Université du Québec
à Rimouski

Identification et développement d'ouvrages de protection côtière pour augmenter la résilience des communautés côtières dans un contexte de changements climatiques

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RÉSUMÉ

Les caractéristiques des environnements côtiers varient à l'échelle du Québec maritime. Plusieurs types d'ouvrage de protection côtière (OPC) existent pour résoudre une problématique d'érosion ou de submersion dans ces environnements. Les effets des OPC sur le système socioécologique côtier (SSEC) sont complexes en raison des nombreuses rétroactions entre les éléments hydrodynamiques et géomorphologiques qui ont aussi des répercussions sur les aspects écologiques et socio-économiques des communautés côtières. Le choix d'un OPC dépend des caractéristiques socioécologiques propres à un secteur de côte, ainsi que des effets souhaités. Cependant, entre 1980 et 2000, au Québec, les OPC ont été aménagés en situation d'urgence et en réaction aux événements de tempête, sans considération des effets indésirables qu'ils pourraient produire. L'objectif principal de cette thèse doctorale est de développer un outil d'aide à la prise de décision élaboré sur une structuration cohérente de l'information permettant de prendre en considération les données tant géomorphologiques et hydrodynamiques, qu'écologiques et socio-économiques nécessaires à l'identification des meilleures alternatives en termes d'OPC au regard des conditions spécifiques d'un SSEC et des besoins exprimés par les acteurs du territoire (professionnels et gestionnaires). Pour ce faire, plusieurs méthodes ont été utilisées : (1) des consultations des acteurs de la zone côtière; (2) un traçage par système d'information géographique des composantes du SSEC; (3) une revue et méta-analyse de la littérature sur les effets des OPC; (4) le développement d'un algorithme; (5) une application d'une analyse multicritère. La thèse est composée de deux volets : (1) caractérisation des interventions passées et établissement d'une base afin d'orienter les décisions futures; (2) développement d'une approche d'évaluation des OPC. Premièrement, en 2017, 97,6 % des OPC présents dans le Québec maritime étaient des enrochements et des murs de protection. Par le passé, en plus de l'urgence des interventions, les principaux facteurs évoqués par les acteurs consultés pour justifier leur choix d'aménagement de ces OPC étaient un manque de connaissance, de financement et de processus collaboratif. Or, les acteurs consultés en 2017-2018 ont démontré une ouverture pour l'utilisation d'une plus grande diversité d'OPC. Ils ont également soulevé un besoin d'acquisition de connaissances scientifiques sur les effets des différents OPC pour pouvoir prendre de meilleures décisions. Les résultats de la méta-analyse de la littérature internationale sur les effets des OPC sur le milieu côtier démontrent que 52,7 % des 355 sites étudiés sont des côtes basses sablonneuses, que les études portent en majorité sur les recharges de plage (40,9 %), les murs de protection (16,7 %) et les brise-lames (12,5 %) et qu'il y a une absence d'études dans un contexte de climat nordique avec la présence de glaces côtières. Ce qui suggère un déséquilibre dans les connaissances scientifiques se rapportant aux effets produits par les OPC sur des environnements côtiers variés, déséquilibre qui doit être redressé afin d'améliorer le processus décisionnel. Deuxièmement, une approche d'évaluation a été développée pour répondre au besoin d'outils d’aide à la décision soulevé par les acteurs du territoire. Cette approche est basée sur la combinaison d’un algorithme d’identification et d’une analyse multicritère. L’algorithme permet d’évaluer et de hiérarchiser des OPC en fonction de leurs effets sur les différents environnements côtiers, et ce en trois étapes. (i) La caractérisation du SSEC est effectuée au moyen d’indicateurs de suivis géomorphologiques (type de côte, substrat) et hydrodynamiques (marnage, vagues, courants). Des données cartographiques (caractérisation côtière, écosystèmes, activités et usages) et hydrodynamiques (vagues et marnage) servent à définir l’état initial des sites à l’étude. (ii) Tirés d’une revue de littérature, les énoncés d’effets observés associés aux caractéristiques environnementales qui y correspondent (type de côte et de substrat, marnage et vagues) ont été compilés dans une base de données, catégorisés et pondérés selon une échelle qualitative de pondération (-5 à 5). Cette échelle est basée sur la pertinence et sur le caractère positif ou négatif des énoncés. (iii) L’information est traitée par l’algorithme sur la base d’une correspondance entre les caractéristiques environnementales du site d’étude et celles enregistrées dans la base de données. L’évaluation et la hiérarchisation des OPC sont réalisées en colligeant et en classant les effets observés connus, produits par ces OPC dans des contextes environnementaux similaires. (iv) Les résultats de l’algorithme présentent la hiérarchisation des OPC selon une structure d’agrégation à plusieurs niveaux qui peut être utilisée par les gestionnaires, les décideurs et les ingénieurs côtiers pour la planification et la conception de projets d’intervention pour protéger des infrastructures ou des milieux sensibles.

L’analyse multicritère est ensuite utilisée pour hiérarchiser les OPC présélectionnés selon les résultats de l’algorithme en trois étapes. (i) Les critères d’évaluation ont été identifiés et pondérés par les acteurs du territoire selon leurs priorités dans le cadre d’une série de cinq ateliers. (ii) Les OPC ont été évalués en regard de chacun des critères et des caractéristiques socioécologiques de quatre secteurs d’études. (iii) Les OPC sont hiérarchisés avec la méthode PROMETHEE. Les résultats de la hiérarchisation montrent que le premier rang est occupé par la végétalisation dans trois des quatre sites et par l’enrochement dans le quatrième site. De manière plus générale, les résultats montrent la pertinence de l’utilisation d’une méthode d’analyse multicritère et de l’implication des acteurs du territoire dans le processus de sélection d’un OPC qui tienne compte des priorités locales et soit adapté aux conditions environnementales. Globalement, cette thèse offre des connaissances permettant d’améliorer le processus décisionnel menant à la sélection d’un OPC. Elle est appuyée sur une approche intégrée et holistique d’identification des OPC adaptés aux conditions spécifiques d’un SSEC, en tenant compte d’une part des effets des OPC sur l’évolution du SSEC et, d’autre part, des besoins exprimés par les acteurs du territoire.

Mots clés : ingénierie côtière, gestion intégrée des zones côtières, processus décisionnel, érosion côtière, submersion côtière, ouvrages de protection côtière, processus participatif, résilience

ABSTRACT

Coastal characteristics vary throughout the Estuary and Gulf of St. Lawrence (EGSL). A variety of coastal defence measures (CDM) are available and can be used for the purpose of preventing coastal erosion and flooding in these types of environments. The effects of CDMs on the coastal socio-ecological system are complex due to site-specific interactions between hydrodynamic and geomorphological conditions, which have repercussions on the ecological and social aspects of coastal communities. Therefore, the choice of CDMs depends on the socio-ecological characteristics of the site, as well as on the desired effects on the ecosystem. However, between 1980 and 2000, in Quebec, CDMs were built in emergency situations without consideration for their possible negative effects. The main purpose of this thesis is to develop an integrated approach to select CDMs that are adapted to the specific conditions of a coastal socio-ecological system while including local actors' (managers and professionals) needs and priorities. In order to do so, a number of methods were used: (1) consultations with local coastal actors; (2) mapping of coastal socio-ecological system components; (3) literature review and meta-analysis of the effects produced by CDMs on the environment; (4) development of an algorithm; (5) multicriteria decision analysis. The thesis is divided in two parts: (1) characterization of past interventions and reorientation of future decisions; and (2) development of a CDMs evaluation approach. First, the characterization of more than 3300 km along the Quebec shoreline determined that in 2017, of the total number of CDMs implemented, 97.6% were rock armour and seawalls. The main factors evoked by the actors to justify their choice were a lack of knowledge, funding and collaborative processes. However, the actors demonstrated an openness for the use of a greater variety of CDMs. In order to be able to make better decisions, they also brought up the need for the acquisition of scientific knowledge on the effects of different CDMs on coastal systems. Yet, the results of a literature meta-analysis showed that 52.7% of the study sites were in low-lying sandy coasts, and that most attention was given to three CDMS: beach nourishments, seawalls, and breakwaters. Also noticeable is the absence of studies in Nordic climate where ice cover is a significant factor in coastal processes. This suggests an imbalance in scientific knowledge that must be addressed in order to improve the decision-making process. Second, an evaluation approach was developed to respond to the need for decision support tools that was raised by actors during the consultation process. This approach is based on the combined use of an identification algorithm and a multicriteria decision analysis. The algorithm allows the evaluation and prioritization of CDMs according to their effects on the different coastal environments. It consists of three steps: (i) the characterization of the coastal socio-ecological system is carried out using geomorphological (coast, substrate) and hydrodynamic (waves, currents, tidal range) monitoring indicators. Cartographic data (coastal characterization, ecosystems, activities and uses) and hydrodynamic data (wave and tidal range) are used to define the initial state of the study sites. (ii) From the literature review, the statements of observed effects associated with corresponding environmental characteristics which were compiled into a database, are then categorized and weighted according to a qualitative weighting scale (-5 to 5). This scale is based on the relevance, and on the positive or negative character of the CDMs. (iii) The user selects CDMs. The information is processed by the algorithm based on a correspondence between characteristics of the study site and those recorded in the database. The evaluation and prioritization of the CDMs are performed by collating and ranking the known observed effects produced by the selected CDMs in similar environmental contexts. The results present the hierarchization of CDMs according to a multilevel aggregation structure, which can be used in different ways by coastal managers, decision makers, and engineers in the planning as well as in the design phases of a project. The multicriteria decision analysis is then used to compare and rate the CDMs, preselected by the algorithm in three steps. (i) The evaluation criteria were identified and weighted by local actors in a series of five workshops. (ii) CDMs were evaluated in relation to each criterion within the local socioecological context of four study sites. (iii) CDMs were hierarchized with the PROMETHEE method. Initial results show that vegetation came first in three of the four sites, while rock armour ranked first in the fourth site. Moreover, the results show the relevance of such a tool with a participatory process to select a CDM which considers local priorities, and is adapted to environmental conditions. Overall, this thesis provides knowledge to improve the decision-making process leading to the selection of a CDM. It is based on an integrated and holistic approach to identify CDMs best adapted to the specific conditions of a coastal socio-ecological system, taking into account the effects of CDM on the evolution of the system, as well as the needs expressed by local actors.

Keywords: coastal engineering, coastal protection, coastal defence measure, decision-making, coastal erosion, integrated coastal zone management, participatory process, resilience

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INTRODUCTION GÉNÉRALE

Les systèmes côtiers sont caractérisés par des épisodes d'érosion et de submersion côtières et, depuis plusieurs siècles, les sociétés humaines ont aménagé des ouvrages de protection côtière (OPC) pour s'y prémunir (Charlier *et al.*, 2005). Toutefois, dans les dernières décennies, une augmentation de l'artificialité des côtes a été constatée à l'échelle mondiale, en réponse aux effets des changements climatiques et au développement des zones côtières (Dugan *et al.*, 2011 ; Gittman *et al.*, 2015 ; Horstman *et al.*, 2009a). Les communautés côtières font maintenant face à une augmentation de l'impact des épisodes d'érosion et de submersion côtière exacerbées par l'augmentation du niveau marin relatif (Church et White, 2011 ; Horton *et al.*, 2014 ; IPCC, 2021 ; Nicholls et Cazenave, 2010) et dans les régions froides par la diminution de la période avec un couvert de glace (Barnhart *et al.*, 2014 ; Corriveau *et al.*, 2019b ; Manson et Solomon, 2007 ; Senneville *et al.*, 2014). Au Québec, les communautés côtières de l'estuaire et du golfe du Saint-Laurent (EGSL) ont été développées sur des côtes généralement sensibles à l'érosion (Bernatchez et Dubois, 2004). Entre les années 1980 et le début des années 2000, des structures réflectives, soit des enrochements et des murs de protection, ont été aménagées en situation d'urgence et en réaction aux événements de tempête (Boyer-Villemaire *et al.*, 2015). Les gestionnaires et les professionnels ont justifié la sélection de cette solution unique par un manque de connaissance sur la dynamique côtière et un manque d'outil pour prendre de bonnes décisions (Drejza *et al.*, 2011 ; Fraser *et al.*, 2017 ; Guénette *et al.*, 2019 ; Marie *et al.*, 2017). Pourtant, la littérature scientifique internationale montre qu'il existe une grande diversité de types d'OPC qui engendrent des effets spécifiques sur les systèmes côtiers dans lesquels ils sont implantés (Sauvé *et al.*, s. d.).

Or, les systèmes côtiers sont caractérisés par une dynamique qui résulte de processus non linéaires à échelles multiples qui impliquent des interactions entre les aspects géomorphologiques, hydrodynamiques, écosystémiques et sociaux (Baquerizo et Losada, 2008 ; Polasky *et al.*, 2011), ainsi qu'une incertitude inhérente amplifiée par les effets des changements climatiques (Hallegatte, 2009 ; Wahl *et al.*, 2017). Cette complexité rend chaque site unique et nécessite une démarche spécifique pour prendre en considération ses caractéristiques dans l'identification de l'OPC le mieux adapté au contexte (Jones *et al.*, 2014).

Dans cette introduction, les enjeux associés au processus décisionnel menant à la sélection d'OPC sont présentés en regard des caractéristiques du système socioécologique (SSEC) de l'EGSL et insérés dans le contexte de l'amélioration de la résilience des communautés côtières. Ensuite, les objectifs de la thèse sont présentés. Finalement, l'approche méthodologique générale de la thèse est détaillée.

1. SYSTÈME SOCIOÉCOLOGIQUE CÔTIER

En gestion environnementale, la théorie générale des systèmes développée par von Bertalanffy (1950) a contribué à l'avancement des connaissances dans la compréhension des interactions entre l'humain et son environnement en proposant des notions de non-linéarité, d'incertitude, d'émergence, d'échelle et d'auto-organisation. Cette théorie a influencé les travaux de Holling qui, tout au long de sa carrière, a contribué à l'essor du concept de système socioécologique, soit des systèmes adaptatifs complexes qui présentent une dynamique périodique, multiéchelle et chaotique (Gunderson et Holling, 2002 ; Holling, 1973). Ce concept est considéré par certains comme fondamental pour les enjeux associés au développement durable et à l'interaction entre la société et l'environnement (Adger, 2006 ; Eakin et Luers, 2006 ; Folke, 2006 ; Folke *et al.*, 2010 ; Gallopín, 2006 ; Gallopín *et al.*, 2001 ; Ostrom, 2009 ; Prior et Eriksen, 2013 ; Turner *et al.*, 2003 ; Walker *et al.*, 2004).

Les systèmes socioécologiques sont caractérisés par une incertitude inhérente (Brookes, 2009 ; Holling, 1978) qui provient de quatre principales sources (Allen *et al.*, 2011 ; Williams, 2011).

1. L’observabilité partielle réfère à la définition de l’état du système lors de son étude préalablement à une intervention.
2. L’incertitude structurelle découle d’un manque de connaissance sur la dynamique du système.
3. Les variations environnementales découlent des conditions environnementales qui agissent sur le système et de leur évolution à travers le temps.
4. La contrôlabilité partielle réfère au niveau d’adaptabilité des mesures mises en place pour contrôler un aléa au regard de l’état et de la dynamique du système ainsi que de l’influence des conditions environnementales sur son évolution.

Compte tenu de ces quatre sources d’incertitude, les connaissances et les données disponibles sur le système ainsi que le processus décisionnel menant à une intervention influencent grandement le degré d’incertitude (Brookes, 2009).

Les systèmes côtiers sont des systèmes socioécologiques, car ils sont composés de processus non linéaires qui ont des échelles spatio-temporelles multiples et qui résultent de l’interaction entre les conditions morphologiques, topobathymétriques et hydrodynamiques (Baquerizo et Losada, 2008 ; Fabbri, 1998). Ces interactions ont ultimement des rétroactions sur les écosystèmes et les milieux sociaux et économiques (Polasky *et al.*, 2011). Ainsi, les communautés côtières font partie intégrante des systèmes socioécologiques côtiers. Elles doivent composer avec cette dynamique complexe entre les milieux environnemental et humain qui engendre des enjeux importants associés à l’érosion et à la submersion côtière (Degbe, 2009 ; Goussard, 2014 ; Jouzel *et al.*, 2015 ; Marchand, 2010 ; Silva *et al.*, 2014). Pour faire face à ces enjeux, les interventions réalisées par les communautés côtières peuvent modifier les processus naturels et engendrer des changements environnementaux (Bernatchez et Fraser, 2012 ; Cooper *et al.*, 2020 ; Dugan *et al.*, 2008 ; Moschella *et al.*, 2005).

À l’échelle du Québec maritime laurentien, cette dynamique propre à chaque site est d’autant plus complexe compte tenu de la variation des milieux environnementaux et humains sur les 4 184 km de côte[1]. Ce territoire côtier s'étend entre les MRC de La Côte-de-Beaupré et du Golfe-du-Saint-Laurent sur la rive nord de l'EGSL et la MRC de Bellechasse sur la rive sud jusqu'à la MRC d'Avignon dans la baie des Chaleurs, et inclut aussi la MRC des Îles-de-la-Madeleine (Arsenault *et al.*, 2021).

1.1 Milieux environnementaux

Le Québec maritime est constitué d'une diversité d'environnements côtiers dont les caractéristiques varient et sont spécifiques à chaque segment géomorphologique de côte, soit la référence linéaire pour caractériser la finesse de l'échelle spatiale. La longueur d'un segment géomorphologique est définie par l'uniformité de ses caractéristiques géomorphologiques (type de côte, état de la côte (érosion, accumulation, stable), artificialité ou état de l'artificialité). Dans le Québec maritime, elle varie entre 5 m, soit une longueur minimale définie méthodologiquement (Arsenault *et al.*, 2021), et approximativement 10 km. À l'échelle d'un segment géomorphologique, les milieux environnementaux présentent des distinctions géomorphologiques, hydrodynamiques et écosystémiques.

1.1.1 Composantes géomorphologiques

D'un point de vue géomorphologique, les milieux environnementaux peuvent, entre autres, être distingués par le type de côte et le type de substrat ainsi que par différents processus d'érosion et de sédimentation. Les types de côtes du Québec maritime sont nombreux et spatialement diversifiés (figure 1) : 60,5 % sont meubles et 39,5 % sont rocheuses ; 70,4 % sont basses et 29,5 % sont des falaises. Ces côtes sont majoritairement stables ou végétalisées (50,5 %). Le tiers des côtes est caractérisé par un état semi-végétalisé ou actif ou vif, ce qui indique la présence de processus d'érosion (Arsenault *et al.*, 2021). Certains segments de côtes sont également artificialisés par un ouvrage de protection ou une

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[1] Ce total inclut seulement la partie habitée de l'île d'Anticosti (Minganie) et les villages de la MRC du Golfe-du-Saint-Laurent.

infrastructure côtière (Bernatchez *et al.*, 2020b). À la figure 1, la catégorie « Côte artificielle » est utilisée lorsqu'il n'est plus possible de distinguer le type de côte qui était présent avant les modifications anthropiques (Arsenault *et al.*, 2021). Dans l'EGSL, l'action des vagues est le principal agent d'érosion côtière par la mise en suspension, puis le transport des sédiments par les courants côtiers. Toutefois, cet aléa peut être engendré par plusieurs autres processus en fonction notamment de la lithostratigraphie de la côte (Bernatchez et Dubois, 2004). Un bilan des connaissances sur la dynamique de l'érosion côtière du Québec maritime a été publié par Bernatchez et Dubois (2004). Ce bilan regroupe les processus d'érosion en cinq catégories : aérodynamiques/hydrodynamiques, hydrogéologiques/gravitaires, météorisation, biologique et anthropique.

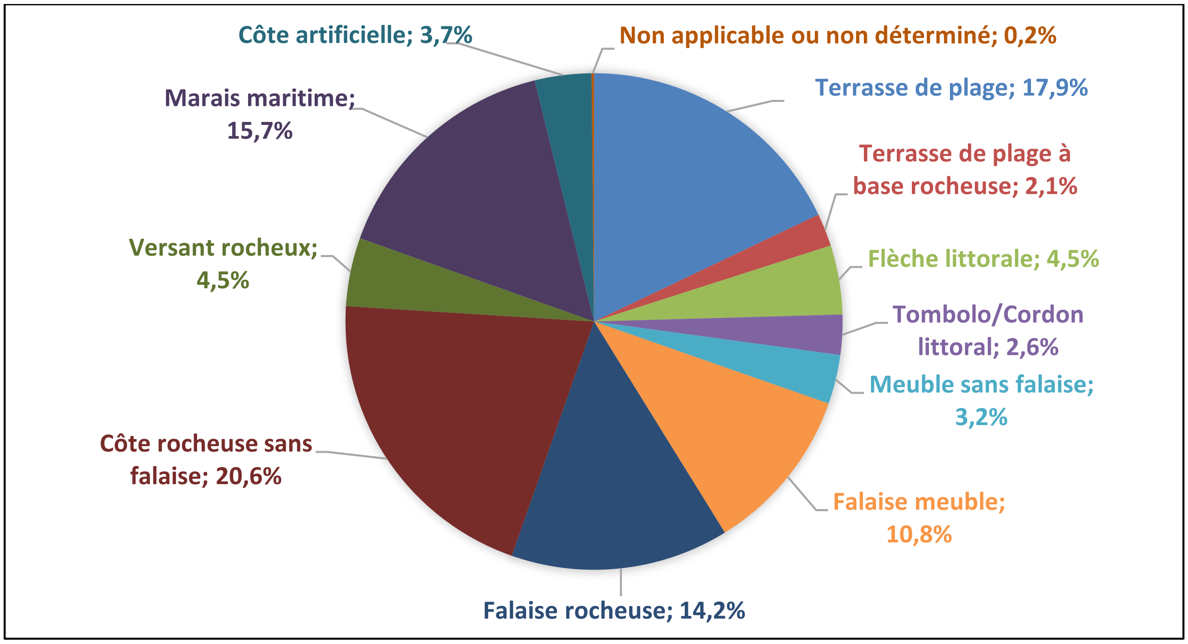

Figure 1. Pourcentage des types de côtes du Québec maritime
(données tirées de Arsenault et al. (2021))

1.1.2 Composantes hydrodynamiques

Les composantes hydrodynamiques, en plus d'être un processus d'érosion majeur, sont des facteurs importants du transport sédimentaire et du profilage des côtes (Bernatchez et

Dubois, 2004). Les principales composantes sont les vagues, les niveaux d'eau et les courants. Ils varient largement à l'échelle de l'EGSL. Le modèle WaveWatch III permet, entre autres, de modéliser la climatologie des vagues et des niveaux d'eau ainsi que les niveaux d'eau du passé récent (1980 – 2010) (Bandet *et al.*, 2020 ; Bernatchez *et al.*, 2017a ; Lambert *et al.*, 2015). La variation de la hauteur de vague significative du 99^{e} percentile à l'échelle de l'EGSL est présentée à la figure 2. Un événement de tempête est caractérisé par le franchissement de cette valeur (Bandet *et al.*, 2020). Les zones à hauteur de vagues significatives élevées sont situées au nord-est des Îles-de-la-Madeleine, puis dans la zone entre les Îles-de-la-Madeleine, la péninsule acadienne et l'île d'Anticosti. Les zones de faible hauteur de vagues significatives sont situées dans l'estuaire moyen et à l'ouest de la Baie-des-Chaleurs.

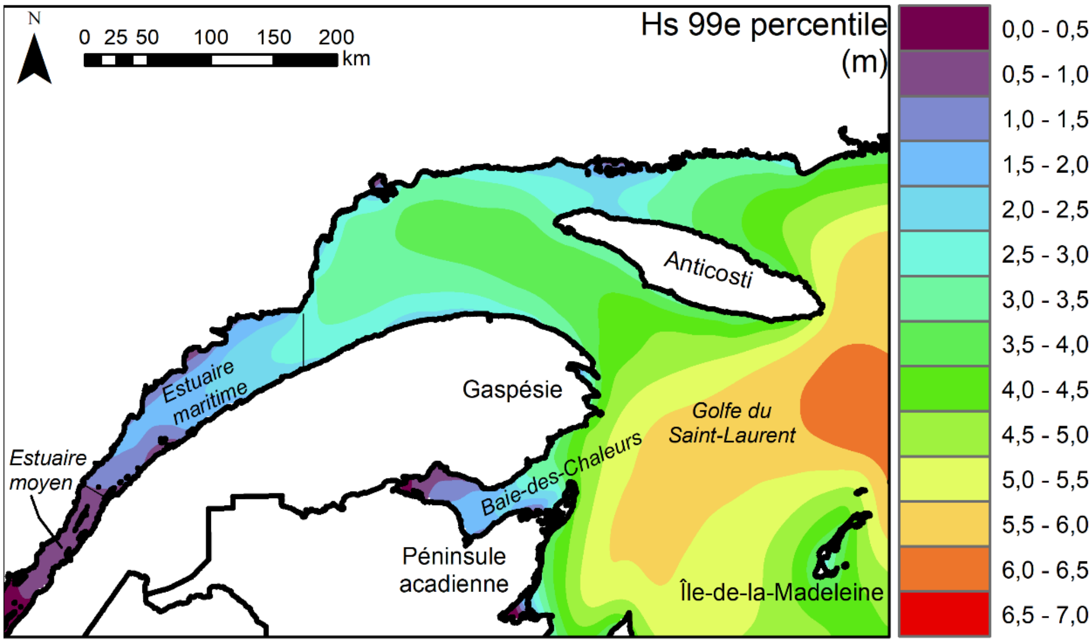

Figure 2. Variation de la hauteur de vague significative (Hs) du 99^{e} percentile, pour la période 1980 - 2010 dans l'EGSL, modélisée avec WaveWatch III (Bernatchez *et al.*, 2017a)

Le niveau d'eau varie également à l'échelle de l'EGSL (figure 3). Les Îles-de-la-Madeleine sont à proximité d'un point amphidromique où l'amplitude de la marée est proche de zéro. Un accroissement progressif de l'amplitude de l'onde de marée est observé vers l'ouest où le marnage moyen est microtidal sur la pointe gaspésienne, l'île d'Anticosti et la Minganie, puis mesotidal dans la Baie-des-Chaleurs et l'estuaire maritime et macrotidal dans l'estuaire moyen et haut estuaire.

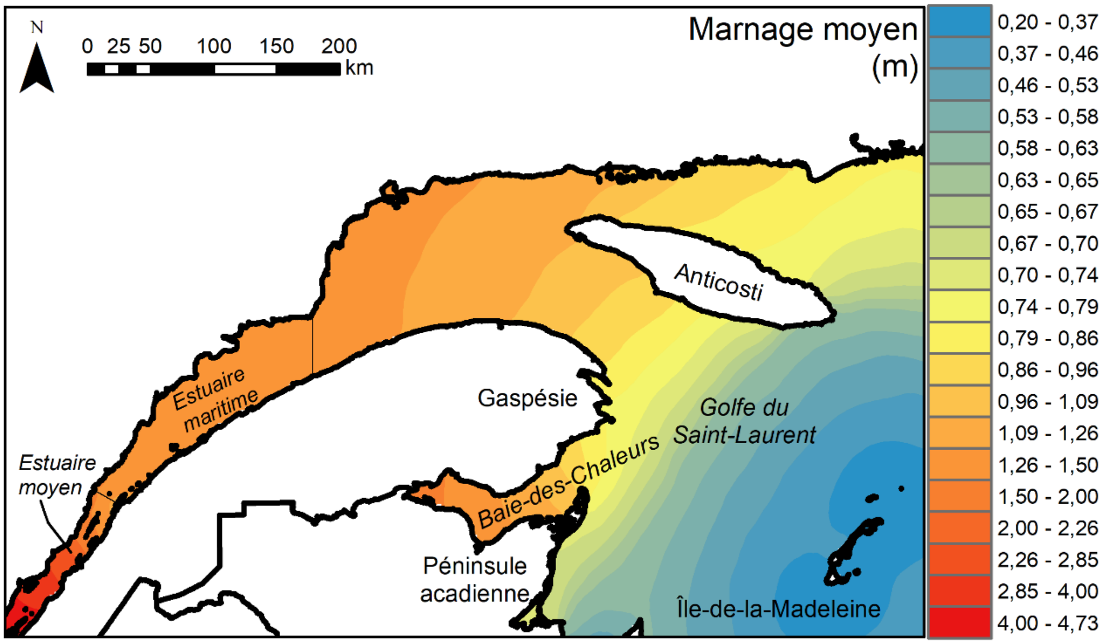

Figure 3. Variation du marnage moyen à l'échelle de l'EGSL (données générées avec WaveWatch III, voir Bandet et al. (2020))

1.1.3 Composantes écosystémiques

Les composantes géomorphologiques, hydrodynamiques et physico-chimiques vont favoriser la formation de différents types d'écosystèmes côtiers en raison de la variation des caractéristiques abiotiques. En fonction de ces caractéristiques, les écosystèmes côtiers fournissent des habitats qui sont associés à des assemblages d'espèces (Charles *et al.*, 2016). Ultimement, les écosystèmes côtiers engendrent des services écologiques dont l'importance est largement reconnue dans la littérature scientifique (Barbier *et al.*, 2011 ; Costanza *et al.*, 2014). Une cartographie des écosystèmes côtiers du Québec maritime a permis d'établir 35 sous-types d'écosystèmes côtiers (Jobin *et al.*, 2021). Ceux dont la superficie totale est supérieure à 1,0 % du total sont présentés à la figure 4.

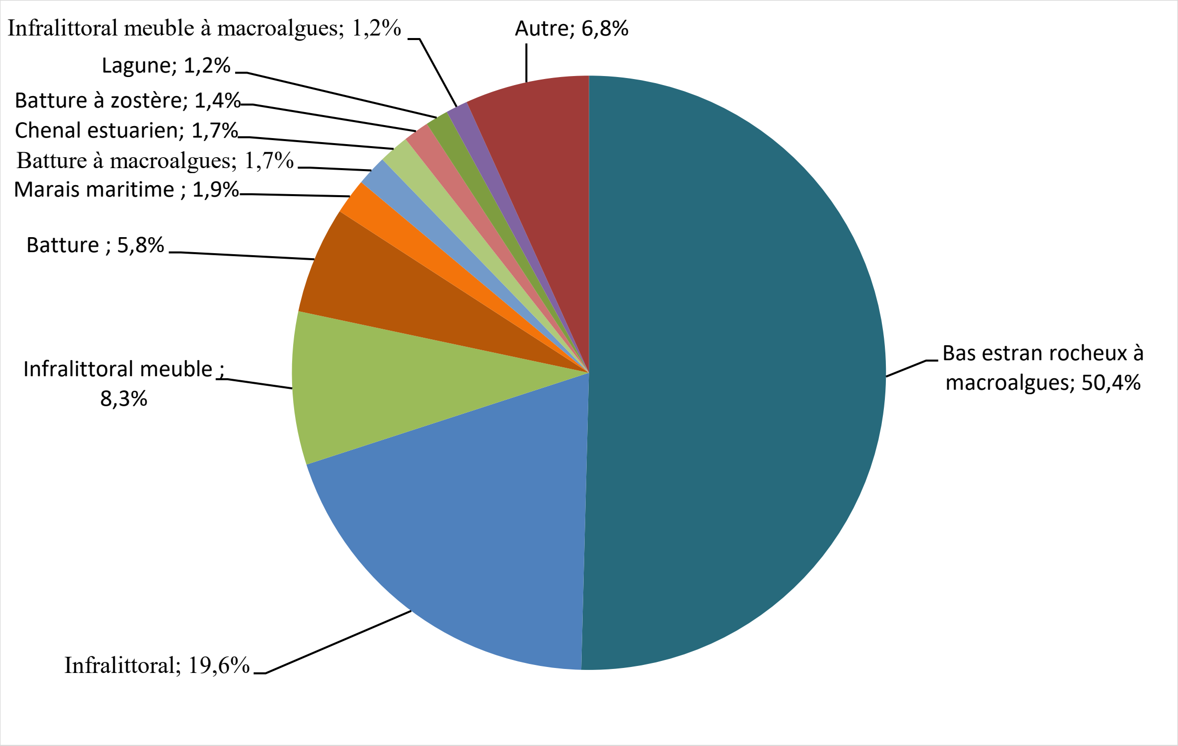

Figure 4. Pourcentage de la superficie des principaux écosystèmes côtiers du Québec maritime tiré de Jobin *et al.* (2021) (données tirées de LDGIZC (2021)). Les écosystèmes qui présentent un pourcentage supérieur à 1,0 % sont affichés

Le bas estran rocheux à macroalgues (50,4 %) et la batture (5,8 %) sont les deux sous-types d'écosystèmes côtiers dont la superficie est la plus importante dans le Québec maritime. La proportion des autres sous-types d'écosystèmes côtiers varie entre 0,1 % et 1,9 % (LDGIZC, 2021).

1.2 Milieu humain

Historiquement, les côtes ont été propices à l'établissement des communautés humaines sur le territoire québécois. D'abord, les Premières Nations y ont développé une économie de subsistance basée sur la pêche et la chasse (Pintal, 2009), puis sur l'agriculture (Jean, 2012). Ensuite, l'établissement des colons français a eu pour effet de concrétiser ces activités. La pêche, important secteur économique des 18^{e} et 19^{e} siècles (Desjardins *et al.*, 1999 ; Fortin et Lechasseur, 1993), a engendré une amplification de la littoralisation dans l'EGSL. Phénomène également accentué au 19e siècle par le tourisme balnéaire qui a favorisé l'aménagement d'infrastructures routières et ferroviaires (Archambault, 2017). Au 20e siècle, l'industrie de la pêche subit un déclin alors que l'industrie forestière connait un essor (Pinna *et al.*, 2009). La population des communautés côtières du Bas-Saint-Laurent, de la Gaspésie et des Îles-de-la-Madeleine ainsi que de la Côte-Nord est en baisse de -0,9 % entre les recensements de 2016 et 2021 (Statistique Canada, 2021). Lors du recensement de 2021, les résidents des municipalités côtières du Québec maritime comptaient pour 4,5 % de la population québécoise (Statistique Canada, 2021).

Ces résidents bénéficient des ressources tirées des milieux environnementaux pour l'exploitation de services, la pratique d'activités récréatives et sociales ainsi que la détente (Liquete *et al.*, 2013). D'ailleurs, sur le territoire du Québec maritime, 249 types d'activités et 118 types de sites d'intérêt ont été dénombrés pour un total de 4639 activités pratiquées à divers endroits (socioculturelles, scientifiques et éducatives, récréatives, et exploitation commerciale de la ressource) et 19 304 différents sites d'intérêt (haute valeur socioculturelle, écologique ou patrimoniale, lieu de loisirs, utilisation du territoire) (Paul-Hus *et al.*, 2021). Un tel bassin d'activités assure une qualité de vie aux résidents côtiers qui accordent toutefois une importance particulière aux activités située à proximité de leur lieu de résidence (Friesinger et Bernatchez, 2010 ; Hellequin *et al.*, 2013 ; Meur-Férec *et al.*, 2011). Les communautés humaines présentent également des distinctions selon les contextes organisationnels, sociaux, économiques, démographiques et d'isolement.

La forte concentration de populations, d'infrastructures, d'activités, de sites d'intérêt, en plus d'infrastructures patrimoniales et de sites archéologiques amplifie les enjeux d'exposition à l'érosion et à la submersion côtière (Bernatchez *et al.*, 2015 ; Bernatchez et Drejza, 2015 ; Marie *et al.*, 2021). D'autant plus que depuis quelques décennies, les impacts de ces aléas côtiers sont exacerbés par les effets des changements climatiques (IPCC, 2021) et l'accélération du développement anthropique en zone côtière (Félix *et al.*, 2012). Les littoraux de l'EGSL ne font pas abstraction de cette tendance. Entre 2000 et 2020, d'importantes tempêtes ont provoqué des dommages considérables aux infrastructures en bordure du littoral, notamment en octobre et en décembre 2005, en décembre 2010, en décembre 2016 et en septembre 2019 (Bernatchez *et al.*, 2011, 2012 ; Corriveau *et al.*, 2019a, 2019b ; Didier *et al.*, 2015 ; Quintin *et al.*, 2013). D'ici 2065, 5426 bâtiments, 295 km de route et 26 km de voies ferrées pourraient être exposés à l'érosion sans la mise en place ou l'entretien de solutions d'adaptation (Bernatchez *et al.*, 2015). Dans ce contexte, les acteurs de la zone côtière, dont les gestionnaires et les professionnels de même que les résidents côtiers, doivent tenir compte de ces enjeux.

1.3 Effets des changements climatiques

Les effets généralisés et rapides des changements climatiques planétaires sont indéniablement associés aux activités humaines antérieures et actuelles (IPCC, 2021). Les projections de divers scénarios d'évolution établis dans le 6^{e} et dernier rapport du GIEC (2021) démontrent une certaine incertitude pour l'ensemble des principaux effets associés aux changements climatiques (hausse des températures, précipitation, sécheresse). En zone côtière, les principaux effets sont la hausse du niveau marin, la diminution du couvert de glace ainsi qu'une intensification des tempêtes et de leur occurrence.

L'accélération de la hausse du niveau marin est une conséquence importante des changements climatiques à l'échelle mondiale (IPCC, 2021 ; Nicholls et Cazenave, 2010 ; Nicholls et Tol, 2006a). Entre 1901 et 2018, la hausse du niveau moyen de la mer a été de 0,20 m à l'échelle planétaire avec un taux d'augmentation qui a accéléré à partir des années 1960 à 3,7 mm/an (IPCC, 2021). Les projections de hausse du niveau marin pour 2100 réalisées par le GIEC (2021) varient entre 0,28 à 0,55 m (scénario SSP1-1.9) et 0,63 à 1,02 m (scénario SSP5-8.5). À l'échelle de l'EGSL, une augmentation du niveau marin relatif de 0,03 à 0,87 mètre est projetée en fonction des valeurs médianes des scénarios RCP 2.6 et 8.5 (Oppenheimer *et al.*, 2019) et du secteur dans l'EGSL (Bernatchez *et al.*, 2020a).

Dans les climats nordiques comme dans l'EGSL, la présence d'un couvert de glace offre une protection naturelle au littoral en atténuant l'impact des vagues durant la période hivernale (Senneville *et al.*, 2014), une période durant laquelle la fréquence des tempêtes est plus élevée (Bernatchez et Dubois, 2004 ; Senneville *et al.*, 2014). Or, la diminution de la couverture de glace de mer pourrait être de 67 % pour la période 2041-2070 comparativement à la période 1981-2010 (Senneville *et al.*, 2014). Une diminution du nombre de jours avec de la glace d'estran est également projetée d'ici 2055, soit une diminution comprise entre 19 % et 58 % pour le haut estran et entre 20 % et 64 % pour le bas estran selon les régions de l'EGSL (Corriveau *et al.*, 2019b).

L'évolution du climat de vagues dans l'EGSL a été modélisée avec le modèle WaveWatch III en fonction des séries temporelles de hauteur de vague et des couvertures de glaces hivernales (Bandet *et al.*, 2020). Il en résulte que la moyenne annuelle des épisodes de forte énergie de vague actuellement à environ 4 annuellement, augmentera à pratiquement 10 à compter de 2041. L'amplification de l'occurrence et de l'intensité de ces épisodes est due à la diminution de la superficie du couvert de glace et conséquemment à la réduction de l'atténuation de l'énergie des vagues (Bandet *et al.*, 2020). Ainsi, une augmentation de 5 à 10 % des hauteurs de vagues significatives extrêmes est projetée dans l'EGSL durant le 21^{e} siècle (Ruest *et al.*, 2016). L'augmentation du flux d'énergie à la côte associée aux vagues est directement corrélée avec la réduction du couvert de glace et favoriserait l'accélération de l'érosion, des falaises notamment (Bernatchez *et al.*, 2021).

Ainsi, la hausse du niveau marin et la diminution du couvert de glace en période hivernale engendrent une augmentation de l'exposition des côtes à l'occurrence et l'intensité des tempêtes. Les communautés côtières doivent donc composer avec une augmentation des risques d'érosion et de submersion côtière par la mise en place de mesures d'adaptation afin d'augmenter leur résilience (Drejza *et al.*, 2019 ; IPCC, 2021 ; Le Cozannet *et al.*, 2013).

2. AUGMENTATION DE LA RÉSILIENCE DES COMMUNAUTÉS CÔTIÈRES

Les communautés côtières doivent mettre en place des solutions d'adaptation pour limiter la hausse projetée des impacts indésirables des aléas côtiers et ainsi augmenter leur résilience. Plusieurs solutions d'adaptation peuvent être utilisées pour augmenter la résilience des communautés côtières, dont les ouvrages de protection côtière.

2.1 Concept de résilience

Le GIEC définit le concept de résilience de la manière suivante : « capacité d'un système social, économique ou environnemental à faire face à des perturbations […] en répondant ou en se réorganisant de façon à maintenir leurs fonctions, leurs identités et leurs structures essentielles, tout en maintenant la capacité de s'adapter, d'apprendre et de se transformer » (GIEC, 2014). Cette définition peut être divisée en deux segments qui regroupent différents sous-concepts (tableau 1) (Folke, 2006 ; Garschagen, 2013). Le premier segment est lié à la capacité d'absorption des systèmes. Elle inclut les sous-concepts d'auto-organisation et de rétablissement. Le second segment est lié à la capacité d'adaptation des systèmes. Elle inclut l'apprentissage et la transformation.

Tableau 1

Sous-concepts intégrés dans les définitions du concept de résilience

Sous-concepts	**Définition**
Capacité d'absorption-	Capacité d'absorber des perturbations tout en maintenant les fonctions (Folke, 2006)
Auto-organisation-	Capacité à maintenir ou recréer ses propriétés face aux perturbations sans besoin d'aide externe pour persister (Lebel et al., 2006; Mileti, 1999; Ronan & Johnston, 2005).
Rétablissement-	Processus vers un retour à un état normal en réponse à une perturbation (Platt *et al.*, 2016)
Capacité de réponse-	Capacité d'ajustement à une perturbation, d'atténuation des dommages potentiels, de tirer avantage des opportunités et de faire face aux conséquences (Gallopín, 2006).
Capacité d'adaptation-	Capacité d'ajustement des systèmes, des institutions, des êtres humains et d'autres organismes, leur permettant de se prémunir contre les risques de dégâts, de tirer parti des occasions ou de réagir aux conséquences (GIEC, 2014).
Apprentissage-	Capacité de se souvenir et de prendre de l'expérience des aléas antérieurement vécus, de prendre des moyens pour acquérir des connaissances sur le système socioécologique et d'innover dans un cycle adaptatif itératif (Berkes, 2007 ; Koontz *et al.*, 2015 ; Tribbia et Moser, 2008).
Transformation-	Capacité à déplacer le développement du système vers d'autres voies émergentes et même en créer de nouvelles (Folke, 2016).

Concrètement, la capacité d'absorption a un état initial qui est fonction des caractéristiques environnementales (géomorphologie et écosystème). Puis, les solutions d'adaptation mises en place par les acteurs permettent de gérer la capacité d'absorption du système (Berkes, 2007 ; Lebel *et al.*, 2006) et ainsi de réduire les conséquences des aléas naturels. Ces stratégies peuvent être sous forme de plans de mesures d'urgence, de mesures d'adaptation des infrastructures ou d'ouvrages de protection côtière aménagés sur le littoral.

La capacité d'adaptation est identifiée dans la littérature scientifique comme un concept propre (Smit et Wandel, 2006) généralement défini comme la capacité d'un système à planifier et à se préparer pour répondre efficacement aux aléas naturels ainsi qu'à se rétablir, à se restaurer et à mieux se reconstruire par l'implantation de stratégies d'adaptation (Klein *et al.*, 2003 ; UNISDR, 2015). La capacité d'adaptation est dynamique et spécifique au contexte de chaque communauté (Smit et Wandel, 2006). Généralement, le concept de capacité d'adaptation est intégré dans les définitions du concept de résilience en lien avec les aléas naturels.

2.2 Solutions d'adaptation en zone côtière

Dans le contexte de la gestion des aléas côtiers, les solutions d'adaptation visent à augmenter la capacité d'absorption du système dans l'objectif de réduire les impacts indésirables des risques côtiers. La mise en place d'une stratégie d'adaptation peut cependant améliorer ou dégrader l'état du système. En cas de dégradation, le terme « mal adaptation » est employé pour signifier l'absence d'adaptation ou une détérioration de l'état du système (Juhola *et al.*, 2016 ; Magnan *et al.*, 2016 ; Smit *et al.*, 2000). Les solutions d'adaptation peuvent être divisées en quatre catégories : outils de réglementation, mesures de gestion du territoire, mesures sociales et ouvrages de protection côtière (figure 5). Les outils de réglementation sont les règlements adoptés par les décideurs gouvernementaux pour assurer la protection du public. Les mesures de gestion du territoire sont orientées sur les changements ou les restrictions d'utilisation du territoire ainsi que sur les mesures de planification et de gestion mises en place par les gouvernements locaux et régionaux. Les mesures sociales sont les mesures mises en place pour intégrer les acteurs du territoire côtier dans le processus d'adaptation de leur communauté (Arlington Group Planning and Architecture, 2012). Les ouvrages de protection côtière sont présentés dans la prochaine section.

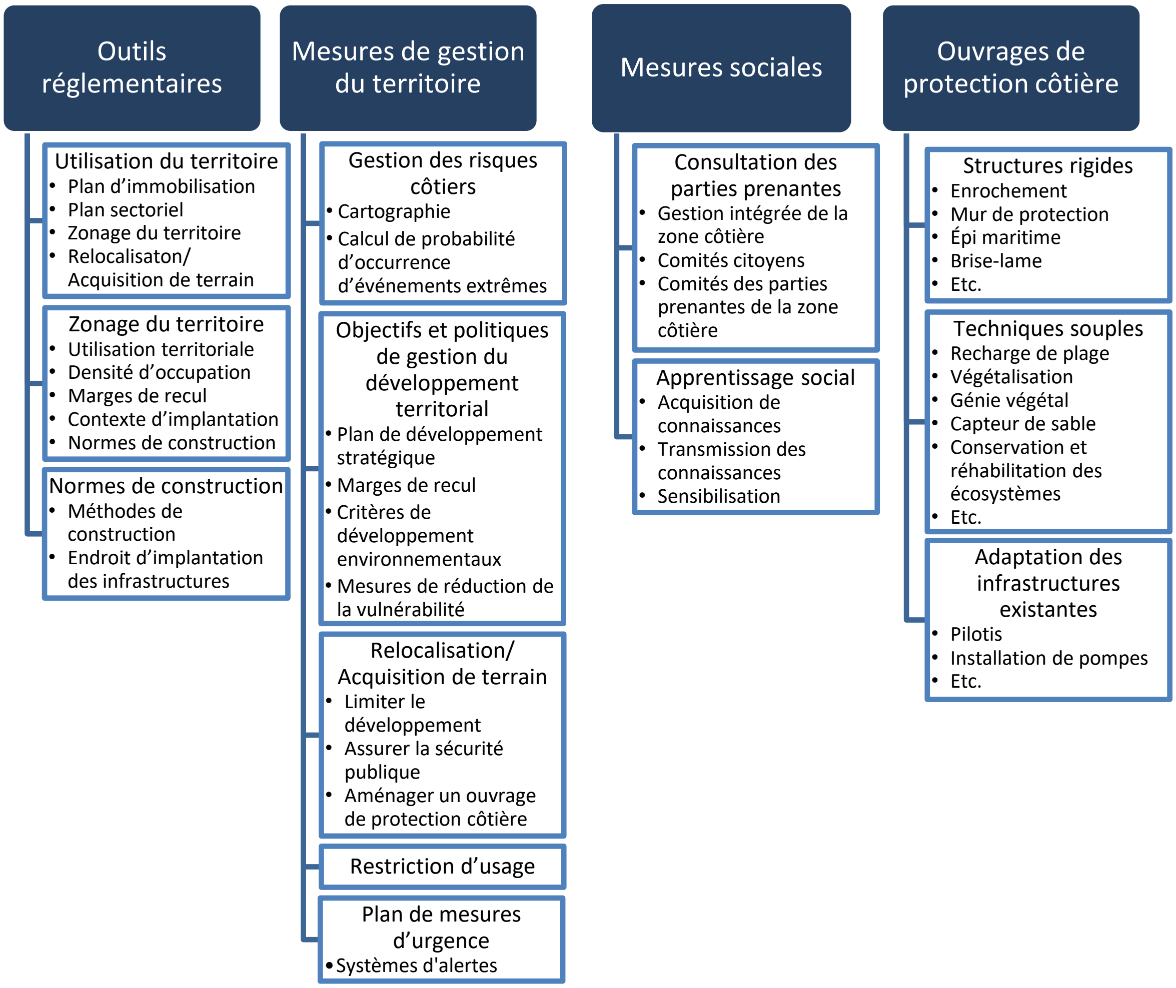

Figure 5. Quatre catégories de solutions d'adaptation aux aléas côtiers. Certaines solutions d'adaptation sont classées dans plus d'une catégorie (adapté de Arlington Group Planning and Architecture, 2012)

Le niveau d'implication des différentes parties prenantes peut être très variable selon le type de solution ou si le processus décisionnel est basé sur une approche intégrée ou non (Bongarts Lebbe *et al.*, 2021).

2.3 Ouvrages de protection côtière

Les ouvrages de protection côtière (OPC) sont les mesures mises en place pour limiter l'effet de l'érosion et de la submersion côtière. Une revue de littérature des articles scientifiques, de guides de conception ainsi que de rapports de firmes d'ingénierie a permis d'établir une typologie des OPC (Sauvé et al., 2021). Ils ont été classés, d'abord, en deux grandes catégories, soit les structures rigides et les techniques souples (tableau 2 et tableau 3). Les structures rigides sont des dispositifs stables de dissipation de l'énergie des vagues ou des courants, constituées de matériaux rigides comme des pierres, du béton, du bois ou de l'acier et visant à maintenir ou à consolider des secteurs côtiers spécifiques. Elles sont dimensionnées selon deux types généraux de structures, soit les structures de type monticule de pierres (enrochements, brise-lames, jetées et digues) et les structures verticales (principalement des murs de protection). Les techniques souples sont des moyens flexibles de réaménagement du littoral, qui agissent sur le bilan sédimentaire par l'ajout de sédiments ou par des techniques végétales permettant de retenir les sédiments. Les sous-catégories d'OPC ont été regroupées en fonction de leur effet sur le milieu côtier, puis subdivisées en types et sous-types.

La catégorie *techniques souples*, principalement les techniques végétales, intègre les solutions fondées sur la nature dans un objectif de protection côtière (e.g. nature-based solutions, living shoreline, ecosystem based adaptation). Ces techniques sont généralement composées d'une combinaison d'OPC et elles peuvent également inclure des structures rigides comme des brise-lames ou des épis (Bilkovic *et al.*, 2017a).

Tableau 2

Ouvrages de protection côtière inclus dans la catégorie des structures rigides (**sous-catégorie**, type, *sous-type*) (tiré de Sauvé *et al.*, 2021)

Nom	Définition
Structure réflexive	Catégorie d'OPC dont les composantes sont aménagées sur la côte et parallèlement à celle-ci, dont l'objectif est de maintenir le trait de côte à un endroit fixe et qui a pour effet de réfléchir l'énergie des vagues.
Mur de protection	Ouvrage aménagé sur la côte, parallèlement à celle-ci, composé de béton, de bois, d'acier, de pneus, etc., vertical ou avec une pente abrupte, dont l'objectif est de stabiliser la position du trait de côte.
Caisson	Sous-type de mur de protection, composé de casiers de bois ou de métal remplis avec des pierres.
Gabion	Sous-type de mur de protection, composé de casiers formés de fils de fer tressés remplis avec des pierres.
Enrochement	Ouvrage aménagé sur la côte, parallèlement à celle-ci, recouvrant le talus d'une côte naturelle ou d'un remblai, composé de blocs de pierre, d'unités de béton préfabriquées, de béton, etc., dont l'objectif est d'arrêter le recul du trait de côte et de dissiper une partie de l'énergie des vagues.
Revêtements en unités de béton	Ouvrage aménagé sur la côte, parallèlement à celle-ci, recouvrant le talus d'une côte naturelle ou d'un remblai, composé d'unités de béton préfabriquées
Structure de sédimentation	Catégorie d'OPC aménagée sur l'estran ou l'avant-plage, dont l'objectif est d'ajuster la dynamique hydrosédimentaire afin de favoriser la sédimentation à des endroits déterminés.
Brise-lames	Ouvrage aménagé au large, parallèlement à la ligne de rivage, généralement composé de pierres imbriquées avec une certaine pente, dont l'objectif est d'atténuer l'énergie des vagues et de provoquer le dépôt de sédiments entre l'ouvrage et la ligne de rivage.
Brise-lame émergé	Brise-lames dont l'élévation de la crête est supérieure en tout temps au niveau de l'eau et est rarement franchie par les vagues.
Brise-lame à crête basse	Brise-lames dont l'élévation de la crête est approximativement égale au niveau de l'eau et est régulièrement franchie par les vagues.
Brise-lame submergé	Brise-lames dont l'élévation de la crête est inférieure en tout temps au niveau de l'eau.
Récif artificiel	Sous-type de brise-lames à crête basse ou submergé, à couche unique, composé de pierres du même calibre, qui se reforme en fonction de l'action des vagues jusqu'à un état d'équilibre.
Seuil submergé	Variante d'un brise-lames submergé, aménagé à proximité de la côte, conçu pour réduire le transport sédimentaire transversal en agissant comme une barrière.
Épi maritime	Ouvrage aménagé sur l'estran, perpendiculairement à la ligne de rivage, composé généralement de bois ou de pierres et dont l'objectif est de capter les sédiments transportés par les courants littoraux.
Épi imperméable	Épi maritime ne permettant pas le passage de la dérive littorale et du transport sédimentaire longitudinal
Épi perméable	Épi maritime permettant le passage de la dérive littorale et du transport sédimentaire le long de la côte.
Jetée	Ouvrage généralement rectiligne et aménagé perpendiculairement à la ligne de rivage, de plus grandes envergures qu'un épi imperméable, visant à contrôler la dérive littorale ou à empêcher l'accumulation de sédiments à l'exutoire d'une rivière ou à l'entrée d'un port. Une jetée a généralement pour effet de créer une nouvelle cellule hydrosédimentaire.
Autres ouvrages rigides	Catégorie regroupant des OPC n'ayant pas les mêmes objectifs ou les mêmes effets sur la dynamique côtière que ceux des autres catégories de structures rigides.
Rip-rap	Revêtement de matériaux grossiers (62-300 mm), disposés en pente douce sur une plage, afin de stabiliser le profil de plage et de maintenir les matériaux en place.
Digue	Remblai longitudinal, aménagé sur l'arrière-plage ou l'arrière-côte, généralement composé de terre compactée, parfois de béton, et visant à contrôler la submersion.
Aboiteau	Sous-type de digue comprenant des clapets qui permettent la sortie de l'eau de ruissellement et empêchent l'entrée de l'eau salée.

Tableau 3

Ouvrages de protection côtière inclus dans la catégorie des techniques souples (**sous-catégorie**, type, *sous-type*) (tiré de Sauvé *et al.*, 2021)

Nom	Définitions
Recharge sédimentaire	Catégorie d'OPC consistant à déposer des sédiments d'emprunt sur une plage dans le but de reprofiler certaines sections de la plage afin d'augmenter sa capacité de dissipation de l'énergie des vagues ainsi que sa largeur et de rééquilibrer le bilan sédimentaire de la cellule hydrosédimentaire. Une recharge sédimentaire peut être localisée sur des secteurs précis du profil de plage (recharge de dune, recharge de plage, recharge d'avant-plage, etc.).
Recharge sédimentaire	
Recharge de dune	Dépôt de sédiments d'emprunt au niveau de la dune afin d'en augmenter le volume et la hauteur.
Recharge de plage	Dépôt de sédiments d'emprunt sur la haute plage, le haut estran ou le bas estran.
Recharge d'avant-plage	Dépôt de sédiments d'emprunt au niveau de la plage sous-marine, souvent du côté mer des barres subtidales, afin de provoquer le déferlement des vagues dans cette zone.
Méga-recharge	Dépôts d'une grande quantité de sédiments d'emprunt (de l'ordre de plusieurs millions de mètres cubes) afin de favoriser la répartition sédimentaire à l'échelle d'une cellule hydrosédimentaire sur plusieurs décennies.
Remblai (OPC)	Ouvrage de protection côtière consistant à ajouter du matériel sédimentaire d'emprunt sur la haute plage ou le haut estran sans effectuer de reprofilage.
Mesure de dérivation sédimentaire	Mesure permanente aménagée afin de rétablir le transport sédimentaire bloqué par un obstacle (p. ex. une jetée).
Technique végétale	Catégorie d'OPC basée sur l'utilisation de végétaux dont les systèmes racinaires retiennent les sédiments et les feuilles freinent les courants.
Végétalisation	Plantation de végétaux adaptés à la dynamique du secteur, dans des secteurs où la végétation est morcelée, peu dense ou absente, sans toutefois faire l'objet d'une conception de génie.
Génie végétal	Techniques végétales, étant le sujet d'une conception, basées sur l'utilisation de végétaux et d'autres matériaux principalement d'origine végétale comme armature.
Écran organique	Technique artisanale composée d'amas de matière organique, de branches ou de troncs d'arbres, plus ou moins agencés ensemble sur la ligne de rivage ou sur le talus côtier.
Autres techniques souples	Catégorie regroupant des OPC n'ayant pas les mêmes objectifs ou les mêmes effets sur la dynamique côtière que ceux des autres catégories de techniques souples.
Capteur de sable	Aménagements implantés sur les côtes sableuses, généralement dunaires, utilisés pour contrôler l'érosion éolienne par une obstruction du vent à proximité du sol et pour créer des zones propices à la déposition de sable.
Ganivelle	Sous-type de capteur de sable, fait de lattes de bois jointes par un fil de fer.
Drainage	Aménagements implantés sur les plages sableuses, sous la surface de la plage, utilisés pour drainer la plage afin de réduire le transport sédimentaire dirigé de la zone du *swash* vers la plage sous-marine.

Au regard de ce vaste répertoire d'ouvrages de protection côtière, les décideurs des communautés côtières doivent sélectionner un scénario adapté à la dynamique du site d'intervention. Or, chaque ouvrage de protection côtière présente des distinctions quant aux effets géomorphologiques, hydrodynamiques, écologiques et socio-économiques sur la dynamique du système socioécologique côtier, en plus de distinctions quant à leur coût, leur durée de vie et leur efficacité.

Au Québec, historiquement, les enrochements et les murs, soit des structures réflectives, ont été les solutions préconisées en majorité (97,6%, en 2017) pour faire face à l'érosion côtière (Bernatchez et al., 2020, 2017, 2008; Sauvé et al., 2020) : une solution quasi unique appliquée sans égards aux particularités locales des systèmes socioécologiques côtiers sur les plans géomorphologiques, hydrodynamiques, écosystémiques et sociaux. Or, ce type d'aménagement généralement réalisé en réaction aux aléas côtiers n'est pas adapté à la majorité des systèmes côtiers et contribue, entre autres, à réduire la largeur et à abaisser le niveau des plages sur les côtes basses sablonneuses (Bernatchez et Fraser, 2012 ; Dugan *et al.*, 2008), en plus d'affecter les écosystèmes côtiers (Airoldi *et al.*, 2005). Conséquemment, la capacité naturelle des écosystèmes côtiers à absorber l'énergie des vagues est affaiblie, augmentant ainsi le risque d'érosion et de submersion côtière (Bernatchez *et al.*, 2011 ; Cooper *et al.*, 2020 ; Dugan *et al.*, 2011 ; Jolicoeur et O'Carroll, 2007 ; Moschella *et al.*, 2005). Une autre conséquence liée aux structures réflectives est le coincement côtier qui engendre une perte de superficie des écosystèmes côtiers lorsqu'un obstacle (naturel ou anthropique) empêche leur migration naturelle vers l'intérieur des terres dans un contexte de hausse du niveau marin (Bernatchez et Quintin, 2016 ; Doody, 2004 ; Pontee, 2013). Finalement, les perturbations aux écosystèmes côtiers associées à l'aménagement de structures réflectives engendrent des changements dans la composition, l'abondance et la diversité des espèces et peuvent avoir des conséquences importantes sur la productivité et les cycles de nutriments, menant potentiellement à la perte de services écologiques (Airoldi *et al.*, 2005 ; Martin *et al.*, 2005).

Les gestionnaires territoriaux au sein des communautés côtières justifient le choix quasi unique de structures réflectives par la méconnaissance des aléas côtiers ainsi que par un nombre insuffisant d'outils qui permettent l'identification d'OPC qui sont adaptés aux conditions environnementales locales (Bernatchez *et al.*, 2008 ; Drejza *et al.*, 2011 ; Fraser *et al.*, 2017 ; Friesinger et Bernatchez, 2010 ; Guénette *et al.*, 2019 ; Marie *et al.*, 2017 ; Sauvé *et al.*, 2020). Dans ce contexte, l'étude du processus décisionnel menant à la sélection d'ouvrages de protection côtière est nécessaire afin d'augmenter la résilience des communautés côtières du Québec maritime.

3. PROCESSUS DÉCISIONNEL EN MILIEU CÔTIER DANS UN CONTEXTE D'INCERTITUDE ASSOCIÉ AUX CHANGEMENTS CLIMATIQUES

Dans l'optique où l'analyse des solutions d'adaptation mène vers la protection des infrastructures et de la population à risque au moyen d'un OPC, un processus d'analyse doit être enclenché pour identifier l'OPC le plus approprié selon le système socioécologique. Le cycle de vie utile d'un ouvrage de protection côtière peut être divisé en six phases qui s'étendent entre le processus de planification et le démantèlement à la fin de la vie utile de l'ouvrage (USACE, 2006b). Le processus décisionnel (figure 6) est inséré dans la première phase, soit le processus de planification, une phase durant laquelle l'enjeu et les résultats attendus sont définis de manière à orienter les phases subséquentes.

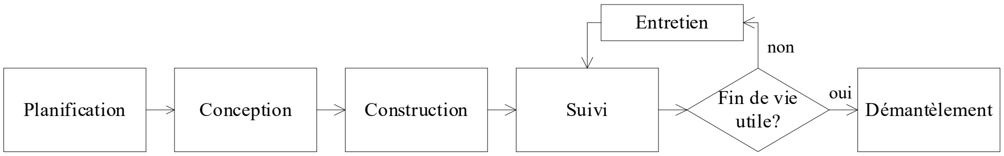

Figure 6. Cycle de vie utile d'un projet d'intervention avec un ouvrage de protection côtière

Le processus de planification menant à l'aménagement d'un OPC peut comprendre généralement plusieurs phases qui impliquent, entre autres, dans un cycle itératif, l'établissement de scénarios d'intervention ainsi que l'analyse et la comparaison de ces scénarios. Le processus de planification est divisé en 6 étapes dans le *Coastal Engineering Manual* (2006b) :

1. définition du problème et des opportunités;
2. projection de l'évolution du système si aucune action n'est réalisée;
3. établissement de scénarios d'intervention;
4. analyse des effets des scénarios;

5. évaluation de scénarios secondaires;
6. choix d’un scénario.

Les 5 premières étapes visent à répertorier l’ensemble de l’information disponible pour réaliser la meilleure décision au regard des objectifs établis. Le processus de conception fait suite au processus de planification. Il est davantage axé sur les aspects techniques à considérer de manière à répondre aux objectifs du projet.

Dans le cinquième rapport du GIEC, Jones et al. (2014) ont défini ce que devrait être une bonne décision : une décision mise en œuvre dans les limites d’un système, de ses processus, ses ressources et son cadre institutionnel tout en tenant compte des connaissances scientifiques disponibles. Une bonne décision a une durée de vie utile et une démarche établie pour assurer son efficacité. Une bonne décision émerge généralement de processus dont :

- les objectifs sont bien définis ;
- une variété de scénarios et des compromis sont considérés ;
- les meilleures données scientifiques pour comprendre les conséquences potentielles sont utilisées ;
- plusieurs points de vues sont pris en considération pour en venir à une décision ;
- les règles et normes en vigueur sont intégrées.

Également, tel qu’exprimé par André et al. (2010), une décision est potentiellement influencée par plusieurs facteurs de nature institutionnelle, organisationnelle, politique, sociopolitique, économique, scientifique et technologique (tableau 4).

Tableau 4

Sept facteurs influençant une décision (établi par André et al. (2010))

Contraintes institutionnelles

- Cadre légal et réglementaire, etc.
- Modèles de comportements, de valeurs et de croyances formés avec le temps

Contraintes organisationnelles

- Distribution du pouvoir au sein de l'État
- Fonctionnement entre les pouvoirs politique, exécutif et administratif
- Fonctionnement des relations entre les différents niveaux de gouvernement

Dimensions politiques

- Pressions exercées à l'échelle locale, régionale, nationale ou internationale
- À l'échelle nationale, corresponds aux idéologies défendues par le parti au pouvoir, plutôt qu'aux caractéristiques objectives d'un État

Dimensions sociopolitiques

- Caractérisation en particulier des décisions environnementales
- Légitimation de la participation de la société civile aux processus de décision qui amène les résidents à exiger plus d'accès à l'information et à s'impliquer encore plus activement
- Opinion publique non négligeable

Dimensions économiques

- Situation économique de l'État.
- Mise au second rang de la protection environnementale pour assurer la création de projets dans les régions grandement touchées par le chômage

Dimensions scientifiques

- Concerne les données colligées des études d'impacts, la qualité de l'évaluation environnementale, l'incertitude inhérente, de même que le débat scientifique autour des enjeux du projet
- Manque d'information et degré d'incertitude élevé dans la majorité des dossiers de gestion environnementale
- Présence de divergence d'opinions entre des experts ou des professionnels qui engendre des craintes au sein de la population et donne beaucoup de latitude au décideur.

Dimensions technologiques

- Intégration d'une technologie pour la réalisation du projet, de sa faisabilité sur les plans technique et économique ainsi que de sa fiabilité de fonctionnement.
- Sans preuve d'efficacité ou sans approbation d'un comité d'experts indépendants, il y a peu d'intérêt pour une technologie ayant un impact moindre sur l'environnement

Le processus décisionnel menant à la sélection d'un OPC est complexe en raison de la dynamique non linéaire à échelles spatio-temporelles multiples des systèmes socioécologiques côtiers (Baquerizo et Losada, 2008 ; Fabbri, 1998 ; Polasky *et al.*, 2011), des effets spécifiques de chaque OPC et de l'incertitude des projections climatiques (Polasky *et al.*, 2011). Les approches d'analyse probabiliste traditionnellement utilisées dans plusieurs champs d'ingénierie comme source d'information pour caractériser l'incertitude et ainsi orienter les décisions (Hallegatte, 2009) ne sont pas conçues pour intégrer ce niveau d'incertitude (Cavallo et Ireland, 2014). Les décideurs doivent donc prendre des décisions sans avoir pleinement les connaissances nécessaires, mais en exploitant au maximum les connaissances disponibles au moment de prendre la décision (Polasky *et al.*, 2011). Ainsi, l'acquisition de connaissances scientifiques est essentielle à l'amélioration du processus décisionnel (Polasky *et al.*, 2011). Les approches décisionnelles novatrices sont interdisciplinaires, basées sur la reconnaissance de l'incertitude et sur une combinaison de méthodes d'analyse pour aider la prise de décision (Fabbri, 1998 ; Marttunen *et al.*, 2017 ; Polasky *et al.*, 2011).

L'aide à la prise de décision est l'ensemble des processus destinés à créer les conditions favorables à la production d'information pertinente et à son utilisation appropriée afin d'en arriver à de bonnes ou de meilleures décisions (Jones *et al.*, 2014). Les méthodes de support à la prise de décision ont été développées et sont utilisées dans un contexte de prise de décision en environnement, car elles permettent d'améliorer la compréhension des relations entre les variables et d'ainsi considérer les effets des scénarios sur de multiples dimensions des systèmes socioécologiques (tableau 5) (Gamper et Turcanu, 2007). Ces méthodes ne remplacent pas le processus de planification. Elles y jouent un rôle de support objectif en présentant de l'information supplémentaire qui permet d'analyser la dynamique du système et de hiérarchiser différents scénarios d'intervention (Gamper et Turcanu, 2007 ; Westmacott, 2001).

Tableau 5

Catégorie et description de divers types de méthodes de support à la prise de décision

Listes de contrôle

- Liste générale définissant un projet, incluant les composantes principales, les caractéristiques environnementales, les impacts potentiels ou mesures d'atténuation, pour en faire ressortir l'information clé comme les exigences en matière de données, les options d'étude, les questions à répondre (André *et al.*, 2010 ; Therivel et Morris, 2009). Simple à utiliser, facile à modifier et aide-mémoire des points essentiels. Ne démontre pas la complexité du système étudié (André *et al.*, 2010).

Matrices d'impact

- Tableau d'interaction entre les composantes environnementales et les activités d'un projet de manière à établir une synthèse visuelle par l'identification des liens de cause à effet de façon simple et transparente en attribuant une pondération à chaque élément évalué (André *et al.*, 2010 ; Therivel et Morris, 2009). Méthode critiquée : laisse trop de place à la subjectivité, égalité potentielle des éléments lorsque la pondération est sujette à des calculs, impossible de rendre compte de la complexité du système, etc. (André *et al.*, 2010)

Réseaux et systèmes

- Illustration et description des liens entre les activités d'un projet et les composantes environnementales utiles pour identifier et évaluer les liens de cause à effet et les rétroactions entre les éléments d'un système, les sources d'impact et les impacts primaires et secondaires (André *et al.*, 2010 ; Therivel et Morris, 2009). Démontre la complexité du système, requière et encourage l'interdisciplinarité. Systèmes : long et coûteux à développer ; réseaux : n'admettent pas de dimension temporelle (André *et al.*, 2010).

Systèmes d'information géographique

- Environnement numérique conçu pour la représentation, l'analyse et la modélisation de la répartition spatiale de composantes environnementales en s'appuyant sur une base de données à partir de laquelle des opérations sont réalisées. Approche systémique qui accroît la comparabilité entre diverses sources de données. Temps et coûts élevés (André *et al.*, 2010).

Méthode de superposition

- Superposition de couches d'information géoréférencée de types environnemental ou social afin de qualifier un espace en fonction d'aptitudes ou de résistance environnementales et d'ainsi identifier les zones de moindre résistance (André *et al.*, 2010 ; Therivel et Morris, 2009). Permets de considérer des indicateurs non quantifiables et de déterminer les zones en fonction de leur potentiel. Exercice potentiellement illogique mathématiquement (André *et al.*, 2010).

Modèles

- Représentation simplifiée physique ou numérique de la réalité par l'utilisation de modèle à échelle réduite ou numérique afin de structurer l'analyse, d'identifier des indicateurs ou de comparer des solutions potentielles. Permets d'intégrer les interactions entre les indicateurs environnementaux, d'étudier un projet dans sa globalité, de projeter les effets de scénarios, etc. Coûteux et sujet à des simplifications excessives ou à une interprétation erronée de certains paramètres (André *et al.*, 2010).

Système expert

- Outils informatiques permettant de suivre un raisonnement logique pour la résolution de problème qui s'appuie sur une base de connaissances créée par des experts pour analyser des données soumises par l'utilisateur et arriver à une conclusion par déductions basées sur des probabilités (André *et al.*, 2010).

Évaluation du risque

- Outils et techniques pour structurer et évaluer l'information disponible sur les risques environnementaux, puis établir une décision entre plusieurs scénarios en se basant sur l'équilibre entre les risques, les coûts et les avantages (Brookes, 2009).

Tableau 5 (suite)

Catégorie et description de divers types de méthodes de support à la prise de décision

Méthodes multicritères

- Catégorie de méthodes variées généralement basées sur des critères ou des variables menant à la structuration de l'information permettant d'orienter les décisions :
- Comparaison par critères : définition des critères et addition de leur pondération (André *et al.*, 2010)
- Méthode ordinale : classement de scénarios les uns par rapport aux autres sur la base de la hiérarchisation des variables et du classement des scénarios en regard de chaque variable selon une relation de supériorité. Ne tiens pas compte de l'écart entre les scénarios et le choix des variables peut largement influencer le résultat (André *et al.*, 2010).
- Analyse multicritère : comparaison de scénarios au regard de plusieurs critères permettant l'intégration d'une logique à acteurs multiples. L'idée est de (1) pondérer les critères, (2) évaluer les scénarios au regard de chaque critère et (3) hiérarchiser les scénarios sur la base des étapes 1 et 2 (André *et al.*, 2010 ; Franco et Lord, 2011).
- Analyse coût-avantage : évaluation économique de scénarios au regard de variables dans l'objectif de déterminer le scénario le plus efficace économiquement (Tudela *et al.*, 2006).

À l'échelle mondiale, l'aide à la décision dans un contexte de gestion de la zone côtière est orientée sur l'évaluation des risques (Viavattene *et al.*, 2018) et de la vulnérabilité (Johnston *et al.*, 2014 ; Le Cozannet *et al.*, 2013), des effets écosystémiques (Granek *et al.*, 2009), de la planification spatiale du territoire côtier (Bagheri *et al.*, 2013 ; Kitsiou *et al.*, 2002) ainsi que de l'identification de stratégies de gestion du littoral (Félix *et al.*, 2012). Suite à une revue de la littérature scientifique, l'unique méthode d'aide à la décision trouvée qui a été employée pour évaluer les OPC en fonction du milieu d'implantation est l'analyse coût-avantage (ACA) (Amadio *et al.*, 2022 ; André *et al.*, 2016 ; Polomé *et al.*, 2005). L'ACA est basée sur une unité d'agrégation monétaire pour comparer les impacts économiques de différentes options d'adaptation qui sont techniquement réalisables.

Au Québec, le processus décisionnel pour l'identification d'OPC utilisé par les firmes d'ingénierie est limité généralement à une analyse comparative de critères qualitatifs ou, simplement, sur l'expérience des ingénieurs spécialisés (Sauvé *et al.*, 2020). Or, ces approches ne proposent pas de méthode d'aide à la décision pour l'évaluation d'OPC basée sur une analyse holistique du SSEC et n'impliquent généralement ni les acteurs locaux et régionaux ni les résidents. Le consortium Ouranos a notamment utilisé l'ACA sur neuf secteurs d'études au Québec et dans les provinces maritimes de l'est du Canada pour évaluer différentes options d'adaptation, dont les ouvrages de protection côtière (Circé *et al.*, 2016c, 2016d, 2016e, 2016b, 2016a ; Leclerc et Dupuis, 2008). Si la transposition en unité monétaire semble assez intuitive pour certains critères (coût des solutions d'adaptation, évaluation foncière, etc.), elle est moins bien adaptée pour les impacts intangibles (effet sur les écosystèmes, sur le paysage, sur les activités pratiquées, etc.) (Bryce *et al.*, 2016 ; Chan *et al.*, 2012 ; McCauley, 2006 ; Tudela *et al.*, 2006). Il devient alors nécessaire de multiplier les hypothèses pour parvenir à comparer des critères hétéroclites sur une base monétaire commune.

Les méthodes d'analyse multicritère sont basées sur des unités comparatives neutres ou adaptées à chaque critère (Maystre *et al.*, 1994). Elles ont été développées pour agréger chacun des scénarios relativement à chacun des critères en fonction d'un système de pondération défini (Caillet, 2003). Elles peuvent se diviser en trois types : agrégation complète, agrégation partielle, agrégation itérative (André *et al.*, 2010 ; Gamper et Turcanu, 2007 ; Maystre *et al.*, 1994). L'agrégation complète aboutie à une solution unique, synthétique, exhaustive et définitive (André *et al.*, 2010). L'agrégation partielle considère l'incomparabilité entre les scénarios par un système référentiel de préférence basé sur la notion de surclassement (André *et al.*, 2010). L'agrégation itérative est fondée sur un processus de tâtonnement qui permet d'explorer l'espace de faisabilité des scénarios à travers un dialogue avec les décideurs (Gamper et Turcanu, 2007). Les méthodes d'analyse multicritère basées sur une agrégation partielle sont les mieux adaptées à une gestion holistique du territoire, car l'ensemble des dimensions considérées par un ou plusieurs acteurs sont intégrées dans l'analyse (Garmendia et Gamboa, 2012). Selon plusieurs études, les méthodes de surclassement les plus utilisées en gestion environnementale sont ELECTRE et PROMETHEE (Ananda et Herat, 2009 ; Cinelli *et al.*, 2014 ; Herve et Roca, 2013 ; Huang *et al.*, 2011 ; Pohekar et Ramachandran, 2004 ; Wang *et al.*, 2009). Ces méthodes ont été utilisées dans un contexte de gestion de l'environnement côtier et maritime (tableau 6).

Tableau 6

Exemples d’études basées sur les méthodes d’analyse multicritère PROMETHEE et ELECTRE utilisées dans un contexte de gestion de l’environnement côtier

PROMETHEE	ELECTRE
Abdel-Basset et al. (2021)	Isik et demi (2017)
Kovačić et al. (2020)	Fetanat et Khorasaninejad (2015)
Wu et al. (2020)	Maslov et al. (2014)
De Boni et al. (2018)	
Zafirakou et al. (2018)	
Mladineo et al. (1992)	

4. OBJECTIFS DE RECHERCHE

L’objectif principal de cette thèse doctorale est de développer un outil d’aide à la prise de décision élaboré sur une structuration cohérente de l’information permettant de prendre en considération les données tant géomorphologiques et hydrodynamiques, qu’écologiques et socio-économiques nécessaires à l’identification des meilleures alternatives en termes d’ouvrages de protection côtière au regard des conditions spécifiques d’un SSEC et des besoins exprimés par les acteurs du territoire (professionnels et gestionnaires). Les quatre objectifs spécifiques du projet de recherche sont :

1. Évaluer le processus décisionnel actuel, menant à la sélection d’ouvrages de protection côtière au Québec, en y impliquant les acteurs du territoire côtier (gestionnaires et professionnels des municipalités, MRC, ministères, organismes et Premières Nations, résidents côtiers, ainsi que professionnels des entreprises œuvrant en génie et en aménagement côtier) en vue d’identifier les actions potentielles qui pourraient être entreprises afin d’améliorer le processus décisionnel et le développement du génie côtier (chapitre 1);
2. Répertorier les connaissances scientifiques à l’échelle internationale sur les effets des ouvrages de protection côtière sur le SSEC afin de les contextualiser selon les caractéristiques environnementales dans lesquelles ils ont été observés, puis déterminer si les connaissances scientifiques dans les différents milieux

environnementaux sont pertinentes ou déficientes pour la gestion des zones côtières (chapitre 2);

3. Développer une méthode d'évaluation et de hiérarchisation des OPC en fonction de différents ensembles de caractéristiques environnementales côtières en se basant sur une synthèse qualitative de leurs effets tels que répertoriés dans la littérature scientifique, puis intégrer les résultats au processus décisionnel afin d'en arriver à une présélection d'OPC qui soient adaptés aux conditions du milieu d'étude (Chapitre 3);
4. Adapter l'utilisation d'une méthode d'analyse multicritère de manière à hiérarchiser des ouvrages de protection côtière tout en impliquant les professionnels et gestionnaires du territoire côtier dans l'identification et la pondération des critères de sélection (chapitre 4).

5. APPROCHE MÉTHODOLOGIQUE GÉNÉRALE

Le processus décisionnel menant à la sélection d'un ouvrage de protection côtière[2] peut largement varier en fonction de plusieurs facteurs : connaissances des gestionnaires, des professionnels et des décideurs, disponibilité d'outils d'aide à la décision et des données pertinentes, consultation des parties prenantes, temps nécessaire pour l'analyse, temps disponible avant une intervention, etc. Plusieurs de ces facteurs ont d'ailleurs été soulevés par le passé par des acteurs de la zone côtière comme étant des obstacles à la sélection d'ouvrages de protection côtière (OPC) qui soient adaptés aux milieux ciblés pour une intervention (Bernatchez *et al.*, 2008 ; Drejza *et al.*, 2011 ; Friesinger et Bernatchez, 2010 ; Guénette *et al.*, 2019 ; Marie *et al.*, 2017).

L'approche méthodologique générale de la thèse s'inscrit dans une optique de contribution à l'amélioration de ce processus décisionnel. L'approche est basée sur une analyse du SSEC de manière à considérer les caractéristiques environnementales

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[2] Dans le contexte de cette thèse, le terme « processus décisionnel » est utilisé pour signifier « processus décisionnel menant à la sélection d'un ouvrage de protection côtière ». Il englobe les phases de planification et de conception du cycle de vie d'un projet d'intervention avec un ouvrage de protection côtière.

(géomorphologiques, hydrodynamiques et écosystémiques) et sociales (activités, usages et priorités des acteurs) à l'échelle locale pour proposer des OPC adaptés aux milieux dans lesquels une intervention est nécessaire.

La thèse peut être divisée en deux volets et deux chapitres chacun. Chaque chapitre présente des approches méthodologiques spécifiques (tableau 7) qui ont permis de répondre à des objectifs distincts. Le premier volet qui inclut les chapitres 1 et 2, est consacré à la caractérisation des interventions passées et à l'établissement d'une base afin d'orienter les décisions futures. Le chapitre 1 est dédié à la caractérisation des OPC présents sur le littoral de l'Est du Québec et des connaissances des acteurs en ce qui concerne les OPC, puis à l'identification de besoins pour l'amélioration de la sélection et de la gestion des OPC. Le chapitre 2 est consacré à l'établissement d'un portrait des connaissances scientifiques sur les effets des OPC à l'échelle internationale, puis à une discussion sur l'utilité de ces connaissances et sur la nécessité d'acquérir les connaissances manquantes pour la gestion de la zone côtière et le processus décisionnel.

Le deuxième volet qui inclut les chapitres 3 et 4, est consacré au développement d'une approche d'évaluation et de hiérarchisation d'ouvrages de protection côtière. Le chapitre 3 présente le développement d'une méthode pour établir un portrait des connaissances scientifiques par une synthèse qualitative des effets des OPC en regard de caractéristiques environnementales spécifiques à un secteur à l'étude, de manière à évaluer, hiérarchiser et présélectionner des ouvrages de protection côtière qui soient adaptés au contexte local afin de limiter les impacts environnementaux. Le chapitre 4 est dédié à l'utilisation d'une méthode d'analyse multicritère pour hiérarchiser des ouvrages de protection côtière, présélectionnés selon la méthode établie au chapitre 3, en tenant compte des priorités des acteurs du territoire par le biais de l'identification et de la pondération des critères d'évaluation.

De manière générale, la synthèse descriptive des OPC effectuée par Sauvé et al. (2021) a été utilisé dans cette thèse pour caractériser les effets des OPC sur le SSEC.

Tableau 7

Présentation des objectifs et des approches méthodologiques spécifiques aux quatre chapitres de la thèse

Chapitre 1

The role of the decision-making process on shoreline armoring: A case study in Quebec, Canada

Objectifs :

1. Caractériser l'artificialité des côtes dans l'Est du Québec
2. Déterminer le rôle occupé par les acteurs de la zone côtière dans le processus décisionnel menant à la sélection d'un OPC
3. Identifier des actions potentielles pour améliorer le développement du génie côtier

Méthodologie :

- Traçage et caractérisation du trait de côte
- Ateliers de consultation
- Questionnaires semi-dirigés

Chapitre 2

Case studies on coastal defence measures: A meta-analysis of literature to ultimately improve decision-making

Objectifs :

1. Identifier les caractéristiques côtières dans lesquelles les études de cas sur les OPC ont été réalisées
2. Déterminer dans quels environnements côtiers chaque type d'OPC a été étudié
3. Identifier l'utilité des connaissances scientifiques actuelles et les améliorations nécessaires pour obtenir un meilleur processus décisionnel

Méthodologie :

- Revue de littérature
- Méta-analyse

Chapitre 3

Identification of coastal defence measures best adapted to mitigate hazards in specific coastal systems: Development of a dynamic literature meta-analysis methodology

Objectifs :

- Développer un algorithme afin de réaliser une méta-analyse dynamique de la littérature scientifique et d'ainsi réaliser une synthèse qualitative des effets des OPC au regard des caractéristiques du site d'étude.

Méthodologie :

- Revue de littérature
- Développement d'une base de données
- Développement d'un algorithme d'identification

Chapitre 4

Multicriteria decision analysis to assist in the selection of coastal defence measures: involving coastal managers and professionals in the identification and weighting of criteria

Objectifs :

1. Déterminer la pertinence d'une méthode d'aide à la prise de décision comme outil pour structurer et analyser un problème de manière à identifier les conflits et la synergie entre les scénarios et mener les décideurs à considérer l'ensemble des dimensions et des conséquences associées à la sélection d'un OPC.
2. Évaluer les bénéfices d'un processus décisionnel participatif impliquant les gestionnaires et les professionnels de la zone côtière dans l'identification et la pondération des critères de sélection d'un OPC.

Méthodologie :

- Identification des OPC à évaluer avec le CDMIA (chapitre 3)
- Ateliers de consultation
- Utilisation d'une méthode d'analyse multicritère

CHAPITRE 1
INFLUENCE DU PROCESSUS DÉCISIONNEL SUR L'ARTIFICIALITÉ DES CÔTES : ÉTUDE DE CAS AU QUÉBEC, CANADA

1.1 RÉSUMÉ EN FRANÇAIS DU PREMIER ARTICLE

L'artificialité des côtes affecte les processus côtiers. Les ouvrages de protection côtière peuvent contribuer à réduire la capacité naturelle des écosystèmes côtiers à absorber l'énergie des vagues, lorsqu'ils ne sont pas adaptés au milieu dans lequel ils sont implantés. Ce projet a été réalisé dans la province de Québec au Canada sur les côtes de l'EGSL, sur le territoire de 21 municipalités régionales de comté (MRC). Les objectifs de l'article sont de caractériser l'artificialité des côtes de l'Est du Québec, de déterminer le rôle occupé par les professionnels et les gestionnaires côtiers, les résidents côtiers, ainsi que les firmes œuvrant en génie et en aménagement côtier dans le processus décisionnel menant à la sélection d'un ouvrage de protection côtière (OPC), puis d'identifier des actions potentielles par chacun de ces acteurs pour améliorer le développement du génie côtier. Premièrement, plus de 3 300 km de côte ont été segmentés et caractérisés, ce qui a permis de déterminer la proportion du littoral occupée par des structures artificielles. En 2017, les OPC occupaient environ 10 % du littoral. De ce nombre, 97,6 % étaient des structures réflectives. Deuxièmement, trois types distincts de consultations ont été réalisées en 2017 et 2018 auprès de 300 professionnels et gestionnaires, 494 résidents côtiers et 51 professionnels de firmes environnementales et d'ingénierie. Les objectifs étaient d'évaluer leur connaissance des types d'OPC et de leurs effets respectifs et de discuter du processus décisionnel menant à la sélection d'OPC. Les résultats des consultations montrent un changement significatif dans les OPC désirés en comparaison avec des études antérieures dont les conclusions pointaient largement vers des structures réflectives. Toutefois, même si les techniques souples ont été identifiées comme favorables lors de cette série de consultation, les structures réflectives ont tout de même, jusqu’à présent, été majoritairement aménagées sur les littoraux de l’Est du Québec. Cette dichotomie peut être expliquée par plusieurs facteurs : un manque de connaissance, un manque de financement, un manque de processus collaboratif, ainsi qu’une réglementation trop restrictive pour des solutions innovantes. En plus d’une augmentation du financement pour l’aménagement, le suivi et l’entretien des OPC et pour des études de cas et des projets pilotes, les principales solutions proposées pour améliorer le développement du génie côtier sont des projets interdisciplinaires et intégrés, l’ajustement de la réglementation environnementale, ainsi que le développement d’un outil qui permette aux décideurs d’évaluer chaque OPC dans un contexte particulier de manière à identifier la solution la plus appropriée et à prendre de meilleures décisions à long terme.

Cet article, intitulé « *The role of the decision-making process on shoreline armouring: A case study in Québec, Canada* », a été corédigé par l’auteur de cette thèse, ainsi que les professeurs Pascal Bernatchez et Mathias Glaus. Il a été publié dans le journal *Ocean and Coastal management* en décembre 2020. En tant que premier auteur, ma contribution fut de réaliser la majeure partie de la recherche sur l’état des connaissances, le développement des méthodologies utilisées pour les différentes consultations, l’analyse des données, puis la rédaction de l’article. En tant que second auteur, Pascal Bernatchez a contribué à la recherche sur l’état de l’art, l’analyse des données et la révision de l’article. En tant que troisième auteur, Mathias Glaus a contribué à l’analyse des données et à la révision de l’article. Également, Évelyne Arsenault, Stéphanie Friesinger, Steve Dugas, Maude Blain, Catherine Paul-Hus, Mireille McGrath-Pompon, Christian Fraser, Ariane Jobin, Laurie Desrosiers-Leblanc, Maud Touchette, Guillaume Marie et Sandrine Papageorges, toutes et tous de la Chaire de recherche en géoscience côtière de l’Université du Québec à Rimouski, ont contribué à la caractérisation côtière et à la planification et la réalisation des consultations. Les résultats de cet article ont été présentés en partie dans le cadre du 14e colloque sur les risques naturels au Québec au 87e congrès de l’ACFAS tenu à l’Université du Québec en Outaouais.

1.2 THE ROLE OF THE DECISION-MAKING PROCESS ON SHORELINE ARMORING: A CASE STUDY IN QUÉBEC, CANADA

ABSTRACT

Shoreline armoring has repercussions on coastal processes, including reducing the width and height of sandy beaches, which affect coastal ecosystems and ecosystem services. This project, consisting of two parts, was carried out in the Canadian province of Quebec, on the coasts of the St. Lawrence Estuary and Gulf, which cover the territory of 21 coastal Regional County Municipalities (RCM). The objectives were to characterise shoreline armoring in Eastern Quebec, to determine the role played by coastal managers, coastal citizens, and coastal engineers in the coastal defence decision-making process, and to identify possible actions to be taken by each stakeholder to improve coastal engineering development. First, over 3300 km of shoreline were segmented and characterised, allowing the mapping of what proportion of the shoreline was covered by artificial structures. In 2017, coastal defence measures (CDM) occupied about 10% of the shoreline, and 97.6% of them were reflective rigid structures. The second part of the project involved three different consultations carried out in 2017 and 2018 with 300 coastal managers, 494 coastal residents and 51 professionals from environmental and engineering firms to assess their knowledge of CDM types and functions, and to discuss about the decision process leading to the CDM identification. Results of the consultations show a significant change in the type of desired solutions compared to previous studies where rigid structures were clearly preferred. But despite a greater prioritization of soft techniques by professionals from municipalities, ministries' managers and coastal citizens, the rigid structures continue to be the type of solution mostly implemented along Quebec's coasts. This difference can be explained by a number of factors: a lack of specialized knowledge; a lack of funding; a lack of collaborative process; and regulations that are too restrictive for innovative CDM. In addition to an increase of funding for preventive CDM, for long term CDM monitoring and maintenance, for case studies and pilot projects, the main solutions proposed were interdisciplinary projects based on consultation, adjustment of environmental regulations, and development of a tool that would

enable decision-makers to evaluate each option in a particular context, so as to identify the most appropriate solutions and make better decisions for the long term.

Keywords: coastal engineering, shoreline armoring, decision-making, consultation process, integrated coastal zone management

1.3 INTRODUCTION

Coastal erosion is a natural phenomenon affecting shorelines worldwide. Ever since the establishment of human societies along shorelines, coastal defence measures have been implemented in response to coastal erosion and flooding (Charlier et al., 2005). In recent decades however, the effects of climate change added to the coastal zone development have led to an increase in artificial barriers and shoreline armoring (Dugan et al., 2011; Gittman et al., 2015; Horstman et al., 2009).

Shoreline armoring refers to the construction of coastal defence structures and of port facilities or other artificial means of supporting coastal development (Dafforn et al., 2015; Dethier et al., 2016; Gittman et al., 2015). It is estimated that 50% of the world coastlines are currently threatened by anthropic development (Dafforn *et al.*, 2015 ; Manno *et al.*, 2016) and that anthropogenic factors have been the main drivers of morphological changes in sandy coastlines in recent decades (Vousdoukas *et al.*, 2020). Available data published in the literature show a particularly high level of shoreline armoring in the following regions: 27% in Japan in 1992 (Koike, 1996); 16% in the North Sea in 2006 (EEA, 2006); over 8% in the Mediterranean Sea in 2006 (EEA, 2006); 32 % of the Northern Irish coast in 2009 (Cooper *et al.*, 2020); 46 % of England's coastline and 28 % of Wales's coastline in 2010 (Defra, 2010); 14% in the United States in 2015. Today, these levels are likely to be much higher considering the increased development of coastal zones (Horstman *et al.*, 2009b).

Shoreline armoring modifies coastal processes. Not only does it contribute to reducing the width and height of sandy beaches (Bernatchez *et al.*, 2011 ; Bernatchez et Fraser, 2012 ; Dugan *et al.*, 2008), but it also reduces coastal ecosystems' natural capacity to attenuate wave energy (Cooper *et al.*, 2020 ; Dugan *et al.*, 2011 ; Moschella *et al.*, 2005), thereby increasing the risk of coastal erosion and flooding (Bernatchez *et al.*, 2011 ; Didier *et al.*, 2015). Moreover, disturbance to coastal ecosystems caused by shoreline armoring leads to changes in species composition, abundance and diversity, and can have significant consequences on the productivity and nutrient cycles, ultimately affecting ecosystem services (Airoldi *et al.*, 2005 ; Martin *et al.*, 2005).

In the Canadian province of Quebec, on the coasts of the St. Lawrence Estuary and Gulf, municipalities have developed along the littoral, which is made up of low-lying sandy coasts, as well as sandy, clayed and rocky sedimentary cliffs sensitive to erosion (Bernatchez et Dubois, 2004). The average shoreline retreat in unconsolidated formations varies between 0.5 and 2.0 m/yr (Bernatchez et Dubois, 2004). Consequently, more than 5426 buildings will be exposed to erosion by 2065 if no adaptation measures are implemented and existing defense structures are not maintained (Bernatchez *et al.*, 2015). Between the 1980s and the early 2000s, coastal defence structures (seawalls and rock armour) were built in emergency situations after storms events. A better approach would have been an integrated decision making process (Boyer-Villemaire *et al.*, 2015) which should be the basis when analyzing the impacts of coastal defence measures on coastal socio-ecological systems (Baquerizo et Losada, 2008 ; Polasky *et al.*, 2011). Coastal dynamics result from multi-scale non linear processes involving hydrodynamic conditions in interaction with changing topo-bathymetry and morphologic conditions (Baquerizo et Losada, 2008), which have feedback effects on ecosystems and social aspects (Polasky *et al.*, 2011). In the context of climate change, sea level rise and extreme sea levels will increase coastal impacts (Church et White, 2011 ; Nicholls et Cazenave, 2010 ; Nicholls et Tol, 2006b), but also increasing the uncertainty in decision-making (Hallegatte, 2009 ; Wahl *et al.*, 2017). This site-specific complexity, together with the involvement of multiple stakeholders and agencies, must be considered in coastal zone management. In order to identify the best-adapted coastal defence measure (Jones *et al.*, 2014), a transparent, reliable and flexible decision-making process is essential (Reed, 2008). Common approaches based on probabilistic analysis to characterise uncertainties have produced successful results in many engineering fields, but fail to manage uncertainties when the system is unpredictable, in constant evolution, and adapting to new conditions (Brugnach *et al.*, 2008). Also, knowledge and technical progress acquired through global coastal zone research are rarely applied or they are implemented at a slow pace by coastal managers and decision-makers, who tend to analyse problems locally without considering the ecological or social impacts (Baquerizo et Losada, 2008). In that context, it is difficult to make sound decisions. However, it is important for decision-makers to integrate existing science and knowledge into their processes while being aware of the unknown or unpredictable factors (Polasky *et al.*, 2011).

The purpose of this article is (1) to characterise shoreline armoring in Eastern Quebec; (2) to determine the role that coastal managers, coastal citizens, and coastal engineers play in the decision-making process about coastal defences; and (3) to identify possible actions to be taken by each stakeholder to improve coastal engineering development. We conclude by explaining how a better decision-making process could lead to coastal defence measures that are better adapted to local conditions.

1.4 STUDY AREA

1.4.1 Local and geomorphological context

The study was carried out in the Canadian province of Quebec, on the coasts of the Estuary and Gulf of St. Lawrence (EGSL), covering more than 3300 km of coastlines, from Tadoussac to Natashquan on the North Shore of the St. Lawrence and from Berthier-sur-Mer on the south shore of the St. Lawrence to Pointe-à-la-Croix in Chaleur Bay, as well as in the Magdalen Islands in the gulf of St. Lawrence (figure 7). From the upstream end of the estuary to the Gulf of St. Lawrence, the environment changes from macrotidal (> 6m) to microtidal tides (<1m) and from a fetch-limited coastline to a coastline highly exposed to storm surges (Didier *et al.*, 2020 ; Ruest, 2014). The diversity of the coasts of the EGSL is largely attributed to the geological context, but also to the last glaciation and to the postglacial seas which covered the territory and which left important unconsolidated deposits. The main types of coasts in eastern Quebec are igneous rocky coasts (mainly in the North Shore, 25%), beach terraces (21%), rocky cliffs (14%), unconsolidated cliffs (13%), marshes (8%) and spits (6%) (Drejza *et al.*, (2014); figure 8 and figure 9). The sandy coasts are particularly sensitive to wave actions, as are the rocky cliffs which are composed of sandstone and limestone (figure 9). As for the unconsolidated cliffs, often made of marine clay topped with sand, they are particularly sensitive to hydrogeological processes which cause significant landslides (Bernatchez et Dubois, 2004), but also to erosion by cryogenic processes (Bernatchez *et al.*, 2008, 2011; Boucher-Brossard et al., 2015).

1.4.2 Human context and administrative structure governing coastal development

Historically, villages and municipalities have developed along the EGSL coastline and are connected to each other by national roads (132,138, 199, highway 20) that border the coastline. Thus, 207 km of road segments including 112 km of national roads, and 90 km of railway segments are less than 15 m from the coastline (Drejza *et al.*, 2014). The infrastructure related first to the fishing industry and then to tourist activities is located very close to the coast (Drejza *et al.*, 2011). There are also significant industrial-port complexes, particularly on the North Shore (e.g., Baie-Comeau, Sept-Îles, Port-Cartier, Havre-Saint-Pierre, Cacouna, Rimouski, Matane, Gaspé). The Magdalen Islands present a particular context; the villages are built on the rocky islands which are connected by large systems of tombolos and dunes on which the road 199 was built. The issues associated with coastal hazards are therefore numerous along the EGSL: residential, commercial buildings, road and railway, aqueduct and sewer systems, port and fishing infrastructures, touristic infrastructures, heritage and archaeological sites and infrastructures and also ecological issues (Bernatchez *et al.*, 2015 ; Drejza *et al.*, 2019 ; Fraser *et al.*, 2017). Hazards also affect the quality of life of coastal populations (e.g. stress, financial costs).

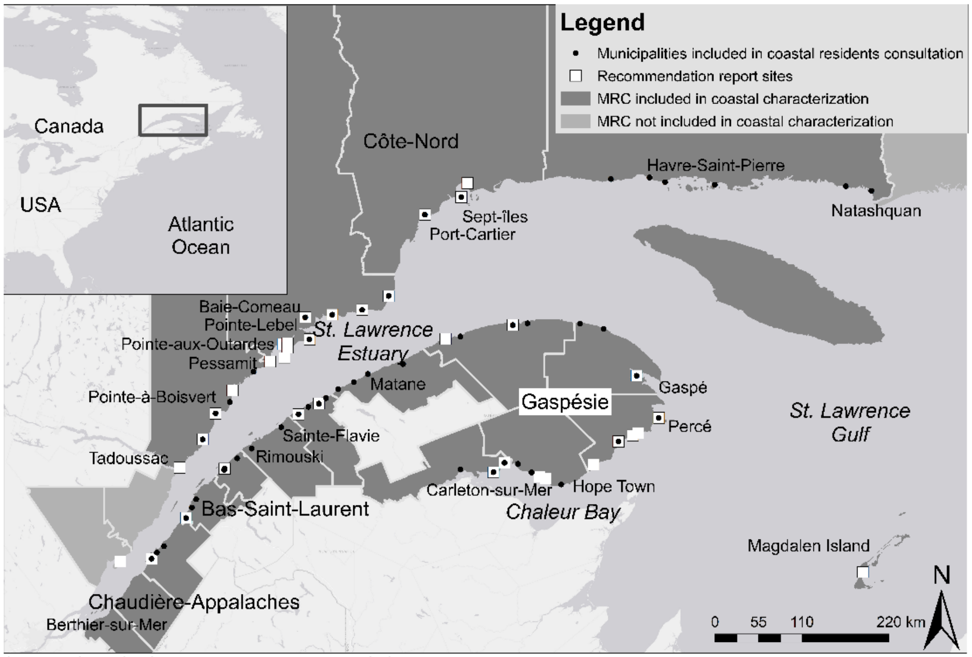
The population in 2016 for the North Shore (92 515), Bas-Saint-Laurent (197 385) and Gaspésie-Magdalen Islands (90 310) regions totaled 380 210 inhabitants distributed in 121 municipalities (Statistique Canada, 2016). The population density is very low and varies between 0.4 inh./km^2 for the North Shore to 8.9 inh./km^2 for the Bas-Saint-Laurent. The municipalities of the study area are grouped for land management in 21 coastal Regional County Municipalities (RCM) (figure 7). The RCMs are regional administrative entities. Under Quebec's Act Respecting Land Use Planning and Development, RCMs are responsible for developing and implementing land use and development plans (ministère des Affaires municipales, des Régions et de l'Occupation du Territoire du Québec, 2009). They also develop civil protection plans and adopt maps of risk zones to limit development in these zones under the Civil Protection Act (Drejza et al., 2011). Municipalities then have the obligation to integrate these rules into their urban plan. The ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC) of the Government of Québec are the environmental authority for the terrestrial part of projects through the Environmental Quality Act and the Protection Policy for Lakeshores, Riverbanks, Littoral Zones and Floodplains. Fisheries and Oceans Canada (DFO) are the environmental authority for the aquatic part of projects, notably with the Oceans Act and the Fisheries Act. The private and public domain of the State is defined in the Civil Code of Quebec from the high-water line (CcQ 1991, c. 64, a. 919; Bureau de l'arpenteur général du Québec, 2013). This corresponds to the level for the highest tide in March, averaged over a period of 19 years. Citizens who wish to set up a protective structure along their land must obtain a permit from the municipality which can accept or not according to municipal regulations and environmental laws. Any intervention in the domain of the State or in fish habitat requires an authorization from the MELCC and DFO. For more details, Boyer-Villemaire et al. (2015) summarize the institutional measures for coastal management in Quebec.

1.5 METHODS

The study was divided in two parts: (1) coastal segmentation in which shoreline armoring was characterised; (2) consultations with coastal zone stakeholders, in which subjects related to different coastal defence measures were discussed.

1.5.1 Coastal segmentation and characterization

Considering the low accuracy of the existing digital coastline (scale of 1: 20,000 from topographic maps), we have digitized the coastline over more than 3300 km (figure 7), using the most recent digital aerial photographs available (between 1996 and 2018, depending on the region) (Arsenault *et al.*, 2021 ; Bernatchez *et al.*, 2020b). The coastline was segmented in geomorphologic homogeneous segments, and characterised using a Geographical Information System (ArcGIS v9.2 to 10.6.1). Shoreline armoring was thus mapped from two sets of high-resolution oblique images taken by helicopter in September 2010 and 2017. This includes coastal defence measures (CDM), port facilities, boat put-ins, bridge piers, aboiteaux, embankments, and dams at the mouth of rivers. The computation of length of all shoreline armoring types were accounted for their linear footprint on the ground. In the case of groins, only the width was added to the computation.



Source: Esri, Garmin, OpenStreetMap; Projection: NAD83; Autors: LDGIZC

Figure 7. MRC and coastal municipalities of Eastern Quebec involved in different parts of the study

Figure 8. Types of coast on the North Shore of the St.Lawrence river in 2017. (A) Sandy cliff – Rock armour at the left, Pointe-aux-Outardes. (B) Landslide in unconsolidated cliff – The rock armour has been displaced by landslide, Pointe-Lebel. (C) Natural cliff composed of sand, silt and clay, typical of the large deltaic complexes of the North Shore, Pessamit. (D) Spit and marsh, Pointe-à-Boisvert. (E) Beach terrace - Houses protected by Rock armour, Sept-Îles

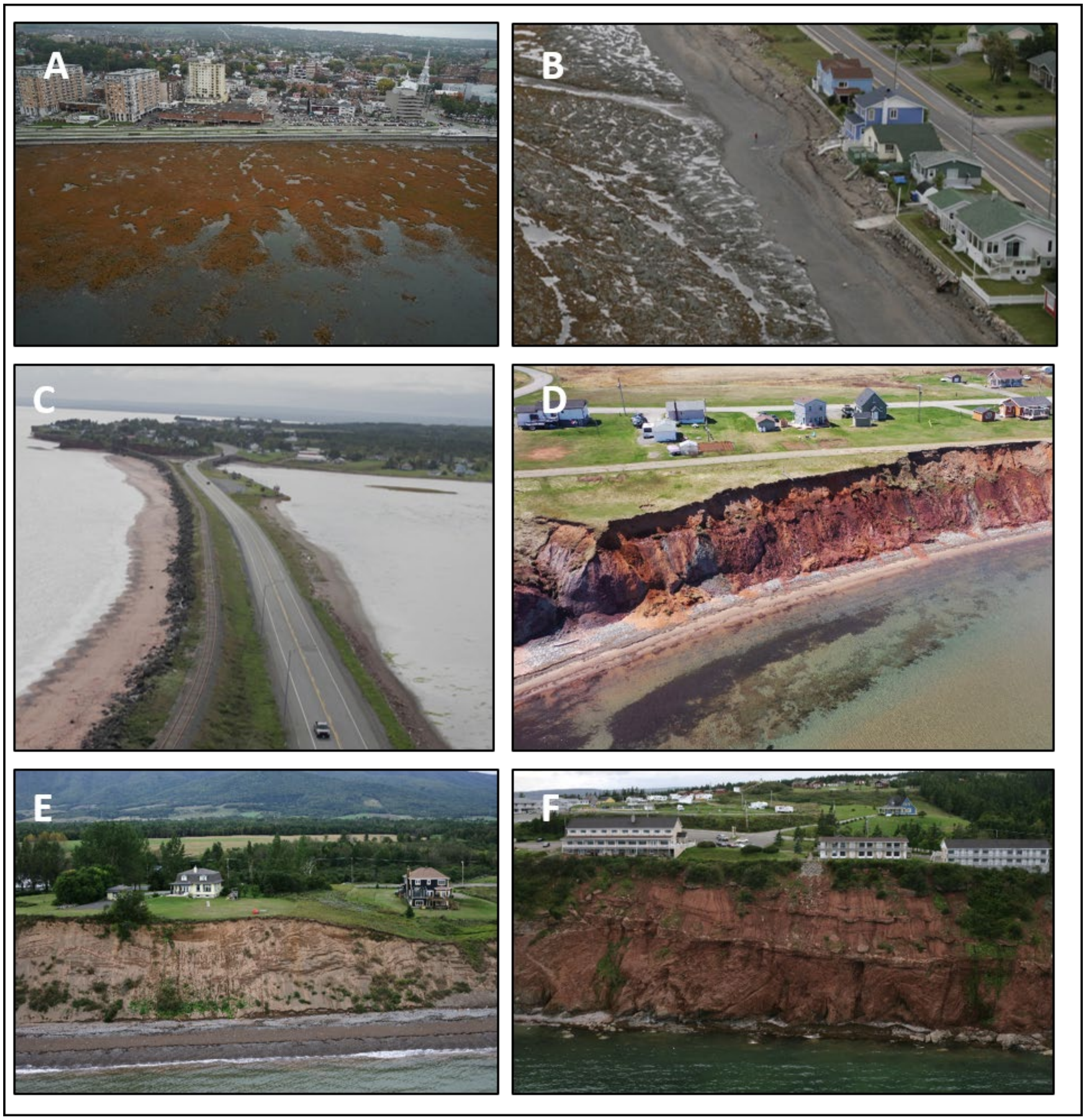


Figure 9. Types of coasts for the Bas-Saint-Laurent and Gaspésie-Magdalen Island regions. (A) Boulevard, hotels and commercial buildings protected by wall in front of a marsh – Rimouski. (B) Houses and national road 132 build on the beach terrace – citizens have put up wall and rock armour, Sainte-Flavie. (C) Railway and national road 132 build on spit protected by rock armour (D) Argillite and glaciomarine cliff – With the cliff retreating, the street was abandoned and two residences were moved, Magdalen Island. (E) Houses on the top of a Sandy cliff, Carleton (F) Motels on the top of a sandstone cliff, Percé

1.5.2 Consultations with coastal zone stakeholders

Coastal zone stakeholders were consulted in three different ways in the context of the Coastal Resilience project (LDGIZC, 2017) held in collaboration with 121 municipalities and 21 coastal MRC of Eastern Quebec (figure 7).

First, a workshop was organized in each of the 21 MRCs during the winter of 2017. Participants comprised managers and professionals from local municipalities, coastal MRCs and relevant ministries, as well as representatives from local and regional organizations and members of local First Nation communities. Invitations to the workshops were sent to 563 stakeholders who were also encouraged to invite relevant colleagues. Various activities were carried out during these workshops. One of the aims was to discuss the needs and tools required to facilitate coastal hazard management. Participants were divided into groups of approximately five people, and round-table discussions based on the World Cafe methodology (Brown et al., 2005) were organized to allow stakeholders to express their views on the issues they faced (tableau 8). Stakeholders were also asked to identify, through a voting system, the types of CDMs they thought most appropriate for different coastal geomorphological types (tableau 8). They were presented with a list of ten CDMs most often used and five coastal types, and were given five tokens per coastal type. For each coastal type, they were asked to weigh the CDMs using their tokens according to the CDM they considered the most appropriate. They were also allowed to write on a piece of paper CDMs that were not included in the list of ten.

Second, in the summer and fall of 2017, semi-structured interviews with residents who live with the consequences of coastal erosion and flooding were conducted in 50 municipalities of the administrative regions of Bas-Saint-Laurent, Gaspésie and the Côte-Nord. (figure 7; tableau 8). In Quebec, as in many countries, the coastline and beaches are public property. However, coastal residents own land immediately adjacent to the shoreline which they are responsible for protecting. A door-to-door survey was carried out in each sector. These interviews were aimed at owners and residents who live along the coast for at least eight months a year, so that only those who have to manage potential or real coastal risks were included. A sample (N) of 494 coastal residents were interviewed. The interviews, approximately one hour long, were conducted by nine different interviewers using a questionnaire designed to assess residents' knowledge of the coastal zone, what problems they perceived, and their need to adapt to coastal erosion and flooding.

Third, environmental and engineering firms whose mandate included coastal engineering or development were consulted in the spring of 2018. A sample of relevant firms was selected by using a governmental company search tool, by consulting environmental and coastal engineering reports, and by snowball sampling. Of the twenty-four firms contacted, seventeen agreed to participate. Between 1 and 6 professionals per firm, depending on its size, were consulted individually. Altogether, our team met with 51 professionals from various functions and disciplines (engineers, geomorphologists, geographers, oceanographers, hydrologists and biologists). The interviews took the form of a discussion with a semi-structured questionnaire focused mainly on three topics (tableau 8): (1) the concerns and needs of companies at various stages of their engineering and coastal-development projects; (2) what parameters are considered in the analysis and design of CDMs; (3) what decision-making process is used to identify the best solution for different coastal communities.

Tableau 8

Questions asked to coastal zone stakeholders during consultations

Coastal managers

- Identify the appropriate solutions based on the type of shoreline.
- What are your needs in terms of adaptation to coastal hazards?
- What type of decision support tools would be most appropriate for your community?

Coastal residents

- What importance do you give to the implementation of protective measures (ranging from revegetation to rockfill) to protect coastal areas from coastal erosion and submersion?
- Have actions or measures been undertaken along your land or residence to reduce the impacts of coastal erosion and submersion?
- Are actions planned or desired to reduce the impacts of coastal erosion or submersion along your property?
  - If yes, which ones?
  - Why?

Environmental and engineering firms

Question asked during discussion:

- Do you consider the availability and competence of the workforce to be sufficient?
- What are the obstacles you encounter with regards to the feasibility of your projects?
- What obstacles do you encounter with regards to solutions analysis (recommendation) and design?
- What are the obstacles to the implementation of innovative solutions (other than reflective structures)?

Questions asked during semi-structured questionnaire:

- What types of mandates does your company obtain from its clients in the field of coastal engineering?
- In the context of your company’s mandates to analyze possible solutions, what deliverables do you produce in the decision-making process for the selection of a CDM?
- When you have to make a recommendation from among several options, how do you proceed?
- Do you use a decision-making support tool?

1.5.3 Content analysis of CDM recommendation reports

A content analysis of CDM recommendation reports written by coastal environmental and engineering firms in the province of Quebec between 1990 and 2018, was carried out. The reports were obtained by sending requests to Coastal Resilience Project participants. Nineteen of the twenty-eight documents received were considered pertinent and integrated into the analysis. Relevant content was extracted from the reports using an evaluation list based on elements associated with coastal dynamics, coastal modeling, coastal adaptation strategies, CDM design and decision-making processes. The information thus obtained was entered into a database and later analysed. The analysis was done for each study site described in the recommendation reports.

1.6 RESULTS

1.6.1 Shoreline armoring in Eastern Quebec

Artificial structures (CDMs, port facilities and other artificial objects supporting coastal development) covered about 386 km, or 11.7% of the 3300 km Eastern Quebec shoreline length. CDMs made up over 83.8% of this total, and covered 9.8% of the shoreline.

The increase in kilometers of CDM between September 2010 and 2017 is shown in tableau 9. In both 2010 and 2017, over 97% of the CDMs in this region were reflective structures, especially rock armour (over 67% of all CDMs). New CDMs implemented between 2010 and 2017 were identified when a coastal segment was natural in 2010 and artificial in 2017 or when the type of artificial structure changed between 2010 and 2017. Structures that disappeared (approx. 21.1 km) are not shown in tableau 9. Results show that rock armour was the structure most commonly implemented between 2010 and 2017, with an added length of 40.8 km. Clearly, reflective structures were the most common type: in 2017, they covered 97.6% of the area devoted to CDMs, while other hard-engineering techniques and soft techniques occupied just 1.4% and 1.0% respectively. Further, only, 3.2% of the newly implemented structures between 2010 and 2017 employed soft techniques.

Tableau 9

Evolution of the length of coastal defence measures in Eastern Quebec between September 2010 and 2017

Coastal defence measures	CDM length				New CDMs installed between 2010 and 2017	
	2010		2017			
	(km)	(%)	(km)	(%)	(km)	(%)
Reflective structures	**302.5**	**98.5**	**315.6**	**97.6**	**48.5**	**95.0**
Rock armour	198.0	64.5	217.2	67.2	40.8	79.8
Seawall	104.5	34.0	98.4	30.4	7.7	15.1
Other hard engineering	**4.0**	**1.3**	**4.4**	**1.4**	**0.9**	**1.8**
Breakwater	0.2	0.1	0.7	0.2	0.4	0.8
Dike	0.7	0.2	0.7	0.2	0.0	0.1
Groin	2.9	0.9	2.7	0.8	0.3	0.6
Rip-rap	0.2	0.1	0.2	0.1	0.2	0.4
Soft techniques	**0.7**	**0.2**	**3.4**	**1.0**	**1.6**	**3.2**
Beach nourishment	0.4	0.1	2.6	0.8	1.0	2.0
Organic screen	0.1	0.0	0.2	0.1	0.2	0.4
Sediments trap/ Geotextile	0.2	0.1	0.2	0.1	0.1	0.1
Vegetation addition	0.0	0.0	0.3	0.1	0.3	0.7
Total CDM length	**307.2**	**100.0**	**323.3**	**100.0**	**51.0**	**100.0**

1.6.2 Stakeholders' role in the choice of coastal defence structures

In the following sections, the role of each stakeholder is described, their preferences and knowledge of coastal defence measures are presented, and obstacles to the implementation of CDMs other than reflective structures are identified.

1.6.2.1 Role of coastal managers

The various workshops held during winter 2017 and spring 2018 brought together a total of 300 local and regional coastal community managers from different professions (land planning, urbanism, geography, geomatics, engineering, etc.) and functions (director, administrator, environmental coordinator, inspector, etc.). The number of workshop participants varied between 5 and 24.

In past studies, coastal managers have attributed their preference for reflective structures to a lack of understanding of coastal processes and hazards, and to an insufficient number of tools for the identification of adaptation strategies (Drejza *et al.*, 2011 ; Friesinger et Bernatchez, 2010). In that context, workshop participants were asked to identify, in an open question, their needs (e.g., knowledge, access to data, scientific support, etc.) in terms of adaptation to coastal hazards, and the types of tools (e.g., cartography, sensitization tools, etc.) they thought appropriate to facilitate the management of coastal risks in their community. Coastal managers identified 193 tools and 188 needs, which were grouped into categories (Guénette *et al.*, 2019 ; Marie *et al.*, 2017). Only the relevant categories related to CDM selection and implementation are presented here. It is interesting to note that, out of a total of 23 tool categories, adaptation strategy identification tools came 2nd in priority, which demonstrates their importance. Of the 188 needs identified, those related to CDM selection and implementation were grouped into six categories (tableau 10).

Coastal community managers were also asked to identify the solutions which they thought suitable for different types of coast. The aim was to place participants in a coastal geomorphological context and to evaluate their CDM choices according to their actual knowledge. Tableau 11 compares participants' preferred solutions for each type of coast to the type of CDMs actually present in the region. Eco-engineering is defined as a category of CDM which combines systems ecology with the process of engineering design based on the use of plants and other materials as framework. Other adaptation techniques (non-intervention, managed retreat, etc.) were added by participants and are presented in tableau 11. However, as they are not considered to be shoreline armoring, they are not discussed in this paper.

In 4 of the 5 coastal types, reflective structures were ranked fourth by participants, while soft techniques were ranked first. Even for rocky cliffs (a naturally reflective coastal environment where reflective structures may be appropriate), coastal community managers tend to favour non-intervention (35.5%) or the use of a soft technique (19.5%); only 15.8 %

thought a reflective structure was appropriate in this situation. In reality, reflective structures are currently the most common CDM used for all of the coastal types.

Tableau 10

Needs related to CDM selection and implementation identified by local and regional Stakeholders

Adapting regulations	
- Reduce time required to obtain authorization certificates from Environment Ministry	- Allow Environment Ministry analysts to recommend innovative CDM
CDM identification	
- Alternative options to hard defence structures	- CDM adapted to long-term forecasting
- CDM adapted to each sediment cell	- Access to scientific expertise to validate CDM
- Decision making support tool	
CDM implementation	
- Facilitate CDM implementation	- Pilot projects and case studies for new types of CDM
Dialogue between stakeholders	
- Dialogue between all government levels	- Intervention planning based on regional strategy
- Implementation of integrated coastal zone management	- Harmonization of analytical approaches between engineers and others scientists
CDM Funding	
- Changing the eligibility criteria for CDM funding	- Funding for citizens, to cover the cost of hiring expertise and implementing preventive solutions
- Long term funding for CDM maintenance	Funding for prevention
- Funding for CDM implementation	- Funding for human resources to accelerate project deployment
- Funding for pilot projects	
Decision-making	
- Political courage in decision-making process	

Tableau 11

Weighted percentages given by participants to coastal defence measures according to coastal types (CDMs in italics were added by participants; CDMs marked with a * were neither response options nor added by participants, but were present on shoreline; W is for weighted by participants and M is for measured on Eastern Quebec shoreline)

Coastal defence measures	**Unconsolidated cliff**		**Rocky cliff**		**Salt marsh**		**Beach terrace**		**Spit**	
	W	**M**	**W**	**M**	**W**	**M**	**W**	**M**	**W**	**M**
Reflective structures	**18.7**	**98.9**	**15.8**	**99.7**	**3.1**	**74.3**	**4.0**	**97.9**	**7.1**	**93.5**
Rock armour	17.0	86.7	14.5	82.9	2.8	69.7	4.0	66.1	6.6	70.1
Seawall	1.7	12.2	1.3	16.8	0.3	4.7	-	31.5	0.5	23.8
Other hard engineering	**32.1**	**0.4**	**23.6**	**0.3**	**25.5**	**25.7**	**26.9**	**1.5**	**28**	**5.0**
Breakwater	17.5	-	12.7	-	17.2	5.3	12.5	0.2	15.0	-
Groin	14.2	0.4	10.6	0.3	8.0	0.8	14.4	1.1	13.0	4.9
Rip-rap	0.2	-	-	-	0.2	1.9	-	0.1	-	0.2
Cliff top stabilization	0.2	-	0.2	-	-	-	-	-	-	-
Rolodune	-	-	0.1	-	0.1	-	-	-	-	-
*Dike	-	-	-	-	-	17.7	-	0.1	-	-
Soft techniques	**36.5**	**0.8**	**19.5**	**0.0**	**40.5**	**0.0**	**61.9**	**0.9**	**48.8**	**1.0**
Beach nourishment	12.4	0.7	9.1	-	5.7	-	27.2	0.5	16.6	0.9
Sediment trap	0.6	-	1.4	-	0.8	-	5.6	0.1	9.7	-
Vegetation addition	22.3	-	8.8	-	33.0	-	29.1	0.1	22.5	-
Eco-engineering	1.2	-	0.2	-	0.7	-	-	-	0.1	-
Coastal restoration	-	-	-	-	0.3	-	-	-	-	-
*Organic screen	-	0.1	-	-	-	-	-	0.1	-	0.1
Other adaptation strategies	**12.7**	**-**	**41.1**	**-**	**30.9**	**-**	**7.2**	**-**	**16.0**	**-**
Non-intervention	8.1	-	35.5	-	25.9	-	6.2	-	12.6	-
Other	4.6	-	5.6	-	5.0	-	1.0	-	3.4	-

1.6.2.2 Role of environmental and engineering firms

The types of coastal defence measures historically recommended by coastal environmental and engineering firms in Eastern Quebec (figure 7) were compiled through content analysis of recommendation reports. The nineteen CDM recommendation reports selected for analysis, were produced by eleven firms between 1990 and 2018. The number of study sites in each report varies between 1 and 19. The percentages shown in tableau 11 are based on the total CDM recommended yearly. Between 1990 and 2010, reflective structures were the most commonly recommended CDM. However, after 2010, recommendations for soft techniques tended to increase while those for reflective structures decreased.

Tableau 12

Percentages of types of CDMs recommended in the reports of engineering firms, 1988-2018

	Number of reports	Number of study site	**Reflective structures**	Seawall	Rock armour	**Other hard engineering**	Groin	Rip-rap	**Soft techniques**	Beach nourishment	Embankment	Vegetation addition	**Other adaptation strategies**	Non-intervention	Relocation	Land zoning
1988	1	11	**90,9**	-	90,9	-	-	-	-	-	-	-	**9,1**	-	9,1	-
1989	1	15	**100,0**	-	100,0	-	-	-	-	-	-	-	-	-	-	-
1990	2	20	**90,0**	5,0	85,0	-	-	-	-	-	-	-	**10,0**	-	10,0	-
1992	2	11	**90,9**	-	90,9	-	-	-	-	-	-	-	**9,1**	-	9,1	-
1994	3	5	**60,0**	-	60,0	**20,0**	20,0	-	-	-	-	-	**20,0**	-	20,0	-
1996	1	1	**100,0**	-	100,0	-	-	-	-	-	-	-	-	-	-	-
1998	1	1	**100,0**	-	100,0	-	-	-	-	-	-	-	-	-	-	-
1999	1	3	**66,7**	-	66,7	**33,3**	33,3	-	-	-	-	-	-	-	-	-
2000	1	2	-	-	-	**50,0**	50,0	-	**50,0**	50,0	-	-	-	-	-	-
2001	2	5	**100,0**	40,0	60,0	-	-	-	-	-	-	-	-	-	-	-
2004	2	7	**71,4**	28,6	42,9	**28,6**	28,6	-	-	-	-	-	-	-	-	-
2007	2	8	**37,5**	-	37,5	**12,5**	12,5	-	**25,0**	-	12,5	12,5	**25,0**	-	12,5	12,5
2010	1	1	**100,0**	-	100,0	-	-	-	-	-	-	-	-	-	-	-
2011	1	4	**25,0**	-	25,0	-	-	-	**50,0**	50,0	-	-	**25,0**	-	25,0	-
2012	3	3	**33,3**	33,3	-	-	-	-	**66,7**	66,7	-	-	-	-	-	-
2013	4	7	**14,3**	-	14,3	-	-	-	**57,1**	57,1	-	-	**28,6**	28,6	-	-
2014	2	4	-	-	-	**25,0**	-	25,0	**75,0**	75,0	-	-	-	-	-	-
2015	3	5	**40,0**	-	40,0	-	-	-	**40,0**	40,0	-	-	**20,0**	-	20,0	-
2016	2	3	**33,3**	-	33,3	-	-	-	**66,7**	66,7	-	-	-	-	-	-
2017	2	2	**33,3**	-	33,3	-	-	-	**66,7**	66,7	-	-	-	-	-	-
2018	2	2	-	-	-	-	-	-	**100,0**	100,0	-	-	-	-	-	-

Professionals from coastal environmental and engineering firms operating in the province of Quebec were interviewed with the goal of establishing a base for improvement of future coastal engineering projects. They were asked to identify, based on their experiences, obstacles to the implementation of CDM other than reflective structures (tableau 13). Three categories of limitations emerged from the discussion: engineer professional responsibilities, regulation, and financial support.

Tableau 13

Obstacles to the implementation of CDM other than reflective structures

Engineers' professional responsibilities
Obligation to guarantee results and efficiency of coastal defence measures, which favours reflective structures with well defined design criteria
Risk supported by firms rather than by public authorities resulting in a conservative design
Decision-making process led by engineers who do not have sufficient knowledge of coastal dynamics
Regulation complexity
Inconsistency between provincial and federal regulations
Restrictions from provincial Environment Quality Act
Financial support
Lack of financial support for case studies and pilot projects
Lack of financial support for monitoring and maintenance
Absence of financial support for coastal citizens by public authorities

The first obstacle to the implementation of CDMs other than reflective structures, as identified by professionals from various disciplines, is the Engineers' professional responsibilities derived from the Quebec Professional Code and the Professional Engineers Act. Under the Act, an engineer who performs engineering acts must guarantee his/her professional liability and he/she is responsible for his/her actions' consequences. In order to be able to make recommendations, and ensure the effectiveness of a CDM, an engineer must understand its behaviour in a given environment. However, few case studies have been carried out in a northern climate context, with low temperatures and ice pressure conditions like those found in the maritime regions of Quebec. This increases the uncertainty regarding the quality and efficiency of the CDM chosen. Given the lack of relevant information, engineers are faced with two possible solutions: (1) avoid CDM with high level of uncertainty; (2) increase security factors. In the first case, engineers tend to recommend conventional CDMs with known behaviour, such as reflective structures. In the second case, when engineers recommend CDMs other than reflective structures, they tend to increase CDM size by adopting conservative designs in order to cover their risks. This results in CDM construction costs that are higher than necessary. As another consequence of their professional liability, engineers tend to take a leading role in the decision-making process, and even though other disciplines are integrated into the different phases of the projects, engineers generally have the last word on the recommendations.

The second obstacle to using different types of CDM is the complexity of the regulatory framework, caused by the absence of agreement between provincial and federal regulations, and by the slow processes mandated under the province's Environmental Quality Act. In Canada, there are two legislation levels, federal and provincial, that do not have an integrated application procedure for issuing certificates of authorization. A project can be accepted by one level and be refused by the other, or environmental compensation measures may be required by one level and not by the other. In the province of Quebec, according to the Environment Quality Act, "any project involving the dredging, digging, filling, levelling off or backfilling […] over a distance of 500 m or more or an area of 5 000 m^2 or more […]", is subject to an environmental impact assessment and review procedure. Per se, no CDM is advantaged or disadvantaged by this regulation. However, according to the Environmental Quality Act, environmental monitoring is required for beach nourishment, while rock armour is not subject to this requirement. As a consequence, beach nourishment projects costs are largely increased, leading to the abandonment of this type of project. Reflective structures, on the other hand, are not subject to an environmental monitoring, and are often understandably favoured over the use of more soft techniques.

The third obstacle to non-reflective solutions is the lack of financial support for the implementation, monitoring and maintenance of CDMs. Monitoring ensures the quality and sustainability of a CDM project by following its evolution, evaluating its effectiveness, and optimizing its maintenance. It also enables the collection of data to assess the CDM' performance, thus continuously improving the knowledge about CDM behaviour in specific environmental conditions. Even though monitoring and maintenance are essential to the viability of a CDM project, our interviews indicate that government funding is focused on the development phase rather than on the entire life cycle of a CDM. Moreover, decision-makers tend to choose reflective structures that require less maintenance than soft techniques. The professionals interviewed also reported that coastal residents lack the funds to hire engineering firms. This results in interventions that favour shoreline armouring without consideration for coastal dynamics. Finally, our interviewees felt that public authorities and citizens see reflective structures as a cost-effective long-term solution.

As a final step in identifying why “softer” CDMs are so rarely used, environmental and engineering firms were asked in a semi-structured questionnaire to describe the mandates they receive from their clients, and the deliverables that follow. A vast majority of firms (15/16) had been commissioned to analyse possible adaptation strategies, and the main deliverable was usually (14/15) a report recommending one solution among several adaptation strategies. For 8 of the 15 firms, that recommendation was based on a multicriteria analysis using a qualitative comparative grid. Only one firm used the more reliable method of multicriteria analysis based on a recognized methodology for one of its projects. These results are comparable to those obtained through content analysis of the recommendation reports mentioned in section 2.2 where, in 8 of the 39 reports, recommendations were based on a decision-making support tool. In 6 of the reports, the multicriteria analysis was based on a qualitative comparative grid; one was based on an analysis of advantages/disadvantages; and one did not mention its method.

1.6.2.3 Role of coastal residents

A sample (N) of 494 coastal residents were interviewed during the summer and fall of 2017 in the administrative regions of Bas-Saint-Laurent (40.4 %), Gaspésie (24.2 %) and Côte-Nord (35.4 %). The respondents were asked to rate the importance of implementing coastal defence measures to protect coastal lands from erosion and flooding, on a sliding scale from very important to not important. The majority (74%) found it very important, while 20% said it was important, 1% said it was less important and 1% did not consider it important. Coastal citizens were asked if actions or measures had been undertaken along their land or residence to reduce the impacts of coastal erosion and flooding. For analysis purposes, the respondents were divided in two groups: group 1, 288 coastal residents who already had a coastal defence measure on their land (58%); group 2, 206 coastal residents without a coastal defence measure (42%).

All coastal residents were asked if they wanted or planned actions to reduce the impact of coastal erosion or flooding along their property. Nearly half of the respondents (52%) answered in the affirmative. Respondents were then asked which CDM they wanted or planned to implement, and the main reasons why they felt it was needed. Since some residents currently have more than one CDM along their property, and because they were allowed to choose more than one additional CDM , the N values shown in tableau 14 and tableau 15 are higher than the number of respondents.

Tableau 14 shows the proportion of respondents with an existing CDM who want or are planning for another, together with their rationale. CDM types currently on respondents' land, are shown in the first column. CDM types, wanted or planned for by respondents, are shown in the first row. Percentages were calculated on the total N for each group. In group 1, 66% of respondents (N=196) wished for or planned to implement at least one new CDM to be used in combination with the one they currently had. The main reasons given for choosing a reflective structure were that this is a solution that works, that it prevents erosion and flooding, and that it provides adequate protection. The main reasons given for the choice of breakwater or groins are that it encourages sediment accumulation, prevents erosion, and dissipates wave energy. Finally, soft techniques were chosen for their natural approach, capacity to dissipate wave energy and increase land stabilization.

Tableau 14

Occurrence and percentage of coastal residents with a CDM currently on their land (group 1), who want or plan implementation of additional one(s), and the main reasons why

	Wanted or planned CDM		
Current CDM	Reflective structure $N_{\text{tot wanted}} = 94$ (48.0%)	Breakwater or groin $N_{\text{tot wanted}} = 30$ (15.3%)	Soft techniques $N_{\text{tot wanted}} = 134$ (68.4%)
Reflective structures $N_{\text{tot current}} = 141$ (71.9 %)	57 (29.1%) - CDM combination - Prevent erosion - Protection - Solution that works - Wave energy dissipation	17 (8.7%) - Encourages sediments accumulation and wave dispersion - CDM combination - Natural approach Prevent erosion - Wave energy dissipation	67 (34.2%) - CDM combination - Land stabilization - Natural approach - Prevent erosion - Wave energy dissipation
Breakwater or groin $N_{\text{tot current}} = 12$ (6.1 %)	6 (3.1%) - Prevent erosion	3 (1.5%) - Encourages sediments accumulation and wave dispersion - Retain ice - Wave energy dissipation	3 (1.5%) -
Soft techniques $N_{\text{tot current}} = 105$ (53.6 %)	31 (15.8%) - Solution that works - CDM combination - Prevent or slow down erosion - Prevent flooding - Protection	10 (5.1%) - Best solution - Encourages sediments accumulation and wave dispersion - CDM combination - Prevent erosion - Retain ice - Wave energy dissipation	64 (32.7%) - Best solution - Encourages sediments accumulation and wave dispersion - CDM combination - Natural approach - Protection - Land stabilization - Wave energy dissipation

Tableau 15 shows that, of the respondents without CDM on their land (group 2), 34% wish or plan to implement some kind of CDM. Tableau 15 also lists the reasoning behind their choice of CDM type.

Tableau 15

Occurrence and percentage of respondents without CDM on their land (group 2), who plan for or want some, and the main reasons why

Coastal defence measures	**N**	**Main reasons**	
Reinforcing structures	**43** (60.6%)		
Rock armour	32 (45.1%)	- Prevent erosion - Protection	- Solution that works/Best solution
Seawall	7 (9.9%)	- Prevent erosion - Protection	- Solution that works/Best solution
Rock armour + seawall	4 (5.6%)	- Solution that works	- Protection
Breakwater or groin	**29** (40.8%)		
Breakwater	16 (22.5%)	- Wave energy dissipation - Prevent/slow down erosion	- Stop waves - Aesthetic
Groin	13 (11.3%)	- Prevent erosion - Wave energy dissipation	- Natural approach - Solution that works
Soft techniques	**52** (73.2%)		
Beach nourishment	18 (25.4%)	- Aesthetic - Natural approach	- Prevent erosion
Sediment trap	3 (4.2%)	- Natural approach	
Vegetation addition	31 (43.7%)	- Land stabilization - Natural approach - Prevent erosion	- Protection - Solution that works
Other measures (Construction on piles, sensitization, relocation, etc.)	**22** (31.0%)	- Best protection solution against erosion and flooding	

Reflective structures are the main measures used by coastal residents who already have a CDM (tableau 14). This result is in accordance with the findings of Friesinger and Bernatchez (2010) who observed that more than 98% of coastal residents favoured hard engineering (rock armour, seawall, rock groins). Tableau 14 and tableau 15, which show that soft techniques are now favoured by coastal residents over reflective structures. Breakwaters or groins are lesser-known techniques, and are the options least often chosen by coastal residents.

Respondents were also asked to identify which stakeholders they thought should be involved in CDM identification in their municipality. The majority of respondents (74%) considered it very important to set up a consultation committee of all the stakeholders involved in coastal zone management (such as affected residents, municipalities, regional county municipality, local elected officials, ministries, scientific community, local and regional organizations, consulting firms, etc.), while 18% considered it important, 1% considered it less important, and 2% considered it unimportant. It was also noted during the interviews that many respondents believed in the importance of the principle, but in practice, they questioned the feasibility and effectiveness of this type of approach.

1.7 DISCUSSION

Coastal zone stakeholder consultation results show that the managers, citizens and firms who were consulted during 2017 and 2018 are open to a greater CDM diversity. Coastal managers who had previously attributed their choice of reflective structures to a lack of understanding of coastal processes and hazards (Bernatchez *et al.*, 2008 ; Drejza *et al.*, 2011 ; Friesinger et Bernatchez, 2010), now ranked soft techniques first in four of the five coastal geomorphological types. This shift in perceptions of rigid structures is also observable for coastal citizens. In 2005 et 2006, despite the fact that coastal citizens of Québec were aware of hard engineering’s negative impacts, the vast majority of coastal residents believed rock armour to be the best solution to coastal erosion, and that this kind of CDM provides a feeling of security (Friesinger et Bernatchez, 2010) while our results indicate that they now prefer further soft techniques. This shift in perception of rigid structures may be due to sensitization made by autorities folowing storm events with 100 years return period. Environmental and engineering firms tend to propose and recommend softer techniques like beach nourishment more often now than they did 10 years ago. Despite this, rock armour was still the most common type of CDM built between 2010 and 2017. In that context, there is room for improvement and each stakeholder has a role to play in the refinement of the decision-making process, and in the development of coastal engineering in Quebec.

1.7.1 Improving the decision-making process

Once CDM has been chosen as adaptation strategy, there are still many alternatives to consider, which could create different effects on coastal socio-ecological systems. In that context, the decision-making process is particularly important when selecting the type of CDM best adapted to the local environment. Stakeholders suggested several improvements to the decision-making process: better collaboration, access to a tool to facilitate CDM selection, creation of interdisciplinary projects, and a fair and transparent competitive bidding process with clear specifications of mandates, requirements, objectives and methods.

In order to improve CDM selection and implementation, coastal managers pointed to the need for a better collaboration between all government levels, implementation of integrated coastal zone management, development of a regional intervention strategy, and harmonization of analytical approaches between engineers and others scientists. Coastal residents, in a proportion of 74%, consider it very important to form a consultation committee that includes all stakeholders. In contrast, of the 39 recommendation reports analysed, only 2 included local stakeholders in their decision-making process, and as previously reported in the literature, stakeholders involved in the decision-making process are often limited to experts and authorities (Brouwer et Van Ek, 2004 ; Gamper et Turcanu, 2007) while others stakeholders are only involved in the implementation phase (Reed, 2008).

A well-run inclusive committee with clear goals, flexibility and openness of mind could improve social learning and stakeholders' involvement in coastal zone adaptation to climate change (Jones *et al.*, 2014 ; Lebel *et al.*, 2010). It could also favour institutional embedding of coastal zone stakeholders' participation, an element that is essential to the long-term success of a participatory process (Reed, 2008). Lebel et al. (2010) identified the advantages of stakeholders' participation which are: conflict reduction and consensus building on monitoring and evaluation criteria; empowerment of stakeholders to influence decisions on adaptation strategies; increased fairness of decisions and actions; and reduction of informational and normative uncertainty.

Coastal managers have identified diverse needs to improve the decision-making process, such as provision of a decision-making support tool; access to scientists able to validate and justify their choice of CDM; better knowledge of alternatives to reflective structures; evaluation of CDM for each sediment cell; and long-term forecasting (tableau 7). They bring to light a number of inadequacies in the current decision-making process, and give an indication of how it could be significantly improved. In general, a sound decision tends to emerge from a process that considers several options based on the latest scientific advances, and a wide range of views including an evaluation of the potential trade-offs (Jones *et al.*, 2014).

Results of the weighting percentage given by coastal managers to CDM according to coastal types (tableau 11) show that they are open to using soft techniques. However, the rejection of reflective structures even for suitable coastal types like rocky cliffs can demonstrates that coastal managers don't fully understand coastal systems' local peculiarities. It may also be related to aesthetic or environmental values. Reflective structures are not suitable for 97.6 % of coastal environments (tableau 9), but they are appropriate in some geomorphological contexts, e.g. along coasts exposed to landslides. There remains a need for knowledge transfer to stakeholders to improve their understanding of the strengths and uses of each type of CDM. This is particularly the case for the types of CDM that are less often used, and for the structures, least often chosen by coastal residents. The knowledge transfer to engineering firms on morphosedimentary dynamics and socio-ecological systems is also necessary since the content analysis of reports and the mapping of CDM types indicate that reflective rigid structures have continued to be implemented for inappropriate coastal systems (beach terrace, spit, dune).

Coastal managers and citizens' lack of knowledge about the selection of CDMs leads them to rely almost entirely on environmental and engineering firms to make recommendations when intervention is required. However, the ability of firms to make sound recommendations is hindered by a number of factors mentioned during the consultation. For instance, a lack of consistency and clarity in the competitive bidding process, engineers' limited knowledge with regards to coastal dynamics, and a lack of collaboration between experts from related disciplines. To improve the decision-making process, engineering firms indicated that public authorities could provide better specifications for mandate requirements, objectives and methods. In addition, interdisciplinarity, recognition of other specialized complementary disciplines, and an integrated consultation process as mentioned above, could significantly improve the relevance of the recommendations in coastal engineering reports. Further enhancements to the decision-making process are associated with coastal engineering, and are presented in section 1.7.2.

1.7.2 Coastal engineering development in Quebec

During the three consultations conducted in 2017 and 2018, many needs were identified to improve coastal engineering development in Quebec. Subsequently, a list of possible actions to be undertaken by coastal managers, coastal residents, and environmental and engineering firms was compiled under each category of stakeholders (tableau 16). Since many of the actions were connected to the political domain, the category Politician was added to the list of stakeholders.

Tableau 16

Possible actions by each stakeholder to help improve coastal engineering development in Quebec

Politician	
- Provide funding for case studies and pilot projects - Provide funding for preventative CDM	- Provide long term funding for CDM monitoring and maintenance - Review some rules of the Environmental Quality Act
Coastal managers	
- Reduce time required to obtain authorization certificates from Environment Ministry	- Implement a regional intervention strategy
Coastal residents	
- Form citizen committees	- Implement a regional intervention strategy
Engineers and firms	
- Provide funding for case studies and pilot projects	- Provide training for employees - Collaborate with other specialized complementary disciplines

A major action to be taken in the political sphere is to increase funding for each phase of the CDM life cycle, starting with the funding of case studies and pilot projects by both government and private firms to meet the need for strong knowledge of coastal processes. Lack of case studies and functional design guidance have been an obstacle to CDM implementation in the USA in the past (Rosati, 1990), and the same applies to the province of Quebec where the climatic conditions are specific.

CDM implementation as an emergency response was frequent in Quebec between the 1980s and the early 2000s and it has led to an increase in the number of reflective rigid structures like rock armour. In order to prioritize a more preventive approach, the Quebec government adopted the Civil Protection Act in 2001, followed by the Framework for the Prevention of Risks in 2005 and finally in 2014 a Quebec Policy of Civil Security (MSP, 2014). To be in line with this, a second area of funding at the government level is required to promote the implementation of coastal defence preventive measures rather than ones built in reaction to emergencies as observed following the December 2010 storm event. Implementation of preventive CDM allows a better knowledge of coastal socio-ecological system dynamics and improves the decision-making process.

Environmental and engineering firms have identified long term funding for CDM implementation, monitoring and maintenance as an important need. In a context of climate change associated with rising sea levels (Church et White, 2011 ; Nicholls et Cazenave, 2010 ; Nicholls et Tol, 2006b) and a decrease in the number of days with coastal ice coverage (Corriveau *et al.*, 2019b ; Ruest, 2014), it is difficult to accurately design a CDM. To compensate for the uncertainties, engineering firms tend to increase safety factors, which does not always lead to the best-adapted solution. Long-term financial support would facilitate adaptive coastal zone management by progressively developing and adapting CDMs based on the most current projections of climate change effects (Allen *et al.*, 2011). The adaptive management approach is based on the fact that decisions must be made within the inherent uncertainty and unpredictability of complex socio-ecological system dynamics, and the approach should incorporate social-learning and current scientific knowledge when available (Allen *et al.*, 2011 ; Folke, 2016). Long-term financial support would allow CDMs to be designed with a reduced useful life span, thus enabling adaptation to system changes. Long-term funding would also enable geomorphological and structural monitoring that would lead to the evaluation of CDM effectiveness in the context of environmental change. Monitoring observations could also be the basis for, or an addition to, a case study aimed at replicating the CDM in a comparable coastal environment.

In Quebec, under the Environmental Quality Act and the Protection Policy for Lakeshores, Riverbanks, Littoral Zones and Floodplains, beach nourishment is considered an embankment which greatly limits the use of this method. An environmental impact assessment is required for an intervention of more than 500 linear meters or an area of 5 000 m^2 and over. Since this process can take many years, this requirement has been identified as a major restriction, leading to hard engineering being favoured at the expense of beach nourishment. It would therefore be an environmental gain to review some of the rules of this act to allow and encourage beach nourishment projects where appropriate.

The first need is to reduce the time required to obtain an authorization certificate for a CDM, which could be solve by increasing human resource in Environment ministry. The current restrictive and lengthy process discourages stakeholders from exploring the possibility of implementing preventive measures, and leads them to remain passive until they are forced to react to damage caused by an event. A preventive approach could start with the formation by coastal managers of a regional intervention committee including coastal citizens, and the development of a common intervention plan based on sediment cells and socio-ecological system.

When it comes to private land, it would be advantageous for citizens to form their own CDM committees, and unite their efforts to secure financial support, which could be used to hire engineering firms and get better analysis of coastal dynamics. The creation of such committees would also favour social learning, (Koontz et al., 2015) which is key to building resilience. The scientific and societal knowledge acquired in this way would facilitate implementation of CDMs that are better adapted to the geomorphology along citizens' properties.

During consultations, the major need identified by environmental and engineering firms was the necessity for better knowledge of CDM behaviour in a northern climate, especially the interaction of the different CDM with coastal ice. Investing in research and development would alleviate their current lack of knowledge about CDM behaviour in a northern climate context, which leads to a reluctance to implement CDMs other than reinforcing hard structures. Furthermore, because of the small number of projects in coastal engineering in Quebec and Eastern Canada, firms do not specialize in that particular field. Rather, they tend to hire a versatile workforce that can work on a variety of projects-- and when the need arises, they subcontract to specialized external resources. In that context, environmental and engineering firms should encourage their professionals to enroll in continuing education to improve their knowledge of specialized topics such as coastal dynamics at the sediment cell scale, as well as encourage collaboration with other specialized complementary disciplines.

1.8 CONCLUSION

As elsewhere in the world, the coastline of Eastern Quebec has seen an increase in its artificiality in the last decades. In 2017, about 11% of the coastline was occupied by such structures, most of which (88.3%) were coastal defence measures. Until 2017, the most-used coastal defence measures were reflective structures (97.6%), while soft techniques were much less common (5.9%). The results of consultations with stakeholders in the area show that there is now a greater openness to the use of CDMs other than reflective structures. However, this openness has not been translated into action, as rock amour was the most implemented CDM between 2010 and 2017.

From the consultations, possible solutions were identified to improve the decision-making process and the coastal engineering development in the province of Quebec; these were mainly related to increases in funding, projects based on consultation and interdisciplinarity, and a review of government regulations, mainly the Environmental Quality Act and the Protection Policy for Lakeshores, Riverbanks, Littoral Zones and Floodplains. Coastal erosion problems are complex and cannot be solved with a single solution such as the commonly used rock armour. There currently exists a diversity of CDM alternatives, each with their specific effects on coastal socio-ecological systems. Given the multiplicity of possible options, the complexity of their interrelations with the different coastal systems, and the uncertainties brought about by climate change, a well defined, flexible and integrated decisional process is essential, but there still remains a need for a tool that would enable decision-makers to evaluate each option in a specific context, to identify the most appropriate solutions, and to make better decisions for the long term.

1.9 ACKNOWLEDGMENTS

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CHAPITRE 2

BESOIN D’UN MEILLEUR SUIVI DES EFFETS DES OUVRAGES DE PROTECTION COTIERE SUR LES SYSTEMES SOCIO-ECOLOGIQUES COTIERS DE MANIERE A AMENAGER DES STRUCTURES MIEUX ADAPTEES A LA DYNAMIQUE COTIERE LOCALE

2.1 RÉSUMÉ EN FRANÇAIS DU DEUXIÈME ARTICLE

Le processus décisionnel dans le contexte d’un SSEC implique une complexité spécifique à chaque site qui découle de la relation entre les conditions géomorphologiques et hydrodynamiques et qui engendre de l’incertitude dans les processus environnementaux. De plus, les projections montrent une augmentation prochaine du niveau marin relatif qui aura pour effet de complexifier davantage le processus décisionnel. Les connaissances scientifiques peuvent contribuer à réduire cette incertitude inhérente. Elles sont essentielles à la prise de décision quant aux ouvrages de protection côtière (OPC) adaptés aux conditions environnementales spécifiques d’un secteur d’étude. Cet article est basé sur une méta-analyse de 355 sites d’études d’OPC tirés de 301 publications scientifiques. Les objectifs sont d’identifier les OPC et les caractéristiques environnementales ayant été évalués, puis de recommander des améliorations à apporter aux connaissances scientifiques afin de perfectionner le processus décisionnel. Il a été démontré que les sites d’étude ne sont pas distribués uniformément à l’échelle mondiale. Alors que plusieurs études ont été réalisées en Europe (n=151), aux États-Unis (n=151) et en Australie (n=30), peu ont été réalisées en Afrique et en Asie où la densité de la population vivant dans des zones côtières à risque est élevée. Aussi, aucun site en climat nordique n’a été répertorié malgré le rôle majeur des glaces sur les processus côtiers dans ces zones. Cinq variables de base sont généralement utilisées dans les publications pour caractériser l’environnement physique : type de côte, type de substrat, marnage ainsi que climat de vagues et de courants. Cependant, seulement 13 des

355 publications incluent une caractérisation complète basée sur les cinq variables. Les variables les plus présentées sont les types de côte (77,2 %) et de substrat (72,7 %). Les OPC sont majoritairement étudiés dans un contexte de côte basse meuble (59,4 %) et sableuse (74,6 %). L'information sur le marnage, le climat de vagues et de courants est beaucoup plus rare. Depuis 1990, 3 des 10 types d'OPC identifiés dans les publications ont été étudiés plus fréquemment : recharge de plage (164), mur de protection (67) et brise-lame (50). Les effets géomorphologiques des OPC sont les plus étudiés (55,1 %), suivis par les effets écologiques (31,2 %), hydrodynamiques (9,1 %) et sociaux (4,6 %). Dans l'ensemble, cette méta-analyse contribue à identifier les lacunes dans les connaissances scientifiques sur les effets des OPC sur le SSEC à l'échelle internationale. Cette information permet d'orienter les besoins en matière d'acquisitions de connaissances.

Cet article, intitulé « *A need to better monitor the effects of coastal defence measures on coastal socio-ecological systems in order to implement structures that are better suited to the coastal zone* », a été corédigé par l'auteur de cette thèse, mes deux directeurs, Pascal Bernatchez et Mathias Glaus ainsi que Sophie Moisset et Marc-Olivier Goudreault. Il a été soumis dans le journal *Ocean and Coastal management* en novembre 2021. Les commentaires des réviseurs ont été reçus en janvier 2022. La version présentée dans ce chapitre n'est pas la version finale. Par contre, les réponses aux commentaires des réviseurs sont incluses dans cette version. En tant que premier auteur, ma contribution fut la majeure partie de la recherche sur l'état des connaissances, la structuration de la base de données, la revue de littérature sur les effets des OPC, la compilation et l'analyse des données, puis la rédaction de l'article. En tant que second auteur, Pascal Bernatchez a contribué à la rédaction et à la révision de l'article ainsi qu'à l'analyse des données. En tant que troisième auteure, Sophie Moisset a participé à la revue de littérature, à la compilation et l'analyse des données, à la rédaction et la révision de l'article. En tant que quatrième auteur, Mathias Glaus a contribué à l'analyse des données et à la révision de l'article. En tant que cinquième auteur, Marc-Olivier Goudreault a contribué à la revue de littérature et à la compilation des données ainsi qu'à la révision de l'article. Également, Marie-Andrée Roy et Maude Corriveau ont contribué à la structuration de la base de données.

2.2 A NEED TO BETTER MONITOR THE EFFECTS OF COASTAL DEFENCE MEASURES ON COASTAL SOCIO-ECOLOGICAL SYSTEMS IN ORDER TO IMPLEMENT STRUCTURES THAT ARE BETTER SUITED TO THE COASTAL ZONE.

ABSTRACT

Decision-making in a coastal socio-ecological system involves managing a site-specific complexity arising from the interaction between hydrodynamic and morphological conditions, and resulting in uncertain patterns. In addition, projections show that sea level will rise in the near future, thus increasing the uncertainty of coastal dynamics behaviour, and adding a layer of complexity to the decision-making process. Scientific knowledge can help reduce inherent uncertainties, and is essential when it comes to making sound decisions on the choice of appropriate coastal defence measures (CDMs) adapted to specific coastal environments. This paper is based on a meta-analysis of 355 CDMs case studies drawn from 301 publications. The objectives were to identify which CDMs and coastal characteristics had been evaluated in published case studies and, based on the findings, to recommend areas of improvement necessary for a better decision-making process. The meta-analysis showed that study sites are not evenly distributed around the world. Most originate from Europe (n=151), the USA (n=151) and Australia (n=30), while few studies have been carried out in Africa and Asia where dense population resides in high risk zones. Also noticeable, is the absence of sites in Nordic climates where ice plays a major role in the erosion process. Five basic variables (coastal type, sediment type, wave characteristics, tidal range, and currents or sediment transport characteristics) are used in publications to characterize study sites according to their physical components. However, only 13 of the 355 sites included a complete characterization using the 5 variables, of which coastal and sediment types are the most frequently identified (77.2% and 72.7% respectively). In general, CDMs are studied in the context of unconsolidated low shore (59.4%) and in sandy environments (74.6%). Information on tidal range, wave climate, and currents, or sediment transport characteristics, is much scarcer. Since 1990, 3 of the 10 CDMs identified in the studies have received more attention than the others; these are beach nourishments, seawalls and breakwaters, with respective cumulative study sites of 164, 67 and 50. The geomorphological effects of CDMs are the most studied (55.1%), followed by ecological (31.2%), hydrodynamic (9.1%), and social (4.6%). Overall, this meta-analysis helped identify knowledge gaps regarding CDMs effects on coastal socio-ecological systems at an international level, and is an indication of where local governance should orient future knowledge acquisition.

Keywords: Coastal engineering, Coastal protection, Coastal defence measures, Decision-making, Coastal erosion, Integrated coastal zone management

2.3 INTRODUCTION

Shorelines worldwide are affected by coastal hazards such as erosion, flooding, and landslides, which have been mitigated by coastal communities for several centuries, by means of a variety of coastal defence measures (CDMs) (Charlier *et al.*, 2005 ; Kraus, 1996). Over the past decades, coastal risks have been accentuated by direct and indirect anthropogenic pressures. Direct pressures are due to an increase in coastal zone occupation with the development of major cities, ports, transportation infrastructures, and residential districts, while indirect pressures are related to human activities which produce greenhouse gases and lead to climate change (Pranzini *et al.*, 2015). Climate change generates an acceleration in sea level rise and, in cold regions, an increase of ice-free period duration, both of which exacerbating the impact of coastal hazards on the communities (Barnhart *et al.*, 2014 ; Church et White, 2011 ; Kopp *et al.*, 2016 ; Nicholls et Cazenave, 2010 ; Nicholls et Tol, 2006b ; Oppenheimer *et al.*, 2019). In response to the growing urbanization of coastal zones and exposure to coastal hazards, the last decades have seen a significant increase in the use of artificial barriers and shoreline armouring in many regions worldwide (Dugan *et al.*, 2011 ; Gittman *et al.*, 2015 ; Horstman *et al.*, 2009b ; Pranzini *et al.*, 2015 ; Sauvé *et al.*, 2020). Shoreline armouring can have a negative impact on the dynamics of coastal socio-ecological systems, for instance, by causing a reduction in the width and height of sandy beaches (Bernatchez and Fraser, 2012; Bernatchez et al., 2011; Dugan et al., 2008), a reduction in natural capacity to attenuate wave energy (Cooper *et al.*, 2020 ; Dugan *et al.*, 2011 ; Moschella *et al.*, 2005), changes in species composition, abundance and diversity, and consequently on ecosystem services (Airoldi *et al.*, 2005 ; Martin *et al.*, 2005).

Although hard structures continue to be the predominant option, soft solutions, like beach and dune nourishment or vegetation, seem to be increasingly prioritized (Dyckman *et al.*, 2014) due to economic (maintaining beaches for tourism) or ecological reasons in addition to offering social benefits (Elko *et al.*, 2021 ; Hinkel *et al.*, 2013). Considering the environmental impacts of hard protection, they are often presented in opposition to soft protection in adaptation strategies (Bongarts Lebbe *et al.*, 2021). However, beach nourishment can also have ecological impacts, for example by modifying the structure and composition of benthic communities (Fegley *et al.*, 2020 ; Peterson *et al.*, 2014) or on seagrass meadows, the effects of which can be felt on slowing natural recovery for a long time (González-Correa *et al.*, 2008). Others opt for hybrid approaches that combine hard structures with soft techniques, the latter allowing to mitigate the impacts of hard structures while offering environmental benefits (Mamo *et al.*, 2022). In a desire to better live with nature and take into account coastal ecosystems and their ecological services in the choice of adaptation measures, several types of solutions have been deployed mainly during the last decade aimed at creating and restoring habitats from a coastal protection perspective (Currin *et al.*, 2008 ; Smith *et al.*, 2020). Various terms are used to designate these solutions and can be grouped under three main terms, Living Shoreline, Nature-based solutions (or nature based defences) and ecosystem based adaptation (Gracia *et al.*, 2018 ; Smith *et al.*, 2020). These solutions are based on the principle that certain coastal ecosystems, such as marshes, mangroves, seagrass meadows and biogenic reefs, attenuate hydrodynamic forces (wave, surge and flow) and promote accretion, thus reducing coastal risks (Barbier, 2020 ; Gracia *et al.*, 2018 ; Morris *et al.*, 2019). The main measures deployed so far are the restoration or creation of marshes and mangroves, with or without low rock sill, riprap or fences (Kibler *et al.*, 2019 ; Mitchell et Bilkovic, 2019 ; Polk *et al.*, 2021 ; Smith *et al.*, 2018 ; Van Cuong *et al.*, 2015) and Oyster reefs (Morris *et al.*, 2021) with sometimes the combination of these three habitats (Donnelly *et al.*, 2017). Some projects that integrate different nature-based solutions (NBS) also aim to move infrastructure inland and remove hard protection while restoring ecosystems (Sutton-Grier *et al.*, 2015 ; Toft *et al.*, 2021). As noted in the review by Smith et al., (2020) on Living Shorelines projects, the application of these solutions is still limited and mainly concentrated in the United States. The evaluation of their effectiveness is still mainly based on modeling (Kumar *et al.*, 2021) and data from monitoring and in situ measurements remain fragmentary (Polk *et al.*, 2021 ; Polk et Eulie, 2018 ; Smith *et al.*, 2018 ; Vuik *et al.*, 2016). Therefore, knowledge of their potential impacts on the coastal zone is still very limited.

Although the only long-term solution to completely eliminate coastal risks and the impacts that human interventions can have on ecosystems and their ecological services is the removal of infrastructure from areas at risk (Cooper et Mckenna, 2008), the use of defence structures in the short to medium term is likely to remain a preferred option (Hinkel *et al.*, 2018). The use of classic cost-benefit analysis (CBA), which is based solely on the comparison of the loss of the value of the assets without adaptation measures and the cost for protection works and their maintenance, often favors the installation of hard structures particularly in densely built-up areas (Amadio *et al.*, 2022 ; Ha *et al.*, 2021). The use of CBA for the identification of solutions also promotes the protection of high-value properties and is questionable in terms of social justice (Siders et Keenan, 2020). Some CBAs integrate the theoretical value of the potential loss of ecosystems and their ecological services that will result from coastal erosion without taking into account the impacts of the defence structures on marine ecosystems, which also favors the installation of protection works (Roebeling *et al.*, 2018). However, incorporating the potential environmental impacts of hard structures into CBA analyses can make a significant difference in the long-term choice of solution type, even encouraging relocation (André *et al.*, 2016). Some CBAs also show that there may be greater benefits from combining NBS or green solution and hard structures than using hard protection alone (Alves *et al.*, 2018 ; Thi Oanh *et al.*, 2020). In addition to these analyses, which are generally done at the level of a neighborhood or a city and whose initiatives are generally supported by local or national governments, there are also individual initiatives to protect private properties on the seashore for which hard structures are largely preferred.

Regardless of the approach used to identify adaptation solutions, knowledge of the potential impacts of protective works on the coastal zone should be crucial in the decision-making process. The impacts are generally classified according to the category of works ranging from the most significant impacts with hard infrastructures to the least significant impacts with Living Shorelines solutions. However, the same structure, whether it is considered hard (e.g. wall) or soft (e.g. beach nourishment) will have different impacts depending on the type of coastal environment in which it is implemented, in particular depending on the type of coast, the type of substrate, the tidal regime (micro to macrotidal) and the hydrodynamic conditions (low to high energy) or even according to its location in the hydrosedimentary cell. A hard structure, such as a wall or rock armour, which increases wave reflection will have a greater impact along a dissipative sandy coast than on the edge of a cliff where the environment is already naturally reflective (Bernatchez et Fraser, 2012). It is also recognized that groins lead to a sedimentary deficit downdrift (Molina *et al.*, 2019), but this sedimentary impact will be significant if it is located in the updrift part of the sedimentary cell whereas it will be negligible if it is located in the downdrift part of the hydrosedimentary cell.

Considering the complexity of coastal environments, do studies on the impacts of CDMs cover the diversity of coastal type and coastal dynamics? Are they well distributed geographically and where populations are most vulnerable to coastal hazards? Do we have a truly exhaustive picture of the impacts of all types of defence structures? In the context where environmental compensation measures are increasingly used to "replace" the potential losses of the implementation of a protective work, it is permissible to question whether the environmental monitoring of the different types of CDM are sufficient and standardized considering the diversity of coastal systems. To make this concept effective, decision-makers must be provided with tools enabling them to assess the potential impacts of the different options.

Based on a meta-analysis of case study publications regarding the impact of CDMs on coastal socio-ecological systems, the purpose of this article is not to review the impacts of CDMs, but rather to analyze the physical contexts in which CDMs monitoring was carried out and to identify gaps in the scientific knowledge related to CDMs, and to determine whether such knowledge would be helpful in making sound decisions in any type of coastal environment. We first list the scientific articles on protective structures according to the type of coast, then carry out an analysis of the articles presenting original results on the impacts of CDMs. We conclude by discussing the geographical distribution of the literature at the international level to identify the kind of improvement necessary for global-scale adaptation planning and for a better decision-making process to reduce coastal risks for the most vulnerable coastal communities.

2.4 METHODOLOGY

A literature review was conducted to look at studies on coastal defence measures (CDMs) and to determine the types of coastal environment in which they were carried out. This was followed by a meta-analysis of the relevant publications. CDMs are coastal adaptation measures implemented to limit or prevent coastal erosion, flooding or landslides. The CDM categories included in the meta-analysis are presented and described in tableau 17. These categories may include CDM subtypes that have been aggregated for the analysis.

2.4.1 Publications selection

A literature search to identify case study publications on CDMs was conducted via *Scopus*, *Web of Science*, and *Google scholar*, and was limited to articles from 1970 to 2019, with a cut-off date of 31 December 2019. The category, subcategory, type, and subtype presented in tableau 17, were the terms used to search titles, abstracts or key words.

Three levels of screening were used to identify appropriate articles:

- At the first level, the following articles were excluded: articles from the grey literature, articles based on model studies (physical or numerical) and reviews. Therefore, only study cases and theses were included. Grey literature was excluded due to the variability in their public accessibility which could lead to an uneven distribution at an international scale.
- The second level excluded articles that did not evaluate one or more of the following CDMs effects: geomorphological, hydrodynamic, ecological or social.
- The last level excluded articles that did not answer positively to all of the three following questions: (1) Does the article include observations made directly by the authors? (*c.-à-d.,* with original data); (2) if so, do the observations indicate changes to the coastal system relative to a baseline condition?; (3) if so, were the changes caused by a CDM?.

Tableau 17

Definition of coastal defence measures categories integrated in the meta-analysis (category, subcategory, type)

CDM category	Definition	Subtype
1.0 Rigid structure	**Rigid structures are CDMs made of rigid materials, such as stones, concrete, wood or steel, to dissipate waves or current energy. They are designed to maintain or consolidate specific coastal areas.**	**- Rubble-mound structure**
1.1 Reflective structure	A CDM category whose components are built on, and parallel to the shoreline, and whose purpose is to maintain the coastline in a fixed location (Dugan *et al.*, 2011 ; Griggs et Fulton-Bennett, 1988 ; Kraus, 1988 ; USACE, 2006c). The name of the category came from its effect of reflecting the incident wave energy.	- Armour structure
1.1.1 Rock armour	Structure mainly made of stone blocks, prefabricated concrete units, etc., covering the slope of a natural shoreline, an embankment or a dike (CIRIA *et al.*, 2007 ; USACE, 2006a).	- Revetment - Enrockment, rock armour
1.1.2 Seawall	Seawall: Structure mainly made of concrete, wood, steel, tires, etc., built vertically or with a steep slope (Burcharth et Steven, 2003 ; Kraus et McDougal, 1996).	- Bulkhead
1.2 Other hard engineering	CDM category whose components do not have the same objectives or effects on coastal dynamics as reflective structures	
1.2.1 Breakwater	Sloped structure built offshore, parallel to the shoreline, and mainly made of stone blocks. Its purpose is to attenuate wave energy offshore, and cause sediment to be deposited between the structure and the shoreline. (Bertasi *et al.*, 2007 ; Chasten *et al.*, 1993 ; Dally et Pope, 1986 ; Dugan *et al.*, 2011 ; Jackson *et al.*, 2015 ; Nordstrom, 2014 ; USACE, 2006c ; Van Rijn, 2011).	- Emerged breakwater - Low-crested structure - Submerged breakwater - Sill - Headland breakwater - Artificial reefs
1.2.2 Groin	Structure built on the foreshore, perpendicular to the shoreline, mainly made of wood or stone, and whose purpose is to capture sediment carried by longshore currents (Balsillie et Berg, 1972 ; Basco et Pope, 2004 ; Kraus *et al.*, 1994 ; Rankin *et al.*, 2004 ; Trampeneau *et al.*, 2004).	- Permeable groin - Impermeable groin - Long groin - Short groin - Notched groin
1.2.3 Dike	Alongshore embankment implemented on the backshore and generally composed of compacted soil. Dikes are mainly designed to prevent coastal flooding. They can be covered by rock armour or other types of revetment.	- Dike - Polders
1.2.4 Rip-rap	Gently sloping structure composed of coarse sedimentary material, usually the size of pebbles and small blocks (62-300 mm), deposited on the shore to stabilize its profile and hold the material in place.	- Rip-rap

Tableau 17 (suite)
Definition of coastal defence measures categories integrated in the meta-analysis (category, subcategory, type)

2.0 Soft techniques	**Soft techniques are flexible means of shoreline remediation that act on the sediment budget by adding sediments or using vegetation techniques to retain it.**	-
2.1 Beach nourishment	A CDM category built from the deposition of borrow sediment on a beach with the purpose of reprofiling sections of it to increase its wave energy dissipation capacity, its width, and to rebalance the sediment budget within the sediment cell. A beach nourishment is located on specific areas of the beach: dune, beach, shoreface, nearshore (Campbell et Benedet, 2006 ; Dean, 2002 ; Hamm *et al.*, 2002 ; Hanson *et al.*, 2002).	- Dune nourishment - Dune construction - Shore nourishment - Nearshore nourishment - Shoreface nourishment - Mega-nourishment
2.2 Sediment trapping	A CDM implemented on sandy coasts, usually dunes, used to control wind erosion by obstructing the wind close to the ground, and to create areas conducive to sand deposition (Li et Sherman, 2015). Sand fencing is a common technique for sediment trapping made of wooden slats joined by a wire (Gouguet, 2018 ; Grafals-Soto et Nordstrom, 2009 ; Khalil, 2008).	- Sand fence - Fascine
2.3 Vegetation addition	Planting of vegetation adapted to the dynamics of the site in areas where the vegetation is fragmented, sparse or absent (Bouma *et al.*, 2014). This technique is not subject to engineering design.	- Vegetation
2.4 Nature-based solutions	A category of CDM which combines systems ecology with the process of engineering design, and is based on the use of plants, biogenic reefs and other materials as a framework (Polk *et al.*, 2021 ; Smith *et al.*, 2020).	
2.5 Beach drainage system	A CDM implemented below the surface of sandy beaches used to drain the beach. The aim is to reduce cross-shore sediment transport (Ciavola *et al.*, 2011).	- Beach drainage system - Vertical drainage - Horizontal drainage

2.4.2 Data extraction

A three-level database was developed using Microsoft Access® to compile the data extracted from the selected articles (tableau 18): (1) publication details, (2) environmental characteristics of the study sites and (3) observed CDM effects.

Tableau 18

Information extracted from each of the selected articles, according to three levels in the Microsoft Access$^{®}$ database

Level 1: Publications details
Authors, title, year of publication, journal
Level 2: Environmental characteristics of study sites*
Country, region, location, coastal type, sediment type, tidal range, waves and currents characteristics, mention and use of sediment cell concept
Level 3: Observed CDM effect
Type of CDM subject to study, authors' observation statements of the CDM effects, type of CDM effects based on authors' observation (used to classify CDM effects), categorization of the type of CDM effect (geomorphological, hydrodynamic, ecological or social)
** If an article included more than one study site, each was entered separately in level 2*

The information available in the articles was transcribed in its entirety in the Microsoft Access® database, and was then homogenized using adapted classification systems:

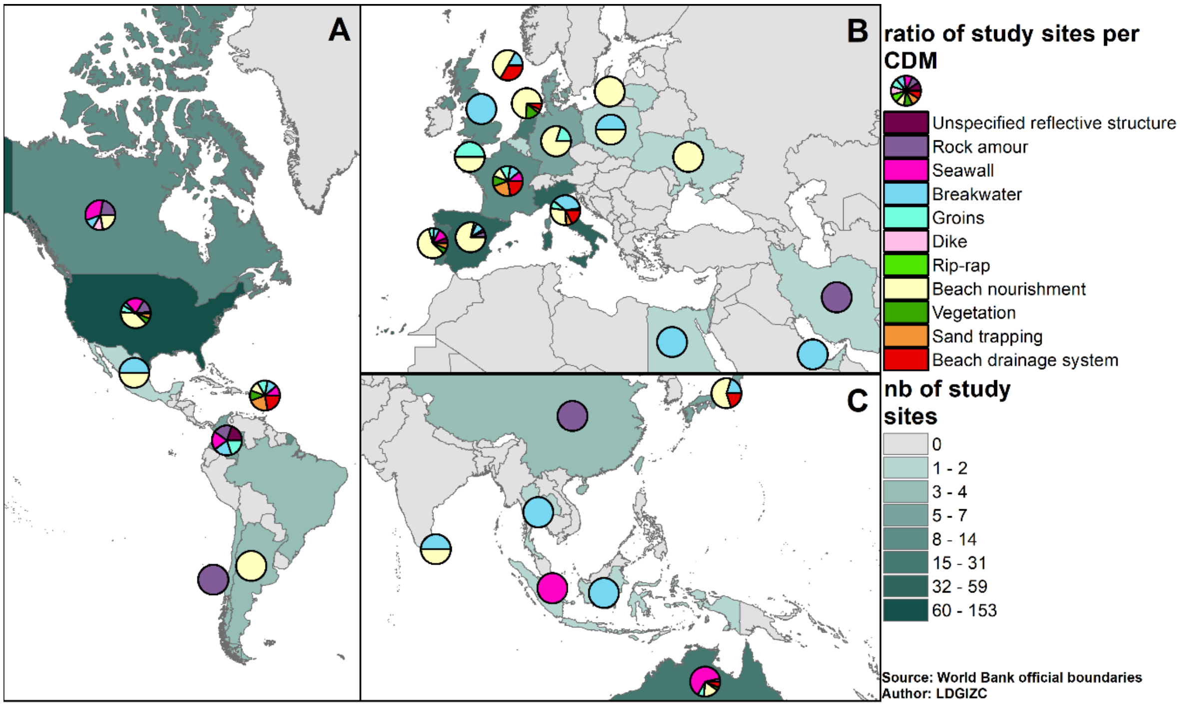
- Coastal types were classified based on the work of Bird (2008), Davidson-Arnott (2010), and Davis and Fitzgerald (Davis et Fitzgerald, 2020).
- Sediments were classified using Friedman and Sanders size scale (Friedman et Sanders, 1978) for unconsolidated sediments: clay (0.001-0.004 mm); silt (0.004-0.063 mm); sand (0.063-2 mm); gravel (2-64 mm); cobbles (64-256 mm); boulders (> 256 mm). Sediment types for rocky shore and cliff were marked down as inapplicable because the geological features were far less frequently specified. The unconsolidated cliff type, also called coastal bluffs, is an escarpment generally composed of ancient marine, fluvial, glacial or glacial deposits (clay, silt, sand, glacial and fluvioglacial damicton). The rocky cliff type is an escarpment of consolidated rock sometimes topped by an unconsolidated deposit. It range from soft rock (sandstone, siltstone and shale) to hard rock (limestone, basalt, or ganite).
- Wave characteristics were dependent on the information available in the articles. When available, the significant wave height offshore was used to classify the wave regime for each site: low energy (< 1 m); moderate energy (1 – 2 m); high energy (> 2 m). The significant wave height is defined as the average of the highest third of the waves in a wave train.
- For tidal range, Davies' shoreline classification system (1964) was used: microtidal (< 2 m); mesotidal (2-4 m) and macrotidal (> 4 m). To this, the classes tideless (0 m) and megatidal (> 8 m) were added. Levoy et al. (2000) used the term megatidal to refine the existing classification and capture beaches with a spring tidal range of more than 8 m.

- Currents were not classified due to the scarcity and disparity of information. Currents are defined as any form of nearshore water circulation cause by wind-generated waves, wind, tides, etc.

In cases where information on the characterization of a particular study site was missing from one or more articles, it was sometimes possible to draw it from similar sites already described in the database. If information was still missing, it could possibly be retrieved from outside sources. For example, visual characterization of a coast and sediment types could be conducted using Google Earth tools®, whereas the tidal range could be obtained using data available online. However, information concerning wave or current characteristics was scarcer. This information retrieval is later referred to in the text as characteristic homogenization and internet research.

2.5 RESULTS

A total of 301 publications describing 355 study sites were included in the meta-analysis. According to the database, study sites were not evenly distributed around the globe (figure 10), as most of the research was conducted in the United States (n=151, mainly on the East Coast), Europe (Italy, n=46; Spain, n=33; and the Netherlands, n=27), and Australia (n=30, mainly in Sydney Harbour).



Source: World Bank official boundaries
Author: LDGIZC

Figure 10. Total number of study sites and ratio of study sites per CDM per country. A) America, B) Europe, North Africa, Western Asia, C) Southeast Asia and Oceania

2.5.1 Study sites characterization

Study sites can be described by five basic variables: (i) coastal type, (ii) sediment or lithology type, (iii) wave characteristics, (iv) tidal range, and (v) currents or sediment transport characteristics. However, only 13 of the 355 study sites' descriptions included these 5 variables. Information on currents or sediment transport characteristics was seldom available and was inconsistent. For that reason, it was not classified or used in the tables below. For each subcategory under the remaining four variables, the number of case studies per coastal type was tallied (tables 19 to 21). Also, the number of case studies was tallied according to the mention or the use of littoral cell concept. It is presented in tableau 22 by coastal type.

Coastal types were identified in 77.2% of the cases, before characteristic homogenization and internet research. Once homogenized the data showed that the coastal type most frequently analyzed was beach terrace (41.4%). In lesser proportion were dunes

(15.8%), barrier island (15.2%), rocky shores (10.7%) and salt marshes (6.5%), while studies on CDMs along unconsolidated cliffs and rocky cliffs are rare (tableau 19). Moreover, 59.4% of the study sites are included in the coastal category unconsolidated low shore which includes beach terraces, barrier islands, littoral spits and welded barrier/tombolo. In tableau 19, the type of coast identified as *Other* includes artificial coasts and coast with multiple types. Also, in table 19 to 23, the term rocky shore is used to indicate low coasts with a rocky base.

Coastal Sediment or lithology types were identified in 72.7% of the cases, before characteristic homogenization and internet research. Once the data were homogenized, regardless of coastal type, the sediment class by far the subject of most studies was sand (74.6%), followed by rocky substrates (11.3%) and pebble beaches (5.4%) (tableau 19). Studies on the combination of unconsolidated low shores and sand are the most frequent (59.4%). Also, the unconsolidated cliffs that were studied were all composed of sand (tableau 20). It is worth noting that in 91.3% of the case studies on salt marshes, the sediment type is not available, probably because marshes are usually composed of mud.

Tableau 19

Number of study sites according to the binary relationship between the type of coast and the type of sediment

	Sediment or lithology		Clay	Silt	Sand	Pebbles	Rocky coast	n.a.	**Total**
Coast	Beach terrace	n	-	-	123	19	-	5	**147**
		%	-	-	83.7	12.9	-	3.4	**41.4**
	Littoral spit	n	-	-	3	-	-	-	**3**
		%	-	-	100.0	-	-	-	**0.8**
	Barrier island	n	-	-	54	-	-	-	**54**
		%	-	-	100.0	-	-	-	**15.2**
	Welded barrier/tombolo	n	-	-	7	-	-	-	**7**
		%	-	-	100.0	-	-	-	**2.0**
	Dune	n	-	-	56	-	-	-	**56**
		%	-	-	100.0	-	-	-	**15.8**
	Unconso. cliff	n	-	-	15	-	-	-	**15**
		%	-	-	100.0	-	-	-	**4.2**
	Salt marsh	n	1	1	-	-	-	21	**23**
		%	4.3	4.3	-	-	-	91.3	**6.5**
	Rocky cliff	n	-	-	-	-	1	-	**1**
		%	-	-	-	-	100.0	-	**0.3**
	Rocky shore	n	-	-	-	-	38	-	**38**
		%	-	-	-	-	100.0	-	**10.7**
	Other	n	-	-	4	-	1	2	**7**
		%	-	-	57.1	-	14.3	28.6	**2.0**
	Not available	n	-	-	3	-	-	1	**4**
		%	-	-	75.0	-	-	25.0	**1.1**
	Total	**n**	**1**	**1**	**265**	**19**	**40**	**29**	355
		%	**0.3**	**0.3**	**74.6**	**5.4**	**11.3**	**8.2**	

Information on wave climate, tidal range and currents was found far less frequently in case study publications. Descriptions of currents or sediment transport were only found in 11.8% of the cases. Wave characterization was conducted in only 33.5% of the cases, before characteristics homogenization and internet research. Even after homogenization and internet research, more than half the studies did not include wave height analysis (54.9%). This is especially true for rocky shores (100.0%), salt marshes (100.0%) and unconsolidated cliffs

(60.0%). In the few case studies where wave climate was analyzed, the predominance is for low wave height (20.0%), then moderate (16.3%), and finally high wave height (8.7%) (tableau 20).

Tableau 20

Number of study sites according to the binary relationship between the type of coast and the wave climate

Wave classification			Low	Moderate	High	n.a.	**Total**
Coast	Beach terrace	n	19	31	21	76	147
		%	12.9	21.1	14.3	51.7	41.4
	Littoral spit	n	-	1	1	1	3
		%	-	33.3	33.3	33.3	0.8
	Barrier island	n	3	22	7	22	54
		%	5.6	40.7	13.0	40.7	15.2
	Welded barrier/tombolo	n	2	4	-	1	7
		%	28.6	57.1	-	14.3	2.0
	Dune	n	6	11	22	17	56
		%	10.7	19.6	39.3	30.4	15.8
	Unconso. cliff	n	1	-	5	9	15
		%	6.7	-	33.3	60.0	4.2
	Salt marsh	n	-	-	-	23	23
		%	-	-	-	100.0	6.5
	Rocky cliff	n	-	-	-	1	1
		%	-	-	-	100.0	0.3
	Rocky shore	n	-	-	-	38	38
		%	-	-	-	100.0	10.7
	Other	n	-	1	2	4	7
		%	-	14.3	28.6	57.1	2.0
	Not available	n	-	1	-	3	4
		%	-	25.0	-	75.0	1.1
	Total	**n**	**31**	**71**	**58**	**195**	**355**
		%	**8.7**	**20.0**	**16.3**	**54.9**	

Tidal range was identified in 40.8% of the case studies, but this number increased to 88.2% after internet research. Most of the case studies included in this meta-analysis were conducted in microtidal (63.7%) and mesotidal (21.1%) environments (tableau 21).

Tableau 21

Number of study sites by binary relationship between the type of coast and the tidal range

	Tidal range		Tideless	Microtidal	Mesotidal	Macrotidal	Megatidal	n.a.	**Total**
Coast	Beach terrace	n	-	88	33	7	-	19	147
		%	-	59.9	22.4	4.8	-	12.9	41.4
	Littoral spit	n	-	2	1	-	-	-	3
		%	-	66.7	33.3	-	-	-	0.8
	Barrier island	n	-	43	7	-	-	4	54
		%	-	79.6	13.0	-	-	7.4	15.2
	Welded barrier/tombolo	n	-	7	-	-	-	-	7
		%	-	100.0	-	-	-	-	2.0
	Dune	n	1	29	21	2	1	2	56
		%	1.8	51.8	37.5	3.6	1.8	3.6	15.8
	Unconso. cliff	n	-	5	5	-	-	5	15
		%	-	33.3	33.3	-	-	33.3	4.2
	Salt marsh	n	-	16	3	-	-	4	23
		%	-	69.6	13.0	-	-	17.4	6.5
	Rocky cliff	n	-	1	-	-	-	-	1
		%	-	100.0	-	-	-	-	0.3
	Rocky shore	n	-	31	2	-	1	4	38
		%	-	81.6	5.3	-	2.6	10.5	10.7
	Other	n	-	4	2	-	-	1	7
		%	-	57.1	28.6	-	-	14.3	2.0
	Not available	n	-	-	1	-	-	3	4
		%	-	-	25.0	-	-	75.0	1.1
	Total	**n**	**1**	**226**	**75**	**9**	**2**	**42**	**355**
		%	**0.3**	**63.7**	**21.1**	**2.5**	**0.6**	**11.8**	**-**

A mention of the littoral cell concept in introduction or study site description was identified in 11.5% of the case studies, while the concept was used in only 5.9% of the case studies to analyze the CDM effects. The concept was mainly used in beach terrace and dune, which are the two most present coastal types in the database.

Tableau 22

Number of study sites by binary relationship between the type of coast and the mention in introduction or the study site description or the use in CDM effects analysis of the littoral cell concept

	Littoral cell concept		Mention in introduction or study site description	Used in CDM effects analysis	
Coast	Beach terrace	n	16	7	
		%	4.5	2.0	
	Littoral spit	n	-	-	
		%	-	-	
	Barrier island	n	-	-	
		%	-	-	
	Welded barrier/tombolo	n	5	2	
		%	1.4	0.6	
	Dune	n	15	10	
		%	4.2	2.8	
	Unconso. cliff	n	-	-	
		%	-	-	
	Salt marsh	n	1	-	
		%	0.3	-	
	Rocky cliff	n	-	-	
		%	-	-	
	Rocky shore	n	3	2	
		%	0.8	0.6	
	Other	n	1	-	
		%	0.3	-	
	Not available	n	-	-	
		%	-	-	
	Total	**n**	**41**	**21**	**355**
		%	**11.5**	**5.9**	

2.5.2 Coastal defence measures study cases

According to the database, 10 types of coastal defence measures (CDMs), which can be subdivided into 22 CDM subtypes (tableau 17), were identified worldwide in the scientific literature. The total scientific articles resulting from the literature search presented in section 2.4.1 indicate a total number of publications for each CDM category varying between 2590 (beach nourishment) and 51 (vegetation addition) (tableau 23). Breakwater (1650), groin (951), seawall (851), and dike (632) have a total scientific article higher than 500. After the application of the three levels of screening used to identify appropriate articles with observed CDM effect used in the meta-analysis, the percentage of articles varies between CDM. The highest is vegetation addition (33.3%) and the lowest is dike (0.2%). The median value for all the CDMs is 4.9%.

Tableau 23

Pourcentage of appropriate article with CDM effect used in the meta-analysis in regard to the total scientific articles on CDM resulting form the literature search

CDM	**Total scientific articles resulting from the literature search**	**Appropriate articles with observed CDM effect used in the meta-analysis**	
	n	**n**	**%**
Reflective structure	179	4	2.2%
Rock armour	386	31	8.0%
Seawall	851	66	7.8%
Other hard engineering	-	-	-
Breakwater	1650	45	2.7%
Groin	951	24	2.5%
Dike	632	1	0.2%
Rip-rap	54	1	1.9%
Soft technique	-	-	-
Beach nourishment	2590	126	4.9%
Beach drainage system	260	14	5.4%
Sediment trapping	157	15	9.6%
Vegetation addition	51	17	33.3%

The number of study sites presented in the appropriate articles used for the meta-analysis varies between CDMs (figure 11 – the 8 CDMs most frequently studied in the scientific literature). Between 1970 and 1990, very few CDMs were studied worldwide.

During the 1990s, three CDMs stood out and were more frequently studied: beach nourishment, seawalls and breakwaters, but in the early 2000s, beach nourishment's cumulative number started to drastically increase. At the cut-off year of 2019, beach nourishment studies were predominant, with a cumulative number reaching 164 in 2019 marked by an increased growth between 1990 and 2019. The second most studied CDMs, at the cut-off year of 2019, were seawalls and breakwaters, with 67 and 50 respectively. Finally, the number of case studies on groins, rock armours, vegetation additions, sediment trapping, and beach drainage systems remained low over the period 1970-2019, even though there was a slight increase in the years 2000, with numbers reaching between 18 and 32, by the end of 2019. If nature-based solutions have an increased popularity in the past decade (Bilkovic *et al.*, 2017b ; Smith *et al.*, 2020), there is still a lack of study on the effects and efficiency of those solutions.

Beach nourishments was mainly studied in the context of beach terrace (43.3 and to a lesser extent in dunes (23.8%) and barrier island (22.6%). In those types of coasts, 94.8% of beach nourishment studies were in sandy substrate coasts, and 4.6% in pebbles substrate coasts. Seawall studies, depending on the type of coast, were more balanced with 32.8% of the studied sites in unconsolidated low shores (beach terrace, littoral spit, barrier island, and welded barrier/tombolo), 35.8 % in rocky shores, and 16.4% in salt marshes. Breakwaters were mainly studied in beach terrace (58.0%), unconsolidated low shores (68.0%) and to a lesser extent in rocky shores (12.0%), dunes (8.0%), barrier island (6.0%) and salt marshes (4.0%). For the distribution of the remaining CDMs according to the type of coast, the reader can refer to tableau 24.

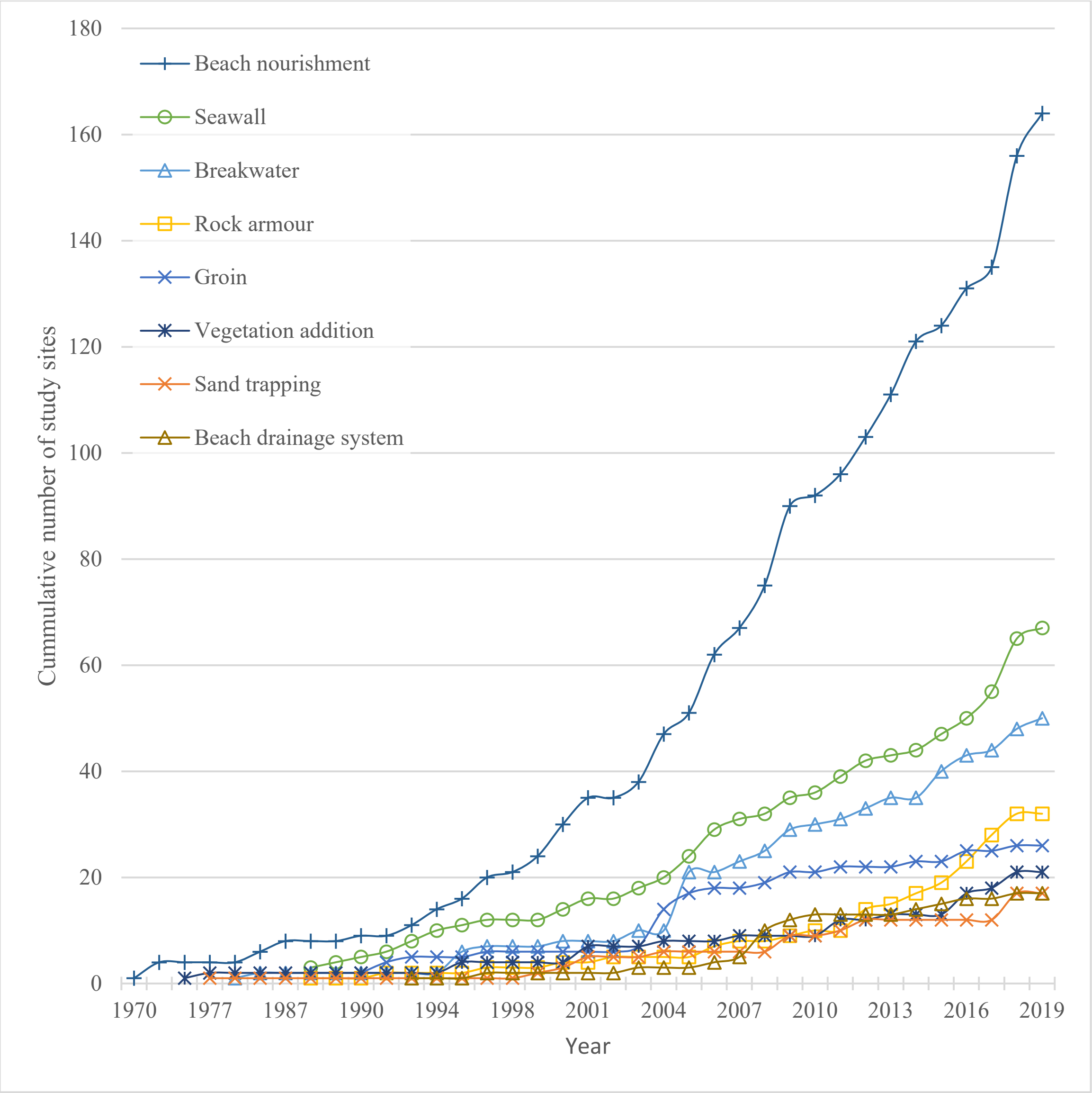


Figure 11. Cumulative number of study sites per CDM, between 1970 and 2019. CDMs with a cumulative number of study sites lower then 10 in 2019 were excluded from the graph (*c.-à-d.,* unspecified reflective structure (n=4), rip-rap (n=1) and dike (n=1)).

Tableau 24

Number of study sites according to the binary relationship between the type of coast and the CDM type. Unconso.: unconsolidated. n.a.: not available. Four study sites referred to unspecified reflective structures without specifying a precise CDM

		CDM	Reflective structure	Rock armour	Seawall	Other hard engineering	Breakwater	Groin	Dike	Rip-rap	Soft technique	Beach nourishment	Beach drainage	Sediment trapping	Vegetation addition	**Total**
Coast	Beach terrace	n	1	11	19	-	29	15	-	-	-	71	11	3	3	**163**
		%	25.0	34.4	28.4	-	58.0	57.7	-	-	-	43.3	61.1	17.6	14.3	**-**
	Littoral spit	n	-	1	-	-	-	1	-	-	-	1	-	-	-	**3**
		%	-	3.1	-	-	-	3.8	-	-	-	0.6	-	-	-	**-**
	Barrier island	n	-	-	3	-	3	4	-	-	-	37	2	8	3	**60**
		%	-	-	4.5	-	6.0	15.4	-	-	-	22.6	11.1	47.1	14.3	**-**
	Welded barrier/tombolo	n	-	-	-	-	2	1	-	-	-	5	-	2	1	**11**
		%	-	-	-	-	4.0	3.8	-	-	-	3.0	-	11.8	4.8	**-**
	Dune	n	-	2	2	-	4	3	-	-	-	39	5	4	8	**67**
		%	-	6.3	3.0	-	8.0	11.5	-	-	-	23.8	27.8	23.5	38.1	**-**
	Unconso. cliff	n	-	1	4	-	1	-	-	1	-	8	-	-	-	**15**
		%	-	3.1	6.0	-	2.0	-	-	100.0	-	4.9	-	-	-	**-**
	Salt marsh	n	1	9	11	-	2	1	1	-	-	-	-	-	6	**31**
		%	25.0	28.1	16.4	-	4.0	3.8	100.0	-	-	-	-	-	28.6	**-**
	Rocky cliff	n	-	-	1	-	-	-	-	-	-	-	-	-	-	**1**
		%	-	-	1.5	-	-	-	-	-	-	-	-	-	-	**-**
	Rocky shore	n	1	7	24	-	6	-	-	-	-	-	-	-	-	**38**
		%	25.0	21.9	35.8	-	12.0	-	-	-	-	-	-	-	-	**-**
	Other	n	1	1	2	-	3	1	-	-	-	2	-	-	-	**10**
		%	25.0	3.1	3.0	-	6.0	3.8	-	-	-	1.2	-	-	-	**-**
	Not available	n	-	-	1	-	-	-	-	-	-	1	-	-	-	**2**
		%	-	-	1.5	-	-	-	-	-	-	0.6	-	-	-	**-**
	Total	**n**	**4**	**32**	**67**	**-**	**50**	**26**	**1**	**1**	**-**	**164**	**18**	**17**	**21**	**401**
		%	**1.0**	**8.0**	**16.7**	**-**	**12.5**	**6.5**	**0.2**	**0.2**	**-**	**40.9**	**4.5**	**4.2**	**5.2**	**-**

Regardless of the CDM being considered, geomorphological effects are the most studied (55.1%), followed by ecological (31.2%) and hydrodynamic (9.1%) (tableau 25). The social effects are only studied in 4.6% of the cases. Geomorphological effects (69.3%) of beach nourishment are the most studied, followed by ecological (20.6%) and hydrodynamic (4.6%). The seawalls are studied more frequently in relation to their ecological effects (57.1%), followed by geomorphological (31.9%) and hydrodynamic (9.9%). Finally, breakwaters are studied in relation to their geomorphological effects in 44.6% of the cases, ecological in 28.9%, and hydrodynamic in 19.3%. Among all the studies on beach nourishment, seawalls and breakwaters, less than 7.2% include observations on their social repercussions.

Tableau 25

Number of study sites according to the binary relationship between the type of CDM effect and the CDM category. Six study sites referred to unspecified reflective structures without specifying a precise CDM

		Indicator								
		Geomorphological		Ecological		Hydrodynamic		Social		**Total**
		n	%	n	%	n	%	n	%	**n**
Coastal defence measure	Reflective structure	2	33.3	-	-	3	50.0	1	16.7	**6**
	Rock armour	10	27.0	-	-	26	70.3	1	2.7	**37**
	Seawall	29	31.9	9	9.9	52	57.1	1	1.1	**91**
	Other hard engineering	-	-	-	-	-	-	-	-	**-**
	Breakwater	37	44.6	16	19.3	24	28.9	6	7.2	**83**
	Groin	19	48.7	10	25.6	7	17.9	3	7.7	**39**
	Dike	-	-	-	-	1	100	-	-	**1**
	Rip-rap	1	100	-	-	-	-	-	-	**1**
	Soft technique	-	-	-	-	-	-	-	-	**-**
	Beach nourishment	151	69.3	10	4.6	45	20.6	12	5.5	**218**
	Beach drainage system	18	75.0	4	16.7	1	4.2	1	4.2	**24**
	Sediment trapping	17	94.4	-	-	1	5.6	-	-	**18**
	Vegetation addition	14	60.9	-	-	9	39.1	-	-	**23**
	Total	**298**	**55.1**	**49**	**9.1**	**169**	**31.2**	**25**	**4.6**	**541**

2.6 DISCUSSION

Coastal hazards, as any environmental issue, are complex, multi-scale, a dominant source of uncertainties, and have an impact on numerous actors and agencies (Bongarts Lebbe *et al.*, 2021 ; Hinkel *et al.*, 2018 ; Reed, 2008). In general, and more specifically in a context of climate change, coastal communities may improve their resilience to coastal hazards by implementing a CDM. However, the wide range of choices of CDMs and their effects on all aspects of coastal socio-ecological systems, make the decision-making process extremely difficult and complex.

This meta-analysis has several implications for the decision-making process as it highlights two main issues: (i) study sites' characterization is generally poor, and (ii) scientific knowledge on CDMs and their associated effects on different types of coasts is incomplete due to an imbalance in the studies carried out worldwide. Consequently, decisions regarding the implementation of CDMs might be biased as it is based on fragmented knowledge.

2.6.1 Improvement to characterization of study sites

Data acquisition can be expensive and time consuming. However, if every case study was to include a complete and clear description of the coastal environment, better comparisons between sites, and improvment to CDMs evaluation could be made (figure 12). Consequently, scientific knowledge regarding the impact of each type of CDM in a variety of environments could be greatly improved to facilitate the decision-making process. At the very least, a combination of five variables should be monitored and used to describe the physical environment of a coast for which a CDM is to be identified and designated: coastal type, sediment or rock type, wave characteristics, tidal range, and currents or sediment transport characteristics. Additionally, ecological and social variables, as well as information regarding coastal dynamics, erosion process and extreme total water level (still water level, storm surge and run-up level), should be integrated into study sites' characterization. The extreme total water level would be particularly valuable when comparing the CDMs designs (USACE, 2006a).

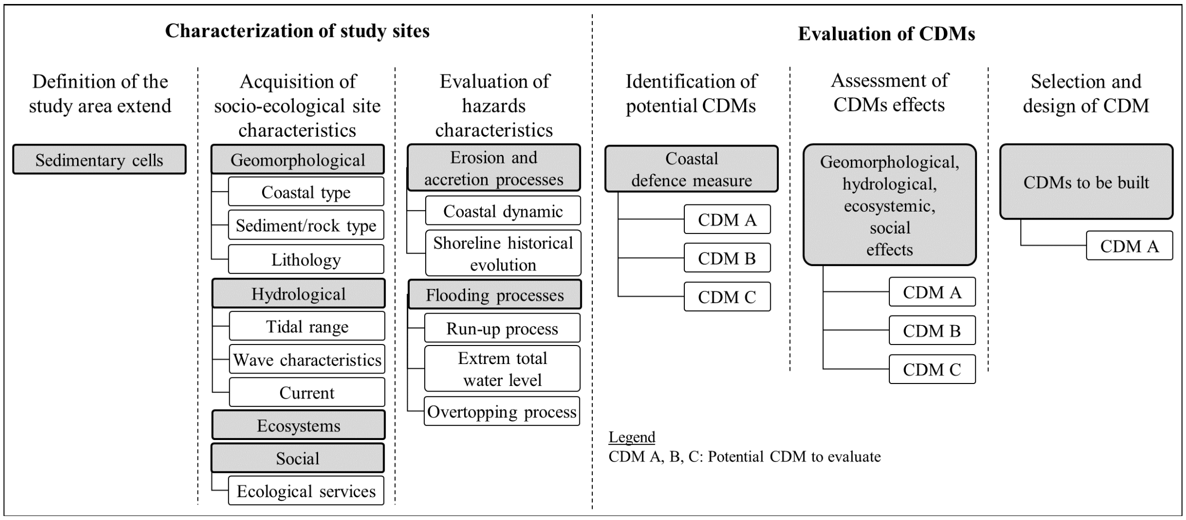


Figure 12. Elements to include in the description of coastal environnement in order to improve the characterisation of study site and the evaluation of CDMs.

2.6.1.1 Coastal types

According to our analysis, coastal types are frequently identified, but not always accurately. For example, approximately a third of coastal types are identified as *beach.* However, while some authors identified beaches as a type of coast (Bird, 2008), others considered it a part of the shore profile (Davidson-Arnott, 2010 ; Davis et Fitzgerald, 2020 ; Masselink *et al.*, 2011). A basic Google Earth validation showed that beaches can be subclassified as beach terraces, barrier islands and spit, dune systems, unconsolidated cliffs, etc. A more specific coastal type identification would give the reader a better indication of the long-term evolution of the coast. By taking the long-term evolution into consideration, the CDM choice and design would be in phase with the erosion process (*c.-à-d.,* hydrodynamic, aerodynamic, land slide, suffusion, gullying, cryogenic, etc. (Bernatchez et Dubois, 2004)). The analysis of shoreline historical evolution would also make it possible to assess sediment inputs and accumulation processes, which are essential elements when identifying certain structures such as groins (Guimarães *et al.*, 2016). Ultimately, it would contribute to the implementation of CDMs adapted to natural dynamics, regardless of the uncertainties to which coastal socio-ecological systems are subjected.

Rocky cliffs are largely under-represented in CDMs studies. However, the rocky cliffs retreat pose a significant risk to people and infrastructure (Haque *et al.*, 2019 ; Spooner *et al.*, 2013). The retreat of rocky cliffs can be dominated by wave action (Bezerra *et al.*, 2011 ; Hackney *et al.*, 2013), by gravity, hydrogeological or cryogenic processes (Highland et Bobrowsky, 2008 ; Lantuit *et al.*, 2013 ; Pierre et Lahousse, 2006) or by the combination of marine and subaerial processes which can accelerate erosion rates (Del Río et Gracia, 2009 ; Young *et al.*, 2009). The development of basal notches by waves can also be impacted by beach dynamics (accretion, erosion, width) and shore platform geomorphology in front of the rocky cliff (Kline *et al.*, 2014 ; Walkden et Hall, 2005). All these processes can trigger massive rock slope failure, rock fall and landslides, which are often sudden and unpredictable, and can result in many casualties (Haque *et al.*, 2019). Protecting the rocky cliff toe with rigid structures has been preferred in the past, and although such structures reduce the potential cliff retreat and the probability of landslides, they do not eliminate it (Lee *et al.*, 2001 ; Stavrou *et al.*, 2011). The complexity of rocky cliffs' erosion dynamics, and the risk they represent requires adapted solutions based on the causes and mechanisms of mass movements behaviour (Nunes *et al.*, 2009).

2.6.1.2 Sediment and geology types

Sediment and geology types are identified in approximately a third of the cases, and the majority of the times, the case studies are conducted on unconsolidated shores such as unconsolidated low shores, dunes, and unconsolidated cliffs.

With regard to rocky shores and salt marshes, there is a clear lack of information on the type of rock or sediment. In the case of rocky shores, this might be explained by the fact that the dominant CDM studies on this type of coast are seawalls (tableau 24) for their ecological effects (tableau 25), and such studies rarely integrate a sediment or geological characterization. In the case of salt marshes, this may be due to the fact that this type of environment is generally dominated by fine sediments, especially muddy sediments.

Sediment or rock type is a key variable in the decision-making process as each class of sediment will react differently to the implementation of a CDM. For instance, on unconsolidated low shores, sand is more likely than pebbles to be subject to re-suspension due to hydrodynamic or aerodynamic processes. Therefore, CDMs' impacts on sediment transport patterns, either positive or negative, are a function of particle size and kinetic energy. For example, it is well known that reflective structures have negative impacts on sandy low-lying coasts (Bernatchez et Fraser, 2012) due to the reflected wave energy on the substrate. The behaviour and durability of a beach nourishment are also influenced by the particle size of the sediment used to nourish the beach (Benedet *et al.*, 2004 ; Bitan et Zviely, 2020 ; Campbell et Benedet, 2006 ; Dean, 2002). The texture of the sediments is equally important in marshes. For example, sandy sediments which are less cohesive than fine sediments are more easily erodible, and are less conducive to the development of diatoms that help protect the foreshore surface from erosion (Schoutens *et al.*, 2019).

On unconsolidated cliffs, rocky shores and rocky cliffs, the lithology and structure is important because it determines the resistance to erosion and the mode of retreat (Bernatchez et Dubois, 2004 ; Emery et Kuhn, 1982 ; Hapke *et al.*, 2009). Unconsolidated cliffs can be made up of a wide variety of sediments (clay, silt, sand, glacial and fluvioglacial damicton). However, in all of the CDMs studies carried out along unconsolidated cliffs, the sediments were composed of sand, so that there is a significant lack of knowledge on other types of cliffs. While the erosion of sandy cliffs is mainly caused by wave action, the retreat patterns of other types of cliffs are much more complex since they are influenced by several types of subaerial processes (Bernatchez et Dubois, 2004 ; Joyal *et al.*, 2016). For example, depending on latitude, clay cliffs are dominated by hydrogeological or cryogenic processes that are likely to trigger large-scale landslides or mudflows, which have the potential to destroy infrastructures and cause mortality. The presence of a beach can also protect the cliff toe and reduce cliff retreat (Sallenger *et al.*, 2002 ; Young *et al.*, 2016). A coarse-grained sediments beach will generally have a steeper slope and offer less protection to the unconsolidated cliff toe than a fine-grained dissipative beach (Sunamura, 2015). In this context, it is important to consider the nature of the foreshore sediments, as any intervention, including defence structures, may lead to a reduction in the width and height of the beach, and promote the retreat of the cliff.

Therefore, it is important to know the specific sediment and lithology type in order to be able to accurately analyze the erosion processes involved, and choose a CDM that is better adapted to the environmental conditions.

2.6.1.3 Wave, tidal range and current type

Wave energy characterization, when available, is generally defined by its significant wave height (H_s), which is a data recognized and widely used by the scientific community. However, a lack of contextualization in which the data was obtained (water depth, sampling frequency, etc.) hinders the accurate classification of wave energy. In addition, some case studies used qualitative rather than quantitative characterization of wave energy (such as *moderate wave climate*), which is not precise enough to be able to estimate the wave height. A detailed contextualization would help to better classify wave energy. Access to long-time series of wave conditions for a given site has been a problem for the analysis of coastal hazards and the design of protective structures (Dodet *et al.*, 2011 ; Idier *et al.*, 2020 ; Power *et al.*, 2019), but the situation has improved over the past decade with the development of numerical modelling (Li *et al.*, 2018 ; Morim *et al.*, 2019 ; Vitousek *et al.*, 2017). This type of information is pertinent as the significant wave height is generally the statistical value used, among others, in the design of a CDM, to calculate extreme wave height (quantile level $H_{s99\%}$, $H_{s95\%}$) and return periods (Tsoukala *et al.*, 2016) as well as to calculate the total water level, extreme wave run-up, and overtopping processes during storm events (Guimarães *et al.*, 2015 ; Leaman *et al.*, 2021 ; Lerma *et al.*, 2018). A mischaracterization of the wave climate could thus lead to damage or even failure of a CDM.

Tidal range is characterized slightly more frequently than wave energy, using spring tidal range height or Davies' classification (Davies, 1964): microtidal, mesotidal or macrotidal. Tidal range can be used for the classification of the coastal process (Davis et Hayes, 1984). It can also be used for the estimation of the total water level in combination with the storm surge and the run-up levels to evaluate coastal flood hazards or to define the crest height in the design process of a CDM (Brown *et al.*, 2012 ; CIRIA *et al.*, 2007 ; USACE, 2006a). Tide can also generate important tidal currents, and related sediment transport in the nearshore area, which can influence CDMs' structural behaviour and related effects on coastal socio-ecological systems (CIRIA *et al.*, 2007 ; USACE, 2006a). This analysis also shows the need to improve our knowledge in environments with strong waves (H_s> 2 m) and where the tidal range is greater than 4 m.

Currents characterization is scarce, *c.-à-d.,* only found in 9.1% of the cases. However, when available, currents are often quantified, and they are generally defined by one of the following types: littoral drift or longshore currents, sediment transport, cross-shore currents or tidal currents. It can be assumed that the studies only include the predominant currents, but information on the intensity of longshore and cross-shore currents could be of value for a better understanding of sediment transport dynamics at the study site. Some CDMs are known to modify currents and sediment transport. For example, following the construction of a groin, it is expected that the longshore drift will be interrupted or deviated offshore (Dette *et al.*, 2004 ; Trampeneau *et al.*, 2004), leading to sediment accumulation on the updrift side, and erosion on the downdrift side of the groin. Coastal currents, particularly tidal currents, as well as wave heights are fundamental in the sedimentation process of salt marshes (Coulombier *et al.*, 2012 ; Murphy et Voulgaris, 2006). It is therefore surprising that studies on CDMs for this type of coast do not include hydrodynamic components (table 4). In this type of environment, poorly designed or poorly adapted rigid structures in particular, can lead to major ecological impacts (Balouskus et Targett, 2016 ; Bilkovic et Mitchell, 2013 ; Bozek et Burdick, 2005 ; Landry et Golden, 2017 ; Patrick *et al.*, 2016 ; Theuerkauf *et al.*, 2017). Yet, our meta-analysis showed that rigid structures were predominant in salt marshes.

Knowledge on the currents types, direction and intensity would help anticipate the morphological response of the site to a CDM prior to its implementation (USACE, 2006a).

Knowledge of changes to the coastal dynamics of the last decades could help the decision-making process and CDM's design. Thus, in addition to the five variables described previously, a good site characterization should include a history of the coast's evolution over time, for example (i) is the coast subject to accretion or erosion? If so, at what rate? (ii) Is the phenomenon occurring at a local (*e.g.,* hot spots) or regional scale? (iii) Are reasons given for the occurrence of the phenomenon? (*e.g.,* reduction of fluvial sediment inputs following the instalment of dams or presence updrift of structures that modify sediments' flux). Knowledge and use of the concept of sedimentary cells when choosing a protective structure or when setting up coastal infrastructure should also make it possible to better assess their impacts on the adjacent coastal zone, and determine whether they will generate coastal erosion and coastal flooding downstream of the littoral drift (Dolan *et al.*, 1987 ; Suanez, 2009).

2.6.2 Scientific knowledge in the decision-making process

Existing knowledge drawn from studies regarding the impact of CDMs on coastal socio-ecological systems can help improve the decision-making process. The greatest challenge is to find case studies conducted in similar geomorphological and hydrodynamic environments (*c.-à-d.,* with the same coastal type, sediment type, wave regime, tidal range and currents) in relation to different CDMs, to be used as a reference. Despite the large amount of study sites identified in this meta-analysis (*c.-à-d.,* 355), fulfilling all of these conditions appears to be difficult. Thus, uncertainties are introduced, due to the necessity to extrapolate the available data or dismiss one or more of the required conditions, which further complicate the decision-making process. This meta-analysis exposed the state of knowledge regarding coastal environments in which impacts of CDMs are studied. Knowledge gaps were identified in terms of the lack of studies on certain types of CDMs and coastal characteristics.

2.6.2.1 Geographical distribution in the literature inconsistent with risk levels and impact of climate change

The results of this meta-analysis show that the 355 study sites are not evenly distributed globally. Studies are mostly located in Europe, in the United States, and to a lesser extent in Australia. The lack of knowledge on CDMs is of particular concern for Africa and Asia considering the level of risk to coastal hazards in these regions. According to the study by Neumann et al. (2015), the five most populous countries in the world with coastal zones' elevation of less than 10 m (Low-elevation coastal zone, LECZ) are located in Asia. China, India, Bangladesh, Indonesia and Vietnam alone accounted for 56% of the global population living in the LECZ, and on the continent of Asia, 137 million people were living in the 100-year coastal flood zone (Neumann *et al.*, 2015). Demographic projections for the next decades indicate that Africa will be the continent that will record the highest rates of growth and urbanization in the LECZ (Neumann *et al.*, 2015). With the highest percentage of sandy coast in the world (67%), the coastline of the African continent is particularly vulnerable to coastal erosion where the net balance of coastal evolution between 1984 and 2016 was dominated by erosion (Luijendijk *et al.*, 2018). With the sea level rise projected for 2100, more than half of the world's sandy coasts will be severely affected by erosion, particularly in parts of the West African Coast, South Asia, Australia and Central America (Vousdoukas *et al.*, 2020). We can assume that in this context, the beach nourishment option will continue to be popular, at least in the short and medium term, in developed regions where the presence of tourists ensures an income that makes it an advantageous cost / benefit option (Hinkel *et al.*, 2013 ; Nicholls *et al.*, 2011). But this raises issues of equity for adaptation in developing regions where higher coastal risks, lower level of protection, and scarce local scientific knowledge on CDMs make it difficult to determine the most appropriate adaptation measures (Jurjonas et Seekamp, 2020 ; Siders, 2019 ; Siders et Keenan, 2020). It will therefore be essential to reduce this gap in scientific knowledge in the next decade. Without adaptation measures, Asia would be the hardest hit by population migration due to rising sea levels (Nicholls *et al.*, 2011). Port cities, which are often densely populated and where economic activity is significant, require measures to protect coastal infrastructures. The study by

Nicholls et al. (2007) on the exposure to coastal flooding of 136 large port cities around the world, shows once again that several of the largest port cities most exposed to extreme sea levels are located in Asia, notably in China, India, Bangladesh and Vietnam. By 2070, the 20 cities that will experience the greatest increase in the exposure of their population (> 250%) are all located in Asia (17) and Africa (3), in particular due to the growth of their population and urbanization in coastal areas (Nicholls *et al.*, 2007).

An absence of complete CDM studies in a Nordic climate context is also noticeable, given the fact that shorelines and permafrost coasts in cold regions occupy more than one third of the world's coastlines (Byrne et Dionne, 2002 ; Lantuit *et al.*, 2012). The effects of global warming, particularly significant in the north (IPCC, 2021), cause melting of the permafrost and an increase of the ice-free period duration, which will accelerate in the future, will lead to the retreat of the coastline (Manson et Solomon, 2007 ; Ogorodov *et al.*, 2020 ; Overeem *et al.*, 2011), and increase the frequency of coastal flooding events (Radosavljevic *et al.*, 2016). Melting permafrost causes landslides, mud flows and retrogressive thaw slump. In addition, the prolonged contact between water and cliff toe due to declining sea ice, increases the thermo-abrasion and risk of block collapse (Günther *et al.*, 2013 ; Lantuit *et al.*, 2013 ; Lantuit et Pollard, 2008). Some regions of the Arctic are already experiencing accelerated coastal erosion (Günther *et al.*, 2013 ; Jones *et al.*, 2009 ; Lantuit *et al.*, 2013). Some coastal communities are stuck between, on one side, terrestrial hazards such as avalanches and landslides, and on the other side, erosion and coastal flooding (Jaskólski *et al.*, 2018). Climate change is therefore causing damage to coastal communities' infrastructures, in some cases, leading to authorities being forced to relocate villages (McNamara et Des Combes, 2015 ; Shearer, 2012). Paradoxically, with the reduction in sea ice cover and the opening of the Seaway in the Arctic over a longer period, the development of port infrastructure for the exploitation of natural resources is increasing (Liu *et al.*, 2021 ; Pahl et Kaiser, 2018). Currently, rigid structures seem to be favoured as protective measures in the Arctic. Ice presents a considerable engineering challenge, as it can have a significant impact on the structural integrity of CDMs, particularly during storms when ice pushing against structures and ice pile-up overtopping can cause serious damages (Forbes *et al.*, 2004). In addition, in temperate and cold environments, plant biomass is at its minimum in the winter, during stormy periods. Ice generally mows low marsh plants every winter and may also restrict the extend of coastal marshes (Allard *et al.*, 1998). This has the effect of reducing the attenuation of wave energy by vegetation during the storm period (Schoutens *et al.*, 2019), and could therefore reduce the effectiveness of soft solutions including revegetation as a living shoreline approach. Studies will be necessary to assess the actual effectiveness of soft solutions in cold regions. Studies are needed, not only on the potential impacts of CDMs on communities, but also on coastal ecosystems, since marine biological resources are sources of subsistence food for several northern communities (Landauer et Juhola, 2019). In order to develop global adaptation strategies for northern coastal regions, considerable efforts will have to be made to improve knowledge on the application of different adaptation measures, with experimental tests, a rigorous environmental monitoring program, and the integration of traditional knowledge.

Globally, local governance can hinder the implementation of adaptative strategies with, for example, outdated regulation; short term funding for case studies, preventive strategies, monitoring and maintenance; non-participatory and site by site intervention strategies (Albert *et al.*, 2018 ; Manrique *et al.*, 2018 ; Sauvé *et al.*, 2020). Scientific knowledge and an adaptive governance approach can contribute to the development of effective adaptation strategies and to the improvement of existing ones in response to coastal hazards (Koontz *et al.*, 2015). Communities in lesser-known coastal environments have a lower adaptive capacity due to a lack of scientific knowledge and a higher degree of uncertainty in the CDM decision-making process (Allen *et al.*, 2011 ; Pahl-Wostl, 2009). The result of this meta-analysis clearly identifies knowledge gaps at an international level. On this basis, local governance should orient their future knowledge acquisition toward regions that have been neglected up until now. Also, as shown in tableau 25, CDM behavior monitoring and case studies are still made by discipline silos while it is shown that iInterdisciplinary collaborations and development of innovative solutions in complex contexts would go a long way to further the expertise in coastal environment and CDM behaviour (Morrison et al., 2018).

2.6.2.2 A need for a better representation of the diversity of coastal systems and better suited CDMs to support decision-making processes

Unconsolidated shores, mainly sandy shorelines such as beach terraces, barrier islands, dunes and spits dominate this meta-analysis. The importance of tourism and infrastructures, which contributes to the growth of the gross domestic product and have a positive impact on the local economy (Houston, 2013 ; Phillips et Jones, 2006 ; Pranzini *et al.*, 2015), explain in part the interest in studying and protecting such regions. These types of coasts occupy more than a third of the world's coastlines (Luijendijk *et al.*, 2018), and are also highly developed and densely populated (Kulp et Strauss, 2019 ; Merkens *et al.*, 2016). Because sandy low-lying coasts are particularly sensitive to erosion and coastal flooding, populations living in these regions are at high risk in a context of sea level rise (Kopp *et al.*, 2017 ; Muis *et al.*, 2016 ; Vitousek *et al.*, 2017 ; Vousdoukas *et al.*, 2020). These factors also explain that knowledge of defence measures used in these areas (*i.e.* beach nourishment, breakwater, groin, and seawall) is fairly advanced compared to CDMs used to protect other types of coasts such as rocky shores, salt marshes and unconsolidated or rocky cliffs. The lack of interest in studying CDMs for the latter types of coasts, especially for rocky shores and rocky cliffs may be due to their better resistance to damage caused by wave energy. With only one study retained according to the criteria of our meta-analysis, it is surprising that unconsolidated sediment cliffs have not been the subject of more CDMs studies because these environments are subject to several erosion processes and modes of retreat (Bernatchez et Dubois, 2004), among others, basal undermining by waves, landslides, clay flows, suffosion and thermo-abrasion; they therefore present a high risk for populations in several regions of the world (Haque *et al.*, 2016, 2019). As for cliffs, due to the complexity of erosion processes and recession modes, expert judgment-based approaches combined with probabilistic prediction methods and modelling of the recession process should be used for the selection of adaptation solutions (Castedo *et al.*, 2012 ; Hackney *et al.*, 2013 ; Lee *et al.*, 2001 ; Walkden et Hall, 2005).

Salt marshes, formed in the intertidal zone of sheltered coasts, are more sensitive to the long-term sea level rise and sediment budget (Craft *et al.*, 2009), but can also be affected by storms and washover sediments along backbarrier marshes and spits (Leonardi *et al.*, 2018 ; Schuerch *et al.*, 2018). Yet salt marshes are nowadays recognized as key ecosystems providing many goods and services for the society (McLeod *et al.*, 2011 ; Perillo *et al.*, 2019). Healthy salt marshes attenuate wave energy, thus reducing the risk of coastal flooding during storms (Gedan *et al.*, 2011 ; Zhu *et al.*, 2020), as well as the chance of breaching and impacting hard structures (Zhu *et al.*, 2020). In the long term, the greater the width of the marsh, the greater its capacity to attenuate wave energy (Willemsen *et al.*, 2020). The reduction of wave loads on hard structures by vegetated salt marshes should also enable the use of lower crested structures, reduce maintenance costs, and increase the lifespan of protective structures (Vuik *et al.*, 2016, 2019). However, in coastal marshes, studies have mainly focused on seawalls and rock armour, whereas these structures can reduce the resilience of marshes to absorb wave energy. Hard rigid structures can constitute a barrier to the movement of organisms (Gehman *et al.*, 2017) or to the distribution of larvae, reduce access to nurseries formed by marshes (Hendon *et al.*, 2000), reduce the taxon richness of biological resources (Morley *et al.*, 2012), and have negative repercussions on benthic infauna that can be felt up to subtidal habitats (Seitz *et al.*, 2006). Understanding the potential effects of CDMs in these ecosystems should thus not be neglected in order to preserve that valuable resource. Nature-based solutions for coastal protection such as the Living Shoreline Approach have been particularly popular over the past decade (Bilkovic *et al.*, 2017b ; Smith *et al.*, 2020). This approach aims in particular at transplanting shoreline vegetation with or without low rock sills (Currin *et al.*, 2010), in order to reduce coastal erosion (Polk *et al.*, 2021 ; Polk et Eulie, 2018), and increase community resilience to storms (Smith *et al.*, 2018). However, the use of this approach remains rare along urbanized areas (Scyphers *et al.*, 2020), even if, in some regions, an increase in requests for permits for this type of solution has been observed in recent years (Stafford et Guthrie, 2020).

Considering that the level of wave energy attenuation through marshes can vary seasonally due to the phenology of the plants, and also according to their physiological traits, it is important to increase the effectiveness of nature-based shoreline protection to have a strategy that will include both the tidal flat and the lower and upper marshes (Schoutens *et al.*, 2019, 2020). A better knowledge of the vegetal and geomorphological characteristics of the intertidal zone, and of its temporal evolution can reduce the uncertainties in the level of protection of nature-based flood defences (Vuik *et al.*, 2018). Decision-makers could thus be more inclined to opt for a hybrid defence solution including revegetation of the intertidal zone instead of traditionally engineered solutions since it allows immediate protection while promoting ecological benefits. However, the expertise and knowledge to design this type of approach is still limited (Sutton-Grier *et al.*, 2015). Due to a lack of knowledge of their effectiveness, costs and benefits, hybrid and natural options may be overlooked during cost benefit analysis, in favour of traditional hard structures for which the cost-benefits are better documented (Sutton-Grier *et al.*, 2015).

The number of study sites related to each CDM varies widely, but the prominence of studies on beach nourishments, seawalls and breakwaters has been made clear. Beach nourishment is being studied with increasing frequency, as it represents a soft and more natural alternative to rigid structures, such as seawalls or rock armour. Still, it is not without ecological consequences, as its higher maintenance requirements generate recurring perturbations to the ecosystems (Speybroeck *et al.*, 2006). This may prove to be more expensive in the long run; as well, the financial support necessary for maintenance may be difficult to obtain. On the other hand, seawalls, which are prominent in many European countries (Pranzini *et al.*, 2015), are hard structures known to be detrimental when implemented on the wrong type of coast (Basco, 2006 ; Gittman *et al.*, 2015 ; Kraus et McDougal, 1996 ; Ruggiero, 2009), but they are also perceived by local communities as the most efficient and safest CDMs to date (Friesinger et Bernatchez, 2010 ; Sauvé *et al.*, 2020). Breakwaters can also be a good, well-known alternative to reflective structures. Still, they must be effectively designed to avoid negative effects (Dally et Pope, 1986 ; Pope et Dean, 1987). The number of studies on the geomorphological effects of rock armour revetments is surprisingly low, given how frequently they are being implemented in Europe (Pranzini *et al.*, 2015) and in Canada (Sauvé *et al.*, 2020). Other CDMs, which may be appropriate depending on the site of implementation, are underrepresented. Case studies on rip-rap effects are almost absent from the literature. A considerable amount of research on dikes is available, but it is mostly related to the overtopping processes, rather than the impacts of dikes on coastal socio-ecological systems. Thus, to improve scientific knowledge so as to make it useful for the decision-making process, future research should be based on a better coastal system characterization (coastal and sediment types, tidal, waves and currents characteristics, as well as historical evolution of the coasts), and a greater diversity in the types of coasts and CDMs subject to evaluation.

The meta-analysis showed that, regardless of the type of coast or CDM, the geomorphological effects have been studied most frequently. This result is coherent with the fact that in the majority of coastal protection plans, the main objective is to limit or stop the erosion process. Knowledge of the ecological effects of some of the CDMs is also fairly advanced, for instance, in the case of beach nourishment, seawalls, breakwaters and rock armour. Nowadays, the obtention of CDMs' construction permits is often conditional upon approval of an environmental impact assessment and, depending on the results, on the implementation of environmental compensatory measures. Therefore, engineering firms are required with increasing frequency, to study the effects of CDMs on the ecological system, not only during the decision-making process, but also once the project is finished. It also seems easier to obtain a permit for conventional rigid structures than for nature-based and hybrid approaches (Sutton-Grier *et al.*, 2015). Hydrodynamics effects are less frequently studied, as demonstrated in our meta-analysis, by the fact that characterization of wave energy, tidal range, and currents is scarcer than geomorphological characterization. Still, the influence of a CDM on local hydrodynamic conditions has direct repercussions on geomorphological and ecological aspects. A better understanding of that influence would contribute to improving the knowledge of the geomorphological, ecological and social aspects of ecosystems. Finally, there are few studies regarding the repercussions of CDMs on the social aspect of ecosystems, and scientific knowledge is scarce, though estimations can be made through extrapolations from geomorphological, hydrodynamics or ecological effects. A greater knowledge and integration of ecological services during the process of identifying adaptation solutions would not only allow for a more accurate assessment of their sociocultural effects, but would also help decision-makers identify solutions that are more suited to the specific coastal socio-ecological conditions (Jacob *et al.*, 2021).

2.7 CONCLUSION

The literature review and meta-analysis of 355 study sites from 301 publications on coastal defence measures (CDMs) revealed a number of strengths and weaknesses in the scientific knowledge, and in the information that is currently available. While 5 variables (coastal type, sediment type, wave characteristics, tidal range, and currents or sediment transport characteristics) are typically used to characterize the physical environment of a study site, less than 4% of the studies included a complete characterization using the 5 variables. Coastal and sediment types are the variables most often identified in about 75% of the cases, while information concerning wave climate, tidal range and currents is much scarcer. A complete characterisation by the monitoring of those variables would improve the comparison between sites, improve the scientific knowledge related to the effects of a variety of CDMs on different coastal environments, and help enhance the CDM choice and design. Globally, more specific information would give a better indication of the long-term evolution of the coast and the erosion process of the study site. For instance, a better characterisation of sediment type would give information on its susceptibility to re-suspension and transport by hydro or aerodynamic process. With regard to cliffs, the lithology is important because it determines the resistance to erosion and the mode of retreat. More specific details on significant wave height are also important as it is generally used as the statistical basis for the design of a CDM. Wave characterisation combined with tidal range is used to calculate the total water level, extreme wave run-up, and overtopping processes during storm events. Information on currents is fundamental to the design process as some CDMs lead directly to their alteration, and can significantly affect the prevailing geomorphological and ecological conditions. Moreover, study sites' characterization could be improved by the addition of ecological and social variables, as well as information regarding coastal dynamics, erosion process and extreme total water level.

Knowledge gaps were identified in terms of the lack of studies in some countries, types of CDMs and coastal characteristics. The 355 study sites are mostly located in Europe, in the United States and in Australia, while the lack of knowledge on CDMs is of particular concern for Africa and Asia where a large human presence occupies regions of high risk to coastal hazards. Moreover, an absence of study sites in northern climates is noticeable. While the ice cover is expected to decrease and cause shoreline retreat in the next decades, ice pressure and ice pile-up overtopping structures are also of concern, and a particular challenge to coastal engineers.

Of the ten different types of CDMs identified in the studies, three stand out as the most frequently studied since the 1990s: beach nourishments, seawalls, and breakwaters, with respective cumulative studies of 164, 67, and 50, as of 2019. Generally, about 60% of the CDMs were studied in the context of unconsolidated low shore. This may be explained by the fact that, while being particularly sensitive to erosion and coastal flooding, these types of coasts attract high density population and economic development. Meanwhile, the lack of interest in studying CDMs in relation to other types of coasts, especially rocky shores and rocky cliffs, may be due to their resistance to damage caused by wave energy.

Addressing the gaps that were identified in this meta-analysis is crucial in order for the decision-makers to be able to find long-term solutions that are best adapted to specific environments, and can effectively mitigate future threats. Studies in Nordic regions, in Africa and Asia are necessary, as are studies on CDMs other than beach nourishments, seawalls, and breakwaters, and on types of coast other than unconsolidated shores. A thorough and standardized characterisation of physical features is also essential to the understanding of the long-term evolution of the shoreline.

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CHAPITRE 3

IDENTIFICATION D'OUVRAGES DE PROTECTION CÔTIÈRE LES MIEUX ADAPTÉS POUR LA RÉDUCTION DES RISQUES DANS DES SYSTÈMES CÔTIERS SPÉCIFIQUES : DÉVELOPPEMENT D'UNE MÉTHODE DE MÉTA-ANALYSE DYNAMIQUE DE LA LITTÉRATURE

3.1 RÉSUMÉ EN FRANÇAIS DU TROISIÈME ARTICLE

Le processus décisionnel sur les ouvrages de protection côtière (OPC) est complexe et contient plusieurs sources d'incertitude en raison des interactions spécifiques à chaque site entre les composantes géomorphologiques et hydrodynamiques qui ont des répercussions sur les aspects écologiques et sociaux. Les connaissances scientifiques sur les effets des OPC et les données qui en découlent peuvent être traitées de manière à réduire l'incertitude inhérente au processus décisionnel et à les rendre utiles pour les décideurs. L'objectif de cet article est de présenter le développement d'un algorithme conçu pour évaluer et hiérarchiser des OPC en fonction de leurs effets sur les différents types d'environnements côtiers. Basé sur des publications scientifiques contenant 411 études de cas, un total de 1709 énoncés relatifs aux effets des OPC tels qu'observés par les auteurs sur les caractéristiques environnementales de secteurs d'étude (type de côte et de substrat, marnage et climat de vagues) ont été entrés dans une base de données, catégorisés, puis pondérés selon une échelle qualitative (-5 à 5). L'utilisateur sélectionne des OPC ainsi que des caractéristiques environnementales (type de côte et de substrat, marnage et climat de vagues). Puis, l'algorithme traite l'information en établissant une correspondance entre les caractéristiques environnementales sélectionnées et celles enregistrées dans la base de données afin d'évaluer les OPC en identifiant, compilant et classant les effets observés dans des contextes environnementaux similaires. Le résultat est un outil qui permet de traiter, de structurer et de concrétiser les connaissances scientifiques en lien avec les effets des OPC sur le système côtier. Cet outil est un complément aux outils d'analyse couramment utilisés dans le processus décisionnel et de conception d'un OPC. Les résultats de l'algorithme présentent la hiérarchisation des OPC selon une structure d'agrégation à plusieurs niveaux qui peut être utilisée par les gestionnaires, les décideurs et les ingénieurs côtiers. L'algorithme, basé sur des caractéristiques environnementales standardisées (type de côte et de substrat, marnage et climat de vagues), peut être appliqué à l'ensemble des côtes à l'échelle mondiale.

Cet article, intitulé « *Identification of coastal defence measures best adapted to mitigate hazards in specific coastal systems: development of a dynamic literature meta-analysis methodology* », a été corédigé par moi et mes deux directeurs, Pascal Bernatchez et Mathias Glaus. Il a été publié dans le journal *Journal of Marine Science and Engineering* en mars 2022. En tant que premier auteur, ma contribution fut de réaliser la majeure partie de la recherche sur l'état des connaissances, la structuration de la base de données, la revue de littérature sur les effets des OPC, la compilation et la pondération des énoncés d'effets observés par les auteurs, le développement de l'algorithme d'identification d'OPC, l'analyse des résultats de l'algorithme ainsi que la rédaction de l'article. En tant que second auteur, Pascal Bernatchez a contribué à la réflexion sur la structure de l'algorithme, à l'analyse des données, à la rédaction et à la révision de l'article. En tant que troisième auteur, Mathias Glaus a contribué à la réflexion sur la structure de l'algorithme, à l'analyse des données ainsi qu'à la rédaction et à la révision de l'article. Sophie Moisset et Marc-Olivier Goudreault ont contribué à la revue de littérature et à la compilation des données. Sophie Moisset a également contribué à la pondération des énoncés d'effets observés. Marie-Andrée Roy et Maude Corriveau ont contribué à la structuration de la base de données.

3.2 IDENTIFICATION OF COASTAL DEFENCE MEASURES BEST ADAPTED TO MITIGATE HAZARDS IN SPECIFIC COASTAL SYSTEMS: DEVELOPMENT OF A DYNAMIC LITERATURE META-ANALYSIS METHODOLOGY

ABSTRACT

The decision-making process of the coastal defence measures (CDMs) is complex and filled with uncertainties due to site-specific interactions between hydrodynamic and geomorphological conditions, which have repercussions on the ecological and social aspects of coastal communities. Scientific knowledge of the effects of CDMs contributes to the reduction in inherent uncertainties and facilitates the decision-making and design processes. The goal of this article is to present an algorithm designed to evaluate and hierarchize CDMs in relation to different coastal environments. Drawn from 411 published scientific case studies, a total of 1709 authors' observation statements regarding the effects of CDMs on the study sites' environmental features (type of coast, type of substrate, tidal range, and wave climate) were entered in a database, categorized, and weighted according to a qualitative scale. The algorithm processes the information by establishing a correspondence between user-selected environment features and those stocked in the database, and it evaluates user-selected CDMs in relation to the specified coastal characteristics by identifying, collating, and rating the effects as observed in similar contexts. The result is a tool able to process, structure, and concretize scientific knowledge regarding CDMs and their effects on coastal systems. It is complementary to existing tools currently used in the decision-making and design processes of the CDMs. The results present the hierarchization of CDMs according to a multilevel aggregated structure, which can be used in different ways by coastal managers, decision-makers, and engineers. The algorithm, based on standardized coastal characteristics, can be applied to any shoreline worldwide.

Keywords: coastal engineering; coastal protection; coastal defence measures; decision-making process; coastal erosion; integrated coastal zone management; CDMIA

3.3 INTRODUCTION

Coastal systems are affected by coastal hazards such as erosion, flooding, and landslides. Coastal defence measures (CDMs) have been implemented to mitigate these hazards since the establishment of human societies along shorelines (Charlier *et al.*, 2005). However, coastal erosion and flooding have been exacerbated in recent decades by the effects of climate change, sea-level rise (Church et White, 2011 ; Nicholls et Cazenave, 2010 ; Ranasinghe, 2016 ; Wong *et al.*, 2014), and anthropogenic activities (Dafforn *et al.*, 2015 ; Manno *et al.*, 2016 ; Vousdoukas *et al.*, 2020), which have led to an increase in shoreline armouring worldwide (Dugan *et al.*, 2011 ; Gittman *et al.*, 2015 ; Horstman *et al.*, 2009b ; Sauvé *et al.*, 2020).

The dynamics of coastal systems consist of multi-scale, non-linear processes, resulting from the interaction between hydrodynamic and morphological conditions (Baquerizo et Losada, 2008), which have feedback effects on ecosystems and on the social aspects of coastal communities (Polasky *et al.*, 2011). Historically, hard reflective coastal defence structures have been implemented on shorelines without consideration for coastal dynamics and with potentially negative environmental impacts (Airoldi *et al.*, 2005 ; Bernatchez *et al.*, 2011 ; Dugan *et al.*, 2011 ; Martin *et al.*, 2005 ; Moschella *et al.*, 2005). The selection of this type of CDM can be explained by a lack of knowledge regarding coastal dynamics and a lack of tools available to make sound decisions (Betzold et Mohamed, 2017 ; Bruun, 1988 ; Fraser *et al.*, 2017 ; Huang et Ells, 2020 ; Marie *et al.*, 2017 ; Sauvé *et al.*, 2020). In addition, the effect of climate change on coastal systems renders their behaviour more difficult to predict and increases the uncertainty of their analysis (Baquerizo et Losada, 2008 ; Barzehkar *et al.*, 2021b ; Polasky *et al.*, 2011). In general, integration of the most current scientific knowledge into coastal management approaches tends to be slow (Baquerizo et Losada, 2008). However, given the unpredictability brought on by climate change, such knowledge is becoming more and more critical and can greatly contribute to the integrality of the CDM decision-making process by reducing inherent uncertainties (Polasky *et al.*, 2011).

The data acquisition methods and tools already in use, such as field measurements and analysis, physical and numerical modelling, and decision-support tools, provide important information to the planification process and design of CDMs (Barzehkar *et al.*, 2021b ; USACE, 2006a). Currently, the design of CDMs is mostly based on the technical aspects meant to solve shoreline retreat issues, rather than on a complete analysis of the effects of CDMs on the socio-ecological system (Sauvé *et al.*, 2020). Generally, scientific information regarding the effects of CDMs is integrated into the planification or design process in the form of a brief pros and cons lists. Still, to the authors' knowledge, a tool with the capacity to directly and efficiently integrate scientific knowledge of the effects of CDMs into the evaluation process is not currently available. Scientific knowledge regarding the effects of CDMs remains unbalanced as the majority of case studies have been conducted on beach nourishment, seawalls, and breakwaters, mainly in a context of low-lying sandy coasts (Sauvé *et al.*, s. d.). Thus, there is a need for the development of a tool that is flexible enough to allow easy integration of new scientific data as they become available, to allow the data to be structured in a way that is useful to the direct evaluation of CDMs, and to allow variations in the environmental features between the implementation sites and the case studies.

Based on a literature review of case study publications regarding the effects of coastal defence measures (CDMs) on coastal systems, the purpose of this article is to present the development of an algorithm capable of conducting a dynamic meta-analysis of relevant publications and forming a qualitative synthesis to be used in the CDM decision-making process. The idea is to use this algorithm for the purpose of the characterization and pre-analysis of CDMs in relation to different coastal contexts. More specifically, the sub-objectives are (1) to extract and store in a database information regarding CDMs and their effects on the coastal system, as well as the physical characteristics of the environment in which the case studies were carried out and (2) to aggregate these observed effects based on systemic indicators and a qualitative rating scale. The algorithm should therefore make it possible to identify and hierarchize CDMs with the lowest impact on specified coastal systems.

3.4 METHODS

The coastal defence measure identification algorithm (CDMIA) is developed to (1) conduct a dynamic meta-analysis of the effects of CDMs on coastal systems, (2) centralize and structure the existing scientific knowledge drawn from published studies, (3) evaluate, compare, and rank CDMs in different environmental contexts, and (4) yield useful information to support the decision-making process. A graphical synthesis of the CDMIA is presented in figure 13. First, the CDMIA is based on the evaluation of the authors' observation statements of the effects of CDMs (figure 14). Second, the user selects from a pre-established list the relevant environmental features and CDMs to be evaluated. Third, the CDMIA is executed in three consecutive steps leading to the evaluation and ranking of the CDMs.

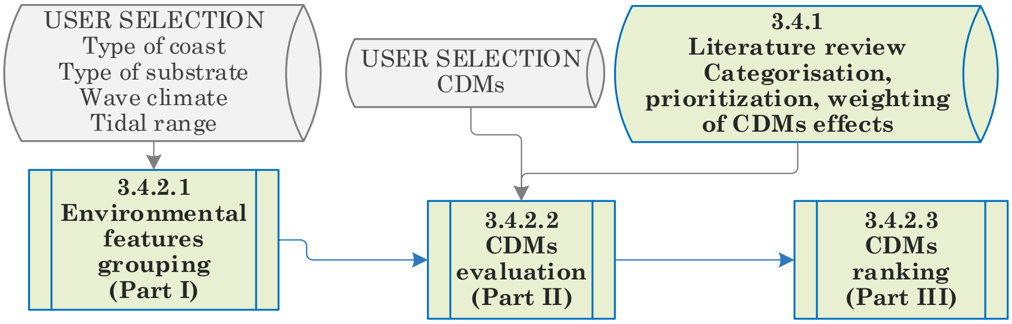


Figure 13. Graphical synthesis of the CDMIA

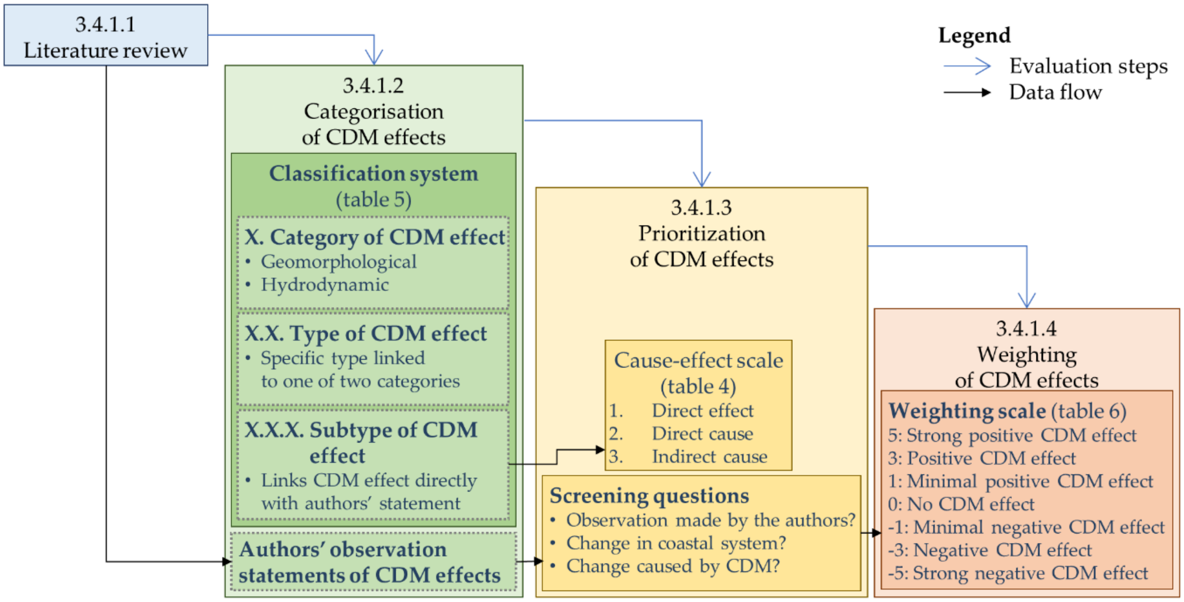


Figure 14. Logical schema for the evaluation of authors' observation statements of the effects of CDMs

3.4.1 Evaluation of Authors' Observation Statements of the effects of CDMs

The evaluation of CDM effects is based on (1) a literature review, (2) the categorization of CDM effects, (3) the prioritization of observed CDM effects at the subtype level, and (4) the weighting of the CDM effects statements (Figure 2). The first version of the CDM identification algorithm (CDMIA) has the capacity to evaluate CDMs according to their geomorphological and hydrodynamic effects. The CDMIA was developed with the possibility of integrating plugins in order to add further extension modules and allow the evaluation of CDMs according to their ecological and social effects as well. Modules evaluating the ecological and social effects will be included in a future version of the CDMIA.

3.4.1.1 Literature Review

The methodology employed for the literature review is based on research conducted via Scopus, Web of Science, and Google scholar and was limited to CDM studies dated between 1970 and 2019, inclusively. CDMs are coastal adaptation measures implemented to limit or prevent coastal erosion, flooding, or landslides. The CDM categories included in the meta-analysis are presented and described in tableau 26.

Tableau 26

Definition of coastal defence measure categories included in the rigid structure category integrated into the meta-analysis (**category**, subcategory, *type*)

CDM Category	Definition	Subtype
1.0 Rigid structure	Rigid structures are CDMs made of rigid materials, such as stones, concrete, wood, or steel, to dissipate waves or current energy. They are designed to maintain or consolidate specific coastal areas.	
1.1 Reflective structure	A CDM category whose components are built on, and parallel to, the shoreline whose purpose is to maintain the coastline in a fixed location (Dugan *et al.*, 2011 ; Griggs et Fulton-Bennett, 1988 ; Kraus, 1988 ; USACE, 2006a). The name of the category came from its effect of reflecting the incident wave energy.	
1.1.1 Rock armour	Structure mainly made of stone blocks, prefabricated concrete units, etc., covering the slope of a natural shoreline, an embankment or a dike (CIRIA *et al.*, 2007 ; USACE, 2006a).	• Revetment • Enrockment
1.1.2 Seawall	Structure mainly made of concrete, wood, steel, tires, etc., built vertically or with a steep slope (Burcharth et Steven, 2003 ; Kraus et McDougal, 1996).	
1.2 Other hard engineering	CDMs whose components do not have the same objectives or effects on coastal dynamics as reflective structures	
1.2.1 Breakwater	Sloped structure built offshore, parallel to the shoreline, and mainly made of stone blocks. Its purpose is to attenuate wave energy offshore and cause sediment to be deposited between the structure and the shoreline. (Bertasi *et al.*, 2007 ; Chasten *et al.*, 1993 ; Dally et Pope, 1986 ; Dugan *et al.*, 2011 ; Jackson *et al.*, 2015 ; Nordstrom, 2014 ; USACE, 2006c ; Van Rijn, 2011).	• Emerged breakwater • Low-crested structure • Submerged breakwater • Sill • Headland breakwater
1.2.2 Groin	Structure built on the foreshore, perpendicular to the shoreline, mainly made of wood or stone whose purpose is to capture sediment carried by longshore currents (Balsillie et Berg, 1972 ; Basco et Pope, 2004 ; Kraus *et al.*, 1994 ; Rankin *et al.*, 2004 ; Trampeneau *et al.*, 2004).	• Permeable groin • Impermeable groin
1.2.3 Dike	Alongshore embankment implemented on the backshore and generally composed of compacted soil. Dikes are mainly designed to prevent coastal flooding. They can be covered by rock armour or other types of revetments.	
1.2.4 Rip-rap	Gently sloping structure composed of coarse sedimentary material, usually the size of pebbles and small blocks (62–300 mm), deposited on the shore to stabilize its profile and hold the material in place.	• Rip-rap

Tableau 25 (suite)

Definition of coastal defence measure included in the soft techniques category integrated into the meta-analysis (**category**, subcategory, *type*)

CDM Category	Definition	Subtype
2.0 Soft techniques	Soft techniques are flexible means of shoreline remediation that act on the sediment budget by adding sediments or using vegetation techniques to retain it.	
2.1 Beach nourishment	A CDM built from the deposition of borrow sediment on a beach with the purpose of reprofiling sections of it to increase its wave energy dissipation capacity and its width and to rebalance the sediment budget within the sediment cell. A beach nourishment is located on specific areas of the beach: dune, beach, shoreface, nearshore (Campbell et Benedet, 2006 ; Dean, 2002 ; Hamm *et al.*, 2002 ; Hanson *et al.*, 2002).	• Dune nourishment • Shore nourishment • Nearshore nourishment • Shoreface nourishment • Mega-nourishment
2.2 Sediment trapping	A CDM implemented on sandy coasts, usually dunes, used to control wind erosion by obstructing the wind close to the ground and to create areas conducive to sand deposition (Li et Sherman, 2015). Sand fencing is a common technique for sediment trapping made of wooden slats joined by a wire (Gouguet, 2018 ; Grafals-Soto et Nordstrom, 2009 ; Khalil, 2008).	• Sand fence
2.3 Vegetation addition	Planting of vegetation adapted to the dynamics of the site in areas where the vegetation is fragmented, sparse, or absent (Bouma *et al.*, 2014). This technique is not subject to engineering design.	• Vegetation
2.4 Beach drainage system	A CDM implemented below the surface of sandy beaches, used to drain the beach. The aim is to reduce cross-shore sediment transport (Ciavola *et al.*, 2011).	• Vertical drainage • Horizontal drainage

A three-level screening process was used to select relevant publications:

1. Step 1: Case studies were exclusively selected from field measurements and analysis and numerical and physical models.
2. Step 2: Articles selected in step 1 were screened out when they did not evaluate one or more of the following CDM effects: geomorphological or hydrodynamic.
3. Step 3: The remaining articles were retained only if they responded positively to all of the three following questions: (1) does the article include observations made directly by the authors (i.e., with original data)? (2) If so, do the observations indicate changes to the coastal system relative to a baseline condition? (3) If so, were the changes caused by a CDM?

A total of 411 publications were retained; they contained 1709 statements of observed CDM effects (supplementary S1). Information was extracted from the selected publications and organized in the database using three levels (tableau 27).

Tableau 27

Structure of the database which contains the information extracted from each of the selected publications

Level 1: Publication details Authors, title, year of publication, and journal
Level 2: Environmental characteristics of study sites * Country, region, location, coastal type, sediment type, tidal range, waves, and current characteristics
Level 3: Observed CDM effects Type of CDM subject to study, authors' observations statements of the CDMs effects, type of CDM effects based on authors' observation (used to classify CDM effects), and categorization of CDM effect type (geomorphological or hydrodynamic)

* If an article included more than one study site, each was entered individually in level 2.

The environmental characteristics, as described by the authors of the study sites (level 2), were homogenized using adapted classification systems (tableau 28). The currents were not classified, due to the scarcity and disparity of information.

Tableau 28

Classification systems used to homogenize four types of study site environmental features, as described by the authors in scientific publications. These four types are used in the algorithm as base variables to evaluate CDMs according to different coastal systems

Type of coast
Littoral spit, beach terrace, barrier island, welded barrier/tombolo, dune, unconsolidated cliff, salt marsh, and rocky cliff. Adapted from the work of Bird (2008), Davidson-Arnott (2010), and Davis and Fitzgerald (2020).
Type of substrate
Clay (0.001–0.004 mm), silt (0.004–0.063 mm), sand (0.063–2 mm), gravel (2–64 mm), cobbles (64–256 mm), and boulders (>256 mm). Based on the Friedman and Sanders size scale (Friedman et Sanders, 1978) for unconsolidated sediments.
Wave characteristics
Low energy (<1 m), moderate energy (1–2 m), and high energy (>2 m).
Tidal range
Tideless (0 m), microtidal (<2 m), mesotidal (2–4 m), macrotidal (>4 m), and megatidal (>8 m). Adapted from the Davies' shoreline classification system (Davies, 1964) and the work of Levoy et al. (Levoy *et al.*, 2000) (2000).

3.4.1.2 Categorization of CDM Effects

A three-level classification system for CDM effects (category, type, and subtype) was developed to facilitate the analysis of the authors' observation statements in the database. The first level allows a sorting under one of two categories, either geomorphological or hydrodynamic. The second level allows the grouping of statements according to a broad type of observed effect. The third level links the specific CDM effect directly with the authors' statement. The categorized CDM effects used in the analysis are presented in tableau 29 (columns entitled *CDM* effect categorization and Description).

3.4.1.3 Prioritization of CDM Effects at the Subtype Level

The CDM effect subtypes are classified in a priority order based on a three-level cause–effect scale: direct effect, direct cause, and indirect cause (tableau 29). This scale is added to tableau 30 (column entitled Level on the cause–effect scale and justification). Level 1 corresponds to the observation of the direct effect of a CDM on coastal erosion or accretion. Direct effects are prioritized as they are related to the observation of a tangible change in coastal erosion or the accretion processes which the implementation of a CDM is meant to control. Level 2 corresponds to the observation of a phenomenon that leads to coastal erosion or accretion. Direct causes are classified in second order as they lead to processes that can cause coastal erosion or accretion but are not the main intended effect related to the implementation of a CDM. Still, CDMs, such as breakwater or groin, can be implemented to control the process at that level. Level 3 corresponds to the observation of a phenomenon that indirectly causes coastal erosion or accretion. Indirect causes are classified in third order as they lead to processes that can indirectly cause coastal erosion or accretion.

Tableau 29

Cause–effect scale for the prioritization of CDM effects at the subtype level

Level		Definition
1	Direct effect	Observation directly related to coastal erosion or accretion
2	Direct cause	Observation of a phenomenon causing coastal erosion or accretion
3	Indirect cause	Observation of a phenomenon that indirectly causes coastal erosion or accretion

Tableau 30

Categorization system (category, type, subtype) and prioritization of CDM effects (geomorphological category)

CDM Effect Categorization	Description	Level on the Cause–Effect Scale and Justification
1. Geomorphological		
1.1. Erosion/Accretion		
1.1.1. Accretion	Sediment deposition	**Direct effect** (level 1) Direct observation of coastal erosion or accretion
1.1.2. Scouring	Erosion at the foot of a CDM	
1.1.3. Sediment budget	Summation of the sediment volume supplied and lost to a coastal compartment in a defined period	
1.1.4. Shoreline movement	Retreat or advance of the shoreline	
1.1.5. Flanking	Erosion of the unprotected beach adjacent to the end of a CDM	
1.1.6. Erosion	Observation of erosion in general without mention of specific form of erosion	
1.1.7. Beach height	Variation in beach level	
1.1.8. Beach width	Variation in beach width	
1.1.9. Geomorphological recovery	Interference on the natural erosion and accretion cycle of the beach	
1.1.10. Sediment retention	Interference of hydrodynamic conditions leading to successive accretion and erosion zones	
1.2. Topo-bathymetry profile		
1.2.1. Beach profile	Variation in beach slope or equilibrium profile	**Indirect cause** (level 3) Underwater sediment movement caused by a change in hydrodynamic conditions
1.2.2. Bar system	Formation or disappearance of bars	
1.2.3. Topography	General elevation of the coast	
1.2.4. General variation in bathymetry	Modification of the bathymetry in general	
1.2.5. Localized variation in bathymetry	Underwater local formation of a trough or mound	
1.3. Sediment transport		
1.3.1. Sediment dispersion	Modification resulting in the dispersion of sediments	**Direct cause** (level 2) Interception of sediment supply is a cause of erosion
1.3.2. Longshore transport	Modification of longshore transport	
1.3.3. General sediment transport	Modification of sediment transport in general without mention of sediment dispersion, longshore, or cross-shore transport	
1.3.4. Cross-shore transport	Modification of cross-shore transport	

Tableau 29 (suite)

Categorization system (category, type, subtype) and prioritization of CDM effects (hydrodynamic category)

CDM Effect Categorization	Description	Level on the Cause–Effect Scale and Justification
2. Hydrodynamic		
2.1. Wave properties		
2.1.1. Wave angle	Modification of wave angle	**Direct cause** (level 2) A change in the wave angle of incidence and intensification of obliquely incident wave attack are causes of beach erosion
2.1.2. Wave properties	General modifications of wave properties	
2.2. Current		
2.2.1. Water circulation	General modification of water circulation (eddy current, circular current, etc.)	**Indirect cause** (level 3) Currents are causes of sediment transport which is a direct cause of erosion.
2.2.2. Cross-shore current	Modification of cross-shore current	
2.2.3. Longshore current	Modification of longshore current	
2.2.4. Rip current	Creation or modification of rip current	
2.3. Underground water		
2.3.1. Thickness of the unsaturated beach layer	Modification of the thickness of the unsaturated beach layer	**Direct cause** (level 2) A rise in beach water table is a cause of erosion.
2.3.2. Infiltration/Percolation	Modification of the infiltration or percolation of water on the beach surface	
2.3.3. Water table level	Modification of the water table level	
2.4. Run-up process		
2.4.1. Backwash/Swash	Modification of wave backwash or swash	**Direct cause** (level 2) Modification of wave dissipation on the beach resulting in sediment transport.
2.4.2. Overtopping	Overtopping of a CDM	
2.4.3. Run-up	Modification of wave run-up	
2.5. Dissipation process		
2.5.1. Breaking	Modification of wave breaking process	**Direct cause** (level 2) Increased wave energy and wave reflection are causes of erosion
2.5.2. Diffraction	Modification of wave diffraction	
2.5.3. Wave energy	General modification of wave energy dissipation	
2.5.4. Wave height	Modification of wave height	
2.5.5. Reflection	Modification of wave reflection	
2.5.6. Transmission	Modification of wave transmission	
2.5.7. Refraction	Modification of wave refraction	**Indirect cause** (level 3) Refraction results from change to bathymetry (direct cause)

3.4.1.4 Weighting of Authors' Observation Statements

The significance of the CDM effects, as observed by the authors in the scientific literature, was evaluated using a weighting scale. As the majority of the authors' observations present in the scientific literature are qualitative, the weighting scale is a qualitative scale from strong negative (−5) to strong positive (+5) (tableau 31). Where quantitative results were provided in the observation statement, a ratio was established, and the quantitative value was transposed into the qualitative scale (tableau 35, third column). The quantitative ratio is related to the percentage of change observed by an author or by an estimation of the change based on the data presented in a publication.

Tableau 31

Weighting scale used for the evaluation of authors' observation statements

Level	Description	Quantitative Ratio	Authors' Observation Statement Examples
5	Strong positive CDM effect based on amplifying terms or a mention of long-term effect	>70%	Efficiently traps sediment (Aminti *et al.*, 2004); significant sand accumulation (Wang et Kraus, 2004); long-term build up of sediment (Barnard *et al.*, 2009)
3	Positive CDM effect	>40 ≤ 70%	Wave height transmission […] was approximately 0.5 (Turner *et al.*, 2001); Control […] the wave-induced circulation pattern (Cáceres *et al.*, 2005b)
1	Minimal positive CDM effect based on limiting terms or a statement associated with a trend	>10 ≤ 40%	Tends to cause accumulation (Martin *et al.*, 2005); covered by a thick layer of sediment (Vaselli *et al.*, 2008)
0	No CDM effect	−10 to 10%	No tendency to form salient was observed (Martinelli *et al.*, s. d.)
−1	Minimal negative CDM effect based on limiting terms or a statement associated with a trend	<−10 ≥ −40%	Minimizing the downdrift erosion associated with the groin (Wang et Kraus, 2004)
−3	Negative CDM effect	<−41 ≥ −70%	Erosion of the beaches (Bernatchez et Fraser, 2012); lowered elevation of the beach toe (Heerhartz *et al.*, 2014)
−5	Strong negative CDM effect based on amplifying terms or a mention of long-term effect	<−70%	Strong [wave] reflection (Bernatchez *et al.*, 2011); heavy erosion in the gaps between breakwater (Lamberti et Mancinelli, 1996)

3.4.2 Coastal Defence Measure Identification Algorithm

The purpose of the coastal defence measure identification algorithm (CDMIA) is to evaluate the performance of CDMs in relation to specific coastal characteristics. First, a correspondence is established between user-selected environmental features (type of coast (TC), type of substrate (TS), wave climate (WC), and tidal range (TR)) and those available in the database. Then, the user-selected CDMs are evaluated according to their effects on the specified environmental features.

The CDMIA execution is divided into three successive parts (figure 13). In the first part, groups are created from the user-selected environmental features, each group comprised of one environmental feature from each of the four types (TC, TS, WC, and TR, tableau 28). In the second part, for each CDM and for each group of environmental features (part I), a correspondence is established with similar variables present in the database. The associated authors' observed CDM effects are then selected by the CDMIA and evaluated according to their category and weight. In the third part, the CDMs are ranked in connection with the evaluation made in part II.

The CDMIA was developed using Visual Basic for Applications with Microsoft Excel ©, which was chosen for its accessibility. In the following sections, the words in brackets are related to functions or variables in the CDMIA procedure figures.

3.4.2.1 Environmental Features Grouping (Part I)

The first action of the CDMIA is a manual selection, by the user, of environmental features from four pre-established lists consisting of the elements itemized under each of the four types of environmental features, as presented in tableau 28. For each type, any number of elements can be selected by the user. Based on the user selection, the first part of the CDMIA procedure is the creation of groups (a group) of environmental features that will define the specific environmental conditions against which the CDMs will be evaluated.

The CDMIA will create individual groups composed of one element from each type of environmental feature: type of coast (TC), type of substrate (TS), wave climate (WC), and tidal range (TR). It will then combine each environmental feature from one type with one feature from each of the remaining 3 types (figure 15 and tableau 32). This action will be repeated until every possible combination is achieved, thus forming multiple groups.

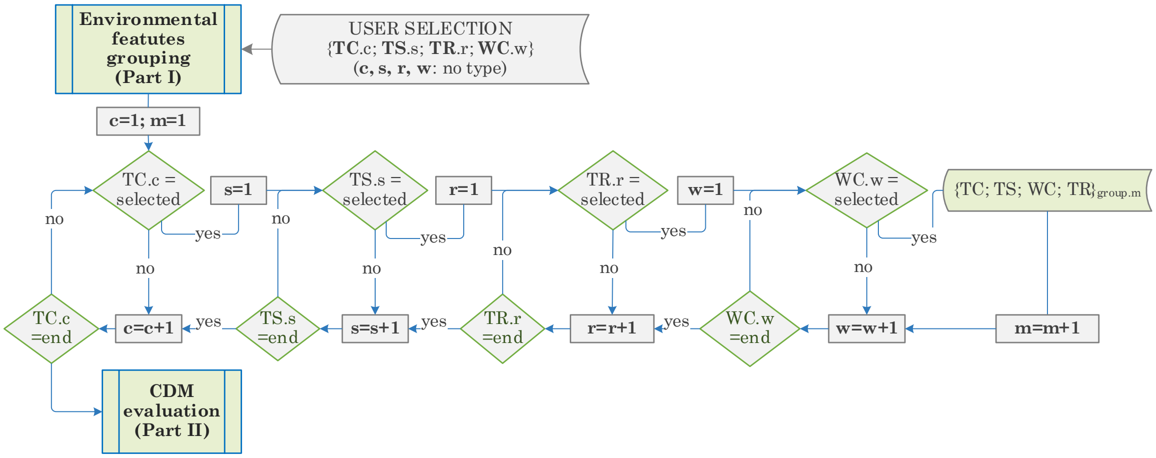


Figure 15. CDMIA procedure for the grouping of environmental features

Tableau 32

Example grouping of environmental features according to a hypothetical user selection

	User Selection	**Resulting Groups**
Type of coast	• Littoral spit (LS)	• Group 1 (LS, S, LE, Micro)
	• Unconsolidated cliff (UC)	• Group 2 (LS, G, LE, Micro)
Type of substrate	• Sand (S)	• Group 3 (UC, S, LE, Micro)
	• Gravel (G)	• Group 4 (UC, G, LE, Micro)
Wave characteristics	• Low energy (LE)	
Tidal range	• Microtidal (Micro)	

The central element of the CDMIA is divided in two fields; under the characterization fields is a list of environmental features (TC, TS, WC, and TR) with a CDM, and under the result fields is a list of evaluation criteria (tableau 33). For each user-selected CDM, an evaluation is performed in relation to each group of environmental features. The results of the evaluation are compiled in the result fields. Two main loops make up the CDMIA: CDM

(CDM.k) and group (group.m). The relation between the loops can be translated as follows: CDM.k ⊆ group.m. It allows the evaluation of each CDM against each group of environmental features. The results of the different analyses are recorded in the result fields and will be used to ultimately establish a hierarchy between the CDMs in relation to each group of environmental features.

Tableau 33
Fields with their list of evaluation criteria

Characterization Fields	**Result Fields**
• Groups (group.m)	• Number of observed CDM effects (nb.OE)
- Type of coast (TC)	• Enlargement degree reached (en)
- Type of substrate (TS)	• Correspondence index (CI)
- Tidal range (TR)	• Threshold percentage reached (thres.pct)
- Wave climate (WC)	• Weighted average (weig.avg)
• Coastal defence measure (CDM.k)	• Position of the CDM in the final ranking (pos)

3.4.2.2 CDM Evaluation (Part II)

The second part of the CDMIA is the CDM evaluation process (figure 16). For each CDM and for each group of environmental features selected by the user (Part I), a correspondence is established with similar variables present in the database (FCT nb.obs.effect); then, the number of observed effects (nb.OE) associated with these variables is tallied up.

If the nb.OE is larger than 0, the related environmental features (TC, TS, WC, and TR) are registered in a secondary table. If the nb.OE is larger than a minimum number of observed CDM effects determined by équation 1 below (nb.OE.min, Equation (1)), the evaluation of the CDM effects is based on the environmental features entered in the secondary table. The results of the evaluation are recorded in the result fields (tableau 33). If the nb.OE is smaller than the nb.OE.min, an enlargement (en, tableau 34) of the original environmental features is conducted, which results in a decrease in the value of the correspondence index (CI, équation 2), an indicator of uncertainty. Following the enlargement process, the nb.OE is retallied. This loop is carried out until the nb.OE is larger than the nb.OE.min or until the highest degree of enlargement (en) has been reached. At that point, if the nb.OE is still smaller than the nb.OE.min, the CDM is rejected.

Once each CDM selected by the user has been evaluated in relation to each group of environmental features, a ranking of CDMs (part III) is carried out.

The tally of observed CDM effects defines whether the available information related to that CDM, in a given coastal system context, is sufficient to be used in the decision-making process. The purpose of this function is to extract from the database, and record in a separate table, the observed effects of a CDM (CDM.k) in combination with the associated environmental features (TC, TS, WC, and TR) and then to tally up the number of occurrences (nb.OE).

The minimum number of observed CDM effects (nb.OE.min) deemed acceptable to support the decision-making process is calculated based on the total number of observed effects in the context of the broad coastal category to which the specific type of coast, originally selected, is related (nb.OE.tot). For example, if the originally selected type of coast (TC) is a beach terrace, the nb.OE.tot will be calculated based on all types of coast in the category of "unconsolidated coast" (beach terrace, dune, littoral spit, barrier island, and unconsolidated cliff). Once calculated, the nb.OE.min is used to determine whether an enlargement of the original environmental features (en, tableau 34) is required.

The calculation of the nb.OE.min is based on a polynomial equation which delineates an attenuation ratio between the nb.OE.min and the nb.OE.tot (équation 1). The equation was built by the authors to obtain a high ratio value (approx. 0.3) when the nb.OE.tot is low and a progressive attenuation which converges toward a minimal increase around a nb.OE.tot value of 350 (ratio of 0.14). The analysis is therefore based on a lower number of observed effects but a better match with the environmental characteristics of the study area.

$$\mathrm{nb.OE.min} = -0.0005 \cdot \mathrm{nb.OE.tot}^2 + 0.32 \cdot \mathrm{nb.OE.tot} - 0.5 \qquad \text{Équation 1}$$

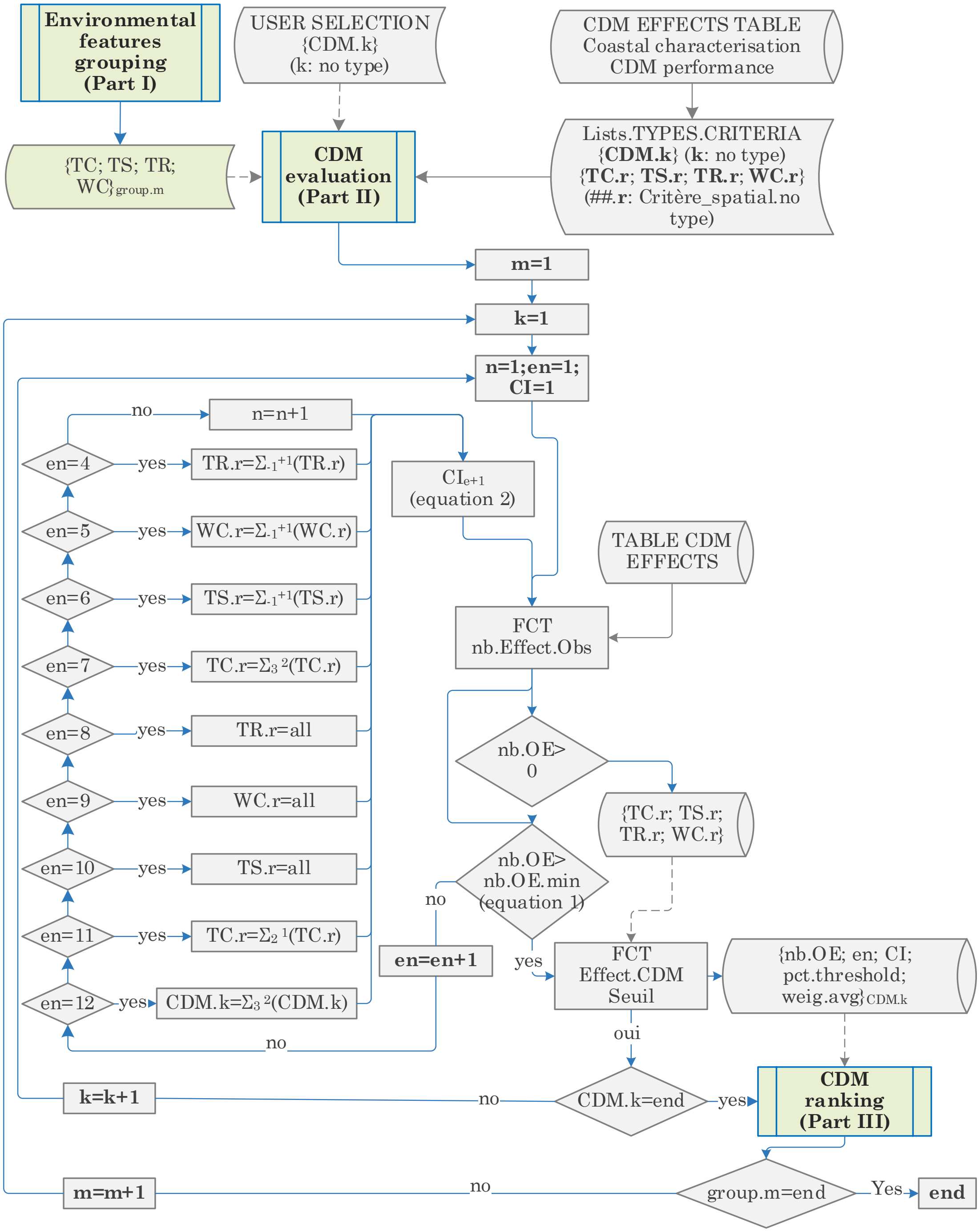


Figure 16. Graphic illustration of CDMIA procedure for CDM evaluation

The relationships between the different types of environmental features and the different types of CDMs are not fully covered in the scientific literature (Sauvé *et al.*, 2020).

A function to expand the user-selected environmental features was therefore developed to enlarge the applicability of the available information. This is necessary, even though the enlargement (en) of the user-selected environmental features will result in a decrease in accuracy with the corresponding characteristics compiled in the database. In order to reach an acceptable compromise, twelve degrees of enlargement were defined (tableau 34).

Tableau 34

Degrees of enlargement of user-selected environmental features

Degree	**Description**	
1	Initial criteria and direct effects	-
2	Initial criteria and addition of direct causes to the direct effects	n = n + 1
3	Initial criteria and addition of indirect causes to the direct causes and direct effects	n = n + 1
4	Integration of the immediate lower and upper tidal range classes	$\mathrm{TM.r} = \sum_{-1}^{+1}(\mathrm{TM.r})$
5	Integration of the immediate lower and upper wave climate classes	$\mathrm{TV.r} = \sum_{-1}^{+1}(\mathrm{TV.r})$
6	Integration of the immediate lower and upper types of substrate classes	$\mathrm{TS.r} = \sum_{-1}^{+1}(\mathrm{TS.r})$
7	Integration of all subtypes into the initial type of coast	$\mathrm{WC.r} = \sum_{3}^{2}(\mathrm{WC.r})$
8	Integration of all tidal range classes	$\mathrm{TM.r} = \mathrm{all}$
9	Integration of all wave climate classes	$\mathrm{WC.r} = \mathrm{all}$
10	Integration of all types of substrate classes	$\mathrm{TS.r} = \mathrm{all}$
11	Integration of all subtypes of coast into the subcategory of coast	$\mathrm{TC.r} = \sum_{2}^{1}(\mathrm{TC.r})$
12	Integration of all subtypes of CDM included in the same type	$\mathrm{CDM.r} = \sum_{3}^{2}(\mathrm{CDM.r})$

A correspondence index (CI) was integrated into the CDMIA to characterize the uncertainty of the information used in the evaluation of the CDM effects. CI has an initial value of 1 and is reduced according to a polynomial function (équation 2), which is directly related to the degree of enlargement (en). This equation was built to represent the exponential decreasing rate of accuracy between the degrees of enlargement. A visual analysis resulted in the definition of the parameters of the third-degree polynomial equation.

$$CI = -0.0013en^3 + 0.015en^2 - 0.07en + 1.06 \qquad \text{Équation 2}$$

The function Effect.CDM was developed to evaluate the CDM effects on specific environmental features. First, in connection with the environmental features selected by the function nb.OE, and recorded in the secondary table, the function Effect.CDM tallies the number of observed CDM effects (nb.OE) per each level of the weighting scale (−5 to 5, tableau 31). Second, Effect.CDM classifies and tallies the number of observed CDM effects by subtype, type, and category. The sum of the subtypes is the total of a type, and the sum of the types is the total of a category.

3.4.2.3 CDM Ranking

The CDM ranking is based on three criteria: the threshold percentage reached (thres.pct), the weighted average (weig.avg), and the correspondence index (CI) (figure 17). In the case of a tie, the weighted average has precedence over the correspondence index. A selected CDM is removed from the ranking when the observed effects are null following a 12-degree enlargement of the initial environmental context.

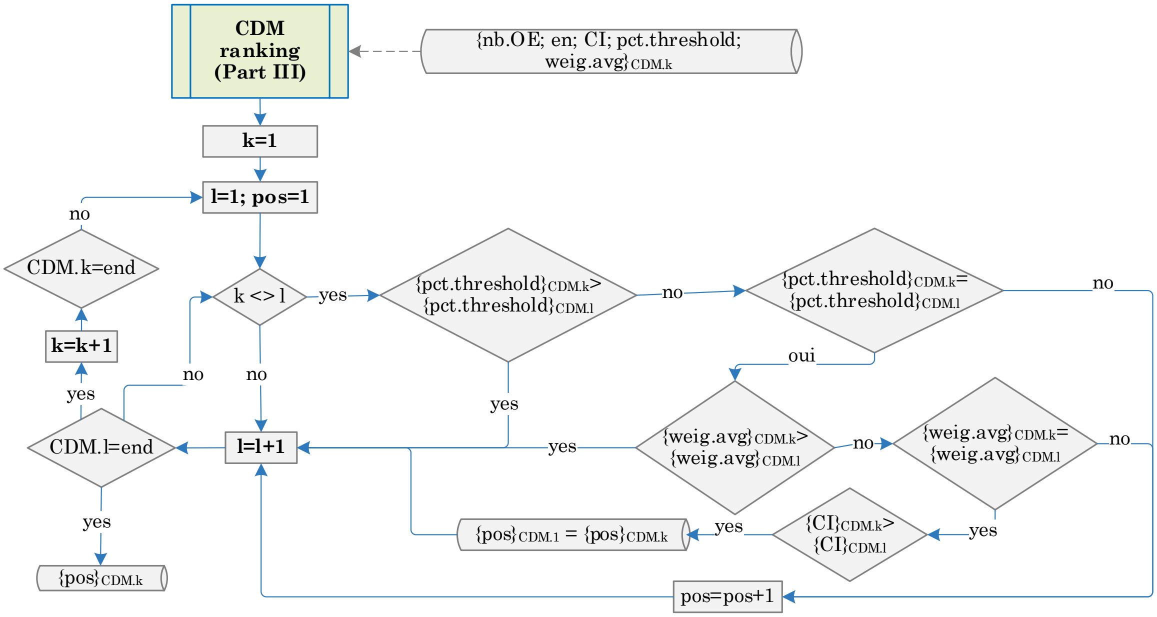


Figure 17. Ranking procedure

A threshold percentage (thres.pct) is used to identify at which level of the weighting scale a defined percentage value of observed effects is reached. Following a sensitivity analysis, the thres.pct value was set at 60%. Under each level of the weighting scale, the percentage of observed effects in relation to the total number of observed effects is calculated. The thres.pct function calculates, for each CDM, the cumulative percentages from the highest level of the weighting scale (5) to the lowest (−5). The level at which the cumulative percentage of 60% is reached becomes one of the CDM performance indicators.

A weighted average (weig.avg) is used to obtain an overall score on the weighting scale. For each level of the weighting scale, the number of observed effects is multiplied by their corresponding level value. The results are then added up, and the sum is divided by the total number of observed effects.

3.5 RESULTS

3.5.1 CDMIA Contextualized Results

The next two subsections present, as an example, the CDMIA results in the context of a littoral sandy spit, a mesotidal coast, and a low energy wave climate (Hs < 1.0 m). More CDMIA results examples are presented in supplementary materials (S2).

3.5.1.1 Summary Hierarchization

Tableau 35 presents an example of a summary hierarchization generated by the CDMIA. Column 3 shows the level on the weighting scale at which the threshold percentage (pct.thres) is reached, and column 4 shows the weighted average (avg). These two indicators give information on the performance of the CDM. The correspondence index (CI) and the number of observed CDM effects included in the evaluation (nb.OE) are shown in columns 5 and 6. These two indicators give information on the uncertainty of the results. Columns 7 to 13 show the distribution of the nb.OE for each level of the weighting scale.

Tableau 35

Summary hierarchization resulting from the evaluation of CDM geomorphological effects. The results presented, as an example, are in an environmental context described as littoral sandy spit, mesotidal coast, and low energy wave climate (Hs < 1.0 m). The background blue shades is used to give a visual indication of the distribution of the nb.OE on the weighting scale

Rnk	**CDM**	**Pct. Thres**	**Avg**	**CI**	**nb.OE**	**−5**	**−3**	**−1**	**0**	**1**	**3**	**5**
									(%)			
1	Land vegetation	3	3.026	0.375	38	-	-	-	2.6	2.6	86.8	7.9
2	Permeable drainage layers	3	3.00	0.697	1	-	-	-	-	-	100	-
2	Aquatic vegetation	3	3.00	0.697	1	-	-	-	-	-	100	-
4	Mega-nourishment	3	2.70	0.375	30	-	6.7	-	10.0	-	63.3	20.0
5	Sediment derivation method	3	2.538	0.697	13	7.7	7.7	-	-	-	53.8	30.8
6	Nearshore nourishment	3	2.032	0.697	31	-	6.5	-	19.4	9.7	54.8	9.7
7	Permeable groin	3	1.529	0.859	17	5.9	11.8	5.9	5.9	-	64.7	5.9
8	Jetty	1	3.00	0.859	2	-	-	-	-	50.0	-	50.0
9	Vertical beach drainage system	1	1.833	0.859	6	-	-	-	16.7	33.3	50.0	-
10	Beach nourishment	1	1.793	0.859	111	0.9	6.3	0.9	25.2	10.8	43.2	12.6
11	Horizontal beach drainage system	1	1.792	0.859	24	-	4.2	-	20.8	25.0	41.7	8.3
12	Emerged breakwater	0	0.24	0.697	25	4.0	32.0	4.0	12.0	4.0	40.0	4.0
13	Impermeable groin	−1	0.241	0.859	29	-	37.9	3.4	13.8	6.9	27.6	10.3
14	Low-crested breakwater	−3	−0.588	0.859	51	11.8	43.1	2.0	2.0	3.9	29.4	7.8
15	Submerged breakwater	−3	−0.676	0.859	68	11.8	44.1	1.5	2.9	4.4	27.9	7.4
16	Rip-rap	−3	−1.00	0.375	7	-	42.9	14.3	28.6	-	14.3	-
17	Seawall	−3	−2.586	0.697	58	13.8	62.1	8.6	13.8	-	1.7	-
18	Rock armour	−3	−3.30	0.697	20	30.0	60	-	10.0	-	-	-

There is a complementarity between pct.thres and avg: when both numbers are fairly close in value, the results can be considered conclusive, but when there is a significant difference between the two numbers, a threshold effect occurs and indicates the necessity to scrutinize the results. For example, with a pct.thres set at 60%, a threshold effect will occur when 59% of the observed effects is reached at level 3 on the weighting scale, and 60% is reached at level −1. In tableau 35, a threshold effect occurs in the case of low-crested breakwater, which reaches the pct.thres at level −3 but has an avg of −0.588, a fairly large difference between the two values. A closer look at the results shows that even though the two values are in the negative range, a large number of observed effects (41.1%) are actually in the positive range of the weighting scale.

3.5.1.2 Detailed Results

The hierarchization of the information provides detailed results according to several levels of aggregation. The analysis of the CDM effects can be adapted to the user's needs, while maintaining a proximity to the raw data (characteristics of the study area and the observed CDM effects) which were processed and structured in a way to provide relevant information for the CDM decision-making and design processes.

A detailed results list (tableau 36) presents the observed CDM effects subdivided by the three levels of the cause–effect scale (tableau 29) and the three levels of classified CDM effects (tableau 30). The top line is the aggregation of all the observed effects within the geomorphological category (Agg, tableau 36, column 3) and corresponds to the results presented in the summary hierarchization (see tableau 35, rnk 10, Beach nourishment). The first degree of data disaggregation is by level on the cause–effect scale ([DirE = direct effect; DirC = Direct cause; IndC = Indirect cause], tableau 36, column 3). The second and third are by type and subtype of observed effects, respectively.

Tableau 36

Detailed results list of the observed effects of beach nourishment subdivided into geomorphological categories (category, type, *subtype*). The results presented, as an example, are in an environmental context described as litoral spit, sand, mesotidal coast, and low energy wave climate (Hs < 1.0 m). The background blue shades is used to give a visual indication of the distribution of the nb.OE on the weighting scale

Rnk	**CDM**	**Level**	**Category of CDM Effect**	**nb.OE**	**Avg**	**−5**	**−3**	**−1**	**0**	**1**	**3**	**5**
									(%)			
10	Beach nourishment	Agg	Geomorphological	111	1.793	0.9	6.3	0.9	25.2	10.8	43.2	12.6
		DirE	Geomorphological	67	2.522	-	-	-	20.9	11.9	47.8	19.4
			Erosion/Accretion	67	2.522	-	-	-	20.9	11.9	47.8	19.4
			Accretion	9	3.667	-	-	-	-	-	66.7	33.3
			Sediment budget	24	3.083	-	-	-	8.3	16.7	41.7	33.3
			Shoreline movement	17	1.588	-	-	-	35.3	17.6	47.1	-
			Erosion	6	0.833	-	-	-	83.3	-	-	16.7
			Beach height	3	2.333	-	-	-	-	33.3	66.7	-
			Beach width	7	2.857	-	-	-	14.3	-	71.4	14.3
			Geomorphological recovery	1	3	-	-	-	-	-	100.0	-
		DirC	Geomorphological	14	0.857	-	14.3	-	42.9	-	42.9	-
			Sediment transport	6	2.5	-	-	-	16.7	-	83.3	-
			Longshore transport	2	3	-	-	-	-	-	100.0	-
			General sediment transport	2	3	-	-	-	-	-	100.0	-
			Cross-shore transport	2	1.5	-	-	-	50.0	-	50.0	-
			Run-up process	1	−3	-	100.0	-	-	-	-	-
			Run-up	1	−3	-	100.0	-	-	-	-	-
			Dissipation process	7	0	-	14.3	-	71.4	-	14.3	-
			Wave energy	3	−1	-	33.3	-	66.7	-	-	-
			Wave height	4	0.75	-	-	-	75.0	-	25.0	-
		IndC	Geomorphological	1	−3	-	100.0	-	-	-	-	-
			Topo-bathymetric profile	29	0.724	3.4	13.8	3.4	27.6	13.8	34.5	3.4
			Beach profile	9	−0.111	-	33.3	11.1	22.2	-	33.3	-
			Bar system	18	0.944	5.6	5.6	-	27.8	22.2	38.9	-
			General variation in bathymetry	2	2.5	-	-	-	50.0	-	-	50.0
			Current	1	−3	-	100.0	-	-	-	-	-
			Cross-shore current	1	−3	-	100.0	-	-	-	-	-

The disaggregated information shows both the positive and negative CDM effects, which are indicators of a CDM's strengths and weaknesses. This information can be used to improve CDM design. Improvements can also sometimes be achieved by using a combination of complementary CDMs. For example, when looking at the broad

Erosion/Accretion classification, based on a large number of observations (tableau 30, nb.OE, column 5, nb.OE = 67), beach nourishment has a generally positive effect. Still, drilling down into the details reveals that 83.3% of the observed effects under the subtype "erosion" (observation of erosion in general, tableau 30) are neutral or show no evidence that beach nourishment has a positive or negative effect on the general erosion of the beach. Thus, an engineer could use this information to improve the efficiency of beach nourishment against erosion, by combining it with a complementary CDM. Moreover, under the subtype beach profile beach nourishment shows a negative average (−0.111) based on nine observations. However, this average is close to a neutral effect as 33.3% of the observations are at the -3 level on the weighting scale, 33.3% are at level 3, and 22.2% are at level 0. Therefore, the negative average (tableau 36, column 6: avg) is based on only a ninth of the observations (c.-à-d., 11.1% at level −1). Again, an engineer could adjust the design by using, for example, a better adapted granulometry.

3.5.2 CDMIA Overall Results

The CDMIA was developed with the objective of obtaining a detailed assessment of CDMs in relation to a specific group of environmental features. In order to evaluate the overall performance of the CDMIA according to variations in environmental features, an analysis of the results, based on the averaging of correspondence indexes (CI), was conducted for each group of features. Moreover, the overall performance of CDMs, in each group of environmental features, was conducted through an averaging of the weighted averages.

The averages of the CI values vary between 1 and 0 and are presented in tableau 37. A value of 1 indicates a perfect correspondence, while a value near 0 indicates an absence of correspondence. The averaging of the CI values gives an indication of the accuracy of the results in each group of environmental features.

The CDMIA's highest level of accuracy is associated with unconsolidated low coast (littoral split, beach terrace, barrier island, and welded barrier/tombolo) with substrates corresponding to silt, sand, or pebbles. Eighteen CDMs were evaluated in relation to these coastal characteristics, and the resulting average CI values varied between 0.665 and 0.770.

Tableau 37

Average correspondence index (CI) and number of CDMs evaluated (CI (nb.CDM)) for each group of environmental features (type of coast, type of substrate, tidal range, and wave climate). The background colours are associated with CI values (red [0] < yellow [0.5] < green [1])

	Littoral Spit	**Beach Terrace**	**Barrier Island**	**Welded Barrier/ Tombolo**	**Dune**	**Unconsolidated Cliff**	**Salt Marsh**	**Rocky Cliff**
Clay								
Microtidal								
Low	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.628 (5)	0.000 (0)
Moderate	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.628 (5)	0.000 (0)
High	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.628 (5)	0.000 (0)
Mesotidal								
Low	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.628 (5)	0.000 (0)
Moderate	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.628 (5)	0.000 (0)
High	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.628 (5)	0.000 (0)
Macrotidal								
Low	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.628 (5)	0.000 (0)
Moderate	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.628 (5)	0.000 (0)
High	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.628 (5)	0.000 (0)
Silt								
Microtidal								
Low	0.712 (18)	0.726 (18)	0.722 (18)	0.715 (18)	0.000 (0)	0.393 (18)	0.632 (5)	0.000 (0)
Moderate	0.715 (18)	0.760 (18)	0.749 (18)	0.742 (18)	0.000 (0)	0.404 (18)	0.635 (5)	0.000 (0)
High	0.742 (18)	0.684 (18)	0.679 (18)	0.679 (18)	0.000 (0)	0.404 (18)	0.632 (5)	0.000 (0)
Mesotidal								
Low	0.712 (18)	0.726 (18)	0.722 (18)	0.715 (18)	0.000 (0)	0.393 (18)	0.632 (5)	0.000 (0)
Moderate	0.715 (18)	0.760 (18)	0.749 (18)	0.742 (18)	0.000 (0)	0.404 (18)	0.648 (5)	0.000 (0)
High	0.742 (18)	0.684 (18)	0.679 (18)	0.679 (18)	0.000 (0)	0.404 (18)	0.632 (5)	0.000 (0)
Macrotidal								
Low	0.687 (18)	0.692 (18)	0.690 (18)	0.690 (18)	0.000 (0)	0.393 (18)	0.632 (5)	0.000 (0)
Moderate	0.690 (18)	0.708 (18)	0.706 (18)	0.706 (18)	0.000 (0)	0.404 (18)	0.635 (5)	0.000 (0)
High	0.706 (18)	0.665 (18)	0.665 (18)	0.665 (18)	0.000 (0)	0.404 (18)	0.632 (5)	0.000 (0)

Tableau 28 (suite)
Average correspondence index (CI) and number of CDMs evaluated (CI (nb.CDM)) for each group of environmental features (type of coast, type of substrate, tidal range, and wave climate). The background colours are associated with CI values (red [0] < yellow [0.5] < green [1])

Sand								
Microtidal								
Low	0.712 (18)	0.736 (18)	0.733 (18)	0.715 (18)	0.566 (20)	0.393 (18)	0.000 (0)	0.560 (2)
Moderate	0.715 (18)	0.770 (18)	0.753 (18)	0.742 (18)	0.574 (20)	0.405 (18)	0.000 (0)	0.560 (2)
High	0.742 (18)	0.695 (18)	0.679 (18)	0.679 (18)	0.558 (20)	0.406 (18)	0.000 (0)	0.560 (2)
Mesotidal								
Low	0.712 (18)	0.737 (18)	0.728 (18)	0.715 (18)	0.567 (20)	0.393 (18)	0.000 (0)	0.560 (2)
Moderate	0.715 (18)	0.770 (18)	0.753 (18)	0.742 (18)	0.571 (20)	0.405 (18)	0.000 (0)	0.560 (2)
High	0.742 (18)	0.688 (18)	0.679 (18)	0.679 (18)	0.554 (20)	0.410 (18)	0.000 (0)	0.560 (2)
Macrotidal								
Low	0.687 (18)	0.694 (18)	0.690 (18)	0.690 (18)	0.553 (20)	0.393 (18)	0.000 (0)	0.560 (2)
Moderate	0.690 (18)	0.710 (18)	0.706 (18)	0.706 (18)	0.557 (20)	0.405 (18)	0.000 (0)	0.560 (2)
High	0.706 (18)	0.665 (18)	0.665 (18)	0.665 (18)	0.534 (20)	0.406 (18)	0.000 (0)	0.560 (2)
Pebbles								
Microtidal								
Low	0.712 (18)	0.726 (18)	0.722 (18)	0.715 (18)	0.000 (0)	0.393 (18)	0.000 (0)	0.560 (2)
Moderate	0.715 (18)	0.760 (18)	0.749 (18)	0.742 (18)	0.000 (0)	0.404 (18)	0.000 (0)	0.560 (2)
High	0.742 (18)	0.684 (18)	0.679 (18)	0.679 (18)	0.000(0)	0.404 (18)	0.000 (0)	0.560 (2)
Mesotidal								
Low	0.712 (18)	0.726 (18)	0.722 (18)	0.715 (18)	0.000 (0)	0.393 (18)	0.000 (0)	0.560 (2)
Moderate	0.715 (18)	0.760 (18)	0.749 (18)	0.742 (18)	0.000 (0)	0.404 (18)	0.000 (0)	0.560 (2)
High	0.742 (18)	0.684 (18)	0.679 (18)	0.679 (18)	0.000 (0)	0.404 (18)	0.000 (0)	0.560 (2)
Macrotidal								
Low	0.687 (18)	0.692 (18)	0.690 (18)	0.690 (18)	0.000 (0)	0.393 (18)	0.000 (0)	0.560 (2)
Moderate	0.690 (18)	0.708 (18)	0.706 (18)	0.706 (18)	0.000 (0)	0.404 (18)	0.000 (0)	0.560 (2)
High	0.706 (18)	0.665 (18)	0.665 (18)	0.665 (18)	0.000 (0)	0.404 (18)	0.000 (0)	0.560 (2)
Cobbles								
Microtidal								
Low	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.000 (0)	0.560 (2)
Moderate	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.000 (0)	0.560 (2)
High	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.000 (0)	0.560 (2)
Mesotidal								
Low	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.000 (0)	0.560 (2)
Moderate	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.000 (0)	0.560 (2)
High	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.000 (0)	0.560 (2)
Macrotidal								
Low	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.000 (0)	0.560 (2)
Moderate	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.000 (0)	0.560 (2)
High	0.529 (18)	0.529 (18)	0.529 (18)	0.529 (18)	0.000 (0)	0.385 (18)	0.000 (0)	0.560 (2)

Tableau 38 shows a sampling of the results and the average values of the correspondence index (CI). The detailed results are not presented here due to lack of space, but it is worth mentioning that the lowest CI value was 0.375, and the highest values varied between 0.794 and 1. The lowest CI was associated with either mega-nourishment, rip-rap or land vegetation and can be explained by the low number of observed effects found in the literature in relation to these protection measures, and the fact that enlargement had to be used in these cases in order to reach the nb.OE.min (see section 3.4.2.2). At the other end of the spectrum, maximum CI values were obtained when the number of observed effects was higher than the nb.OE.min, and enlargement was not necessary. In such cases, there is a better match between the study area features and those compiled in the database and thus better accuracy in the results. A perfect correspondence (CI = 1) was reached in seven of the 4374 cases (0.160%) (combination of a set of environmental features and a CDM). Of these seven cases, the nb.OE was higher or equal to 10 in two cases, between 5 and 9 in two cases, and lower than 5 in the remaining three cases.

Salt marsh, with clay or silt substrate, presents an adequate accuracy with an average CI value varying between 0.628 and 0.648. However, this result was based on only five CDMs with a sufficient number of observed effects to be included in the analysis. Meanwhile, the data for the unconsolidated cliff were based on the evaluation of 18 different CDMs, but the accuracy was low, with an average CI value varying between 0.385 and 0.406. A CI value of zero occurs when there is no observed effect associated with a CDM, or when illogical groups of environmental features are formed (e.g., dune with substrates other than sand; salt marsh with sand, pebbles, cobbles, and boulders, etc.). Rocky cliff behind an unconsolidated beach was retained in the analysis because a few sites in which CDM effects were observed consisted of an unconsolidated coast backed by a rocky cliff. Still, only two CDMs were evaluated in such environments.

The performance evaluation of each CDM in different environmental contexts was calculated by averaging the weighted average values of the CDM effects for each type of coast (tableau 38). The average number of observed effects (avg. nb.OE) was included in tableau 38 to contextualize the averaging results.

Tableau 38

Averaging of weighted average values of CDM effects by type of coast. Average nb.OE is written between brackets (avg. nb.OE)).

CDM	**Littoral Spit**	**Beach Terrace**	**Barrier Island**	**Welded Barrier/ Tombolo**	**Dune**	**Unconsolidated Cliff**	**Salt Marsh**	**Rocky Cliff**
Rigid structure								
Rock armour	-3.41 (18.8)	-3.41 (18.8)	-3.41 (18.8)	-3.41 (18.8)	-3.19 (26)	-3.19 (26)	-3.00 (1)	-3.00 (1)
Seawall	-2.41 (51.5)	-2.41 (51.5)	-2.41 (51.5)	-2.41 (51.5)	-2.58 (89)	-2.58 (89)	-2.25 (4)	-5.00 (1)
Emerged breakwater	0.27 (24.6)	0.27 (24.6)	0.27 (24.6)	0.27 (24.6)	-0.22 (18)	0.05 (43)	5.00 (1)	- (0)
Impermeable groin	0.12 (39.5)	0.12 (39.5)	0.12 (39.5)	0.12 (39.5)	-0.74 (23)	-0.43 (76)	- (0)	- (0)
Low-crested breakwater	-0.48 (56.4)	-0.51 (54.9)	-0.48 (56.4)	-0.48 (56.4)	-0.63 (67)	-0.63 (67)	- (0)	- (0)
Permeable groin	1.18 (29.2)	1.20 (28.9)	1.18 (29.2)	1.18 (29.2)	1.47 (45)	1.47 (45)	- (0)	- (0)
Rip-rap	-1.00 (7)	-1.00 (7)	-1.00 (7)	-1.00 (7)	-1.00 (7)	-0.94 (6.9)	- (0)	- (0)
Submerged breakwater	-0.78 (83.6)	-0.53 (75.9)	-1.12 (73.2)	-0.78 (83.6)	-0.88 (97)	-0.88 (97)	- (0)	- (0)
Jetty	3.00 (2)	3.00 (2)	3.00 (2)	3.00 (2)	3.00 (2)	3.00 (2)	- (0)	- (0)
Soft technique								
Beach nourishment	1.95 (188.3)	1.92 (177.2)	1.90 (171.4)	1.95 (188.3)	1.97 (65)	2.02 (308)	- (0)	- (0)
Dune nourishment	- (0)	- (0)	- (0)	- (0)	1.67 (3)	- (0)	- (0)	- (0)
Nearshore nourishment	2.03 (31)	2.03 (31)	2.03 (31)	2.03 (31)	1.42 (42.7)	1.80 (98)	- (0)	- (0)
Mega-nourishment	2.70 (30)	2.70 (30)	2.70 (30)	2.70 (30)	2.82 (28.4)	2.70 (30)	- (0)	- (0)
Sediment derivation method	2.54 (13)	2.57 (12.9)	2.54 (13)	2.54 (13)	2.54 (13)	2.54 (13)	- (0)	- (0)
Horizontal beach drainage system	1.57 (34.7)	1.57 (34.7)	1.57 (34.7)	1.57 (34.7)	1.67 (18)	1.48 (60)	- (0)	- (0)
Vertical beach drainage system	1.83 (6)	1.83 (6)	1.83 (6)	1.83 (6)	1.47 (5.9)	1.63 (16)	- (0)	- (0)
Permeable drainage layers	3.00 (1)	3.00 (1)	3.00 (1)	3.00 (1)	3.00 (1)	3.00 (1)	- (0)	- (0)
Sediment trapping	- (0)	- (0)	- (0)	- (0)	2.63 (40)	- (0)	- (0)	- (0)
Land vegetation	3.03 (38)	3.03 (38)	3.03 (38)	3.03 (38)	2.99 (20.7)	3.03 (38)	1.00 (1)	- (0)
Aquatic vegetation	3.00 (1)	3.00 (1)	3.00 (1)	3.00 (1)	3.00 (1)	3.00 (1)	2.00 (3)	- (0)

In general, soft techniques score higher than rigid structures for all types of coasts. All soft techniques present a weighted average higher than 1 in the analyzed coastal types. Land vegetation, aquatic vegetation, and permeable drainage layers present the highest average, with a value of 3 when associated with unconsolidated coasts. However, the results of the latter two are based on only one observed effect. Mega-nourishment, sediment derivation, and sediment trapping, in connection with unconsolidated coasts (sediment trapping only applies to dunes), present results higher than 2.5 with minimum and maximum values of 2.54 (all unconsolidated coasts combined with all other environmental features) and 3.80 (beach terrace, sand, microtidal, and high energy waves). Sediment derivation methods are generally used as a corrective measure when a primary CDM causes sediment retention (e.g., jetty or groin). Frequently used CDMs, such as beach nourishment, dune nourishment, and nearshore nourishment, present an averaging of weighted average values between 1.42 and 2.03, with minimum and maximum values of 1.31 (dune, sand, and high energy waves) and 2.03 (all unconsolidated low coasts, sand or pebbles, and high-energy waves). As for rigid structures, emerged breakwater in a salt marsh context and jetty in six of the eight coastal types showed the best performances. However, their averaging of weighted average values was based on only one and two observed effects, respectively. In association with all unconsolidated coasts, permeable groin presents results higher than 1, as does emerged breakwater, except in a dune context for the latter. Lastly, rock armour, seawall, low-crested breakwater, rip-rap, and submerged breakwater all show negative results in most types of coasts.

3.6 DISCUSSION

Uncertainties are inherent to coastal systems, therefore decision-makers must take them into consideration when evaluating coastal defence measures (Baquerizo et Losada, 2008 ; Polasky *et al.*, 2011). In recent years, decision-support tools have been increasingly used in environmental management (Barzehkar *et al.*, 2021b ; Walling et Vaneeckhaute, 2020 ; Wong-Parodi *et al.*, 2020) to help decision-makers assess, in an objective way, multiple potential solutions to solve complex and inherently uncertain problems (Walling et Vaneeckhaute, 2020 ; Wong-Parodi *et al.*, 2020). Ultimately, decision-support tools act as an objective support which structures information in a way that hierarchizes CDMs in relation to their effects on the systems' dynamics (Gamper et Turcanu, 2007 ; Westmacott, 2001). It also allows decision-makers to choose the best solution in accordance with their priorities and preferences (McIntosh *et al.*, 2011 ; Saaty, 2008).

In coastal engineering, solutions are generally site specific, designed with standard procedures but without a design code (Kamphuis, 2000). The construction of a CDM best adapted to the needs of a specific site can only be accomplished through a multiphase process in which a variety of scenarios are evaluated in order to solve a predefined problem before moving on to the design phase (USACE, 2006a). In addition, cutting-edge scientific knowledge is essential to the planification and design processes in order to reduce uncertainties (Folke *et al.*, 2005 ; Kamphuis, 2000 ; Pahl-Wostl, 2009). Therefore, there is a need for the use of decision-support tools to facilitate the evaluation of scenarios and answer the predefined project objectives, while considering the relation between the CDMs and the environmental characteristics (Westmacott, 2001).

Examples of decision-support tools used for different aspects of coastal zone management are models for climate and offshore and nearshore wave climate, geographical information systems, Bayesian network, and multicriteria decision analysis (MCDA) (Barzehkar *et al.*, 2021b). Still, to the authors' knowledge, a decision-support tool that integrates scientific knowledge into the CDM decision-making process has not been developed to date for use in the field of coastal engineering and management.

3.6.1 Contribution to Coastal Engineering and Management

The coastal defence measure identification algorithm (CDMIA) was developed to answer a need to integrate the most current site-specific scientific knowledge into the decision-making process and as a tool to facilitate the selection of the best adapted CDMs (Friesinger et Bernatchez, 2010 ; Guénette *et al.*, 2019 ; Marie *et al.*, 2017 ; Sauvé *et al.*, 2020). Once the relevant information found in multiple scientific publications is entered in the database, the CDMIA organizes and processes the data. It establishes links between the coastal features, defining an intervention site and features already present in the database, and it ranks selected CDMs against these site-specific features, using the most recent scientific knowledge. This assures that the site-specific complexity is integrated into the analysis, and the results are presented in a multilevel aggregated structure, offering several options to select from, including design adaptations to achieve the best CDM performance (Jones *et al.*, 2014). The CDMIA can be applied at different levels to accommodate the users' (coastal managers, decision-makers, and engineers) requirements. It establishes a variety of scenarios to be considered, and it also provides information that is helpful to the design process. Moreover, it has the capacity to analyze the accuracy of the results for each CDM in relation to multiple sets of environmental features, thus adding a level of confidence to the decision-making process.

The optimal use of the highest aggregation level (summary hierarchization) is in the phase of establishing CDM scenarios. As a pre-selection tool, it provides the users with an overall CDM evaluation. At this level, all of the authors' observation statements of CDM effects (nb.OE), drawn from the scientific literature, are aggregated to generate a global evaluation. The CDMIA facilitates the integration of scientific knowledge in a concise and structured manner and is meant to be used in connection with existing technical tools, such as numerical models and decision-support systems. The purpose of these tools is to help decision-makers understand the interactions between variables in the natural and social systems (Westmacott, 2001) in order to better assess the individual CDM's characteristics and behaviour in different environmental contexts. The disaggregated data (detailed results list) allows the results to accurately represent the primary authors' observation statements of CDM effects. At the design phase, it offers information useful to the assessment of the strengths and weaknesses of CDMs and of the possible benefits of using complementary CDMs in combination with each other. It therefore contributes to the comprehensive analysis of CDMs at the scale of a coastal system rather than at the conventional local scale based solely on technical aspects (Sauvé *et al.*, 2020).

As mentioned above, the processed data provided by the CDMIA can give an overview of the general accuracy of the results for all CDMs in relation to multiple sets of environmental features. This can be helpful to coastal managers or engineers who wish to make a quick assessment of CDM performance against characteristics of a specific intervention site.

3.6.2 CDMIA Analysis

Based on observations of the algorithm dynamics and on a sensitivity analysis, the number of observed CDM effects (nb.OE) proved to be a key parameter within the CDMIA because it relates to all the internal parameters, and it has an influence on the accuracy and the uniformization of the results. While scientific knowledge contributes to the reduction in the coastal system's inherent uncertainty (Koontz *et al.*, 2015), the nb.OE is directly related to the reliability of the CDMIA results. The CDMIA was designed for continuous improvement by the addition of information from new scientific publications. Thus, the accuracy of the results obtained with the first version of the CDMIA will be improved in future versions with the addition of new data and an increased number of observed CDM effects (nb.OE).

The addition of observed effects will lead, in three possible ways, to a substantiation of the information and a reduction in uncertainty, depending on whether the information being added is related to a new CDM or new environmental features. First, new observed effects related to a CDM and a set of environmental features that are both already present in the database will lead to an increase in the nb.OE and, therefore, a concretization of the information related to that specific CDM. Second, new observed effects related to a CDM already present in the database, but in a new environmental context, will lead to an increase of the CI value and to a global increase in the nb.OE. Therefore, the uncertainty will be reduced by a better correspondence between the environmental characteristics of the intervention site and those stocked in the database. Third, new observed effects related to a CDM that is not present in the database will increase the diversity of CDMs associated with specific environmental features and potentially widen the choice of appropriate solutions for intervention sites in a similar context. Ultimately, the ongoing integration of scientific knowledge contributes to the continuous improvement of the decision-making process (André *et al.*, 2010 ; Polasky *et al.*, 2011). It is also in keeping with adaptive management approaches, which are useful when making decisions within the inherent uncertainty and unpredictability of complex coastal systems (Allen *et al.*, 2011 ; Folke, 2016). Additionally, it contributes to the increase in the coastal communities' overall resilience (Lebel *et al.*, 2006 ; Pahl-Wostl, 2009).

3.6.2.1 Accuracy of the Results

The accuracy of the CDMIA results is related to both exogenous and endogenous sources of uncertainty. The exogenous uncertainty is directly related to the number of observed effects (nb.OE) associated with each CDM and found in the scientific literature: a larger nb.OE leads to the consolidation of the observations and lowers the uncertainty of the results. Still, a minimum number of observed effects (nb.OE.min) is required to ensure the reliability of the results. The correspondence index (CI), strictly a function of the degree of enlargement (en), was incorporated into the CDMIA as an indicator of uncertainty when the nb.OE was initially lower than the nb.OE.min, and enlargement is necessary in order to broaden the analytical framework. A joint interpretation of the results must be performed between the CI and the nb.OE because of their interdependency: (i) an increased nb.OE leads to a decrease in uncertainty; (ii) an increased nb.OE, through enlargement, lowers the CI and leads to an increase in uncertainty. Therefore, a balance must be reached between the nb.OE and the CI.

The endogenous uncertainty is related to internal parameters in the CDMIA (i.e., nb.OE.min and en). Even though these parameters were validated through a sensitivity analysis, their variation can influence the results of the CDMIA. However, if the nb.OE were the same for all CDMs, the endogenous uncertainty would be eliminated because the nb.OE.min would have the same value for all CDMs. The application of the nb.OE.min, as a threshold, corroborates the results by ensuring that the effects, at the subtype level, were observed a minimum number of times. The very low number of cases where a perfect correspondence was reached with an nb.OE higher than 5 (4 out of 4374 cases) shows the need for the application of the nb.OE.min equation and for the use of an enlargement function to increase the nb.OE. As a reduction in accuracy ensues from these actions, a validation of the results is necessary. As new studies in different environmental contexts emerge and are integrated into the database, the accuracy of the results will improve. That is why the CDMIA was designed to accommodate new scientific research.

3.6.2.2 Uniformization of the Results

A uniformization of the results tends to occur with two of the CDMIA’s internal functions: the degree of enlargement (en) and the minimum number of observed CDM effects (nb.OE.min). The uniformization is directly proportional to the degree of enlargement. For example, two different CDMs, but of the same type and in the same subcategory of coast, with an enlargement of 12, would have an identical evaluation. However, this uniformization tendency would be attenuated by the integration into the system of data from new scientific publications, which would contribute to an increase in the nb.OE, and a decrease in enlargement degree necessary to attain the nb.OE.min.

The value of the minimum number of observed CDM effects (nb.OE.min) is important in order to balance the correspondence index (CI) against the nb.OE. For instance, in the context of a low number of study sites for a specific coastal type, if the value of the nb.OE.min is high it will lead to a high nb.OE but also to a low CI value as a high degree of enlargement will be needed in order to meet the minimal requirements. This will lead to a uniformization of the results. It is therefore preferable to have a lower nb.OE.min in order to reduce the degree of enlargement and increase the variability of the results. In the end, the nb.OE will be lower but with a higher correspondence index (CI) and thus higher accuracy.

3.6.2.3 Comparison with Other Decision-Support Tools

While CDMIA contains sources of exogenous and endogenous uncertainties, each decision-support tool generally used in coastal management, such as numerical modelling and multicriteria decision analysis (MCDA), has its own uncertainties.

The uncertainties in numerical models of climate change projections are related to unknown future emissions, internal climate variability, and inter-model differences (Hawkins et Sutton, 2009, 2011 ; Kirtman *et al.*, 2013). Concerning nearshore models, Kroon et al.

(2020) have demonstrated that, in mega-nourishment, 50% of the variance in the loss of sedimentary volume, over a 2.5-year period, is attributed to the models' uncertainties. In MCDA, which allows the integration of local actors in the decision-making process, uncertainties arise from the elicitation of criteria weights by different stakeholders and also from the process of aggregating criteria weights (Hyde *et al.*, 2004 ; Kheireldin et Fahmy, 2001 ; Moshkovich *et al.*, 1998). However, these uncertainties can be mitigated by combining MCDA with other analytical methods (Mardani *et al.*, 2015 ; Marttunen *et al.*, 2017).

Despite their drawbacks, these tools are relevant to the decision-making process (Walling et Vaneeckhaute, 2020 ; Wong-Parodi *et al.*, 2020). Considering the inherent uncertainties of coastal systems, different sources of information add knowledge to the decision-making process, thus widening the choices and improving the suitability of adaptation solutions. The combination of pertinent decision-support tools provides more suitable and reliable information (Barzehkar *et al.*, 2021a). Combining CDMIA with other decision-support tools is worthwhile when considering the multiple aspects of coastal systems in the decision-making process, because each has a different purpose. For instance, while the climate models' projections provide data that are at the basis of the analysis, the CDMIA helps concretize and structure the information in a comprehensive and useful way for decision-makers.

3.7 CONCLUSIONS

An identification algorithm was developed to (1) conduct a dynamic meta-analysis of CDM effects on coastal systems, (2) centralize and structure the existing scientific knowledge drawn from published studies, (3) evaluate, compare, and rank CDM in different environmental contexts, and (4) yield useful information to support the decision-making process. The evaluation starts with the establishment of a correspondence between environmental features characterizing an intervention site and information from the case study publications previously stocked in a database. Once a correspondence is established, the evaluation is formulated according to a qualitative weighting scale (−5 to 5) used to hierarchize the CDMs. Based on two performance indicators (weighted average and threshold percentage reached) and two accuracy indicators (correspondence index and number of observed CDM effects), the results are structured under the several levels of aggregation meant to be used by coastal decision-makers and engineers for different purposes and at different stages of the decision process. First, a summary hierarchization presents the ranking of CDMs at the highest aggregation level. It provides an overall evaluation of CDMs and can optimally be used as a pre-selection tool for decision-makers. Second, the detailed results are presented under several disaggregated levels, providing information on the CDM's strengths and weaknesses, which can be used in the design stage of the process. In addition, a macro analysis gives an idea of the overall accuracy of the results, and the overall evaluation of the CDMs under different sets of environmental features. Moreover, CDMIA could be used in combination with other decision-support tools to widen its scope and to include into the decision-making process multiple aspects of coastal systems. The database will be updated on a regular basis to ensure the continuous relevance of the CDMIA. In the future, extension modules will be developed and integrated into the programme to allow the evaluation of the CDMs in relation to their ecological and social effects. Finally, the operationalization of the CDMIA will eventually be possible by completing a form in Microsoft Excel$^{©}$ or through a geographical information system via a linkage to the type of coast, type of substrate, tidal range, and wave climate.

CHAPITRE 4

ANALYSE MULTICRITÈRE POUR LA SÉLECTION D'OUVRAGES DE PROTECTION CÔTIÈRE : IMPLICATION DES GESTIONNAIRES ET PROFESSIONNELS CÔTIERS DANS L'IDENTIFICATION ET LA PONDÉRATION DES CRITÈRES DE SÉLECTION

4.1 RÉSUMÉ EN FRANÇAIS DU QUATRIÈME ARTICLE

Les systèmes socioécologiques côtiers sont des systèmes adaptatifs complexes caractérisés par un processus non linéaire et une dynamique à échelles spatio-temporelles multiples. Ces systèmes sont sujets à des épisodes d'érosion et de submersion côtière imprévisibles dont l'intensité est accentuée par les effets des changements climatiques. Une pression additionnelle est engendrée par une forte présence d'activités et de développement anthropique qui attirent plusieurs acteurs aux intérêts potentiellement divergents. Alors que les ouvrages de protection côtière (OPC) ont été aménagés pour atténuer les effets des aléas côtiers depuis plusieurs siècles, un manque de connaissances et d'outils pour prendre de bonnes décisions a mené les décideurs à favoriser les murs de protection ou les enrochements sans considérer leurs effets sur le SSEC. Les analyses multicritères, peu utilisées pour la sélection d'OPC, sont des outils qui permettent de faciliter le processus décisionnel lorsque plusieurs scénarios sont envisageables et que la décision repose sur plusieurs critères parfois conflictuels. PROMETHEE, une méthode de surclassement, a été choisie comme analyse multicritère pour l'évaluation d'OPC sur quatre sites d'étude caractérisés par des caractéristiques environnementales et sociales distinctes. La première phase du projet est basée sur un processus participatif dans lequel plusieurs acteurs ont été impliqués. L'objectif était de déterminer la pertinence et les bénéfices d'une analyse multicritère qui implique différents gestionnaires et professionnels de la zone côtière dans l'évaluation d'OPC adaptés au contexte socioécologique de chaque site. Premièrement, les acteurs de plusieurs organisations ont été invités à des ateliers tenus en rapport avec chaque site d'étude. Ils ont été amenés à identifier et à pondérer des critères de sélection d'OPC en fonction des priorités et des intérêts de leur organisation respective. Deuxièmement, avec la méthode PROMETHEE, les OPC ont été évalués en regard de chaque critère et des conditions socioécologiques locales. Troisièmement, les OPC ont été hiérarchisés. Les résultats initiaux montrent que le premier rang dans la hiérarchisation est occupé par la végétalisation pour trois des quatre sites et par l'enrochement pour le quatrième site, mais que les recharges de plage et les épis perméables devraient tout de même être considérés dans de futures analyses. À la suite de l'analyse du processus participatif, il est suggéré de remplacer l'identification des critères par la présentation d'une liste préétablie de critères à partir de laquelle les décideurs pourraient faire une sélection. Ainsi, une liste standardisée de critères assurerait un format compatible à l'analyse multicritère. Ultimement, une analyse multicritère combinée à un processus participatif est une méthode flexible qui permet de structurer les multiples aspects associés à la sélection d'un OPC et un outil qui peut contribuer significativement au processus décisionnel et à l'ingénierie côtière.

Cet article, intitulé « *Multicriteria decision analysis to assist in the selection of coastal defence measures: involving coastal managers and professionals in the identification and weighting of criteria* », a été corédigé par moi et mes deux directeurs, Pascal Bernatchez et Mathias Glaus. Il a été publié dans le journal *Frontier in Marine Science* en avril 2022. En tant que premier auteur, ma contribution fut de réaliser la majeure partie de la recherche sur l'état des connaissances, le développement des méthodologies utilisées pour l'exercice d'identification et de pondération des critères de sélection des OPC par les acteurs, la mise en application de la méthode PROMETHEE, l'évaluation des OPC en regard des critères, l'analyse des données, puis la rédaction de l'article. En tant que second auteur, Pascal Bernatchez a contribué à l'évaluation des OPC en regard des critères, à l'analyse des données, puis à la rédaction et à la révision de l'article. En tant que troisième auteur, Mathias Glaus a contribué à la réflexion sur le processus de consultation et sur la mise en application de la méthode PROMETHEE, à l'analyse des données ainsi qu'à la rédaction et à la révision de l'article. Stéphanie Friesinger, Maud Touchette, Christian Fraser et Catherine Paul-Hus ont contribué à la planification et à la réalisation des consultations. Stéphanie Friesinger a également participé à l'évaluation des OPC en regard de chaque critère de sélection.

4.2 MULTICRITERIA DECISION ANALYSIS TO ASSIST IN THE SELECTION OF COASTAL DEFENCE MEASURES: INVOLVING COASTAL MANAGERS AND PROFESSIONALS IN THE IDENTIFICATION AND WEIGHTING OF CRITERIA

ABSTRACT

Coastal socio-ecological systems are complex adaptive systems with nonlinear changing properties and multi-scale dynamics. They are influenced by unpredictable coastal hazards accentuated by the effects of climate change, and they can quickly be altered if critical thresholds are crossed. Additional pressures come from coastal activities and development, both of which attracting stakeholders with different perspectives and interests. While coastal defence measures (CDMs) have been implemented to mitigate coastal hazards for centuries, a lack of knowledge and tools available to make informed decision has led to coastal managers favouring the choice of seawalls or rock armours with little consideration for socio-ecological systems features, and stakeholders' priorities. Though it is not currently widely applied in coastal zone management, multicriteria decision analysis (MCDA) is a tool that can be useful to facilitate decision making. PROMETHEE, an outranking method, was chosen to support the multicriteria decision analysis for the evaluation of CDMs in the context of four study sites characterized by distinct environmental features. The aim was to determine the relevance and benefits of a MCDA by integrating coastal zone stakeholders in a participatory decision-making process in order to select CDMs that are better adapted to the whole socio-ecological system. First, in a series of five workshops, stakeholders were asked to identify and weigh criteria that were relevant to their local conditions. Second and third, CDMs were evaluated in relation to each criterion within the local context, then, hierarchized. Initial results show that vegetation came first in three of the four sites, while rock armour ranked first in the fourth site. A post-evaluation of the participatory process indicated that the weighting phase is an effective way to integrate local knowledge into the decision-making process, but the identification of criteria could be streamlined by the

presentation of a predefined list from which participants could make a selection. This would ensure criteria that are standardized, and in a format that is compatible with the MCDA. Coupled with a participatory process MCDA proved to be a flexible methodology that can synthetize multiple aspects of the problem, and contribute in a meaningful way to the coastal engineering and management decision-making process.

4.3 INTRODUCTION

In most regions of the world, the economic and social benefits in coastal zones tend to increase when population grows together with industrial and recreational activities (Airoldi et al., 2005; Dugan et al., 2011; Gittman et al., 2015). This attracts stakeholders with different perspectives and interests. As any socio-ecological system, coastal environments are complex adaptive systems with nonlinear changing properties and multi-scale dynamics that can be quickly and even irreversibly altered if critical thresholds are crossed. They are affected by multiple drivers of change, and subject to reciprocal feedbacks between social and natural components (Folke, 2016; Gallopín, 2006; Holling et Gunderson, 2002). Coastal systems are also influenced by uncertain coastal hazards, such as erosion and flooding, which are accentuated by the effects of climate change (Church et White, 2011 ; Nicholls et Cazenave, 2010 ; Ranasinghe, 2016 ; Wong *et al.*, 2014).

Coastal defence measures (CDMs) have been implemented to mitigate coastal hazards ever since the establishment of human settlements in coastal zones (Charlier et al., 2005). In the last decades, coastal zone development and the effects of climate change have led to an increase in shoreline armouring, mainly through the implementation of hard coastal defence structures (seawalls and rock armours) (Bernatchez et Fraser, 2012 ; Sauvé *et al.*, 2020), which can have a significant impact on coastal socio-ecological systems (Dugan *et al.*, 2011 ; Moschella *et al.*, 2005). In the Canadian province of Quebec, on the coasts of the St. Lawrence Estuary and Gulf, coastal defence structures were implemented as emergency measures, between the 1980s and the early 2000s, and it is still the case today, though to a lesser extent (Boyer-Villemaire et al., 2015). A lack of knowledge and tools available to make informed decisions has led to coastal managers favouring the choice of seawalls or rock armours over other types of CDMs (Drejza *et al.*, 2011 ; Friesinger et Bernatchez, 2010 ; Marie *et al.*, 2017). In addition, incomplete scientific knowledge with regard to CDMs effects on different types of coasts, an imbalance in scientific studies worldwide (Sauvé *et al.*, s. d.), and uncertainties brought about by varying climate projections (Polasky *et al.*, 2011), all add complexity to the decision-making process, and most certainly play a part in the reluctance by coastal managers to explore lesser known alternatives.

Knowledge and learning process are key to improving the resilience of coastal socio-ecological systems, and overcoming difficulties and uncertainties associated with the complex, and sometimes conflictual environmental management issues (Folke *et al.*, 2005 ; Garmendia *et al.*, 2010 ; Koontz *et al.*, 2015). Decision-making, traditionally the sole responsibility of scientists and experts, today tends to involve different stakeholders in an attempt to improve the transparency and flexibility of the process, and to implement measures that are better adapted to the whole socio-ecological system (Garmendia et al., 2010; Jones et al., 2014; Marttunen et al., 2017; Reed, 2008). A participatory process, implemented at an early stage by combining local interests and needs with scientific knowledge, leads to interventions that are better adapted to local socio-cultural and environmental conditions, and allows easier and more accurate monitoring and managing of environmental changes by local communities (Jacob *et al.*, 2021 ; Reed, 2008).

The decision-making process can also be enhanced by the use of decision support systems which are developed to improve the understanding of complex problems (National Research Council, 2009 ; Westmacott, 2001). Multicriteria decision analysis (MCDA) is one of the support systems used to facilitate decision making in cases where a variety of alternatives are possible, and depend on multiple and sometimes conflicting criteria. It is based on a pairwise comparison between different alternatives rated against every criterion from a set of pre-defined decision criteria (Marttunen et al., 2017; Scott et al., 2012). Criteria are parameters used to assess how each scenario would contribute to the achievement of a project objective (André et al., 2010). The criteria cover multiple aspects of the issue, while taking into consideration the needs and expectations of local stakeholders (Garmendia *et al.*, 2010). Within the decision-making process, once the problem, the context, and the objective have been established, MCDA is applied, and generally consists of three steps: criteria identification and weighting; scenario evaluation according to each criterion; and scenarios hierarchization (Dodgson *et al.*, 2009). The aim of criteria identification is to select a complete set of criteria that are mutually independent, without duplication, applicable to the local context, and consistent with effects occurring over time (De Bruin *et al.*, 2009). In the scientific literature, criteria identification is typically undertaken by scientists or experts (e.g. Chang et al., 2012; Monterroso et al., 2011; Trutnevyte et al., 2011) or, in more advanced participatory processes, by stakeholders through questionnaires, workshops, etc. (e.g. Antunes et al., 2011; Garmendia et Gamboa, 2012; Garmendia et al., 2010; Stagl, 2006; Trutnevyte et al., 2012). Criteria weighting can be defined as the measure of the importance of criteria according to stakeholders, experts, and scientists (Garmendia et Gamboa, 2012; Stagl, 2006). A group of stakeholders can agree on a set of criteria without attaching the same importance to each criterion (Garmendia et Gamboa, 2012). For the evaluation of scenarios according to each criterion, and for the scenarios hierarchization, MCDA can be divided into three types of methodology: complete aggregation methods, outranking methods, and iterative, trial-error methods (André *et al.*, 2010 ; Gamper et Turcanu, 2007 ; Maystre *et al.*, 1994). Complete aggregation methods allow the comparison of scenarios by aggregating all criteria into a single, synthetized, and exhaustive performance vector (André *et al.*, 2010). Outranking methods, through a preferential reference system, compare scenarios against a set of predefined criteria (André *et al.*, 2010 ; Gamper et Turcanu, 2007). Iterative, trial-error methods are based on a process that explores the feasibility of scenarios as discussed in successive dialogues with decision-makers (Gamper et Turcanu, 2007). Outranking methods are best suited to holistic land management because they take into account all stakeholders concerns, and integrate them into the analysis (Garmendia et Gamboa, 2012). MCDA outranking methods, such as PROMETHEE and ELECTRE, are generally applied to solve discrete choice problems by focusing on pairwise comparisons between different options (Belton et Stewart, 2002).

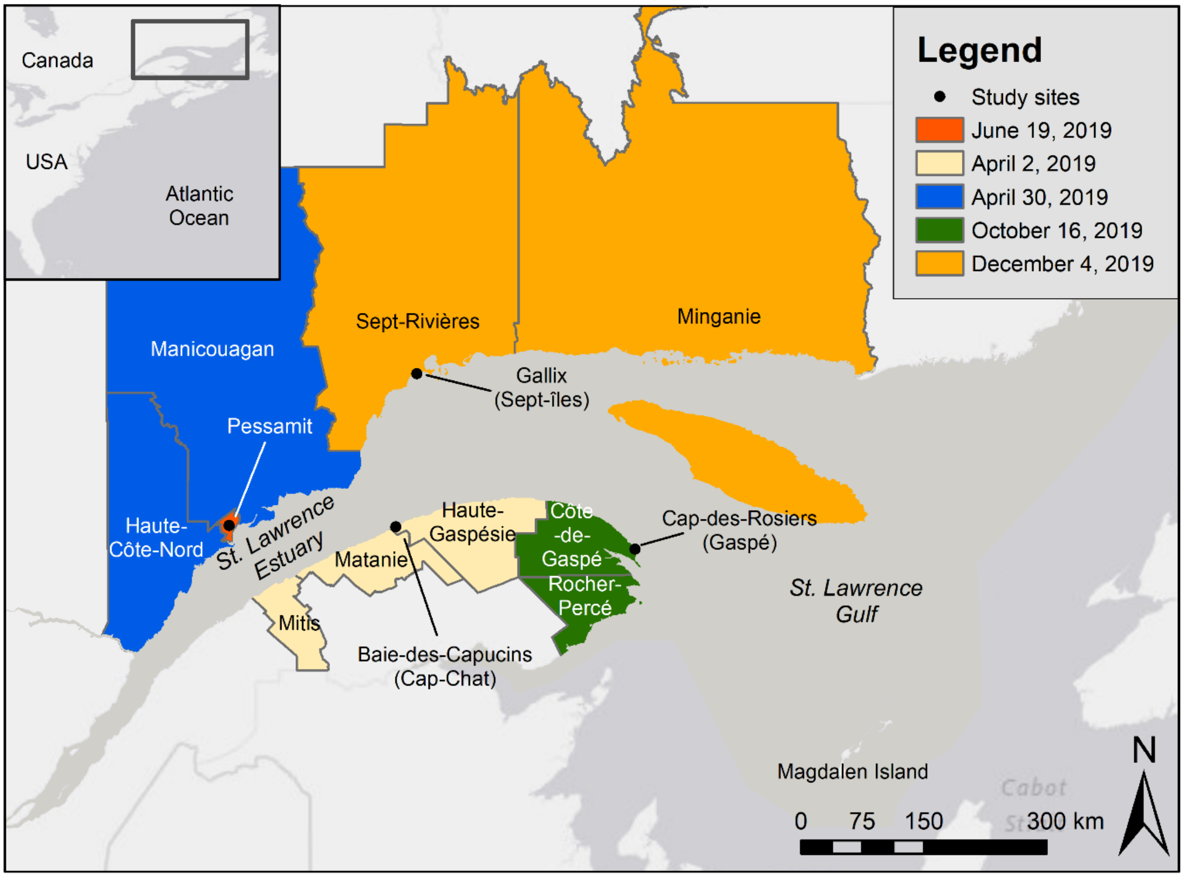
While MCDA has been used in many environmental management contexts (Ananda et Herat, 2009 ; Gamper et Turcanu, 2007) and in engineering problem solving in a marine context (Abdel-Basset *et al.*, 2021 ; Jajac *et al.*, 2019 ; Tavra *et al.*, 2017 ; Zafirakou *et al.*, 2018), to the authors' knowledge, it has not been applied to the evaluation and hierarchization of CDMs. From the review of scientific literature, it appears that cost-benefit analysis (CBA) has been the only decision support system used in such context (Polomé *et al.*, 2005). CBA is based on the evaluation of alternatives in terms of monetary units. It is fairly intuitive and straightforward for some aspects of the coastal system, but it is not appropriate or sophisticated enough when intangible and non-monetary characteristics, like aesthetic values or ecological impacts, are criteria identified as important factors in the decision-making process. The process of monetization leads to giving a monetary value to social or environmental non-market components (Bryce et al., 2016; Chan et al., 2012; McCauley, 2006). In contrast, MCDA is based on evaluation units that are specific to each of the selected criterion, which is one of the reasons why several European Union countries and United Nations' documents recommend the use of MCDA rather than CBA (Gamper et Turcanu, 2007).

Based on the results of an extensive participatory process held in Eastern Quebec, the aim of the present study is to determine the relevance of a multi-criteria decision analysis (MCDA) as a tool to structure and analyze a complex problem related to the selection of CDMs, while taking into account their effect on the socio-ecological system. The study also aims at assessing the benefits of a participatory decision-making process, which involves coastal zone managers and professionals in the identification and weighting of criteria used for the selection of coastal defence measures.

4.4 METHODS

4.4.1 Study sites

The studies were carried out in the Canadian province of Quebec, on the coasts of the Estuary and Gulf of St. Lawrence (EGSL). Four municipalities, characterised by distinct geomorphological, hydrodynamic, ecological or socio-economic features (figure 19), were selected as study sites: Pessamit, Gallix (Sept-Îles), Cap-des-Rosiers (Gaspé), and Baie-des-Capucins (Cap-Chat) (figure 18).



Source: Esri, Garmin, OpenStreetMap; Projection: NAD83; Autors: LDGIZC

Figure 18. Sites and MRCs from Eastern Quebec included in the study, with the workshops' dates in the legend


A) Pessamit B) Sept-îles (Gallix)


C1) Cap-Chat (Baie-des-Capucins) C2) Cap-Chat (Baie-des-Capucins)


D1) Gaspé (Cap-des-Rosiers) D2) Gaspé (Cap-des-Rosiers)

Figure 19. Study sites. (A) Pessamit: indigenous community located on a sandy littoral spit with wide unvegetated sandy foreshore. (B) Sept-Îles (Gallix): sandy beach terrace with a narrow band of sea cabbage characterised by the formation and disappearance of a sandy triangular salient. (C1, C2) Cap-Chat (Baie-des-Capucins): beach terrace of coarse sand, cobbles and pebbles, fronted by a wide vegetated salt marsh. (D1, D2) Gaspé (Cap-des-Rosiers): rocky cliff with an unconsolidated top and a lower foreshore of cobbles partially covered by rockweeds

4.4.1.1 Pessamit

Pessamit is an indigenous community located on the North Shore of the St. Lawrence maritime estuary. Pessamit's coast, which extends over a 12 km span, is mainly composed of unconsolidated cliffs (53.7%), littoral spit (21.0%), salt marsh (20.7%), and beach terrace (4.6%). The tidal range is mesotidal and the offshore significant wave height (95th percentile) is 0.85 m (depth of 132 m). The study site is located on a sandy littoral spit. A wide unvegetated sandy foreshore is present in front of the coast. The study site is a part residential, and part public sector, highly frequented by the local community for a variety of uses and activities: off-road vehicles, boat launching, gatherings, walking, beach activities, archeological site, waterfowl concentration area, etc.

4.4.1.2 Gallix (Sept-Îles)

Sept-Îles is located on the North Shore of the Gulf of St. Lawrence. The study site, Gallix, is located in the Sainte-Marguerite Bay, which extends along 26.90 km, and is mainly composed of littoral spit (10.4 %), unconsolidated cliff (47.0 %), beach terrace (41.8 %), and rocky shore (0.8 %). The tidal range is mesotidal and the offshore significant wave height (95th percentile) is 0.75 m (depth of 90 m) (Corriveau *et al.*, 2021). The study site is located on a sandy beach terrace, and is characterised by the formation and disappearance of a sandy triangular salient (figure 20). This dynamic is generated by estuarian currents and littoral drift. Storm events, between 2009 and 2017, have caused high shoreline retreat (7.96 m/yr), leading to a shoreline enlargement on the west side of the coastal sector (figure 20). A new salient slightly to the east was formed between 2013 and 2016, and was still present in 2017. That new salient modifies the longitudinal sediment transport processes, leading to an offshore sediment deviation. Sediments are redirected towards the coast, further to the West, resulting in a sediment progradation in the coastal sectors (Corriveau *et al.*, 2019c). A rock armour structure is present between the salient formed in 2013-2016, and the high shoreline retreat sector (figure 20). The sandy lower foreshore is partially covered (0-25 %) by a narrow band of macroalgua (mainly *laminaria longicruris*). A bar system is also present in front of the study site. The study site is a residential sector, with high scenic and socio-cultural values, and is mainly used by the local community for fishing, nautical and beach activities, gatherings, walking, etc. It is also a waterfowl concentration area, and spawning ground for capelin.

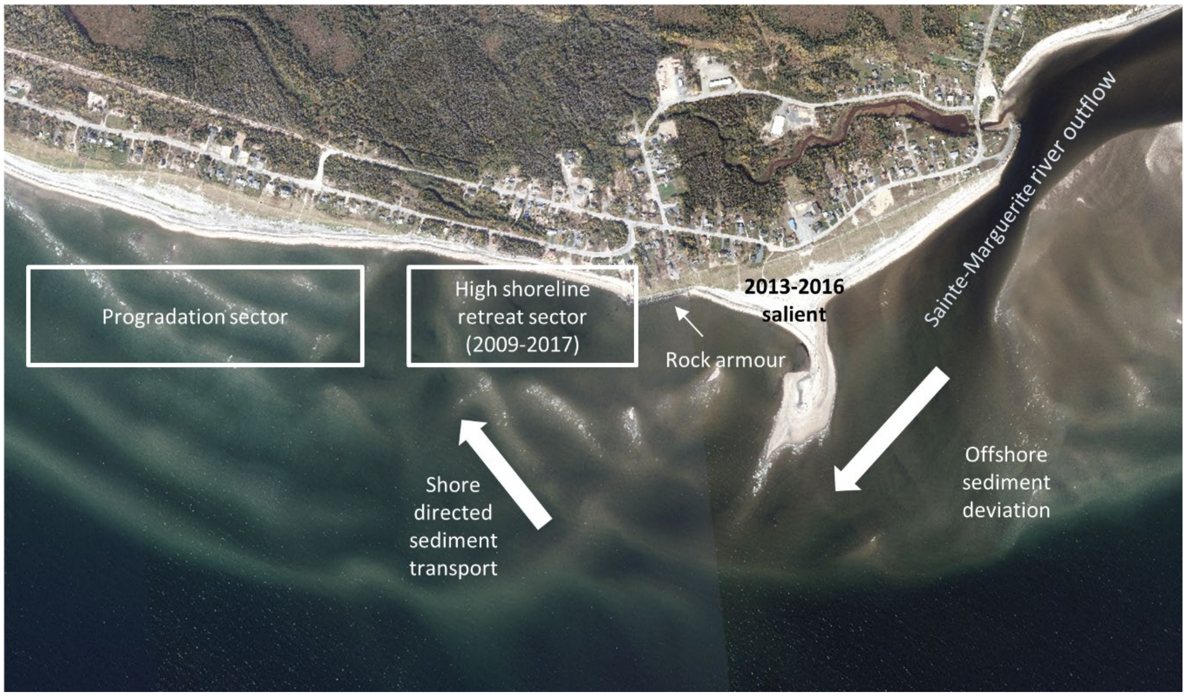


Figure 20. Coastal dynamic illustration from the Gallix study site (modified from Corriveau et al. (2019c))

4.4.1.3 Baie-des-Capucins (Cap-Chat)

Cap-Chat is located on the Gaspé Peninsula on the south shore of the St. Lawrence river. Baie-des-Capucins, a bay located east of Cap-Chat, extends over approximately 3.2 km, and is mainly composed of beach terrace (54.4 %), unconsolidated cliff (15.0 %), rocky cliff (10.3 %), and salt marsh (8.1 %). The study site is located on a beach terrace composed of a mixture of coarse sand, cobbles and pebbles, and by a wide salt marsh vegetated with *spartina alterniflora*. The bay's entrance is partially (1-25%) vegetated with *Zostera marina* and *Fucus sp*. The tidal range is mesotidal and the wave energy is low. The littoral drift is directed towards the inside of the bay. The site is a biodiversity hotspot, and the main activities are nautical activities, walking and fishing. The national road 132 is, in some areas, less than 5 metres from the shoreline.

4.4.1.4 Cap-des-Rosiers (Gaspé)

Gaspé is located on the Gaspé Peninsula on the south shore of the Gulf of St. Lawrence. Cap-des-Rosiers, a former village annexed to the town of Gaspé, is located at the far north-east end of the Gaspé peninsula. The study site is located on a rocky cliff stretch of coast with an unconsolidated lower (cobbles) foreshore and a rocky infralittoral zone. The lower foreshore is partially (0-25%) covered by macroalgua (mainly *fucaceae*). The tidal range is mesotidal and the offshore significant wave height from ESE-SE reached more than 3 m between November 2017 and 2019 (Savoie-Ferron *et al.*, 2020). The study site is a residential sector with low density activities. Still, tourism infrastructures, such as motels, are present in Cap-des-Rosiers due to the proximity of the Forillon National Park, which brings a high volume of tourism during the summer season. The main activities are gatherings and relaxation. Cap-des-Rosiers is a biodiversity hotspot, and has a high socio-cultural value with, among others, the Cap-des-Rosiers lighthouse, the tallest in Canada. The national road 132 is, in some areas, less than 5 metres from the cliff.

4.4.2 Selection of coastal defence measures to be evaluated

CDMs that were suitable for each of the four study sites were pre-selected, either by a comitee of experts, or by using a coastal defence measure identification algorithm (CDMIA) developed by Sauvé et al. (2022). The number of CDMs can vary from site to site (tableau 39). The CDMIA processed information that was drawn from 411 published scientific case studies, which included 1709 statements on the effects of CDMs on the environment as observed by the authors of the studies. It then established a correspondence between user-selected environmental features, and those stocked in the database, and it evaluated user-selected CDMs in relation to the specified coastal characteristics by identifying, collating, and rating their effects as observed in similar contexts. Since few CDMs studies have been conducted on rocky cliffs, the CDMs deemed suitable for the terrain at Cap-des-Rosiers, were selected by a comitee of experts, instead of through the CDMIA. In the case of Baie-des-Capucins which is characterized by two types of coasts, a beach terrace and a salt marsh, the results of the CDMIA from both types of coasts were combined to select CDMs adapted to such conditions. Also, in Baie-des-Capucins, the low-crested breakwater scenario was based on a living shoreline rock sill concept (Bilkovic *et al.*, 2017a). The selected CDMs were then evaluated with the use of a MCDA methodology.

Tableau 39

CDMs pre-selected for 3 of the study sites using Sauvé et al.'s CDMIA (n.d.), and in the case of Cap-des-Rosiers, selected by a comitee of experts, with the number of CDMs per site

Study sites			
Pessamit	Gallix, Sept-îles	Baie-des-Capucins, Cap-Chat	Cap-des-Rosiers, Gaspé
CDMs			
Land vegetation Foreshore nourishment Permeable groin Beach nourishment Emerged breakwater Impermeable groin	Land vegetation Foreshore nourishment Permeable groin Beach nourishment Emerged breakwater Impermeable groin Submerged breakwater	Vegetation Beach nourishment Low crested breakwater Permeable groin	Rock armour Seawall Emerged breakwater Low-crested breakwater Beach nourishment
Number of pre-selected CDMs			
6	**7**	**4**	**5**

4.4.3 Multi-criteria decision analysis

For the multi-criteria decision analysis, an outranking method was preferred, as it allows an evaluation between scenarios that initially do not appear to be comparable with each other, and it maintains ranking units that are specific to each criterion (Gamper et Turcanu, 2007 ; Garmendia et Gamboa, 2012). The PROMETHEE method was chosen as multi-criteria decision-making tool, using the VISUAL PROMETHEE software

(VPSolutions, 2013). It was preferred for its stability (Brans *et al.*, 1986), and because it is widely used in environmental management contexts (Behzadian *et al.*, 2010).

4.4.3.1 PROMETHEE method

The PROMETHEE method is based on a pairwise comparison between different alternatives, following their assessment A = $\{a_1, a_2, \ldots, a_n\}$ against each criterion c_k ($\Delta_k(a_i, a_j)$) from a defined set of criteria C = $\{c_1, c_2, \ldots, c_m\}$ (équation 3). The variations in the results of the assessments $\Delta_k(a_i, a_j)$ associated with criterion c_k, are translated into a preference index $P[\Delta_k(a_i, a_j)]$ through a preference function, which lies between 0 and 1, 1 being a strong preference, and 0 meaning no preference. In this study, the usual preference function was used; it corresponds to the optimization of values without threshold, that is, larger values are better than lower ones. The multicriteria index $\pi(a_i, a_j)$ is the weighted sum of the preference index P, and is calculated by dividing the preference index by the weight w_k, which is a measure of the importance of the criterion c_k determined by workshop participants (équation 4). The leaving $\Phi^+(a_i)$ and entering $\Phi^-(a_i)$ flows are then calculated in relation to the multicriteria index. The leaving flow expresses the extent to which a_i outranks all other alternatives (équation 5), and the entering flow expresses how much a_i is outranked by all other alternatives (équation 6). Thus, the best alternative has the highest leaving flow and the lowest entering flow. The net flow is the sum of the leaving and entering flows and represents an overall ranking. All criteria were set as maximum with the exception of the criteria whose evaluation was based on the 5 points impact qualitative scale (geomorphological effects, ecological effects and aesthetics). The specificities of the PROMETHEE method are described in the works of Brans et al. (1986) and in the Visual PROMETHEE software's manual (VPSolutions, 2013).

$$\boldsymbol{\Delta_k(a_i, a_j) = c_k(a_i) - c_k(a_j)} \qquad \text{Équation 3}$$

$$\boldsymbol{\pi(a_i, a_j) = \sum_{x \in k} P_k(a_i, a_j) \Big/ \sum_{k} w_k} \qquad \text{Équation 4}$$

$$\boldsymbol{\Phi}^{+}(\boldsymbol{a_i}) = \sum_{\boldsymbol{k}} \boldsymbol{\pi}(\boldsymbol{a_i}, \boldsymbol{x}) \qquad \text{Équation 5}$$

$$\boldsymbol{\Phi}^{-}(\boldsymbol{a_i}) = \sum_{\boldsymbol{x} \in \boldsymbol{k}} \boldsymbol{\pi}(\boldsymbol{x}, \boldsymbol{a_i}) \qquad \text{Équation 6}$$

4.4.3.2 Criteria identification and weighting

Coastal zone stakeholders were consulted in the course of two action research projects, with the aim of developing tools to improve coastal planning and protection, and to facilitate the choice of solutions adapted to climate change, in the short, medium and long terms. First, four workshops were organized between April and December 2019, in Eastern Quebec, in the context of the Coastal Resilience project. Stakeholders who were invited to the workshops included administrative personnel and professionals from local municipalities and coastal MRCs (regional county municipalities), relevant ministries, local and regional organizations, and members of the First Nations (tableau 40). Second, in June 2019, in the context of a project entitled *Identification de solutions d'adaptation aux aléas côtiers pour augmenter la résilience des communautés des Premières Nations dans un contexte de changements climatiques*, a workshop was organized in Pessamit. Participants to this workshop comprised administrative personnel and professionals from the community. Through various activities, one of the aims was to integrate stakeholders into the decision-making process leading to the implementation of coastal defence measures, by asking them to identify and weigh the CDMs selection criteria (figure 21). The locations of the four study sites and five workshops are shown in figure 18.

For Pessamit, all participants were employees of the municipality, many of them, members of the First Nations; they were all recorded under Municipality rather than First Nations to avoid duplication.

Using an adaptation of the World Cafe methodology (Brown et al., 2005), the participants were separated into rotating discussions groups of between five and fifteen people. The aim was to allow participants to express their views on different subjects related to coastal management, each within a 25-minute time frame. With two facilitators in charge of the discussion, one table was dedicated to discussing relevant criteria to be integrated in the decision-making process for the selection of coastal defence measures.

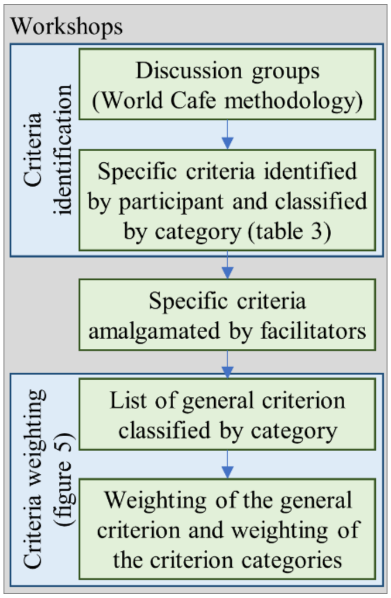


Figure 21. Graphical representation of the method used for the implication of workshop participants in the identification and weighting of the CDMs selection criteria

At the beginning of the discussion, participants were presented with a brief description of factors affecting the CDMs decision-making process, in order for them to understand the context before identifying the CDMs selection criteria. The question "*In your opinion, which are the criteria to be considered when a coastal defence measure must be selected?*" was asked of participants to start the discussion. Five criteria categories written on cards were presented to participants as a guide (tableau 41). Specific criteria identified by participants were written on post-it notes and affixed to their corresponding category. The selection criteria identified by participants of one table served as a basis for discussion in the following rotating groups.

Tableau 40

Number of participants per organisation (MAMH: Ministry of Municipal Affairs and Housing; MELCC: Ministry of Environment and Climate Change; MERN: Ministry of Energy and Natural Resources; MFFP: Ministry of Forests, Wildlife and Parks; MSP: Ministry of Public Security; MSSS; Ministry of Health and Social Services; MTQ: Ministry of Transports; MRC: regional county municipality)

	Coastal resilience project				**Innus III project**
Organisation	**Haute-Côte-Nord, Manicouagan**	**Sept-Rivières, Minganie**	**Mitis, Matane, Haute-Gaspésie**	**Côte-de-Gaspé, Rocher-Percé**	**Pessamit**
Ministry	**8**	**7**	**5**	**10**	**-**
MAMH	1	1		-	-
MELCC	2	1	1	2	-
MERN	1	1	-	1	-
MFFP	-	1	-	-	-
MSP	3	2	3	2	-
MSSS	-	-	1	-	-
MTQ	1	1	-	5	-
Municipality	**6**	**4**	**1**	**2**	**-**
MRC	-	2	1	1	-
Municipality	6	2	-	1	12
ONG	**2**	**6**	**1**	**5**	**-**
First Nations	**5**	**2**	**1**	**-**	**-**
Total	**21**	**25**	**8**	**17**	**12**

Tableau 41

Criteria categories presented to participants

Criteria categories	**Description**
Economic context	Criteria related to costs, benefits, economic issues.
Environmental context	Criteria related to environmental impacts.
Social context	Criteria related to acceptability, accessibility, activities, culture.
Project management	Criteria related to planning and execution of construction site.
Technical characteristics	Criteria related to coastal defence measure behaviour, reliability.

A weighting method was established to allow participants to assess the importance of the criteria they previously identified. A three steps classification system was created: first, a list of criteria, as identified by the participants, was compiled; second, from that list, criteria that were similar in nature were amalgamated by the facilitators under a maximum of five general criteria per criteria category; third, the general criteria were grouped under five criteria categories.

Each criteria category was limited to a maximum of five general criteria to limit the total number of criteria, and because it was deemed sufficient to capture and adequately represent all of the criteria identified by the participants. Each general criterion was written on a card with the list of similar criteria originally identified by the participants. The weighting of the general criteria was carried out in two steps. The voting table was divided into six sections: one for each criteria category with its list of general criterion, and one which listed the five criteria categories (figure 22).

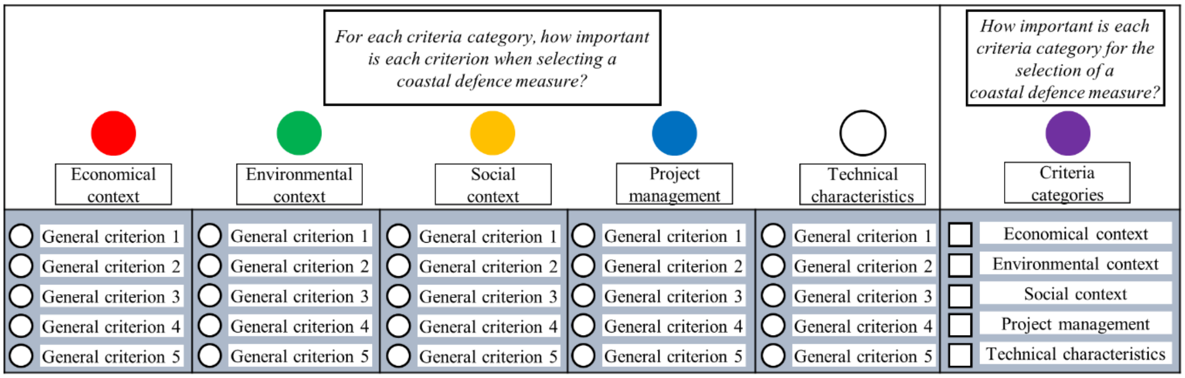


Figure 22. Voting table illustration

As a first step, each general criterion card was placed on the voting table under its respective category, with a corresponding voting box. Each participant was given ten tokens per criteria category to weight each general criterion according to the question "*For each criteria category, how important is each criterion when selecting a coastal defence measure?*". As a second step, the five criteria categories' cards were placed in the sixth section, each with a corresponding voting box. As for the previous exercise, participants were given ten tokens to weight the criteria categories according to the question “*How important is each criteria category for the selection of a coastal defence measure?*”.

4.4.3.3 CDMs evaluation according to each criterion

The evaluation of CDMs in relation to each criterion was based on experts’ judgement, and on different sources of data such as literature reviews, reports on CDMs, etc. In the PROMETHEE method, different rating scales can be defined, depending on the nature of the criterion. Here, two scales were used: a 9 points qualitative scale for the criteria that lead to the comparison of CDMs’ performance relative to each other (very good (9) , very good – good, good, good – average, average, average - bad, bad, bad – very bad, and very bad (1)); and a 5 points impact qualitative scale for the criteria that lead to the evaluation of the direct effects of CDMs on the coastal system (very low (5), low, moderate, high, very high (1)). Two qualitative scales were used for the evaluation of criteria due to a lack of quantitative local data. For example, the evaluation for the cost related criteria was based on the cost of previous projects at a national scale.

4.5 RESULTS

4.5.1 Identified and weighted CDM criteria

Following the five workshops, the criteria identified by the participants were standardized with uniform wording, and classified under five categories (tableau 42). A comprehensive list of sixteen criteria that were mutually independent, without duplication, relevant to the context, and consistent with effects occurring over time, was thus established (figure 23). The list of criteria built during the five workshops was used in the analysis of the four study sites described above, even though only one of the workshops was specific to a study site (Pessamit). Of the remaining workshops, three drew participants from regions around and including a study site, and one was held in a region that did not include a study site (the MRC of Haute-Côte-Nord and Manicouagan).

Tableau 42

Standardized criteria identified by participants during the workshops

Criteria	Definition
Economic context	
Economic repercussions	Indirect economic development benefits.
Construction costs	Initial CDM building costs including cost of materials, labour force, and equipment.
Maintenance costs	Funds required to maintain optimum CDM performance including cost of materials, labour force, and equipment.
Environmental context	
Geomorphological effects	Importance of the modifications generated by the CDM on the morphology of a sediment cell.
Ecological effects	Importance of the modifications generated by the CDM on the ecosystem of a sediment cell.
Indirect environmental benefits	Environmental benefits through the creation or the maintenance of ecological services
Social context	
Social repercussions	Impacts on the community's quality of life and activities, as well as on cultural and patrimonial aspects.
Social perception	Public perception of the CDM.
Aestheticism	Visual impact and potential for the integration of the CDM into the broader landscape.
Project management	
Ability to achieve	Ability to implement a CDM in terms of completion time, and availability of labour force and expertise at the municipal level.
Regulatory liability	Likelihood of the CDM being subject to local regulations and environmental impact assessment.
Technical feasibility	Complexity of the CDM construction depending on the type of structure, availability of materials and accessibility to the site.
Technical characteristics	
Adaptability	Capacity for the CDM to be adapted to changes in the environmental parameters.
Durability	Length of time a CDM can retain its integrity with minimal maintenance.
Efficiency	Ability of the CDM to slow down the retreat of the shoreline and to protect the coastal infrastructures during an event, as long as it is in perfect condition, of standard dimensions and appropriate to local hydro-sediment cell dynamic.
Maintenance	Frequency of maintenance required to preserve the effectiveness of the CDM.

As shown in figure 23, the identification and weighting of criteria vary between workshops. First, not all criteria were selected in every workshop, as some may not have been relevant or important to the particular context. The adaptability criterion for instance was only identified in the case of Cap-des-Rosiers, while the maintenance and indirect environmental effects were not selected at the Pessamit workshop. Second, the weight assigned to different criteria varied between workshops, and the data range is wide. In general, the average weight is highest for ecological effects and social repercussions. In the case of Baie-des-Capucins, the weight given to the construction cost criterion is the highest among all criteria for all workshops.

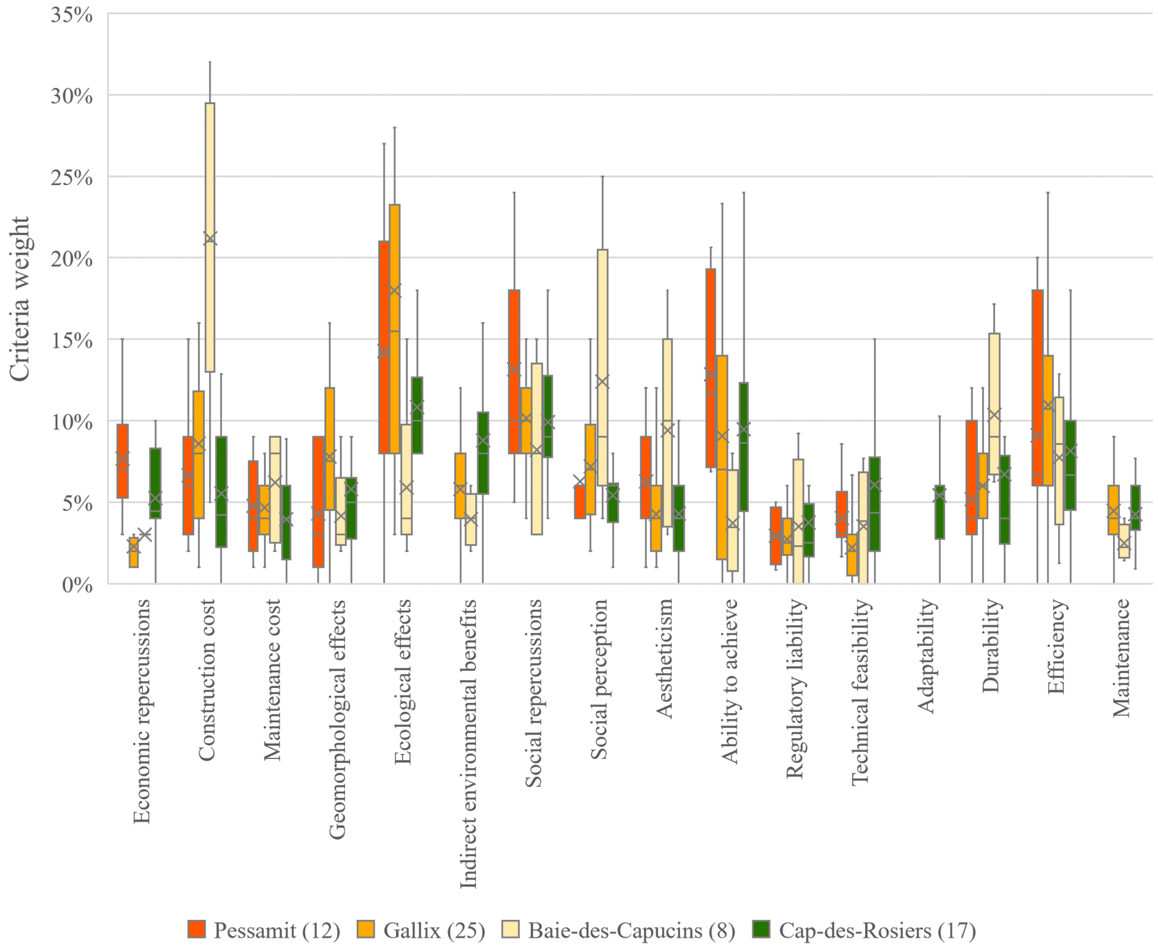


Figure 23. Standardized criteria identified by participants and their weighting range for each workshop. Number of participants per site is indicated in parenthesis

For the purpose of weighting analysis, an average baseline can be calculated by dividing 100 percent by the number of identified criteria. For example, in Cap-des-Rosiers, 16 criteria were identified by workshop participants for an average baseline of 6.25%. While the majority of the criteria weight values are close to 6.25%, the ecological effects and social repercussions criteria are nearly twice the average value, which is an indication of the high importance accorded to these criteria by local stakeholders.

4.5.2 CDMs evaluation

CDMs evaluation was carried out in two phases: (1) weighting of each CDM in relation to each criterion; (2) final hierarchization.

4.5.2.1 CDMs evaluation in relation to each criterion

The CDMs evaluation is dependent on each criterion (tableau 42), and on the socio-ecological features associated with each site. The evaluation scale was adapted to the nature of each criterion.

The evaluation of the CDMs in relation to each criterion and to each study site's socio-ecological features is presented in tableau 43, with rationale where relevant.

4.5.2.2 CDMs hierarchization

The CDMs hierarchization is thereafter presented in diamond shape figures for each study site (figure 24). This shape shows the overall ranking (Φ net) along the vertical axis, as well as the leaving Φ^+ and entering Φ^- flows along the left edges of the diamond. Each CDM is represented by a grey dot. For one CDM to be ranked higher than another, it must outperform it on both the leaving and entering flow axes.

Tableau 43

Weighting of CDMs in relation to each criterion and sites' characteristics, with relevant rationale

Criteria	**Sites**	Rock armour	Seawall	Emerged breakwater	Low-crested breakwater	Submerged breakwater	Impermeable groin	Permeable groin	Beach nourishment	Foreshore nourishment	Vegetation
Economic repercussions	*Pessamit*	-	-	9	-	-	5	5	7	6	5
	Gallix	-	-	9	-	9	5	5	7	6	5
	Baie-des-Capucins	-	-	-	5	-	-	5	5	-	5
	Cap-des-Rosiers	5	5	9	9	9	-	-	5	-	-
	Breakwaters: possible colonization by species of high economic interest. (Baie-des-Capucins: low-crested breakwater option in the salt marsh: expected results would not be the same as for conventional breakwaters). **Nourishments:** none of the site are currently tourist sites; potential for development of tourism in Gallix and Pessamit.										
Construction costs	*Pessamit*	-	-	2	-	-	5	5	3	2	9
	Gallix	-	-	2	-	2	5	5	3	2	9
	Baie-des-Capucins	-	-	-	2	-	-	5	3	-	9
	Cap-des-Rosiers	7	5	2	2	2	-	-	3	-	-
	Breakwaters: offshore construction. **Groins**: land construction. **Beach nourishment:** land construction. **Foreshore nourishment:** offshore construction; same material as beach nourishment. **Vegetation:** very low-cost material.										
Maintenance costs	*Pessamit*	-	-	3	-	-	6	6	2	1	9
	Gallix	-	-	3	-	5	6	6	2	1	9
	Baie-des-Capucins	-	-	-	4	-	-	6	2	-	9
	Cap-des-Rosiers			3	4	-	-	-	2	-	9
	Breakwaters: offshore construction; low to moderate maintenance frequency. **Groins**: land construction; moderate maintenance frequency. **Beach nourishment:** land construction; high maintenance frequency. **Foreshore nourishment:** offshore construction; high maintenance frequency. **Vegetation:** high maintenance frequency; very low-cost material.										
Geomorphologic effects	*Pessamit*	-	-	2	-	-	2	4	4	4	3
	Gallix	-	-	2	-	3	2	4	4	4	3
	Baie-des-Capucins	-	-	-	3	-	-	3	4	-	3
	Cap-des-Rosiers	4	4	2	3	-	-	-	4	-	-
	Breakwaters: beach widening; offshore transport reduction. **Permeable groin**: sediment accumulation; beach widening. (Emerged breakwater and impermeable groin may cause sediment retention. Baie-des-Capucins: accumulation effect reduced due to a low longshore sediment transport). **Nourishments:** increase sediment budget for the sediment cell (at a higher level for beach nourishment. Cap-des-Rosiers: reduce the interaction between cliff and waves). **Vegetation:** sediment stabilisation and sediment accumulation acceleration at a small local scale. **Rock armour and seawall:** effects similar to the natural effects generated by the cliff.										
Ecological effects	*Pessamit*	-	-	2	-	-	3	3	3	3	5
	Gallix	-	-	2	-	2	3	3	3	3	5
	Baie-des-Capucins	-	-	-	3	-	-	3	3	-	5
	Cap-des-Rosiers	4	4	3	3	-	-	-	3	-	-
	Breakwaters: loss of sedimentary habitat; species dispersal, loss of micro-habitats, siltation, water quality degradation. (Baie-des-Capucins: reduce ecological effects due to low hydrodynamism). **Groin**: loss of sedimentary habitat; physical barrier. **Nourishments:** organism burial; increasing temporary turbidity; modification of substrate permeability; ecosystem assemblage modifications. **Vegetation:** coastal ecosystem maintenance. **Enrockement and seawall:** effects similar to the natural effects generated by the cliff.										

Tableau 43 (suite)

Weighting of CDMs in relation to each criterion and sites' characteristics, with relevant rationale

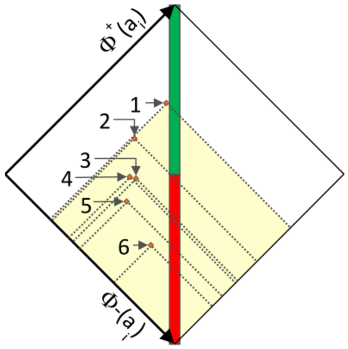
Criteria	**Sites**	Rock armour	Seawall	Emerged breakwater	Low-crested breakwater	Submerged breakwater	Impermeable groin	Permeable groin	Beach nourishment	Foreshore nourishment	Vegetation
Indirect environmental benefits	*Pessamit*	-	-	-	-	-	-	-	-	-	-
	Gallix	-	-	4	-	4	4	5	6	5	8
	Baie-des-Capucins	-	-	-	4	-	-	5	5	-	6
	Cap-des-Rosiers	4	5	6	6	-	-	-	6	-	-
	Rock armour: reduces beach ecosystem width due to encroachment. **Seawall:** limited effects in a context of reflective rocky cliff. **Breakwater:** increase potential ecosystem habitats in Cap-des-Rosiers' rocky environment; reduction of ecological services in sandy Gallix and in Baie-des-Capucins' salt marsh. **Beach nourishment**: increase beach ecosystem width. **Vegetation:** increase of the actual vegetated area in Gallix more than the actual vegetated area in Baie-des-Capucins.										
Social repercussions	*Pessamit*	-	-	3	-	-	3	4	6	6	5
	Gallix	-	-	3	-	3	3	4	6	6	5
	Baie-des-Capucins	-	-	-	4	-	-	4	6	-	5
	Cap-des-Rosiers	5	5	5	5	-	-	-	6	-	-
	Breakwaters and groins: create an obstacle to navigation; potential formation of rip currents; increases the area for recreational use in the medium term. (Permeable groins: similar effects but on a smaller scale. Cap-des-Rosiers: less activities on the beach). **Nourishments:** increased area for recreational use **Vegetation:** no repercussion.										
Social perception	*Pessamit*	-	-	3	-	-	2	2	4	4	7
	Gallix	-	-	8	-	8	6	2	7	7	9
	Baie-des-Capucins	-	-	-	2	-	-	1	2	-	3
	Cap-des-Rosiers	4	9	1	1	-	-	-	1	-	-
Aestheticism	*Pessamit*	-	-	1	-	-	3	3	4	5	5
	Gallix	-	-	1	-	5	3	3	4	5	5
	Baie-des-Capucins	-	-	-	2	-	-	3	4	-	5
	Cap-des-Rosiers	4	3	2	3	-	-	-	4	-	-
	Emerged breakwaters: offshore visual obstacle; no similarity with natural landscape. **Groins:** limited similarity with landscape (for wooden groin). **Beach nourishments:** similarity with the natural landscape. **Vegetation:** strong similarity with the natural landscape.										
Ability to achieve	*Pessamit*	-	-	7	-	-	8	8	7	5	9
	Gallix	-	-	7	-	7	8	8	7	5	9
	Baie-des-Capucins	-	-	-	7	-	-	8	7	-	9
	Cap-des-Rosiers	9	9	7	7	-	-	-	7	-	-
	Breakwaters: expertise to be refined, but present in Quebec; mechanical equipment available. **Groins**: expertise present in Quebec; equipment widely available. **Nourishments:** expertise under development in Quebec; mechanical equipment widely available (land-based sediments); dredging available, but rare and complex from a regulatory point of view. **Vegetation:** expertise available.										
Regulatory liability	*Pessamit*	-	-	1	-	-	3	1	3	1	5
	Gallix	-	-	1	-	1	3	1	3	1	5
	Baie-des-Capucins	-	-	-	1	1	3	1	3	1	5
	Cap-des-Rosiers	5	5	1	1	-	-	-	3	-	-

Tableau 43 (suite)

Weighting of CDMs in relation to each criterion and sites' characteristics, with relevant rationale

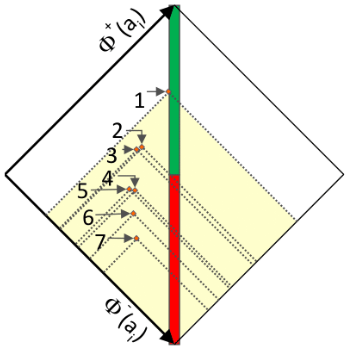
Criteria	**Sites**	Rock armour	Seawall	Emerged breakwater	Low-crested breakwater	Submerged breakwater	Impermeable groin	Permeable groin	Beach nourishment	Foreshore nourishment	Vegetation
Technical feasibility	*Pessamit*	-	-	1	-	-	7	7	7	3	9
	Gallix	-	-	1	-	1	7	7	7	3	9
	Baie-des-Capucins	-	-	-	1	-	-	7	7	-	9
	Cap-des-Rosiers	4	3	1	1	-	-	-	7	-	-
	Breakwaters: complex structures with several layers built underwater and offshore. **Groins**: simple structures; land construction. **Nourishments:** relatively simple technique; land and offshore construction sites. **Vegetation:** expertise available.										
Adaptability	*Pessamit*	-	-	-	-	-	-	-	-	-	-
	Gallix	-	-	-	-	-	-	-	-	-	-
	Baie-des-Capucins	-	-	-	-	-	-	-	-	-	-
	Cap-des-Rosiers	4	2	4	4	-	-	-	9	-	9
	Rock armour, Breakwaters: structures can be adapted. **Seawall**: complex to adapt. **Nourishments, vegetation:** adapt naturally.										
Durability	*Pessamit*	-	-	5	-	-	6	6	2	2	1
	Gallix	-	-	5	-	7	6	6	2	2	1
	Baie-des-Capucins	-	-	-		-	-	6	2	-	1
	Cap-des-Rosiers	8	9	5	6	-	-	-	1	-	-
	Breakwaters, groins: structures made of materials potentially subject to movement (emerged: continuously exposed to wave action). **Nourishments:** continuously exposed to wave action; unconsolidated materials. **Vegetation:** rare exposure to wave action; low resistance materials.										
Efficiency	*Pessamit*	-	-	7	-	-	5	5	7	6	2
	Gallix	-	-	7	-	6	5	5	7	6	2
	Baie-des-Capucins	-	-	-	7	-	-	5	7	-	2
	Cap-des-Rosiers	7	8	7	7	-	-	-	5	-	-
	Breakwaters: reduce wave energy offshore; lead to sediment deposit. **Groins**: lead to sediment deposit on medium term. **Nourishments:** stabilize or advance the coastline; are dependent on maintenance. **Vegetation:** stabilizes sediment at a minor scale.										
Maintenance	*Pessamit*	-	-	-	-	-	-	-	-	-	-
	Gallix	-	-	6	-	6	6	6	2	2	1
	Baie-des-Capucins	-	-	-	6	-	-	6	2	-	1
	Cap-des-Rosiers	8	7	6	6	-	-	-	2	-	-

a)



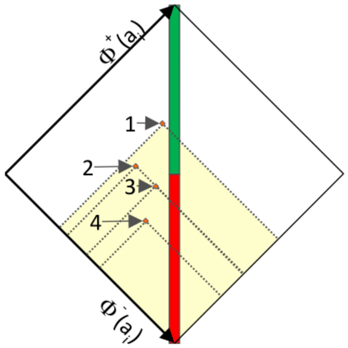
RNK	CDM	net flows (Φ)	leaving flows (Φ^+)	entering flows (Φ^-)
1	Vegetation	0.418	0.686	0.268
2	Beach nourishment	0.209	0.489	0.280
3	Permeable groin	-0.018	0.361	0.379
4	Foreshore nourishment	-0.0282	0.374	0.403
5	Impermeable groin	-0.162	0.280	0.4415
6	Emerged breakwater	-0.418	0.222	0.641

b)



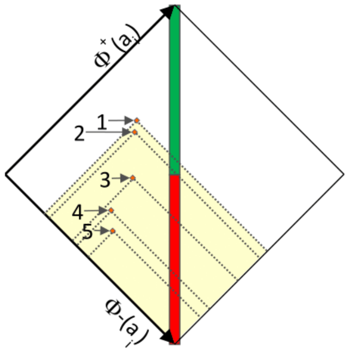
RNK	CDM	net flows (Φ)	leaving flows (Φ^+)	entering flows (Φ^-)
1	Vegetation	0.484	0.723	0.239
2	Beach nourishment	0.158	0.483	0.325
3	Permeable groin	0.146	0.462	0.316
4	Foreshore nourishment	-0.085	0.327	0.412
5	Impermeable groin	-0.094	0.338	0.432
6	Submerged breakwater	-0.231	0.265	0.496
7	Emerged breakwater	-0.378	0.199	0.577

c)



RNK	CDM	net flows (Φ)	leaving flows (Φ^+)	entering flows (Φ^-)
1	Vegetation	0.296	0.614	0.318
2	Low-crested breakwater	0.056	0.411	0.355
3	Beach nourishment	-0.097	0.398	0.495
4	Permeable groin	-0.255	0.293	0.548

d)



RNK	CDM	net flows (Φ)	leaving flows (Φ^+)	entering flows (Φ^-)
1	Rock armour	0.318	0.547	0.230
2	Seawall	0.249	0.506	0.257
3	Beach nourishment	-0.022	0.367	0.389
4	Low-crested breakwater	-0.215	0.205	0.420
5	Emerged breakwater	-0.330	0.154	0.484

Figure 24. CDMs hierarchization presented in a diamond figure with the net, leaving and entering flows for each study site; a) Pessamit; b) Gallix; c) Baie-des-Capucins; d) Cap-des-Rosiers

For the Pessamit site, the analysis of the results shows that, according to the workshop participants' preferences, vegetation is ranked first followed by beach nourishment. Despite the large outperformance of vegetation over beach nourishment on the net and leaving flows, their respective entering flows are quite close together, thus weakening the general outperformance of the vegetation option. In third and fourth ranks, while permeable groin outperforms foreshore nourishment on the leaving flow axis, foreshore nourishment outperforms permeable groin on the entering flow. This results in a quasi-tie on the net flow axis. Meanwhile, impermeable groin and emerged breakwater come last, in fifth and sixth ranks, respectively.

For the Gallix site, the vegetation option is ranked first as shown by its significant outperformance over all other CDMs. In second and third ranks, a quasi-tie between beach nourishment and permeable groin on the net flow axis is explained by an outperformance of foreshore nourishment on the leaving flow, and an outperformance of permeable groin on the entering flow. Impermeable groin and foreshore nourishment are also on a quasi-tie in fourth and fifth ranks, respectively, while submerged breakwater and emerged breakwater are ranked sixth and seventh.

The top five CDMs for the Pessamit and Gallix sites are in the same order. Two reasons can explain the similarity. First, their socio-ecological systems are comparable. The environmental characteristics of both sites are low-lying sandy coast with a sandy lower foreshore, mesotidal shoreline, and a low energy environment (<1 m). Also, both sites are part residential part public localities, mostly frequented by the local community for a variety of uses and activities. Due to these similarities, the evaluation of the CDMs in relation to each criterion is equivalent for all criteria with the exception of social perception (tableau 43). Second, the difference in average weight is below 3 % for seven of the 13 and 15 criteria identified, respectively, in Pessamit and Gallix (figure 24). The local stakeholders' preferences were quite similar in nearly half of the identified criteria, though variances explain differences in the net, leaving, and entering flows between the two sites (figure 24). While the final ranking for the top 5 options is equivalent in both sites, inner differences shown by the above-mentioned three indicators, provide information that is relevant to the decision-makers.

For the Baie-des-Capucins site, the vegetation alternative also outperformed all other CDMs. In second and third ranks, while low-crested breakwater outperformed beach nourishment on the net, and entering flow axes, both are on a quasi-tie on the leaving flows axis. It is to be noted here that, because of the presence of salt marsh, the low-crested breakwater scenario was actually based on a living shoreline rock sill concept (Bilkovic *et al.*, 2017a). Finally, permeable groin was ranked fourth.

As for Cap-des-Rosiers, rock armour outperformed all other CDMs, but seawall is a close second. Beach nourishment, low-crested breakwater and emerged breakwater were ranked third, fourth and fifth, respectively. The evaluated CDMs and the final ranking is quite different from the other three sites, which is explained by their significantly dissimilar local conditions.

4.5.2.3 Robustness analysis

An analysis was performed to evaluate the robustness of the CDMs hierarchization method in relation to each criterion (figure 25). The circles and triangles show the highest and lowest thresholds at which there is a change in ranking of the top 3 CDMs for a given criterion. For example, in Pessamit under the criterion *Economic repercussions*, the CDM ranked first is outperformed by the CDM ranked second above 21.06%, but it is never outperformed by the CDM ranked third. Also, in Pessamit with regard to the three criteria *Ecological effects, Regulatory liability*, and *Technical feasibility*, the circles representing CDMs 1, 2, and 3 are all at 100%. This means that no change occurs in the top 3 CDMs' ranking, no matter the weight attributed to those criteria. An empty criterion cell indicates that the criterion was not identified at the site's workshop.

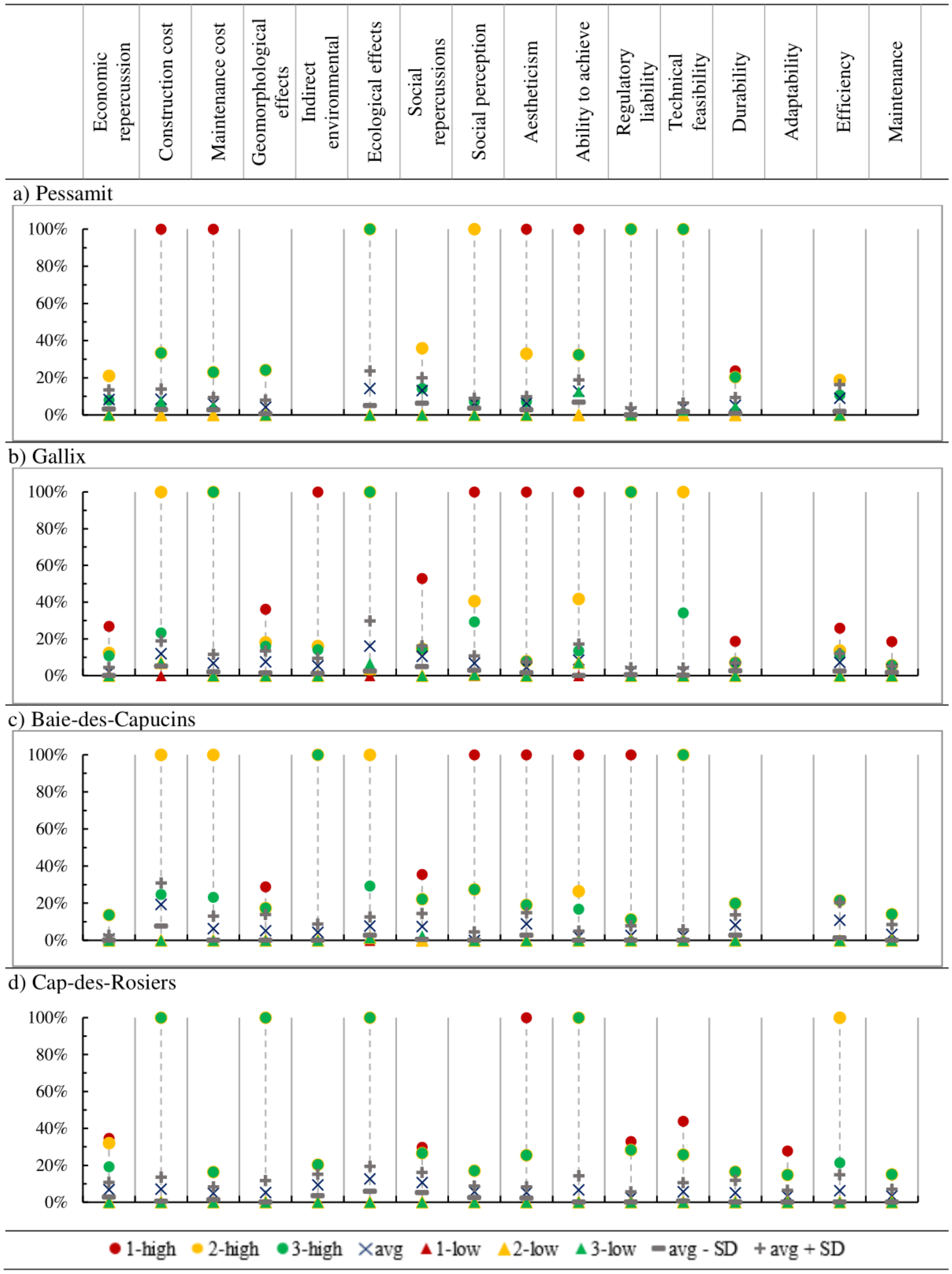


Figure 25. Robustness analysis of CDMs ranked 1 (red), 2 (yellow), and 3 (green), in relation to each criterion for each site. The vertical axis shows the average criteria weight in percentage. The circles and triangles show the highest and lowest thresholds at which there is a change in the top 3 ranked CDMs for a given criterion. The blue X shows the criterion weighted average. The grey plus and minus signs show the weighted average plus and minus the standard deviation

The grey plus and minus signs show the weighted average plus or minus the standard deviation. For example, if there is no circle or triangle within the range of the standard deviation (between the plus and minus signs), any change to the weight of the criteria would not affect the ranking, which is an indication that the results are robust. In Pessamit and Gallix, the CDMs ranked 1 and 2 are outside the standard deviation range for all criteria, which indicates that the results are robust for the first two CDMs. On the other hand, because CDM ranked 3 sometimes falls within the standard deviation range, it may be outperformed by the CDM ranked 4 if a change occurs in some of the criteria weight values. This shows that the results for CDM ranked 3 are not as robust as the ones for the first two CDMs. In Cap-des-Rosiers, all of the CDMs fall outside of the standard deviation range. This indicates that, in the case of the first three CDMs, the results would not be affected by any change in the criteria weights. In Baie-des-Capucins, the CDM ranked 3 falls within the standard deviation range for the criteria *Construction costs*, and *Social repercussions*. In this case, two out of sixteen criteria would not be enough to change the ranking.

Considering figure 23 and figure 24, even though the results are not equally robust in all cases, vegetation, beach nourishment, and permeable groin were ranked first, second, and third, respectively, for the three study sites with a sandy low coast (Pessamit, and Gallix). As for Cap-des-Rosiers, with a cliff coast that is naturally reflective, rock armour and seawall were solidly ranked first and second. These results are in line with those obtained through the CDMIA developed by Sauvé et al (2022), but the MCDA adds a layer of refinement to the assessment.

In Pessamit, the quasi-tie between permeable groin and foreshore nourishment in third and fourth ranks (figure 23a) is validated by the robustness analysis, which shows that the lowest and highest thresholds of the CDM ranked 3 (represented by a green triangle and a green dot, respectively), each fall within the standard deviation range in 5 of the criteria (figure 24a). In Gallix, the quasi-tie between beach nourishment and permeable groin (figure 23b, ranks 2 and 3, respectively) is confirmed by the robustness analysis, which shows the permeable groin's lowest threshold falling within the standard deviation in 3 of the criteria, and the highest threshold, in 6 of the criteria (figure 24b). In Baie-des-Capucins, there is no quasi-tie in the CDMs hierachization (figure 23c). Indeed, the robustness analysis shows that the thresholds for CDMs ranked 1 and 2 all fall outside of the standard deviation, and even though, in one criterion, the highest threshold falls within the standard deviation for the CDMs ranked three (permeable groin) (figure 24c), any change in the criteria weighting would not be enough to affect the final hierarchization. In Cap-des-Rosiers, the CDMs hierarchization is unambiguous (figure 23d), and is validated by the robustness analysis which shows that, for all criteria, the top 3 CDMs fall outside the standard deviation (figure 24d).

4.6 DISCUSSION

In order to solve a predefined coastal erosion or flooding problem with a solution that is adapted to the specific socio-ecological context, a variety of scenarios must be considered in a multiphase process before the design and construction phases are undertaken (USACE, 2006b). In most cases, decision-making has traditionally been limited to engineers, experts and scientists (Garmendia *et al.*, 2010 ; Sauvé *et al.*, 2020), and have led to a high rate of shoreline artificiality worldwide, the majority consisting of hard coastal defense structures (Cooper *et al.*, 2020 ; EEA, 2006 ; Gittman *et al.*, 2015 ; Koike, 1996 ; Sauvé *et al.*, 2020 ; Valloni *et al.*, 2003). In the past decade, a trend reversal has been observed with the implementation of soft techniques like beach nourishment or vegetation (Sauvé *et al.*, s. d.), ecological approaches (Morris *et al.*, 2018, 2019) such as Engineering With Nature in the U.S.A. (Bridges *et al.*, 2018) or Building With Nature in The Netherlands (de Vriend et Van Koningsveld, 2012 ; van Slobbe *et al.*, 2013), and the use of ecological or socio-economic enhancements in the design of hard structures (Evans *et al.*, 2017 ; Schoonees *et al.*, 2019 ; Vuik *et al.*, 2019). Still, the decisions regarding the selection of CDMs are not systematically being made through a participatory process (O'Riordan, 2005 ; Sauvé *et al.*, 2020).

In recent years, decision support tools have been increasingly used in the field of environmental management (Barzehkar *et al.*, 2021a ; Walling et Vaneeckhaute, 2020 ;

Wong-Parodi *et al.*, 2020). One of the main reasons being the need for a framework to support the meaningful integration of multiple stakeholders in the decision-making process (Wong-Parodi *et al.*, 2020). Such tools help decision-makers address complex and inherently uncertain problems related to socio-ecological systems (Baquerizo et Losada, 2008 ; Polasky *et al.*, 2011) by objectively structuring and analyzing the information, and by offering multiple solutions for consideration (Walling et Vaneeckhaute, 2020 ; Wong-Parodi *et al.*, 2020).

4.6.1 Relevance of MCDA as a tool to evaluate CDMs

Cost benefit analysis (CBA) and multicriteria decision analysis (MCDA) are both used for different purposes in environmental and coastal zone management, and in the evaluation of ecosystem services (Horstman *et al.*, 2009a ; Saarikoski *et al.*, 2016). CBA is often used to analyze CDMs, but rarely through a process of prioritization (Boyer-Villemaire *et al.*, 2016 ; Chow *et al.*, 2017 ; Polomé *et al.*, 2005 ; Thi Oanh *et al.*, 2020). CBA has been used more frequently to assess the cost of CDMs' maintenance, to compare the pros and cons, and the costs of scenarios with or without a CDM (Ha *et al.*, 2021 ; Maia *et al.*, 2015) or to evaluate a single given solution in monetary terms (Lima *et al.*, 2020). There are two schools of thought regarding CBA and MCDA. The selection of one over the other depends on the project objectives. While CBA can be useful in some contexts (Gamper et Turcanu, 2007 ; Horstman *et al.*, 2009a), MCDA are better suited to the processing of tangible and intangible information obtained when, among others, multiple stakeholders are involved, when all aspects of communities' well-being are taken into consideration, and when scientific uncertainty and spatiotemporal ecological impacts are significant factors in the decision-making process (Alves *et al.*, 2018 ; Saarikoski *et al.*, 2016 ; Wegner et Pascual, 2011). CDMs can have different effects on the components of the socio-ecological system, and these effects are usually measured in incommensurable scales and units (Choo *et al.*, 1999). MCDA are best adapted to the evaluation and comparison of CDMs because they allow the simultaneous analysis of dissimilar measurement units that are specific to each criterion (Horstman *et al.*, 2009a).

The output reports from the three phases of the MCDA PROMETHEE method combined with the robustness analysis (figure 26) provide the decision-makers with a structured, transparent and integrated analysis, and, as an end result, present alternatives that take stakeholders' preferences into account, and are more likely to be acceptable to all parties (McIntosh *et al.*, 2011 ; Saarikoski *et al.*, 2016 ; Saaty, 2008). First, the criteria, identified and weighted by workshop participants, give an indication of the local stakeholders' overall priorities and, more specifically, identifies conflicts and agreements within the consulted group, with regard to each criterion. Decision-makers can use that information, and manage conflictual issues by eliciting further discussion and exploring trade-offs in order to build a consensus around the most suitable solution. Second, the effects of each CDM are evaluated in relation to each criterion. This can be used in the design process to identify conflicts and synergies between CDMs, and to make end users (decision-makers, coastal managers or coastal engineers) aware of the effect of a CDM on individual criteria. Moreover, as mentioned in section 2.3.3, the PROMETHEE method allows the use of different rating scales depending on the nature of each criterion. Thus, when relevant data is available, the accuracy of the results could be improved by using quantitative scale for some of the criteria (e.g. cost related criteria). Third, the CDMs hierarchization, in the diamond figure, shows the interpretation of the results on three axes, and establishes equivalencies between scenarios. For example, in Pessamit and Gallix, there was a quasi-tie between two CDMs. In such cases, the decision-makers should consider both options on the same level. Finally, the robustness analysis gives an indication of how trustworthy the CDMs hierarchization results are. Reflected in the results is the objective of a MCDA, which is not necessarily to point to a unique solution. Rather, it provides a layered structure to facilitate the evaluation of different alternatives, suitable to answer a complex problem. In doing so, MCDA helps the decision-makers examine all aspects of the problem, understand the consequences surrounding the choice of one or a combination of CDMs, and choose the best alternative in accordance with their priorities and preferences.

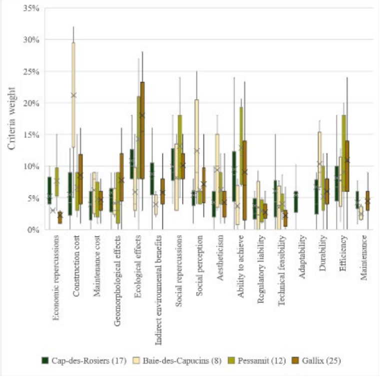
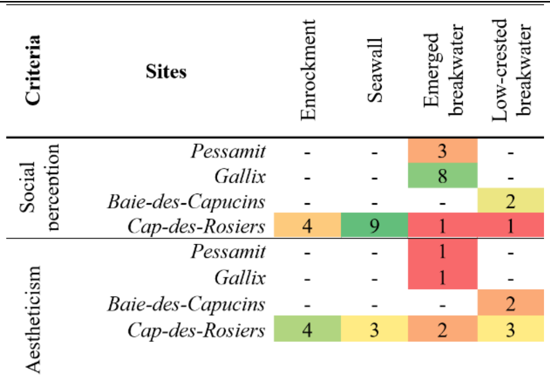


Figure 23

- Preliminary observation on the robustness of the hierarchization: for each criterion, a narrow range in the weighting results indicates high robustness



Criteria	Sites	Enrockment	Seawall	Emerged breakwater	Low-crested breakwater
Social perception	*Pessamit*	-	-	3	-
	Gallix	-	-	8	-
	Baie-des-Capucins	-	-	-	2
	Cap-des-Rosiers	4	9	1	1
Aestheticism	*Pessamit*	-	-	1	-
	Gallix	-	-	1	-
	Baie-des-Capucins	-	-	-	2
	Cap-des-Rosiers	4	3	2	3

Tableau 43

- Evaluation of the CDMs according to each criterion

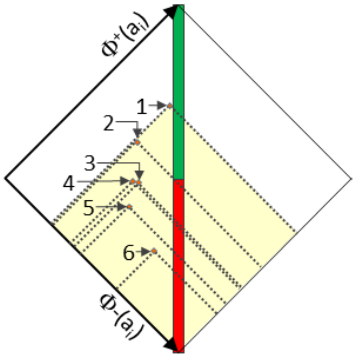


Figure 24

- CDMs hierarchization

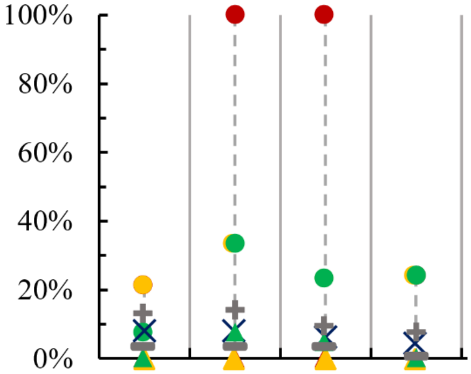


Figure 25

- Analysis and confirmation of observations made at the CDMs hierarchization phase

Figure 26. Illustration of the three phases of the MCDA process and robustness analysis in different report formats

In comparison, while CBA, like MCDA, is conducted in a process involving a few sequential steps (Boardman *et al.*, 2017 ; Saarikoski *et al.*, 2016), these are only related to solving the economic efficiency of scenarios (Wegner et Pascual, 2011). The monetary units used in CBA for the valuation of environmental features can limit the stakeholders in the expression of their preferences (Saarikoski *et al.*, 2016 ; Wegner et Pascual, 2011). Decision-making based on CBA is focused on an economic perspective, and the analyzed components of the socio-ecological system do not provide as much information to decision-makers, coastal managers and coastal engineers, as MCDA does.

4.6.2 Analysis of the participatory process involving criteria identification and weighting

Following the uniformization process, a standardized list of 16 criteria was established (tableau 42), based on the criteria identified by participants during the course of five workshops (figure 22). The identification exercise and subsequent discussions were useful for participants to enhance their understanding of the potential effects of CDMs on socio-ecological systems, and to learn how the relative values attached to each criterion, by different stakeholders, can influence the final decision (e.g. Garmendia and Stagl (2010), Grêt-Regamet et al. (2017), and Reed, (2008)).

However, the exercise led to an over specificity of the criteria, which happens when different criteria statements have a similar meaning, and when the theoretical basis used for the evaluation cannot reflect the accuracy of each statement. Another issue was the process of synthetizing the criteria identified by participants into a concise standardized list, which had to be achieved in a short time to avoid slowing the pace of the workshop, and to allow enough time for the participants to weigh the criteria. The lack of time may have resulted in the presence of inconsistencies in the categories and groupings created during the workshop. These observations were made during the first workshop of the series. However, the same approach was maintained for reasons of methodology and consistency between workshops. The uniformization of the criteria, identified by the participants, certainly influences the interpretation of the results. Subsequent work regarding the use of multicriteria analysis for the evaluation of CDMs should consider taking advantage of the established list of 16 criteria, in order to avoid a repetition of this phase of the process, and allow more time for the weighting phase. Prior to the workshops, the list can be modified or expanded, depending on the context and environmental conditions.

Despite these drawbacks, the use of multicriteria analysis is advantageous, especially when dealing with complex problems. Its capacity to integrate and process subjective information obtained from local stakeholders in participatory processes, is invaluable to an inclusive decision-making process. In the future, the participatory process could be improved by allowing more time for discussion on the values and weighting of the criteria. For instance, participants could be asked to select from a pre-established list of criteria, following a thorough presentation describing the meaning, the scope, and the limits of each criterion. A better understanding of each criterion by participants, would result in a set of criteria that is more accurate, and more representative of their local socio-ecological contexts. Allowing more time to the weighting phase would also possibly result in more accuracy, and narrower ranges in the weighted values.

4.6.3 Contribution to coastal engineering and management

The proposed MCDA approach is a flexible and ajustable tool that could contribute to coastal engineering and management by its capacity to structure and analyze the multiple dimensions of a complex problem, that are not necessarily easy to quantify. The method helps compare alternatives in relation to all relevant criteria (Choo *et al.*, 1999 ; Horstman *et al.*, 2009a), while taking into consideration their relative importance, as rated by different local stakeholders. The end result is a better knowledge of the specific context, and is more likely to lead to a solution that is well adapted to the environment in question. This would answer a need raised, in the past, by coastal decision-makers for the necessity to make better decisions related to CDMs (Drejza *et al.*, 2011 ; Friesinger et Bernatchez, 2010 ; Marie *et al.*, 2017). The inclusion of coastal managers and professionals in the criteria identification and weighting phases, is in line with a trend to involve more social stakeholders in environmental management (Garmendia et al., 2010; Jones et al., 2014; Marttunen et al., 2017; Reed, 2008). It gives decision-makers a better understanding of local conditions, priorities and interests, and it enhances the stakeholders' comprehension of all issues related to the interaction between CDMs and socio-ecological systems. The approach is conducive to supporting discussions in a group of stakeholders from different disciplines and functions. Therefore, the solutions emerge from an interdisciplinary exchange process (Gamper et Turcanu, 2007), which contributes to increasing the resilience of the socio-ecological system (Folke, 2016). In three of the four study sectors presented in this article, the MCDA approach made it possible to consider solutions other than rock armour and seawalls which have, up until now, often been implemented in Quebec, regardless of the type of coastal environment (Bernatchez et Fraser, 2012 ; Sauvé *et al.*, 2020).

4.7 CONCLUSION

Coastal zone managers and professionals were involved in a participatory process, which led to the identification and weighting of criteria for the purpose of selecting CDMs that are suitable to specific conditions. A multicriteria decision analysis approach was used to evaluate and hierarchize CDMs. The methodology was applied to four study sites in the province of Quebec, Canada: Pessamit, Gallix, Baie-des-Capucins, and Cap-des-Rosiers. The study sites have distinct geomorphological, hydrodynamic, ecological or socio-economic characteristics. PROMETHEE, an outranking method, was chosen to carry out the multicriteria analysis. First, a set of 16 criteria were identified and weighted by participants of five workshops. Second, CDMs were evaluated in relation to each criterion, and according to local socio-ecological features. Third, CDMs were hierarchized using the information obtained in the first two steps. Results show that vegetation holds the first rank in the Pessamit, Gallix, and Baie-des-Capucins sites, while rock armour is first in Cap-des-Rosiers. Still, deeper analysis indicates that, because of their high ranking, beach nourishment and permeable groin are options that are worthwhile considering. Finally, the results are supported by a robustness analysis. The Pessamit, and Gallix sites have similar results, which are explained by the comparability of their environmental characteristics and coastal activities. Findings regarding criteria identification and weighting as a participatory process can be divided in two parts. First, the criteria as identified by workshop participants were too specific, making it difficult to synthetize into a concise and comprehensive list useful for the evaluation of CDMs. To alleviate this problem, this phase of the process could be substituted by a detailed presentation of a pre-established list of criteria, followed by a discussion leading to the selection and weighting, by participants, of relevant criteria from the predefined list. Second, the weighting process was found to be a highly effective way to integrate local knowledge into the decision-making process. The three stages of the multicriteria decision analysis facilitate the decision-making process by presenting the results in a structured, transparent and integrated way, while taking stakeholders' preferences into account. Ultimately, the multicriteria decision analysis coupled with a participatory process is a flexible methodology that structures multiple aspects related to the selection of a CDM. It is a tool that can appreciably improve the coastal engineering and management decision-making process, and contribute to a better understanding of the socio-ecological systems.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

PS defined the state of knowledge, developed and executed the methodology, analyzed the data, and wrote the manuscript. PB contributed to the execution of the methodology and the editing of the manuscript. MG contributed to the development and execution of the methodology, the analysis of the results, and the editing of the manuscript. All authors contributed to the article and approved the submitted version.

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CONCLUSION GÉNÉRALE

Dans le cadre de la conclusion générale, les résultats obtenus dans les quatre chapitres de cette thèse sont mis en commun et discutés de manière à montrer leur pertinence dans le but d'améliorer de manière holistique la gestion des zones côtières. La structure de la démarche de la thèse est schématisée à la figure 27. Cette structure regroupe les quatre chapitres ainsi que les interrelations entre les éléments méthodologiques et les résultats de chacun d'eux.

Le chapitre 1 est basé sur deux éléments méthodologiques : (1) le traçage et la caractérisation du trait de côte de l'EGSL et (2) la consultation des acteurs de la zone côtière du Québec maritime. La caractérisation du trait de côte a permis d'établir que 97,6 % des ouvrages de protection côtière (OPC) aménagés dans l'EGSL en 2017 étaient des structures réflectives. La consultation des acteurs de la zone côtière a d'abord permis de constater une ouverture pour l'utilisation d'une plus grande diversité d'OPC. Ce constat, additionné aux besoins associés à l'aménagement d'OPC identifiés par les acteurs, a permis d'appuyer les trois chapitres subséquents dans un objectif de contribution à l'amélioration du processus décisionnel et du génie côtier en général. Ainsi, les chapitres 2, 3 et 4 répondent à des besoins identifiés par les acteurs de la zone côtière.

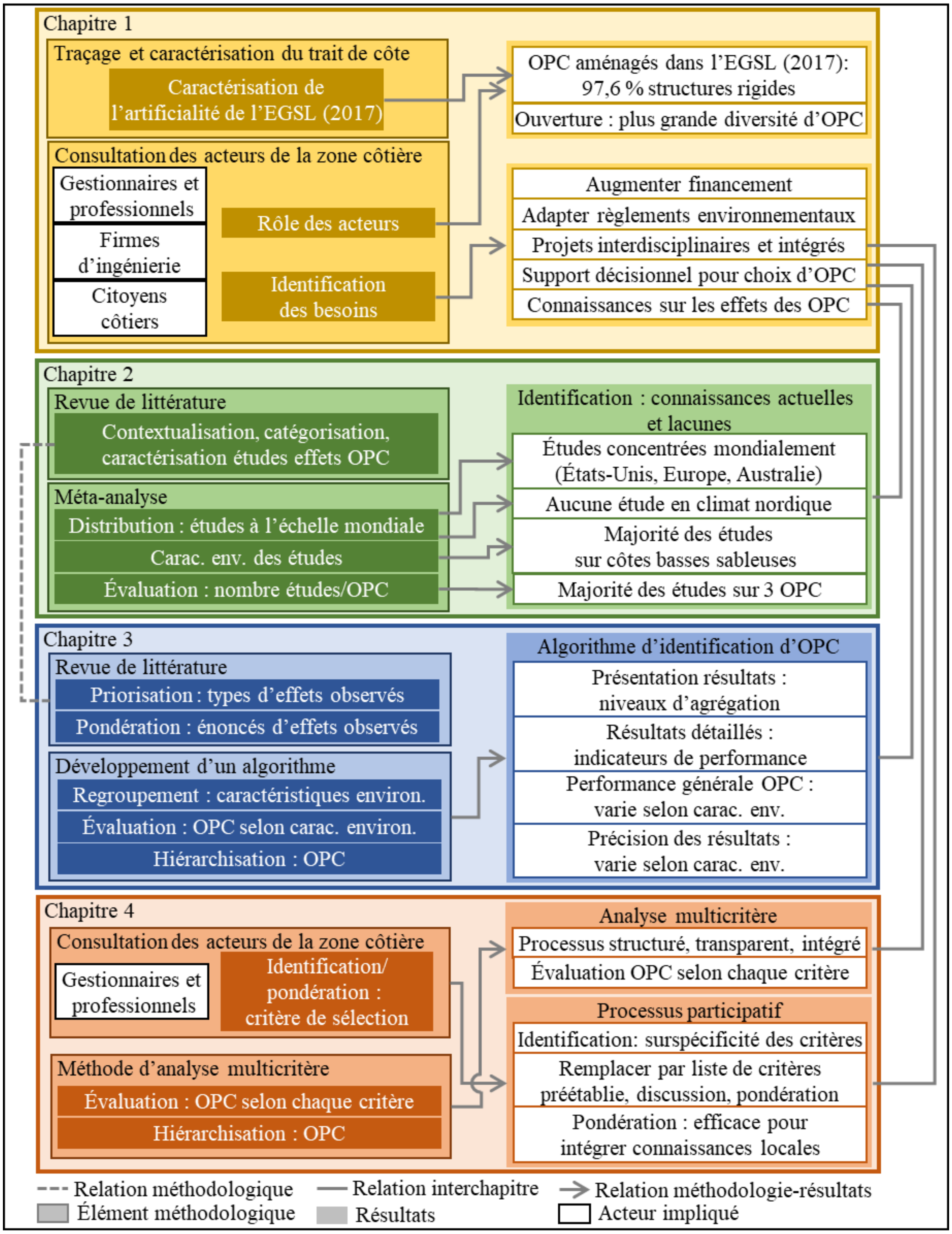


Figure 27. Interrelation entre les éléments méthodologiques et les résultats des chapitres de la thèse

Une revue de littérature utilisée dans les chapitres 2 et 3 a permis de caractériser la diversité d'OPC utilisée à l'échelle mondiale et de caractériser l'état des connaissances scientifiques de leurs effets respectifs sur les systèmes côtiers. Sur la base de cette revue de littérature, une méta-analyse a été effectuée dans le chapitre 2 afin d'établir les connaissances actuelles sur les effets des OPC en termes de répartition à l'échelle mondiale, de caractéristiques environnementales des études ainsi que du nombre d'études par OPC. Les résultats démontrent entre autres que les études qui ont réalisé un suivi environnemental des effets des OPC sont concentrées aux États-Unis, en Europe et en Australie, l'absence d'étude en climat nordique, la concentration des études dans un contexte de côtes basses sableuses ainsi que la concentration des études sur les recharges sédimentaires, les murs de protection et les brise-lames.

Ensuite, deux méthodes (chapitres 3 et 4) ont été présentées pour répondre directement à des besoins de support décisionnel pour le choix d'OPC soulevés par les acteurs de la zone côtière (chapitre 1). Le chapitre 3, aussi basé sur la revue de littérature, présente le développement d'un algorithme pour l'évaluation, la hiérarchisation et l'identification d'OPC en fonction des effets observés et publiés dans la littérature scientifique ainsi que des caractéristiques environnementales du secteur d'étude (type de côte, type de substrat, marnage, énergie des vagues). En plus de répondre à un besoin de support décisionnel pour le choix d'OPC, cette méthode permet de répondre à un besoin de connaissances sur les effets des OPC soulevés par les acteurs (chapitre 1). Le chapitre 4 est basé sur deux éléments méthodologiques : (1) une consultation des acteurs de la zone côtière et (2) une méthode d'analyse multicritère. La consultation des acteurs de la zone côtière a permis de former une liste de critères de sélection sur la base d'un processus participatif impliquant les gestionnaires et professionnels des communautés côtières dans l'identification et la priorisation des critères. Dans un deuxième temps, cette liste a été utilisée dans une méthode d'analyse multicritère afin de hiérarchiser les OPC ce qui a mené à un processus structuré, transparent et intégré.

La conclusion générale a été structurée de manière à présenter dans les prochaines sections la contribution de la thèse, l'opérationnalisation de la démarche proposée et les perspectives de développement. Finalement, cette section aborde les perspectives de projets de développement et de recherche.

1. CONTRIBUTION DE LA THÈSE

Individuellement, chacun des chapitres composant la thèse contribue à l'amélioration du processus décisionnel menant à la sélection d'un ouvrage de protection côtière par :

- l'identification des besoins soulevés par les acteurs du territoire côtier (chapitre 1);
- la définition de l'état des connaissances scientifiques sur les effets des OPC à l'échelle internationale (chapitre 2);
- le développement d'une méthode de méta-analyse dynamique de la littérature scientifique sur les effets des OPC (chapitre 3);
- la combinaison d'une méthode d'analyse multicritère et d'un processus participatif afin d'évaluer et d'identifier des OPC (chapitre 4).

Globalement, la mise en commun de la matière de chacun des chapitres permet de dégager une dynamique qui dicte la contribution globale de la thèse et qui est discutée dans les prochaines sous-sections :

- la combinaison de l'algorithme et de l'analyse multicritère offre une approche d'évaluation et de hiérarchisation d'ouvrages de protection côtière basée sur une analyse holistique du système socioécologique côtier;
- la pérennisation de l'information par une structure cohérente des connaissances scientifiques et des priorités des acteurs locaux;
- la diminution de l'incertitude par l'intégration de connaissances dans le processus décisionnel;
- le développement du génie côtier.

1.1 Démarche d'évaluation et de hiérarchisation d'ouvrages de protection côtière

La démarche d'évaluation et de hiérarchisation des OPC proposée répond à un besoin soulevé par les acteurs du territoire pour des outils d'aide à la décision (chapitre 1). Elle a été élaborée sur une structuration cohérente de l'information qui permet de prendre en considération les données tant géomorphologiques et hydrodynamiques, qu'écologiques et socio-économiques nécessaire à l'identification des meilleures alternatives en termes d'OPC. Ainsi, elle contribue à baser la sélection des OPC sur une analyse holistique du SSEC et à obtenir un portrait global de l'effet potentiel des OPC sur ses composantes. Premièrement, l'évaluation effectuée avec l'algorithme d'identification est réalisée à une échelle spatiale fine, soit un segment géomorphologique, en fonction d'un ensemble de quatre variables environnementales qui correspondent aux caractéristiques géomorphologiques et hydrodynamiques d'un segment de côte. L'interprétation des résultats détaillés permet d'analyser, en regard des types d'effet observé, les effets géomorphologiques des OPC, puis d'extrapoler ces résultats pour analyser les effets écosystémiques et sociaux à l'échelle de la cellule hydrosédimentaire. Deuxièmement, l'évaluation, effectuée avec l'analyse multicritère et le processus participatif, permet de tenir compte de la dynamique multiacteurs, ce qui complète l'analyse holistique du SSEC. Ultimement, la démarche forme un outil d'aide à la prise de décision qui permet de classer, structurer et hiérarchiser afin que l'information soit présentée de manière à éclairer la conception et la sélection des OPC réalisée, respectivement, par les ingénieurs et les décideurs.

1.2 Pérennisation de l'information par une structure cohérente des connaissances

La démarche proposée permet la structuration cohérente et pérenne des connaissances scientifiques, puis des priorités des acteurs du territoire afin de faciliter l'utilisation de ces connaissances dans les processus de planification et de conception des OPC.

D'abord, une base de données a été développée afin de répertorier les énoncés sur les effets (tels qu'observés par les auteurs) engendrés par les OPC sur les aspects géomorphologiques, hydrodynamiques, écosystémiques et sociaux des zones côtières. Ces énoncés sont associés aux caractéristiques environnementales propres aux sites dans lesquels les effets ont été observés lors de l'intégration dans la base de données. La base de données a été développée de manière à être mise à jour périodiquement par l'intégration de nouvelles études de cas. Ainsi, les mises à jour permettent d'assurer la pérennité de l'information qui en est extraite. La première version de la base de données comprend un total de 411 publications scientifiques desquelles ont été extraits 1709 énoncés d'effet. Dans le contexte de la thèse, la base de données a été utilisée pour effectuer la méta-analyse des études de cas sur les effets engendrés par les OPC (chapitre 2) ainsi que pour le développement de l'algorithme d'identification des OPC (chapitre 3). Par ailleurs, elle a mené à la rédaction d'une synthèse des connaissances intitulée *Caractérisation et effets des ouvrages de protection côtière sur les systèmes côtiers : synthèse descriptive en vue d'une intervention sur le littoral* (Sauvé *et al.*, 2021).

Ensuite, la structure en trois étapes de la méthode d'analyse multicritère permet d'évaluer et de hiérarchiser les OPC en regard des priorités des acteurs locaux et des connaissances disponibles sur l'effet des OPC sur le système côtier selon chaque critère utilisé dans l'analyse. Cette structure permet d'assurer une mise à jour efficace de l'information en cas de réévaluation et d'ainsi évaluer les effets des changements d'information sur la hiérarchisation des OPC.

Globalement, la structuration de l'information permet d'établir une base commune de comparaison des OPC qui a priori présentent des effets distincts sur le SSEC. Elle permet également de définir une normalisation de la sélection des scénarios d'OPC basée sur les avancées scientifiques. De cette manière, l'approche permet de réduire la subjectivité et l'incertitude associée à des approches de sélection basées uniquement sur les connaissances d'experts (Brugnach *et al.*, 2008) et aider les décideurs responsables à prendre de bonnes décisions.

1.3 Diminution de l'incertitude dans un processus d'aide à la prise de décision

L'acquisition de connaissances est un aspect clé pour réduire l'incertitude associée au processus décisionnel (Polasky *et al.*, 2011) et pour augmenter globalement la résilience des communautés côtières (Lebel *et al.*, 2006 ; Pahl-Wostl, 2009). La thèse contribue à l'acquisition de trois types de connaissances : (1) connaissances sur le contexte du processus décisionnel, (2) connaissances scientifiques sur les OPC et leurs effets et (3) connaissances sur le contexte local d'un site d'intervention.

Premièrement, le processus décisionnel passé et actuel a été caractérisé lors de la consultation réalisée auprès des professionnels et gestionnaires des zones côtières, des résidents côtiers et des entreprises œuvrant en génie et en aménagement côtier dans le Québec maritime afin d'identifier les interventions réalisées antérieurement sur le littoral ainsi que les éléments qui ont mené à leur sélection (chapitre 1). Cette caractérisation permet de définir un état de référence afin de mesurer l'effet des connaissances acquises sur le processus décisionnel et sur les OPC aménagés sur les côtes du Québec maritime. Concrètement, deux besoins ont été traités dans le cadre de cette thèse : un besoin sur l'accessibilité aux connaissances scientifiques sur les OPC (chapitre 2) et un besoin sur un outil d'aide à la prise de décision (chapitres 3 et 4).

Deuxièmement, la thèse contribue à intégrer les connaissances scientifiques sur les effets des OPC dans le processus décisionnel. La base de données sur les effets des OPC offre un portrait des connaissances scientifiques à l'échelle internationale. La recherche effectuée dans cette base de données facilite l'identification d'études sur un OPC et un contexte environnemental spécifique. Deux méthodes ont été utilisées pour exploiter cette base de données et ainsi contribuer à la réduction de l'incertitude dans le processus décisionnel : une méta-analyse (chapitre 2) et un algorithme d'identification (chapitre 3). La méta-analyse permet d'identifier les OPC et les contextes environnementaux dans lesquels ils ont été étudiés. L'algorithme permet d'évaluer et de hiérarchiser les OPC dans un contexte environnemental spécifique en donnant de l'information sur le degré de correspondance entre les contextes environnementaux initial et utilisé dans l'analyse. Ainsi, ces deux méthodes permettent de définir l'incertitude quant aux connaissances scientifiques disponibles pour un contexte environnemental spécifique afin d'anticiper les effets potentiels d'un OPC sur le système côtier. Cette information peut également être utilisée pour déterminer les besoins en termes d'acquisition de connaissances pour des contextes environnementaux sans étude.

Troisièmement, la thèse contribue à l'utilisation des connaissances locales dans le processus décisionnel par l'utilisation d'une analyse multicritère et l'intégration des acteurs locaux au processus d'identification et de pondération des critères de sélection d'un OPC (chapitre 4) permettant de sélectionner et de concevoir des OPC qui sont mieux adaptés aux conditions environnementales et socioculturelles locales. De plus, l'utilisation de processus participatifs et collaboratifs permet le transfert de connaissances bidirectionnel : les acteurs du territoire amènent des connaissances sur le contexte local aux chercheurs et les chercheurs amènent des connaissances scientifiques aux acteurs du territoire. Le partage des connaissances permet d'augmenter la résilience et l'adaptation des communautés côtières (Chaffin *et al.*, 2014 ; Khunwishit *et al.*, 2018 ; Lebel *et al.*, 2006). Finalement, la démarche proposée se présente également comme une plateforme d'arrimage des connaissances multiacteurs où les connaissances scientifiques et les connaissances locales sont répertoriées, structurées et analysées de manière à hiérarchiser les OPC en regard de l'ensemble des connaissances disponibles pour un site d'intervention.

1.4 Développement du génie côtier au Québec

L'ingénierie côtière est une discipline à la fois très ancienne et très nouvelle (Kamphuis, 2000). Depuis plusieurs siècles, les sociétés ont aménagé des OPC pour se prémunir contre l'érosion et la submersion côtière (Charlier *et al.*, 2005). Aujourd'hui, plusieurs pays comptent sur des systèmes de protection côtière sophistiqués, alors que d'autres demeurent dans des situations précaires (chapitre 2). Au Québec, l'ingénierie côtière, telle que reconnue à l'échelle internationale, est une discipline peu pratiquée (chapitre 1). Historiquement, la problématique d'érosion côtière a généralement été résolue sur la base d'aspects géotechniques par des techniques de stabilisation de talus, ce qui a mené à des interventions locales par une solution quasi unique (structures réflectives) sans égard à la dynamique du système côtier. Cependant, comme démontré au chapitre 1, plus récemment, la discipline a tendance à évoluer en partie parce que les acteurs consultés, incluant les firmes d'ingénierie, ont fait preuve d'ouverture à une plus grande diversité d'OPC et que la dynamique du système côtier est maintenant intégrée à l'analyse de solutions.

La pratique de l'ingénierie côtière implique plusieurs enjeux qui ont une influence sur le processus décisionnel (tableau 4). Deux enjeux sont particulièrement importants : (1) la dynamique complexe des systèmes socioécologiques côtiers et (2) le manque de ressources financières à long terme pour l'aménagement, le suivi et l'entretien d'OPC. Premièrement, d'un point de vue scientifique, les interactions entre la dynamique du système socioécologique côtier et les OPC engendrent des effets spécifiques qui combinés à l'incertitude associée aux changements climatiques, complexifient fondamentalement la tâche de l'ingénieur. D'autant plus que l'ampleur des effets généraux spécifiques à chaque type d'OPC peut conceptuellement fluctuer sur un intervalle de variabilité en fonction des caractéristiques du SSEC et du dimensionnement final de l'OPC. Un ingénieur côtier doit avoir les connaissances pour positionner le dimensionnement final dans cet intervalle afin d'y intégrer les effets positifs et d'appliquer des mesures afin d'atténuer les effets négatifs. Généralement, l'incertitude associée aux changements climatiques est intégrée au dimensionnent des OPC par l'application de facteurs de sécurité qui prennent en considération des scénarios climatiques extrêmes sur une perspective à long terme (chapitre 1). Par exemple, la hauteur des OPC est augmentée de 48 à 56 % en raison des projections de hausse du niveau marin (Arns *et al.*, 2017). Conséquemment, les coûts de construction des OPC sont amplifiés. L'idée est donc d'adapter les cadres décisionnels pour intégrer cette incertitude. Deuxièmement, au Québec, mais également ailleurs à travers le monde, le manque de ressources financières pour l'aménagement, le suivi et l'entretien d'OPC (chapitre 1) influence fortement le processus de sélection d'un OPC. La stabilité de l'OPC doit être assurée afin de garantir une durée de vie qui convient au mode de financement, malgré la complexité et l'incertitude inhérente au milieu environnemental dans lequel l'intervention doit être réalisée. Conséquemment, deux situations sont privilégiées : (i) les OPC à longue durée de vie; (ii) la conception d'OPC à plus faible durée de vie est modifiée et adaptée pour en augmenter la pérennité. D'abord, l'importance accordée à la durée de vie est surpondérée ce qui favorise les structures rigides (chapitre 1) en raison de leur structure et leurs matériaux constitués de pierres, de béton, de bois ou d'acier. Ensuite, le manque de financement, combiné à l'absence de système de normalisation et à un manque de suivi des connaissances scientifiques, contribue à ce que le dimensionnement des OPC souples, telles les recharges sédimentaires, soit orienté sur la stabilité de l'ouvrage pour en garantir une durée de vie sans entretien, ce qui mène à un dimensionnement qui est largement supérieur à ce qui est défini dans les guides de conception et la littérature scientifique internationale. Or, ce type de stratégie orienté sur la gestion d'une seule variable engendre des changements non contrôlés des autres composantes du système socioécologique (Folke, 2006 ; Holling et Gunderson, 2002).

Ce besoin pour améliorer la pratique du génie côtier a été identifié dans le cadre de cette thèse lors de la consultation des professionnels et gestionnaires des communautés côtières ainsi que des professionnels des entreprises œuvrant en génie et en aménagement côtier (chapitre 1). Le financement à long terme faciliterait l'application de mesures de gestion adaptative des zones côtières par l'ajustement progressif des OPC en fonction des nouvelles connaissances acquises sur l'évolution du système côtier. La gestion adaptative est un processus itératif par lequel l'environnement institutionnel et les connaissances environnementales sont évalués et révisés de manière à effectuer des actions d'adaptation en fonction des connaissances incomplètes, de l'incertitude et de la non-linéarité des systèmes (Allen *et al.*, 2011 ; Folke *et al.*, 2002 ; Lebel *et al.*, 2006). Ainsi, l'action est posée en fonction des connaissances actuelles en prévoyant que des modifications y seront apportées une fois que les connaissances le permettront. Dans le contexte de la sélection d'OPC, l'idée est de sélectionner des OPC qui s'adaptent naturellement aux changements environnementaux ou dont la structure peut facilement être modifiée en fonction d'une révision du dimensionnement suite à l'acquisition de nouvelles connaissances environnementales.

De plus, l'algorithme d'identification (chapitre 3) et l'analyse multicritère (chapitre 4) peuvent contribuer à adapter le dimensionnement des OPC de manière à réduire l'intervalle de variabilité en donnant de l'information sur les effets potentiels et sur les priorités des acteurs locaux. La pérennité de la démarche développée est également inscrite dans une optique de gestion adaptative en permettant l'ajustement progressif de l'évaluation des OPC en fonction du développement de nouvelles connaissances.

2. OPÉRATIONNALISATION DES MÉTHODES PROPOSÉES

L'algorithme d'identification (chapitre 3) et l'analyse multicritère (chapitre 4) sont deux méthodes complémentaires d'évaluation des ouvrages de protection côtière (OPC) qui peuvent être insérées dans différents cadres d'analyse de solutions et qui permettent d'intégrer différents acteurs de la zone côtière au processus décisionnel.

2.1 Opérationnalisation du processus décisionnel

Deux méthodes d'aide à la prise de décision adaptables aux caractéristiques locales des systèmes socioécologiques côtiers sont présentées aux chapitres 3 et 4. Ces deux méthodes peuvent être utilisées de manière combinée ou indépendante dans différents cadres d'évaluation déjà présents dans le cycle de vie utile d'un OPC, notamment le processus de planification et le processus de conception (figure 6).

L'approche proposée consiste à utiliser les deux méthodes de manière combinée afin de former une approche d'évaluation objective, holistique et intégrée, et ainsi contribuer simultanément à la planification et à la conception d'OPC (figure 28). Elle est appuyée sur l'état initial d'un SSEC à l'étude qui est définie en fonction de ses composantes géomorphologiques, hydrodynamiques, écosystémiques et socioculturelles.

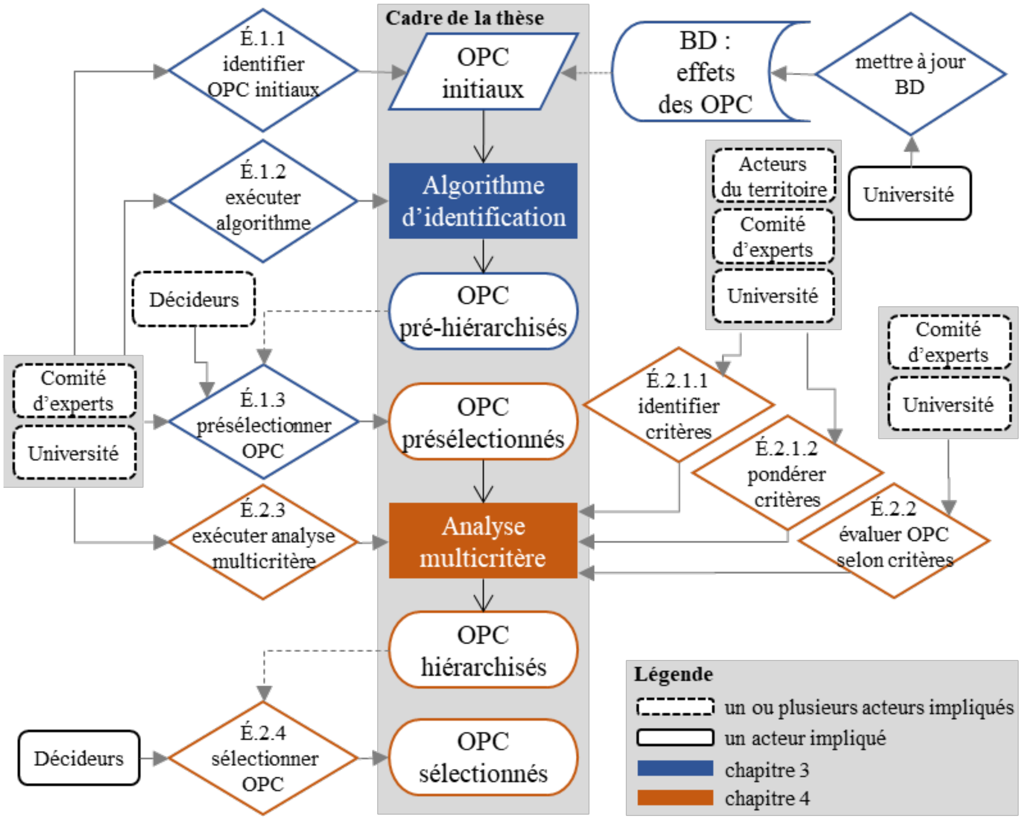


Figure 28. Schématisation de l'implication d'un comité d'expert, de l'université, des acteurs du territoire et des décideurs dans l'opérationnalisation de l'outil d'aide à la prise de décision basé sur deux méthodes : un algorithme d'identification (étape 1) et une analyse multicritère (étape 2)

Une évaluation de l'effet potentiel de scénarios d'OPC est ensuite effectuée en regard de cet état initial. Comme décrit aux chapitres 3 et 4, l'analyse part d'une structuration des connaissances scientifiques et d'un processus participatif qui procurent l'information nécessaire aux décideurs pour qu'ils puissent prendre de bonnes décisions quant au scénario à adopter, et aux ingénieurs pour qu'ils puissent concevoir des OPC de manière à réduire les effets négatifs sur le SSEC.

2.2 Implication des acteurs dans l'opérationnalisation

La participation de ces acteurs doit être structurée afin de justifier la pertinence de leur implication dans le processus d'évaluation des OPC. L'opérationnalisation de l'approche proposée passe par quatre catégories d'acteurs : comité d'experts, université, acteurs du territoire et décideurs (figure 28).

La catégorie *Comité d'expert*s peut être composée d'acteurs interdisciplinaires provenant de divers ministères ou firmes d'ingénierie dont les membres ont une connaissance avancée sur la dynamique du SSEC et sur les ouvrages de protection côtière. La catégorie *Université* regroupe des chercheurs universitaires et des étudiants gradués qui ont une compréhension approfondie de l'état des connaissances scientifiques liées à la dynamique du SSEC et aux ouvrages de protection côtière. La catégorie *Acteurs du territoire* peut être composée d'acteurs locaux tels que de résidents côtiers, des parties prenantes aux intérêts économiques, environnementaux ou sociaux dont les connaissances sur le milieu local sont avancées. La catégorie *Décideurs* comprend les acteurs habiletés à prendre les décisions dans l'exercice de leurs fonctions.

L'opérationnalisation de l'outil d'aide à la prise de décision proposé peut impliquer ces catégories d'acteurs selon l'une des deux méthodes et les spécificités des étapes qui les définissent. La première méthode est l'algorithme d'identification et la première étape, l'identification des OPC à évaluer (É.1.1). Cette opération nécessite des connaissances sur le contexte environnemental, social et économique du site d'intervention ainsi qu'un jugement sur le degré de pertinence des OPC à intégrer à l'analyse. À cette étape, le nombre d'OPC rejetés est faible. L'identification des OPC à évaluer peut être réalisée par le comité d'experts ou l'université. La seconde étape (É.1.2) est l'opérationnalisation de l'algorithme. Elle consiste à sélectionner quatre types de caractéristiques environnementales (type de côte, type de substrat, marnage et type de vague) à partir d'une liste préétablie (section 3.4.2.1). L'évaluation des OPC est effectuée par l'algorithme en regard de cette sélection qui devrait corresponde aux caractéristiques environnementales du secteur d'étude. Cette étape peut être exécutée par un membre du comité d'experts ou de l'université. L'algorithme a été conçu pour intégrer les nouvelles informations sur les OPC et leurs effets sur le milieu environnemental à la base de données (décrite à la section 3.4.1.1). La mise à jour à intervalle régulier de la base de données permet d'assurer la pérennité de l'algorithme par la concrétisation de l'information et une augmentation de la précision des résultats selon le cas : (i) information est associée à un OPC qui sont déjà présents dans la base de données; (ii) à l'ajout de caractéristiques environnementales; ou (iii) à de nouveaux OPC (section 3.6.2.1). La troisième étape (É.1.3) est la présélection d'OPC en fonction des résultats obtenus avec l'algorithme en vue de la prochaine phase du processus décisionnel. La structuration de l'information scientifique réalisée avec l'algorithme permet d'analyser les effets potentiels selon deux indicateurs de performance (atteinte du pourcentage seuil et moyenne pondérée), deux indicateurs de précision (indice de correspondance et nombre d'effets observés et la distribution des effets observés sur l'échelle de notation (5 à -5) (section 3.6.1). Cette étape peut être réalisée par le comité d'experts, l'université ou les décideurs. Elle nécessite une bonne connaissance des indicateurs utilisés dans l'algorithme pour établir la hiérarchisation des OPC.

Dans l'approche proposée, la seconde méthode utilisée dans le processus décisionnel est l'analyse multicritère. Elle est mise en application à la suite de l'évaluation des OPC qui a été préalablement réalisée par l'algorithme d'identification. La première étape de l'analyse multicritère est l'identification (É.2.1.1) et la pondération (É.2.1.2) des critères d'évaluation. Ces étapes peuvent impliquer les acteurs du territoire, le comité d'experts et l'université. Ces étapes ont été réalisées par les acteurs du territoire dans le contexte du chapitre 4. La pondération des critères d'évaluation d'OPC par les acteurs du territoire dans le cadre d'un processus participatif a été concluante. Cependant, il a été démontré que la formation d'une liste de critères d'évaluation concise et compréhensive est complexifiée par une surspécificité des critères énoncés par les acteurs du territoire (section 3.6.2). La deuxième étape (É.2.2) est l'évaluation des OPC en regard de chacun des critères. Cette étape doit être réalisée par le comité d'experts ou l'université. Elle nécessite des connaissances approfondies sur les OPC et leurs effets sur le système socioécologique côtier, car l'information obtenue a cette étape est utile dans le processus de conception pour l'identification de synergie entre les OPC complémentaire. La troisième étape (É.2.3) est l'exécution de l'analyse multicritère. Cette étape doit être réalisée par le comité d'experts ou l'université, car une connaissance du logiciel d'analyse multicritère est nécessaire. La quatrième étape (É.2.4) est la sélection des OPC par les décideurs. À cette étape, l'ensemble de l'information produite par les deux méthodes qui composent l'outil d'aide à la prise de décision est exploitable pour prendre une décision éclairée. L'algorithme d'identification présente de l'information technique par une structuration cohérente et une contextualisation des connaissances scientifiques au regard des caractéristiques du secteur d'intervention (section 3.6.1). Puis, l'analyse multicritère permet aux décideurs d'examiner de manière holistique un problème complexe, de faciliter la compréhension des enjeux entourant les solutions potentielles et ainsi de faire un choix selon leurs priorités, leurs préférences et les impacts appréhendés des ouvrages identifiés (section 3.6.1).

3. PERSPECTIVES DE DÉVELOPPEMENT

La démarche proposée permet de réaliser une évaluation objective, holistique et intégrée, et ainsi contribuer simultanément à la planification et à la conception d'OPC. Il demeure que certains aspects peuvent être développés pour diminuer l'incertitude et pour augmenter la diversité des éléments analysés.

3.1 Études de cas sur les effets des ouvrages de protection côtière

Le manque de connaissance sur le comportement et les effets des ouvrages de protection côtière est évident dans plusieurs types d'environnement côtier (chapitre 2). Considérant l'importante variabilité des types d'environnement côtier à l'échelle du Québec maritime, ce manque de connaissance engendre une variabilité de l'incertitude dans le processus de planification et de conception des OPC qui dépend des caractéristiques environnementales du site d'intervention. L'algorithme d'identification permet de structurer et de synthétiser les connaissances scientifiques de manière à faciliter la compréhension de cette incertitude dans le processus décisionnel.

Également, le manque d'étude de cas a été soulevé lors de la consultation des entreprises œuvrant en génie et en environnement côtier. Les entreprises avaient alors spécifié, entre autres, le manque d'études dans un contexte nordique avec présence de glace (Sauvé *et al.*, 2020). Ce manque a subséquemment été confirmé par une méta-analyse de la littérature scientifique (chapitre 2). Or, il a été démontré que les glaces de mer et d'estran ont un effet direct sur la géomorphologie côtière et vice-versa (Corriveau *et al.*, 2019b). Ce manque de connaissance est particulièrement préoccupant dans le contexte du Québec maritime où les OPC auront nécessairement des interactions avec les glaces de mer et d'estran ce qui pourrait occasionner des effets environnementaux et des effets structuraux sur l'OPC.

3.2 Algorithme d'identification : évaluation des effets écosystémiques et sociaux

L'évaluation des OPC réalisée par l'algorithme d'identification repose sur une base de données construite à partir d'information tirée de publications d'ouvrages scientifiques. Cette base de données contient 1709 énoncés d'effets produits par les OPC (tels qu'observés par des chercheurs) sur les aspects géomorphologiques, hydrodynamiques, écosystémiques et sociaux des milieux côtiers. L'algorithme d'identification a été développé pour établir une correspondance entre quatre variables d'un secteur d'étude et ceux qui sont enregistrés dans la base de données : le type de côte, le type de substrat, le marnage et le type de vague.

Le chapitre 3 présente le développement de l'algorithme d'identification et les résultats de l'évaluation des OPC en regard de leurs effets géomorphologiques et hydrodynamiques. Ce module ne tient donc pas compte des énoncés d'effets écosystémiques et sociaux qui sont contenus dans la base de données. En fait, deux modules supplémentaires de l'algorithme ont été développés pour évaluer ces effets. L'idée initiale était de présenter une hiérarchisation des OPC distincte pour les effets géomorphologiques, écosystémiques et sociaux. Cependant, les résultats obtenus avec les modules écosystémique et social étaient imprécis et par ce fait, n'ont pas été retenus pour la première phase du développement de l'algorithme.

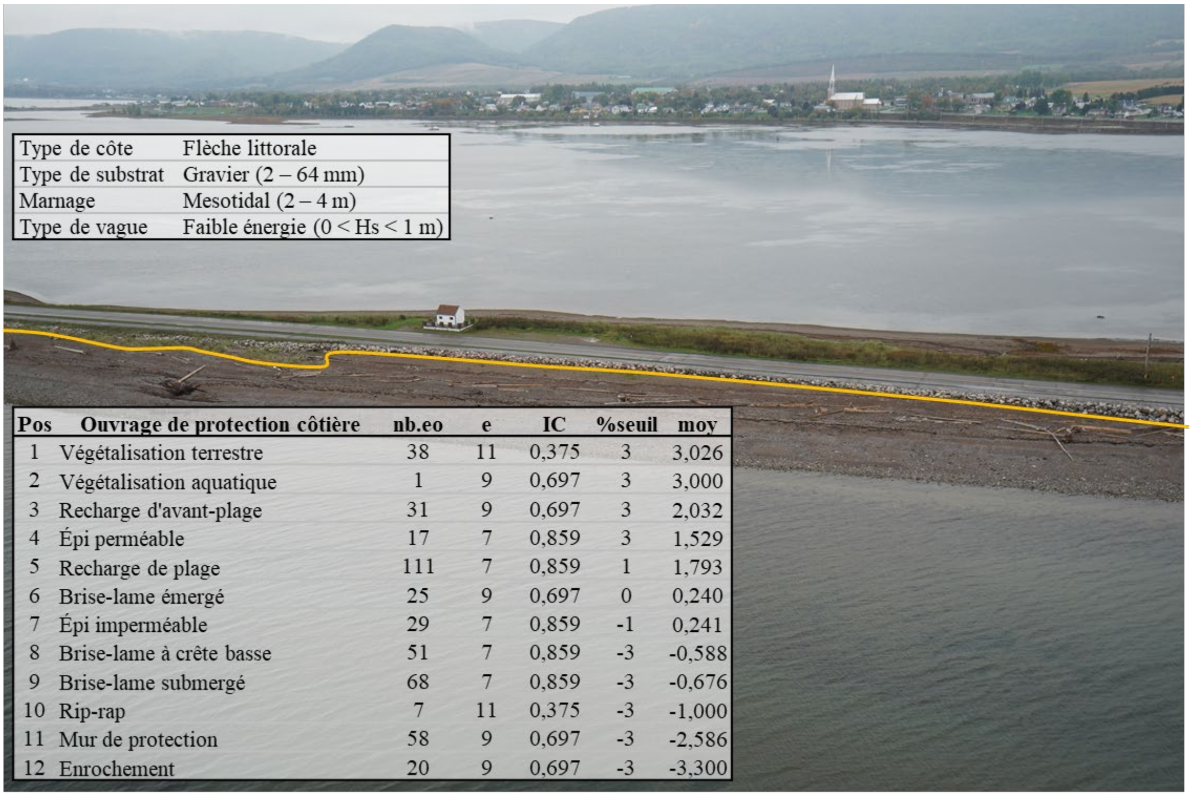
Pour le module écosystémique, cette imprécision est principalement expliquée par le fait que la correspondance était basée sur l'hypothèse qu'un site avec un ensemble de variables géomorphologiques et hydrodynamiques défini est favorable à la formation d'un écosystème donné. De ce fait, les quatre variables environnementales utilisées pour le module géomorphologique étaient utilisées. Cependant, la majorité des études de cas sur les effets écosystémiques et sociaux des OPC ne contiennent pas de description de ces variables (chapitre 2). Également, ces effets résultent généralement d'un changement de nature géomorphologique ou hydrodynamique causé par un OPC. Ainsi, pour améliorer la précision des résultats du module écosystémique dans une deuxième phase du développement de l'algorithme, une revue de littérature devra être réalisée afin d'élargir la base de données pour y intégrer les causes directes et indirectes générales des changements dans différents types d'écosystèmes côtiers. Ces causes pourront ensuite être couplées aux effets géomorphologiques et hydrodynamiques des OPC et combinées aux effets écosystémiques présents dans la base de données pour évaluer les effets écosystémiques potentiels sur le milieu d'intervention.

Pour le module social, l'évaluation est actuellement effectuée à l'échelle des services écologiques en étant basée sur une relation de cause à effet entre les trois premières étapes du modèle en cascade de Haines-Young et Potschin (2010), soit les propriétés et les fonctions, les services écologiques. Plusieurs fonctions écologiques engendrent un service écologique et plusieurs effets observés influencent chaque fonction écologique. Ainsi, ces relations sont représentées dans une matrice sur laquelle l'algorithme est référé pour évaluer les effets des OPC sur chaque service écologique. L'évaluation est alors réalisée selon le même principe que le module géomorphologique. Dans une deuxième phase du développement de l'algorithme, il serait pertinent de réduire l'échelle d'analyse en appliquant les effets des OPC directement aux usages pratiqués dans la zone côtière afin de concrétiser les effets des OPC sur les aspects sociaux du SSEC. Les usages sont associés aux bénéfices écologiques, soit la quatrième étape du modèle en cascade. Ainsi, la concrétisation des effets des OPC permettrait aux acteurs locaux d'obtenir une meilleure projection des différents scénarios d'intervention sur leurs activités.

3.3 Intégration à un système d'information géographique (SIG) en ligne

Les résultats de l'algorithme d'identification (chapitre 3) et de l'analyse multicritère (chapitre 4) pourraient être ajoutés à une plateforme cartographique accessible sur Internet à des gestionnaires et des professionnels de différentes organisations associées à la zone côtière. L'arrimage à un SIG permettrait de représenter les résultats de l'algorithme pour un segment de côte spécifique en fonction des quatre variables de base, soit le type de côte, le type de substrat, le marnage et le type de vagues (figure 29).

Les résultats de la hiérarchisation des OPC avec l'analyse multicritère pourraient également être présentés de la même façon. À noter que la pondération des critères n'étant pas réalisée dans chaque municipalité, une échelle de couleur pourrait être ajoutée à la représentation des résultats pour indiquer si les résultats sont basés sur une pondération des critères à l'échelle de la municipalité, de la MRC, de la région ou de la province. La provenance de la pondération et l'année de réalisation pourraient également être mentionnées.



Type de côte	Flèche littorale
Type de substrat	Gravier (2 – 64 mm)
Marnage	Mesotidal (2 – 4 m)
Type de vague	Faible énergie (0 < Hs < 1 m)

Pos	Ouvrage de protection côtière	nb.eo	e	IC	%seuil	moy
1	Végétalisation terrestre	38	11	0,375	3	3,026
2	Végétalisation aquatique	1	9	0,697	3	3,000
3	Recharge d'avant-plage	31	9	0,697	3	2,032
4	Épi perméable	17	7	0,859	3	1,529
5	Recharge de plage	111	7	0,859	1	1,793
6	Brise-lame émergé	25	9	0,697	0	0,240
7	Épi imperméable	29	7	0,859	-1	0,241
8	Brise-lame à crête basse	51	7	0,859	-3	-0,588
9	Brise-lame submergé	68	7	0,859	-3	-0,676
10	Rip-rap	7	11	0,375	-3	-1,000
11	Mur de protection	58	9	0,697	-3	-2,586
12	Enrochement	20	9	0,697	-3	-3,300

Figure 29. Exemple de représentation dynamique sur le trait de côte de la hiérarchisation des OPC générée par l'algorithme d'identification en fonction de quatre variables

3.4 Contribution à un processus décisionnel générique

Historiquement, la conception des OPC a été basée sur l'expérience des ingénieurs, sur des équations empiriques ainsi que sur de la modélisation physique à échelle réduite (Hamm *et al.*, 2002 ; Karambas et Samaras, 2014). De manière générale, l'outil d'aide à la prise de décision proposé vient complémenter le processus actuel de conception des OPC et le processus décisionnel plus générique actuellement utilisés en bonifiant l'information obtenue avec les méthodes d'analyse traditionnelle. L'intégration de la modélisation numérique à la démarche d'évaluation et de hiérarchisation des OPC proposée permettrait d'évaluer techniquement les scénarios retenus par les décideurs (figure 30). Un prédimensionnement de ces scénarios serait réalisé en fonction des guides de référence et des études scientifiques. Ensuite, ils seraient intégrés à un modèle numérique permettant de projeter l'évolution géomorphologique à court, moyen et long terme en fonction de séries temporelles de données hydrodynamique. Finalement, ces scénarios pourraient être comparés à l'état initial du système côtier (sans OPC) pour mesurer les effets de chacun d'eux.

La démarche pourrait être structurée de manière à effectuer l'évaluation et la hiérarchisation des OPC de manière itérative en trois étapes. À l'étape 1, les OPC présélectionnés en fonction des résultats de l'algorithme seraient évalués avec l'analyse multicritère. À l'étape 2, certains OPC seraient retenus pour être insérés dans un modèle numérique. À l'étape 3, au regard des résultats des trois méthodes, des combinaisons d'ouvrages de protection côtière pourraient être formées en fonction des synergies entre les OPC. Finalement, les étapes deux et trois pourraient être répétées dans des itérations subséquentes afin d'évaluer les nouvelles combinaisons d'OPC.

Également, la démarche proposée a été développée pour évaluer et hiérarchiser des OPC dans un objectif d'adaptation des communautés côtières aux changements climatiques. Toutefois, d'autres solutions d'adaptation non structurelles (figure 5) sont actuellement exclues du processus d'évaluation. Or, les solutions d'adaptation non structurelles pourraient être ajoutées à la démarche d'évaluation au sein de l'analyse multicritère en adaptant les critères de sélection.

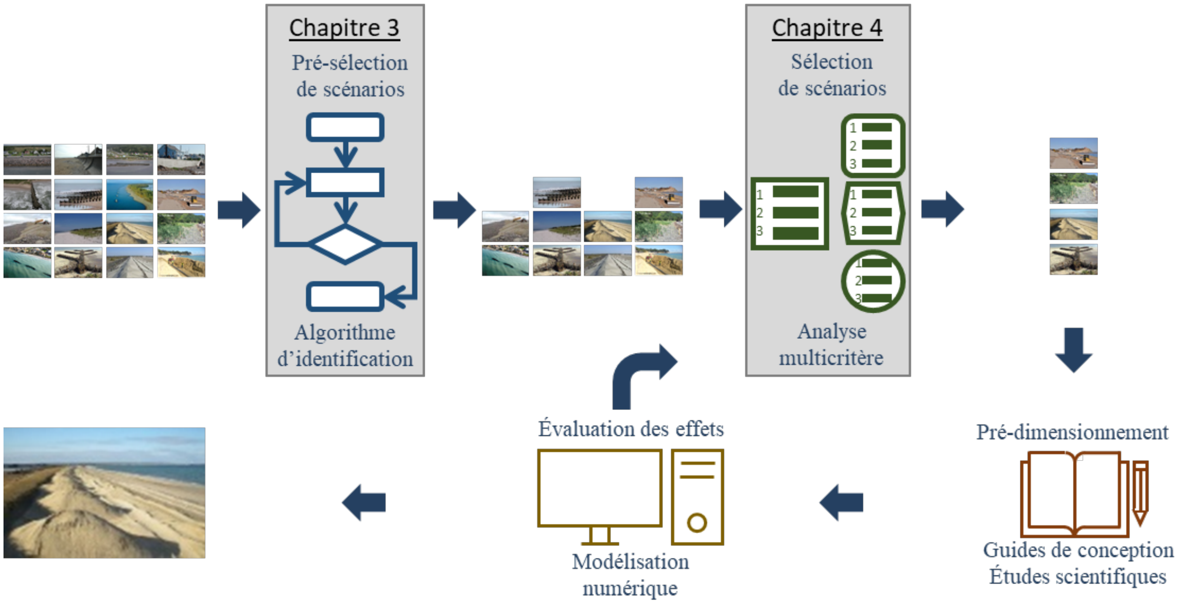


Figure 30. Suite d'outils à intégrer à l'approche proposée

L'utilisation de la modélisation numérique est relativement récente pour l'évaluation des effets et la conception des OPC sur la dynamique côtière. Quelques études ont été réalisées dans les années 1990. Toutefois, l'utilisation de la modélisation numérique a été plus fréquente à compter du milieu des années 2000 pour évaluer les effets de quelques types d'OPC : brise-lame (e.g., Cáceres et al., 2008, 2005; Chen et al., 2017; Ranasinghe et al., 2010; Razak and Nor, 2018) ; épi maritime (e.g., Dabees and Humiston, 2004; Kristensen et al., 2016; Rocha et al., 2013; Vaidya et al., 2015; Zhang and Stive, 2019) ; mur de protection (e.g., Ahmad et al., 2019; Ayat et al., 2017; Wang et al., 2015) ; recharge sédimentaire (e.g., Coelho et al., 2020; Karambas and Samaras, 2014; Tonnon et al., 2018).

La modélisation du système côtier est reconnue pour contribuer à la prise de décision (Samaras *et al.*, 2016). Dans ce contexte, plusieurs types de modèles numériques complémentaires peuvent être utilisés. Pour l'évaluation des effets des OPC, les modèles numériques permettant de projeter les processus morphologiques côtiers responsables des changements dans la zone côtière sont utilisés. Ces modèles ont été largement améliorés dans les dernières décennies (Ashton et Murray, 2006 ; Hans Hanson, 1989 ; Lesser, 2009 ; Warner *et al.*, 2010), ce qui a permis d'en améliorer largement la précision (Kroon *et al.*, 2020). Il demeure que la calibration, les limites techniques et les sources d'incertitude doivent être considérées dans l'analyse pour obtenir des résultats représentatifs, fiables et utiles dans le processus décisionnel.

3.4.1 Calibration des modèles

Un des principaux enjeux pour la calibration des modèles numériques est le manque d'accessibilité aux séries de données hydrodynamiques *in situ* à long terme et de données morphologiques locales (vagues au large, courants, topobathymétrie, niveau atteint par le run-up, taille des sédiments, etc.) (Dodet *et al.*, 2011 ; Idier *et al.*, 2020 ; Kroon *et al.*, 2020 ; Power *et al.*, 2019 ; Villaret *et al.*, 2016). Alors que le développement de la modélisation numérique au cours de la dernière décennie a permis de combler en partie ce manque, notamment pour les données de vagues au large (Bandet *et al.*, 2020 ; Morim *et al.*, 2019 ; Vitousek *et al.*, 2017), selon les entreprises consultées, des données *in situ* demeurent sporadiques (vagues à la côte, courants, substrat, etc.), ce qui représente toujours un enjeu pour l'application et la calibration de modèles numériques pour l'évaluation des effets des OPC sur plusieurs sites d'intervention (Sauvé *et al.*, 2020).

3.4.2 Limites techniques

Un autre enjeu est associé aux limites techniques des modèles numériques pour représenter avec une précision suffisante les détails qui caractérisent certains OPC (comme les épis perméables). Ce type d'OPC exige une calibration supplémentaire associée aux composantes structurales (Zhang et Stive, 2019) afin de représenter avec exactitude les effets réels et ainsi comparer les OPC sur une base réaliste.

3.4.3 Sources d'incertitudes

Les modèles numériques contiennent également des sources d'incertitude intrinsèque et épistémique (Kroon *et al.*, 2020 ; Van Gelder, 2000 ; Van Vuren, 2005). L'incertitude intrinsèque est associée à l'apparition aléatoire de processus naturels dans le temps et l'espace. Théoriquement, elle ne peut pas être réduite. L'ampleur de cette source d'incertitude peut varier selon l'étendue des échelles spatiale et temporelle (Kroon *et al.*, 2020). Par exemple, la variabilité spatiale de l'élévation des profils de plage peut avoir une influence significative sur la dérive littorale (Mil-Homens, 2016). Également, la modélisation de l'évolution de la morphologie côtière est sensible à la variabilité temporelle des séries de données utilisées en intrant comme le forçage des vagues (Southgate, 1995). Selon Kroon et al. (2020), après 2,5 années de suivi d'une méga-recharge, l'incertitude intrinsèque explique 50 % de la variance d'un changement volumétrique projeté de 1 million de mètres cubes considérant un écart-type de 15 %. En considérant la variabilité de l'incertitude selon l'étendue de l'échelle spatio-temporelle, une augmentation de l'incertitude est attendue pour des recharges de plage de moindre volume en raison d'un plus faible potentiel de changement. Ainsi, il est peu probable que l'incertitude soit négligeable pour des simulations supérieures à une échelle temporelle mensuelle sans analyse statistique complémentaire (Kroon *et al.*, 2020).

L'incertitude épistémique des modèles numériques est associée à l'état des connaissances, des modèles et des méthodes pour évaluer les processus. Ainsi, elle peut être réduite en fonction des ressources utilisées pour le développement du modèle (Kroon *et al.*, 2020). Les principales sources d'incertitude sont l'inadéquation des modèles, l'attribution de valeurs aux paramètres et les limites numériques (de Vriend, 1987 ; Grunnet et Ruessink, 2005 ; Simmons *et al.*, 2017). Généralement, l'inadéquation d'un modèle est causée par des processus physiques manquants (Huisman *et al.*, 2016) ou par la réduction de la complexité des processus par l'utilisation de modèles 1D ou 2D et de formules de transport des sédiments simplifiées (Kroon *et al.*, 2020). L'incertitude entourant l'attribution des valeurs aux paramètres du modèle est due au manque de données *in situ* pour la caractérisation de l'environnement côtier. Par exemple, les résultats des modèles sont particulièrement sensibles à la vitesse de sédimentation et à la taille des sédiments, données qui ne sont pas toujours disponibles (Villaret *et al.*, 2016). L'incertitude associée aux limites numériques est due à la résolution spatio-temporelle, l'ordre de la schématisation numérique et la technique d'accélération morphologique (Luijendijk *et al.*, 2019). Pour la modélisation à long terme, un des principaux enjeux est la combinaison des processus hydrosédimentaires à courte et grande échelle spatio-temporelle (Ranasinghe *et al.*, 2011 ; Roelvink, 2006).

Une expertise en modélisation numérique des systèmes côtiers est donc nécessaire pour assurer la qualité et la pertinence des résultats obtenus. Globalement, la modélisation numérique permettrait de compléter l'approche proposée pour une évaluation technique des OPC sélectionnés avec l'analyse multicritère. Il demeure que les enjeux soulevés doivent être résolus pour assurer une application de cet outil à l'ensemble des sites d'intervention.

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