The Logic Scoring of Preference Method for Marine Spatial Planning and Decision-Making: A Case Study of Acoustic Refugia for Killer Whales

by

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Abstract

Marine noise pollution is recognized as a stressor to endangered southern resident killer whales (SRKW) in the Salish Sea, Canada and USA. Low-noise locations can be identified using geographic information systems (GIS) and multicriteria evaluation (MCE) methods. However, commonly used spatial MCE are limited in their ability to properly identify and represent complex habitat suitability requirements. The main objectives of this thesis research are to implement GIS-based Logic Scoring of Preference (LSP), as a generalised MCE method, for suitability analysis of acoustic refugia of SRKW, develop different decision scenarios, and integrate multiple stakeholder perspectives for overall suitability analysis. The results indicate that the GIS-based LSP decision method can successfully identify suitable locations for SRKW acoustic refugia that can be used for establishing protected areas. This research advances GIS-based MCE methods as part of marine spatial planning (MSP) and decision-making processes accounting for diverse interested parties with conflicting priorities.

Keywords: Geographic Information Systems (GIS); Multicriteria Evaluation (MCE); Logic Scoring of Preferences (LSP); Overall Integrated Suitability Analysis (OISA); Marine Spatial Planning (MSP); Marine noise pollution

This thesis is dedicated to my mother and father,

whose love has seen me through.

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List of Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
ABM	Agent-Based Models
AHP	Analytic Hierarchy Process
AIS	Automatic Identification System
BC	British Columbia
CPA	Conjunctive Partial Absorption
DPA	Disjunctive Partial Absorption
GCD	Graded Conjunction/Disjunction
GIS	Geographic Information Systems
HPC	Hard Partial Conjunction
HPD	Hard Partial Disjunction
LSP	Logic Scoring of Preference
MCDA	Multicriteria Decision Analysis
MCE	Multicriteria Evaluation
MPA	Marine Protected Area
MSP	Marine Spatial Planning
NMFS	National Marine Fisheries Service (United States)
NOAA	National Oceanic and Atmospheric Administration (United States)
OISA	Overall Integrated Suitability Analysis
OWA	Ordered Weighted Averaging
PCB	Polychlorinated Biphenyls
SEL	Sound Exposure Level
SPC	Soft Partial Conjunction
SPD	Soft Partial Disjunction
UTM	Universal Transverse Mercator
WLC	Weighted Linear Combination

Chapter 1.

Introduction

1.1. Marine Noise Pollution and Killer Whales

Excessive sound in the marine environment, known as marine noise pollution, has long been recognized as a threat to marine organisms, many of which are sensitive to noise (Richardson et al 1995, Frantzis 1998, Nowacek et al 2007, Southall et al 2008, Popper and Hawkins 2012). Sources of marine noise such as sonar, marine fossil fuel exploration, marine construction activities, and marine vessel traffic are regulated in both Canada and the USA (NMFS 2008, Fisheries and Oceans Canada 2018); however, anthropogenic noise in the ocean continues to be a stressor to sensitive marine species. Killer whales (*Orcinus orca*) are a species that has been noted as sensitive to acoustic disturbance (Williams et al 2006, Lusseau et al 2009), and the Southern Resident Killer Whale (SRKW) population that inhabit the Salish Sea, a region of coastal British Columbia, Canada and Washington, USA, is considered endangered (Ford et al 2017). The Species at Risk Act in Canada and Endangered Species Act in the USA both mandate protection for “critical habitat” of endangered species, and Canada has included acoustic habitat characteristics in its official definition of critical habitat (Williams et al 2021).

Research on marine noise pollution and SRKW has identified behavioural responses of *orca* to noise from nearby vessels (Erbe 2002, Holt et al 2009, Lusseau et al 2009, Bubac et al 2021), quantified the effect of noise on their normal behaviours (Miller 2006, Williams et al 2006, Holt et al 2011), and assessed noise levels in important SRKW habitat areas (Williams et al 2015, Veirs et al 2016, Cominelli et al 2018). These studies are useful to inform policies intended to limit the effects of marine noise pollution on SRKW, and the most prominent approach towards noise from vessel traffic is creating protected areas where vessels must reduce their speed, maintain a minimum distance from *orca*, or avoid the area entirely (Williams et al 2014, Williams et al 2019). One unique type of habitat that is important to long-term SRKW population viability is areas that are highly suitable for normal SRKW behaviour with relatively low noise levels, termed “acoustic refugia” (Lacy et al 2017, McWhinnie et al 2017). While preliminary “interim sanctuary zones” have been established in SRKW summer habitat in Canada (Transport Canada 2022), a comprehensive spatial plan for the Salish Sea has not been developed.

Marine spatial planning is an approach to determining the distribution of marine resources across space and time to achieve societal goals, explicitly taking the marine ecosystem into consideration (Douvere 2008). It involves various participating decision-makers such as regulatory agencies, commercial stakeholders, Indigenous rights holders, and other interested groups. The Salish Sea, where SRKW forage on migrating chinook salmon during the summer months, is used extensively by humans for commercial shipping, transportation, commercial and recreational fishing, and recreational boating, among other uses (Hauser et al 2007). The region has deep cultural significance as the ancestral homeland of Coast Salish Indigenous peoples. Marine spatial planning efforts in the Salish Sea must balance these important uses of space with ecological considerations, not only for *orca* but for many species that inhabit the area. Due to the complexity of spatial planning for the Salish Sea region, spatial decision-making methods can assist planners and other participants in their deliberations.

1.2. Spatial Multicriteria Decision Analysis

Spatial multicriteria decision analysis (MCDA) refers to a collection of methods to support decision-making about spatial problems (Malczewski 2011), including multicriteria evaluation (MCE) (Malczewski and Jankowski 2020). For example, MCDA methods have been applied to site selection problems (Feo and de Gisi 2014), land conservation (Messer and Allen 2010), natural hazards risk assessment (Karlsson et al. 2017), and environmental management (Huang et al. 2011), among other applications. Geographic information system (GIS) are commonly coupled with MCE methods to assist in various decision-making and site selection problems. Geospatial data layers representing spatial criteria are standardized using suitability functions and weighted using a prioritization method, then combined using an aggregation method. The most common procedure uses the Analytic Hierarchy Process (AHP) to determine criteria weights (Saaty 1980) and Weighted Linear Combination (WLC) to combine criteria and calculate an overall suitability score for all locations in the study area (Malczewski 2000).

In marine spatial planning research, MCE methods have been developed for suitability analysis of locations for species conservation planning (Mourao et al 2014) and industrial sites such as offshore wind farms or aquaculture sites (Gimpel et al 2015, Divu et al 2021). MCE methods have also been used to evaluate the performance of established spatial management plans (Fu et al 2021). Moreover, MCE can be used to explore various scenarios, such as by adjusting input criteria or weight values that represent environmental conditions or stakeholder preferences, to better understand uncertainties and tradeoffs between different stakeholders' priorities (Wood and Dragicevic 2007, Tuda et al 2014, Janssen et al 2015).

1.2.1. Logic Scoring of Preference

Conventional MCDA procedures are limited in their ability to incorporate conditional or optional requirements of decision-makers and typically rely on additive scoring methods, such as WLC, that have limited ability to properly incorporate larger number of criteria (Dujmović and De Tré 2011). Accurately representing the effects of marine noise pollution on SRKW in combination with factors that make a location suitable as an acoustic refuge requires a method with complex logical operators to better represent the decision-making process. Logic Scoring of Preference (LSP) is a decision method originating from soft computing theory that can represent conditional requirements using a set of aggregation operators that express the degree to which multiple criteria must be satisfied simultaneously and whether any criteria are mandatory or optional (Dujmović 2007, Dujmović et al. 2010). The method can also incorporate an unlimited number of criteria without diminishing the effect of any one criterion due to the hierarchical structure of aggregation used in LSP (Dragićević and Hatch 2018). LSP has been applied with GIS to assess land-use suitability (Montgomery et al. 2016), groundwater pollution risk (Rebolledo et al. 2016), urban land use change (Dragićević and Hatch 2018), and even in three-dimensional urban applications (Munn et al 2022). It has been demonstrated that LSP is more intuitive and logically flexible than other common GIS-based MCE suitability analysis methods due to its stepwise process and greater range of logic aggregators, making it more similar to real human reasoning in decision-making (Montgomery and Dragićević 2016, Dujmović 2018).

1.2.2. Overall Integrated Suitability Analysis

Conventional MCE methods are limited in their ability to represent the preferences of multiple participants accurately and simultaneously in a decision-making process. In contrast, the hierarchical structure of the LSP decision method enables simultaneous suitability analysis of different perspectives by choosing weights and aggregators that precisely represent the preferences of each participant. The Overall Integrated Suitability Analysis (OISA) method (Dujmović 2018) enables combination of suitability maps that represent perspectives of each stakeholder, expert, or other participant that are then combined using a final aggregator, integrating all perspectives into one overall integrated suitability map. The aggregation functions used in LSP provide an intuitive representation of different relationships among decision-makers such as trade-offs between differing objectives, consensus among decision-makers, or complementary objectives (Shen et al 2021).

1.2.3. Three-Dimensional Multicriteria Evaluation

Most GIS-based MCE methods combine multiple criteria as layers in raster GIS data format, that is, a regular lattice of equal-sized cells that store values representing geospatial information. This is fundamentally a 2D representation in which the cells of a raster GIS data layer are georeferenced, and suitability functions can be deployed and then represented as maps for each criterion. Geospatial data are usually two-dimensional (2D) thus MCE methods produce suitability scores that can be visualized as 2D suitability maps or represent the vertical dimension as an attribute of 2D objects or grid cells (Longley 2011, Lin et al. 2014). However, many geospatial environments and phenomena in the real world are essentially three-dimensional (3D). Methods for three-dimensional (3D) spatial analysis have been developed that use identically sized cubes, known as voxels (Greene 1989), to partition 3D space in the same way that the equal-sized cells of a raster partition 2D space (Jjumba and Dragićević 2016). For urban applications, 3D spatial data has been used for volumetric analyses (Ahmed and Sekar 2015, Biljecki et al 2016), however only few recent studies address the 3D GIS-based MCE approaches predominantly for urban suitability analysis (Munn and Dragićević 2021). Because the marine environment is inherently 3D and marine organisms routinely move between shallow and deep areas of the ocean, 3D analysis methods to support conservation planning have been developed (Venegas-Li et al 2017, Manea et al 2019, Doxa et al 2022); however, 3D MCE has not yet been applied in the marine environmental management context.

1.3. Research Questions and Objectives

MCE methods are appropriate for the identification of acoustic refugia because of the need to combine several criteria from disparate sources; however, GIS-based MCE methods have not yet been applied to marine noise pollution research. Furthermore, more advanced GIS-based MCE methods such as LSP enable complex logical operations to represent decision-maker preferences realistically and LSP has been shown to provide a more accurate assessment of suitability than other MCE methods (Montgomery and Dragićević 2016). Due to the three-dimensional nature of the marine environment, a 3D MCE method would be more appropriate than the predominant 2D MCE approaches; however, existing 3D spatial analysis and modeling methods have not been integrated with GIS-based MCE. GIS-based MCE methods have been used to support marine spatial planning; however, conventional MCE methods cannot simultaneously evaluate multiple decision-making perspectives and integrate them in a way that represents various relationships among decision-makers.

To address these limitations of current spatial decision analysis methods for marine noise pollution and the lack of integration of three spatial dimensions with spatial multicriteria decision analysis tools, the following research questions are the basis of this thesis research:

1) How can an advanced spatial multicriteria method be applied to the identification of suitable locations for marine acoustic refugia in both 2D and 3D?

2) How can the LSP method be applied to integrate diverse decision-making perspectives in marine spatial planning?

To address the research questions, this thesis research aims to develop MCE suitability analysis based on the GIS-based Logic Scoring of Preference (LSP) method and apply them to a marine environmental management problem to identify suitable acoustic refugia for SRKW and to generate possible outcomes for marine spatial planning in the Salish Sea. The thesis research objectives are as follows:

1) Develop and implement a GIS-based LSP method to assess marine noise pollution and identify suitable acoustic refugia for southern resident killer whales in the Salish Sea;

2) Using the GIS-based LSP method, develop multiple scenarios based on possible decision-making perspectives that consider 3D nature of marine environment and combine them using the overall integrated suitability analysis (OISA) method.

1.4. Study Area and Datasets

The Salish Sea is an inland tidal sea of the North Pacific Ocean with depths up to 650m consisting of Georgia Strait, Juan de Fuca Strait, and Puget Sound, along with their interconnecting channels and coastal fjords (Barrie et al 2011). The border between Canada and the United States of America (USA) bisects the Strait of Juan de Fuca as well as Haro Strait, separating the Gulf Islands (Canada) and San Juan Islands (USA). The Salish Sea, especially Haro Strait, is designated critical habitat for the Southern Resident Killer Whale (SRKW) population by Fisheries and Oceans Canada (Ford et al 2017). Haro Strait connects the straits of Georgia and Juan de Fuca and is a major shipping lane as well as being the core summer foraging region for SRKW (Hauser et al 2007, Veirs et al 2016).

SRKWs inhabit the study area during the summer season from approximately May until late October because their primary prey species, Chinook salmon (*Onchorynchus tshawytscha*), migrate through the region on an annual basis (Hanson et al 2010). A secondary prey species, Chum salmon (*Onchorynchus keta*), also migrates through the area annually in October and November (Nichol and Shackleton 1996). Because of its position between several commercial shipping and passenger ferry ports (Nanaimo, Vancouver, and Victoria in Canada and Bellingham, Port Angeles, Tacoma, and Seattle in the U.S.A.), large ships commonly transit through the Salish Sea.

The geospatial data used for this thesis research is summarized in Table 1.1. It includes a coastal bathymetric elevation model, points of fish observation, locations of kelp beds, water treatment plants, parks and protected areas, designated fishing areas, and industrial sites, ports and terminals, and aquaculture sites. Datasets were provided

Table 1.1: Datasets used in this thesis research.

Dataset	Format	Source	Projection
Automatic Identification System (AIS) Vessel Points	File geodatabase (.gdb)	US NOAA 2017, 2019	UTM Zone 10N
British Columbia Coastal Elevation Model	NetCDF	US NOAA 2013	WGS 1984
BC Coastal Resources Information Management System (aquaculture sites, fish observations, kelp beds, industrial sites, fishing areas)	ArcGIS Shapefile	BC Ministry of Forests* 2019	WGS 1984
Water Treatment Plants	Excel Spreadsheet (.xlsx)	Government of Canada 2019	None
BC Protected Areas	ArcGIS Shapefile	BC Ministry of Forests 2019	WGS 1984
Canadian National Parks	ArcGIS Shapefile	Government of Canada 2019	Canada Albers
Washington State Parks	ArcGIS Shapefile	State of Washington 2019	UTM Zone 10N
BC Pelagic Marine Ecounits (water temperature, salinity)	ArcGIS Shapefile	BC Ministry of Forests 2019	WGS 1984
Pacific Salmon Commission Fishing Management Zones	ArcGIS Shapefile	BC Marine Conservation Analysis 2013	UTM Zone 10N
Reported Salmon Catch, 2019	Portable Document Format (.pdf)	Pacific Salmon Commission 2020	None

by the US National Oceanographic and Atmospheric Administration (NOAA), the governments of Washington, Canada, and British Columbia, specifically the British Columbia Ministry of Lands, Natural Resource Operations, and Rural Development (MFLNRORD), as well as the Marine Conservation Analysis project of the BC Conservation Foundation and the Pacific Salmon Commission. Tabular AIS vessel data for the months of May through September in 2017 and 2019 were converted to vessel movement tracks and the number of unique vessels (based on maritime mobile service identity, MMSI) was determined. In Chapter 3, fishing management zones with annual salmon catch data from the Pacific Salmon Commission were used to represent salmon abundance instead of fish observation points and designated fishing areas. The spatial data were processed to produce the input criteria data layers for the model, and all the raster GIS data layers used for GIS-based LSP-MCE analysis were processed to a spatial resolution of 100m.

1.5. Thesis Overview

This thesis consists of four chapters, including this Introduction. In Chapter 2, the GIS-based LSP method is explained and applied to suitability analysis of acoustic refugia for SRKW in the Salish Sea. The selection of criteria, weight values, and LSP aggregators and the development of suitability functions and the LSP aggregation structure was guided by a review of scientific literature on SRKW habitat requirements and effects of acoustic disturbance from vessel traffic. Using the developed aggregation structure, three scenarios were derived using levels of vessel traffic that occurred in the 2017 Summer foraging season of SRKW: (1) minimum traffic, (2) median traffic, and (3) maximum traffic scenarios. This part of the thesis research identifies locations that are potentially suitable as acoustic refugia and shows that the GIS-based LSP method is applicable to an environmental management problem.

The method presented in Chapter 2 demonstrates the ability of the GIS-based LSP method to incorporate marine noise pollution in the suitability analysis. However, it does not represent the 3D nature of noise pollution and SRKW habitat requirements. In Chapter 3, noise pollution is represented at two different depth levels relevant to SRKW behaviour, capturing the 3D variability of the criterion and its differing effects on foraging and socializing behaviour. The sound propagation model used to estimate noise from vessel traffic is adjusted so that a location's suitability incorporates factors that vary with water depth. Furthermore, the GIS-based LSP method is used to represent multiple possible perspectives on marine spatial planning with regard to acoustic refugia for SRKW. Three decision-making perspectives are represented as suitability analysis scenarios: (A) Behaviour-Oriented, which emphasizes SRKW behavioural ecology; (B) Noise-Oriented, which emphasizes acoustic disturbances to SRKW; and (C) Human-Oriented, which emphasizes human uses of space such as ports, shipping lanes, and aquaculture sites. The suitability maps derived for each scenario are then combined using the OISA method. Six different overall integrated suitability analysis (OISA) scenarios were developed using different aggregators to show several possible outcomes of a marine spatial planning process. The LSP and OISA methods are used to represent different perspectives and to facilitate the decision-making process by enabling participants to visualize “what-if” scenarios.

In conclusion, Chapter 4 reflects on the significance of the thesis research and the limitations of the methods developed. In addition, opportunities for improvements and future research are also discussed along with main contributions to respective scientific fields.

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Chapter 2.

Suitability analysis of acoustic refugia for endangered killer whales (Orcinus orca) using the GIS-based Logic Scoring of Preference method [*]

2.1. Introduction

Commercial shipping traffic in the North Pacific has been increasing over recent decades, raising concerns about increasing ambient noise (Chapman and Price 2011). Conventionally, underwater noise generated by commercial shipping has been considered “ambient noise” (Urick 1983). However, some species of marine organisms are especially vulnerable to noise in the environment, as it can interfere with their normal functions or increase physiological stress. Several studies have highlighted the ability of shipping noise to impact marine mammals due to high sound amplitude at low frequencies used by whales for communication over long distances (Nowacek et al. 2007, Clark et al. 2009, Moore et al. 2012, Pirotta et al. 2012). Recently, high-frequency components of shipping noise have been investigated for possible effects on cetaceans (Hermannsen et al. 2014, Li et al. 2015). *Orcinus orca* (killer whales) are a highly social cetacean species that use acoustic signals to communicate as well as to detect prey via echolocation. Thus, killer whales are vulnerable to high levels of noise that can disrupt these behaviors.

Guidelines for assessment of noise effects on marine mammals, provided by the U.S. National Marine Fisheries Service (NMFS 2018), were initially based on the recommendations of a scientific panel (Southall et al. 2008) and have since been updated. NMFS presents noise effects as temporary and permanent “threshold shifts,” that is, reductions in the hearing sensitivity of affected animals, occurring at a different cumulative sound exposure level ($\mathrm{SEL}_{\mathrm{cum}}$) for each species (NMFS 2018). Continuous

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exposure to noise results in increasingly high $\mathrm{SEL}_{\mathrm{cum}}$, increasing the risk of a threshold shift in a vulnerable animal. Other effects of sound exposure on killer whales include masking of communication or echolocation signals (Au et al. 2004, Miller 2006, Clark et al. 2009, Veirs et al. 2016), disruption of foraging behavior (Lusseau et al. 2009), and increased vocalization volume (Holt et al. 2009). Although killer whales can adapt their behavior to avoid noise, such as by diving deeper when foraging, this imposes energetic and physiological costs (Towers et al. 2019).

Marine noise pollution is a threat to endangered populations of killer whales that inhabit the coastal waters of British Columbia (BC), Canada (Miller 2006, Ayres et al. 2012). It has been shown that killer whale foraging behavior, travelling behavior, and communication call volume are affected by increased noise (Erbe 2002, Lusseau et al. 2009, Holt et al. 2009). There is special concern for the trans-boundary Southern Resident Killer Whale (SRKW) population, which is recognized as endangered in Canada and the U.S.A. (Ford et al. 2017). The population of SRKW has fluctuated between 76 and 89 individuals since 2001 and consisted of 76 individuals as of 2017 (Fisheries and Oceans Canada 2018). SRKWs are at high risk of exposure to noise during the summer months of May through October when they migrate from oceanic waters to the inland sea to access their primary food source, *Onchorhyncus tshawytscha* (chinook salmon) (Nichol and Shackleton 1996, Hauser et al. 2007, Cominelli et al. 2018). This summer habitat area is known as the Salish Sea, an inland tidal sea between Vancouver Island, British Columbia (BC), Canada and the mainland of BC and Washington (WA), U.S.A.

SRKW are also negatively affected by overfishing of salmon, and it has been shown that increasing *tshawytscha* abundance in combination with reducing noise pollution is a feasible strategy to achieve long-term SRKW population growth (Lacy et al. 2017). Killer whales use high-frequency acoustic signals for communication and echolocation, therefore high-frequency components of ship noise have the potential to mask killer whale acoustic signals, interfering with their normal behavior (Miller 2006, Clark et al. 2009, Holt et al. 2009). Efforts to map the spatial distribution of marine noise pollution in killer whale habitat have included assessments of cumulative sound compared to species distributions (Williams et al. 2015) and exposure risk in SRKW habitat (Cominelli et al. 2018).

One policy recommendation to protect species vulnerable to noise pollution is the establishment of marine protected areas (Firestone and Jarvis 2007, Williams et al. 2015, Harris 2017). In addition to protecting known critical habitat areas, there is a need to identify areas of good habitat quality that currently have relatively low noise levels, termed "acoustic refugia" (McWhinnie et al. 2017). Williams et al. (2015) conducted an analysis of species distributions and cumulative sound levels at a large spatial scale, highlighting opportunities to protect areas where species are currently abundant and noise levels are low. The summer habitat of SRKW is one of the noisiest regions studied, making it difficult to assess potential acoustic refugia at a large scale. In addition, using species distribution data to identify habitat areas cannot identify areas with quality habitat characteristics if they are not currently being used by the species of interest.

Several inter-related factors contribute to an area's suitability as a marine acoustic refuge, including the physical environment, prey availability, and noise pollution. Therefore, it is necessary to define a method capable of integrating data and information about relevant factors to identify the suitable locations. Geographic Information Systems (GIS)-based spatial multicriteria evaluation (MCE) methods are used for combining multiple sources of spatial data to determine the suitability of a location for a user-defined decision goal (Malczewski 1999). MCE has been applied in habitat suitability analysis (Store and Kangas 2001, Rodríguez-Freire and Crecente-Maseda 2008, Momeni Dehagi et al. 2018) and conservation planning (Wood and Dragicevic 2007). Several methods for MCE have been integrated with GIS, frequently using approaches based on pairwise comparison of criteria such as the analytic hierarchy process (AHP) (Saaty 1980) with weighted linear combination (WLC) or ordered weighted averaging (OWA) (Yager 1988, Malczewski 2000).

These widely used GIS-based MCE approaches have some limitations. The WLC method is based on linear additive aggregation of criteria that diminishes the importance of all criteria as the number of criteria increases (Dujmovic and De Tré 2011). Moreover, it is unable to represent mutual preference independence in situations where high suitability in one criterion cannot compensate for low suitability in another criterion (Malczewski 2000). For example, in habitat suitability, a species of bird might strongly prefer trees of a certain species to nest in and also the presence of water nearby for catching fish. If either criterion is not satisfied, the location is not suitable habitat. This logical property is called *simultaneity* and the inverse is *replaceability*, also known as ANDness and ORness respectively in reference to Boolean logic operators (Dujmovic 2015). OWA extends the WLC method and is capable of representing degrees of simultaneity and replaceability (Jiang and Eastman 2000). While OWA can represent simultaneity, it cannot model mandatory inputs (Dujmovic and De Tré 2011). For example, in the case where a predator species prefers areas with high abundance of prey and dense foliage in which to hunt, if the prey species is absent from the area, the density of the foliage does not matter. In this case, prey availability is mandatory while foliage is optional.

To overcome these limitations, the Logic Scoring of Preference (LSP) MCE method uses several aggregation functions to combine criteria in a hierarchical aggregation structure (Dujmovic et al. 2010). In contrast with other GIS-based MCE methods, LSP can represent degrees of simultaneity and replaceability as well as optional and mandatory inputs. Also, the hierarchical aggregation structure does not diminish the importance of any one criterion as the number of criteria increases. The LSP MCE method enables more accurate evaluation than other GIS-based MCE methods and thus is appropriate for applications in habitat suitability analysis and can integrate specific considerations such as the case of marine noise pollution. Therefore, the primary objective of this study is to implement the GIS-based LSP MCE method to identify suitable locations of acoustic refugia for killer whales within the Salish Sea.

2.1.1. Study Area and Datasets

The Salish Sea is a nexus of shipping activity in the North East Pacific Ocean situated between the commercial and passenger ferry ports of Nanaimo, Vancouver, and Victoria in Canada and Bellingham, Port Angeles, Tacoma, and Seattle in the USA The Canada-USA border bisects the Salish Sea along Haro Strait, the core summer foraging ground of SRKW (Hauser et al. 2007). The study area is a section of the Salish Sea including Georgia Strait and the Strait of Juan de Fuca as shown in Figure 2.1.

Geospatial data for the BC provincial boundary and the locations of industrial sites, ports, and terminals, aquaculture sites, designated fishing areas, kelp beds, provincial parks and protected areas, and fish observation points were downloaded from the BC data catalog (Government of British Columbia 2019a, 2019b). The locations of water treatment plants and Canadian national parks were provided by the government of Canada (Government of Canada 2019a, 2019b, 2019c). Locations of state parks were provided by the State of Washington (Washington State 2019). Finally, automatic identification system (AIS) data for seagoing vessels in the study area were obtained from the Marine Cadastre project of the U.S. National Oceanic and Atmospheric Administration (NOAA) (NOAA 2019c). The bathymetric coastal elevation model was also provided by NOAA (NOAA 2019a). All spatial datasets were projected to UTM Zone 10N coordinates and converted in a raster GIS environment at 100m spatial resolution for the purpose of the spatial analysis. The LSP-MCE method was implemented in ArcGIS desktop software, version 10.4.1 (Esri 2016) using the GIS.LSP tool (Shen et al 2021) developed in Python (Python Software Foundation 2021) programming language for suitability analysis.

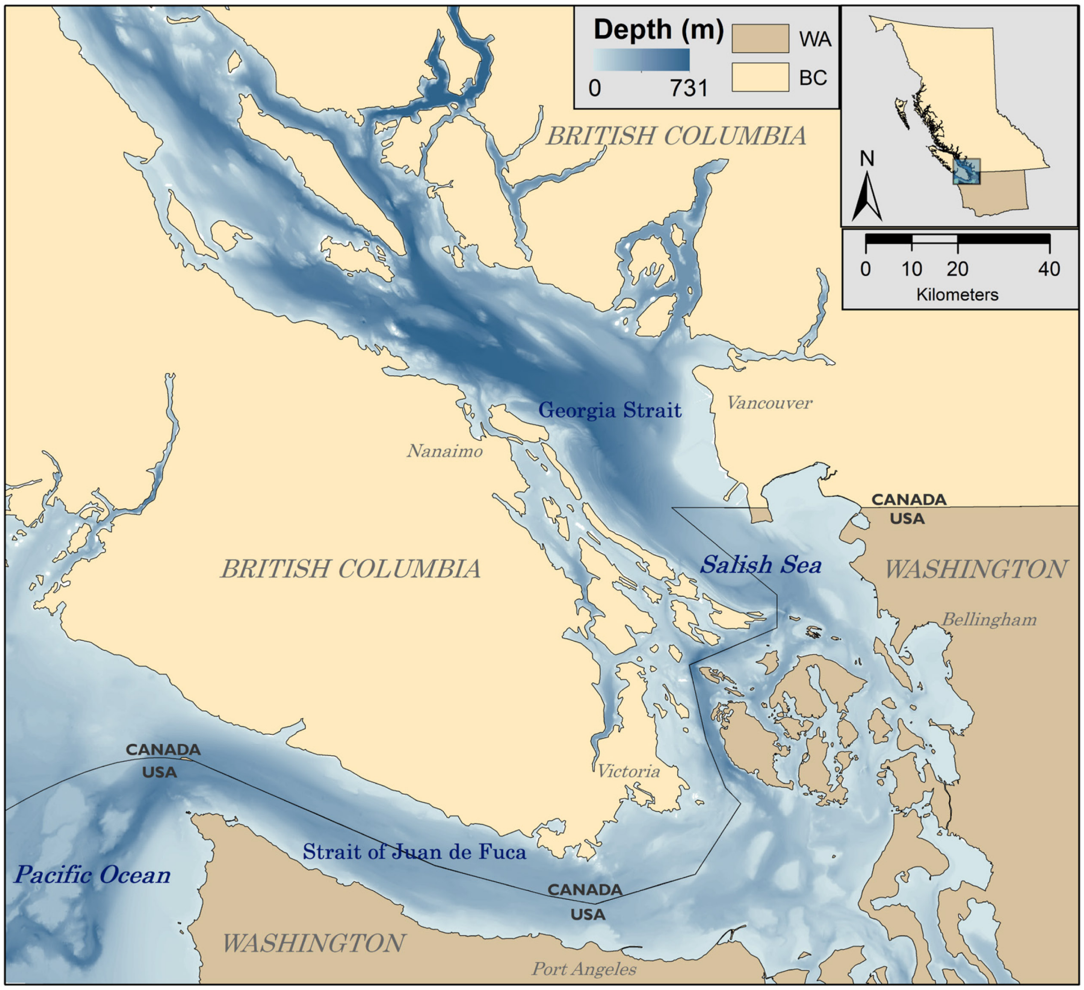

Figure 2.1: **Study area, the Salish Sea with bathymetry, located between British Columbia, Canada and Washington, USA**

2.2. The GIS-based LSP MCE Method

The general spatial or GIS-based MCE analysis consists of a set of criteria input values that are transformed according to suitability functions and weights representing trade-offs between those criteria to generate values for suitability score typically in a raster GIS environment (Huang et al. 2011). Geospatial data used for the analysis correspond to each elementary criterion, also called attributes, and are represented as values assigned to grid cells of a regular lattice. Similarly, the GIS-based LSP-MCE approach adheres to this broad definition but allows for a stepwise decision-making process that can be presented with four stages (Figure 2.2). Stage 1 is centered on

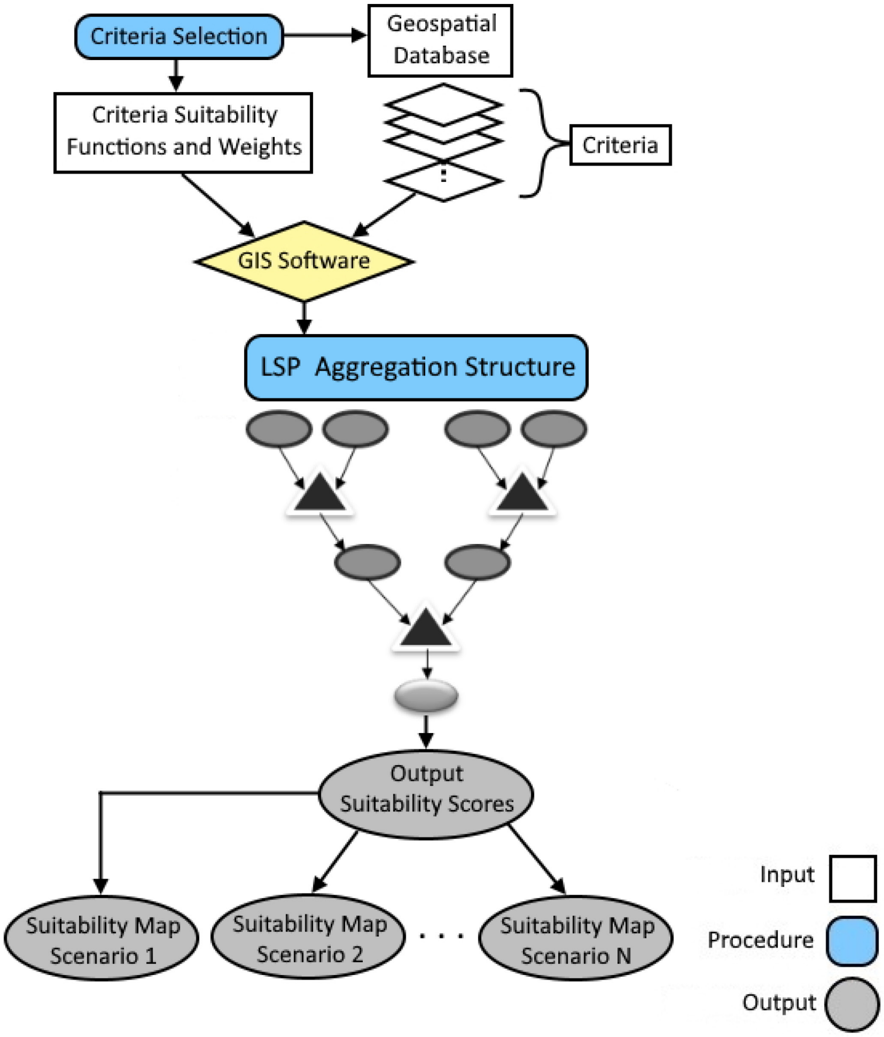

Figure 2.2: **Overview of the GIS-based LSP-MCE methodology for acoustic refugia suitability analysis**

defining the decision problem and selecting the criteria that influence the suitability analysis and collecting data to represent them. To facilitate criteria selection, decision-makers decompose the objective into multiple attributes, which are further decomposed into sub-groups containing elementary criteria.

Stage 2 is developing criteria suitability functions that express the degree to which each elementary criterion input value satisfies the requirements of the decision-maker(s) (Dujmovic and De Tré 2011). A criterion's suitability function transforms its input values to a value between 0 and 1, where 0 represents not satisfying the requirements at all and 1 represents total satisfaction of the requirements. The transformed values are called suitability scores, and each elementary criterion thus has an associated suitability score.

Appropriate aggregators are selected in Stage 3 of the GIS-based LSP method, to combine the suitability scores of criteria in each group into an aggregated suitability scozre using an aggregator that expresses the logical relationship between the criteria such as simultaneity, replaceability, and mandatory or sufficient inputs (Dujmovic 2007). A list of possible LSP aggregators is shown on Table 2.1. The input criteria for each aggregator are assigned weight values that represent their relative importance, and each

Table 2.1: Types of LSP Aggregators (adapted from Dujmovic et al 2010)

Category	Aggregator Type	Description
Conjunctive	Pure Conjunction (C)	The lowest input defines the output.
	Hard Partial Conjunction (HPC)	Low inputs have a greater effect than high inputs. Any input of 0 results in output of 0.
	Soft Partial Conjunction (SPC)	Low inputs have a greater effect than high inputs. Output is 0 if all inputs are 0.
Neutral	Arithmetic Mean (A)	Low and high inputs have equal effects.
Disjunctive	Soft Partial Disjunction (SPD)	High inputs have a greater effect than low inputs. Output is 1 if all inputs are 1.
	Hard Partial Disjunction (HPD)	High inputs have a greater effect than low inputs. Any input of 1 result in output of 1.
	Pure Disjunction (D)	The highest input defines the output.
Compound	Conjunctive Partial Absorption (CPA)	A "mandatory" input defines the maximum output. Optional input increases or decreases the output suitability score.
	Disjunctive Partial Absorption (DPA)	A "sufficient" input defines the minimum output. Optional input increases or decreases the output suitability score.

aggregator outputs a suitability scores representing the group of criteria. Suitability scores are then passed to another aggregator or multiple aggregators to be combined with other suitability scores which is a stepwise process suitable for the decision makers and their deliberations. Moreover, this can be used also to represent multiple scenarios by adjusting data inputs, criteria functions, the choice of aggregators, or criteria weights for each scenario to suit the needs of decision makers, their different priorities or situations related to the decision problem.

Aggregators include a parameter that represents the degree of conjunction or disjunction (Dujmović 2019). As shown in Table 2.1, conjunctive aggregators prioritize low input values whereas disjunctive aggregators prioritize high input values. Such graded conjunction/disjunction (GCD) aggregators are typically implemented using the weighted power mean as shown in Formula 1 (Dujmović et al. 2009):

$$S(s_1, \ldots, s_n) = (W_1 s_1^r, + \cdots + \; W_n s_n^r)^{\frac{1}{r}}, 0 < W_i < 1,$$

$$0 \leq s_i \leq 1, i = 1, \ldots, n, \textstyle\sum_{i=1}^{n} W_i = 1, \; r \in [-\infty, +\infty], 0 \leq S \leq 1 \qquad (1)$$

where *S* is the output value of the aggregator, *s* is the suitability score of the *i*-th input, *W* is the weight value of the *i*-th input, and *r* is the degree of conjunction or disjunction.

Conjunctive and disjunctive partial absorption aggregators are in fact compound aggregators consisting of one conjunctive and one disjunctive aggregator. For a CPA aggregator, the order is conjunctive, then disjunctive, and the reverse is true for a DPA aggregator. Both types of compound aggregators have the additional parameters Penalty (*P*) and Reward (*R*) and require two inputs: one mandatory or sufficient input and one optional input (Dujmović et al. 2009, Dujmović et al. 2010). In a CPA aggregator, if the mandatory input's value (s_{man}) is 0, the output suitability score is 0. If s_{man} < 1 and the optional input's value (s_{op}) = 0, the output suitability score is reduced by *P*. If s_{man} < 1 and s_{op} = 1, the output suitability score is increased by *R*. In a DPA aggregator, the optional input can partially compensate for the more important sufficient input (s_{suf}) (Dujmović et al. 2009). If s_{suf} = 1, the output suitability score is 1, regardless of the value of s_{op}. If s_{suf} = 0 and s_{op} > 0 the output suitability score is increased by *R*. If s_{suf} < 1 and s_{op} < s_{suf}, the output suitability score is reduced by *P*.

Finally, Stage 4 is then to calculate an overall suitability score, also called the preference score, using a suitable LSP aggregator for every raster cell across the study area using the input criteria and aggregation structure, resulting in a suitability map or multiple maps corresponding to each decision scenario.

2.2.1. Selection of Elementary Criteria

The criteria chosen for this research study are presented in Table 2.2 and organized into three groups: habitat suitability (H) coded in green, anthropogenic factors (A) in blue, and noise pollution (N) in orange. Within the habitat suitability group are two sub-groups, foraging (F) (in light green) and socializing (S) (in dark green), representing the two types of killer whale behaviors that require suitable habitat and low noise levels. The foraging group consists of proximity to salmon observation points for Chinook (F_{P1}) and Chum salmon (F_{P2}), salmon swim depth (F_D), and slope (F_S). Socializing requires sufficient depth (S_D) and is supported by proximity to kelp (S_K). The anthropogenic factors group contains proximity to water treatment plants (A_T), designated fishing areas (A_F), and marine protected areas (A_M). Finally, the noise pollution group consists of the received noise level in each of three key frequency bands used by killer whales for pulsed calls (N_C), whistles (N_W), and echolocation clicks (N_E), as well as proximity to industrial sites, ports, terminals, and aquaculture sites (N_I).

Habitat suitability for killer whales mainly depends on prey availability. Resident killer whales including SRKW specialize in hunting fish, specifically salmonids, which distinguishes them from the sympatric transient killer whales that specialize in hunting marine mammals (Heimlich-Boran 1988). Chinook salmon (F_{P1}) are the preferred prey of SRKW, likely due to their larger size and nutritional content (Au et al. 2004, Hanson et al. 2010), and account for approximately 71% of SRKW diet (Ford et al. 2009). Of secondary importance is Chum salmon (F_{P2}), which forms approximately 24% of SRKW diet overall but is especially important during late Fall, when Chinook are not available (Ford et al. 2009). Spatial data on salmon abundance is not readily available; however, points where salmon have been observed are part of the BC government's Coastal Resource Information and Management System (CRIMS). Killer whales prefer to forage close to shore, and it is thought that they use steep, rocky shorelines to trap and catch salmon (Ford et al. 1998). Also, salmon typically swim at depths of 25-80m (Candy and

Quinn 1999). The combination of sufficient depth (F_D) and steep slope (F_S) therefore constitutes suitable foraging terrain.

Table 2.2: Criteria Selected for Acoustic Refugia Suitability Analysis

Group	Criterion	Description	Justification
Habitat Suitability (H)	F_{P1}	Proximity to primary prey (chinook salmon) observation points	Heimlich-Boran 1988, Au et al. 2004, Ford et al. 1998, Ford et al. 2009, Hanson et al. 2010
	F_{P2}	Proximity to secondary prey (chum salmon) observation points	Nichol and Shackleton 1996, Ford et al. 1998, Ford et al. 2009
	F_D	Salmon Swimming Depth	Candy and Quinn 1999
	F_S	Slope	Ford et al. 1998, Au et al. 2004, Hauser et al. 2007
	S_D	Killer Whale Diving Depth	Heimlich-Boran 1988, Baird et al. 2005
	S_K	Proximity to Kelp Beds	Ford 1989, Ford 2009
Anthropogenic Factors (A)	A_T	Proximity to Water Treatment Plants	Andrady 2011, Browne et al. 2011, Wright et al. 2013, Lacy et al. 2017
	A_F	Presence or Absence of Designated Salmon Fishery	Kock et al. 2006, Lachmuth et al. 2011, Towers et al. 2019
	A_M	Proximity to Marine Protected Areas	Firestone and Jarvis 2007, Lachmuth et al. 2011, Williams et al. 2015, Harris 2017
Noise Pollution (N)	N_C	Noise level in the Call frequency band (1-6kHz)	Ford 1989, Ford 1991, Richardson et al. 1995, Erbe 2002, Au et al. 2004, Miller 2006, Holt et al. 2009, Lusseau et al. 2009, Veirs et al. 2016, Lacy et al. 2017
	N_W	Noise level in the Whistle frequency band (8-12kHz)	
	N_E	Noise level in the Echolocation click dominant frequency (40kHz)	
	N_I	Proximity to industrial sites, ports, terminals, and aquaculture sites	Erbe 2002, Lusseau et al. 2009, Ayres et al. 2012

Colours indicate groups of criteria whose suitability scores are aggregated.

🟩	**Habitat Suitability group**	🟩	**Foraging sub-group**	🟩	**Socializing sub-group**
🟦	**Anthropogenic Factors group**	🟧	**Noise Pollution group**		

Killer whales are social animals; however, their social behaviors are difficult to capture with spatial datasets. In the absence of data describing the proximity of individuals or groups to one another, this study aims to include the minimum requirements for social behavior. Killer whale activity is concentrated in the upper 30m of the water column (S_D) (Baird et al. 2005). While play behaviors are typically observed at or near the surface (Heimlich-Boran 1988), longer dives are observed during resting and socializing compared to other behavior types (Ford 1989). Socializing killer whales have also been observed playing with kelp (S_K), which they rub against or wrap around their tails (Ford 1989, Ford 2009).

Anthropogenic factors other than noise pollution can affect a location's suitability. Polychlorinated biphenyls (PCBs) are a chemical pollutant associated with elevated rates of calf mortality in killer whales (Lacy et al. 2017). A major source of PCBs is microplastic particles (Andrady 2011), which can be introduced to the marine environment at sewage treatment facilities (A_T) (Browne et al. 2011). Even if SRKW do not directly ingest microplastic particles or other sources of PCBs, organisms at lower trophic levels can ingest such particles and then pass contaminants through the food chain. PCBs become increasingly concentrated at higher trophic levels (Wright et al. 2013), putting apex predators such as killer whales at higher risk.

Commercial and recreational fishing vessels can compete with killer whales for salmon; furthermore, commercial fishing equipment can disrupt normal foraging behavior by encouraging depredation on longlines (Kock et al. 2006, Lachmuth et al. 2011, Towers et al. 2019). Killer whale dives while depredating can be significantly longer and deeper than normal foraging dives, which causes physiological stress (Towers et al. 2019). Designated salmon fisheries (A_F) are thus unsuitable habitat for killer whales in these respects. In contrast, existing marine protected areas (A_M) restrict vessel activity and may have other characteristics such as greater biodiversity that can contribute to habitat suitability (Harris 2017).

A location cannot be considered an acoustic refuge if noise pollution levels are likely to interfere with killer whale behavior. Killer whales use three different types of vocalizations: pulsed calls, whistles, and echolocation clicks (Ford 1989). Each vocalization type is used during different behaviors and the sounds produced have differing wavelengths that suit their function. Pulsed calls (N_C) are primarily used for communication and have the lowest frequency (1-6kHz); whistles (N_W) are heard primarily during socializing, with a dominant frequency range of 8-12kHz; and echolocation clicks have a high frequency range dominated by 40-50kHz wavelengths (Ford 1989, Ford 1991, Au et al. 2004). Not all vessels are required to broadcast AIS data, so proximity to industrial sites, ports, terminals, and aquaculture sites (N_I) is included to account for additional ship noise.

Sound Propagation Model

As sound travels through a medium such as water, energy is gradually lost due to absorption, reflectance, scattering, and other factors (Etter 2012). To estimate the effects of these factors, there is a need for a sound propagation model to approximate the amount of lost energy between a sound source and sound receiver. The model used in this study calculates the received sound level (RL) in decibels based on a spreading loss formula described by Richardson et al. (1995) as follows:

$$RL = SL - 10logR - 10logR1 - \alpha - AL - 60 \qquad (2)$$

where SL is the sound level in decibels at the source, R is the distance between source and receiver, R_1 is the distance equal to the average depth between source and receiver at which the spreading pattern changes from spherical to cylindrical spreading, α is an energy absorption coefficient in seawater, A_L is duct attenuation or “leakage” (Urick 1983), and *60* approximates the transmission loss at ranges less than 1km. The α coefficient is calculated based on the typical temperature and pH values for the North Pacific Ocean (Hodges 2010). To incorporate the effects of surface waves for the attenuation coefficient A_L, “sea state 3” as light windy conditions and some waves was used as described by Urick (1983). The resulting equation assumes spherical sound spreading from the source to the range R_1, beyond which point a cylindrical spreading pattern is modeled.

In this research study, the received sound level was calculated for each raster cell of the study area using Formula 2. Each noise pollution input raster GIS data layer contains the maximum value in decibels for its frequency band for every cell. This means that when two vessels are at the same range from a given raster cell, the received sound value in that particular raster cell is the louder of the two sources in the relevant frequency band, which depends on the sound spectral profiles of the vessels.

2.2.2. Suitability Functions

Figure 2.3 presents the developed suitability functions that correspond to each elementary criterion. The sub-groups Foraging (F) and Socializing (S) form the habitat suitability group (H). The first two criteria, proximity to Chinook salmon (F_{P1}) and Chum salmon (F_{P2}) observations, are fully satisfied when a location is within 500m of a fish observation point for the correct species. Because observation points are located near rivers and streams, this also reflects the preference of killer whales for foraging close to shore (Heimlich-Boran 1988, Ford et al. 1998). Suitability decreases with increasing distance from fish observation points, however the criteria are never completely unsatisfied because salmon are known to be migrating through the study area (Nichol and Shackleton 1996) and spatial data for specific migration paths are not available. The Foraging Depth criterion (F_D) is partially satisfied if the depth at a location is at least 25m, and fully satisfied if the depth is at least 80m, reflecting the depths at which salmon typically swim (Candy and Quinn 1999). The Slope criterion (F_S) is fully satisfied when slope equals 100%, that is, when the slope is a vertical surface. As mentioned above, killer whales likely use such undersea walls to catch prey (Ford et al. 1998, Hauser et al. 2007).

The Socializing Depth criterion (S_D) is completely satisfied when the depth of a location is at least 30m, supporting the majority of killer whale diving activity (Baird et al. 2005). The Proximity to Kelp Beds criterion (S_K) is completely satisfied when a location is within 500m of a kelp bed. The suitability of a location decreases with increasing distance from kelp beds to capture killer whale play interactions with kelp (Heimlich-Boran 1988, Ford 1989).

In Anthropogenic Factors (A), the Proximity to Water Treatment Plants criterion (A_T) is completely unsatisfied when a location is within 100m of a water treatment plant, and completely satisfied when it is at least 10km away from water treatment plants. This distance is based on the approximate distance between sewage disposal sites and reference sites in Browne et al. (2011), who measured significantly reduced concentrations of microplastic particles at reference sites compared to the sewage disposal sites. The Fishery criterion (A_F) is completely satisfied if a location is not within a designated fishing area, and completely unsatisfied when it is. The Proximity to Marine Protected Areas criterion (A_M) is completely satisfied when a location is within a marine protected area, reflecting the positive effects for habitat suitability resulting from reduced human activity (Lachmuth et al. 2011, Harris 2017).

In the Noise Pollution group (N) criteria, the Noise Level in the Call, Whistle, and Echolocation frequency bands (N_C, N_W, and N_E) are based on the sound level likely to cause masking of the killer whale acoustic signals reported in the literature, termed the "masking threshold" for each frequency band. A received sound level less than the masking threshold results in complete satisfaction of the criterion or maximum suitability. For the Call frequency band (N_C) and the Whistle frequency band (N_W), the masking threshold is 60dB. This is slightly quieter than the ambient noise level of sea state six, which corresponds to very rough waves and near-gale winds (Richardson et al. 1995). Miller (2006) reported up to 91% reduction in communication range for killer whales in sea state six. For the Echolocation frequency band (N_E), the masking threshold is 49dB. Au et al. (2004) note that 49dB is the auditory brainstem response of killer whales and echolocation range should not be affected at or below this sound level; however, echolocation range rapidly decreases in noisier conditions. Killer whales are known to increase the volume of their acoustic signals to compensate for noisy conditions (Holt et al. 2009), therefore received sound slightly above the masking threshold does not necessarily disqualify a location as an acoustic refuge.

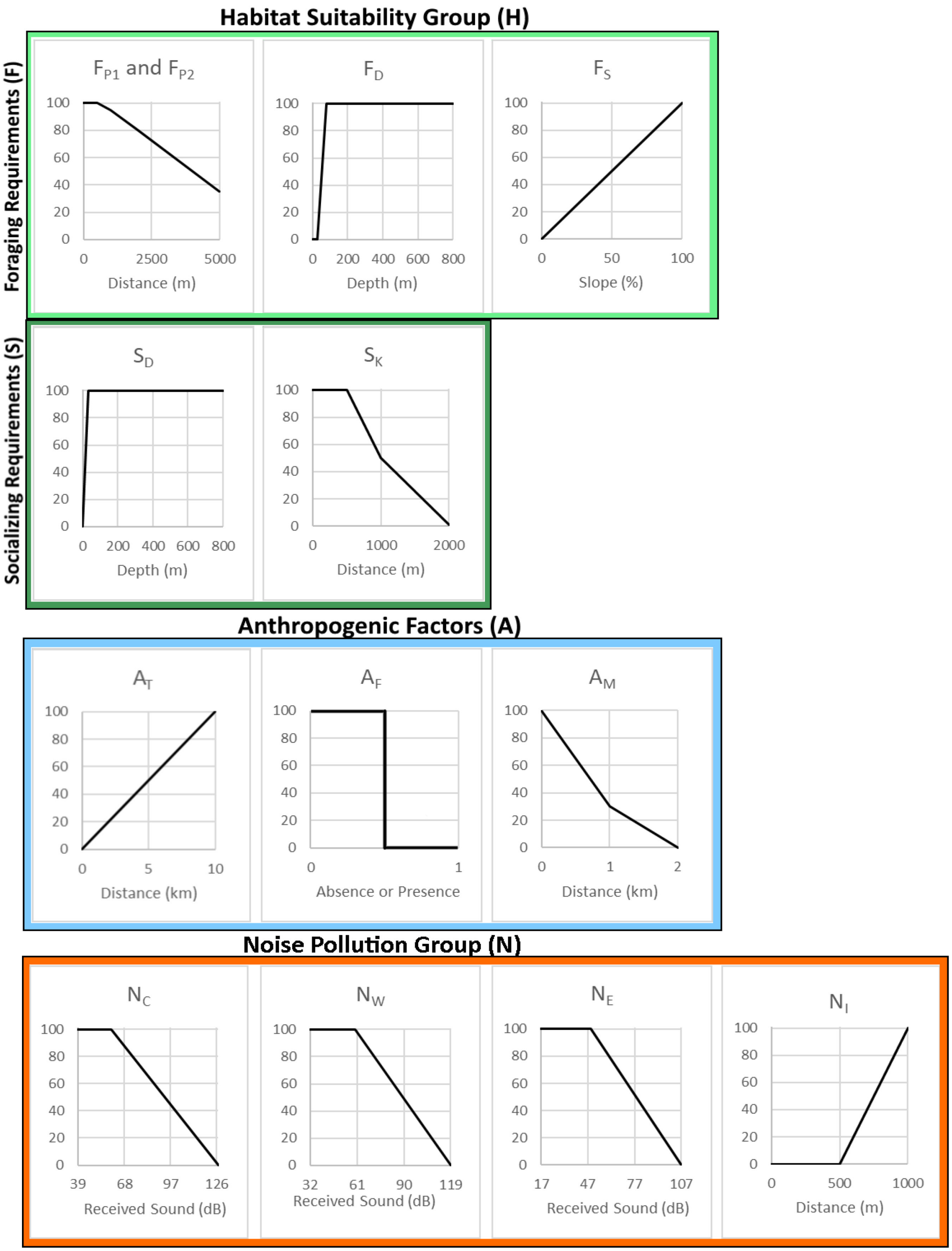

Figure 2.3: Suitability functions for each of the elementary criteria: Primary Prey (FP1), Secondary Prey (FP2), Foraging Depth (FD), Slope (FS), Socializing Depth (SD), Proximity to Kelp Beds (SK), Proximity to Water Treatment Plants (AT), Salmon Fishery (AF), Proximity to Marine Protected Areas (AM), Call Frequency (NC), Whistle Frequency (NW), and Echolocation Frequency (NE)

2.2.3. LSP Aggregation Structure

The LSP aggregation structure involves logical evaluation of the criteria to present how they are connected with the chosen aggregators. For this research study, a combination of graded conjunction and partial absorption functions were chosen and organized in the distributed mandatory/optional aggregation structure described by Dujmovic and De Tré (2011). The LSP structure is presented in Figure 2.4 where inputs are grouped based on similarity or connectedness of criteria and the aggregation functions increase in degree of simultaneity towards the final aggregation step.

Mandatory/optional aggregation functions are used for the prey availability sub-group (F_{P1} and F_{P2}) and the foraging terrain sub-group (F_D and F_S). The prey availability group is aggregated using the CPA aggregator. As noted previously, Chinook salmon (F_{P1}) are the primary prey species of SRKW and their presence in the Salish Sea during the summer months is what draws SRKW to the area (Nichol and Shackleton 1996). The presence of chum salmon (F_{P2}) is desirable; however this species comprises approximately 25% of SRKW diet (Hanson et al. 2010). The maximum reward value is therefore set at 0.25: if the suitability score of F_{P1} is partially satisfied and the suitability score of F_{P2} is 1, the suitability score output of the CPA aggregator would be equal to $F_{P1}(1 + 0.25)$. Suitable depth (F_D) and slope (F_S) are also necessary to support normal foraging behavior and are aggregated using the CPA function. Given the typical salmon swimming depth, it follows logically that steep slopes can only increase suitability when depth is suitable. However, the strong preference for foraging in nearshore areas observed in SRKW (Heimlich-Boran 1988, Ford et al. 1998, Au et al. 2004, Hauser et al. 2007) suggests that the maximum reward for suitable slope should be high, therefore the reward is set at 0.5. The prey availability and foraging terrain sub-groups are then aggregated with equal weight using an HPC function (HC-) to produce the foraging suitability (F) suitability score.

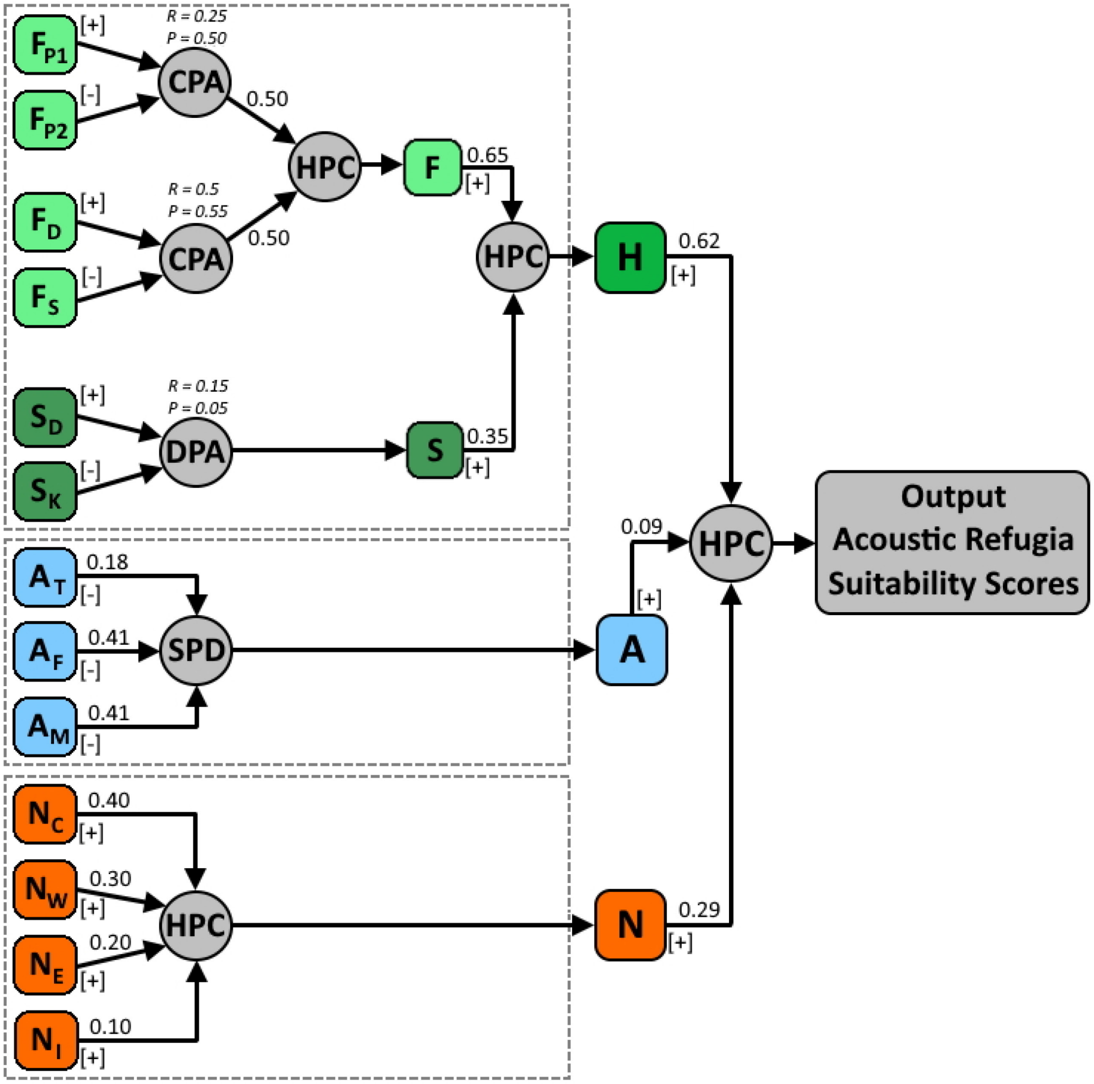

Figure 2.4: **The LSP aggregation structure with criteria ([+] denotes mandatory and [-] optional), corresponding criteria weights indicated on arrows leading to aggregators; reward R and penalty P are noted for each partial absorption aggregator; aggregators used are as follows: CPA conjunctive partial absorption, DPA disjunctive partial absorption, SPD soft partial disjunction, and HPC hard partial conjunction**

Mandatory/optional aggregation functions are used for the prey availability sub-group (F_{P1} and F_{P2}) and the foraging terrain sub-group (F_D and F_S). The prey availability group is aggregated using the CPA aggregator. As noted previously, chinook salmon (F_{P1}) are the primary prey species of SRKW and their presence in the Salish Sea during the summer months is what draws SRKW to the area (Nichol and Shackleton 1996). The presence of chum salmon (F_{P2}) is desirable, however this species comprises approximately 25% of SRKW diet (Hanson et al. 2010). The maximum reward value is therefore set at 0.25: if the suitability score of F_{P1} is partially satisfied and the suitability score of F_{P2} is 1, the suitability score output of the CPA aggregator would be equal to $F_{P1}(1 + 0.25)$. Suitable depth (F_D) and slope (F_S) are also necessary to support normal foraging behavior and are aggregated using the CPA function. Given the typical salmon swimming depth, it follows logically that steep slopes can only increase suitability when depth is suitable. However, the strong preference for foraging in nearshore areas observed in SRKW (Heimlich-Boran 1988, Ford et al. 1998, Au et al. 2004, Hauser et al. 2007) suggests that the maximum reward for suitable slope should be high, therefore the reward is set at 0.5. The prey availability and foraging terrain sub-groups are then aggregated with equal weight using an HPC function (HC-) to produce the foraging suitability (F) suitability score.

The socializing suitability (S) group uses a DPA aggregation function to combine killer whale diving depth (S_D) and proximity to kelp beds (S_K). Because most socializing behavior occurs at or near the surface (Heimlich-Boran 1988, Baird et al. 2005), depth cannot be considered a mandatory input for socializing. Kelp beds occur in shallower, nearshore areas, so it follows that proximity to kelp can partially compensate for shallow depth because diving behavior during socializing can be replaced by play interactions with kelp. However, purely socializing behaviors account for only 12-15% of SRKW activity (Ford et al. 2017), and the killer whale diving depth criterion also represents suitable depth for travelling and resting behaviors which do not involve social or play behaviors. Therefore, to avoid overstating the importance of kelp, the maximum reward for S_K was set to 0.15 to reflect the socializing portion of SRKW activity. Groups F and S form the habitat suitability group, which uses an HPC function (HC).

Criteria in the anthropogenic factors group (A) are combined using the SPD aggregation function. The effects of PCB contamination (represented by A_T) on killer whales are not fully understood, however a population viability analysis indicated that an individual accumulation rate of 5ppm per year would result in a 1% reduction in population growth rate (Lacy et al. 2017). In the same study, lack of prey had a maximum negative effect of nearly 4%, and noise approximately 0.5% (Lacy et al. 2017). Proportionally, PCBs thus account for 18.1% of the modeled reduction in population growth, and A_T is assigned a weight of 0.18 for the SPC aggregator. A_F and A_M do not exactly correspond to a threat to killer whale population growth, both partly representing the effects of noise pollution (through vessel traffic not captured in the AIS data) and prey availability in addition to other effects (e.g. stress of depredation on longlines instead of natural foraging, other benefits of reduced human activity in MPAs) (Harris 2017, Towers et al. 2019). The remaining 82% of the aggregated anthropogenic factors suitability score is thus divided evenly between A_F and A_M (0.41 each).

Each input criterion in the Noise Pollution group (N) is weighted according to the frequency and importance of the killer whale vocalization as reported in the literature. The simple criteria ranking method (Stillwell et al 1981) was used to determine criteria weights for factors in this group. Pulsed calls are the most frequently used vocalization, occurring during all killer whale behaviors (Ford 1991), therefore N_C was ranked highest, resulting in a weight of 0.4. The next most important vocalization is echolocation clicks, which while not frequent are critical to foraging success and vulnerable to masking by noise pollution due to the difference in amplitude between the emitted click and the echo reflected by a target fish (Au et al. 2004). Therefore, N_E was ranked second and assigned a weight of 0.3. Whistles are heard exclusively during socializing behavior and are the least-frequently used vocalization (Ford 1991), thus N_W was ranked third and assigned a weight of 0.2. N_I was ranked fourth, resulting in a weight of 0.1. The input data for criteria N_C, N_E, and N_W are the noise levels estimated by the sound propagation model in each of the three frequency bands. Vessels required to broadcast AIS signals represent a significant portion of sound sources in the Salish Sea; consequently, suitable habitat areas are most impacted by vessel traffic and thus acoustic refuge locations would benefit most from noise pollution management efforts. Therefore, three scenarios have been developed to represent different levels of noise pollution originating from marine vessel traffic in the study area.

In the final stage, the factor groups H, A, and N are aggregated using an HPC function (HC+) into an output suitability score that then can be presented as a suitability map. Weights for the input suitability scores were determined by pairwise comparison and reflect the necessity of suitable habitat for killer whales and high importance of noise pollution in assessing an area's suitability as an acoustic refuge. Groups were compared using the scale established by Saaty (2013) for the Analytic Hierarchy Process, in which the relative importance of criteria is assigned a rank from 1 to 9. A rank of 1 indicates that the paired criteria are of equal importance, whereas a rank of 9 represents that the first criterion in a pair is highly important compared to the second criterion in the pair. For this suitability analysis, group H is considered strongly more important than group A (a rank of 6) and group H is considered slightly more important than Group N (a rank of 2). Group N is considered moderately more important than group A (a rank of 3). These rankings form a priority matrix and the principal eigenvector are calculated for each group, resulting in the priority weights assigned to each group (Saaty 2013). The derived weights are 0.62 for group H, 0.29 for group N, and 0.09 for group A.

The geospatial data and vessel data inputs were transformed into a series of raster GIS data layers as maps representing each elementary criterion. Values contained in each raster cell were then transformed using the corresponding suitability function for each criterion. Criteria map layers were combined as presented in the LSP aggregation structure (Figure 2.4), resulting in suitability scores for each raster cell that collectively form the output suitability map.

2.2.4. Vessel Traffic Scenarios

The three vessel traffic scenarios were derived based on the number of unique vessels present in the study area in May-October of 2017. The unique vessel locations were derived from AIS vessel location data (NOAA 2019c) were selected based on the associated date and time. Scenario 1, *Minimum Traffic*, represents vessel traffic on May 1st, which had the lowest number of vessel transits (182). Scenario 2, *Median Traffic*, represents September 16th, which had 330 vessels as the median value of all recorded transits. Finally, Scenario 3, *Maximum Traffic*, represents traffic on September 1st, which had the highest number of vessel transits, total of 848.

2.3. Results and Discussion

In this research study, input criteria representing killer whale foraging and socializing habitat requirements, anthropogenic impacts on killer whale habitat, and noise pollution from vessel traffic were aggregated using a stepwise, hierarchical aggregation structure to obtain suitable locations for acoustic refugia for SRKW. The GIS-based LSP-MCE method was used to develop three different scenarios representing different levels of vessel traffic. The obtained suitability scores for all three scenarios are presented as acoustic refugia LSP suitability maps, and the results obtained for Median Traffic is depicted in Figure 2.5. The highest obtained suitability score is 0.86, indicating the most suitable location for a killer whale acoustic refuge.

Although decision-makers and environmental managers can choose their way for classifying the obtained scores, for the purpose of this research study, the equal interval classification method has been used as best suited for the continuous values obtained for suitability scores. For each vessel traffic scenario, the acoustic refuge suitability scores are then classified in five equal intervals indicating Very Low (0.0 – 0.17), Low (0.18 – 0.34), Moderate (0.35 – 0.51), High (0.52 – 0.69), to Very High (0.70 – 0.86) suitability. Very High suitability represents an outcome of high satisfaction of several input parameters that follows the logic set by the aggregation structure. Figure 2.6 presents detailed views of two areas with the highest suitability scores indicating the most suitable acoustic refuge areas, the Haro Strait-Boundary Pass region (right of Figure 2.6) and the Upper Georgia Strait region including adjacent fjords (left of Figure 2.6). Vessel tracks are visible on these suitability maps in locations where noise pollution from vessel traffic has significantly affected a location's suitability score.

Several locations in the Salish Sea are identified as highly suitable as acoustic refugia, as presented in Figure 2.5. The locations of these suitable areas do not change in each traffic scenario because they are tied to the habitat factors depth, slope, presence of prey, and presence of kelp, all of which are unchanged by noise pollution. Suitable habitat is found in the nearshore parts of Haro Strait as well as one area in the Strait of Juan de Fuca, in agreement with other studies (Heimlich-Boran 1988, Hauser et al. 2007, Cominelli et al. 2018). As vessel traffic in the Salish Sea increases, these areas might be a greater priority for conservation to preserve foraging grounds for SRKW. Most notably, Haro Strait between southeastern Vancouver Island and the San Juan Islands has been previously identified as a critical habitat area for SRKW with steep slopes that facilitate foraging (Hauser et al. 2007; Veirs et al. 2016, Ford et al. 2017). As SRKW continue to use Haro Strait extensively, its status as a major shipping lane leads to high rates of sound exposure (Cominelli et al. 2018).

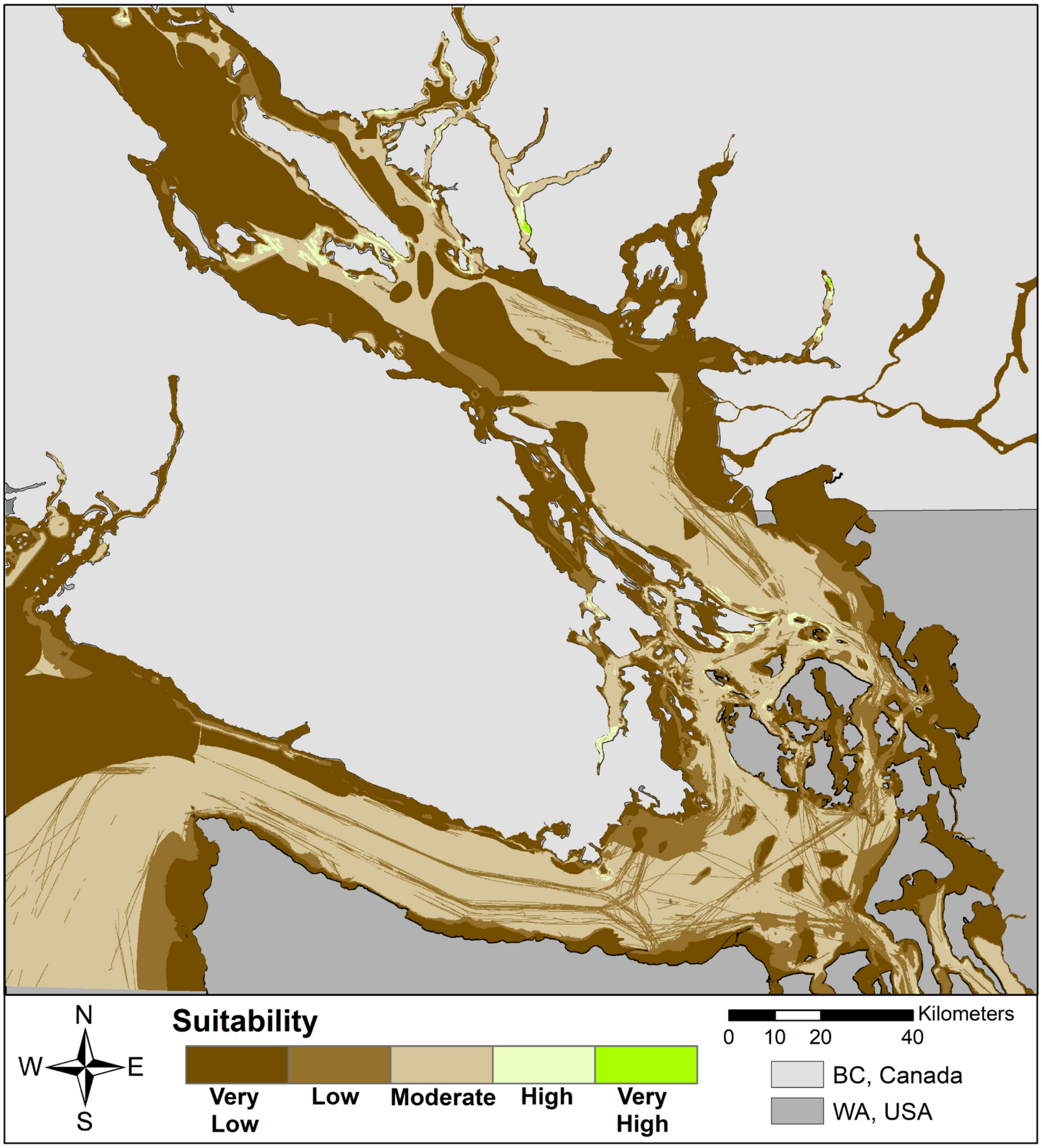

Figure 2.5: Resulting LSP suitability map for Scenario 2, Median Traffic, with five equal classes

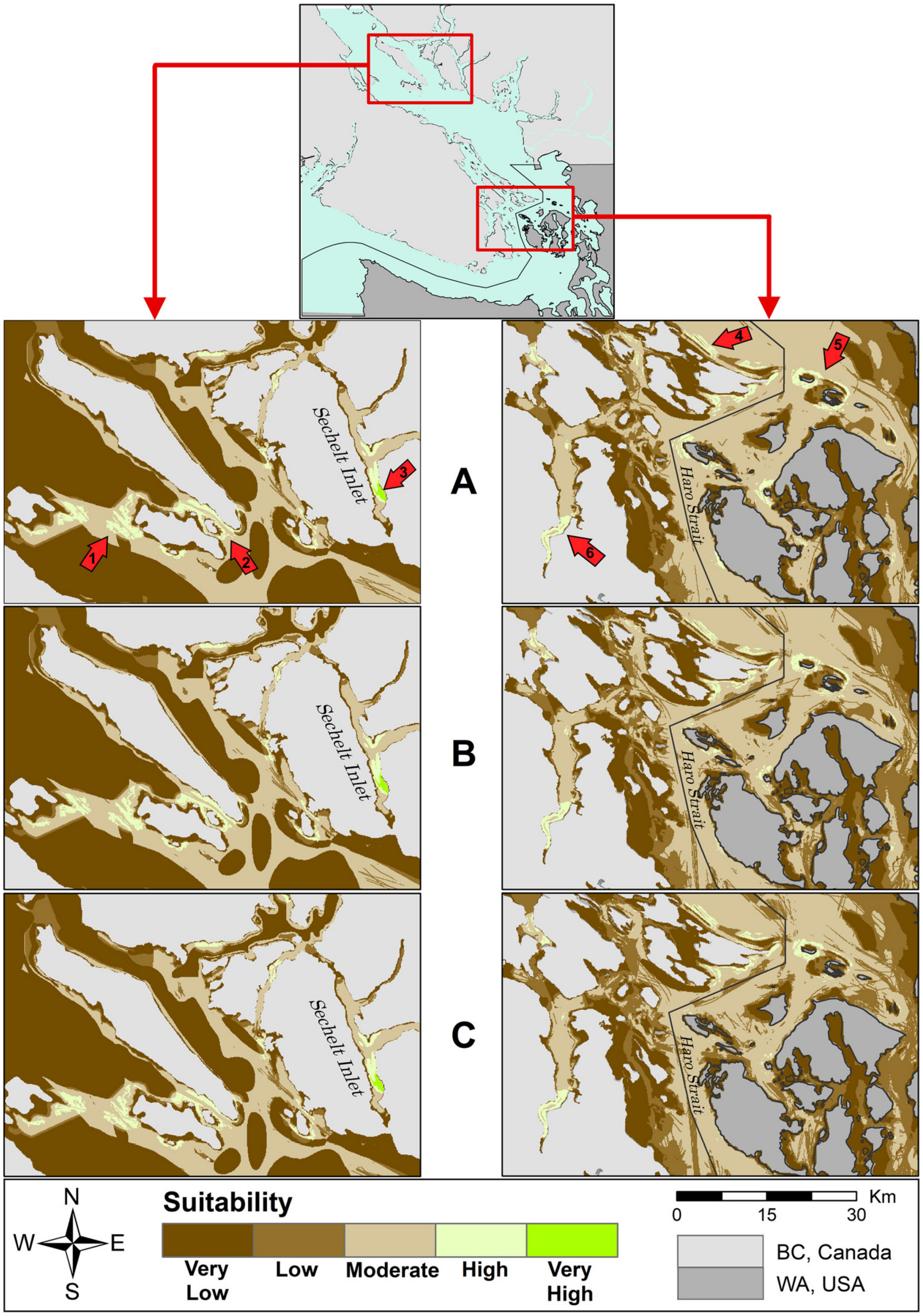

Figure 2.6: The obtained LSP suitability maps with five classes for the Upper Georgia Strait region (left) and region Haro Strait-Boundary Pass region (right) and for each scenario (A) Scenario 1 with Minimum Traffic, (B) Scenario 2 with Median Traffic, and (c) Scenario 3 with Maximum Traffic; arrows indicate high-suitability locations: (1) west of Lasqueti Island, (2) east of Lasqueti Island, (3) Sechelt Inlet, (4) north of Saturna Island, (5) around Patos Island and the Sucia Islands, and (6) Saanich Inlet

While these results indicate the presence of acoustic refugia in Upper Georgia Strait in the north-west part of the study area such as around Lasqueti Island (sites with arrow 1 and 2) and in Sechelt Inlet (site with arrow 3) (Figure 2.6), caution should be taken with any decision-making or policy regarding these areas. Due to unavailability of data, noise pollution from vessels that are not required to broadcast AIS data is not captured in this study, nor is competition for prey with the northern resident killer whale population whose core habitat is Johnstone Strait, just north-west of the study area (Ford et al. 2017). Upper Georgia Strait has not been noted as an important habitat area for SRKW in previous studies (Heimlich-Boran 1988, Hauser et al. 2007). High suitability locations in the Haro Strait-Boundary Pass region that have not been mentioned in other studies include areas north of Saturna Island (site with arrow 4), around Patos Island and the Sucia Islands (site with arrow 5), and in Saanich Inlet (site with arrow 6) (Figure 2.6). Areas in these suitability maps with very low suitability scores are usually due to very shallow depth and low slope values. Several large areas of Very Low suitability are visible in the suitability maps: these areas coincide with designated commercial fishing areas. Lines of low suitability surrounded by moderate suitability areas or lines of moderate suitability surrounded by high suitability areas coincide with the locations of vessel transits.

The GIS-based LSP-MCE suitability analysis method enabled a combination of input data representing several distinct criteria to derive overall suitability scores for acoustic refugia in the Salish Sea. The obtained suitability maps can be used as starting point for decision-making. The input criteria cannot substitute for one another and include pairs of criteria which must be combined in a way that adequately represents their mandatory/optional relationship with each other. In a conventional GIS-MCE suitability analysis using an aggregation method such as WLC, each criterion would be assigned a weight and all criteria would be aggregated in one step. This implies that high values for some criteria can compensate for low values in others; however, this is not acceptable in the case of assessing acoustic refugia. A location cannot be an acoustic refuge for SRKW if its habitat quality is poor even if it is relatively free of noise pollution, nor can it be suitable if conditions are noisy even if habitat quality is good. Using conjunctive aggregators and compound aggregators, the LSP method enables representation of these logical relationships.

Whereas previous studies have emphasized risk of exposure to sound based on killer whale population density or sighting locations and vessel traffic (Williams et al. 2015, Cominelli et al. 2018), the GIS-based LSP-MCE method provides suitability scores for acoustic refugia locations. Locations where noise pollution has affected the suitability score can be identified by comparing scenarios representing different levels of vessel traffic. Furthermore, the LSP-MCE method can identify suitable acoustic refugia in locations that are not frequently occupied by SRKW, such as sites with arrow 4, 5, and 6 (Figure 2.6).

The habitat suitability criteria used in this research study are indicating spatial associations with important killer whale behaviours or the minimum requirements for an area to support those behaviours. Reducing noise pollution in or protecting highly suitable locations can create quiet spaces for killer whales to forage and socialize successfully; however, this would not address the other principal threats to the SRKW population, limited salmon availability and chemical pollutants such as PCBs. For SRKW to make use of suitable acoustic refugia, they must currently travel through large areas with significant noise pollution. It is possible that noise levels in these interceding areas trigger an avoidance response by southern resident killer whales that prevents them from using some acoustic refugia. Observation and mapping of SRKW sightings and linking them to suitable acoustic refugia to assess current SRKW usage of the identified areas could further support noise pollution management efforts. Killer whale encounters are recorded by the Center for Whale Research (Center for Whale Research 2020), however, a robust comparison of encounter locations and these suitability maps is outside the scope of this research study.

This suitability analysis could benefit from refining the sound propagation model to assess marine noise pollution more accurately. For example, cumulative sound from multiple sources has been reported (Pine et al. 2014), but this was not considered in this study due to the coarse temporal resolution. Therefore, the true received sound level in each raster cell at a given moment might be greater than what is reported in this study. Future applications of the LSP-MCE method to identifying acoustic refugia for SRKW, pending on data availability, would benefit from including additional sound sources or using a different measurement of noise pollution that includes noise from smaller vessels that do not broadcast AIS data. For example, acoustic receivers have been deployed in SRKW habitat to establish the present-day soundscape (NOAA 2020). This research could benefit from the addition of input criteria that represent spatial variation in salmon abundance, temporal variation in noise levels, and seasonal variations in salmon abundance or kelp growth patterns.

2.3.1. Management Implications

Like other MCE methods, the GIS-based LSP-MCE approach is a tool for making spatial decisions that can incorporate opinions of multiple stakeholders and can combine data and information from multiple sources. As Huang et al. (2011) note, MCE is a collection of methods that can incorporate decision-maker and stakeholder preferences at each stage of the process including criteria selection, criteria standardization, criteria weights, and decision scenarios. The LSP-MCE method is a stepwise method that allows stakeholders pursue a gradual decision-making process in providing input also on the organization of the aggregation structure and the choice of aggregators (Dujmovic 2019). MCE methods are well-suited to support environmental management decisions because there is often uncertainty about the relative importance of different factors and the quality of data inputs, and because of the need to balance competing interests. In practice, the input parameters of the LSP-MCE method of suitability analysis must be determined as part of a collaborative decision-making process. Furthermore, multiple "what-if" scenarios can be generated based on different inputs so that decision-makers can consider multiple perspectives for environmental management (Malczewski 2004).

The SRKW population is protected in Canada under the Species at Risk Act (SARA) (Fisheries and Oceans 2018), which mandates the identification and management of critical habitat areas including acoustic habitat components for resident killer whales (Fisheries and Oceans Canada 2011). While SRKW are recognized as endangered in the USA, NMFS has declined to list sound as a critical habitat feature, stating that anthropogenic sound is assessed as part of "evaluating impacts to the prey and passage essential features of current critical habitat" (NOAA 2019b). In Canada, recently announced fishery closures and sanctuary zones coincide with high suitability areas found in this study (Transport Canada 2020). Locations with high suitability scores in the minimum traffic scenario but lower suitability scores in the median or maximum traffic scenario are affected by shipping noise and should be considered for ongoing noise-limiting measures such as vessel slowdown zones or adjustment of nearby shipping lanes. High-suitability locations where suitability scores are not significantly different between traffic scenarios should be considered for conservation, as these existing acoustic refugia will be increasingly valuable to SRKW as vessel traffic in the Salish Sea increases in the future.

2.4. Conclusions

The proposed GIS-based LSP method for identifying the locations of acoustic refugia highlights several areas within the Salish Sea as suitable acoustic refugia. These locations could be considered candidate areas for policies that would reduce the impacts of noise pollution such as regulating vessel speed or timing of movements, re-routing shipping lanes, and strengthening regulations in marine protected areas (Harris 2017, Williams et al. 2019, Joy et al. 2019). The applications of GIS-based MCE methods in the scientific literature do not include attempts to address the problem of marine noise pollution. Previous studies have used a spatial overlay method to assess how species' population density and anthropogenic noise levels coincide (Williams et al. 2015, Cominelli et al. 2018), included marine noise as a parameter of population viability analysis (Lacy et al. 2017), and quantitative modeling to assess the effectiveness of policies that would address marine noise impacts on SRKW (Williams et al. 2019, Joy et al. 2019). In contrast with these methods, the LSP-MCE method is a spatial decision-making approach that has been successfully used for conservation planning (Allen et al. 2011), for water quality protection (Dujmović and Allen 2021) and in agricultural applications (Rebolledo et al 2016, Montgomery et al. 2016). This research study's findings confirm that GIS-based LSP method is also suitable for marine spatial planning and environmental management.

The LSP-MCE approach was shown to be successful in identifying suitable locations for acoustic refugia for SRKW based on input criteria representing killer whale habitat requirements, noise pollution, and other factors. The proposed GIS-based LSP-MCE suitability analysis draws on scientific literature to justify the choice of input criteria, suitability functions, criteria weights, and aggregators. However, the obtained results could be strengthened by the input of domain experts on this endangered, transboundary killer whale population and incorporating the specific goals of stakeholders and environmental managers as part of a long-term marine spatial planning process. Stakeholders' input could assist in all stages of the GIS-based LSP method, from the choice of criteria, criteria weights, and soft logic aggregators to the management scenarios, that would all have a direct contribution to the enhanced decision-making process. One limitation of the LSP-MCE method is that it can be perceived by stakeholders and decision-makers as complex or difficult to implement; however, the LSP-MCE method offers the stepwise decision process via aggregators, which is closer to the logic of human reasoning than other MCE approaches. Future research can include performing sensitivity and uncertainty analysis of the LSP method and comparison with other MCE methods to assess the differences between them, as well as comparison of the LSP-MCE suitability maps with mapped killer whale sightings. This research study demonstrates that the GIS-based LSP-MCE method can represent the logical relationships between the factors of killer whale habitat suitability, marine noise pollution, and others and combine them to identify suitable locations for acoustic refugia. Thus, the proposed method can be a useful tool for spatial decision-making for this complex environmental management question and can be applied to other marine suitability analysis contexts such as refugia for other acoustically-sensitive species or assessing suitable locations for protected areas with different sets of criteria.

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Chapter 3.

Integrating multiple perspectives in marine spatial planning using the GIS-based Logic Scoring of Preference method [*]

3.1. Introduction

Recent research indicates that acoustic disturbance is a stressor to marine ecosystems, particularly where marine organisms rely on acoustic signals for their normal behaviours (Popper and Hawkins 2012). Killer whales (*Orcinus orca*) are an apex predator in much of the world's oceans and use acoustic signals to communicate and hunt for prey via echolocation (Heimlich-Boran 1988, Ford 1989, Au et al 2004). Southern Resident Killer Whales (SRKW) are an endangered population of killer whales that inhabit the Pacific coastal waters of Canada and the U.S.A. (Ford et al 2017), and the importance of acoustic characteristics of SRKW habitat for the population's long-term viability has been identified (Lacy et al 2017). One approach to supporting the conservation of this population is creating 'acoustic refugia' where good-quality habitat coincides with low noise levels (McWhinnie et al 2017).

The Salish Sea region, especially Haro Strait and Boundary Pass, has been identified as critical summer foraging habitat for SRKW, which migrate from oceanic waters into the Salish Sea to forage for their primary prey, chinook salmon (*Oncorhynchus tshawytscha)* (Hauser et al 2007, Ford et al 2017). Researchers have observed a correlation between the abundance of chinook salmon in the region and the abundance and health of SRKW (Velez-Espino et al 2014). Therefore, SRKW could be considered an indicator of the health of the Salish Sea ecosystem and an appropriate focal species for marine spatial planning (MSP) (Hooker and Gerber 2004). As a densely populated region, important shipping corridor, and traditional territory of Indigenous

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[*] A version of this chapter, coauthored with S. Dragićević and A. Solomon, will be submitted to the *Ocean & Coastal Management* journal

peoples, spatial planning for the Salish Sea region must be sensitive to the needs and goals of multiple stakeholders and Indigenous rights holders.

MSP is a multi-sectoral process that aims to determine how marine resources will be distributed across space and time with respect to societal goals (Grip and Blomqvist 2021). By definition, a variety of interested parties are involved in MSP and thus diverse perspectives, expertise, and goals must be considered and incorporated in decision-making. Furthermore, large volumes of spatially explicit environmental data-should be considered in the planning process such that decisions are based on the best available data. For spatial planning purposes, spatial multicriteria evaluation (MCE) methods have been developed that leverage geographic information systems (GIS) for spatial decision-making. MCE analysis is a systematic approach to spatial decision-making that provides a logical framework applicable to environmental management (Huang et al. 2011) while considering sometimes conflicting criteria and diverse perspectives of interested parties. Applications of spatial decision-making methods to MSP have included suitability analysis for marine protected areas (Wood and Dragićević 2007), aquaculture (Divu et al. 2021), offshore wind turbines (Gimpel et al 2015), or desalination (Blanco et al 2021). Often, MCE methods for MSP are developed as part of spatial decision support systems intended to assist planners to make informed decisions in conditions of uncertainty and complexity (Javier et al 2013, Tuda et al 2014, Jajac et al 2019). MCE has also been used to evaluate the effectiveness of existing MSP arrangements (Fu et al 2021).

MCE is a collection of decision-making approaches in which input criteria represented by spatial data are converted into a common scale and combined using an aggregation function that incorporates the preferences of decision makers or domain experts (Leake and Malczewski 2000). A common approach, known as Weighted Linear Combination (WLC), involves standardizing criteria input data to a scale of 0 to 1, where 0 represents a totally unacceptable input value and 1 represents a perfectly suitable input value, then computing the weighted arithmetic mean of all input criteria (Malczewski 2000). In this approach, the weight value of each criterion represents its importance to the decision-maker(s) or stakeholders relative to all other criteria. WLC has been criticized for diminishing the importance of each criterion as the number of criteria increases and its limited ability to represent requirements such as simultaneous satisfaction of multiple criteria or asymmetrical aggregation of criteria (Montgomery and Dragićević 2016). It is possible to represent multiple perspectives on the decision problem using WLC-based methods by varying criteria weights to develop different scenarios. The scenarios can be combined into “trade-off” suitability maps that represent areas of agreement and disagreement between different perspectives (Wood and Dragićević 2007, Janssen et al 2015).

The GIS-based Logic Scoring of Preferences (LSP) method is an advanced spatial MCE approach that follows the same general steps of MCE; however, instead of aggregating input criteria in one step using a single aggregation function, criteria in LSP are organized in a hierarchical structure and aggregated in a stepwise manner using a set of functions known as aggregators (Dujmović and De Tre 2011). Aggregators can be conjunctive, representing criteria that must be simultaneously satisfied (simultaneity), or disjunctive, representing criteria among which high input values can compensate for low input values (replaceability). Each aggregator is chosen based on the degree of simultaneity or replaceability that best represents the logical combination of criteria in its group. Furthermore, compound aggregators can be used to represent asymmetrical relationships such as where one criterion is considered mandatory, and a second criterion is considered optional (Dujmović 2007). The GIS-based LSP method has been applied to environmental management contexts including agricultural land suitability analysis (Montgomery et al 2016), marine habitat suitability analysis (Drackett and Dragićević 2021), and water conservation planning (Dujmović and Allen 2020).

The main objective of this research study is to represent multiple perspectives on the suitability of acoustic refugia locations for SRKW using GIS-based LSP as a generalized MCE method while considering both 3D and 2D criteria. The second objective is to integrate the resulting suitability values using an overall integrated suitability analysis (OISA) to represent and combine multiple viewpoints of interested participants in the spatial decision-making process. Based on scientific literature, three hypothetical and contrasting scenarios were developed, each oriented towards different stakeholder perspectives: (1) a killer whale *Behaviour-Oriented* scenario that prioritizes SRKW habitat requirements, (2) a *Noise-Oriented* scenario that emphasizes acoustic characteristics of SRKW habitat to highlight potential acoustic refugia, and (3) a *Human-Oriented* scenario that prioritizes locations away from human-uses such as fisheries and ports. These scenarios were then combined within a larger LSP aggregation structure using six different aggregators to show possible outcomes of the decision-making process. The results of this research study demonstrate that the combination of the GIS-based LSP and OISA methods can effectively represent the stepwise decision-making process. The proposed approach can be used as a tool to support MSP with diverse decision-making participants and complex suitability requirements.

3.2. Methods

3.2.1. Study Area and Data Sets

The study area for this research is a subsection of the Salish Sea that has been identified as the core summer foraging ground of SRKW (Hauser et al. 2007) (Figure 3.1). The area encompasses a small southern part of the Strait of Georgia, Boundary Pass, Haro Strait, and the waters surrounding the Southern Gulf Islands of Canada and the San Juan Islands of the USA. All spatial datasets were retrieved from public repositories. Spatial data about fisheries, kelp beds, aquaculture sites, industrial sites, ports, terminals, and fishing management areas were provided by the Government of British Columbia (Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2019a, 2019b, 2019c, 2020). Spatial data files for water treatment plants and national parks were provided by the Government of Canada (Government of Canada 2019a, 2019b). Locations of state parks were provided by the State of Washington (State of Washington 2021). A bathymetric coastal elevation model and vessel locations from Automatic Identification System (AIS) data were provided by the United States National Oceanic and Atmospheric Administration (NOAA) (NOAA 2019a, 2019b).

All datasets were converted to raster GIS data format at 100m spatial resolution using ArcGIS 14.1.1 (ESRI 2022). In a raster GIS environment, the study area is represented as a regular lattice of equal-area grid cells. Chinook salmon catch per unit effort (CPUE) was derived from the reported catch in fishing management zones in 2019 (Pacific Salmon Commission 2020). The sum of reported commercial and recreational catch in each management zone was multiplied by the ratio of catch per boat days measured by the Albion Test Fishery, then multiplied by the proportion of the geographical area of each management zone included within the study area.

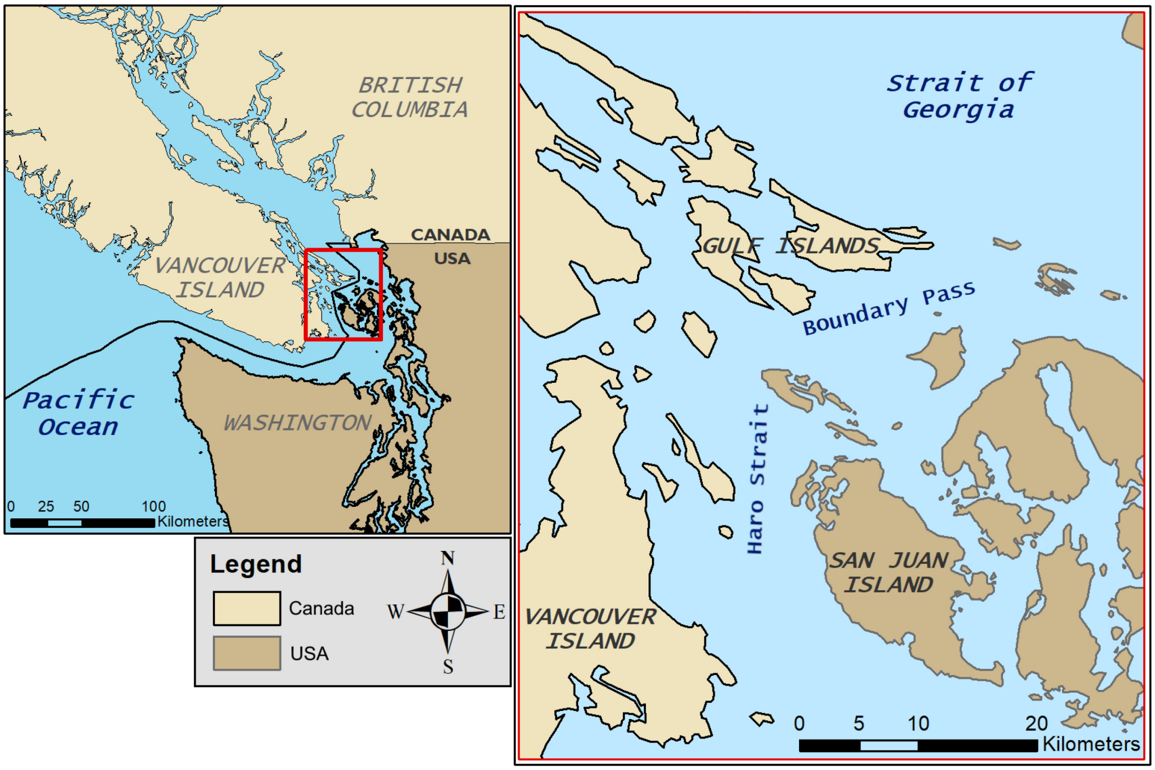

Figure 3.1: The Salish Sea region (left) in Canada and USA, and the study area around Haro Strait and Boundary Pass (right), highlighted in red.

3.2.2. The GIS-based LSP Method

To implement the GIS-based LSP method, stakeholders and decision-makers must first define the goal or problem to be solved and select relevant input criteria. In this research study, all of the perspectives represented are assumed to share the goal of identifying suitable locations for acoustic refugia for SRKW. Stakeholders and decision-makers then decompose the goal into logical components, and further decompose those components until smaller components cannot be deduced: these are the elementary criteria of the decision problem (Dujmović 2007). Then, spatial datasets containing criteria input values must be standardized and weighted before being combined using an aggregation function. The input data values are transformed according to a suitability function to a value between 0 and 1, where 0 represents total dissatisfaction and 1 represents total satisfaction of the stakeholders' requirements (Dujmović and De Tre 2011). The transformed values are referred to as suitability scores.

Groups of suitability scores that represent components of the decision problem are then combined using an aggregation function or aggregator. Instead of a form of weighted arithmetic mean commonly used with WLC-based MCE methods, LSP provides a set of aggregation functions to represent various logical relationships among criteria (Dujmović 2007). The range of graded conjunction/disjunction aggregators spans a spectrum from total simultaneity (pure conjunction) to total replaceability (pure disjunction), and compound aggregators known as partial absorption aggregators that can represent mandatory/optional and sufficient/desired relationships (Dujmović et al 2010). Conjunctive aggregators require simultaneous satisfaction of all criteria, whereas disjunctive aggregators allow a high value in one criterion to compensate for a low value in another criterion (Dujmović and Larsen 2007). Aggregators output a value between 0 and 1, known as a preference score, that represents the degree of satisfaction for a represented component of the decision problem. After every group of elementary criteria is aggregated, preference scores are aggregated with one another in a stepwise manner until one final, overall aggregator is reached that represents overall satisfaction of the stakeholders' preferences.

The LSP-MCE procedure generates suitability values called preference scores, resulting in a suitability map where each raster cell contains an overall preference score (Dujmović and De Tre 2011). The suitability map represents the overall spatial preferences of the stakeholder(s) who choose the elementary criteria, suitability functions, aggregation structure, aggregators, and weight values in a gradual stepwise manner. Suitability maps resulting from multiple stakeholders' suitability analysis procedures can then be combined using another LSP aggregator to represent possible outcomes of a decision-making process, known as integrated overall suitability analysis (OISA) (Dujmović 2018, Shen et al. 2021b). Figure 3.2 presents the schematic diagram of the proposed methodology used in this research study.

Three hypothetical stakeholder perspectives guided the choice of criteria weights and LSP aggregators to develop three scenarios. The first perspective prioritizes killer whale habitat associations based on the behavioural ecology of SRKW and corresponds to Scenario A: Behaviour-Oriented. The second perspective places greater emphasis on acoustic disturbance to SRKW from vessel traffic and corresponds to Scenario B: Noise-Oriented. The third perspective emphasizes human uses of space such as fishing areas, existing protected areas, and others, and corresponds to Scenario C: Human-Oriented.

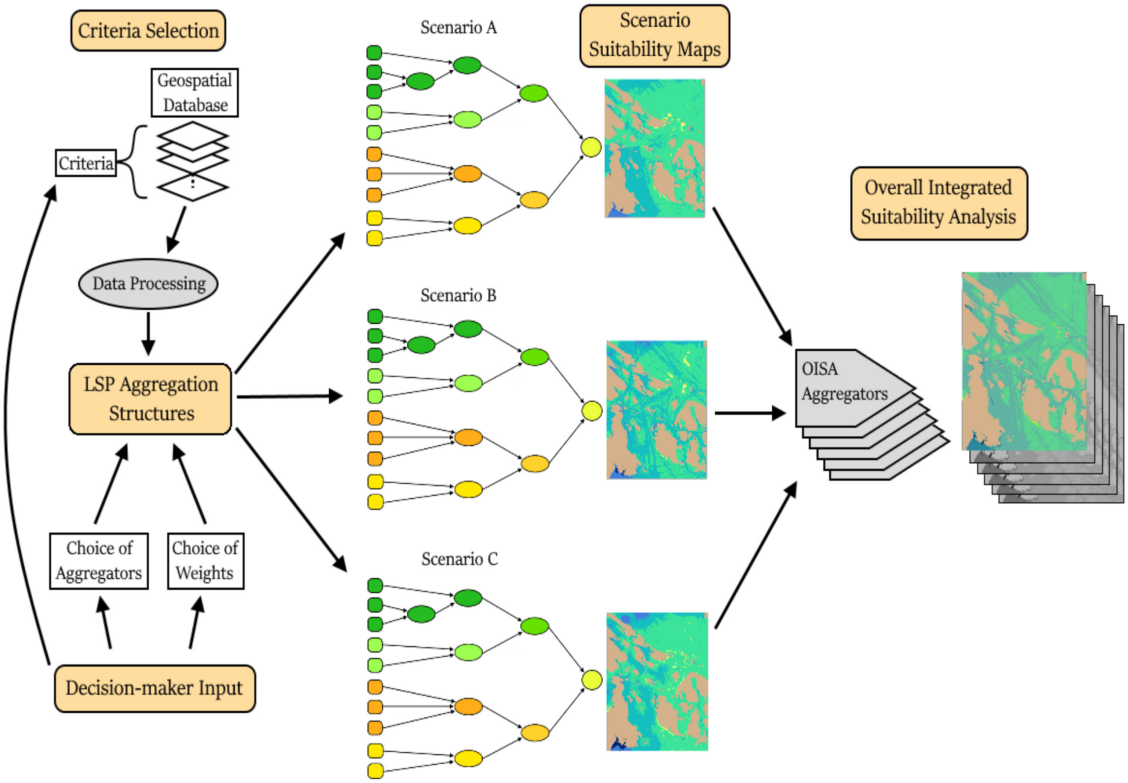

Figure 3.2: **Schematic representation of the proposed GIS-based Logic Scoring of Preference (LSP) decision-making methodology with overall integrated suitability analysis (OISA).**

3.2.3. Selection of Elementary Criteria

To select the elementary criteria for LSP suitability analysis, the goal of identifying suitable locations for acoustic refugia for SRKW was decomposed into two groups and four sub-groups, informed by peer reviewed literature on killer whale behaviour and ecology, marine noise pollution, and management of marine resources in the Salish Sea. The elementary criteria for LSP suitability analysis of acoustic refugia in this research study are shown in Table 3.1 and are grouped as three-dimensional (3D) criteria, which vary with depth, and two-dimensional (2D) criteria. The 3D Criteria group is further decomposed into sub-groups for Foraging Suitability (F) and Socializing Suitability (S). The 2D Criteria group is decomposed into sub-groups consisting of Industrial Sites (I) and Management Areas (M).

Table 3.1: Elementary criteria and suitability functions selected for GIS-based LSP suitability analysis of acoustic refugia

Group	Sub-Group	Criterion	Suitability Function		Description and units	Justification
3D Criteria	**Foraging Suitability (F)**	Slope (F_S)	Value	%	Slope derived from bathymetry [% of 90 degrees]	Heimlich-Boran 1988, Nichol and Shackleton 1996, Au et al. 2004, Wright et al. 2017
			0 100	0 100		
		Prey Availability (F_P)	Value	%	Estimated Chinook Salmon [number of salmon caught per boat day]	Arostegui et al. 2017, Heimlich-Boran 1988, Holt et al. 2019, Wright et al. 2017
			350 935	0 100		
		Noise at 40kHz (F_N)	Value	%	Noise at frequency used for echolocation, with receiver at 100m [dB]	Ford 1989, Ford 1991, Richardson et al. 1995, Erbe 2002, Au et al. 2004, Miller 2006, Holt et al. 2009, Lusseau et al. 2009, Veirs et al. 2016, Lacy et al. 2017, Wright et al. 2017, Holt et al. 2021
			49 124	100 0		
	Socializing Suitability (S)	Noise at 6kHz (S_N)	Value	%	Noise at frequency used for “pulsed calls”, with receiver at 20m [dB]	
			52 127	100 0		
		Kelp Proximity (S_K)	Value	%	Proximity to kelp beds [km]	Ford 1989, Hobday 2000, Ford 2009, Bubac et al 2020
			0 0.5 10	100 100 0		
2D Criteria	**Industrial Sites (I)**	Aquaculture Proximity (I_A)	Value	%	Proximity to aquaculture sites [km]	Callier et al. 2018, Shea et al. 2020
			0 10	0 100		
		Industry and Terminals Proximity (I_T)	Value	%	Proximity to industrial sites, ports, and terminals [km]	Erbe 2002, Lachmuth et al. 2011, Ayres et al. 2012
			0 10	0 100		
		Water Treatment Plant Proximity (I_W)	Value	%	Proximity to water treatment plants [km]	Andrady 2011, Browne et al. 2011, Wright et al. 2013, Lacy et al. 2017
			0 10	0 100		

Group	Sub-Group	Criterion	Suitability Function		Description and units	Justification
2D Criteria	**Management Areas (M)**	MPA Proximity (M_P)	Value 0 10	% 100 0	Proximity to parks with marine area [km]	Firestone and Jarvis 2007, Williams et al. 2015
		Fisheries Proximity (M_F)	Value 0 10	% 0 100	Proximity to Designated Fisheries [km]	Williams et al. 2006, Bubac et al. 2020

Three-dimensional Criteria

Foraging killer whales pursue chinook salmon by diving and pursuing their prey to the sea floor if necessary, usually capturing salmon at a depth greater than 100m (Wright et al. 2017). Killer whales use echolocation to detect and pursue prey while foraging, producing high frequency click sounds (between 30kHz and 60kHz) (Au et al. 2004). Steep slopes may facilitate successful foraging by limiting prey escape routes, and it has been noted that killer whales prefer to forage near to shore (Nichol and Shackleton 1996, Ford and Ellis 2006). Therefore, the criteria selected for group F are Slope (F_S), Prey Availability (F_P), and Noise at 40kHz (F_N).

Sound waves radiate in a three-dimensional (3D) pattern from their source, thus in this research study sound propagation has been considered a 3D criterion. Noise levels for criteria F_N and S_N were calculated using a sound propagation model appropriate for modeling noise from vessel traffic in shallow water environments (Richardson et al. 1995, Drackett and Dragićević 2021). Vessel locations derived from Automatic Identification System (AIS) data represent sound sources, and the sound propagation model incorporates the sound frequency and the depth of the sound receiver, as shown in Formula 3:

$$RL = SL - 10logR - 10logR1 - \alpha - AL - 60 \qquad (3$$

Where *RL* is the received sound level in decibels dB, *SL* is the source sound level in dB, *R* is the distance in km between the source and receiver, R_1 is the approximate distance in km at which the sound wave is trapped between the sea floor and sea surface and thus loses less energy (Richardson et al. 1995), α is an absorption coefficient based on temperature and pH of seawater (Hodges 2010), A_L is an attenuation coefficient dependent on wavelength and receiver depth (Urick 1983), and *60* approximates the loss of energy between the source and a distance of 1km.

For the 3D criteria used for LSP suitability analysis, different combinations of wavelength frequency and receiver depth, which changes the value of the attenuation coefficient A_L for each calculation, were chosen based on literature about killer whale acoustic signals and effects of noise on killer whales. In the Foraging Suitability (F) sub-group, noise from vessel traffic is modeled at 40kHz frequency - the approximate frequency of echolocation signals (Au et al. 2004) - with a receiver at 100m depth to represent the approximate maximum depth of SRKW foraging dives (Holt et al. 2021). In the Socializing Suitability (S) sub-group, noise from vessel traffic is modeled at 6kHz frequency – the approximate frequency of killer whale “pulsed calls” (Ford 1989) – and a depth of 20m to represent the approximate average depth of near-surface behaviours including socializing and travelling (Heimlich-Boran 1988).

Most killer whale behaviour, including socializing, traveling, and resting behaviours occur near the ocean surface (Ford et al. 2017). During these activities, killer whales primarily communicate using pulsed call vocalizations with a frequency of approximately 6kHz (Ford 1989). Socializing killer whales exhibit behaviours such as breaching the water surface, floating at the surface, slapping the water with their tail or fins, and swimming through kelp (Bubac et al. 2020). Previous studies have noted important SRKW habitat areas near kelp beds (Heimlich-Boran 1988). Therefore, the criteria selected for group S are Noise at 6kHz (S_N) and Proximity to Kelp Beds (S_K).

Two-Dimensional Criteria

The 2D criteria group comprises criteria that do not vary with depth and can affect acoustic refuge suitability regardless of killer whale behaviours. This group is decomposed into two sub-groups for Industrial Sites (I) and Management Areas (M). Industrial sites can negatively affect the suitability of a location as an acoustic refuge by being a source of pollution (Andrady 2011, Lachmuth et al. 2011, Shea et al. 2020) or by being an area trafficked by vessels that do not broadcast AIS data (Lusseau et al. 2009). Aquaculture sites can contribute to pollution and affect the health of wild salmonids in their vicinity by being a source of pathogens (Collier et al. 2018, Shea et al. 2020). Industrial sites, ports, and terminals can be a source of noise and chemical pollution due to use by fishing and whale watching vessels (Lachmuth et al. 2011). Water treatment plants are a significant contributor of microplastic particles in the marine environment (Andrady 2011, Browne et al. 2011), which have been noted as a health concern for SRKW (Lacy et al. 2017). Therefore, the criteria selected for sub-group I are Proximity to Aquaculture Sites (I_A), Proximity to Industrial Sites and Terminals (I_T), and Proximity to Water Treatment facilities (I_W).

Sub-group M consists of management areas that can affect a location's suitability as an acoustic refuge. Proximity to existing protected areas can make a location more suitable as an acoustic refuge and might be easier to designate as protected area (Harris 2017, Williams et al. 2019). Fishing areas contribute to noise pollution (Bubac et al. 2020), and locations nearby can be more difficult to designate for conservation.

3.2.4. Suitability Functions

Suitability functions are used to transform the input values representing elementary criteria to a standardized scale based on stakeholder preferences or the requirements and constraints of the decision problem. The suitability functions used in this research study are also presented in Table 3.1, are based on the information provided from the scientific literature on killer whale behaviour, ecology, and conservation. Steeper slopes facilitate SRKW foraging, therefore the suitability function for criterion F_S monotonically increases from 0% at 0 degrees slope (a horizontal surface) to 100% at 90 degrees slope (vertical surface), expressed as a percentage of 90 degrees. Suitability for criterion F_P is based on the estimated prey requirements for the current SRKW population and for long-term population recovery, which varies based on characteristics of individual killer whales such as age, sex, pregnancy status, health, and others. The suitability score of F_P monotonically increases from the number of salmon per day required for the current SRKW population, 350, to the upper confidence interval of the estimated salmon per day required for SRKW population growth, 953.33 (Williams et al. 2011). Noise at 40kHz (F_N) affects killer whale foraging by masking echolocation signals, which should not be affected if the noise is 49 dB or lower (Au et al. 2004). Suitability satisfaction of this criterion monotonically decreases from 100% satisfaction at 49 dB to 0% satisfaction at 124 dB, the highest sound level at 40kHz modeled in the study area.

In the Socializing Suitability (S) sub-group, noise at 6kHz (S_N) criterion suitability monotonically decreases from 100% at 54 dB, the lowest noise level at 6kHz modeled in the study area, to 0% at 127 dB, the highest noise level modeled at 6kHz. Holt et al. (2009) note that killer whales increase the volume of their calls in noisy conditions, indicating that noise can make communication difficult. Kelp can drift some distance away from kelp beds and thus be available to socializing orca for interaction. For example, Hobday (2000) observed detached kelp rafts travel 8.5km per day, with a wide range of 0.19 to 29.8km per day. Therefore, a conservative estimate of 5km proximity to a kelp bed is used in this study to represent the radius at which kelp is likely to be available to socializing killer whales. Proximity to kelp beds (SK) suitability monotonically decreases from 100% at within 0.5km of a kelp bed to 0% at 5km or more away from a kelp bed.

In the Industrial Sites (I) sub-group, all criteria are proximity-based, and their suitability monotonically increases from 0% at 0m distance from industrial sites, ports, and terminals to 100% at 10km distance. All criteria in this sub-group represent a form of contamination including pathogens from aquaculture sites (I_A) (Shea et al. 2020) and chemical pollution from both vessel exhaust around ports and terminals (I_T) (Lachmuth et al. 2018) and particles in wastewater around water treatment plants (I_W) (Andrady 2011). Browne et al. (2011) found a significantly lower concentration of microplastic particles at 10km distance from water treatment plants compared to locations close to treatment plants. The Management Areas (M) sub-group criteria are also proximity-based. Marine Protected Areas likely have characteristics such as increased biodiversity and reduced human activity (Harris 2017) that would make an area more suitable as an acoustic refuge. Therefore, suitability for the proximity to marine protected areas criterion (M_P) monotonically decreases from 100% at 0m distance from MPAs to 0% at 10km distance. Interactions between killer whales and fishing vessels can disrupt normal behaviour patterns (Williams et al. 2006, Bubac et al. 2020). Therefore, suitability for the proximity to fisheries criterion (M_F) monotonically increases from 0% at 0m distance from designated fisheries to 100% at 10km distance.

3.2.5. Aggregators and Decision-making Scenarios

LSP aggregators (Dujmović et al. 2010) were selected from a set of fifteen graded conjunction/disjunction aggregators plus two compound aggregators, presented in Table 3.2. Each aggregator in the set represents a different degree of simultaneity (conjunction) or replaceability (disjunction) among the criteria input values it aggregates. Three of the aggregators are pure conjunction (C), weighted arithmetic mean (A) and pure disjunction (D), representing extreme simultaneity, neutrality, and extreme replaceability, respectively. Between C and A are hard and soft partial conjunction (HPC

Table 3.2: LSP Aggregators used in the suitability analysis and their properties (adapted from Dujmović 2018)

<table>
<tr><th></th><th>Aggregator Type</th><th>Code</th><th colspan="2">Role of Input Values</th><th>Effect of High and Low Input Values</th></tr>
<tr><td rowspan="15">Graded Conjunction/ Disjunction</td><td>Pure Conjunction</td><td>C</td><td colspan="2" rowspan="4">Mandatory
Output is 0 if any input value is 0</td><td>Output is equal to the lowest input</td></tr>
<tr><td rowspan="3">Hard Partial Conjunction</td><td>HC+</td><td rowspan="6">Low inputs have greater effect than high inputs.</td></tr>
<tr><td>HC</td></tr>
<tr><td>HC-</td></tr>
<tr><td rowspan="3">Soft Partial Conjunction</td><td>SC+</td><td colspan="2" rowspan="7">Optional
None of the inputs are mandatory or sufficient.</td></tr>
<tr><td>SC</td></tr>
<tr><td>SC-</td></tr>
<tr><td>Neutral</td><td>A</td><td>Low and high inputs have equal effect.</td></tr>
<tr><td rowspan="3">Soft Partial Disjunction</td><td>SD-</td><td rowspan="6">High inputs have greater effect than low inputs.</td></tr>
<tr><td>SD</td></tr>
<tr><td>SD+</td></tr>
<tr><td rowspan="3">Hard Partial Disjunction</td><td>HD-</td><td colspan="2" rowspan="4">Sufficient
Output is 1 if any input value is 1</td></tr>
<tr><td>HD</td></tr>
<tr><td>HD+</td></tr>
<tr><td>Pure Disjunction</td><td>D</td><td>Output is equal to the highest input.</td></tr>
<tr><td colspan="3" rowspan="2"></td><th colspan="2">Role of Input Values</th><th rowspan="2">Penalty and Reward</th></tr>
<tr><td>x</td><td>y</td></tr>
<tr><td rowspan="2">Partial Absorption</td><td>Conjunctive Partial Absorption</td><td>CPA</td><td>Mandatory</td><td>Optional</td><td>$P > R$
When $x > 0$:
Output equals $x(y - P)$ when $x > y$
Output equals $x(y + R)$ when $x < y$</td></tr>
<tr><td>Disjunctive Partial Absorption</td><td>DPA</td><td>Sufficient</td><td>Optional</td><td>$P < R$
When $x < 1$:
Output equals $x(y - P)$ when $x > y$
Output equals $x(y + \mathrm{R})$ when $x < y$</td></tr>
</table>

and SPC) aggregators; likewise, between A and D are hard and soft partial disjunction (HPD and SPD) aggregators. In the set of aggregators used in this research study, three aggregators are used to represent each type of partial conjunction or disjunction. Each partial conjunction aggregator is noted by its type and a plus (+) or minus (-) indicating a greater or lesser degree of simultaneity for conjunctive aggregators or replaceability for disjunctive aggregators. HPC thus includes HC-, HC, and HC+, SPC includes SC-, SC, and SC+, SPD includes SD-, SD, and SD+, and HPD includes HD-, HD, and HD.

Graded conjunction/disjunction aggregators are symmetrical, whereas partial absorption aggregators combine two input values *x* and *y* asymmetrically. The conjunctive partial absorption (CPA) aggregator treats *x* as a mandatory input which must be satisfied: an input value of 0 for *x* results in an output of 0. The disjunctive partial absorption (DPA) aggregator treats *x* as a sufficient input which is more desirable than *y*, but not necessary for partial satisfaction. In the CPA aggregator, *x* is equal to the maximum output value, and in the DPA aggregator, *x* is equal to the minimum output value. In both partial absorption aggregators, the input *y* is optional, but can increase or decrease the output when *y* is lesser or greater than *x* based on adjustable penalty (P) and reward (R) values and the suitability score of *y* (Dujmović and Allen 2020).

Three scenarios representing alternative perspectives were developed based on the scientific literature about killer whale behaviour and ecology, management of acoustic habitats, and management of vessel traffic in the Salish Sea region. Scenario A, called Behaviour-Oriented, emphasizes SRKW habitat factors: slope (F_S), abundance of chinook salmon (F_P), and proximity to kelp beds. Scenario B, called Noise-Oriented, has an increased weight on the noise level criteria (F_N and S_N). Scenario C, called Human-Oriented, emphasizes distance from fisheries (M_F) and de-emphasizes noise pollution from vessel traffic (F_N and S_N). Some of the aggregators used differ between scenarios as shown in Figure 3.3.

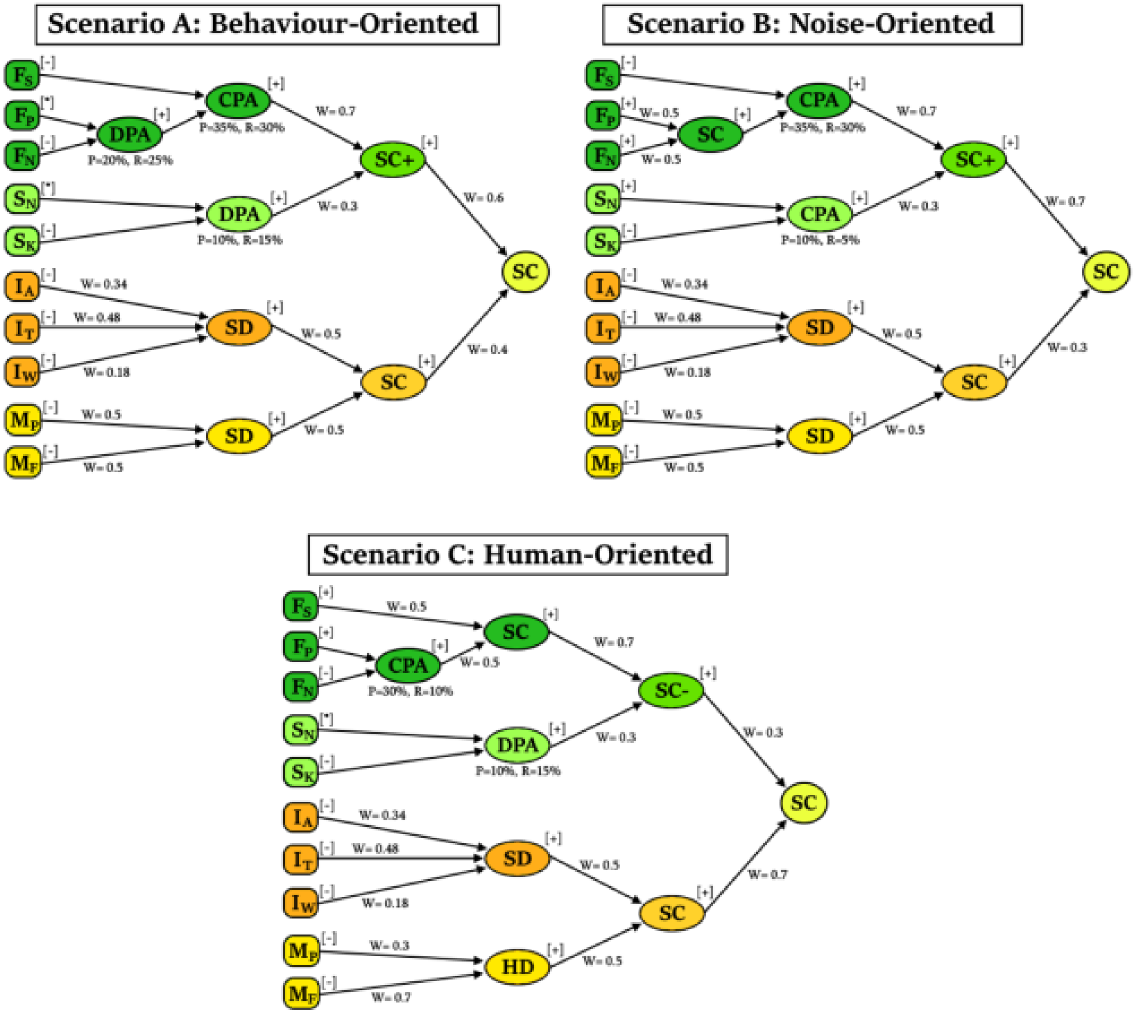

Figure 3.3: LSP aggregation structure for each scenario: Behaviour-oriented Scenario A; Noise-oriented Scenario B; and Human-oriented Scenario C. [+] denotes a mandatory criterion, [*] denotes a sufficient criterion, and [-] denotes an optional criterion. A full description of acronyms can be found in Table 3.1. 3D Criteria group is decomposed into subgroups-consisting of Foraging Suitability (F) and Socializing Suitability (S). The 2D Criteria group is decomposed into sub-groups consisting of Industrial Sites (I) and Management Areas (M). criteria selected for group F are Slope (F_S), Prey Availability (F_P), and Noise at 40kHz (F_N). The criteria selected for group S are Noise at 6kHz (S_N) and Proximity to Kelp Beds (S_K). The criteria selected for sub-group I are Proximity to Aquaculture Sites (I_A), Proximity to Industrial Sites and Terminals (I_T), and Proximity to Water Treatment facilities (I_W).

3.2.6. Overall Integrated Suitability Analysis

OISA is a method of combining decision-making scenarios, such as those presented above, to represent possible outcomes of a decision-making process where different perspectives must compromise and find trade-offs with each other (Dujmović 2018, Shen et al. 2021b). To combine the decision-making scenarios into an overall integrated suitability map, the aggregation structures used for each decision-making scenario can be combined into a larger structure where the final aggregated suitability score of each decision-making scenario is used as an input for an additional OISA aggregator. The aggregator used to combine the decision-making scenarios represents a logical relationship among the stakeholders or perspectives represented by the input scenarios. In this research study, a variety of aggregators were used to show several possible combinations of stakeholder perspectives.

Using different LSP aggregators, different types of OISA maps can be derived from the input suitability maps to explore possible decision choices of various interested parties involved in the spatial planning process. Trade-off maps are derived using a neutral aggregator (A) with varying weight values for each input suitability map. In this case, an input map assigned a higher weight value can be considered to represent a stakeholder perspective that was more prevalent or influential in the planning process, and therefore its preferences have a greater influence on the overall outcome of the process. One can visually see and analyze what trade-offs were made between stakeholders by comparing the output OISA map with the input maps representing perspectives that were assigned a lower weight value. When derived using a conjunctive aggregator (SC or HC), the OISA map represents the logical consensus among the input maps. Because low input values have a greater effect on the output suitability score of a conjunctive aggregator, a location must have a high suitability score in all input maps to receive a high suitability score in the output OISA map. Therefore, locations where all stakeholders agree (that is, where all input suitability values for a location are high) will be more prominent when using a conjunctive aggregator than when using a neutral or disjunctive aggregator. The greater the degree of simultaneity of the aggregator chosen, the stronger the influence of low suitability values. Thus, a stricter form of consensus can be represented using a hard conjunction aggregator (HC), where any input value of 0 will result in an output score of 0: in effect, the stakeholders represented by the input maps can “veto” locations that are not acceptable to them. When derived using a disjunctive aggregator (SD or HD), the OISA map represents a case where any stakeholder's preferred locations are considered acceptable or at least worthy of further investigation.

3.3. Results and Discussion

The obtained results represent multiple stakeholder perspectives on suitability analysis for acoustic refugia for SRKW and obtained suitability scores were used to derive suitability maps. Each stakeholder perspective indicates significant differences between each other in the spatial extent and distribution of suitability scores across the study area. Furthermore, the suitability maps were successfully combined using the OISA method to explore possible outcomes of the spatial decision-making process. The proposed GIS-based LSP methodology was implemented ArcGIS 14.1.1 (ESRI 2022) using the GIS.LPS software tool (Shen et al. 2021a). The obtained suitability values were classified using the equal-interval classification method where they are divided into five classes of equal range: very poor (0.00 - 0.19), poor (0.20 - 0.39), moderate (0.40 - 0.59), good (0.60 - 0.79), and excellent (0.80 - 1.00). The suitability maps representing each scenario were derived and are presented in Figure 3.4.

The marine portion of the study area covers 2269.36km^2, with the remaining 1080.24km^2 being terrestrial. Scenario A is strongly influenced by the locations of habitat association criteria including prey availability, slope, and proximity to kelp beds. Moderate or lower suitability values are concentrated in the south-west part of the study area, where the overall estimated salmon abundance was lower in 2019. Salmon abundance in each fishing management zone varies throughout the SRKW foraging season based on salmon migration patterns, and also on an annual basis: the estimate of abundance used in this study is based on the total salmon catch over an entire season reported for each management zone and thus does not capture these variations at a finer temporal scale or account for annual variations in abundance. In some areas, the effect of noise from vessels is noticeable as lines of moderate suitability surrounded by an area of good suitability. Moderate suitability values are found in 664.70km^2 of the marine part of the study area. Poor and very poor values are especially concentrated in the south-west corner of the study area due to the presence of a water treatment plant as well as a terminal for a passenger ferry that travels between Victoria, Canada, and Port Angeles, USA. In total, poor suitability values cover 38.94km^2, and very poor values cover 1.54km^2 respectively of the marine part of the study area. Excellent suitability values are located in close proximity to kelp beds and steep slopes. A total of 1541.73km^2 was found to have good suitability in this scenario, and excellent suitability values cover 22.45km^2.

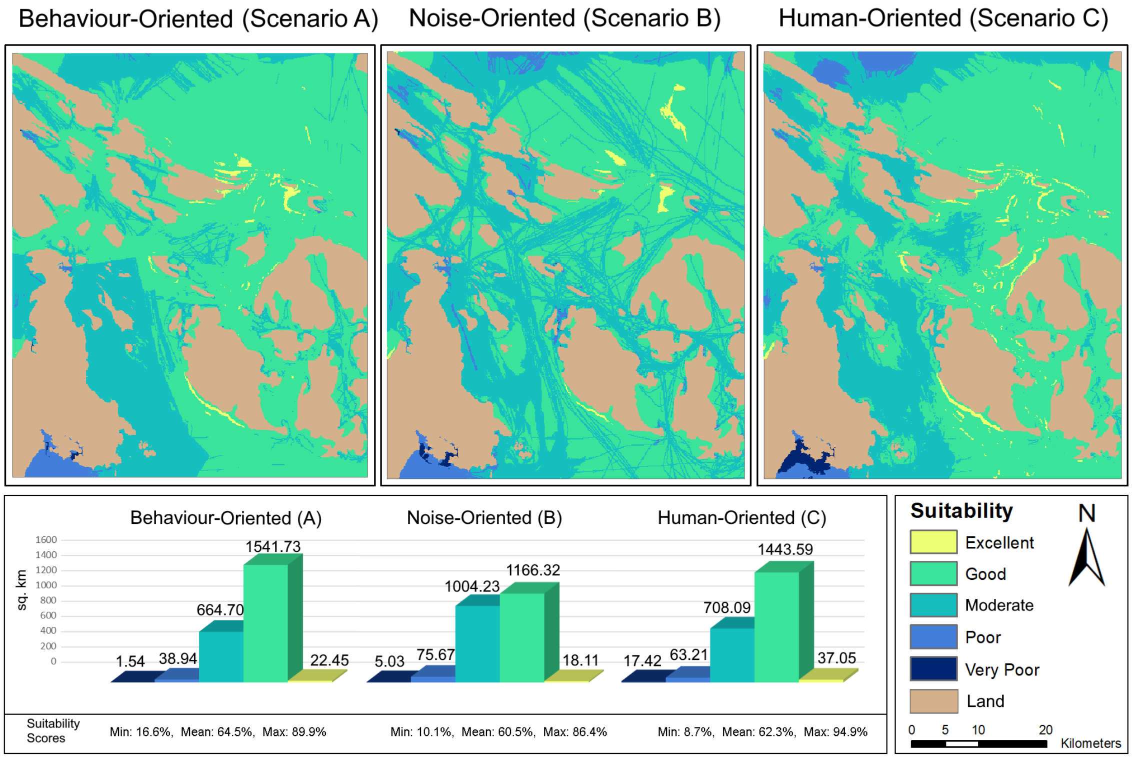

Figure 3.4: **Suitability maps derived for each of the three decision-making scenarios, with summary graphs showing the total area in km^2 in each suitability class.**

Based on the choice of weights and aggregators, the suitability values in Scenario B are primarily influenced by the noise criteria. Vessel tracks are visible across the suitability map where the location of a vessel has reduced suitability values from Good to Moderate or Moderate to Poor. Compared to Scenario A, noise from vessels reduces the area of good suitability values significantly, to 1166.32km^2. Moderate suitability values cover 1004.23km^2 of the study area. Poor and very poor suitability locations are concentrated in the south-west corner of the study area and agree with Scenario A, however there is a greater number of very poor suitability values due to the increased influence of noise. Poor suitability values cover 75.67km^2, and very poor suitability values cover a total area of 5.02km^2. Simultaneously, locations that are farther away from vessel trajectories have a higher suitability score than in other scenarios due to the increased weight of noise criteria. Prey availability, slope, and proximity to kelp beds still have a significant influence, resulting in fairly similar locations of Excellent suitability areas as those in Scenario A. Excellent suitability value areas total 18.11km^2.

Scenario C places a higher weight on 2D criteria and a lower weight on noise criteria within the 3D criteria group. Moderate and lower suitability values thus occur near to designated fisheries and industrial sites. Moderate suitability values are found across 708.09km^2 of the study area, poor suitability values total 63.21km^2 in area, and very poor suitability values total 17.42km^2. The greater area of very poor suitability values is due to the increased weight of the Industrial Sites sub-group (I) compared to Scenarios A and B. Slope (F_S) has a somewhat greater influence on the location of excellent suitability areas compared to Scenario A, because the second aggregator in the Foraging Suitability (F) sub-group is changed from CPA in Scenario A to the symmetrical soft conjunction (SC) aggregator in Scenario C to de-emphasize criterion F_N, increasing the relative importance of F_S. Locations of good suitability values are similar to Scenario A, covering an area of 1443.59km^2, while excellent suitability values are found in a total area of 37.05km^2. Overall, the greatest percentage of marine area is covered by good suitability values, which account for 67.94%, 51.39% and 63.61% of the study area in scenario A, B, and C respectively, while very small areas, 1.63% (Scenario C for excellent) or less (all other scenarios), are covered by the two extremes of excellent or very poor suitability. Unlike the other scenarios, scenario B has similar shares of good (51.39%) and moderate (44.25%) suitability values.

Comparison of the suitability maps derived for each scenario as categorical maps was performed using the Kappa coefficient (Congalton 1991) and the Spatial Analyst module of ArcGIS 14.1.1. Maps for each pair of scenarios have been compared and the Kappa values derived are as follows: for Scenarios A and B is 0.448; for Scenarios A and C is 0.548; and for Scenarios B and C is 0.499. The Kappa coefficient value closer to 1.0 indicates that two maps are almost identical, while values closer to 0 indicate strong dissimilarity among maps. The obtained Kappa values indicate moderately low agreement for all scenario comparisons; therefore, the perspectives represented by each scenario that guided the choices of aggregators and criteria weights led to significant differences in the output suitability maps.

Figure 3.5 present the output maps generated using the OISA method. The suitability maps for each scenario were combined six times using the OISA method and using different input weights and aggregators, to represent possible decision-making outcomes. OISA maps 1, 2, 3, and 4 are obtained using the neutral aggregator (A) with varied weights to show “trade-off” scenarios where each perspective is more or less dominant in the decision-making process. Map 1 uses equal weights of 0.33 for all decision-maker scenarios to show an outcome where all decision-makers compromise equally on their priorities. Map 2 results from weights of 0.4 for Scenarios A and B, and a weight of 0.2 for Scenario C, representing a situation where the Human-Oriented perspective is less influential. Map 3 uses weights of 0.25 for Scenarios A and C, and weight of 0.5 for Scenario C, representing the case where the Behaviour-Oriented and Noise-Oriented perspectives compromise significantly more than the Human-Oriented perspective. Map 4 results from weights of 0.15 for Scenarios A and C, and a weight of 0.7 for Scenario B, showing a case where the Noise-Oriented perspective is very dominant. OISA map 5 results from the use of a conjunctive aggregator (SC) with equal weights for each scenario to represent consensus among all perspectives. Finally, OISA map 6 is based on a disjunctive aggregator (HD) with equal weights, representing a situation where a location is considered potentially suitable if it has a high suitability score in any scenario.

The results of the OISA method show outcomes of a planning process wherein decision-makers must find a compromise between different stakeholder perspectives. Scenarios of ”trade-off” between different approaches, consensus of all stakeholders, and prioritizing the highest suitability score among all decision-makers are represented. The highest proportion of good and excellent suitability values are found in map 6 because its aggregator has the greatest degree of replaceability among all of the integrated aggregators used. In contrast, map 4 has the lowest proportion of good and excellent suitability values because it uses a relatively high weight value for the perspective scenario with the fewest good and excellent suitability values.

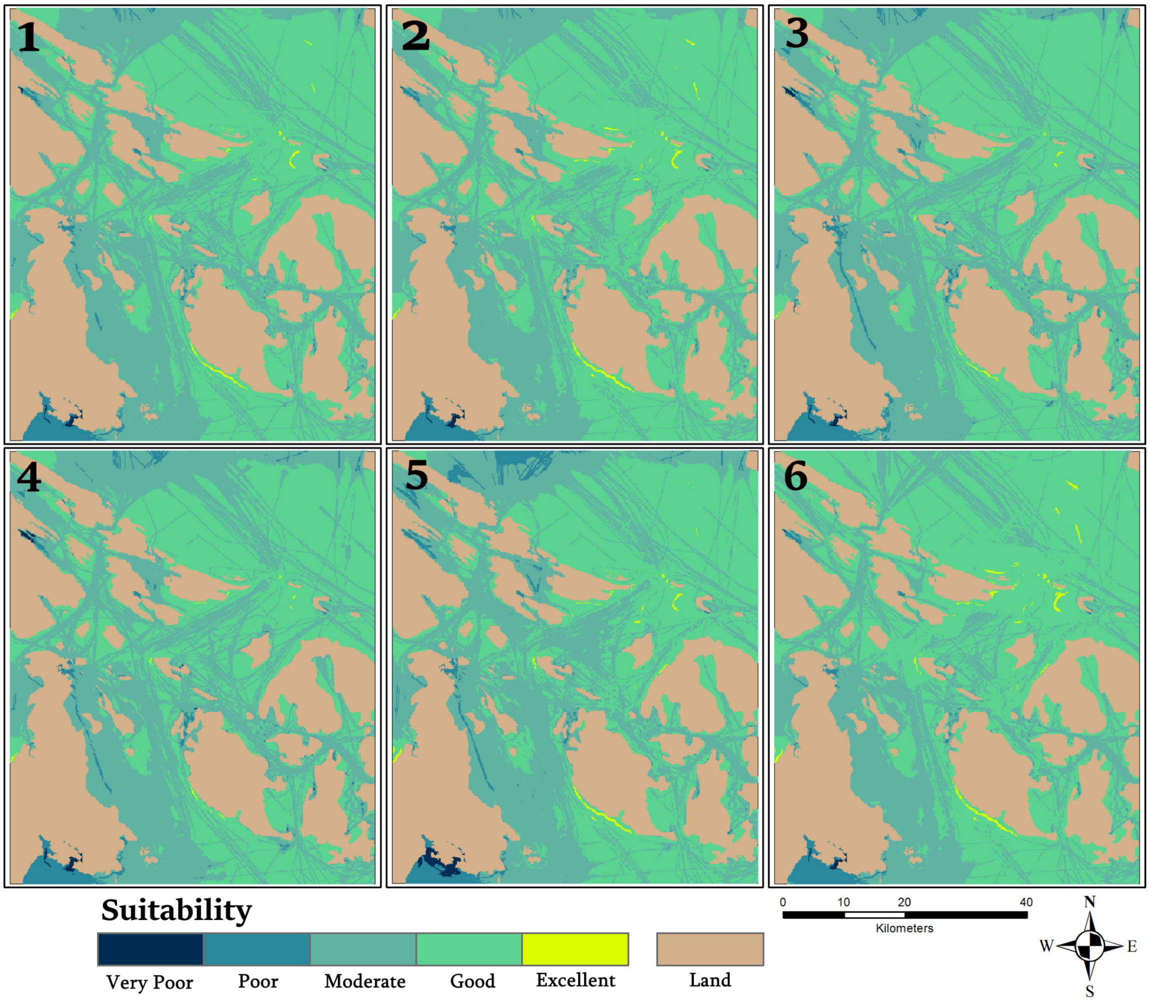

Figure 3.5: **Output overall integrated suitability analysis (OISA) maps derived using various aggregators: the neutral aggregator A (map 1-4) using different combinations of weight values; a conjunctive aggregator (SC) (map 5), and a disjunctive aggregator (map 6).**

The results of the OISA method show outcomes of a planning process wherein decision-makers must find a compromise between different stakeholder perspectives. Scenarios of ”trade-off” between different approaches, agreement of all decision-makers, and prioritizing the highest suitability score among all decision-makers are represented. The highest proportion of good and excellent suitability values are found in map 6 because its aggregator has the greatest degree of replaceability among all the integrated aggregators used. In contrast, map 4 has the lowest proportion of good and excellent suitability values because it uses a relatively high weight value for the perspective scenario with the fewest good and excellent suitability values.

3.4. Conclusions

This study presents the GIS-based LSP method, a complex and generalized MCE method flexible enough to represent multiple stakeholder perspectives in a decision-making process. Moreover, LSP aggregators can then be used to combine those perspectives using an overall integrated suitability analysis (OISA). The aggregator chosen represents a logical relationship of stakeholders' perspectives, such as consensus, trade-offs, or complementary objectives. The GIS-based LSP-MCE method is suitable for MSP processes where regulatory agencies, stakeholders, and Indigenous rights holders have agreed to engage in a collaborative planning process. While the criteria, suitability functions, criteria weights, and aggregators used in this research study were based on literature, the application of the method to suitability analysis of acoustic refugia for SRKW demonstrates its usefulness for MSP broadly.

Future research would benefit from an alternative method of selecting input criteria, suitability functions, criteria weights, and aggregators or designing the LSP aggregation structure. For example, a formal method of eliciting expert opinions such as a Delphi panel (Dalkey and Helmer 1963) using real participants could be used to determine criteria and relative degrees of importance between criteria or appropriate logical relationships among criteria to be aggregated. This research would also benefit from a more refined representation of prey availability across both time and space. For example, seasonal spatial data about chinook salmon abundance in the Salish Sea during their migratory season over multiple years would improve our results. Moreover, data about chemical pollution levels in the region at a fine spatial scale. Furthermore, incorporating the needs and goals of Indigenous rights holders and other participants would enhance the suitability analysis with respect to human uses of space that have social or cultural value. The GIS-based LSP-MCE method can integrate these important requirements and facilitate MSP in the Salish Sea and other marine areas.

The recently-implemented Marine Plan Partnership (MaPP) initiative in British Columbia used spatial decision support tools for zoning of some resource uses and activities (Diggon et al 2022), and the GIS-based LSP method can further assist future MSP initiatives to meet the stated goals of the Canada-British Columbia marine protected area strategy by prioritizing locations of “unique or vulnerable habitats” such as acoustic refugia or other important locations (Governments of Canada and British

Columbia 2014). Internationally, the United Nations has declared a “decade of ocean science for sustainable development” from 2021 to 2030 (UNDOSSD 2022), highlighting the increasing importance of MSP. Incorporating the proposed methodology into an MSP process can enable decision-makers to collaboratively explore, analyse and visualize possible outcomes as part of their deliberations. Moreover, the OISA method provides an intuitive representation of trade-off, consensus, and complementary scenarios that can facilitate collaborative planning. The proposed methodology can be applied to other contexts where marine noise pollution is of concern, and also to marine species conservation planning for species with complex habitat requirements.

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Chapter 4.

Conclusion

4.1. Synthesis of Research

This thesis research develops advanced MCE methods and applies them to an environmental management problem. The GIS-based LSP method, a complex and generalized MCE approach, can assist in marine spatial planning because it can accurately represent complex logical relationships between input criteria to assess suitability for unique habitats like acoustic refugia, while also incorporating other considerations such as proximity to existing marine protected areas or designated fisheries. The method was able to incorporate marine noise, a 3D spatial phenomenon that affects marine organisms differently at different depths. Furthermore, the OISA method enables decision-makers to collaborate more effectively by visualizing possible outcomes that can represent consensus, complementary objectives, or trade-offs among diverse decision-making perspectives.

The research objectives of the thesis were achieved by developing GIS-based LSP suitability analysis for acoustic refugia for SRKW. In Chapter 2, the method was developed, then used to derive suitability maps for three scenarios with differing vessel traffic levels to show how suitable acoustic refugia are affected by noise pollution from vessels in the Salish Sea. The obtained results indicate that potential acoustic refugia exist in the Salish Sea, and that some of these locations are affected by marine noise pollution. High suitability areas were clustered around Haro Strait and Boundary Pass, the known core summer foraging ground of SRKW, due to the presence of steep slopes that support SRKW foraging behaviour; however, these high suitability areas were significantly smaller in higher-traffic scenarios. Some potential acoustic refugia were also identified in the north-western part of Georgia Strait, but it is likely that these locations are not as suitable as they appear due to factors that were not accounted for in the suitability analysis, such as competition for prey with other killer whale populations.

In Chapter 3, the GIS-based LSP method was used to develop scenarios representing differing perspectives on marine spatial planning for acoustic refugia for SRKW by incorporating 3D and 2D criteria, and the OISA method enabled integration of the different perspectives to derive suitability maps that show trade-off, consensus, and complementary scenarios. The results demonstrate that the GIS-based LSP method can successfully incorporate 3D criteria. Furthermore, while highly suitable areas for acoustic refugia were located in the same region, the three decision scenarios resulted in significantly different suitability maps as indicated by Kappa metric comparisons. In each of the scenarios developed in this Chapter, the lowest suitability scores are located in close proximity to industrial sites where vessel traffic is also high, and the highest suitability scores are located in the region of the study area with higher salmon abundance, far away from vessel transit routes where the sea floor surface has steep slope. High suitability areas in the Behaviour-oriented scenario were located near to kelp beds, which facilitate socializing behaviours, whereas high suitability areas in the Noise-Oriented and Human-Oriented scenarios tended to be far away from vessel traffic or designated fishing areas, respectively. The Human-Oriented scenario also emphasized slope slightly more than other habitat-related criteria. Finally, by combining the suitability maps representing each scenario using the OISA method, various “what if” scenarios represent different perspectives and spatial decision outcomes that can inform marine spatial planning.

In Chapters 2 and 3, review of scientific literature on SRKW behaviour and ecology, threats to the SRKW population, and environmental management in the Salish Sea guided the selection of criteria, input data, weights, and the development of suitability functions and LSP aggregation structures. The resulting suitability maps obtained in Chapter 2 correspond well with previous studies of SRKW critical habitat areas, as well as successfully identifying potential acoustic refugia that have not been mentioned in previous research. Therefore, the GIS-based LSP method can be used to highlight potential areas of interest for future spatial planning. The implementation of the OISA method in Chapter 3 demonstrates the potential usefulness of the LSP method in decision-maker discussions for visualizing multiple possible outcome scenarios.

4.2. Future Directions

The GIS-based LSP method is a spatial decision-making approach that can be used in a collaborative MSP process, and the analysis can be improved by involving real decision-makers, experts, stakeholders, and Indigenous rights holders in each step of the methodology. A method of incorporating expert opinions in real time such as a

Delphi panel (Dalkey and Helmer 1963) or spatial Delphi method (Balram et al 2003) would be useful to inform decisions at each stage of the methodology including criteria selection, suitability functions, the development of the LSP aggregation structure, choice of aggregators and weight values. An advantage of the GIS-based LSP method over other commonly used MCE methods is that its hierarchical aggregation structure enables many criteria to be included without diminishing the importance of any one criterion (Montgomery and Dragićević 2016) and decisions are made in a stepwise manner suitable for deliberation of participants (Dujmović 2018). Therefore, a large number of suitability analysis scenarios representing different decision-makers' preferences can be in addition concurrently evaluated and combined using the OISA method. Future work could implement the method using a greater number of input criteria and a greater number of decision-making perspectives than those used in this thesis research, preferably in a direct, real-time collaborative decision-making setting.

Like other MCE methods, the methods developed in this research provide a suitability analysis based on conditions in the study area at a single moment in time. Chapter 2 of this thesis represented three states of vessel traffic, which fluctuates over time, as three different scenarios. Future research can develop more efficient ways to incorporate criteria that fluctuate over time or represent them at a finer temporal resolution. Furthermore, the GIS-based LSP method cannot predict the locations of SRKW in the study area, only assess the suitability of locations for some purpose, such as acoustic refugia. In further research, comparison of suitable locations with recorded SRKW sightings or movement patterns could improve understanding of which criteria are the most important to SRKW. In addition, the movement, behaviour, and interaction of whales in 3D space and time can be represented with geosimulation approaches such as agent-based models (ABM). Such models have been used to assist spatial decision-making for various conservation purposes (Sengupta and Bennett 2003, Zellner et al 2012) and could be applied to the case of SRKW.

It is possible to extend the GIS-based LSP and OISA methods to other marine or in general environmental spatial planning contexts. However, it would be important to perform sensitivity analysis of the GIS-based LSP method. Developing multiple scenarios using different aggregators, as in Chapter 3 of this thesis, is one way of performing sensitivity analysis. Further research can execute a more robust sensitivity analysis by varying criteria suitability functions, input weight values, and aggregators to determine how variance in each part of the method influences the resulting suitability maps (Kaymak and van Nauta Lemke 1998, Feick and Hall 2010, Ligmann-Zielinska and Jankowski 2014).

This thesis research incorporated a 3D criterion in the suitability analysis in Chapter 3 using two input data layers representing marine noise at two different depths. This approach to representing 3D criteria is efficient because it only includes variations in the criteria input data that are relevant to the decision problem. However, this is a fundamentally 2D representation of marine noise. Future research can develop an enhanced 3D representation of marine noise, for example, a 3D geographic automata sound propagation model, which can further improve understanding of how marine noise affects acoustic refugia. Furthermore, there is a lack of available spatial data incorporating seasonal aspects of acoustic refugia suitability such as salmon migration, kelp growth patterns, or seasonal temperature and salinity fluctuations that can affect marine sound propagation. Future research can include input criteria representing seasonal and other factors as such data become available. More research is also needed to establish the minimum required area of potential acoustic refugia or connectedness of acoustic refugia that would be useful to SRKW.

4.3. Thesis Contributions

This thesis contributes primarily to the field of GIScience and spatial decision-making analysis by developing and implementing advanced spatial MCE methods and demonstrating how 3D spatial phenomena can be incorporated for suitability analysis using the complex GIS-based LSP decision method. The proposed novel spatial decision-making methods for the marine environment can also advance the fields of environmental and conservation management. In addition, the developed methods can be used to facilitate marine spatial planning, especially when acoustic effects on marine organisms are important to consider. Moreover, the OISA method of combining decision-makers' preferences into an overall integrated suitability map, has not been previously applied in a marine environment context, nor have more than two decision-maker perspectives been combined using the OISA method with various LSP aggregators.

In environmental management, decisions are frequently made in conditions of significant uncertainty (Polasky et al 2011). The methods developed in this thesis research can be used to assist in a decision-making process to clarify problems and objectives, enhance collaboration among participants and desired outcomes, while also providing visual representations of multiple “what-if” scenarios. Once understood by decision-makers, the aggregators used in the GIS-based LSP method can support in an intuitive way of representing logical relationships among a large number of criteria in the suitability analysis, and also between competing perspectives in a collaborative decision-making process. The proposed methodology can become a valuable tool in deliberations for marine and other spatial planning applications that involve many diverse participants and perspectives addressing complex management problems.

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