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Mapping cumulative impacts on Hong Kong's pink dolphin population

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ABSTRACT

Indo-Pacific humpback dolphins have historically inhabited the northern waters off Lantau Island, Hong Kong; however their numbers have significantly decreased over the past decade, while human pressure has simultaneously increased. Based on a spatio-temporal analysis using a Geographic Information System (GIS), this study aims to assess the cumulative human impacts of local activities on this dolphin population since 1996. After introducing and discussing the multiple approaches, difficulties, and limitations to cumulative effects assessments (CEA), this paper outlines our proposed CEA methodology. Our methodology involves mapping and analysis of anthropogenic marine impacts in relation with historical dolphin distributions in the area. Local scale results show evidence of a relationship between the addition of new high-speed ferry (HSF) routes into the cumulative environment and the decrease in dolphins in a specific region known as the Brothers Islands. These results coincide with past research showing that whales and dolphins are significantly disrupted in the presence of high vessel traffic, which continues to grow in the northern waters off Lantau Island, Hong Kong and in many other places around the world.

1. Introduction

Boasting a population of more than 7 million residents, Hong Kong is one of the most developed and economically successful cities in Asia. With its rapidly expanding economy and population, this city radically highlights the conflict between development and the environment. Coastal development in particular is a major issue in Hong Kong, as it is in many places around the world, as the growing need for space drives land reclamation, resulting in increasing areas of artificial coastline. Over the last two decades approximately 12 square kilometers in western Hong Kong waters has been developed into new land (Clarke, 2013); this transformation has led to a competition for space between humans and the local marine species.

To the west of Hong Kong Island, at the mouth of the Pearl River Estuary, lies Lantau Island, whose northern and western coastlines provide a prime habitat for Hong Kong's dolphins (Fig. 1). Locally known as Chinese White Dolphins, these Indo-Pacific humpback dolphins (*Sousa chinensis*) have attracted growing concern in face of accumulating coastal impacts (Jefferson, 2000; Jefferson et al., 2009). The Whale and Dolphin Conservation Society argues that this dolphin population is "under pressure as it lives in an ever-shrinking, ever-more polluted habitat" (WDCS, n.d.). Impacts such as fishery by-catch, chemical pollution, noise pollution, vessel strikes, climate change, and prey depletion are stressors on global marine mammal populations (Parsons et al., 2007; Reeves et al., 2003; Thompson et al., 2013), and are especially marked in Hong Kong waters. Indeed, Wilson et al. (2008) have argued that no other dolphin population faces as dire a threat as those in the Pearl River Estuary. By one abundance estimate, only 61 dolphins presently remain around Lantau Island (HKCRP, 2013) while there was an estimated 158 in 2003 (HKCRP, 2012). In light of this population decline, some environmental organizations in Hong Kong have requested a proper cumulative effects assessment (CEA) to better identify and mitigate the high level of impacts these dolphins are facing (HK Dolphin Watch, 2005; Parry and Knowles, 2013).

As Hong Kong's practice of CEA has suffered from a lack of statutory guidelines, weak analytical methods, and limited spatial and temporal scope (Yang and Lam, 2001), the research in this paper attempts to establish an improved CEA methodology. This methodology has been developed to identify existing relationships

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Abbreviations: HSF, High Speed Ferry; HKSAR, Hong Kong Special Administrative Region; HKDCS, Hong Kong Dolphin Conservation Society; HKCRP, Hong Kong Cetacean Research Project; DPSE, Dolphins Per Survey Effort.

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Fig. 1. Geographic location of Hong Kong and Lantau Island (Source of the base map: ESRI). The size of the study area is about 20 km^2.

between changes in dolphin population in the northern waters off Lantau Island and changes in cumulative human impacts within that same area, using a Geographic Information System (GIS). Through an extensive spatio-temporal analysis over a period of two decades, this study aims to contribute to the identification of specific human activities that have affected the distribution of Hong Kong's Indo-Pacific humpback dolphin. Beyond this specific case study, this paper provides insight into how a GIS can be applied to assess cumulative marine impacts, and can also help us revisit the way we envision the use of GIS for environmental studies.

2. Contextualization

The Indo-Pacific humpback dolphin, a coastal species whose range extends from central China throughout Southeast Asia and as far west as India (Jefferson, 2000; Jefferson and Rosenbaum, 2014), is an important species in many of its home-range countries. In Hong Kong specifically, numerous tourists come each year to see these animals for their famous vibrant pink color and friendly nature. The official mascot for Hong Kong's reunification with China, this iconic species is an integral part of Hong Kong's heritage, as well as an important member of the local marine ecosystem (Jefferson and Hung, 2004; Parry and Knowles, 2013). Although past research by Jefferson and Hung (2004) show no significant trends in Indo-Pacific humpback dolphin abundance within Hong Kong between the years 1995 and 2002, declining trends in the Hong Kong dolphins have been noticeable since then and seem related to the rapid rates of development and human activities within their habitat (HKCRP, 2012; HKCRP, 2013; Jefferson and Hung, 2004). In fact, this species has been red-listed as “Near Threatened” by the International Union for Conservation of Nature (IUCN) due to identified threats such as habitat and seabed destruction, water pollution, vessel disturbances, and accidental by-catch (IUCN, 2013). Although previous research has investigated the dolphin's ecology (Jefferson, 2000; Parsons, 1998), distribution (Jefferson, 2000; Jefferson and Hung, 2004), behaviors (Jefferson, 2000; Ng and Leung, 2003; Piwetz et al., 2012) and even their reactions to individual human disturbances (Hung, 2008; Jefferson and Hung, 2004; Jefferson et al., 2009; Sims et al., 2012), no studies have attempted to spatially investigate their response to the cumulative impacts in the area to this date.

With increasing rates of marine anthropogenic impacts the need for proper cumulative effects assessments (CEAs) is unprecedented (IPSO, 2013). Geographic Information Systems (GIS) can offer extensive functionalities for spatial investigations, and thus can contribute to the field of CEA. Combined with multi-criteria analysis, GIS can help identify certain spatio-temporal characteristics of cumulative impacts and compare them with biological and ecological spatio-temporal changes. Atkinson and Canter (2011) depict how GIS can be used to assess the cumulative impacts on wildlife populations through construction of multi-criteria habitat suitability models and cumulative disturbance models. Along these lines, the Canadian Environmental Assessment Agency has used GIS to calculate available habitat for specific wildlife species within successive development scenarios (Cumulative Effects Assessment Working Group, 1999). Another similar approach, by Johnson et al. (2005), applies human disturbance coefficients to habitat resource models to predict the levels of habitat loss in different impact scenarios (Johnson et al., 2005). Maxwell et al. (2013) also shows that GIS can be used to map cumulative human impacts on different marine predator species based on their distribution.

Although these approaches provide interesting results, attention must be given to the research process and how the results were derived. Incomplete datasets are often used for certain criteria, and spatial and temporal variability of dynamic processes are rarely accounted for (Halpern et al., 2009). A Canadian wildlife management group conducted a post-hoc comparison of predictions from a GIS-based grizzly bear CEA with raw monitoring data in order to assess the accuracy of CEA models (Stenhouse et al., 2003). Results showed no correlation between CEA predictions and actual monitoring data, thus invalidating the results of the cumulative effects model. The inaccurate results were attributed to the many assumptions made in the model concerning intensities of human use, zones of impact extent, and even species habitat use (Stenhouse et al., 2003). Essentially these findings show that a GIS is only as powerful as the assumptions made within it. Although GIS gives clear quantitative results, data limitations and assumptions or simplifications about ecological processes can lead to potential inaccuracies in the results. These above-mentioned GIS-based CEA models emphasize some of the capabilities of GIS for studying cumulative impacts and help contribute to the understanding and management of our environment; however they also outline the difficulties that a GIS can encounter when modeling the intrinsic complexity of ecological phenomena.

According to Bojórquez-Tapia et al. (2001) critical components in ecological systems cannot always be fully identified and understood, and therefore ecological impact predictions are often tainted with ambiguities and imprecisions. While some of these ambiguities cannot be modeled due to our lack of knowledge (deYoung et al., 2004) others can be addressed using the concept of fuzzy logic, which is based on the probability (and not the certainty) that a geographic location belongs to a given category. Wang and Chen (2010) depict an example of how fuzzy logic can be employed in a cumulative impact assessment. Using a fuzzy approach the authors quantified the risk of multiple air pollutant factors ($PM_{2.5}$, CO, SO_2 and NO_2) from multiple air pollutant sources into an integrated cumulative risk assessment (Wang and Chen, 2010). Following a 5-step methodology, of 1) quantifying evaluation criteria, 2) creating fuzzy membership functions, 3) calculating relative weights for each pollutant factor, 4) aggregating memberships and weights into a model, and 5) assessing the final cumulative risk, Wang and Chen argue that they were able to effectively quantify the cumulative air pollution risk in the state of California. This methodology presents a potentially effective way of computing cumulative impacts, while accounting for uncertainties over space.

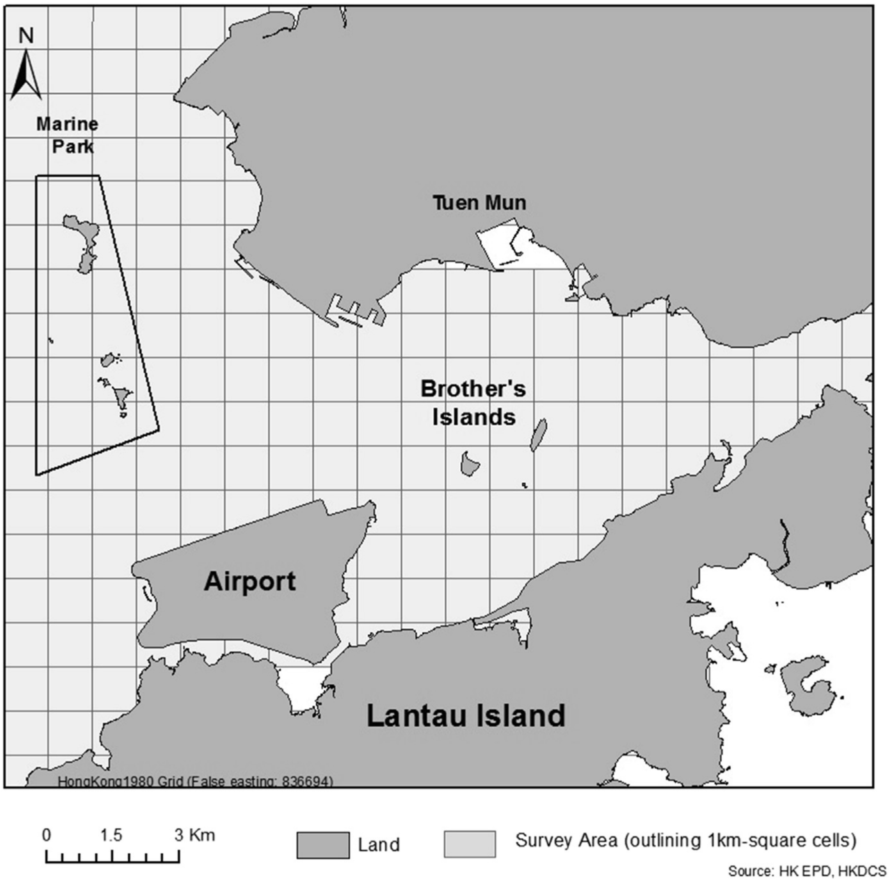
In the specific context of marine CEAs, recent studies have depicted regional ecosystem based approaches (Ban et al., 2010), regional multi-species based approaches (Coll et al., 2012; Reeves et al., 2013), and local single-species based approaches (Moore and Clarke, 2002; Zacharias and Gregr, 2005). These studies use spatial data on multiple human activities and incorporate tailored sensitivities of specific ecosystems to specific stressors (Ban et al., 2010; Coll et al., 2012; Zacharias and Gregr, 2005). This type of methodology allows for a more holistic approach to marine management, and avoids assessing activities in isolation. Although the results of these studies strongly contribute to marine management and help in our understanding of ocean systems, certain limitations and difficulties that were faced must be highlighted. For example, knowledge of impact interactions was limited, and therefore impacts were accumulated on an additive basis even though synergistic and antagonistic relationships may be possible (Ban et al., 2010). Linear disturbance decay functions were assumed (Ban et al., 2010; Coll et al., 2012; Zacharias and Gregr, 2005), and specific factors such as climate change effects were often omitted due to data accessibility issues (Ban et al., 2010; Coll et al., 2012; Reeves et al., 2013). Finally spatio-temporal dynamics were rarely considered, thus discounting past impacts, species migrations, and even inter-annual population variability (Ban et al., 2010; Coll et al., 2012; Zacharias and Gregr, 2005). These studies outline the complexity of assessing cumulative impacts on ecological phenomena and highlight many of the unknown factors in modeling such systems.

3. Methodology

Assessing cumulative impacts requires the relevant comparison of two types of data: spatio-temporal data on human activities and biophysical data on the species and/or habitat under study. For this project, these two datasets were compiled from two data sources. Data on the different human activities in the area of interest was accessed through the Hong Kong Environmental Impact Assessment and Marine Department websites dating back to 1996 (http://www.epd.gov.hk/eia/ & http://www.mardep.gov.hk). These websites compile data on 13 projects that have undergone an Environmental Impact Assessment between 1996 and 2013, and marine traffic data for that same time frame for three different vessel fairways within our study area. These activities were grouped into five main impact types as later discussed in Section 3.2. The dolphin distribution data for each year of the assessment was accessed from the Hong Kong Cetacean Research Project (HKCRP) long-term monitoring database.

3.1. Mapping dolphin distributions

Data on the Indo-Pacific humpback dolphins in Hong Kong has been collected by HKCRP since 1996 under strict and consistent protocols (HKCRP, 2013). Dolphin distribution data is mainly collected at sea, through systematic line-transect surveys. These boat based surveys follow a line transect protocol, where a 15–20 m vessel travels along pre-determined transects at a constant speed of 13–15 km/h. Two "on-effort" observers (one with binoculars) actively search the water surface through a 180-degree field of vision for dolphins. One additional observer rotates in every 30 min to ensure that the observers don't fatigue in their search efforts. Data such as time, position (latitude and longitude), vessel speed, Beaufort sea-state, and visibility is recorded using a Global Positioning System (GPS) unit. Upon dolphin sightings, initial sighting-distance and sighting angle is recorded. Sighting number, time, GPS position, environmental conditions, group size, group composition, boat associations, activity and behavior are also noted. The on-effort sighting data is then normalized by survey effort (100 units) to enable comparison between different areas that were not surveyed equal amounts (Hung, 2008). Data collected under high Beaufort sea-state and low visibility are not included in the analysis, nor are data with low survey effort (less than 10 units). An adjustment is also made to correct for the amount of landmass within each 1 km grid cell. The final data is then mapped for each year of the study onto a GIS raster layer made of 215 cells of 1 km resolution that cover our study area (see Fig. 2). This gives the 18



Source: HK EPD, HKDCS

Fig. 2. Survey area with 1 km^2 cells outlined.

resulting dolphins-per-survey-effort (DPSE) maps, which depict the change through time in annual dolphin distribution between 1996 and 2013.

3.2. *Identifying human impacts*

As emphasized previously, assessing cumulative human impacts on dolphin populations is extremely complex since it involves taking into account a range of local and global criteria such as water pollution levels, noise impacts, ocean currents and topography, fishery stocks, and impacts from climate change such as water temperature increase, ocean acidification, and UV increase (Ban et al., 2010; Coll et al., 2012; Thompson et al., 2013). Although we understand that a comprehensive cumulative impact assessment should take into account as many potential human impacts as possible, in this study we propose to contribute to this herculean task by focusing on the cumulative impact of local development activities on dolphin populations. We are choosing to focus on local development, as there is a general consensus in the literature that the Hong Kong dolphin population is indeed affected by local human activities (HKCRP, 2012; Ng and Leung, 2003; Van Parijs and Corkeron, 2001; Piwetz et al., 2012; Sims et al., 2012; Wilson et al., 2008). In order to reach this goal we have integrated all pertinent marine related human activities in the study area since 1996, assuming that these activities represent the root causes of major local impacts affecting the area of interest during the last two decades (see Tables 1 and 2 for specific activities).

It is often difficult to characterize specific environmental impacts without identifying the causes of impacts first (Ortiz-Lozano, 2012). Therefore we have chosen to base our assessment on the

Table 1
List of human activities incorporated into our cumulative effects assessment (CEA).

Development project or Vessel fairway	Construction-operation-decommission dates	Type of human activity
Tuen Mun River Trade Terminal	1996–1998–present	Land reclamation
North Lantau Expressway	1992–1997–present	Land reclamation
Chek Lap Kok Airport	1992–1998–present	Land reclamation
Contaminated Mud-Pits Group IV	1997–1998–2009	Dredging
Tung Chung Development Phase 1	1997–2000–present	Land reclamation
Urmston Road cargo shipping traffic	prior to 1996–present	Marine traffic
High Speed Ferry service from Sheung Wan and Tsim Sha Tsui regions to Mainland	prior to 1996–present	Marine traffic
Disneyland Theme Park near Penny's Bay	2000–2008–present	Land reclamation
Yam O Road P2	2001–2005–present	Land reclamation
High Speed Ferry service from SkyPier to Mainland and Macau	2004–present	Marine traffic
Contaminated Mud Pits Group V	2007–2008–2015	Dredging
Aviation Fuel Receiving Facility	2008–2010–present	Piling (percussive)
Hong Kong Boundary Crossing Facilities	2011–2016–future	Land reclamation
Hong Kong Link Road 03	2012–2016–future	Land reclamation
Hong Kong Link Road 09	2013–2016–future	Piling (bore)
Contaminated Mud Pits Group VI	2012–2014–2016	Dredging

Table 2
Detailed data for high-speed ferry traffic (HSF) (Sources: Cotaiwaterjet.com, mardep.gov.hk; adapted from Hung, 2008).

HSF General Information	
Boat Type	Catamaran or Jetfoil
Approximate Size	47.5 m long
Approximate Speed	42 knots
Approximate Sail Duration	
Sheung Wan/Tsim Sha Tsui to Mainland	60–180 min (nine different locations)
SkyPier to Mainland	30–70 min (five different locations)
SkyPier to Macau	50 min
Frequency Data (within entire HK area)	
Year	*Total annual HSF trips*
1999	119,810
2000	119,590
2001	122,440
2002	127,378
2003	125,490
2004	143,980
2005	150,160
2006	151,920
2007	163,390
2008	162,380
2009	165,423
2010	177,877
2011	176,209
2012	165,910
2013	161,776

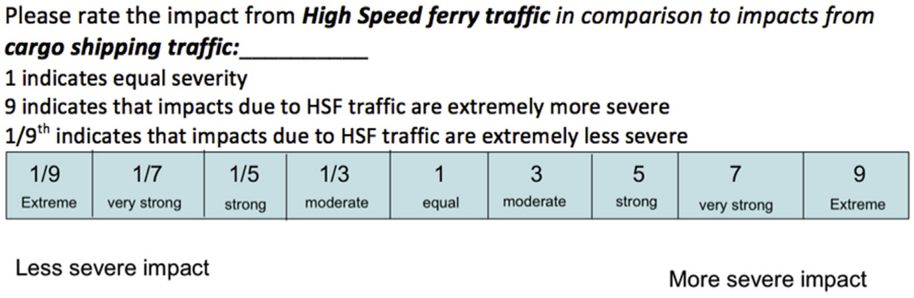
spatial location of local development activities in the area. From that we can infer and characterize the resulting environmental impacts that they cause. The five activities that were identified from existing coastal development in the area are land reclamation projects, pile driving works, dredging works, cargo shipping traffic, and high speed ferry (HSF) traffic. Land reclamation activities have been shown to cause adverse effects on seawater quality, benthic and marine biota, and in turn negative effects on local fish stocks as well (Mostafa, 2012; Priyandes and Majid, 2009). Scoping reports have also suggested that reclamation can fragment Indo-pacific humpback dolphin habitat and indirectly reduce availability of prey resources (Sheehy, 2010). Anthropogenic noise caused by pile-driving activities may affect dolphin behavior over considerable distances by masking vocalizations and echolocation signals (David, 2006). Würsig et al. (2000) showed that humpback dolphin behavior changed (i.e. increased swimming-speeds) during piling projects and some dolphins even temporarily abandoned the area (Würsig et al., 2000). Dredging works can also impact marine mammals. Entrainment of marine organisms, degradation of vital habitats such as seagrass beds and coral reefs, and changes in sediment structure could directly impact dolphin prey resources (Mostafa, 2012; Todd et al., 2014). The main impact of concern from cargo shipping traffic is not usually noise pollution, but disruptions to dolphin behaviors (Jefferson et al., 2009). Cargo ships emit low frequency noises whereas dolphins generally vocalize at higher frequencies therefore noise pollution is not generally an issue, however there is still concern that dolphins need to alter their dive patterns to avoid encounters with heavy vessel traffic (Jefferson et al., 2009). HSF traffic may cause impacts of greater concern as they emit higher frequency noises that are well within the audible range of Indo-pacific humpback dolphin (Airport Authority Hong Kong, 2014; Sims et al., 2012). The faster speeds can also increase chances of cetacean/vessel collisions; past cases of dolphin strandings in the Hong Kong area showed signs of blunt trauma, suggesting collision as the cause of death (Jefferson, 2000). Furthermore, past studies have shown that Hong Kong dolphins exhibit signs of behavioral disturbance in the presence of HSF (HKCRP, 2012; Ng and Leung, 2003).

3.3. *Mapping cumulative human impacts*

Transforming the multiple human activities into GIS impact layers requires following several steps. The first step was to convert the different activities into vector layers that could then be analyzed with a Geographic Information System (GIS). The second step was to assess the potential impacts caused by each activity. This step involved the assessment of each human activity at three different levels. First in terms of the severity of each resulting impact, second in terms of the spatial extent of the resulting impact, and third in terms of its temporal extent (i.e. duration of the impact).

The severity of each impact towards dolphin survival was determined based on expert knowledge. We consulted three experts on dolphin conservation within Hong Kong to assess this severity: the chair of the Hong Kong Dolphin Conservation Society (co-author S.K. Hung) who oversees the long-term dolphin monitoring work by the HKCRP, the senior marine conservation officer at World Wildlife Fund Hong Kong, and the senior tour coordinator of Hong Kong Dolphinwatch Limited. We asked these experts to fill out a standardized pairwise comparison survey in which they rated the severities of each resulting impact from five main human activities, relative to each other (Fig. 3). After receiving feedback from all experts, we calculated the individual weights and averaged the three opinions to get final weighting factors for the impacts from each human activity. Developed by Saaty (1977), the pairwise comparison approach for assigning weights is a coherent method based on the analytic hierarchy process that has been widely used in environmental decision-making (Clevenger et al., 2002; Gonzalez et al., 2007). It is a common practice approach due to its ease of use, ratio scale, and evaluation of qualitative or quantitative criteria (Ishizaka and Labib, 2009). The relative importance between each pair of criteria is identified through a nine-point scale (Fig. 3) and entered into a pairwise comparison matrix (Saaty, 1977). Weights are then calculated by the eigenvalue method (Ishizaka and Labib, 2009). In some cases large differences are present between different expert's opinions on the weight for certain criteria (e.g. the weights vary between 14% and 40% for HSF traffic) and this may be attributed to differences between each expert's individual backgrounds and motivations. Although these differences exist, the importance that experts have given to each criteria is overall comparable and the average values we have calculated capture this relative importance.

The spatial extent of each impact was assessed based on the distance to which the effect of the impact was likely to reach. We varied this distance depending on construction and operation phases for development projects, and depending on relative changes in traffic volume from year to year for marine traffic activities (see Tables 1 and 2). The spatial extent for each impact was determined based on background literature, and dolphin exclusion zones. For instance, past literature has shown that cetaceans can totally abandon entire areas of habitat that undergo high vessel traffic (Bejder et al., 2006; David, 2002; Lusseau, 2004). From this we concurred that the effect of marine traffic may be highly spatial in nature and therefore we increased the spatial extent of marine traffic impacts with increasing traffic volumes. We also took into account dolphin exclusion zones. A dolphin exclusion zone is a specific area around marine construction works in Hong Kong that is consistently monitored for the presence of dolphins; if a dolphin is spotted within the zone, construction work is halted until 30 min after the last sighting (Jefferson et al., 2009). Given the fact that there is no clear spatial limit for the resulting impact of each activity, we used a fuzzy approach to model each impact's spatial extent. As described previously, fuzzy logic in this context, is based on the probability that a given area's capacity to support dolphin



Please rate the impact from ***High Speed ferry traffic*** *in comparison to impacts from* ***cargo shipping traffic:___________***
1 indicates equal severity
9 indicates that impacts due to HSF traffic are extremely more severe
1/9th indicates that impacts due to HSF traffic are extremely less severe

1/9	1/7	1/5	1/3	1	3	5	7	9
Extreme	very strong	strong	moderate	equal	moderate	strong	very strong	Extreme

Less severe impact
More severe impact

Fig. 3. Example template provided to the experts in the pairwise comparison survey.

Table 3
Detailed data for each impact type.

	Land reclamation projects	Pile driving works	Cargo shipping traffic	High speed ferry traffic	Dredging works
Impact Reach – construction phase	Impacts decline linearly through space, reaching zero at a distance of 250 m from the project	Impacts decline linearly through space, reaching zero at a distance of 500 m from the works (or 250 m if work includes bored piling technique)	Impacts decline linearly through space, reaching zero at a distance of 100 m from the vessel fairway Note:Construction phase is considered first year of operation	Impacts decline linearly through space, reaching zero at a distance of 100 m from the vessel fairway Note:Construction phase is considered first year of operation	Impacts decline linearly through space, reaching zero at a distance of 250 m from the works
Impact Reach – operation phase	Impacts decline linearly through space, reaching zero at a distance of 100 m from the project	n/a	Impacts decline linearly through space. The distance at which zero impact is reached varies relative to changes in traffic volume.	Impacts decline linearly through space. The distance at which zero impact is reached varies relative to changes in traffic volume.	n/a
Reference	EIA exclusion zone; Nowacek et al., 2001; David, 2002.	Jefferson et al., 2009; EIA exclusion zone	Nowacek et al., 2001; David, 2002	Nowacek et al., 2001; David, 2002; Ng and Leung, 2003	EIA exclusion zone
Weighting factor (expert opinions & average score)	(53%, 39%, 29%) average = 40%	(14%, 36%, 19%) average = 23%	(5%, 4%, 5%) average = 5%	(23%, 14%, 40%) average = 26%	(5%, 7%, 7%) average = 6%

presence is negatively affected due to nearby human activities. Our use of fuzzy logic dictates that the probability of an impact occurring decreases with distance from an activity. The resultant fuzzy membership GIS layers were then used to further map the cumulative effects. Fuzzy logic is particularly relevant in this project since it allows us to define fuzzy limits to our resulting impacts, and allows the combination of multiple criteria to assess the zones of cumulative effects.

Finally the temporal dimension of each impact was taken into account by differentiating the impact during the construction phase from the operation phase and decommission phase. This was done by distinguishing between differences in the spatial extent of the impact for each of these specific phases (see Table 3). This results in different fuzzy membership layers for the different phases of each human activity. All fuzzy membership layers of the same impact-type and for the same year of the assessment were then summed onto the same GIS layer to account for any additive impact interactions, and to ensure that only one project phase is considered at a time. The resulting five impact layers were then combined based on their respective weighting factors, to produce a final cumulative impact map for one specific year of the study. This entire process was repeated for each of the 18 years of our study period (1996–2013) and from this methodology we produced 18 cumulative impact maps that attempt to depict how the human impacts in North Lantau waters change throughout time and space.

Although our methodology was designed based on background literature and direct collaboration with experts of the Indo-Pacific humpback dolphin, it is important to emphasize that this methodology can only provide an assessment of the cumulative impacts from the specified local activities. There are indeed several decisions that have been based on expert judgment and that cannot be supported by scientific knowledge. The use of dolphin exclusion zones to determine impact extent are such an example; exclusion zones are proposed by the project proponent and approved by the Hong Kong government and are therefore reflective of the Hong Kong EIA process, and not of the actual biological impacts experienced. Henceforth a larger (or smaller) impact reach may in fact be more accurate to model depending on each specific situation. Furthermore by adding the different weighted impacts we assumed simple additive impact interactions and discounted any possible synergistic or antagonistic interactions. Finally, using expert opinion to weigh the impacts is another human-based assumption that could introduce inaccuracies in our model. Despite these limitations, we believe that the methodology we have developed is robust enough to provide an assessment of the cumulative impacts and to evaluate the possible existence of correlations between these cumulative impacts and the change in dolphin distributions in the North Lantau area during the last 18 years.

To analyze any present relationships between the cumulative impacts and the local dolphin distribution, changes over time were assessed using linear regression analysis to find any significant trends. Statistical correlations were then run to determine the significance of any existing relationships. An iterative process of data analysis was employed, going through multiple rounds of analyses in order to investigate a range of potential relationships. The results are presented and discussed in the following section.

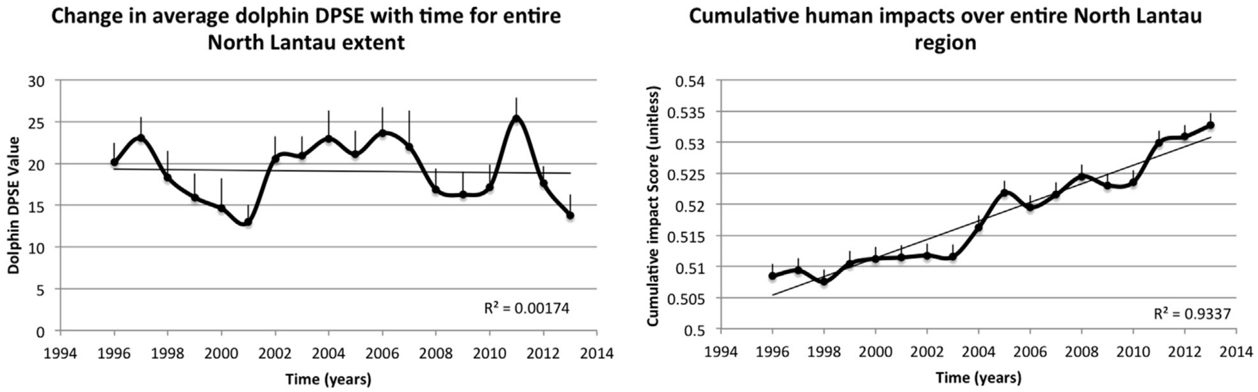


Fig. 4. Left: Linear regression between time and average DPSE over entire North Lantau region. right: Linear regression between time and cumulative human impacts over entire North Lantau region (note: error bars display standard error).

4. Results

A first general analysis was run to compare any annual trends between the mean DPSE values and the mean cumulative human impact scores over the entire study extent. Although the DPSE values showed distinct cyclical fluctuations from year to year, they did not display any significant trends over the entire 18-year span of the study in the North Lantau region (see Fig. 4). On the other hand, the cumulative human impacts showed a significant increasing trend since 1996 (see Fig. 4). This increase is not however correlated in any way to the overall trend in dolphin density ($r = -0.01$, $p > 0.9$). Therefore we cannot establish a relationship between the increasing human impacts and any trends in the dolphin population at the overall scale of our study area between 1996 and 2013. This first result led us to investigate possible relationships between these two phenomena at a finer spatial scale.

The next step of the analysis was designed to identify finer scale areas of the North Lantau region in which local human activities may be correlated with more local scale dolphin density declines. This identification was done through iterative rounds of analysis at the finest scale available. For each 1 × 1 km pixel, the DPSE value was plotted through time and we began to see statistically significant declining DPSE values for certain pixels located in the eastern zone of the analysis extent, and increasing trends in the western zone (see Fig. 5). Specifically, four cells around the Brothers Islands experienced significant declines in DPSE ($R^2 = 0.24$, $p < 0.05$) thus emphasizing the prior need to analyze our results at a finer scale.

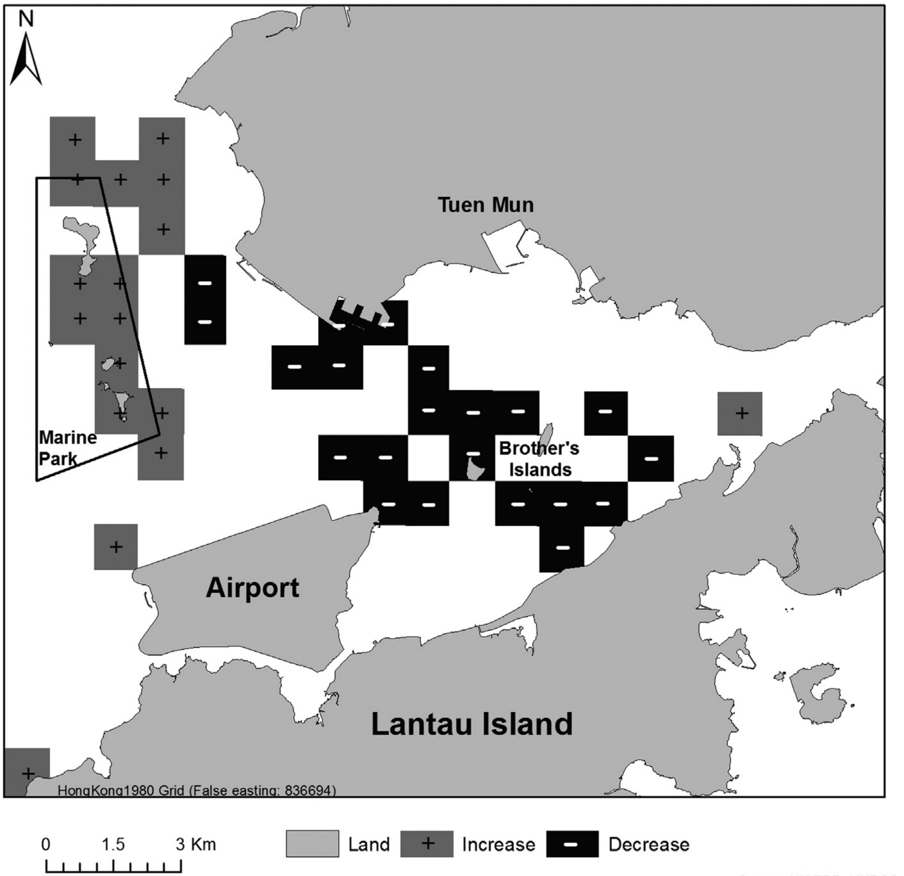
The Brothers Islands is an area of historically high dolphin density (Hung, 2008), and the noted substantial decrease in dolphin density seems to affect not only this site but also a greater zone of the North Lantau region (see Fig. 5). To delineate the zone of substantial decrease in DPSE during the last 18 years, we have systematically expanded the spatial scale of our analysis through four iterative rounds of statistical calculations. The four different spatial scales that were assessed are as follows; Scale 1: four grid cells located near the Brothers Islands; Scale 2: The whole area of the Brothers Islands and Sham Shui Kok; Scale 3: Brothers Islands (including Sham Shui Kok) and northeast region of the airport; and Scale 4: all grid cells northeast of the airport (see Fig. 6). All four scales show a decreasing DPSE trend with time, and a negative correlation with cumulative impacts (see Table 4). Scale 3 depicts the strongest decreasing trend ($R^2 = 0.51$, $p < 0.01$) and strongest negative correlation ($r = -0.74$, $p < 0.01$), and therefore we conclude that the spatial extent of the impact is reflected most accurately through scale three.

A linear regression analysis was then performed between the average DPSE values of scale three and the overall cumulative impact values to determine if the dolphin densities at scale three are a function of the increasing cumulative impact scores (see Fig. 7). Depicting an R^2 value of 0.55 ($p < 0.01$), the regression established a significant negative relationship between the cumulative impacts within North Lantau waters and the declining DPSE values near the Brothers Islands and the NE corner of the airport.

In order to characterize the temporal extent of this decline, a specific decrease in dolphin population was noted between 2003 and 2005, which corresponds to an important increase in impacts during 2004 (see Fig. 5). This increase can be attributed to the implementation of two new high-speed ferry (HSF) routes departing from the airport, since no other impacts occurred in that year besides this HSF implementation (see Fig. 8). This relationship was validated by the correlation in time between the DPSE trend in scale 3 and the cumulative impact trend. Results showed a strong negative correlation ($r = -0.74$) and suggest that the implementation of these ferry routes into the already developed waters off North Lantau may contribute to the local dolphin population decline.

Finally, to determine whether the decline in dolphin density at scale three is due to a decline in overall dolphin abundance or merely due to a shift in dolphin distribution, we refer back to our fine scale analysis of each 1 × 1 km pixel. As seen from this assessment there appears to be an increase in dolphin density in the marine park located in the western part of the study area (see Fig. 5). This notable increase in dolphin density appears correlated in time with the 2004 HSF implementation. Another iterative analysis was run and it was found that a grouping of three pixels within the Marine Park showed the strongest increasing trend with an R^2 value of 0.22 ($p < 0.05$) and a Pearson correlation coefficient (with impacts) of $r = 0.57$ ($p < 0.05$) (see Fig. 9). It was seen that after iterative rounds of analysis this effect diluted out and stabilized very quickly with larger spatial scales showing no increasing trends. In other words, while the spatial extent of the dolphin density decrease concerns a significant area in Northeast Lantau, the spatial extent of the dolphin density increase identified during the same period affects mainly a small zone of three square kilometers within the existing marine park located in Northwest Lantau. Although it is not possible to make any direct connection between these two phenomena given the data available, we can say that for the western zone in general, the dolphin population was at least stable throughout the time frame of our study and certainly not declining. This is an important finding since it confirms the specificity of the localized decreasing trend in abundance in the eastern zone.

In light of this study, we can sketch a possible relationship between the implementation of high-speed ferry (HSF) traffic and the



Source: HK EPD, HKDCS

Fig. 5. Study extent displaying areas of substantial dolphin density increase (medium gray) and decrease (black).

decline in dolphin density around the Brothers Islands, and the increase in dolphin density within the marine park. The coincidence in timing of these effects, may suggest possible impacts of HSF on the dolphins traveling behavior and distribution. Results from HKCRP monitoring data and an EIA study have identified the waters north of the airport as an important dolphin traveling corridor (Airport Authority Hong Kong, 2014; HKCRP, 2014), and therefore support the hypothesis of HSF impacts on dolphin traveling patterns. As mentioned throughout this paper, given the complexity of the phenomena at stake, it is impossible for us to conclude whether HSF traffic alone is a causal factor or whether it is the addition of HSF traffic into the pre-stressed waters and therefore its total cumulative impact. Regardless, the results of this research do emphasize the need for a more systematic study on the impacts of HSF traffic on dolphin traveling patterns and dolphin distributions in Hong Kong waters.

5. Implications for management

Currently in Hong Kong, a proposed project to develop the airport into a three-runway system will involve 6.5 square km of reclamation north of the airport (Airport Authority Hong Kong, 2014; see Fig. 10). The project footprint will overlap with the existing HSF traffic (thus requiring re-routing) and permanently invade the hypothesized dolphin traveling corridor. If this project is to be approved, the traveling corridor will be further reduced and disruptions in this shrinking space may be accentuated by the HSF traffic; further decreases in local dolphin densities may then be expected.

Potential solutions to reduce the associated impacts of HSF traffic include decreasing HSF travel speeds (Chan, 2014). Speed restrictions may be an effective form of impact management, since certain cetaceans (including Indo-pacific humpback dolphins) react more negatively to high-speed boats than other boats (David, 2002; Ng and Leung, 2003). Higher speeds can increase underwater noise, as well as probability of fatal collisions (Airport Authority Hong Kong, 2014; Sims et al., 2012). According to David (2002) serious collisions can occur at speeds of 13 knots or higher, while HSFs in Hong Kong travel at speeds up to 42 knots (Austal, 2009). Reducing the frequency of HSF traffic is another recommended management strategy that could have associated benefits for the local dolphins (Chan, 2014). Previous research has shown that dive-time of Indo-pacific humpback dolphin and residency index of bottlenose dolphin are both negatively affected by high marine traffic density (Lusseau, 2004; Ng and Leung, 2003). By reducing traffic density the associated negative impacts may be alleviated as well. Establishing and properly managing sufficient marine protected areas (MPAs) is another recommended management measure in Hong Kong, as it would enforce speed limits of 10 knots, impose certain fishing bans, and encourage monitoring programs (AFCD, 2000; Chan, 2014). Proper location, size, and connectivity of these MPAs are important factors to consider during the initial establishment process (Roberts et al., 2003). Rerouting of HSF traffic is another management strategy that can be considered, as well as investing in the development of new technologies, such as improved propeller and ship design to reduce noise and severity of collisions, and passive acoustic devices to detect the presence of dolphins (Chan, 2014). Although the above-mentioned marine management

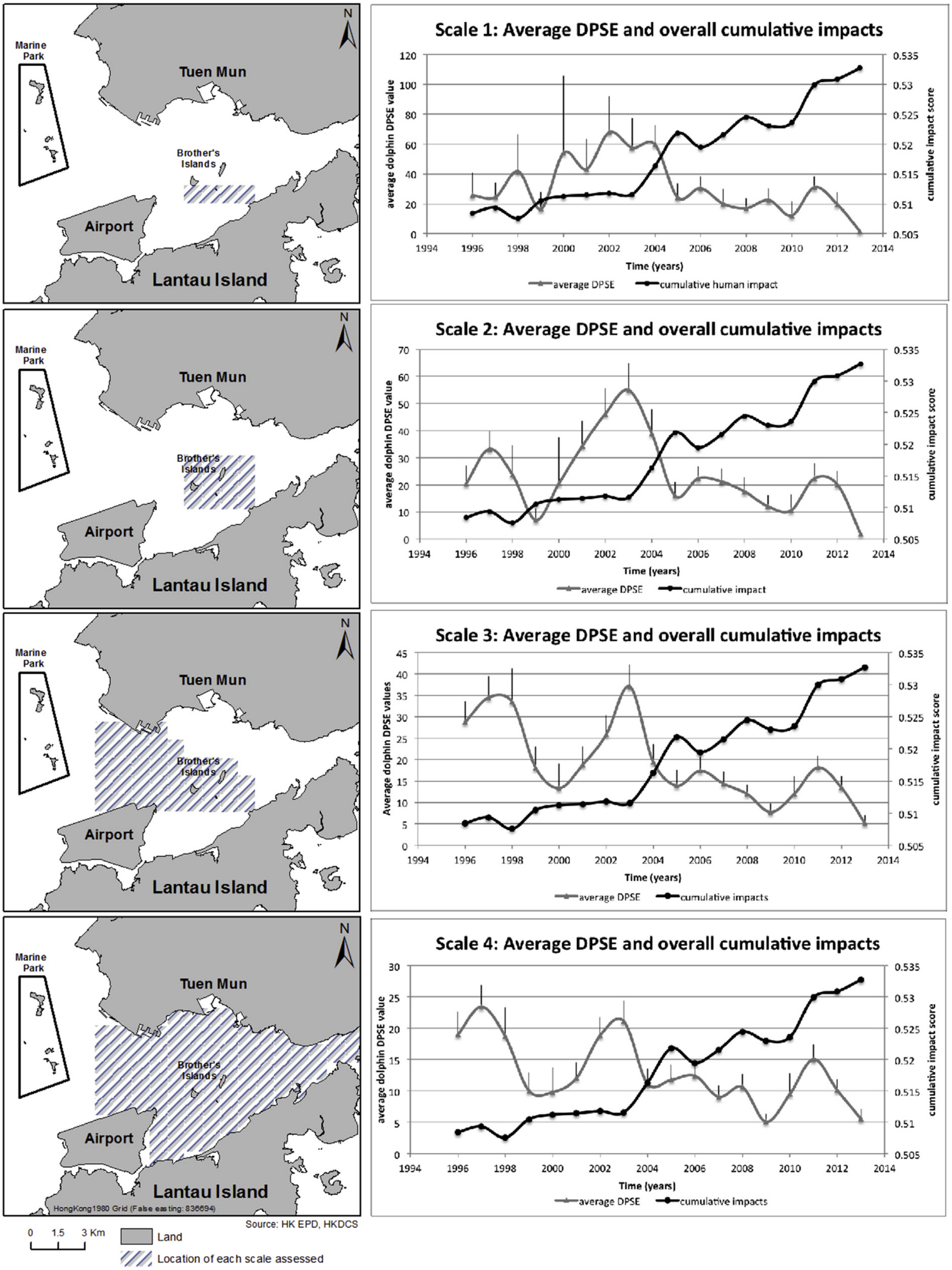


Fig. 6. Spatial scales and respective statistical analysis (error bars = standard error).

Table 4
Statistics for all four spatial scales assessed.

	Linear regression R^2	p-value	Pearson correlation r	p-value
Scale 1	0.20	$p < 0.05$	−0.57	$p < 0.05$
Scale 2	0.14	$p > 0.10$	−0.49	$p < 0.05$
Scale 3	0.51	$p < 0.01$	−0.74	$p < 0.01$
Scale 4	0.41	$p < 0.01$	−0.62	$p < 0.01$

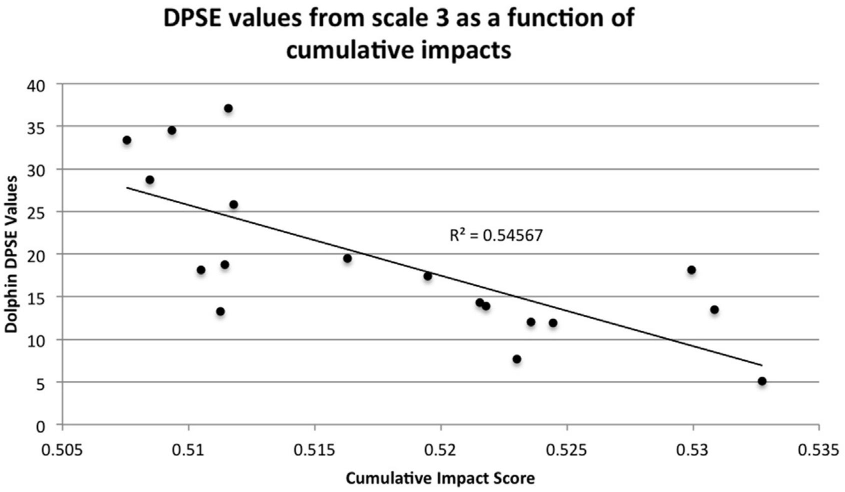


Fig. 7. Regression between scale 3 DPSE and overall cumulative impacts.

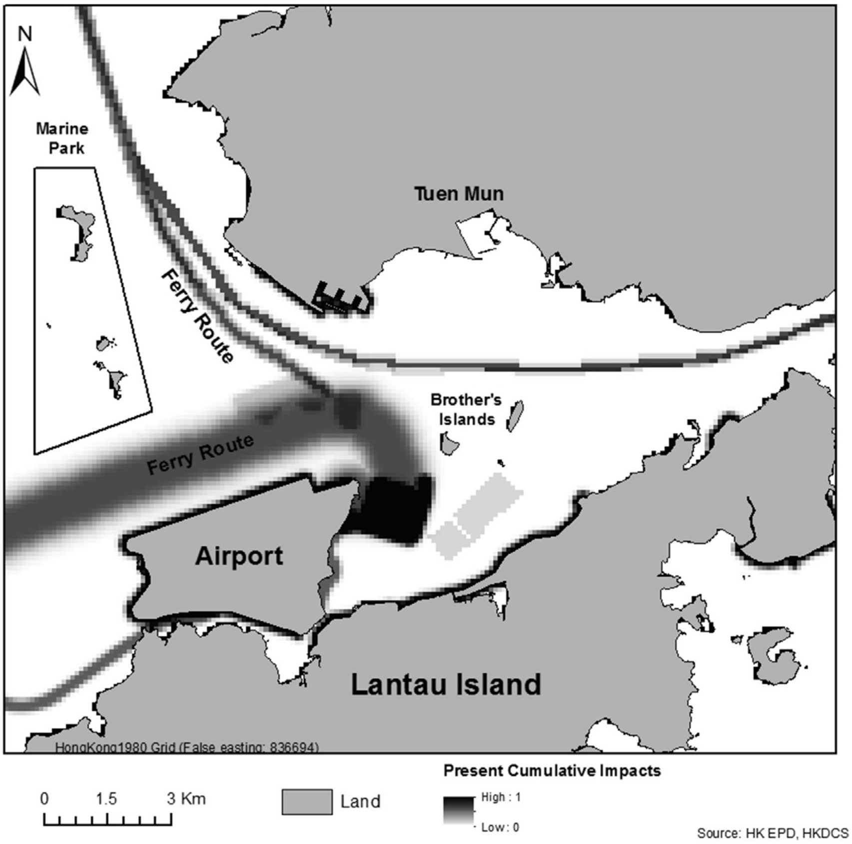


Fig. 8. Present cumulative human impacts (note the ferry routes between the marine park and the Brothers Islands).

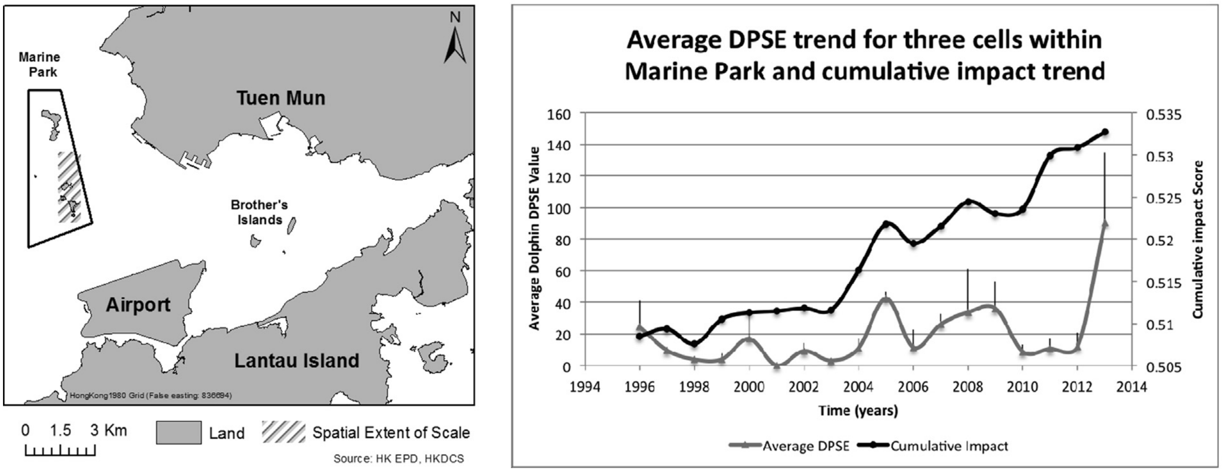


Fig. 9. Western zone analysis (left: spatial extent, right: graphical assessment, error bars display standard error).

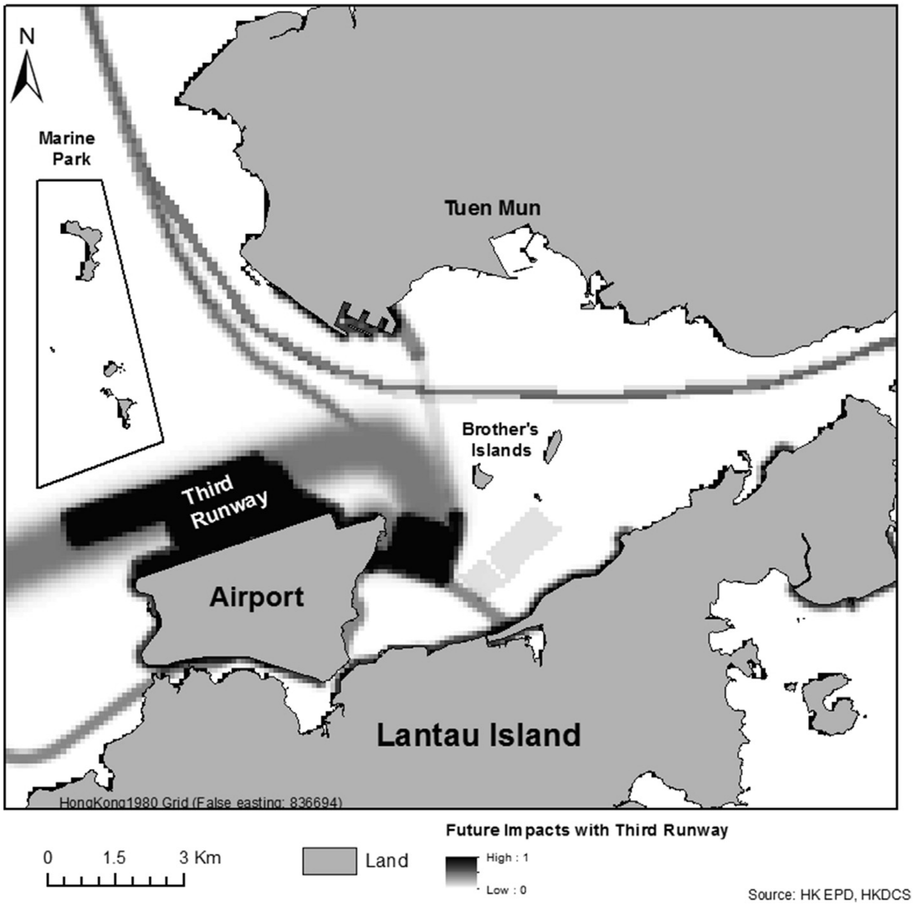


Fig. 10. Future impacts with Airport Third Runway project.

measures are theoretically plausible, the actual benefits for the dolphin population in the North Lantau area remain to be assessed.

If dolphin conservation is to be taken seriously in Hong Kong, dolphin movement patterns should be studied in order to determine if their traveling abilities and spatial distribution are in fact being affected; this can potentially be done through tag-and-track studies (Scott and Chivers, 2009), or more focal follow surveys (HKCRP, 2013; HKCRP, 2014). Hong Kong should also foster larger scale trans-boundary conservation efforts with the People's Republic of China (PRC) and Macau Special Administrative Regions (SAR), as cooperative-management is proven to be a more effective method for conservation work (Donald et al., 2007). In their 2002–2010 Conservation Action Plan for the World's Cetaceans, the IUCN advocates for coordination among conservation bodies and functional international agreements to attain conservation objectives (Reeves et al., 2003). Past examples of effective international agreements include the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS), which has been shown to function as a stimulus for coordinating research efforts and promoting adoption of conservation measures through action plans and working groups (Churchill, 1999). Hong Kong, Macau SAR, and the PRC should consider establishing a similar trilateral agreement in which impacts are properly managed throughout international borders and conservation initiatives are realized.

6. Conclusion

This study provides insight into the spatial and temporal dynamics between local human impacts and dolphin density distributions since 1996 in the North Lantau waters of Hong Kong. Through a spatiotemporal investigation, it was found that although cumulative impacts are not inducing any trends on the North Lantau dolphin population as a whole, a localized area in the eastern zone is experiencing significant declines in dolphin density. We determined that the spatial scale of this decline is best represented around the Brothers Islands and the northeast corner of the airport, and that it correlates in time with the implementation of two new HSF routes. In parallel, we also determined that specific locations in the western zone of the study area experienced correlated increases in dolphin density. Although we were unable to identify the spatial extent of this effect, we can conclude that the cumulative impacts seem to have disrupted the natural dolphin distribution in North Lantau, and that the timing of these impacts highlights the addition of HSF traffic as an important contributing factor in the localized dolphin density decline.

Our results should however be interpreted with caution. Our list of human impacts was not exhaustive, excluding factors such as climate change effects, water pollution and prey resource distribution; and some unavoidable assumptions and simplifications associated to any geospatial analysis were made. Furthermore, edge effects were not accounted for in this assessment (i.e. dolphins traveling outside our study area) and it was assumed that certain projects had zero residual impact during operation phases. These limitations emphasize the difficulties in terms of data acquisition, understanding of ecological phenomena, and incorporation of temporal dynamics when conducting a CEA (Atkinson and Canter, 2011; deYoung et al., 2004). Yet despite certain approximations in our methodology, our findings improve the understanding of cumulative impacts on cetacean populations by highlighting the addition of HSF traffic as a likely contributing impact in the decreasing density of dolphins in North East Lantau.

These results coincide with past research showing that cetaceans are significantly disrupted (avoidance behaviors, increased dive times, changes in vocalizations) in the presence of high vessel traffic (Bejder et al., 2006; HKCRP, 2012; Lesage et al., 1999; Ng and Leung, 2003; Van Parijs & Corkeron, 2001; Sims et al., 2012). The waters north of the airport are identified as an important dolphin traveling corridor (HKCRP, 2013; HKCRP, 2014), and as seen from Fig. 8, these waters also overlap with concentrated HSF traffic, thus strengthening our study findings, which suggest HSF traffic (in already developed waters) as a major dolphin disturbance.

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