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Modeling the distribution of illicit oily discharges detected by aerial surveillance in western Canadian marine waters

Norma Serra-Sogas [a,*], Patrick D. O'Hara [b,c], Rosaline Canessa [a]

[a] Department of Geography, University of Victoria, Victoria, BC V8W 3P5, Canada
[b] Canadian Wildlife Services, c/o Institute of Oceans Science, Sidney, BC V8L 4B2, Canada
[c] Department of Biology, University of Victoria, Victoria, BC V8W 3P5, Canada

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ABSTRACT

Oily discharges from vessel operations have been documented in Canada's Pacific region by the National Aerial Surveillance Program (NASP) since the early 1990s. We explored a number of regression methods to explain the distribution and counts per grid cell of oily discharges detected from 1998 to 2007 using independent predictor variables, while trying to address the large number of zeros present in the data. Best-fit models indicate that discharges are generally concentrated close to shore typically in association with small harbours, and with major commercial and tourist centers. Oily discharges were also concentrated in Barkley Sound and at the entrance of Juan de Fuca Strait. The identification of important factors associated with discharge patterns, and predicting discharge rates in areas with surveillance effort can be used to inform future surveillance. Model output can also be used as inputs for risk models for existing conditions and as baseline for future scenarios.

1. Introduction

Operational oily discharges from vessels are one of the major contributors of oil pollution into the marine environment (GESAMP, 2007), and are a chronic environmental problem particularly to seabird populations worldwide (Camphuysen and Heubeck, 2001; Wiese and Ryan, 2003). Furthermore, the environmental impact of operational discharges is believed to be greater than that of catastrophic accidental events, such as tanker groundings and offshore production blow outs, given the cumulative effects of the constant release of waste oil versus the larger but sporadic accidental oily discharges (Khee-Jin Tan, 2005; Wiese and Ryan, 2003). The estimated global annual amount of oil released into the marine environment from vessel operations (~451,000 tonnes/year) accounts for more than twice the volume of oil released from large accidental spills (~186,000 tonnes/year) (GESAMP, 2007). Pollution from operational discharges is also known as "chronic oil pollution" because of the frequency at which they take place.

The amount and nature of oil discharged during vessel operations often depend upon the type of vessel and the activity being carried out. Traditionally, large ocean-going vessels have been seen as the main vessel type responsible for operational oil discharges, clandestinely discharging oily waste dirty ballast and bilge water as well as waste water from tank washing while navigating away from the coast (GESAMP, 2007). Yet, any motorized vessel (from recreational vessels to cruise ships for example), and human maritime activity involving oil, can contribute to chronic oil pollution (Khee-Jin Tan, 2005). Accidental or intentional oily discharges of waste oil from engine rooms, leaks from propellers and on-deck hydraulics during routine vessel maintenance operations, leaks occurring at reception facilities (i.e., ports) during oil transfer operations, and spills occurring at gas docks or marinas, are all examples of how oil can enter the marine environment (GESAMP, 2007). Hence, chronic oil pollution is expected to be associated with areas dominated by high density of vessel movements and operations, such as designated shipping lanes, busy channels, and ports.

Operational oily discharges have been documented in Canadian waters since the early 1990s by the National Aerial Surveillance Program (NASP), the primary tool available to Transport Canada for monitoring and deterring the discharge of oily waste within Canada's Economic Exclusive Zone (Armstrong and Derouin, 2004). These discharges are generally illegal if they contain a hydrocarbon concentration greater than 15 ppm, as defined by the International Convention for the Prevention of Pollution From Ships (MARPOL 73/78, Annex 1: International Maritime Organization: http://www.imo.org). However, both the National Research Council (2003) and GESAMP (2007) estimate that approximately

* Corresponding author. Address: University of Victoria, PO BOX 3050 STN CSC, Victoria, BC V8W 3P5, Canada. Tel.: +1 250 472 4624; fax: +1 250 721 6216.
E-mail address: normaserra@gmail.ca (N. Serra-Sogas).

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15% of all maritime merchant vessels are not compliant with MARPOL regulations worldwide, which is a significant percentage considering the thousands of vessel that transit the ocean on a yearly basis around the world (Halpern et al., 2008). However, chronic oil pollution can also be associated with other human activities such as tug assisted marine transport, fisheries, and recreational boating. As well, not all illegal discharges contain petroleum oils, and edible oil discharges can be as damaging as discharges of petroleum based oils (McKelvey et al., 1980; Morandin and O'Hara, 2014). For these reasons, and because surveillance programs do not distinguish between edible and non-edible oils, we refer to oil pollution detections as "oily discharges".

One of the biggest challenges of surveillance programs such as the NASP is how to effectively allocate its resources when surveying an enormous area such as Canada's Pacific waters. Additionally, many of the observed oily discharges are identified as mystery spills, meaning that no source can be pinpointed at the time of the detection. This is especially true for oily discharges detected from an aircraft because sampling is difficult, if not impossible, eliminating the possibility of utilizing sophisticated forensic techniques, which are often necessary for a successful prosecution. Detection of oily discharge on the surface of the water is a complex procedure, given that the sources of the discharges tend to be mobile, the available observation window varies widely depending on the weather conditions and sea state (Volckaert et al., 2000), and because vessel operators act clandestinely when intentionally discharging waste oils (Serra-Sogas et al., 2008).

Most previous analyses estimating discharge rates and impacts have focused on larger spills (for example see: Gundlach et al., 1983; Meade et al., 1983; Teal and Howarth, 1984; Piatt et al., 1990; Ketkar and Babu, 1997; Vieites et al., 2004). Although maritime surveillance for oily discharges is increasing globally (for example see: Keramistoglou et al., 2006 [Aegean Sea]; Carpenter, 2007 [Bonn agreement: North Sea]; Ferraro et al., 2007 [Adriatic Sea]; Backer et al., 2010 [HELCOM: Baltic Sea]; Wang et al., 2010 [China]; O'Hara et al., 2013 [Canada]), and although these surveillance systems provide useful data for modeling occurrence and impact of these smaller often unreported spills, there are relatively few studies reporting analytical results based on these data (for example see: Gade and Alpers, 1999; Volckaert et al., 2000; Carpenter, 2007; Ferraro et al., 2007; Serra-Sogas et al., 2008; O'Hara et al. 2013). In this study, we analyzed data collected by the NASP in Canada's Pacific region using regression methods to identify underlying factors that could potentially explain patterns and predict pollution discharge rates in areas with little or no surveillance. With this analysis we aim to shed some light onto the "where and why" of operational oily discharges in Canada's Pacific waters to inform surveillance and enforcement efforts and ultimately reduce the environmental impacts of oily discharges.

We also examine the use of relatively new regression approaches in an attempt to deal with the large number of zeros present in the data that result from observing an event that is rare and difficult to observe. Finally, we hope this research will highlight the importance of collecting accurate oily discharge observations, surveillance effort information and other factors known to affect the probability of detecting oily discharges, to properly model chronic oil pollution not only in western Canadian waters, but in other areas around the world where similar data is being collected.

2. Material and methods

2.1. Study area

The study area (approx. 300,000 km^2) includes almost the entire coastline and marine Economic Exclusive Zone (EEZ) of Canada's west coast and is divided into two regions: Area A and Area B (Fig. 1A). This division was necessary to account for different geographic features (narrow passages in Area B vs. open water in Area A) and maritime uses (e.g., large ocean-going vessels in Area A vs. large ocean-going vessels with small and domestic vessel traffic in Area B), as well as inherent data quality issues in vessel traffic data that were consistent within areas (see below).

Each region was overlaid by a matrix of grid cells to facilitate the aggregation of model variables to the same spatial units. Area A was divided into 10 by 10 km grid cells, and Area B into 3 by 3 km cells. The rationale behind the selection of the two different cell sizes was based on differences in marine vessel traffic monitoring data quality, particularly on differences in positioning frequency between vessels monitored offshore and vessels monitored in internal waters (see Section 2.3 for more information). Most fjords were excluded from the analysis because no shipping traffic data were available at these locations. The offshore limit of Area A (approx. 400 km from British Columbia's mainland) was based on the spatial extent of good quality shipping traffic data and not the Canadian EEZ (Fig. 1A).

Only cells visited at least once by the NASP (38% of the total cells for Area A, and 71% of total cells in Area B) were used to generate the predictive models for both regions. It is important to note that in this study we "predicted" oily discharge probability of occurrence in cells that were both surveyed and not surveyed by the NASP for areas A and B (see Section 2.5).

2.2. Response variable: Number of detected oily discharges

The NASP began surveillance operations in 1994 visually monitoring the Canadian waters in the Pacific region for oil pollution using a Twin Otter 300 (De Havilland DHC-6) aircraft. The Twin Otter aircraft had a maximum flying range of 5 h (K. Pearce, Environment Canada, pers. comm., 2010) and observations were only possible during daylight hours. Each visually observed oily discharge included in this study was identified by NASP flight crew (i.e., pilot, co-pilot, or pollution officer) who also recorded GPS position and time of detection. As mentioned in the introduction, we use the term "oily discharge" as in O'Hara et al. (2013), because not all the observations were verified as petroleum-based, and we made no attempt to differentiate between intentional and accidental discharges.

For this study we use only data collected by the NASP from 1997 to 2007, due to the lack of a continuous temporal dataset before 1997. A total of 328 oily discharge observations were retained for analysis after being temporally associated with a flight path and without location errors. Fig. 1B shows the distribution of oily discharges, where 286 events are found in Area B, and 42 in Area A. Counts of oily discharges per cell were extracted for each area using the grids described above. For Area A oily discharges occupied 3% of the total cells visited by the NASP, while for Area B oily discharges were found in 6% of the total cells with surveillance presence.

2.3. Predictor variables

2.3.1. Surveillance effort

Both oily discharge data and flight path data were provided directly by the NASP. A total of 924 individual flight paths were kept in the final database, after excluding flights with no geospatial information. Based on our observations and in consultation with the NASP pilots, the visual observation swath was estimated, in optimal weather conditions, to extend approximately two kilometers from each side of the aircraft (total swath of 4 km). Total surveillance effort per grid cell was estimated by summing up total area of all flights visiting each of the cells (Fig. 1C). For more