est possible de retrouver l'ensemble des petits bateaux dédiés à l'observation de mammifères marins dans un rayon de 2 000 mètres du bateau observateur échantillonné dans les données AOM, si ce bateau provient de Tadoussac ou de Bergeronnes.

Le modèle d'estimation proposé ici repose sur les observations et simplifications suivantes:

- Le nombre de départs en mer des différentes compagnies est proportionnel à l'achalandage touristique.

- La fluctuation saisonnière de l'achalandage touristique est comparable pour les différents ports d'attache des compagnies.

- La fluctuation journalière de la demande touristique est comparable pour les différents ports d'attache des compagnies.

- Au moins un petit bateau sort en mer pour chaque départ planifié par une compagnie pendant sa période d'activité.

- Au moins une situation est enregistrée dans les données AOM où tous les petits bateaux d'observation des ports de Tadoussac, Bergeronnes et de l'Anse aux Basques sont dans un rayon de 2 000 mètres autour du bateau échantillonné.

L'adaptation de l'offre des excursionnistes à la demande touristique suggère que les compagnies d'excursion sont réparties spatialement sur la surface du PMSSL de façon adaptée à cette demande. Ainsi, la variabilité spatiale de l'achalandage selon la région est absorbée par l'adaptation d'une compagnie concernant le choix des dates de sa période d'activité et l'ajustement de sa flotte au potentiel touristique. La plupart des propriétaires de compagnie ont une bonne expérience du marché du tourisme des excursions et ont par conséquent eu l'occasion au fil des années d'ajuster leur flotte et la planification de leurs sorties à la demande touristique.

Ainsi, l'estimation $N_{c,p,j}$ du nombre de sorties effectuées par des petits bateaux de la compagnie c, le jour j de la période p est :

$$N_{c,p,j} = max\left[\sum_{h=1}^{h=8}\left(f_{p,h} \times OM_{c,p,j,h}\right); \sum_{h=1}^{h=8} d_{c,p,j,h}\right]$$

d'où :

$$N_c = \sum_{p} \sum_{j=1}^{j=A_{c,p}} N_{c,p,j}$$

et finalement pour les 15 compagnies d'excursion ayant des petits bateaux :

$$N_{petits-bateaux} = \sum_{c=1}^{c=15} N_c = \sum_{c=1}^{c=15} \sum_{p} \sum_{j=1}^{j=A_{c,p}} \left\{max\left[\sum_{h=1}^{h=8}\left(f_{p,h} \times OM_{c,p,j,h}\right); \sum_{h=1}^{h=8} d_{c,p,j,h}\right]\right\}$$

avec :

$N_{petits-bateaux}$: Estimation du nombre d'excursions effectuées à bord de petits bateaux dans le PMSSL en 2007 à partir du modèle.

N_c : Nombre de départs de petits bateaux effectués par la compagnie c.

$f_{p,h}$: Facteur d'achalandage touristique pour la période p et la plage horaire h.

F_c : Flotte de petits bateaux (moins de 48 passagers) de la compagnie c.

$A_{c,p}$: Nombre de jours d'activité de la compagnie c pendant la période p.

$d_{c,p,j,h}$: Nombre de créneaux horaires de départs planifiés par la compagnie c sur la plage horaire h du jour j de la période p.

Le facteur $f_{p,h}$ correspond à la fraction de la capacité maximale d'accueil de touristes par les petits bateaux pour la période p, pour la plage horaire h de la journée. C'est donc une mesure d'achalandage relative, pouvant varier de 0 (pas de sorties) à 1 (nombre maximal de bateaux sur l'eau). Par exemple, un facteur $f_{p,h}=1$ signifie que toutes les compagnies doivent sortir tous leurs bateaux pour la plage horaire h pour répondre à la demande touristique. À l'opposé, un facteur $f_{p,h}=0$ signifie qu'il n'y a aucun touriste et que par conséquent, les compagnies ne sortent pas de bateau aux heures planifiées des sorties.

Le reste de la section 5.2.2 est dédié à la présentation de la stratégie de détermination des valeurs du facteur d'achalandage $f_{p,h}$ et de l'ensemble des variables de notre modèle d'estimation.

5.2.2.1.2 Estimation du facteur d'achalandage touristique en milieu de journée $f_{p,midi}$ pour en 2007

Pour faire une estimation du facteur $f_{p,midi}$, compte tenu des données à disposition, le contexte des compagnies de la Côte-Nord est pris comme référence. Les données AOM permettent d'avoir un aperçu de l'achalandage touristique entre le 15 juin et le 30 septembre 2007. En divisant cette fenêtre temporelle en tranches de 2 semaines, nous obtenons un total de 7 périodes distinctes (*i.e.* $p \in [1,7]$). Pour chaque période p, l'estimation du facteur $f_{p,midi}$ est effectuée en divisant le nombre maximal de petits bateaux (extrait des données AOM) autour des sites d'observation de baleines $\lambda_{max,p,midi}$ par la flotte totale des compagnies susceptibles de se retrouver en mer en même temps λ_{tot} :

$$f_{p,midi} = \frac{\lambda_{max,p,midi}}{\lambda_{tot}}$$

En 2007, le $\lambda_{max,p,midi}$ a été calculé à partir des données AOM pour la période de 10 h à 16 h (*cf.* Tableau 5).

Les trois ports de la Côte Nord de Tadoussac, Bergeronnes et l'Anse aux Basques regroupent, à eux seuls, 29 des 43 petits bateaux munis d'un permis d'entreprise d'excursion en mer du PMSSL. Les bateaux des compagnies *dédiés à l'observation de mammifères marins* à partir d'autres ports et ceux offrant des excursions *autres* (non autorisés à faire de l'observation dirigée sur des mammifères marins) se retrouvent rarement dans ce secteur du PMSSL. Ainsi, le potentiel maximal de petits bateaux λ_{tot} présents sur les sites d'observation est fixé à $\lambda_{tot} = 29$.

Tableau 8 :
Évaluation par requêtes sur la base de données AOM de l'agrégation maximale de petits bateaux sur l'heure du midi ($\lambda_{max,p,midi}$) et du facteur d'achalandage touristique équivalent $f_{p,midi}$, pour chaque période en 2007

	$\lambda_{max,p,midi}$ (2007)	Facteur d'achalandage (heure du midi, 2007) $f_{p,midi} = \lambda_{max,p,midi} / \lambda_{tot}$
15 juin-30 juin	8	8/29 = 0.28
1 juillet-15 juillet	15	15/29 = 0.52
16 juillet-31 juillet	20	20/29 = 0.69
1 août-15 août	23	23/29 = 0.79
16 août-31 août	13	13/29 = 0.45
1 septembre-15 septembre	15	15/29 = 0.52
16 septembre-30 septembre	12	12/29 = 0.41

5.2.2.1.3 Calcul des facteurs d'achalandage du matin $f_{p,matin}$ et du soir $f_{p,soir}$ à partir du facteur d'achalandage du midi $f_{p,midi}$ en 1994 et 1995

L'achalandage touristique n'est pas constant au cours d'une même journée. La période favorite des clients excursionnistes se situe entre 10 h et 16 h. C'est à cette période que l'on retrouve les plus grandes agrégations de bateaux sur l'eau. Ceci explique en partie la stratégie d'échantillonnage des AOM du GREMM ces dernières années (excursions du « midi » seulement pour les ports de Tadoussac, Bergeronnes et l'Anse aux Basques) et l'absence dans la base AOM 2007 d'excursions échantillonnées le matin ou le soir. Cependant, en 1994 et 1995, des excursions réparties sur toute la journée ont été échantillonnées dans le projet AOM, offrant le moyen de corriger le facteur $f_{p,h}$ en fonction de l'heure le journée. En notant les agrégations maximales de bateaux pour chaque période en 1994 et 1995 en fonction de la tranche horaire, il est possible d'ajuster $f_{p,h}$ pour tenir compte de la variabilité quotidienne de l'achalandage touristique. Ainsi, dépendamment de la plage horaire h du départ d'une excursion et de la période p considérée, un facteur corrigé $f_{p,h}$ est calculé. La journée est divisée en trois périodes :

1. Avant 10 h (matin) ➔ $f_{p,matin}$.
2. De 10 h à 16 h (midi) ➔ $f_{p,midi}$.
3. Après 16 h (soir) ➔ $f_{p,soir}$.

L'hypothèse principale pour évaluer les $f_{p,h}$ à partir de $f_{p,midi}$ est la suivante :

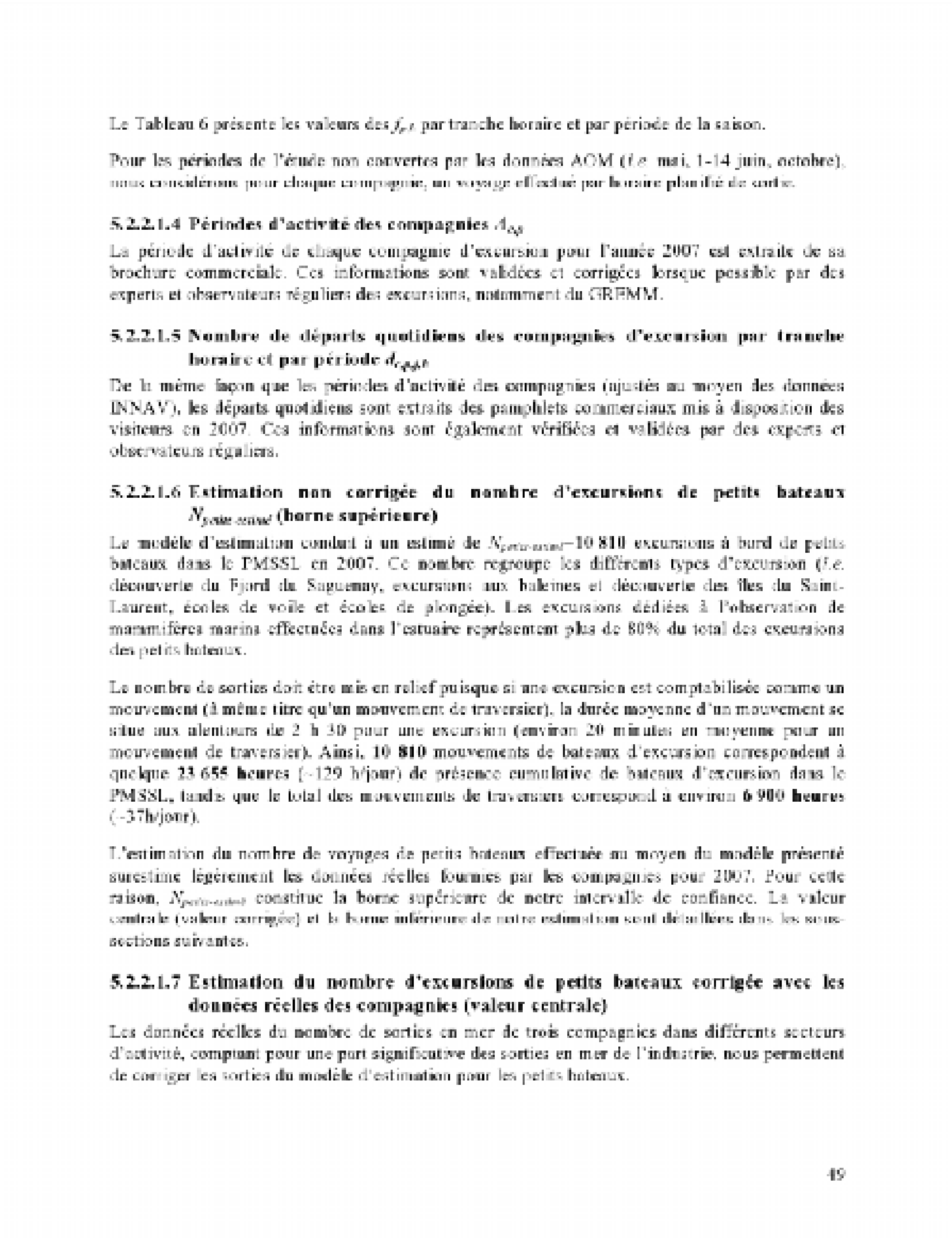
- les fluctuations journalières de l'achalandage touristique en 2007 étaient similaires à celles mesurées en 1994 et 1995.

Le calcul de $f_{p,h}$ est donné par la formule suivante :

$$f_{p,h} = f_{p,midi} \times \frac{\lambda_{max,p,h}}{\lambda_{max,p,midi}}$$

Tableau 6 :
Facteur d'achalandage touristique $f_{p,h}$ ajusté selon heure et la période.

	$\lambda_{max,p,midi}$ 2007	$\lambda_{max,p,midi}$ 1994-95	$\lambda_{max,p,matin}$ 1994-95	$\lambda_{max,p,soir}$ 1994-95	$f_{p,midi}$ 2007	$f_{p,matin}$ 2007	$f_{p,soir}$ 2007
15 juin- 30 juin	8	9	6	7	**0.28**	0.67× $f_{p,midi}$= 0.19	0.78× $f_{p,midi}$= **0.22**
1^{er} juillet- 15 juillet	15	12	10	10	**0.52**	0.83× $f_{p,midi}$= 0.43	0.83× $f_{p,midi}$= **0.43**
16 juillet- 31 juillet	20	14	8	12	**0.69**	0.57× $f_{p,midi}$= 0.39	0.6× $f_{p,midi}$= **0.41**
1^{er} août 15 août	23	22	12	14	**0.79**	0.55× $f_{p,midi}$= 0.43	0.64× $f_{p,midi}$= **0.51**
16 août 31 août	13	13	8	13	**0.45**	0.62× $f_{p,midi}$= 0.28	1× $f_{p,midi}$= **0.45**
1^{er} septembre - 15 septembre	15	8	5	7	**0.52**	0.63× $f_{p,midi}$= 0.33	0.88× $f_{p,midi}$= **0.46**
16 septembre- 30 septembre	12	11	4	9	**0.41**	0.36× $f_{p,midi}$= 0.15	0.82× $f_{p,midi}$= **0.34**



Le Tableau 6 présente les valeurs des $f_{p,t}$ par tranche horaire et par période de la saison.

Pour les périodes de l'étude non couvertes par les données AOM (*i.e.* mai, 1-14 juin, octobre), nous considérons pour chaque compagnie, un voyage effectué par horaire planifié de sortie.

5.2.2.1.4 Périodes d'activité des compagnies $A_{c,p}$

La période d'activité de chaque compagnie d'excursion pour l'année 2007 est extraite de sa brochure commerciale. Ces informations sont validées et corrigées lorsque possible par des experts et observateurs réguliers des excursions, notamment du GREMM.

5.2.2.1.5 Nombre de départs quotidiens des compagnies d'excursion par tranche horaire et par période $d_{c,p,h,t}$

De la même façon que les périodes d'activité des compagnies (ajustés au moyen des données INNAV), les départs quotidiens sont extraits des pamphlets commerciaux mis à disposition des visiteurs en 2007. Ces informations sont également vérifiées et validées par des experts et observateurs réguliers.

5.2.2.1.6 Estimation non corrigée du nombre d'excursions de petits bateaux $N_{petit\text{-}estimé}$ (borne supérieure)

Le modèle d'estimation conduit à un estimé de $N_{petit\text{-}estimé}$=10 810 excursions à bord de petits bateaux dans le PMSSL en 2007. Ce nombre regroupe les différents types d'excursion (*i.e.* découverte du Fjord du Saguenay, excursions aux baleines et découverte des îles du Saint-Laurent, écoles de voile et écoles de plongée). Les excursions dédiées à l'observation de mammifères marins effectuées dans l'estuaire représentent plus de 80% du total des excursions des petits bateaux.

Le nombre de sorties doit être mis en relief puisque si une excursion est comptabilisée comme un mouvement (à même titre qu'un mouvement de traversier), la durée moyenne d'un mouvement se situe aux alentours de 2 h 30 pour une excursion (environ 20 minutes en moyenne pour un mouvement de traversier). Ainsi, **10 810** mouvements de bateaux d'excursion correspondent à quelque **23 655 heures** (~129 h/jour) de présence cumulative de bateaux d'excursion dans le PMSSL, tandis que le total des mouvements de traversiers correspond à environ **6 900 heures** (~37h/jour).

L'estimation du nombre de voyages de petits bateaux effectuée au moyen du modèle présenté surestime légèrement les données réelles fournies par les compagnies pour 2007. Pour cette raison, $N_{petit\text{-}estimé}$ constitue la borne supérieure de notre intervalle de confiance. La valeur centrale (valeur corrigée) et la borne inférieure de notre estimation sont détaillées dans les sous-sections suivantes.

5.2.2.1.7 Estimation du nombre d'excursions de petits bateaux corrigée avec les données réelles des compagnies (valeur centrale)

Les données réelles du nombre de sorties en mer de trois compagnies dans différents secteurs d'activité, comptant pour une part significative des sorties en mer de l'industrie, nous permettent de corriger les sorties du modèle d'estimation pour les petits bateaux.

Les données réelles étant ventilées par mois, un facteur de correction mensuel est calculé pour ces trois compagnies pour corriger les sorties de notre modèle d'estimation associées aux autres compagnies. Les estimés pour les compagnies de chaque secteur d'activité sont corrigés au moyen des données réelles de la compagnie dont les produits offerts sont les plus similaires.

La valeur ainsi corrigée est appelée la valeur centrale de notre estimation. Cette valeur est **10 177** excursions effectuées à partir de petites embarcations ($\leq$48 places).

5.2.2.1.8 Estimation du nombre minimum d'excursions de petits bateaux (borne inférieure)

Pour établir la borne inférieure de notre estimation du nombre d'excursions effectuées à partir des petits bateaux, nous avons considéré toutes les compagnies pour lesquelles la validation des chiffres corrigés n'a pas pu être réalisée par des informations pertinentes ou des données. Pour ces compagnies, nous avons considéré le nombre minimal de sorties en mer, à savoir une excursion d'un bateau par créneau horaire planifié par jour d'activité. Pour les compagnies offrant des départs de Baie-Sainte-Catherine, un estimé conservateur est produit à partir des données du quai en suivant la méthode décrite dans la section 5.2.1.3 pour les grands bateaux d'excursion. Pour les compagnies dont le nombre réel des sorties a été fourni, ces valeurs ont été conservées.

La borne inférieure de cette estimation est 9 549 excursions effectuées par des petits bateaux.

5.2.3 Nombre total de voyages de bateaux d'excursion (grands et petits)

En raison de la différence de dynamique liée aux départs des excursions des différents types de bateaux d'excursion (grands *vs* petits), l'estimation a été divisée en 2 étapes (*cf.* sections 5.2.1 et 5.2.2). Selon les deux modèles d'estimation proposés, le nombre total de sorties en mer $N_{total\ excursions}$ effectuées par les compagnies détentrices d'un permis d'entreprise d'excursion de plus de 10 jours est compris dans l'intervalle :

$$N_{total\ excursions} \in [12\ 131\ ;\ 14\ 015]$$

La valeur centrale finale est 13 073 excursions commerciales dans le PMSSL en 2007.

Plusieurs séries de vérifications ont été conduites avec succès en recoupant diverses informations provenant de jeux de données afin de valider ces estimés.

5.2.4 Évolution depuis 1993

5.2.4.1 Comparaison de l'estimation du nombre d'excursions 1993-2007

À notre connaissance, aucun recensement exhaustif des sorties d'excursions en mer n'a été effectué depuis ces années. Malgré tout, en 1998, les capitaines d'excursion devaient se rapporter au centre de Services de Communications et Trafic Maritimes (SCTM) le plus proche (Québec ou Les Escoumins). Ainsi, en 1998, le total des sorties rapportées au SCTM Escoumins était d'environ 9000 (Dionne 2001). Il s'agit d'une sous-estimation du nombre réel puisque certaines excursions sortant dans la section Sud des limites actuelles du PMSSL (Rivière-du-Loup) se rapportaient au SCTM de Québec et que certains capitaines ne rapportaient pas leur excursion; ceci rend difficile l'estimation d'une marge d'erreur associée à cette valeur conservatrice de 9000 excursions. Toutefois, le nombre estimé dans notre étude (13 073) indique une augmentation des excursions commerciales à l'intérieur des limites du PMSSL depuis 1993, année au cours de laquelle une estimation d'environ 5000 sorties de bateaux d'excursion avait été faite (GREMM 1993).

5.2.4.2 Comparaison de l'offre maximale des excursions 1997-2007

Dans le rapport de Tecsult Environnement Inc. (Tecsult Environnement Inc. 2000) effectué dans le cadre du projet pilote de Zone de protection marine Estuaire en 2000, un recensement de toutes les compagnies offrant des excursions dans l'estuaire a été effectué, incluant les caractéristiques des compagnies (période d'activité, détail de la flotte, détail des secteurs de navigation…). Les auteurs de ce rapport ont calculé une offre maximale de départs d'excursion pour le PMSSL et l'aire de coordination de 12 112 excursions; cette valeur ne peut pas être comparée avec notre estimation de 13 073 excursions puisqu'il s'agit de l'offre maximale en 1997 et que la couverture spatiale des activités est différente de celle de notre étude (PMSSL seulement dans notre cas).

Les offres maximales *OM* calculées précédemment pour les petits et les grands bateaux sont reprises dans cette étude comparative pour 2007. Pour le calcul de 1997, avant la création du PMSSL, seules les compagnies proposant des activités dans les limites actuelles du PMSSL ont été retenues dans le rapport (Tecsult Environnement Inc. 2000) pour la comparaison afin de ne pas biaiser les résultats.

La Figure 7 témoigne d'un potentiel de départs d'excursion supérieur de 7% en 2007 comparativement à 1997. Bien qu'elles ne représentent pas les nombres réels de départs d'excursion commerciale, ces valeurs nous indiquent que l'offre des compagnies, disponible en 2007 était supérieure à celle de 1997. De plus, l'industrie ayant maturé au cours des 10 dernières années, on peut supposer que les gestionnaires des compagnies ont su adapter au fil des ans leur flotte, le nombre de départs quotidiens et les heures de départs, en fonction de la demande. On constate que plusieurs compagnies n'opèrent plus (rachetées pour la plupart) depuis 1997 (Tecsult Environnement Inc. 2000), suggérant là aussi une forme d'adaptation de l'offre à la demande touristique, par un processus de sélection. Enfin, la répartition des différentes compagnies dans les ports de la région a aussi subi des changements en réponse à la localisation de la demande touristique. Ces faits suggèrent que le ratio *excursions effectuées/offre maximale* augmente au fil du temps, à mesure que cette industrie gagne en maturité et que les gestionnaires des opérations des différentes compagnies optimisent et affinent leurs produits pour réduire leurs coûts. Ainsi, il est probable que l'augmentation du nombre réel d'excursions effectuées en 2007 soit supérieure à l'augmentation de 7% du potentiel maximal de l'effort. C'est ce que suggèrent les résultats présentés dans la sous-section précédente où l'augmentation du nombre réel est estimée à 25%.

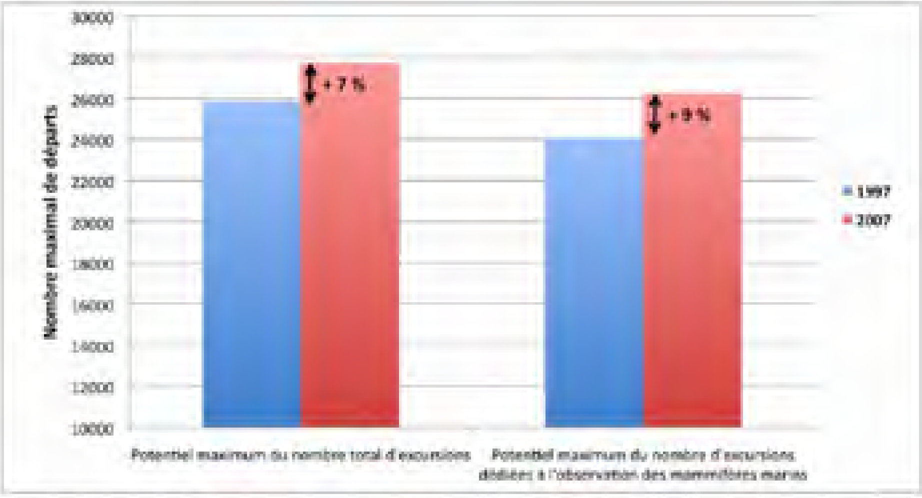


Figure 7 : Comparaison de l'offre maximale d'excursions commerciales dans les limites du PMSSL en 1997 et 2007. L'augmentation du nombre potentiel d'excursions dédiées à l'observation des mammifères marins est plus importante que lorsque tous les types d'excursion sont considérés (respectivement + 9% et + 7%).

Concernant l'achalandage touristique qui n'est pas considéré dans la discussion précédente, la récente étude sur l'estimation de la fréquentation du PMSSL en 2005 (Gosselin 2006), conduit à un total de 449 896 visiteurs du circuit de découverte maritime du PMSSL (incluant excursionnistes, croisiéristes et plaisanciers) en 2005, contre 432 876 en 2003. Bien que les méthodes d'estimation diffèrent, ces chiffres suggèrent que le nombre de visiteurs sur l'eau entre 2003 et 2005 est assez stable (+ −4%). Entre 2003 et 2007, il y a eu une augmentation de 18% du nombre de touristes à bord des croisières internationales sur le Saint-Laurent (Business Research & Economic Advisors 2008). La contribution des visiteurs plaisanciers est faible comparée aux deux autres composantes (*cf.* (Gosselin 2006) p.5), l'absence de données sur leur tendance n'est donc pas un problème majeur. Le nombre de visiteurs faisant des excursions commerciales dans le PMSSL a connu une baisse depuis 2000, passant approximativement de 350 000 en 2001 à 260 000 en 2005 et à 274 000 en 2009 (communication personnelle, D. Gosselin, Parcs Canada).

Pour synthétiser, les éléments trouvés dans la littérature et les informations extraites des bases de données indiquent une hausse de l'offre maximale des excursions en mer dans le PMSSL jusqu'en 2007, associée à une baisse du nombre de touristes de ces excursions depuis 2001. Le nombre d'excursions commerciales est passé d'environ 5 000 départs en 1993 à environ 13 000 en 2007, mais la tendance réelle du nombre de ces sorties en mer reste difficile à estimer pour les dernières années. Après avoir atteint son pic entre la fin des années 90 et le début des années 2000, l'industrie des excursions commerciales du PMSSL semble connaître un déclin, caractérisant une industrie touristique ayant dépassé son stade de maturité (Hoyt 2009). Le nombre de touristes d'excursion commerciale semble s'être stabilisé entre 2005 et 2009 (communication personnelle, D. Gosselin, Parcs Canada).

5.3 Analyse temporelle

L'essentiel des excursions planifiées (excluant les départs sur demande) a lieu en journée dans l'intervalle [6h-20h], sauf pour le cas des sorties nocturnes exceptionnellement offertes par certaines compagnies. Le potentiel maximal du nombre de bateaux d'excursion, activités et ports d'attache confondus est représenté par la Figure 8.

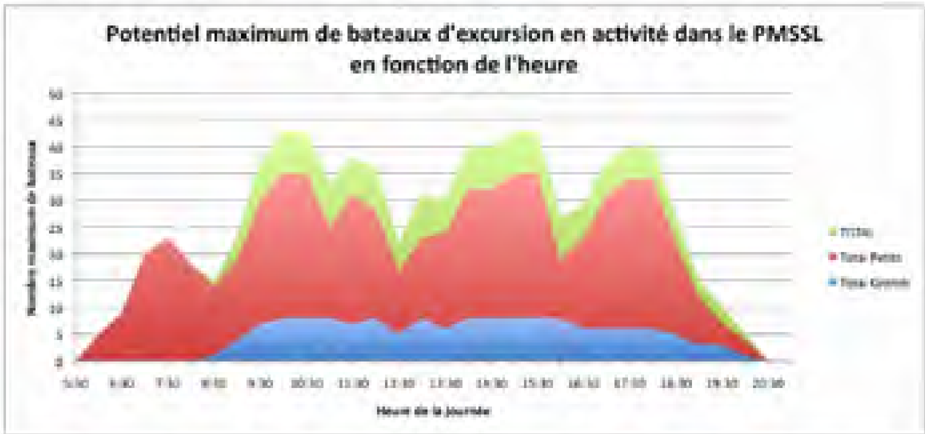


Figure 8 : Potentiel maximal de bateaux d'excursion en activité dans le PMSSL, d'après la flotte et les horaires d'excursion des compagnies pendant la haute saison (juillet-août).

La Figure 8 indique trois pics majeurs d'activités pour les petits bateaux d'excursion :

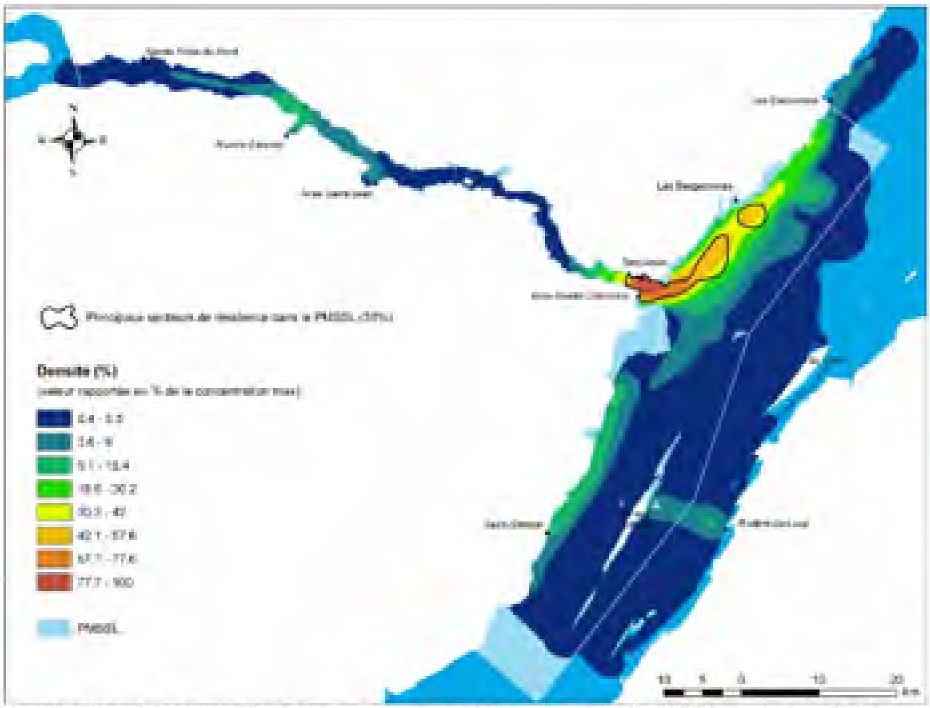
- Entre 9 h et 11h
- Entre 14 h et 16 h
- Entre 17 h et 18 h 30

Pour les grands bateaux d'excursion, l'activité maximale potentielle est plus constante dans le temps et est réduite à l'intervalle [8h30-20h]. Concernant les excursions dédiées à l'observation de mammifères marins seulement, le portrait est semblable puisque la majeure partie de la flotte des bateaux d'excursion est dédiée à cette activité. Il est donc intéressant de constater que la plupart des grands bateaux d'excursion sortent en mer après les petits bateaux plus mobiles, leur laissant le temps de localiser les mammifères marins.

5.4 Analyse spatiale

La Carte 6 indique une concentration des activités des excursionnistes dans le secteur de l'embouchure, ainsi qu'à la tête du chenal Laurentien, ce qui est mis en relief dans le cadre du suivi des activités en mer. Les zones principales d'activité (30% du temps de résidence total) ont été localisées dans l'embouchure pour la plupart, ainsi qu'à la tête du chenal Laurentien. Le secteur au large de Les Bergeronnes ressort également comme un secteur favorisé par les excursionnistes, particulièrement ceux des marinas de Bergeronnes et de l'Anse aux Basques. Finalement, on remarque que les attraits touristiques dans le Saguenay, les abords de l'Île aux

Lièvres ainsi que la Côte de Charlevoix ressortent comme des secteurs secondaires non négligeables.



Carte 6 : Densité des sorties des excursions commerciales dans l'ensemble du PMSSL. (Source : AOM; rayon de recherche = 3000 mètres; résolution du raster créé = 100m). Les valeurs de densité ont été normalisées par la densité maximale (%). L'échelle de couleur repose sur une classification géométrique non linéaire pour faire ressortir les zones d'activité secondaires. L'ensemble des polygones noirs représente 30% du temps passé sur l'eau dans les limites du PMSSL. Pour trois bateaux, les données de 2005 ont été utilisées en raison de leur absence dans l'échantillonnage de 2007. En raison de l'absence de données pour le bateau d'une compagnie, sa trajectoire a été reconstituée manuellement à partir des informations fournies sur son site Internet. Chaque trajectoire a été pondérée par rapport au nombre total de sorties par bateau (ou par type de bateau pour certaines compagnies de pneumatiques). Les principaux secteurs de résidence temporelle sont l'embouchure de la rivière Saguenay, et les secteurs d'observation proche de la côte à tête du Chenal Laurentien et au large de la marina de Bergeronnes. Les autres secteurs fréquentés par les excursions font ressortir les secteurs d'observation de baleines au large de Les Bergeronnes, d'Anse à la Cave et la côte de Charlevoix. Les attraits touristiques comme l'Île aux Lièvres et le Cap Trinité sont également fréquentés.

5.5 Mise à jour 2009

Depuis 2009, une compagnie offre de nouveaux départs à partir de la marina de Tadoussac, dédiés à la découverte du Fjord du Saguenay, ajoutant environ 200 excursions par saison dans le PMSSL et 400 passages dans l'embouchure. La flotte de bateaux au départ de Tadoussac pourrait encore grossir puisqu'une des compagnies déjà implantées à cette marina a racheté le bateau et le permis d'une compagnie précédemment active à partir de l'Anse aux Basques.

6 Bateaux de plaisance

6.1 Détail de la flotte

Les informations concernant la navigation de plaisance proviennent d'une étude réalisée par la firme SOM et pilotée par Daniel Gosselin (Parcs Canada) (Gosselin 2006). En 2006, des plaisanciers des marinas bordant le PMSSL ont été invités à remplir des questionnaires visant à caractériser leurs sorties en mer effectuées dans le PMSSL. Certains plaisanciers ont accepté d'enregistrer leur trajectoire au moyen d'un bâton *track stick*. Ce dispositif permet de recueillir chaque minute, la position, la vitesse et la direction du bateau échantillonné.

Au total, 186 questionnaires ont été complétés pour 26 trajectoires *track sticks* exploitables. Le Tableau 7 permet de juger de la représentativité des trajectoires recueillies par rapport à l'échantillon des plaisanciers interrogés. On constate que hormis pour les marinas de Cap-à-l'Aigle et de La Baie, les données relatives aux répondants sont très similaires à celles relatives aux plaisanciers ayant enregistré leur trajectoire.

Tableau 7 :
Caractéristiques des répondants (questionnaires) et des trajectoires recueillies

	Questionnaires	Trajectoires
Lieu de résidence	**n:181**	**n:26**
	%	%
RMR de Québec	19	27
RMR de Montréal	17	8
Ville Saguenay	13	23
Littoral du Saguenay	6	4
Rive Nord du Saint-Laurent	3	23
Rive-Sud du Saint-Laurent	3	
Ailleurs au Québec	34	
États-Unis	3	8
Type d'embarcation	**n:186**	**n:26**
	%	%
Voilier	74	77
Vedette de croisière (*cruiser*)	26	23
Longueur d'embarcation	**n:185**	**n:26**
	%	%
1 à 29 pieds	43	46
30 pieds ou plus	57	54

	Questionnaires	Trajectoires
Marina	**n:186**	**n:26**
	%	%
Tadoussac	38	39
Cap-à-l'Aigle	31	8
Anse-St-Jean	15	16
La Baie	9	35
Bergeronnes	7	4
Type de répondant	**n:186**	**n:26**
	%	%
Plaisancier touriste	80	81
Plaisancier saisonnier	20	19
Nombre de séjours dans PMSSL	**n:185**	**n:26**
	%	%
1 fois	19	23
2 à 19 fois	46	35
20 à 99 fois	20	27
100 fois ou plus	15	15

6.2 Quantification du nombre de voyages

Tableau 8 :
Nombre de visiteurs plaisanciers dans le PMSSL par catégorie
(extrait de (Gosselin 2006))

	Plaisanciers saisonniers (S)	Plaisanciers touristes (T)	Nombre de jours-visites
Mai	350	50	400
Juin	1 850	150	2 900
Juillet	2 985	1 415	8 500
Août	2 955	1 445	9 700
Septembre	1 200	500	2 500
Octobre	300	-	300
SOUS-TOTAL	9 640	3 560	-
TOTAL	13 200		24 300

Tableau 9 :
Estimation du nombre total de mouvements de bateaux de plaisance dans le PMSSL,
entre mai et octobre 2006

	Nombre de sorties des *saisonniers* (Nombre moyen de passagers à bord du bateau)	Nombre de sorties des *touristes* (Nombre moyen de passagers à bord du bateau)
Mai	87.5 (4 pers./sortie)	25 (2 pers./sortie)
Juin	755.1 (2.45 pers./sortie)	320.1 (3.28 pers./sortie)
Juillet	1 243.8 (2.40 pers./sortie)	2 137.6 (2.58 pers./sortie)
Août	1 226.1 (2.41 pers./sortie)	2 554.9 (2.64 pers./sortie)
Septembre	412.4 (2.91 pers./sortie)	439.2 (2.96 pers./sortie)
Octobre	75 (4 pers./sortie)	-
SOUS-TOTAL	3 800	5 477
TOTAL	9 277 sorties	

Tel que précisé précédemment, les données disponibles pour la plaisance datent de 2006 et sous l'hypothèse réaliste que l'affluence et la dynamique des plaisanciers en 2007 étaient similaires à celle de 2006, ces données servent de base aux analyses suivantes.

L'estimation de l'affluence des plaisanciers touristes en 2006 était de 24 300 jours-visites dans le PMSSL pour l'ensemble de la saison. La ventilation de ces estimations est présentée dans le Tableau 8.

Tel que décrit dans le Tableau 7, les plaisanciers se divisent en 20% de *saisonniers* pour 80% de *touristes*. Un plaisancier est dans la classe *touriste* lorsque son port d'attache n'est pas une des sept (7) marinas bordant le PMSSL (*i.e.* Rivière-du-Loup, Chicoutimi, Tadoussac, Cap-à-l'Aigle, Bergeronnes, Anse-Saint-Jean et La Baie), sans quoi il est dans la classe *saisonnier*. L'affluence des touristes est estimée en nuitées d'amarrage tandis que l'affluence des saisonniers est estimée à partir des abonnements dans les marinas.

Tableau 10 :
Influence de la hauteur de vague sur la présence de plaisanciers en mer, dans l'estuaire (données AOM) et dans l'embouchure (données de Pointe-Noire)

	Conditions de navigation favorables	Conditions de navigation difficiles
Nombre de points dans la base AOM (2007)	3 165	245
Nombre moyen de plaisanciers par point AOM (2007)	0.55	0.07
Nombre moyen de kayaks par point AOM (2007)	2.63	0.28
Nombre de plaisanciers/jour vus dans l'embouchure dans les données de Pointe-Noire (2004)	21.03 (55 jours)	10.06 (10 jours)
Nombre de kayaks/jour vus dans l'embouchure dans les données de Pointe-Noire (2004)	34.49	6.6

Au total, pour les cinq (5) marinas majeures bordant le PMSSL, il y avait 189 embarcations en 2006 qui appartenaient à des saisonniers et 2 975 nuitées ont été vendues à des plaisanciers de passage (484 à des saisonniers hors de leur marina d'attache et 2 491 à des plaisanciers touristes). En moyenne, chaque touriste a effectué 2.7 nuitées dans une des marinas du PMSSL. Au total, 59 saisonniers et 127 touristes ont été sondés, ce qui correspond à environ 31% du nombre total de saisonniers (59/189) et 14% des touristes (127/(2 491/2.7)).

Pour estimer le nombre de mouvements effectués chaque mois par les plaisanciers saisonniers, on divise simplement leur nombre de visites chaque mois par le nombre moyen de personnes à bord du bateau de saisonnier (pour le mois considéré).

Pour estimer le nombre de mouvements effectués chaque mois par les plaisanciers touristes, on divise le nombre de jours-visites (effectués par cette catégorie) par le nombre moyen de personnes par bateau de touriste (pour le mois considéré).

Les différentes valeurs utiles à ces calculs sont extraites par requête dans SPSS 16.0.1 sur la base de données des questionnaires remplis par les plaisanciers, ou bien dans le rapport final de l'étude sur la caractérisation des plaisanciers qui naviguent dans le PMSSL (Gosselin *et al.* 2007). Les résultats sont présentés dans le Tableau 9.

D'après le Tableau 9, le nombre total de sorties effectuées par des plaisanciers en 2006 est de **9 277**. La marge d'erreur associée à l'estimation du nombre de visites (13 200) est de 47% avec une confiance de 95%. Par conséquent, le nombre de sorties (9 277), calculé à partir de cette estimation du nombre de visites dans le PMSSL, est accompagné d'une marge d'erreur importante pour un niveau de confiance de 95%; cette valeur centrale doit donc être considérée avec son intervalle de confiance [4 917; 13 637] sorties de plaisanciers.

6.3 Analyse temporelle

6.3.1 Temps de résidence cumulatif des bateaux de plaisance

Tableau 11 :
Temps cumulatif de résidence des plaisanciers dans le PMSSL, ventilé par mois

	Nombre d'heures dans le PMSSL
Mai	421
Juin	4 121
Juillet	14 341
Août	16 237
Septembre	3 491
octobre	260
TOTAL	**38 871** heures

À partir des trajectoires recueillies, il est possible d'estimer la durée moyenne des sorties en mer pour chaque type de plaisancier. Après calcul du temps passé par chaque trajectoire dans le PMSSL, le temps cumulatif mensuel de résidence des plaisanciers dans le PMSSL est compilé et présenté dans le Tableau 11. À titre indicatif, le temps cumulatif de navigation des traversiers (Rivière-du-Loup—Saint-Siméon et Baie-Sainte-Catherine—Tadoussac) dans le PMSSL pendant la période d'intérêt est d'environ 4000 heures, c'est à dire de l'ordre de 10 fois moins que le temps total de résidence estimé pour les plaisanciers de **38 871** heures. Ces valeurs (temps de résidence cumulatif) servent aux analyses présentées dans les sections 10 et 11.

6.3.2 Variabilité temporelle (saisonnière et journalière)

Si la saison de plaisance s'étend du mois de mai au mois d'octobre, la période la plus achalandée se situe en juillet et août (75% des visites de toute la saison). Les Tableau 9 et Tableau 11 illustrent bien ce phénomène. Toutefois, les questionnaires ayant été remplis entre le 20 juillet et le 2 septembre, il existe un certain biais d'échantillonnage ayant tendance à surreprésenter les plaisanciers naviguant durant cette période, au détriment des mois de mai, juin, septembre et octobre. En effet, il est plus probable d'échantillonner un plaisancier visitant le PMSSL en août si celui-ci est rejoint par le sondeur en août.

Une autre source de fluctuation du nombre de sorties en mer est l'heure de la journée. D'après l'analyse temporelle des trajectoires, les plaisanciers semblent préférer naviguer en avant-midi (plus de 70% des points échantillonnés). Il est toutefois possible que ces données présentent un biais dans le cas où un plaisancier quittant la marina tôt le matin pour naviguer toute la journée, stoppe l'enregistrement de sa trajectoire lors de leur première escale pour remettre le *track stick* à la marina intermédiaire (la méthodologie de retour des *track sticks* se faisait par dépôt dans une des sept marinas bordant le PMSSL). Dans une telle situation, bien que sa journée de navigation ne soit pas terminée, seules les données du matin seraient alors enregistrées.

6.3.3 Variabilité liée aux conditions météorologiques

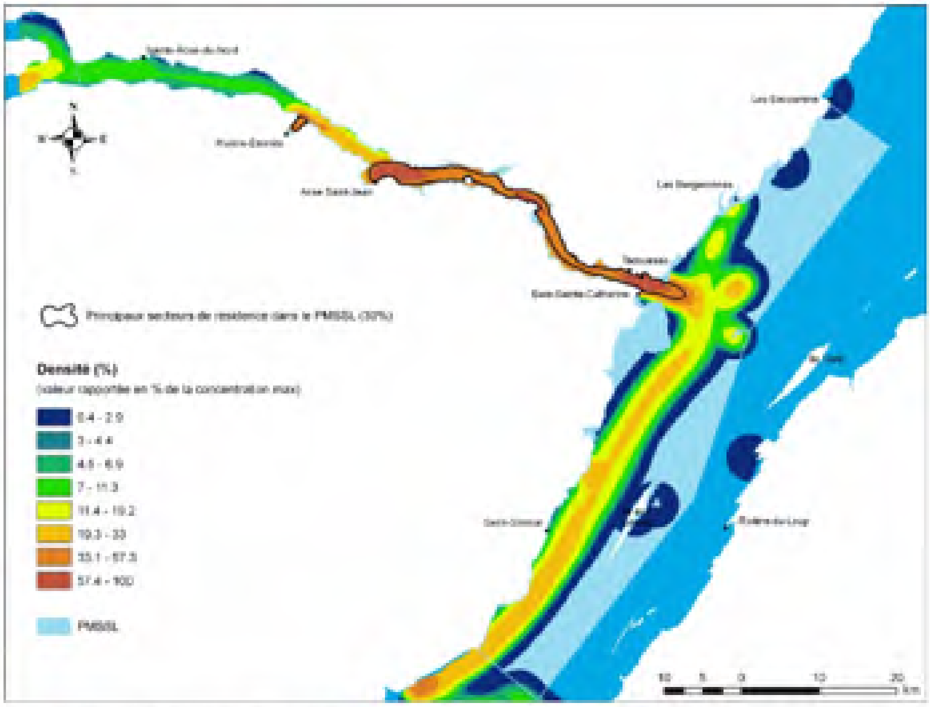
L'affluence des plaisanciers sur les eaux du PMSSL est fortement corrélée aux conditions météorologiques et particulièrement aux conditions de navigation. Ce phénomène peut être mis en évidence dans l'estuaire au moyen des données AOM. Toutes les 10 minutes, à bord du bateau échantillonné, le technicien relève la hauteur des vagues ainsi que la visibilité. Il relève également le nombre de plaisanciers dans un rayon de 2000 mètres autour du bateau échantillonné. Ainsi, en s'assurant de ne conserver que les points échantillonnés en 2007 dont la visibilité était supérieure ou égale à 2000 mètres, on peut faire les deux (2) classes suivantes :

1. Hauteur de vague <u>inférieure strictement</u> à 30 cm : conditions de navigation favorables.
2. Hauteur de vague <u>supérieure ou égale</u> à 30 cm : conditions de navigation difficiles.

Pour chacune de ces deux classes, on peut faire la moyenne du nombre de plaisanciers dans un rayon de 2000 mètres par point d'observation. Cela nous donne une mesure relative de la présence de plaisanciers sur l'eau en fonction des conditions météorologiques. Les valeurs pour chaque classe sont consignées dans le Tableau 10. On note clairement l'impact de la hauteur des vagues sur la présence de plaisanciers. On constate que cette influence est beaucoup plus prononcée dans l'estuaire (facteur 8) que dans l'embouchure (facteur 2). À titre indicatif, on voit que la présence de kayaks de mer est également moins fréquente, par un facteur 9 dans l'estuaire et un facteur 5 dans l'embouchure.

6.4 Analyse spatiale

Après pondération des trajectoires disponibles pour en assurer la représentativité, la Carte 7 décrit l'occupation du territoire du parc par les plaisanciers. Étant données les conditions souvent difficiles de navigation dans l'estuaire, on constate qu'une majorité de plaisanciers reste dans la rivière Saguenay, généralement plus calme. De plus, les paysages magnifiques du Fjord du Saguenay représentent un attrait touristique prisé par les plaisanciers. On constate également qu'il existe un corridor de passage de plaisanciers dans l'estuaire moyen, en amont de Baie-Sainte-Catherine. En effet, de nombreux bateaux de plaisance apprécient la Côte de Charlevoix en parcourant le trajet allant de l'embouchure de la rivière Saguenay à la marina de Cap-à-l'Aigle. C'est la portion du Fjord du Saguenay située entre Rivière-Éternité et Tadoussac qui est la plus densément occupée par les plaisanciers. L'absence de plaisanciers au large du fleuve est un biais d'échantillonnage.



Carte 7 : Densité spatiale des voyages de plaisanciers dans le PMSSL. (Source : SOM-2006 (Gosselin *et al.* 2007); rayon de recherche = 3000 mètres; résolution du raster créé = 100m). Les valeurs de densité ont été normalisées par la densité maximale (%). L'échelle de couleur repose sur une classification géométrique non linéaire pour faire ressortir les zones d'activité secondaires. Cette carte a été obtenue à partir des 26 trajectoires, pondérées pour représenter la proportion des départs par marina. De plus, les endroits privilégiés par les plaisanciers (dans les questionnaires) ont été ajoutés et pondérés proportionnellement au nombre d'excursions. (Source : données sur les plaisanciers, SOM-Parcs Canada). La rivière Saguenay ressort comme la zone principale de navigation pour la plaisance notamment en raison de ses attraits naturels et de ses eaux plus calmes que celles du fleuve. L'Anse-Saint-Jean et l'embouchure du Saguenay sont les deux secteurs les plus utilisés.

7 Navigation reliée aux opérations maritimes

7.1 Détail de la flotte

Cette catégorie regroupe :

- Les bateaux de recherche (ONG, recherche gouvernementale et recherche universitaire);
- Les bateaux de la garde côtière canadienne;
- Les bateaux de surveillance (MPO, Parcs Canada);
- Les bateaux-pilotes (Administration de Pilotage des Laurentides);
- Les autres bateaux de service (Service hydrographique canadien, Dragues…).

Pour les bateaux de cette catégorie, certaines données sont extraites des bases de données AIS-INNAV et PRÉVISION-INNAV. Cependant, compte tenu du fait que certains bateaux n'apparaissent pas dans ces deux bases de données, des informations complémentaires (trajectoires et nombre de sorties en mer) ont dû être obtenues par demande auprès des organismes concernés. Les chiffres présentés sous-estiment malgré tout légèrement le nombre réel de voyages ainsi que la durée de résidence des bateaux de cette composante.

7.2 Quantification du nombre de voyages

Seuls les bateaux de plus de 20 mètres sont obligés de se rapporter au SCTM Escoumins. Ceci implique que les voyages des bateaux de taille inférieure à 20 mètres ne figurent pas dans la base de données de prévision de façon systématique.

Une partie importante des bateaux non comptabilisés dans cette base sont les bateaux-pilotes qui embarquent et débarquent les pilotes à bord des bateaux devant faire appel au service de pilotage (plus de 30 mètres pour les bateaux étrangers et plus de 80 mètres pour les bateaux canadiens).

Dans la base de données AIS-INNAV, le décompte des mouvements des bateaux-pilotes est de **3 244**, ce qui correspond à quelques mouvements près au nombre de voyages de bateaux devant embarquer et débarquer un pilote (marine marchande + croisières internationales + quelques bateaux de la catégorie « Autres »).

Les organismes de recherches dont les relevés sont incomplets dans la base PREVISION-INNAV ont fourni les chiffres de leurs sorties ainsi que les durées; ces valeurs sont simplement additionnées aux valeurs extraites de la base PREVISION-INNAV pour les autres bateaux de cette catégorie.

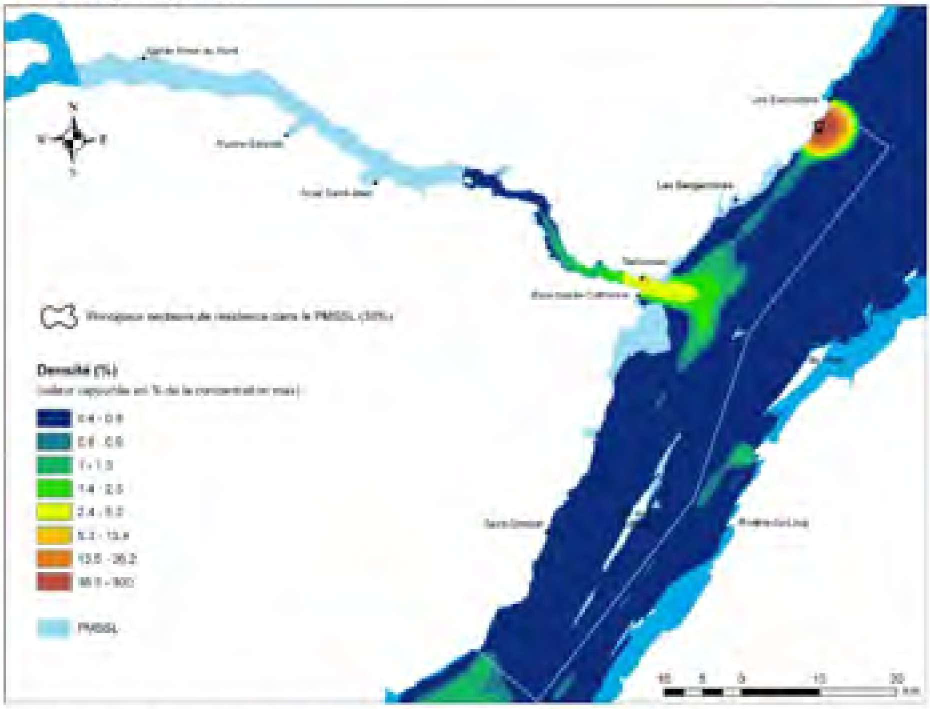
L'estimation du nombre de voyages de bateaux de service (opérations maritimes) est de **3605** mouvements.

7.3 Analyse temporelle

Les bateaux-pilotes sont actifs aux mêmes heures que les navires de la marine marchande, c'est-à-dire que la répartition temporelle de leurs mouvements est presque également répartie selon l'heure de la journée, le jour de la semaine et la période de la saison (*cf* Figure 1, Figure 2, Figure 3).

Les bateaux de patrouille de Parcs Canada sont actifs en journée, principalement aux heures d'opération des bateaux d'excursion, et ce pour toute la période considérée (bien que plus faible en mai et octobre). Cette tendance est la même pour la plupart des bateaux de recherche. Il n'y a pas de tendance particulière dans la distribution temporelle des activités des autres bateaux dédiés aux opérations maritimes.

7.4 Analyse spatiale



Carte 8 : Densité des mouvements des bateaux reliés aux opérations maritimes dans le PMSSL. (Source : données AIS-INNAV; analyse de type *kernel density*; rayon = 3000 mètres; résolution du raster créé = 100m). Les valeurs de densité ont été normalisées par la densité maximale (%). L'échelle de couleur repose sur une classification géométrique non linéaire pour faire ressortir les zones d'activité secondaires. Le secteur de l'Anse aux Basques où les bateaux-pilotes procèdent à l'affectation des pilotes sur les navires en transit ressort comme le principal point chaud. L'embouchure est également utilisée par des bateaux de recherche. L'absence de données en amont de la baie Sainte-Marguerite explique l'absence apparente d'activité dans ce secteur; bien qu'il s'agisse ici d'un biais dû au manque de données, ce secteur supporte moins d'activités que le reste du PMSSL et c'est principalement un pneumatique de la SEPAQ qui le patrouille.

La Carte 8 indique que les bateaux-pilotes actifs dans le secteur des Escoumins représentent la part la plus importante des mouvements dans le PMSSL pour cette composante de la navigation. Le deuxième secteur le plus utilisé par ces activités est l'embouchure du Saguenay. L'estuaire moyen est sous-utilisé par cette composante. L'absence de données en amont de la baie Sainte-Marguerite explique l'absence apparente d'activité dans ce secteur; bien qu'il s'agisse ici d'un biais dû au manque de données, les activités dans ce secteur sont faibles en comparaison du reste du PMSSL.

7.5 Mise à jour 2009

Comme les mouvements de bateaux-pilotes sont proportionnels aux passages de navires requérant le service de pilotage, la baisse du nombre de navires marchands observée en 2008-09 a certainement réduit le nombre de voyages de bateaux-pilotes. Aucun changement majeur ne semble avoir affecté les voyages des autres bateaux de cette catégorie.

8 Kayaks

8.1 Détail de la flotte

Il y avait 14 permis délivrés à des compagnies de kayak en 2007 pour des excursions dans le PMSSL, parmi lesquelles neuf sont situées dans l'aire de coordination du PMSSL (Ménard *et al.* 2007). Aux excursions offertes par ces compagnies s'ajoutent les kayakistes individuels qui accèdent au PMSSL par de nombreux points de mise à l'eau (17 quais, 17 rampes de mise à l'eau et neuf marinas) (Ménard *et al.* 2007).

8.2 Quantification du nombre de voyages

En 2007, on a estimé 44 447 jours-visites de kayakistes dans le PMSSL (communication personnelle, D. Gosselin, Parcs Canada). La situation semble stable entre 2005 et 2009.

8.3 Analyse temporelle

Deux secteurs du PMSSL font l'objet d'un suivi des activités de kayaks (données secondaires); il s'agit de l'embouchure du Saguenay (suivis effectués à partir de Pointe-Noire dans la municipalité de Baie-Sainte-Catherine) et de la baie Sainte-Marguerite sur la rivière Saguenay dans la municipalité de Sacré-Cœur.

Le Tableau 10 met en relief la fluctuation du nombre de kayaks sur l'eau en fonction des conditions de navigation. La période principale d'utilisation de la baie Sainte Marguerite par les kayakistes est de la mi-juillet à la mi-août et cette tendance est stable au fil des ans (Dusque 2006). Dans l'embouchure, les kayakistes sont également présents en plus grand nombre pendant cette même période qui correspond à la période touristique principale (source : données Pointe-Noire, Parcs Canada).

8.4 Analyse spatiale

Les principaux secteurs où ces activités se concentrent sont le Fjord du Saguenay (baie Sainte-Marguerite, l'Anse-Saint-Jean, Baie-Éternité, Anse-de-Roche), l'embouchure (Baie-Sainte-Catherine, Tadoussac) et dans l'estuaire maritime (Cap de Bon-Désir, Anse aux Basques, Anse à la Cave).

8.5 Mise à jour 2009

En 2009, on a estimé 41 747 jours-visites de kayakistes dans le PMSSL, indiquant une légère baisse par rapport à 2007 (communication personnelle, D. Gosselin, Parcs Canada).

9 Autres

Cette catégorie regroupe les bateaux militaires ainsi que les yachts privés de grande taille identifiés dans la base de données PREVISION-INNAV. En raison du manque de données sur les activités de pêche commerciale, la confiance dans les diverses analyses proposées ici est faible. Cette catégorie compte toutefois pour une part marginale des activités de navigation.

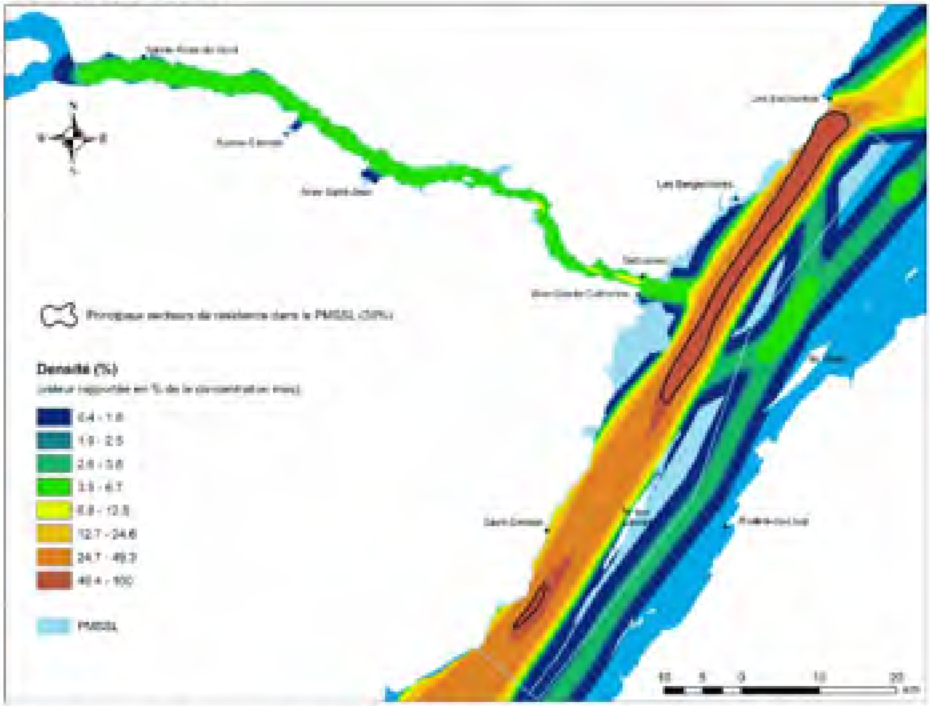
9.1 Quantification du nombre de voyages

Le nombre de voyages extraits de la base de données PRÉVISION-INNAV pour cette catégorie est d'environ **50**. Toutefois, compte tenu du manque de données relatives aux mouvements des bateaux de pêche, ce chiffre sous-estime la réalité.

9.2 Analyse temporelle

Compte tenu du peu de données, aucune analyse temporelle pertinente ne peut être effectuée.

9.3 Analyse spatiale



Carte 9 : Densité des mouvements des bateaux de la catégorie « Autres » dans le PMSSL. (Source : données AIS-INNAV; analyse de type *kernel density*; rayon = 3000 mètres; résolution du raster créé = 100m). Les valeurs de densité ont été normalisées par la densité maximale (%). L'échelle de couleur repose sur une classification géométrique non linéaire pour faire ressortir les zones d'activité secondaires. Le secteur du fleuve situé dans le parc est uniformément utilisé par les bateaux de cette catégorie.

La Carte 9 présente un tableau comparable à celui des navires de la marine marchande dans la mesure où les bateaux qu'on y retrouve ont eu recours pour la majorité au service de pilotage, expliquant cette similarité.

10 Bilan global des activités de navigation dans le PMSSL en 2007

Cette section présente un bilan des analyses effectuées par composante. Il est important de mentionner que les cartes, graphiques et figures présentées dans cette section sont produits à partir des valeurs centrales des estimations du nombre de mouvements des composantes (dans le cas où un modèle a dû être développé).

10.1 Caractérisation des activités de navigation

10.1.1 Quantification du nombre de voyages

Le Tableau 12 présente la synthèse des mouvements de bateaux dans le PMSSL par type. Pour chaque type, un niveau de confiance est donné relativement à l'utilisation de la valeur centrale.

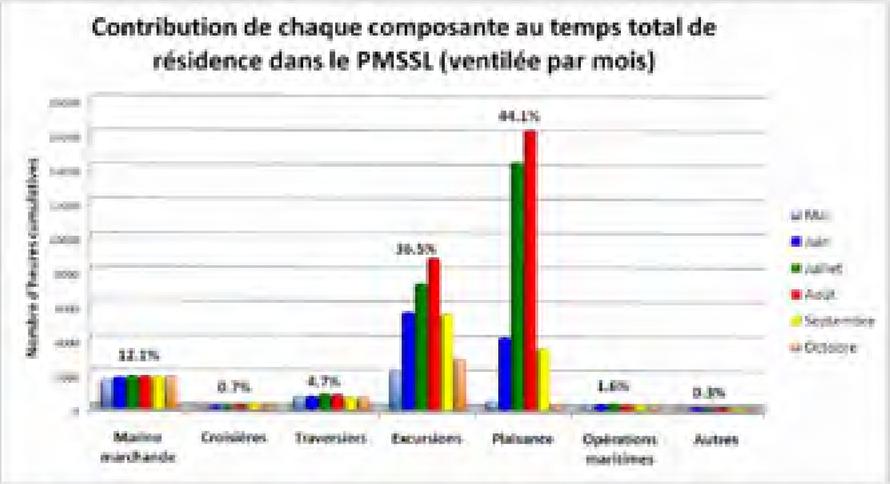


Figure 9 : Contribution de chaque composante au temps total de résidence dans le PMSSL, ventilée par mois. Cette figure utilise les valeurs centrales des estimations du nombre de voyages effectués par chaque composante du trafic maritime.

Dans la Figure 9, la *plaisance* apparaît comme la composante majeure au chapitre du temps de résidence sur l'ensemble de la saison, mais la marge d'erreur associée à l'estimation du nombre de sorties de plaisanciers est élevée (47%). Concernant les composantes *opérations maritimes* et *autres*, le manque de données entraîne leur sous-représentation dans cette figure. Malgré tout, après de nombreuses vérifications effectuées au moyen de plusieurs bases de données, la confiance dans les ordres de grandeur présentés dans la Figure 9 est bonne. Compte tenu de la faible durée des mouvements des traversiers Baie-Sainte-Catherine–Tadoussac, le temps total de navigation (excluant le temps passé aux deux quais) est faible lorsque comparé aux autres composantes majeures. Les *excursions* sont la deuxième composante pour le temps de résidence total et la *marine marchande* la troisième.

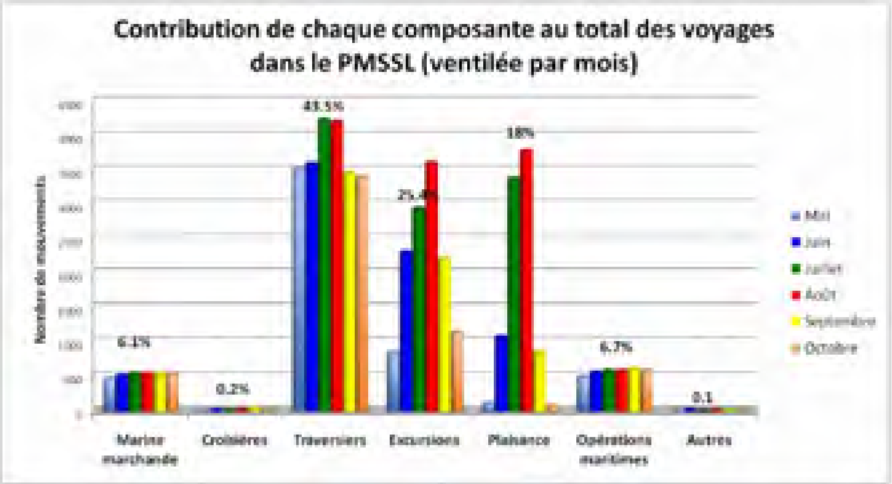


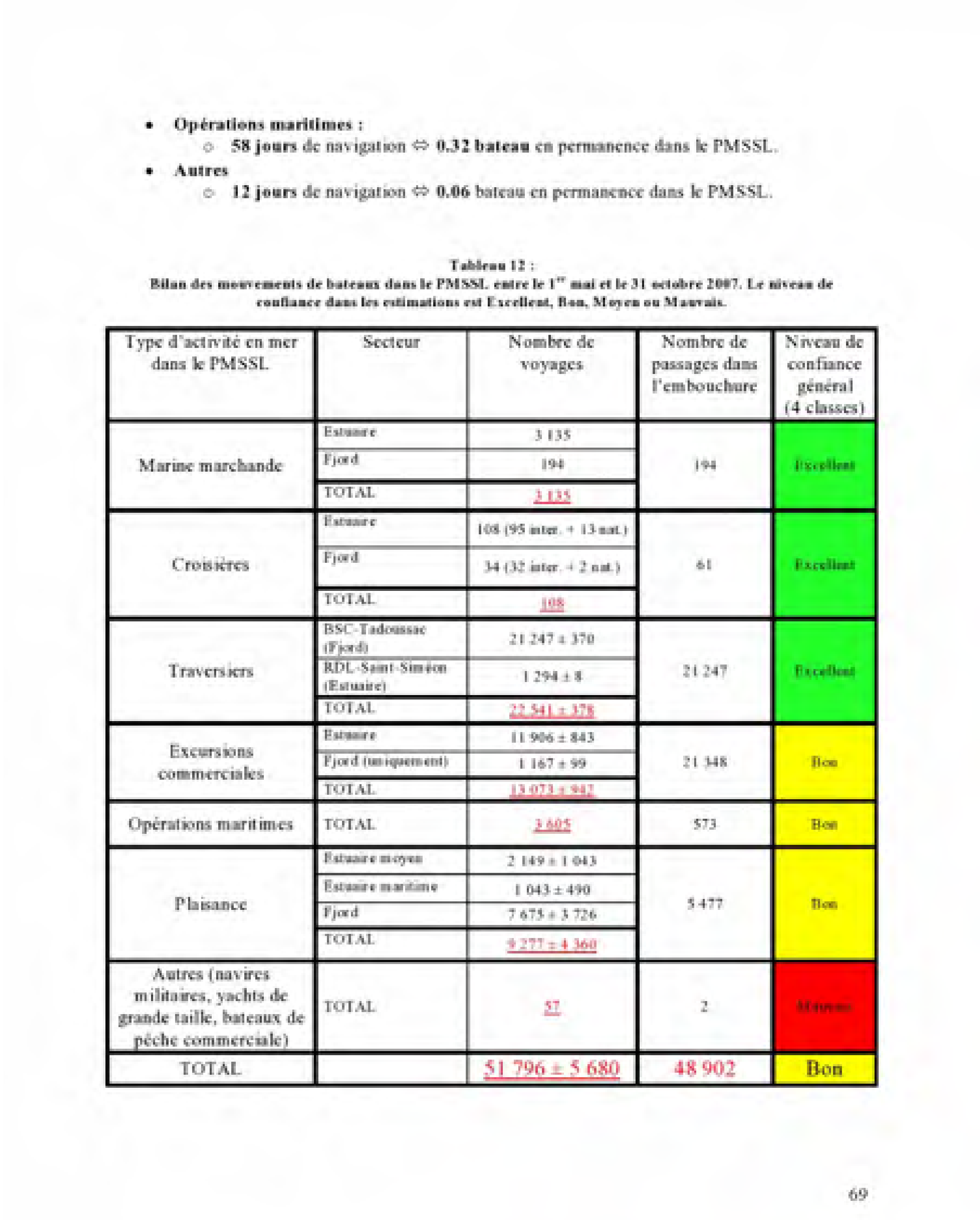
Figure 10 : Contribution de chaque composante au total des voyages dans le PMSSL, ventilée par mois. Cette figure utilise les valeurs centrales des estimations du nombre de voyages effectués par chaque composante du trafic maritime.

La Figure 10 présente la contribution de chaque composante en termes de nombre de mouvements dans le PMSSL. À ce chapitre, les traversiers représentent plus de 43% du total, les excursions arrivant en deuxième position avec plus de 25% et la plaisance en troisième avec 18%. Le bilan général de l'estimation du nombre de voyages est donné dans le Tableau 12 tandis que le temps total de résidence estimé pour chaque composante est donné dans le Tableau 13.

On dénombre ainsi une valeur centrale totale de **51 796** voyages de bateaux de tout type dans le PMSSL pendant la période allant du 1^er^ mai au 31 octobre 2007, comptant pour un estimé de **88 149** heures de temps de mer dans ce secteur.

Le temps de navigation total de chaque composante nous permet de calculer un *nombre équivalent de bateaux de chaque composante présents en permanence dans le PMSSL*. On obtient alors en **moyenne** pour les **184** jours de l'étude :

- **Marine marchande :**
    - **444 jours** de navigation ⇔ **2.41 bateaux** en tout temps dans le PMSSL.
- **Croisières :**
    - **24 jours** de navigation ⇔ **0.13 bateau** en tout temps dans le PMSSL.
- **Traversiers :**
    - **176 jours** de navigation ⇔ **0.96 bateau** en tout temps dans le PMSSL.
- **Excursions :**
    - **1339 jours** de navigation ⇔ **7.28 bateaux** en tout temps dans le PMSSL.
- **Plaisanciers :**
    - **1620 jours** de navigation ⇔ **8.80 bateaux** en tout temps dans le PMSSL.



- **Opérations maritimes :**
    - **58 jours** de navigation ⇔ **0.32 bateau** en permanence dans le PMSSL.
- **Autres**
    - **12 jours** de navigation ⇔ **0.06** bateau en permanence dans le PMSSL.

Tableau 12 :
Bilan des mouvements de bateaux dans le PMSSL entre le 1er mai et le 31 octobre 2007. Le niveau de confiance dans les estimations est Excellent, Bon, Moyen ou Mauvais.

Type d'activité en mer dans le PMSSL	Secteur	Nombre de voyages	Nombre de passages dans l'embouchure	Niveau de confiance général (4 classes)
Marine marchande	Estuaire	3 135	194	Excellent
	Fjord	194		
	TOTAL	3 135		
Croisières	Estuaire	108 (95 inter. + 13 nat.)	61	Excellent
	Fjord	34 (32 inter. + 2 nat.)		
	TOTAL	108		
Traversiers	BSC-Tadoussac (Fjord)	21 247 ± 370	21 247	Excellent
	RDL-Saint-Siméon (Estuaire)	1 294 ± 8		
	TOTAL	22 541 ± 378		
Excursions commerciales	Estuaire	11 906 ± 843	21 348	Bon
	Fjord (uniquement)	1 167 ± 99		
	TOTAL	13 073 ± 942		
Opérations maritimes	TOTAL	3 605	573	Bon
Plaisance	Estuaire moyen	2 149 ± 1 043	5 477	Bon
	Estuaire maritime	1 043 ± 490		
	Fjord	7 675 ± 3 726		
	TOTAL	9 277 ± 4 360		
Autres (navires militaires, yachts de grande taille, bateaux de pêche commerciale)	TOTAL	57	2	Mauvais
TOTAL		51 796 ± 5 680	48 902	Bon

Tableau 13 :
Temps de résidence dans le PMSSL estimé pour chaque composante du trafic maritime sur une base mensuelle. Ces estimés sont effectués à partir des valeurs centrales des estimations du nombre de voyages par composante.

	Temps de résidence par mois (heures)									
	Marine marchande	Croisières		Traversiers		Excursions		Opérations maritimes	Plaisanciers	Autres
		Int.	Nat.	RDL - SS	BSC - TAD	Grands	Petits			
Mai	1 594	17	0	142	513	394	1 752	204	421	40
Juin	1 746	50	9	148	524	1 462	4 134	242	4 121	75
Juillet	1 848	50	0	214	609	2 226	5 019	282	14 341	3
Août	1 831	61	35	191	609	2 136	6 619	218	16 237	82
Septembre	1 818	200	5	136	505	1 684	3 837	234	3 491	50
Octobre	1 824	150	0	142	495	666	2 209	216	260	35
SOUS-SOUS-TOTAL	4 667	528	49	973	3 255	666	2 582	1 396	260	287
SOUS-TOTAL	10 661	577		4 228		32 129		1 396	38 871	287
TOTAL	**88 149 heures**									

10.1.2 Analyse temporelle

La Figure 11 indique que plus de 30% du temps total de navigation entre le 1er mai et le 31 octobre 2007 a eu lieu au mois d'août (le mois le plus occupé), le mois le plus calme étant mai. Dépendamment du mois, la composante majeure n'est pas la même lorsqu'il est question du temps total de navigation. En mai, la marine marchande est majoritaire, suivie par les excursions. En juin, les excursions sont les plus présentes suivies par les plaisanciers. En juillet et août, les plaisanciers sont premiers devant les excursions tandis qu'en septembre et octobre, les excursions repassent en première position. L'importance de la plaisance illustrée dans cette figure découle de la durée moyenne élevée des sorties de plaisanciers (~4 h/sortie en moyenne).

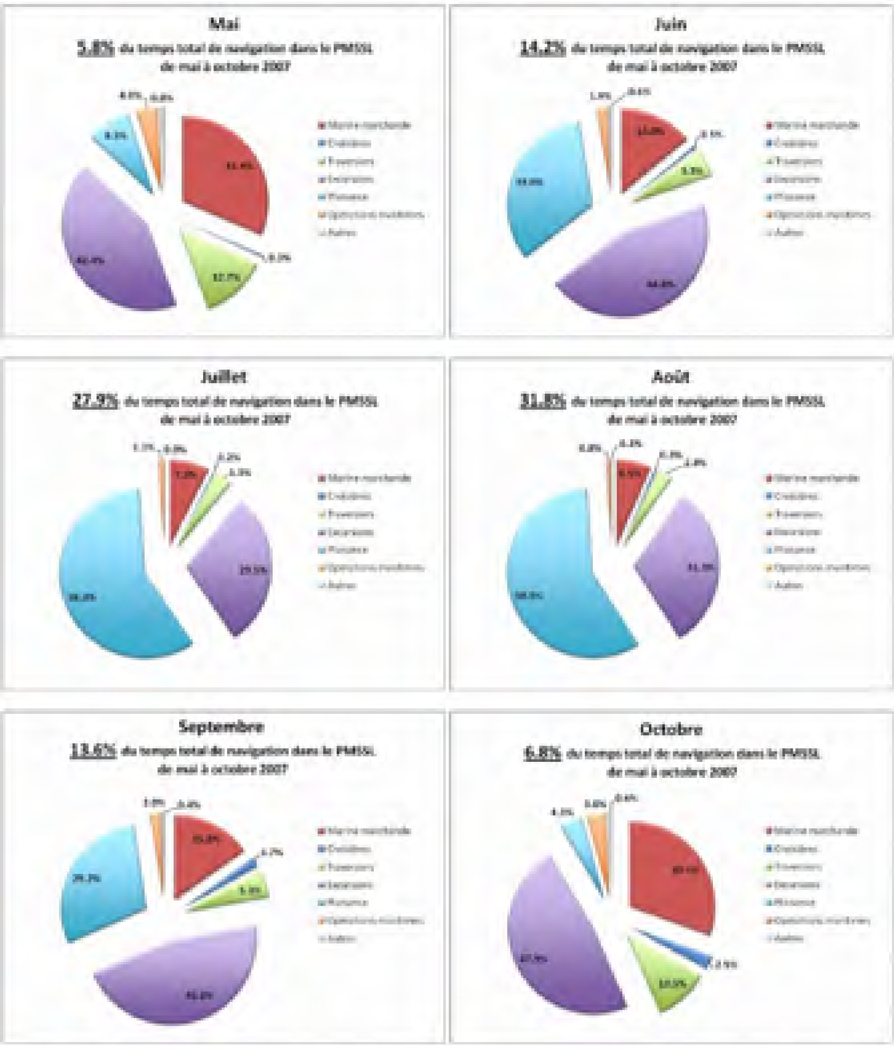


Figure 11 : Ventilation mensuelle du temps total de résidence dans le PMSSL, par les composantes du trafic maritime. Cette figure utilise les valeurs centrales des estimations du nombre de voyages effectués par chaque composante du trafic maritime.

La Figure 12 indique qu'environ 25% du nombre total de voyages effectués entre le 1er mai et le 31 octobre 2007 ont eu lieu au mois d'août, le mois le plus actif. À l'opposé, le mois le plus calme est le mois de mai. Les traversiers restent tout au long de l'été la composante responsable du plus grand nombre de mouvements. À l'exception du mois d'août où les plaisanciers sont deuxièmes en termes du nombre de voyages dans le PMSSL, les excursions sont la deuxième composante pendant les cinq autres mois.

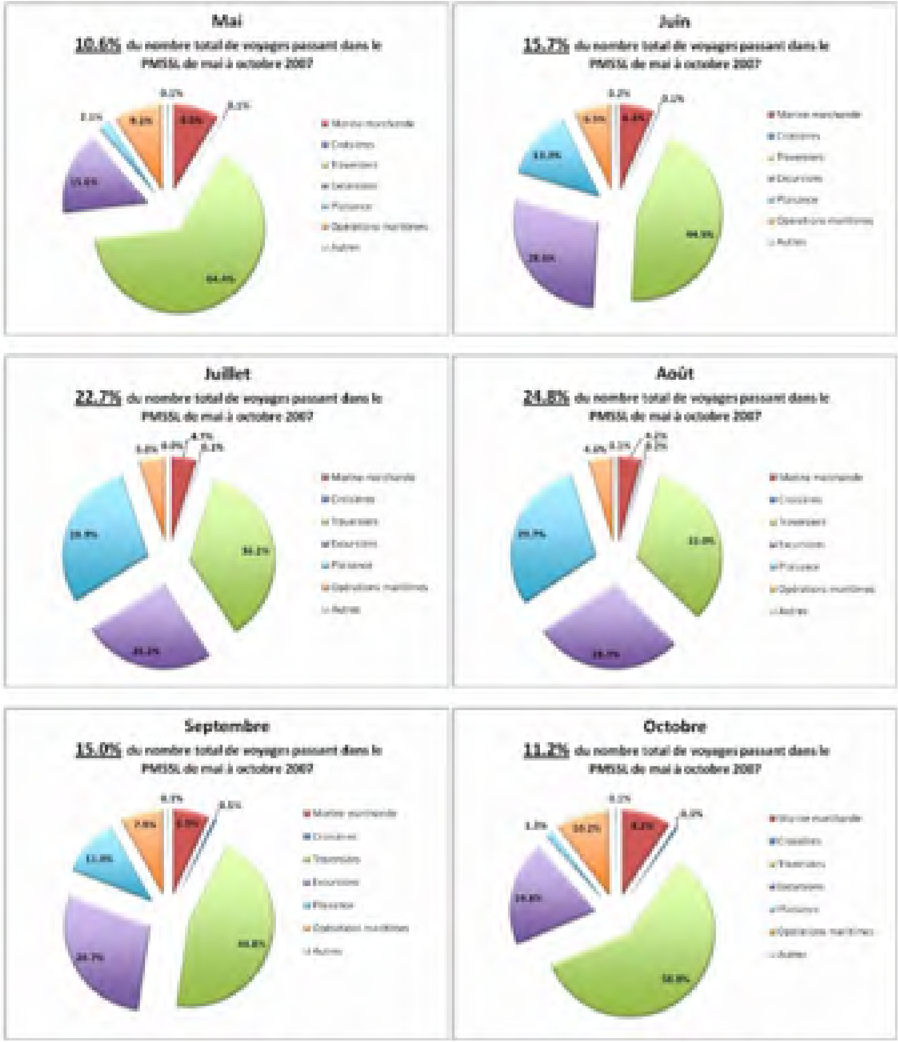
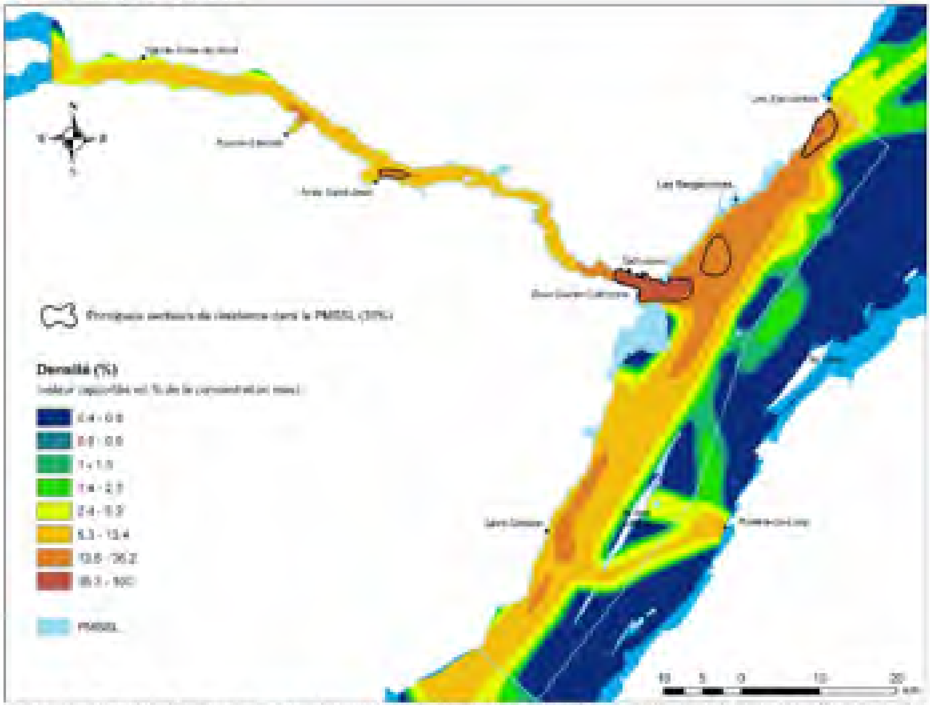


Figure 12 : Ventilation mensuelle du nombre total de voyages dans le PMSSL, effectués par chaque composante du trafic maritime. Cette figure utilise les valeurs centrales des estimations du nombre de voyages effectués par chaque composante du trafic maritime.

10.1.3 Analyse spatiale



Carte 10 : Densité des mouvements de tout le trafic maritime dans l'ensemble du PMSSL, du 1er mai au 31 octobre 2007. Cette carte a été obtenue en faisant la sommation des cartes de densités de chaque composante (Analyse de type kernel density effectuée à partir des trajectoires; rayon de recherche = 3000 mètres; résolution du raster = 100 mètres). Les valeurs de densité ont été normalisées par la densité maximale (%). L'échelle de couleur repose sur une classification géométrique non linéaire pour faire ressortir les zones d'activité secondaires. Cette carte fait ressortir les points chauds du PMSSL, à savoir l'embouchure du Saguenay, le long de la rive Nord dans l'estuaire maritime ainsi que la tête du chenal au complet, la zone d'embarquement des pilotes à l'Anse aux Basques, la côte de Charlevoix, le contournement de la batture aux Alouettes, ainsi que les abords des marinas majeures du Saguenay et du PMSSL en général.

La Carte 10 identifie les secteurs du PMSSL fortement utilisés en termes de nombre de mouvements et en termes de temps de résidence, et ce de façon cumulative pour toute la saison. Les secteurs qui ressortent de manière plus importante en termes de passages (identifiés par l'échelle de couleur dans la Carte 10) sont l'embouchure du Saguenay et la zone d'embarquement des pilotes à l'Anse aux Basques. Les secteurs importants de manière secondaire sont les abords de Saint-Siméon sur la Côte de Charlevoix, l'estuaire maritime (corridor situé à moins de 10km de la rive Nord), les abords de l'Anse Saint-Jean et de Rivière-Éternité dans le Saguenay. Un autre point chaud est la zone de contournement de la batture aux Alouettes; ceci s'explique en grande partie par l'étroitesse du chenal de navigation dans ce secteur et le fait que ce secteur est fréquemment emprunté par les plaisanciers. Finalement, on peut citer la passe de l'Île aux Lièvres qui est un goulot d'étranglement très étroit également, présentant l'option la plus rapide pour quiconque désire joindre les deux rives, dans le secteur Sud du PMSSL.

Les secteurs de fort temps de résidence (identifiés par les polygones noirs dans la Carte 10) sont l'embouchure du Saguenay, la tête du Chenal Laurentien entre Tadoussac et Bergeronnes jusqu'à 5km au large de la rive Nord, les abords du quai des pilotes aux Escoumins et le secteur de l'Anse-Saint-Jean.

Les deux analyses (temps de résidence et nombre de mouvements) permettent d'identifier deux secteurs principaux d'utilisation qui sont l'embouchure du Saguenay et les abords du quai des pilotes aux Escoumins.

10.2 Mise en perspective

Le trafic maritime motorisé ou à voile dans le PMSSL de mai à fin octobre 2007 représente un peu plus de 50 000 mouvements de bateaux, tous types confondus. Pour mettre ces chiffres en perspective dans le contexte global des aires marines protégées, nous présentons ici les chiffres du trafic maritime dans le sanctuaire marin de Gerry E. Studds Stellwagen Bank (SBNMS) situé au large de Boston, Massachusetts[7].

Tableau 14 :
Comparaison entre les activités de navigation annuelles dans le PMSSL et dans le SBNMS. Les chiffres sont arrondis et les ordres de grandeur sont à retenir (sources : (Hatch *et al.* 2008, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Sanctuary Program 2008)).

	PMSSL	**SBNMS**
Superficie (km²)	1 243	2 181
Nombre de voyages annuels pour les composantes majeures de la navigation		
Marine marchande	5 600	4 600 (en 2003)
Croisières	108	300 (en 2005)
Traversiers	42 000	1 600*
Excursions commerciales	13 000 (~275 000 visiteurs/an)	13 000** (~700 000 visiteurs/an)
Plaisance	9 000	235***
Pêche commerciale	rare	51 000 (en 2005)
TOTAL	**69 700**	**70 730**

*Valeur estimée à partir des horaires des traversiers Boston-Provincetown en 2009.
**Valeur estimée à partir des horaires des compagnies d'excursion en 2006.
***Estimation conservatrice à partir des bateaux équipés du système AIS en 2008 (comm. pers., L. Hatch, NOAA).

Le sanctuaire marin de Stellwagen Bank a été choisi pour comparaison étant donnée sa similarité avec le PMSSL sur plusieurs points. Les deux aires protégées ont un mandat de protection des mammifères marins, elles sont dans des secteurs où les activités humaines sont jugées intensives

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[7] http://stellwagen.noaa.gov/

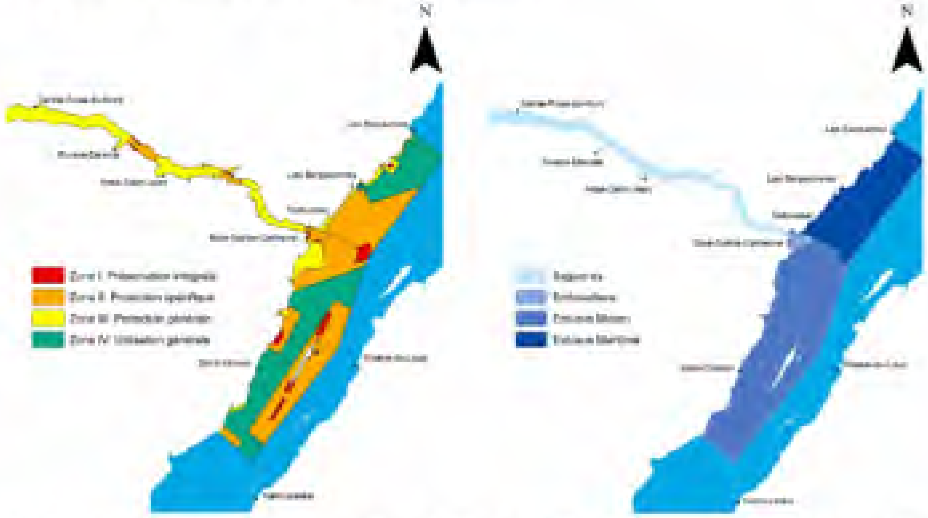
et leur superficie est du même ordre de grandeur. Toutefois, parmi les différences entre ces aires marines protégées, on peut mentionner :

- le PMSSL est situé dans une région plus éloignée des grands centres urbains (~215 km de Québec) que le SBNMS qui est au large de la baie de Boston;
- Le PMSSL est facilement accessible à partir de la côte alors que le SBNMS est situé au large, rendant difficile son accès par des plaisanciers; de même, la plupart des traversiers en opération dans la région de Boston effectuent leurs transits en dehors du SBNMS.

Dans le contexte des aires marines protégées, le SBNMS est considéré comme sujet à de fortes pressions d'origine anthropique (U.S. Department of Commerce. National Oceanic and Atmospheric Administration. National Marine Sanctuary Program 2008). La comparaison des activités sans prélèvement de ressources y prenant place avec celles décrites dans ce rapport permet de conclure que le trafic maritime dans le PMSSL est intensif, dans le contexte des aires marines protégées (cf. Tableau 14). Le nombre de voyages associés à la marine marchande et aux excursions commerciales est comparable pour le PMSSL et le SBNMS. Toutefois, dans le SBNMS, les excursions commerciales principalement reliées à l'observation de mammifères marins sont effectuées à bord de grands bateaux alors que la flotte du PMSSL est majoritairement composée de petits bateaux. Finalement, les activités de pêche dominent le nombre de voyages dans le SBNMS alors que ces activités sont marginales dans le PMSSL. Le portrait des activités de navigation étant différent, la pression exercée sur les écosystèmes est également de nature différente et requiert par conséquent des analyses *ad hoc*.

11 Analyses spécifiques

11.1 Analyse spatiale par secteurs du PMSSL



Carte 11 : Détail des zones définies par le plan de zonage du PMSSL révisé en 2008 (carte de gauche) et des quatre secteurs utilisés dans les analyses sectorielles (carte de droite). (Source : Parcs Canada)

Pour cette analyse, le PMSSL a été divisé en 4 secteurs distincts illustrés dans la Carte 11 :

1. La rivière Saguenay;
2. L'embouchure de la rivière Saguenay;
3. L'estuaire maritime;
4. L'estuaire moyen.

Ce découpage a été choisi pour faire ressortir la situation de la navigation dans les trois écosystèmes distincts du parc marin (estuaire maritime, estuaire moyen et Saguenay) et pour mettre en relief le cas de l'embouchure du Saguenay; ce dernier est sujet à des enjeux spécifiques de gestion, reliés à son importance comme habitat de la population menacée du béluga du Saint-Laurent (Ménard *et al.* 2007) sujette à un nombre important de cooccurrences avec la navigation (Turgeon *et al.* 2008).

Les limites de chacune des zones illustrées dans la Carte 11 ont été extraites à partir de fichiers vectoriels fournis par les gestionnaires du PMSSL.

La Figure 13 illustre le temps de navigation de chaque composante du trafic maritime dans le PMSSL, ainsi que le total du temps de navigation. L'élément le plus saillant est la densité du trafic maritime dans l'embouchure qui contient plus de 13% du temps de navigation total du parc, alors que sa superficie ne représente que 1% de la surface du PMSSSL. Le Saguenay apparaît également un point chaud puisqu'avec 16% de la superficie totale, il contient environ 30% du temps total de navigation dans le PMSSL. La plaisance très active dans le Fjord du Saguenay est la composante qui contribue le plus à l'importance relative de ce secteur.

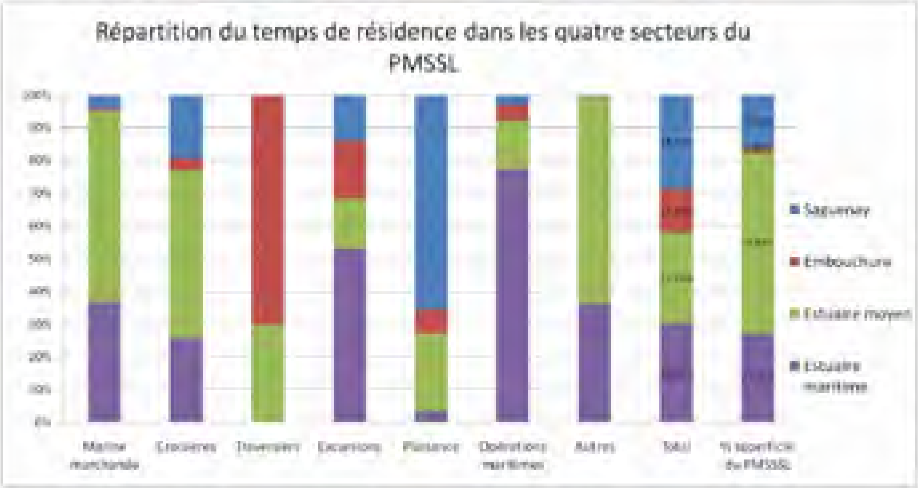


Figure 13 : Proportion du temps passé par chaque composante du trafic maritime dans chacun des quatre (4) secteurs du PMSSL, à savoir l'estuaire maritime, l'estuaire moyen, l'embouchure de la rivière Saguenay, et la rivière Saguenay (excluant l'embouchure). Les périodes d'arrêt aux ports ont été exclues de l'analyse. Ce graphique utilise les valeurs centrales des estimations du nombre de voyages effectués par chaque composante du trafic maritime.

À ce stade, il est intéressant de constater que la plaisance se répartit à plus de 72.5% dans le Saguenay incluant l'embouchure, 3.5% dans l'estuaire maritime et 24% dans l'estuaire moyen. Ces chiffres sont le résultat de la pondération des trajectoires des plaisanciers par le nombre total estimé de sorties et de la durée mesurée de ces sorties. D'autre part, les données recueillies dans les questionnaires sur la caractérisation des sorties des plaisanciers (Gosselin *et al.* 2007) rapportaient que le Saguenay était dans 72% des cas le secteur d'activité principale des sorties (n=560 sorties), l'estuaire moyen étant le secteur principal pour 24% des sorties et l'estuaire moyen comptant pour 4%. Ainsi, nos résultats valident cette répartition des activités dans le secteur du PMSSL tout en utilisant des données de nature différentes (trajectoires *vs* questionnaires). Ceci confirme que malgré leur petit nombre (n=26), la représentativité des trajectoires des plaisanciers pondérées par classe de plaisancier permet d'obtenir une image réaliste de la distribution spatiotemporelle de cette composante du trafic.

Concernant les excursions, plus de 53% de l'activité se situe dans l'estuaire maritime, secteur principal pour l'observation de grands rorquals (Michaud *et al.* 2008), l'estuaire moyen comptant pour 15% du temps de navigation des excursions. Pour sa part, le Saguenay compte pour 13% tandis que l'embouchure regroupe 19% du temps total. Les navettes effectuées entre les ports de Tadoussac et de Baie-Sainte-Catherine expliquent en grande partie le fort temps de résidence des excursionnistes dans l'embouchure du Saguenay.

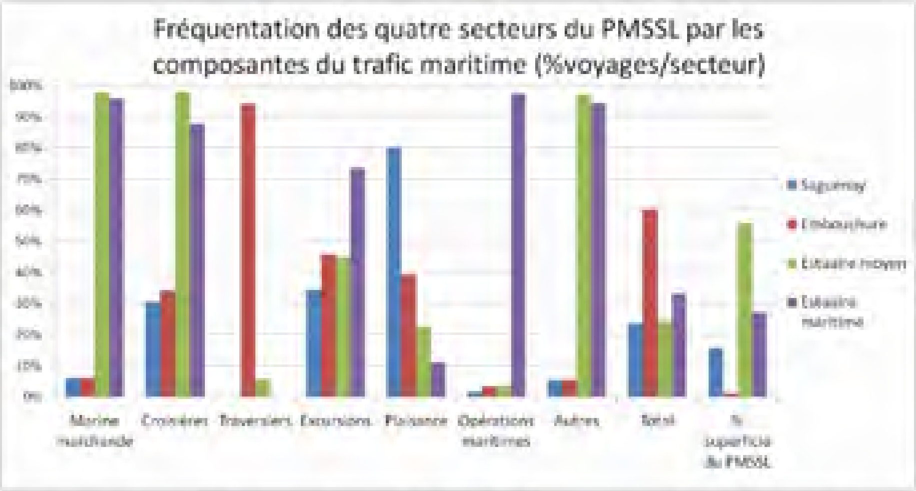


Figure 14 : Fréquentation des quatre secteurs du PMSSL par les composantes du trafic maritime (exprimée par la proportion des voyages ayant utilisé les différents secteurs du PMSSL). Ce graphique utilise les valeurs centrales des estimations du nombre de voyages effectués par chaque composante du trafic maritime.

La Figure 14 indique que plus de 60% des voyages de bateaux de tous types dans le PMSSL utilisent l'embouchure (1% de la superficie), ceci étant principalement attribuable au service de traversier qui relie Baie-Sainte-Catherine à Tadoussac. L'estuaire maritime est le deuxième secteur le plus utilisé du PMSSL puisque plus 30% des voyages y passent.

La Figure 15 illustre la composition de la flotte observable dans chaque secteur du PMSSL (temps de résidence). Rappelons que ce bilan est cumulatif pour toute la saison (du 1^{er} mai au 31 octobre 2007).

D'une façon générale, la Figure 15 indique que l'estuaire maritime est occupé principalement par les bateaux d'excursion suivis de la marine marchande. Les autres composantes n'ont pas un fort temps de résidence dans ce secteur. L'estuaire moyen est dominé par la marine marchande; les routes des navires montants et descendants traversent cette zone dans toute sa longueur tel que suggéré par la densité des trajectoires présentée dans la Carte 2. Les plaisanciers et les excursionnistes ont un temps de résidence similaire dans ce secteur.

L'embouchure du Saguenay est largement dominée par les excursionnistes suivis des traversiers. Pour le pic de la saison (juillet/août), l'importance relative des plaisanciers dans le secteur de l'embouchure est plus importante que celui exposé pour l'ensemble de la saison. Ce fait est présenté plus en profondeur dans la section dédiée à l'embouchure. Enfin, le Saguenay est le secteur privilégié des plaisanciers, qui comptent pour un peu moins de 80% du temps total de navigation dans ce secteur, loin devant les excursions avec moins de 20% du temps total.

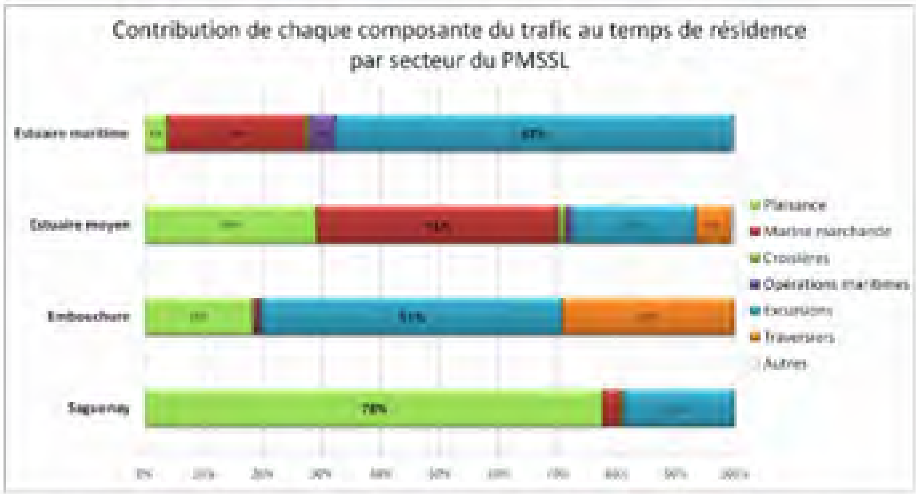


Figure 15 : Contribution des composantes du trafic maritime au temps de résidence des quatre secteurs du PMSSL. Ce graphique utilise les valeurs centrales des estimations du nombre de voyages effectués par chaque composante du trafic maritime.

11.2 Analyse spatiale en fonction du plan de zonage

Le plan de zonage préliminaire du PMSSL de 2008 prévoit quatre types de zone équivalant à quatre niveaux de protection, le type 1 étant attribuée aux zones les plus sensibles, le type 4 étant dédié à une protection plus générale (Parcs Canada 2007). La Figure 16 illustre la répartition du temps total de navigation de chaque composante du trafic dans chacun des 4 types de zone. Environ 40% des activités de navigation se déroulent dans les zones de type 1 (1.44%) et de type 2 (39.36%) à savoir les zones de protection les plus importantes du parc marin et la plupart des composantes y résidant plus de 30% de leur temps de mer. Ces zones les plus sensibles représentent environ 45% de la superficie du parc donc leur utilisation est proportionnelle à leur surface.

Les excursions (~60%) et la traverse Rivière-du-Loup—Saint-Siméon (56%) sont les deux seules composantes du trafic maritime dont les activités se concentrent davantage dans les zones les plus sensibles (types 1 et 2).

Les excursionnistes sont les principaux utilisateurs des zones de type 1, identifiant les secteurs les plus sensibles.

Environ 70% des activités de marine marchande se situent dans les zones de type 3 et 4, les 30% restant étant dans des zones de type 2 majoritairement.

Finalement, il est intéressant de constater que le trafic maritime total se répartit dans les quatre types de zone dans des proportions similaires à celles de leur superficie relative dans le PMSSL.

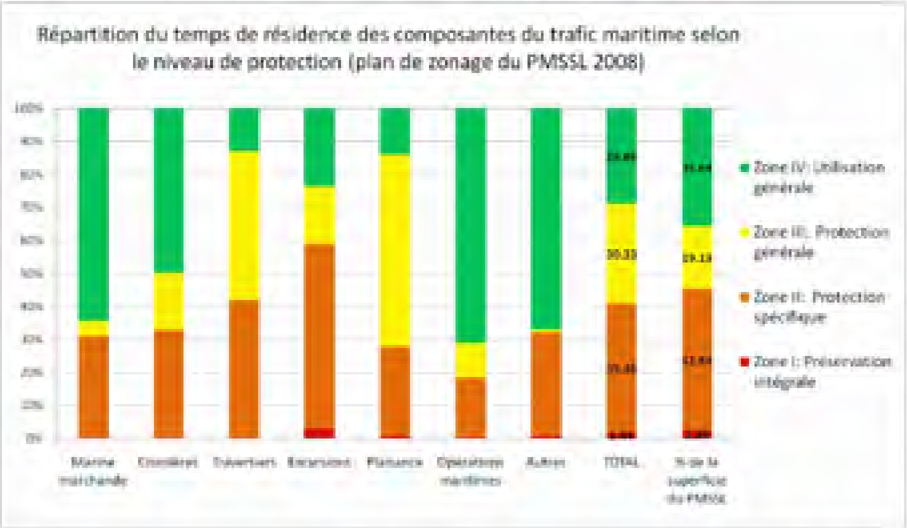


Figure 16 : Proportion du temps passé par chaque composante du trafic maritime dans chacune des quatre (4) types de zones identifiés au plan de zonage préliminaire du PMSSL (2008). Les périodes d'arrêt aux ports ont été exclues de l'analyse.

11.3 Analyse spécifique à l'embouchure de la rivière Saguenay

Le trafic maritime dans le secteur enclavé de l'embouchure est étudié sous plusieurs angles :

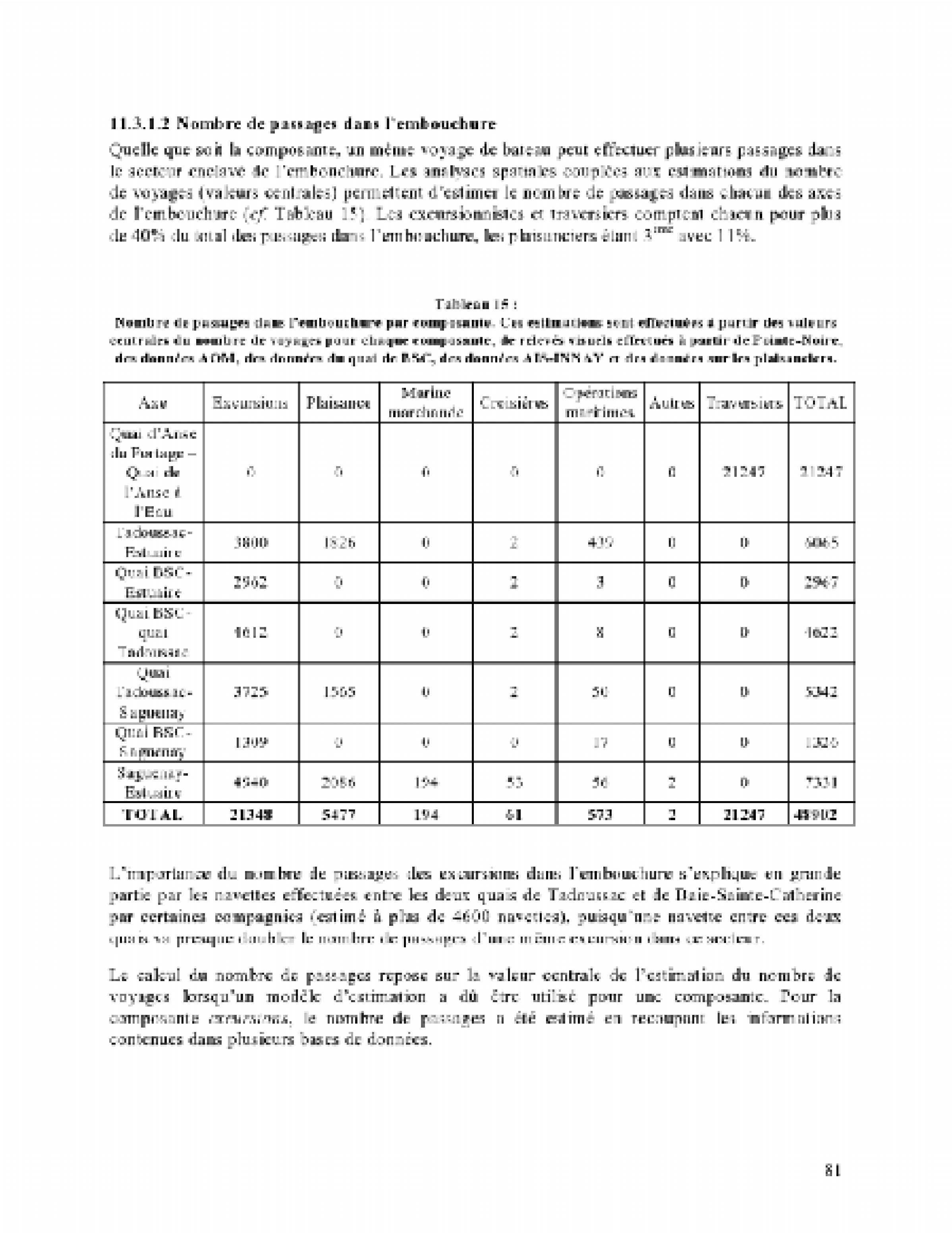
- Nombre de voyages passant par l'embouchure;
- Nombre de passages dans l'embouchure;
- Nombre de passages dans chacune des directions entre les différents sites (quai de Tadoussac, quai de Baie-Sainte-Catherine, rivière Saguenay et estuaire du Saint-Laurent);
- Temps de résidence cumulatif des bateaux.

11.3.1 Mouvements dans l'embouchure

11.3.1.1 Nombre de voyages passant par l'embouchure

Parmi tous les voyages de bateaux utilisant le parc marin, on identifie ici la proportion de ceux qui vont passer au moins une fois dans le secteur enclavé de l'embouchure.

Au total, on estime que près de 60% de tous les voyages passant dans le PMSSL en 2007 sont passés au moins une fois par l'embouchure (*cf.* Figure 14). Considérant que sa superficie représente environ 1% du PMSSL, on mesure à quel point ce secteur est important pour les activités de navigation. Après le traversier Baie-Sainte-Catherine/Tadoussac, ce sont les excursions qui sont les principaux usagers de l'embouchure avec environ 45% des voyages passant dans ce secteur (*cf.* Figure 14 et Figure 15).



11.3.1.2 Nombre de passages dans l'embouchure

Quelle que soit la composante, un même voyage de bateau peut effectuer plusieurs passages dans le secteur enclavé de l'embouchure. Les analyses spatiales couplées aux estimations du nombre de voyages (valeurs centrales) permettent d'estimer le nombre de passages dans chacun des axes de l'embouchure (*cf.* Tableau 15). Les excursionnistes et traversiers comptent chacun pour plus de 40% du total des passages dans l'embouchure, les plaisanciers étant $3^{ème}$ avec 11%.

Tableau 15 :
Nombre de passages dans l'embouchure par composante. Ces estimations sont effectuées à partir des valeurs centrales du nombre de voyages pour chaque composante, de relevés visuels effectués à partir de Pointe-Noire, des données AOM, des données du quai de BSC, des données AIS-INNAV et des données sur les plaisanciers.

Axe	Excursions	Plaisance	Marine marchande	Croisières	Opérations maritimes	Autres	Traversiers	TOTAL
Quai d'Anse du Portage – Quai de l'Anse à l'Eau	0	0	0	0	0	0	21247	21247
Tadoussac-Estuaire	3800	1826	0	2	439	0	0	6065
Quai BSC-Estuaire	2962	0	0	2	3	0	0	2967
Quai BSC-quai Tadoussac	4612	0	0	2	8	0	0	4622
Quai Tadoussac-Saguenay	3725	1565	0	2	50	0	0	5342
Quai BSC-Saguenay	1309	0	0	0	17	0	0	1326
Saguenay-Estuaire	4940	2086	194	53	56	2	0	7331
TOTAL	**21348**	**5477**	**194**	**61**	**573**	**2**	**21247**	**48902**

L'importance du nombre de passages des excursions dans l'embouchure s'explique en grande partie par les navettes effectuées entre les deux quais de Tadoussac et de Baie-Sainte-Catherine par certaines compagnies (estimé à plus de 4600 navettes), puisqu'une navette entre ces deux quais va presque doubler le nombre de passages d'une même excursion dans ce secteur.

Le calcul du nombre de passages repose sur la valeur centrale de l'estimation du nombre de voyages lorsqu'un modèle d'estimation a dû être utilisé pour une composante. Pour la composante *excursions*, le nombre de passages a été estimé en recoupant les informations contenues dans plusieurs bases de données.

11.3.2 Temps de résidence dans l'embouchure

L'embouchure du Saguenay telle que délimitée dans le plan de zonage 2008 du PMSSL (Parcs Canada 2007) est un secteur enclavé dont la surface représente à peine plus de 1% du PMSSL. Son importance, aussi bien en termes de temps de résidence qu'en nombre de passages est très importante comme en attestent les Figure 13,Figure 14 et Figure 15.

Dans la Figure 13, on constate qu'environ 13% du temps total de navigation dans le PMSSL a lieu dans le secteur de l'embouchure. La Figure 15 indique que ce sont les excursionnistes qui sont les principaux utilisateurs de l'embouchure avec environ 50% du temps total de résidence. Les traversiers arrivent ensuite avec 29% du temps total de résidence suivi de la plaisance avec 18%.

La Figure 15 indique qu'il y a en moyenne un ratio de 2.63 excursionnistes/plaisancier dans l'embouchure du Saguenay. Les données AOM, qui surreprésentent les excursionnistes par rapport aux plaisanciers, indiquent un ratio de 3.25 excursionnistes/plaisancier dans l'embouchure. Les données de Pointe-Noire qui surreprésentent les plaisanciers par rapport aux excursionnistes (communications personnelles, Manuela Conversano) indiquent un ratio de 1.5 excursionnistes/plaisancier. Le vrai ratio est donc compris entre 1.5 et 3.25 ce qui indique que le ratio de 2.63 provenant de nos analyses est réaliste.

D'une façon générale, l'occupation maximale de l'embouchure a lieu en juillet et août. On estime que plus de 50% du temps total de navigation des excursionnistes dans ce secteur et plus de 75% du temps total des plaisanciers dans ce secteur ont lieu pendant juillet et août. Ajoutons que c'est également à cette période que les traversiers sont les plus actifs.

12 Conclusion

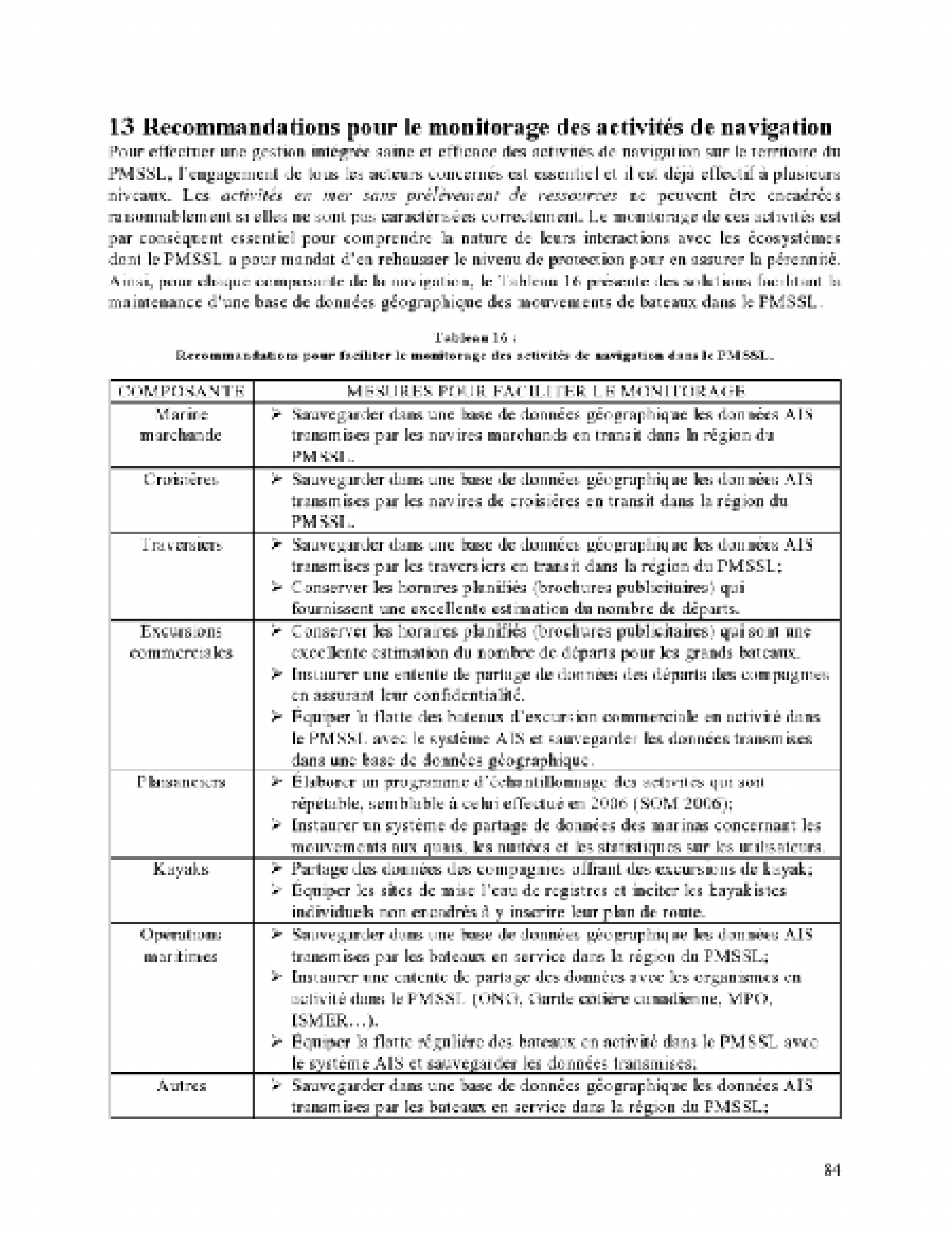
Le rapport sur l'état du parc marin de 2007 faisait état de lacune quant au suivi des activités de navigation dans le PMSSL (Ménard *et al.* 2007). Le présent rapport apporte un éclairage sur les activités dites sans prélèvement de ressources, incluant l'ensemble des activités de navigation à l'exception des activités de pêche commerciale (activités avec prélèvement de ressources). Les chiffres-clés des résultats des analyses présentées se retrouvent dans la section Faits saillants au début de ce rapport.

Il est possible de dégager des patrons spatiaux et temporels de l'utilisation du territoire du parc marin pour chacune des composantes du trafic maritime. Si certaines composantes sont actives de façon régulière de mai à octobre (*e.g.* marine marchande), d'autres sont plus saisonnières (*e.g.* plaisance et excursions pendant les mois de juillet et août).

Les secteurs qui ressortent comme les plus utilisés sur le territoire du PMSSL en 2007 sont l'embouchure de la rivière Saguenay, le secteur du quai des pilotes et les abords des marinas du Saguenay et de l'estuaire du Saint-Laurent. La tête du chenal Laurentien est également un point chaud pendant la période estivale touristique puisqu'un grand nombre d'excursionnistes y convergent pour observer les mammifères marins. Une couverture exhaustive du territoire (notamment pour les kayaks qui sont exclus des analyses spatiales) permettrait probablement de faire ressortir d'autres secteurs secondaires d'activités.

De façon globale, c'est le mois d'août qui présentait les activités de navigation les plus intensives en 2007, aussi bien en ce qui a trait au nombre total de voyages qu'au temps total de navigation dans le PMSSL.

D'une façon générale, la navigation dans le PMSSL est hétérogène et sujette à des changements continuels. Pour en faciliter le monitorage pour les années à venir, nous proposons dans la section suivante une série de recommandations.

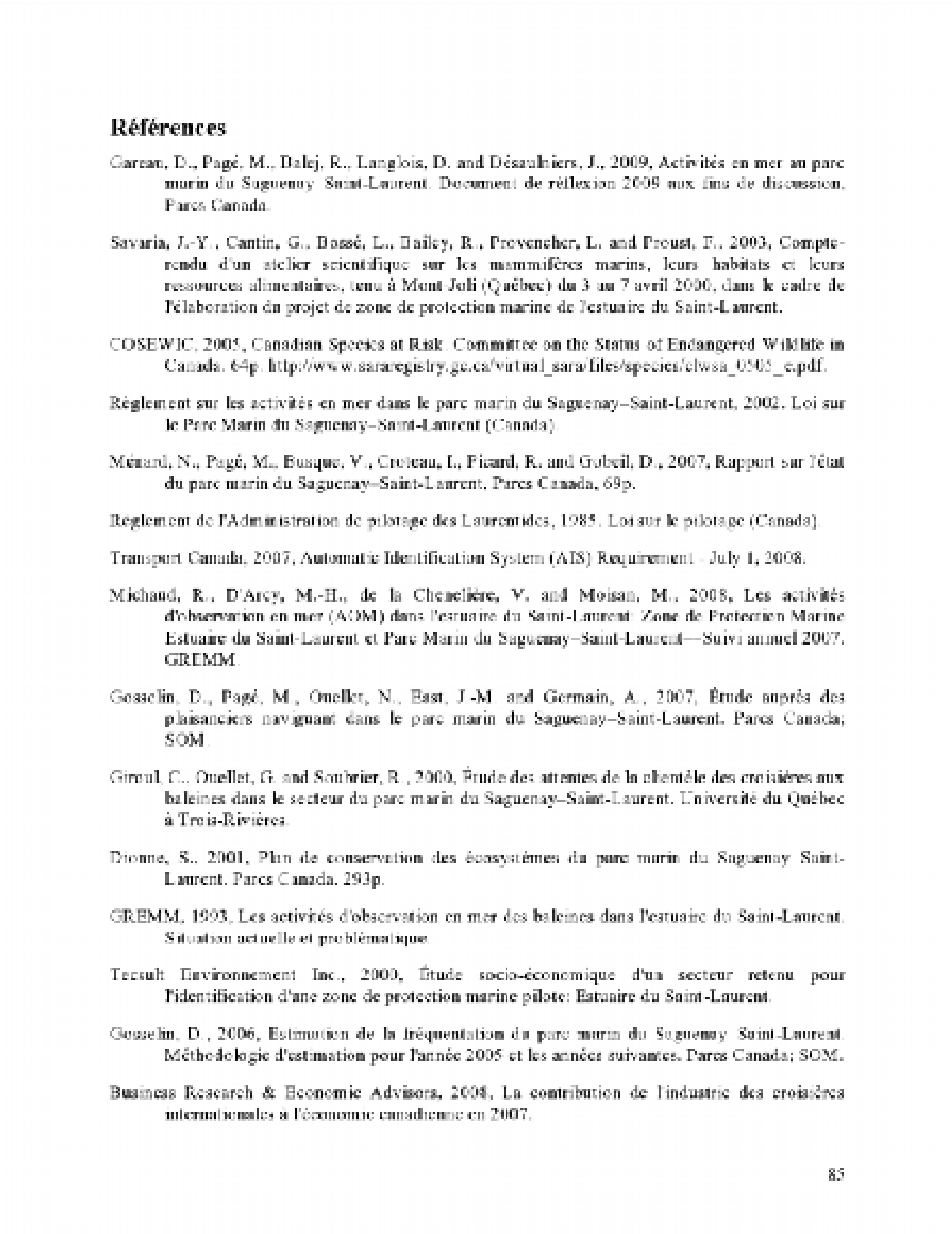


13 Recommandations pour le monitorage des activités de navigation

Pour effectuer une *gestion intégrée* saine et efficace des activités de navigation sur le territoire du PMSSL, l'engagement de tous les acteurs concernés est essentiel et il est déjà effectif à plusieurs niveaux. Les *activités en mer sans prélèvement de ressources* ne peuvent être encadrées raisonnablement si elles ne sont pas caractérisées correctement. Le monitorage de ces activités est par conséquent essentiel pour comprendre la nature de leurs interactions avec les écosystèmes dont le PMSSL a pour mandat d'en rehausser le niveau de protection pour en assurer la pérennité. Ainsi, pour chaque composante de la navigation, le Tableau 16 présente des solutions facilitant la maintenance d'une base de données géographique des mouvements de bateaux dans le PMSSL.

Tableau 16 :
Recommandations pour faciliter le monitorage des activités de navigation dans le PMSSL.

COMPOSANTE	MESURES POUR FACILITER LE MONITORAGE
Marine marchande	➢ Sauvegarder dans une base de données géographique les données AIS transmises par les navires marchands en transit dans la région du PMSSL.
Croisières	➢ Sauvegarder dans une base de données géographique les données AIS transmises par les navires de croisières en transit dans la région du PMSSL.
Traversiers	➢ Sauvegarder dans une base de données géographique les données AIS transmises par les traversiers en transit dans la région du PMSSL; ➢ Conserver les horaires planifiés (brochures publicitaires) qui fournissent une excellente estimation du nombre de départs.
Excursions commerciales	➢ Conserver les horaires planifiés (brochures publicitaires) qui sont une excellente estimation du nombre de départs pour les grands bateaux. ➢ Instaurer une entente de partage de données des départs des compagnies en assurant leur confidentialité. ➢ Équiper la flotte des bateaux d'excursion commerciale en activité dans le PMSSL avec le système AIS et sauvegarder les données transmises dans une base de données géographique.
Plaisanciers	➢ Élaborer un programme d'échantillonnage des activités qui soit répétable, semblable à celui effectué en 2006 (SOM 2006); ➢ Instaurer un système de partage de données des marinas concernant les mouvements aux quais, les nuitées et les statistiques sur les utilisateurs.
Kayaks	➢ Partage des données des compagnies offrant des excursions de kayak; ➢ Équiper les sites de mise l'eau de registres et inciter les kayakistes individuels non encadrés à y inscrire leur plan de route.
Opérations maritimes	➢ Sauvegarder dans une base de données géographique les données AIS transmises par les bateaux en service dans la région du PMSSL; ➢ Instaurer une entente de partage des données avec les organismes en activité dans le PMSSL (ONG, Garde côtière canadienne, MPO, ISMER…). ➢ Équiper la flotte régulière des bateaux en activité dans le PMSSL avec le système AIS et sauvegarder les données transmises;
Autres	➢ Sauvegarder dans une base de données géographique les données AIS transmises par les bateaux en service dans la région du PMSSL;



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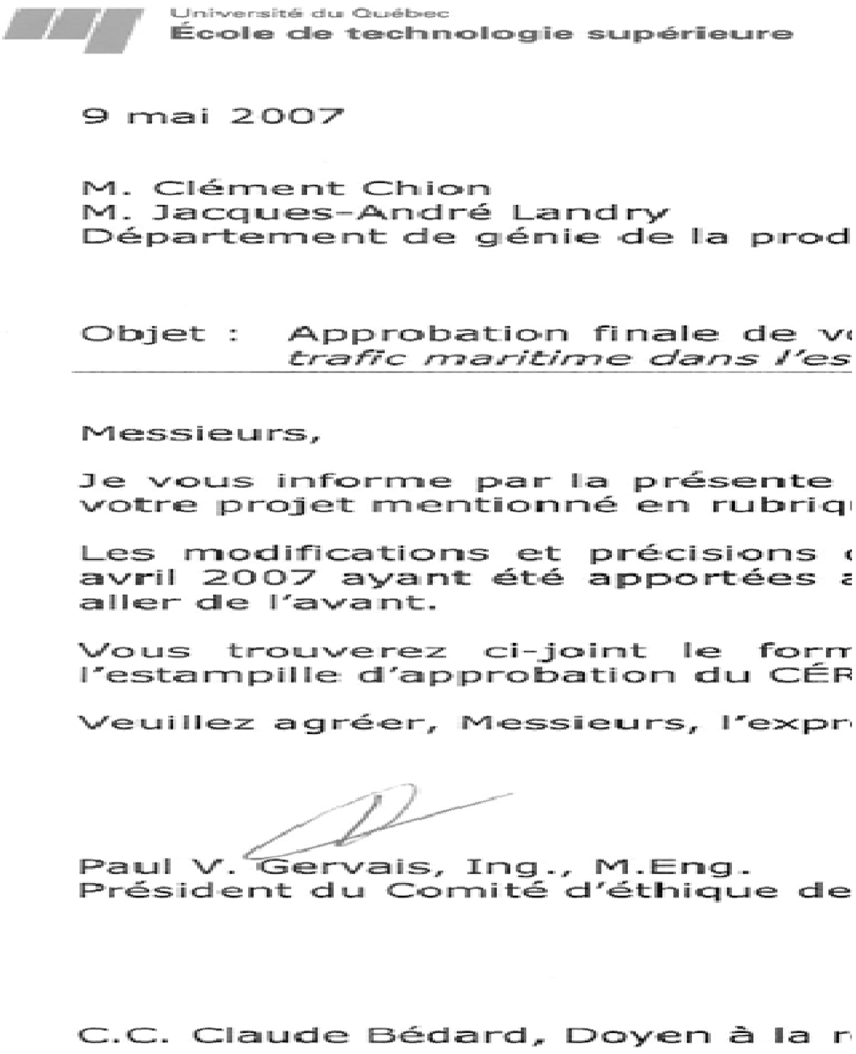
APPENDIX II

APPROVAL OF THE SURVEY CAMPAIGN BY ETHICS COMMITTEES



Université du Québec
École de technologie supérieure

9 mai 2007

M. Clément Chion
M. Jacques-André Landry
Département de génie de la prod

Objet : Approbation finale de v
trafic maritime dans l'es

Messieurs,

Je vous informe par la présente
votre projet mentionné en rubriq

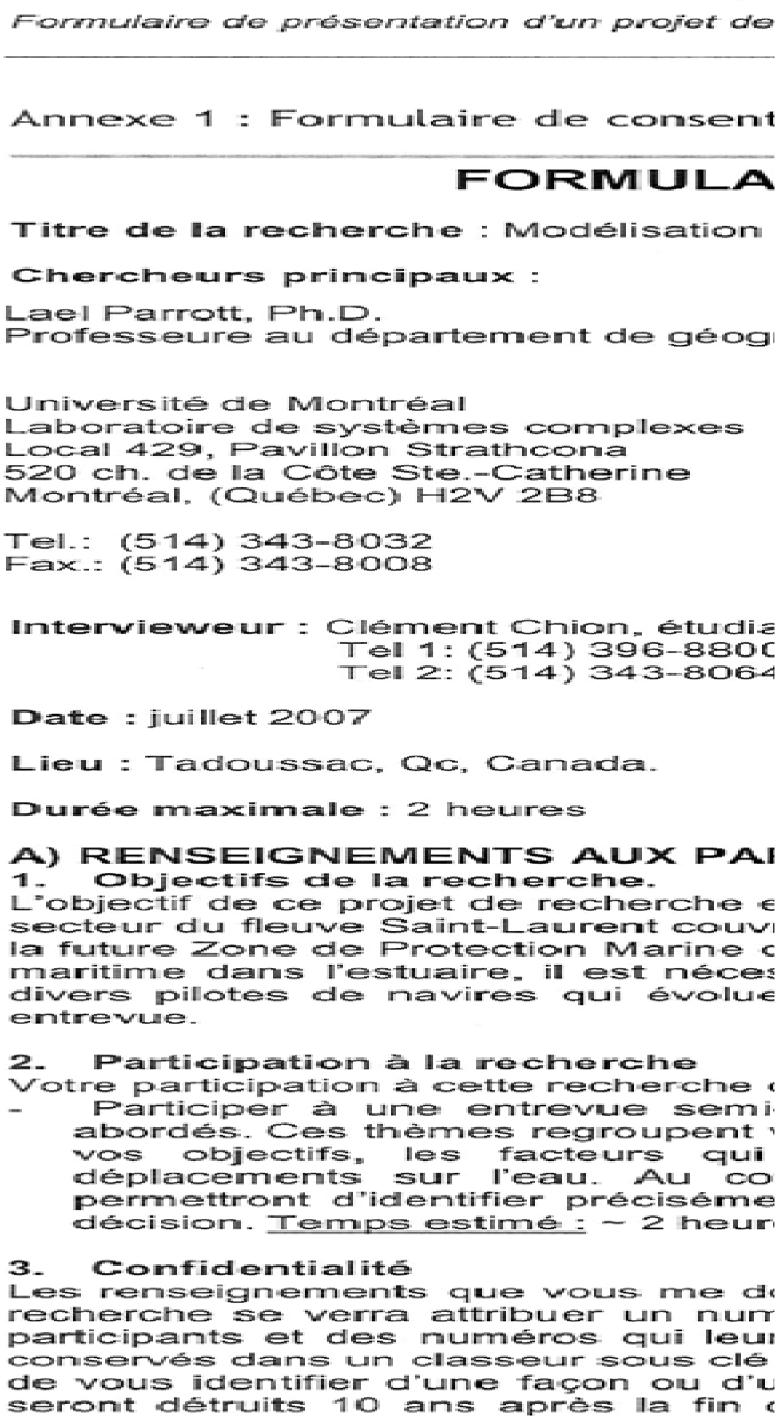
Les modifications et précisions
avril 2007 ayant été apportées a
aller de l'avant.

Vous trouverez ci-joint le form
l'estampille d'approbation du CÉR

Veuillez agréer, Messieurs, l'expr

Paul V. Gervais, Ing., M.Eng.
Président du Comité d'éthique de

C.C. Claude Bédard, Doyen à la r



Formulaire de présentation d'un projet de

Annexe 1 : Formulaire de consent

FORMULA

Titre de la recherche : Modélisation

Chercheurs principaux :

Lael Parrott, Ph.D.
Professeure au département de géog

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Tel.: (514) 343-8032
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Intervieweur : Clément Chion, étudia
Tel 1: (514) 396-880
Tel 2: (514) 343-8064

Date : juillet 2007

Lieu : Tadoussac, Qc, Canada.

Durée maximale : 2 heures

A) RENSEIGNEMENTS AUX PA

1. Objectifs de la recherche.

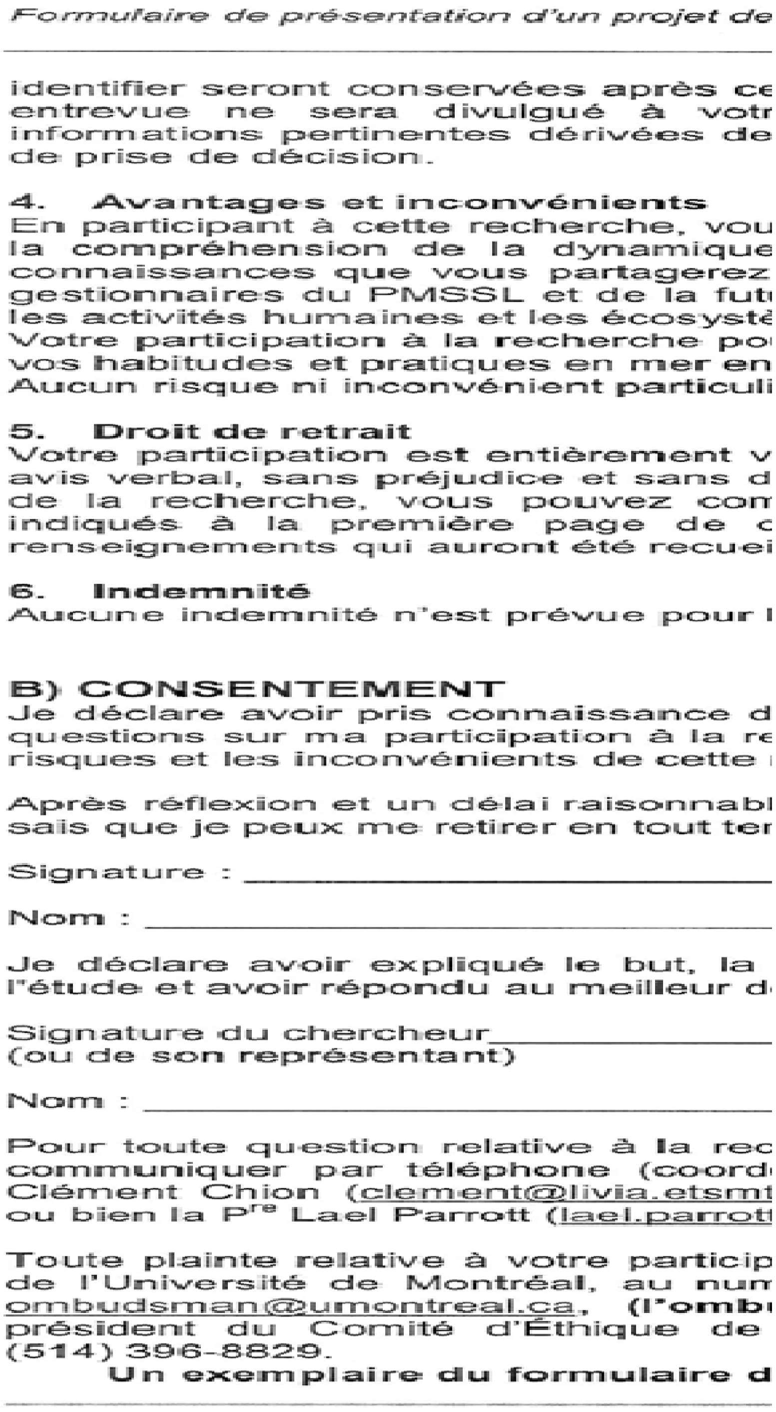
L'objectif de ce projet de recherche e
secteur du fleuve Saint-Laurent couv
la future Zone de Protection Marine c
maritime dans l'estuaire, il est néces
divers pilotes de navires qui évolue
entrevue.

2. Participation à la recherche

Votre participation à cette recherche
- Participer à une entrevue semi
abordés. Ces thèmes regroupent
vos objectifs, les facteurs qui
déplacements sur l'eau. Au co
permettront d'identifier précisém
décision. <u>Temps estimé :</u> ~ 2 heur

3. Confidentialité

Les renseignements que vous me d
recherche se verra attribuer un num
participants et des numéros qui leu
conservés dans un classeur sous clé
de vous identifier d'une façon ou d'u
seront détruits 10 ans après la fin



Formulaire de présentation d'un projet de

identifier seront conservées après ce
entrevue ne sera divulgué à votr
informations pertinentes dérivées de
de prise de décision.

4. Avantages et inconvénients
En participant à cette recherche, vou
la compréhension de la dynamique
connaissances que vous partagerez
gestionnaires du PMSSL et de la futu
les activités humaines et les écosystè
Votre participation à la recherche po
vos habitudes et pratiques en mer en
Aucun risque ni inconvénient particuli

5. Droit de retrait
Votre participation est entièrement v
avis verbal, sans préjudice et sans d
de la recherche, vous pouvez com
indiqués à la première page de c
renseignements qui auront été recuei

6. Indemnité
Aucune indemnité n'est prévue pour l

B) CONSENTEMENT
Je déclare avoir pris connaissance d
questions sur ma participation à la re
risques et les inconvénients de cette r

Après réflexion et un délai raisonnabl
sais que je peux me retirer en tout ter

Signature : ____________________

Nom : ____________________

Je déclare avoir expliqué le but, la
l'étude et avoir répondu au meilleur d

Signature du chercheur____________
(ou de son représentant)

Nom : ____________________

Pour toute question relative à la rec
communiquer par téléphone (coord
Clément Chion (clement@livia.etsmt
ou bien la P^{re} Lael Parrott (lael.parrott

Toute plainte relative à votre particip
de l'Université de Montréal, au num
ombudsman@umontreal.ca, **(l'omb**
président du Comité d'Éthique de
(514) 396-8829.

Un exemplaire du formulaire d

APPENDIX III

WHALE-WATCHING EXCURSIONS' DYNAMICS

1 Whale-watching companies' potential activities

As illustrated by Figure III.1, the maximum potential of activity can bring more than 40 whale-watching boats at sea simultaneously, mostly small zodiac-type boats. Another important thing to be noticed is the potential uninterrupted daily presence of active whale-watching boats, from 6:00AM to 8:00PM.

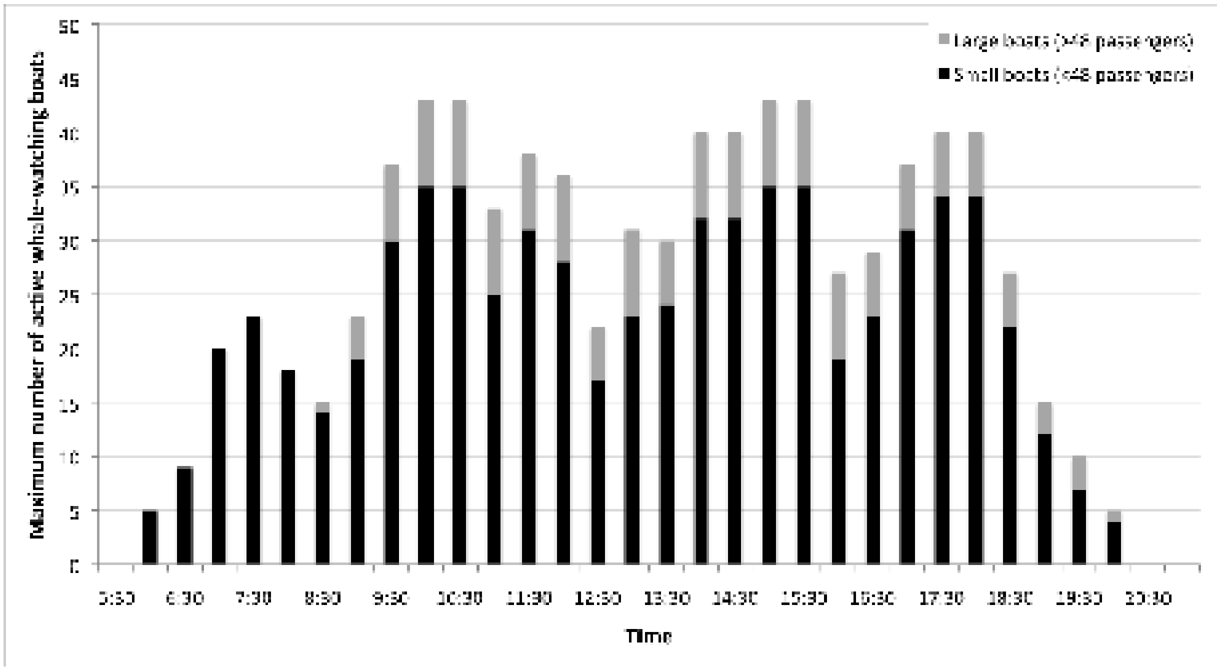


Figure III.1 Maximum number of whale-watching boats potentially active in the SSLMP during the peak of the touristic season, based on operators' schedules (2007) and size of authorized fleet.

2 Success in observing whales

High success rate: **98.89%** of the sampled whale-watching excursions have observed marine mammals, regardless of visibility conditions. What partly explains this high success rate is the fact that fin and minke whales are reliable visitors in the region, and that their location is often predictable from past days' observations (Table IV.1, Figure IV.3, and Figure IV.4 in APPENDIX IV).

3 Species relative attractiveness for observation

Five whale species have been accounting for more than **98%** of animals targeted for observation (in time) onboard excursions for more than 16 years, with great inter-annual variability. Figure III.2 represents the contribution of each species to total observations. They are an average of over 16 years of sampling (1994-2009), weighted according to excursions by port in 2007 to reduce the bias relative to the unbalanced port-wise sampling effort.

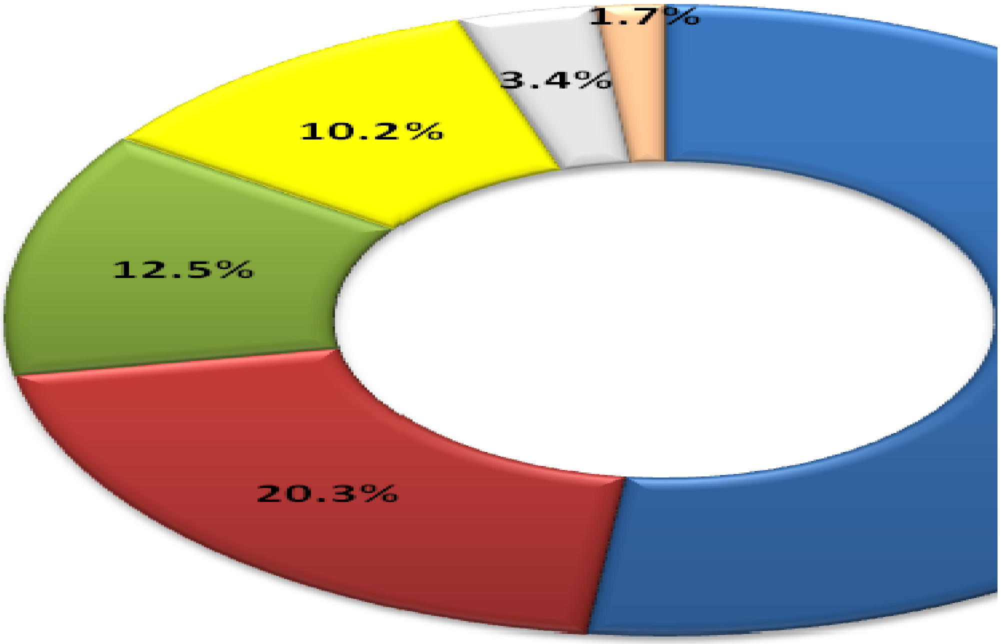


Figure III.2 Species' contribution to observations made by whale-watching excursions for the [1994-2009] period.

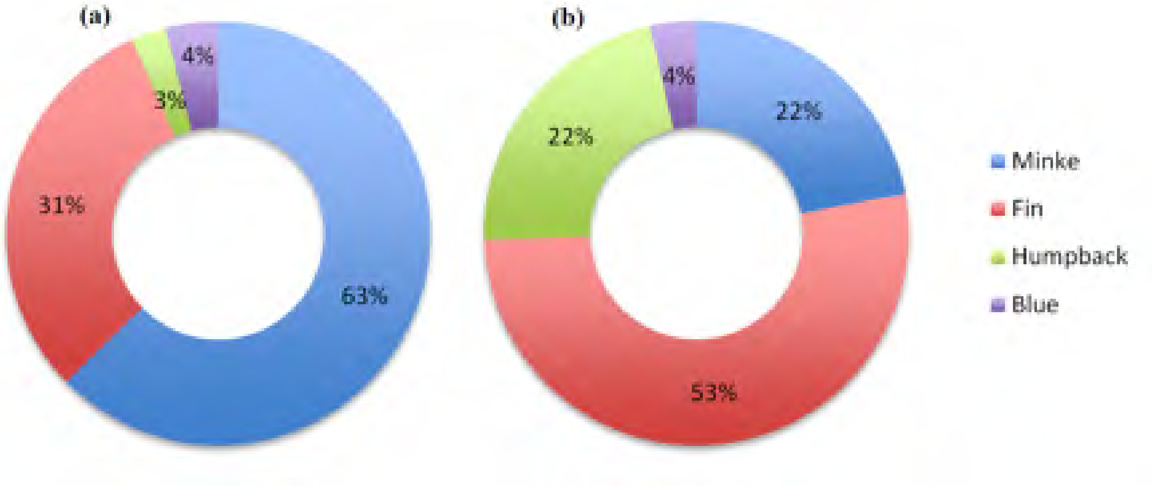


Figure III.3 Discrepancy between (a) rorqual species relative abundance (unpublished results from transect data analyses, GREMM and Cristiane Albuquerque Martins) and (b) their relative contribution in boat-based observations (AOM data), highlighting whale-watching captains' preferences.

The 2005-2009 period is characterized by a regular presence of humpback whales in the area. A species' relative contribution to total observations cannot be inferred from its relative abundance, as shown in Figure III.3. This mainly reflects captain's preferences.

This preference ranking is driven by a combination of interleaved phenomena including species attractiveness (potential spectacular displays), ease of observation (*e.g.* accessibility, fleeing behaviour at the approach of boats, respiratory/diving patterns, distance of localization), and species-specific regulatory rules (Parks Canada, 2002) such as a 400-meters minimum approach distance from blue and beluga whales compared to 100 m from other species (200 m if more than 4 boats in observation).

4 Spatial patterns of activity relative to homeport

Table III.1 shows that the overlap between the core areas of activity for excursions departing from different homeports is very low. A spatialized form of the Jaccard similarity index (pairwise ratio of the union area divided by the intersection area) was calculated to highlight the relative separateness of core areas of activities for excursions departing from adjacent homeports. This index is the highest for Bergeronnes and Tadoussac but remains relatively low (approximately 15%). This highlights the captains' inclination to operate their excursions close to their homeport.

Table III.1 Jaccard index between core areas (50% of the densest areas of activity) of excursions operating from Tadoussac, Bergeronnes, Les Escoumins, and Saint-Siméon. Based on BOI extracted from AOM data, 1994-2008

	Tadoussac	**Bergeronnes**	**Escoumins**	**Saint-Siméon**
Tadoussac	1	0.10	0	0.01
Bergeronnes	0.10	1	0.16	0.007
Escoumins	0	0.16	1	0
Saint-Siméon	0.01	0.007	0	1

5 Boat aggregation in the vicinity of whales by species

The average number of boats within 2 km around an observed whale is **6.34** boats. Only **for 14.5%** of the total observation time, the observing vessel is alone with the pod. **21.9%** of the time, there are at least 10 boats surrounding the targeted whale within 2 km (55% of which lie within a distance of 400 m).

Figure III.4 illustrates clearly the ranking in whale attractiveness when present in the area. All distributions are significantly different from each other, with the lowest pairwise p-value being p=0.012 between minke and blue whales. Humpback whales are the most popular, followed closely by fin, blue, minke, belugas and other species. However, blue whales tend to congregate downstream, far from busy ports, biasing the distribution of Figure III.4 toward low values compared to fin or humpback whales. Further investigations are in progress to disentangle all mixed factors influencing boat aggregations (Michaud *et al.*, (in prep.))

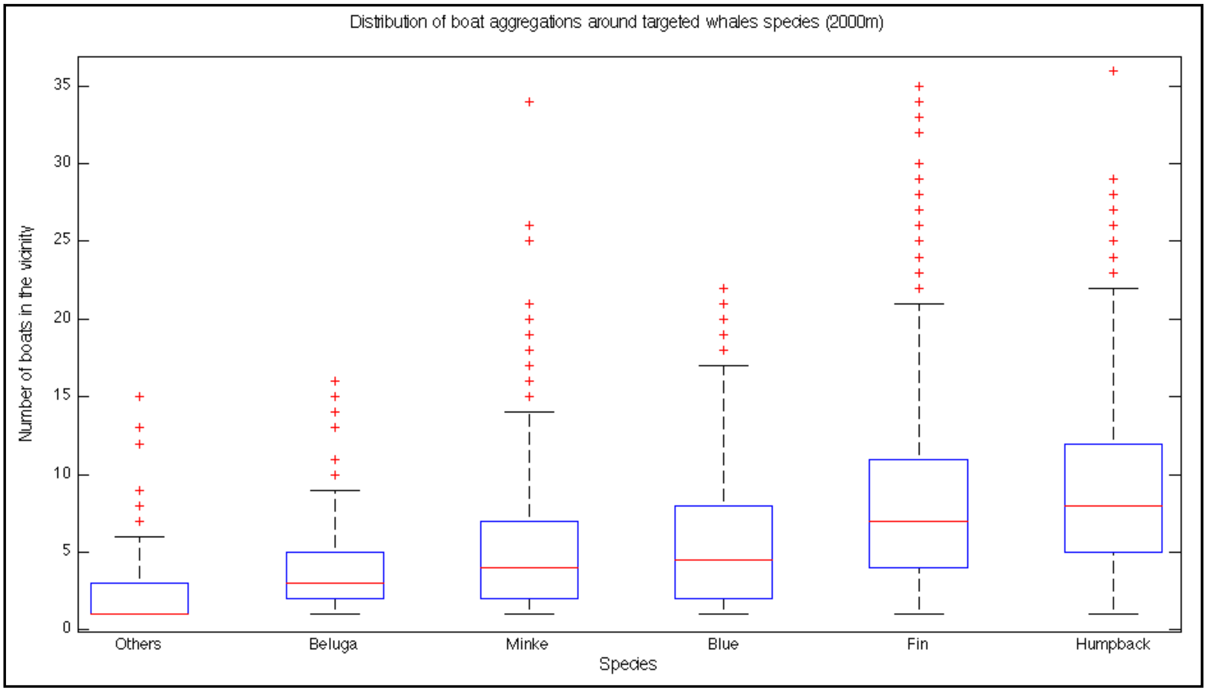


Figure III.4 Distribution of the number of boats within a 2000 meter vicinity of targeted species. The distributions are extracted for observations in the SSLMP, from 1994 to 2009.

6 Other activities

Other discovering activities (e.g. lighthouse, landscape viewing) have been highly encouraged in the past, in order to highlight the unique beauty of the region while decreasing the pressure exerted on whales. Despite improvements in this area for large whale-watching boats (11.5% of excursion time, mainly in the Saguenay), except for companies totally dedicated to landscape viewing, the percentage of these activities remains very low (5.3% of total excursion time), especially for excursions made onboard small vessels (3.3% of excursion time).

APPENDIX IV

SPATIOTEMPORAL PATTERNS OF WHALE SPECIES' DYNAMICS

Here we give some descriptive elements of whale species' spatiotemporal dynamics. Eliciting the factors influencing this dynamics is beyond the scope of this article and is currently under investigation by several researchers in marine mammal ecology.

1 Temporal presence of whale species in the SSLMP region

As illustrated by Table IV.1, minke and fin whales can be considered as safe bets for the whale-watching industry since their presence in the area is highly reliable. On the contrary, the presence of blue whales and humpback whales in the area is more variable. The scarcity of these two species, combined with some dramatic attributes (e.g., the blue whale is the biggest animal having ever lived on Earth and humpback whales occasionally display spectacular behaviours such as fluke-up dives, tail-slapping or breaches) can make them attractive for whale-watching in certain contexts.

Table IV.1 Presence rate of the main whale species in the area of the SSLMP (mid-June to the end of September). Average on ~2100 excursions sampled from 1994 to 2009 (AOM database)

Species	Presence
Minke whale	~100%
Fin whale	~100%
Beluga whale	~100%
Humpback whale	63.9%
Blue whale	55.4%

2 Inter- and intra-annual variability of species' abundance

Species' abundance is variable on different time scales, mainly in response to their prey distribution locally and downstream in the Gulf (Coakes *et al.*, 2005). Figure IV.1 illustrates the inter-annual variability of abundance for the three largest whale species from 2005 to 2009. Abundance partly determines the accessibility of a species for observation (along with spatial distribution).

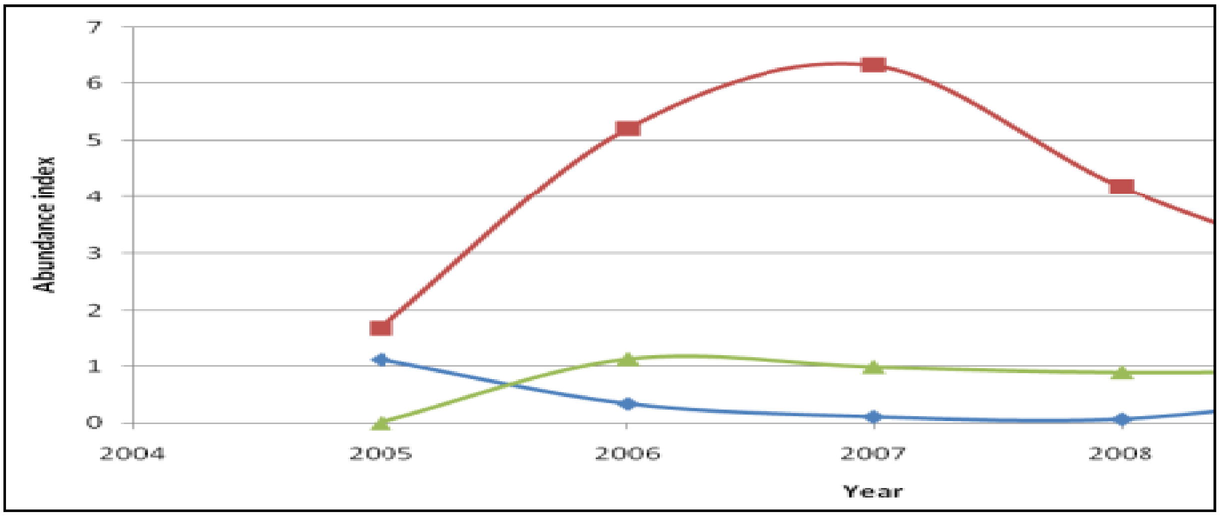


Figure IV.1 Species' inter-annual variability in abundance (attractive species only). The abundance index is a relative measure of rorqual abundance, extracted from the AOM database.

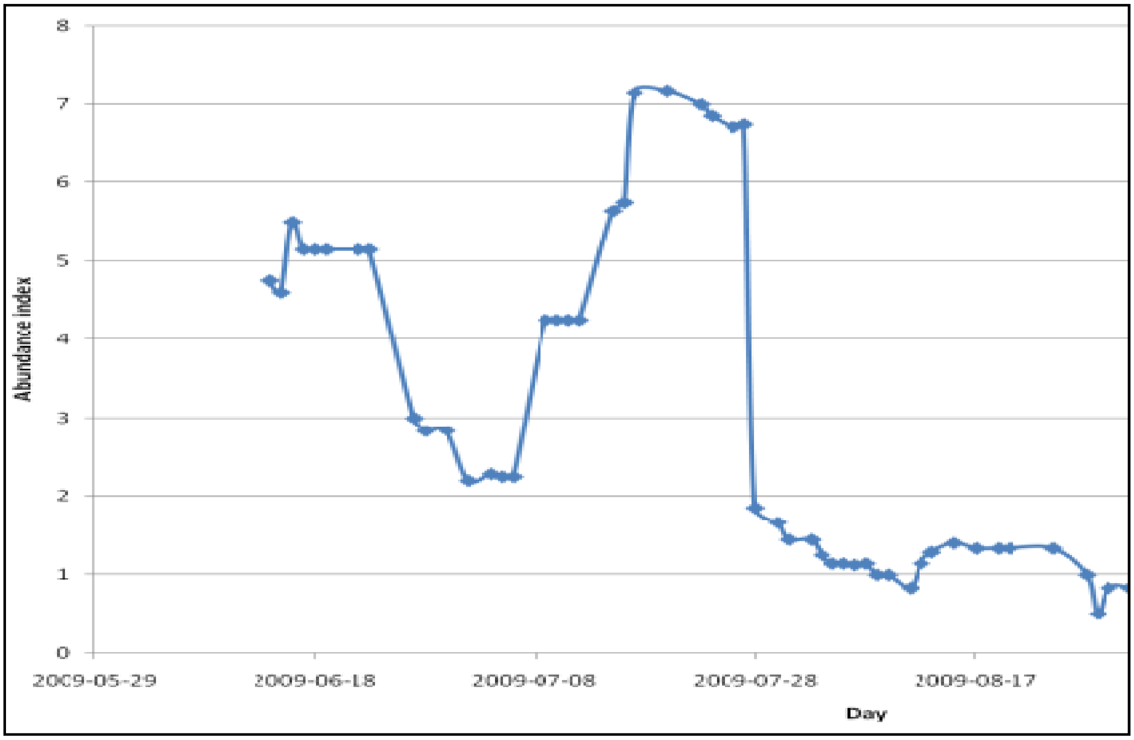


Figure IV.2 Fluctuations of fin whale’s abundance in 2009 in the SSLMP region.

Figure IV.2 illustrates the intra-annual variability in species abundance. This example displays a sudden drop in fin whales abundance at the end of July 2009. This kind of event is frequent in the region where whales’ presence is largely driven by preys’ availability such as krill, plankton, and capelin, themselves highly dependent on oceanographic phenomena (*e.g.* tidal currents, wind, and primary productivity).

3 Short-term spatiotemporal stability of species in the region

From day to day during the summer season, we observe that for fin, minke and humpback species, the minimum distance between sightings is significantly lower than for 2-day or greater lags; in combination with the low median distances from day to day (<1.5 km), these analyses highlight the relatively high foreseeable nature of each species' locations over time. This is not true for blue whales whose dynamics is more uncertain even over short periods of time.

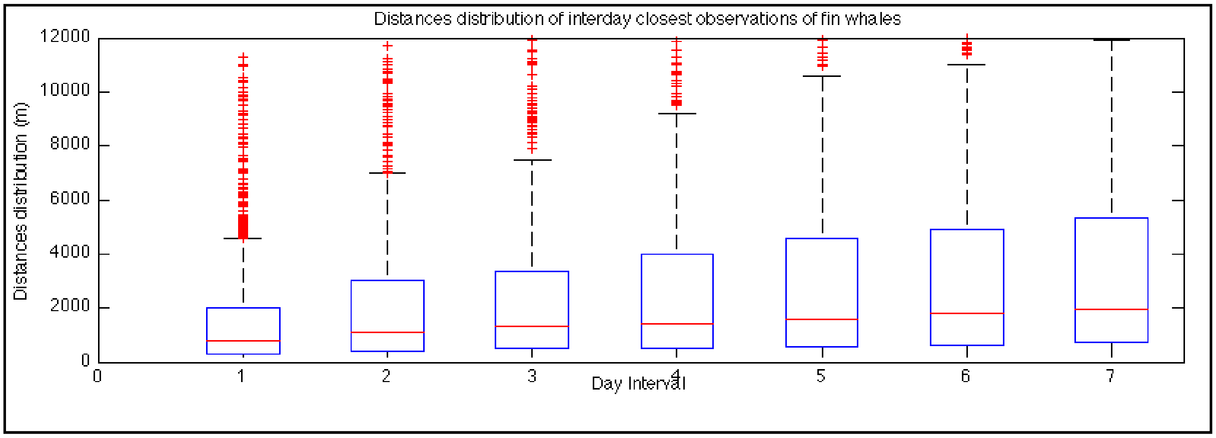


Figure IV.3 Distribution of distances between two observations of fin whales, for 1- to 7-day lags.

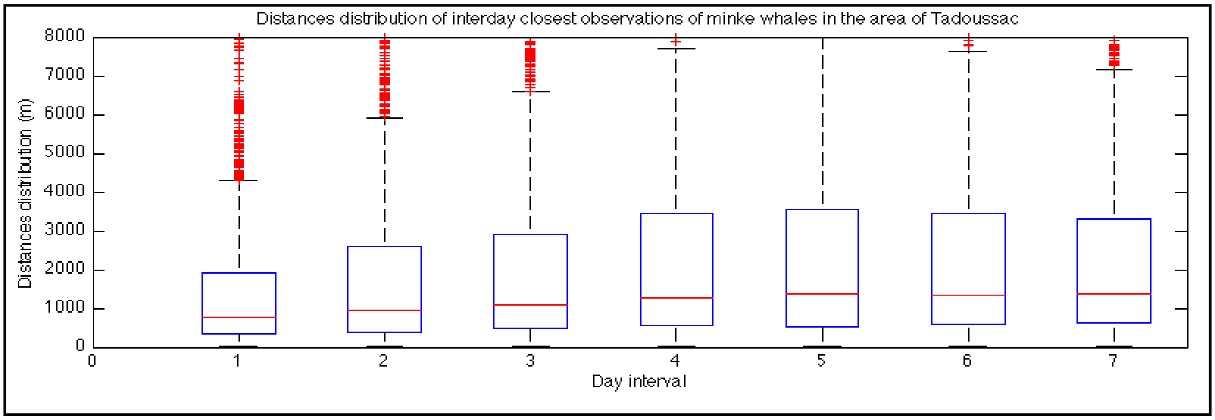


Figure IV.4 Distribution of distances between two observations of minke whales, for 1- to 7-day lags.

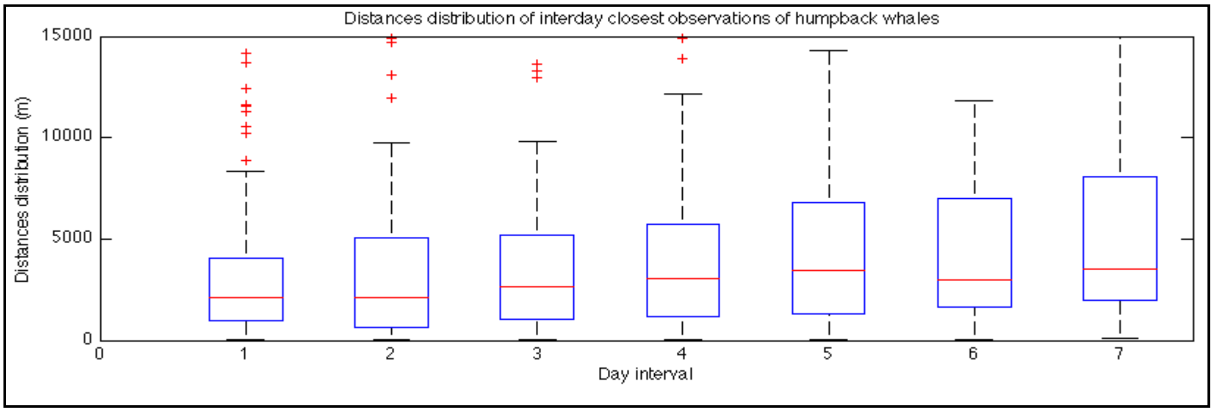


Figure IV.5 Distribution of distances between two observations of humpback whales, for 1- to 7-day lags.

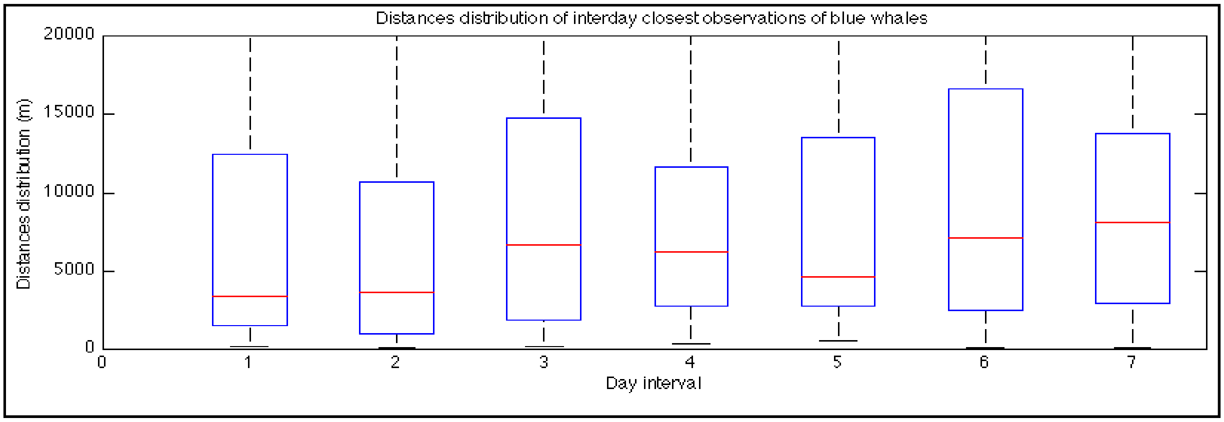


Figure IV.6 Distribution of distances between two observations of blue whales, for 1- to 7-day lags.

We can observe in Figure IV.3 and Figure IV.4 that the uncertainty about the spatial locations of fin and minke whales increases with time lag, along with the median distance. For these species, the closest distance between two observations is significantly lower from day to day than with a 2-day lag (p-value<0.01). This trend is less clear for humpback whales and totally absent for blue whales. However, for humpback whales, the distances remain at a low level (75% of the distances < 4000m) whereas values are significantly higher for blue whales (75% of the distances < 12000m).

This with their relatively high abundance partly explains why the whale-watching industry relies heavily on these two species. Whale-watching activities developed in the early 90's based on fin whales and attractive whales such as blue whales. However, during lean periods when *star* species are absent, activities can be based almost exclusively on the reliable minke whales.

Conversely, Figure IV.6 and Table IV.1 illustrate the reasons why the blue whale cannot be a reliable resource single-handedly for whale-watching activities, even for companies operating from ports located close to their observed distribution.

APPENDIX V

PSEUDO-CODE OF THE RAYBAPP ALGORITHM

```
Initialization
        Add Origin point and the Destination point in a list of points → PATH
        Create a list of paths LIST_OF_CONCURRENT_PATHS
        Add PATH in LIST_OF_CONCURRENT_PATHS
        Take the first path in LIST_OF_CONCURRENT_PATHS → PATH
End Initialization

While PATH is not navigable
        Do
            Find the list of points corresponding to the first non-navigable segment in PATH → [A, B]
            Take the last navigable point before A in PATH → L
            Take the next navigable point after B in PATH → N
            Take the first navigable point (if exists) to the right at 90° of [A, B] midpoint→P1
            Insert p1 in a copy of PATH between N and L → NEWPATH1

            If NEWPATH1 is navigable
                    Return NEWPATH1
            End if

            Else
                    Add NEWPATH1in LIST_OF_CONCURRENT_PATHS
                    Sort LIST_OF_CONCURRENT_PATHS with shortest paths first
            End Else

            Take the first navigable point (if exists) to the left at 90° of [A, B] midpoint →P2
            Insert p2 in a copy of PATH between N and L → NEWPATH2

            If NEWPATH2 is navigable
                    Return NEWPATH2
            End If

            Else
                    Add NEWPATH2 in LIST_OF_CONCURRENT_PATHS
                    Sort LIST_OF_CONCURRENT_PATHS with shortest paths first
            End Else

            Delete PATH from LIST_OF_CONCURRENT_PATHS
            Take the first path in LIST_OF_CONCURRENT_PATHS → PATH
        End Do
End While

Return PATH
```

APPENDIX VI

PSEUDO-CODE OF THE SMOOTHING FUNCTION

```
Initialization
    Take the list of points to be smoothed → PATH
    Initialize a boolean to true → IS_POINT_REMOVED
End Initialization
While IS_POINT_REMOVED is true
    Do
        Set IS_POINT_REMOVED to false
        For (int i=1; i+1< size of PATH; i++)
            Take the ith point in PATH → X
            For (int k = i+2; k<size of PATH; k++)
                Take the kth point in PATH → Y
                If segment [X, Y] is navigable
                    Remove i+1th point in PATH
                    Set IS_POINT_REMOVED to true
                End If
            End For
        End For
    End Do
End While
Return PATH
```

APPENDIX VII

BOUNDED RATIONALITY AND COGNITIVE HEURISTICS

We describe some key concepts from cognitive psychology that were used both for the investigation and the description phase of whale-watching captains in the whale-watching ABM.

1 Principle

Understanding human decision making is a challenging task (Janssen and Ostrom, 2006a). For several decades, cognitive scientists have been developing theories and models to describe underlying processes producing outcomes of humans facing decision problems. Recently, the bounded rationality theory has started to compete with the classical homo economicus view as the mainstream view of rationality (Chase et al., 1998). Classical theories used to consider humans as perfect problem solvers, conveniently allowing the use of well-established logical and statistical theories to explain human decisions (e.g. maximization of expected utility). However, facing an accumulation of evidence that humans regularly derive from models prescribed by classical theories (Kahneman et al., 1982), cognitive scientists turned towards alternative theories. Drawing on Simon's pioneering work (Simon, 1955; Simon, 1982), the bounded rationality paradigm is establishing itself as a major conceptual framework for the descriptive study of human decision making (Chase et al., 1998).

Describing bounded rationality, Simon compares human rationality to a pair of scissors whose two blades are the structure of the decision task and the computational capabilities of the decision maker (Simon, 1990). Accordingly, humans dealing with complex decision problems where an optimal solution (assuming one exists) is unreachable use shortcuts and exploit decision environment patterns to reach a satisficing solution (Simon, 1957). In that sense, human rationality is described as bounded.

2 Cognitive heuristics for decision making

When facing multi-alternative/multi-attribute decision problems, bounded rationality (Simon, 1957) provides descriptive approaches to decision making in lieu of the classical view of the fully rational man whose decisions are driven by the normative laws of logic and probability, by the axioms of expected utility, and by Bayesian statistics (Gigerenzer and Selten, 2001). Following the idea of its founding father Herbert Alexander Simon, Gigerenzer and colleagues have been working to discover models of heuristics of decision making while coping with incomplete information and limited computational capabilities (Gigerenzer and Goldstein, 1996; Gigerenzer and Todd, 1999; Gigerenzer and Selten, 2001). These simple models of humans' decision making processes are named fast and frugal heuristics (Gigerenzer and Todd, 1999; Gigerenzer, 2004). Despite their simplicity, these cognitive heuristics tend to perform as well as more complex models in representing human decision making in certain circumstances of multi-alternative/multi-attribute problems (Brighton, 2006). Among these heuristics, the most popular are satisficing (Simon, 1955); tallying (Dawes, 1979); the recognition heuristic (Goldstein and Gigerenzer, 1999; Goldstein and Gigerenzer, 2002); and Take The Best (Gigerenzer and Goldstein, 1996). Heuristics tested in this study are described below.

2.1 Formalism

Let us define a multi-alternative/multi-attribute decision problem P that a decision maker must solve. The set of candidate alternatives A_i potentially solving P is defined as $S_p=\{A_1, A_2,\ldots\}$. Each candidate alternative A_i is defined by a set of attributes $A_i=\{a^i_1, a^i_2,\ldots\}$. According to Gigerenzer, a model of cognitive heuristic H can be defined as "a rule whose purpose is to describe the actual process – not merely the outcome – of problem solving" (Gigerenzer, 2004). Here, we describe the three cognitive heuristics (drawn from the literature on bounded rationality) tested to model whale-watching captains' decision making. The interested reader can find more about these heuristics in (Gigerenzer and Selten, 2001).

2.2 Satisficing

The satisficing heuristic (Simon, 1955) supports the observation that when dealing with a complex, ill-defined problem, humans cannot find optimal solutions. Particularly, when the information search is costly and decisions must be made in a timely fashion, the decision maker cannot spend time searching for all candidate alternatives. Accordingly, it suffices that a candidate alternative satisfies a predetermined level of requirement (regarding its attributes) for it to be selected. The satisficing heuristic's flowchart is given in Figure VII.1.

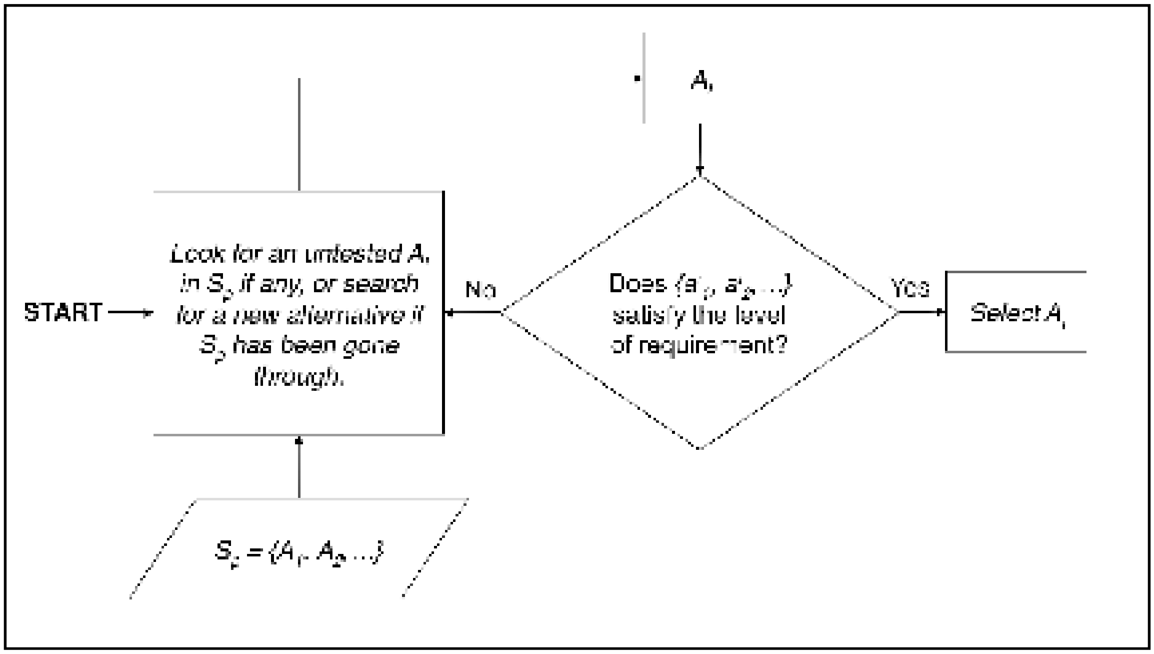


Figure VII.1 Flowchart of the satisficing heuristic.

2.3 Tallying

The tallying heuristic (Dawes, 1979) is a simple linear model related to important concepts in information theory (Gigerenzer and Goldstein, 1996; Martignon, 2001). In decision problems where information is abundant and where alternative attributes are compensatory (no attribute is necessarily more important than the others), simple models like the tallying heuristic can perform well. Each alternative attribute has a value of 1 if it favours the selection of an alternative and 0 otherwise. For each alternative, a score is computed which is simply the sum of all attribute's values. The alternative with the highest score is selected by the decision maker. The choice is made at random in case of a tie. The tallying heuristic's flowchart is given in Figure VII.2.

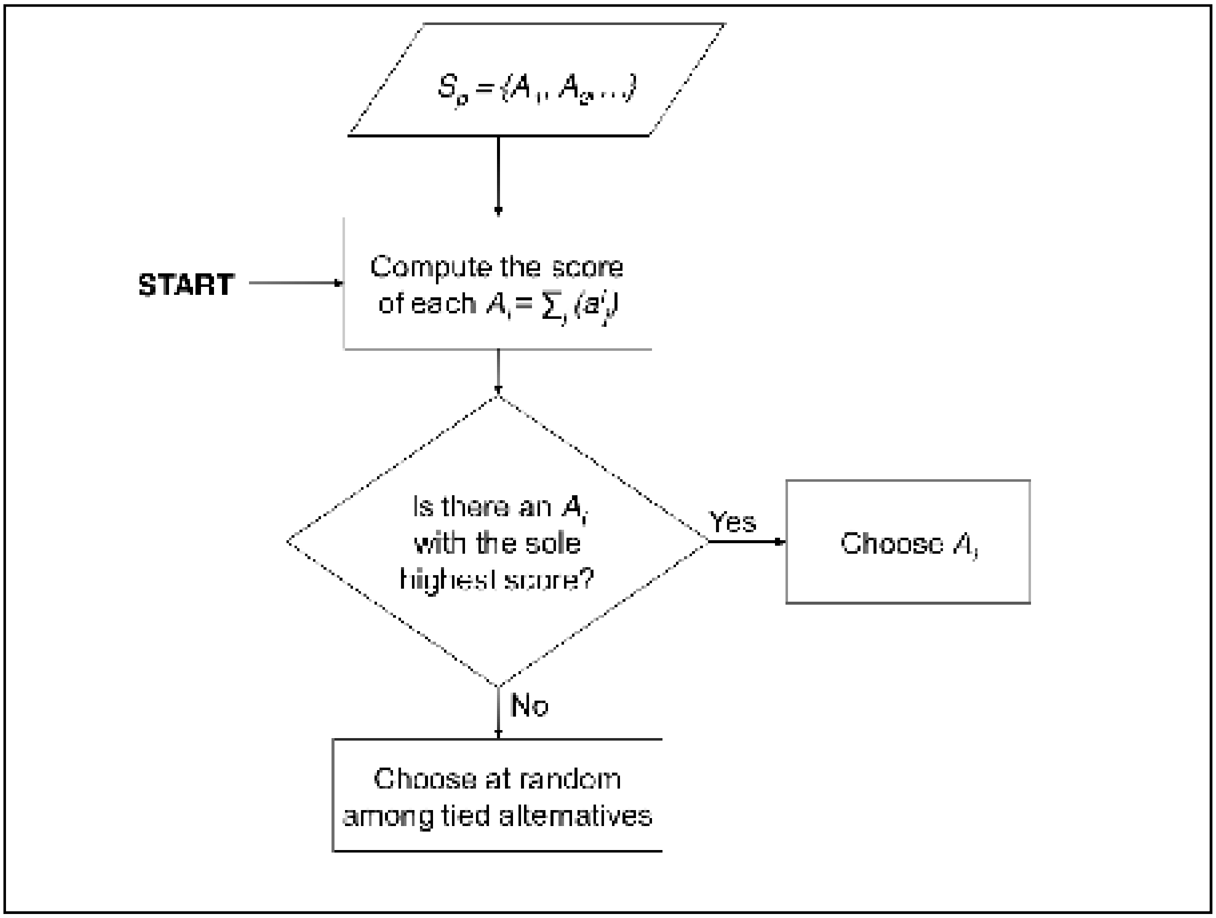


Figure VII.2 Flowchart of the tallying heuristic.

2.4 Take The Best

The Take The Best heuristic (Gigerenzer and Goldstein, 1996) allows the decision maker to exploit the non-compensatory nature of a given decision problem. Cues are ordered according to their ecological validity (Gigerenzer and Goldstein, 1996), that is in decreasing order of the frequency with which they correctly predict the decision. An adequate cue order results from the decision-maker's learning process based on feedback from previous experiences in similar decision contexts (Dieckmann and Todd, 2004). Alternatives are then compared with each other along ordered cues, keeping only the best ones at each step. The choice is made at random in case of a tie when no more attributes are known. This heuristic is frugal in that it can deliver a decision (choice) without going through all cues. The Take The Best heuristic's flowchart is given in Figure VII.3.

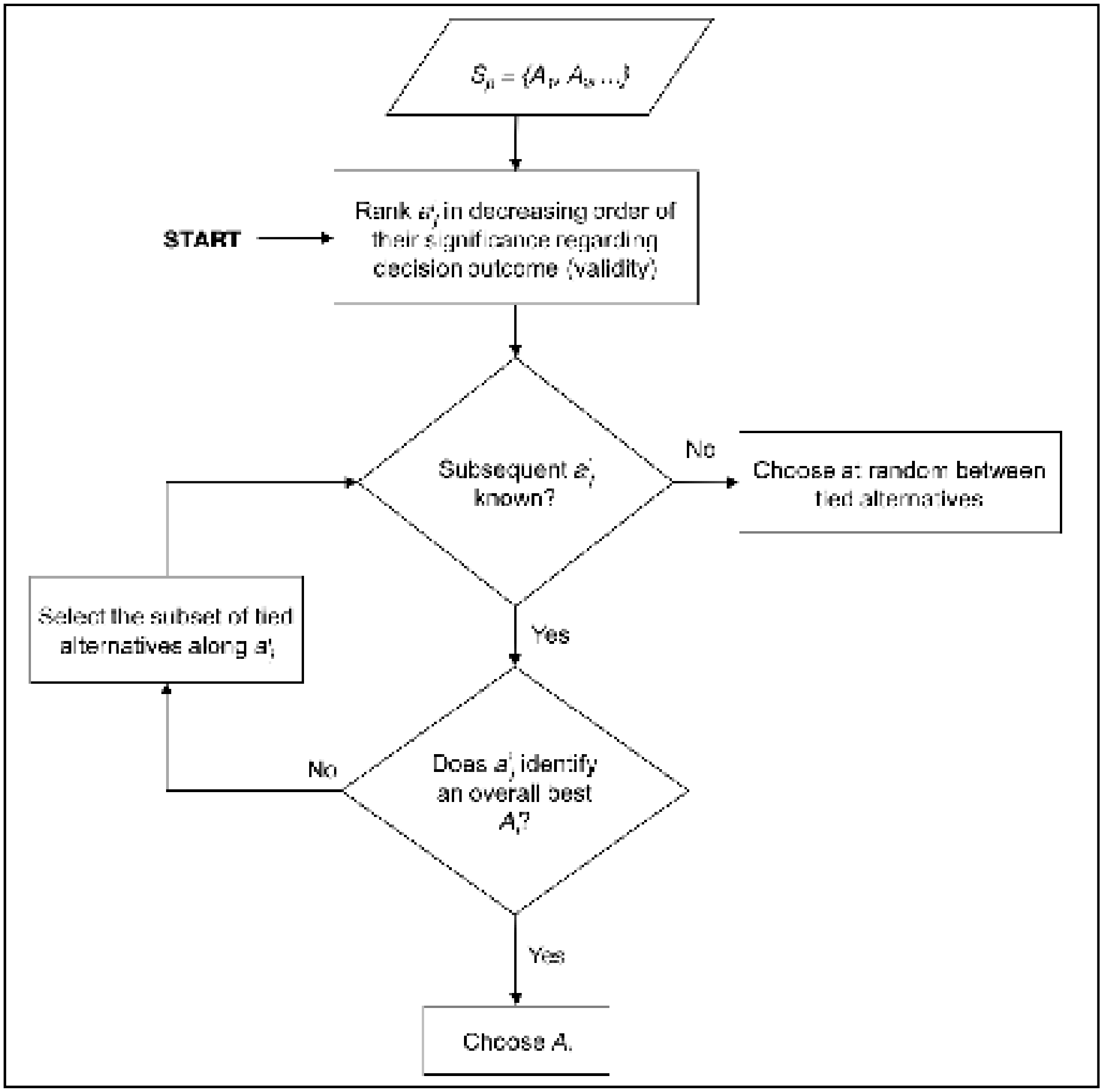


Figure VII.3 Flowchart of the Take The Best heuristic.

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