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Modelling Seabird Oil Spill Mortality Using Flight and Swim Behaviour

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Table of Contents

List of Figures

List of Tables

Summary

Petroleum exploration and production has increased dramatically on Canada's east coast since the 1970s, particularly on the Grand Banks. The Grand Banks is home to a rich assemblage of seabirds, increasing the potential for seabird mortality from accidental spills. In November 2004, roughly 1,000 barrels of crude oil were released at the Terra Nova oil field on the northeast Grand Banks. A subsequent estimate of seabirds at risk from this spill (Wilhelm et al. 2007) highlighted a number of knowledge gaps that impacted mortality estimation. There was a lack of extensive and timely seabird density information and a lack of understanding of the relative oiling risk for seabirds in flight. Wilhelm et al. (2007) employed three different risk factors for seabirds in flight and estimated that between 1,975 and 8,755 murres (*Uria spp.*), and between 0 and 22,418 Dovekies (*Alle alle*) were at risk of oiling during the 2004 spill.

The intention of this project was to improve our ability to predict spill impacts by modelling seabird mortality taking seabird density and behaviour, as well as spill size into account. We achieved three main goals: (1) create a model that simulates seabird movement in relation to a simulated oil slick, (2) collect information on murre flight and swimming activity at sea on their wintering grounds using electronic data loggers, and (3) use this information as input for the model to predict murre mortality, and then validate the results using mortality estimates from the 2004 Terra Nova spill.

The seabird oiling model produced an estimate of 5,987 (95% CI of 1,421 to 10,952) murres killed during the 2004 spill. We conclude that the seabird oiling model produced a more scientifically credible mortality estimate than was previously available, as no assumptions about risk of oiling to murres in flight were needed. Further improvement could be achieved by integrating better seabird movement models, more precise seabird density estimates from at-sea surveys, and more complex oil spill trajectory and fate models, and by extending the analysis to more species, especially the Dovekie.

Sommaire

L'exploration et la production de pétrole ont augmenté de manière marquée sur la côte est du Canada depuis les années 1970, surtout dans la région des Grands bancs. Un grand nombre d'espèces d’oiseaux marin vivent dans la région des Grands bancs, ce qui augmente la possibilité de mortalité des oiseaux marin par suite de déversements accidentels de pétrole. En novembre 2004, environ 1 000 barils de pétrole brut ont été déversés autour du champ de pétrole de Terra Nova dans la région nord-est des Grands bancs. Une estimation des oiseaux marin à risque par suite de ce déversement (Wilhelm et coll. 2007) a mis en évidence un certain nombre de lacunes qui ont eu une incidence sur l'estimation de la mortalité. On a mis en évidence l'absence de renseignements suffisants et en temps opportun sur la densité des oiseaux marin et le manque de compréhension du risque relatif de mazoutage pour les oiseaux de mer en vol. Wilhelm et coll. (2007) ont utilisé trois facteurs de risque différents pour les oiseaux de mer en vol et ont estimé qu'entre 1 975 et 8 755 guillemots (*Uria spp.*) et entre 0 et 22 418 mergules nains (*Alle alle*) ont fait face au risque de mazoutage pendant le déversement de 2004.

Ce projet vise à améliorer notre capacité de prévoir les conséquences d’un déversement en créant un modèle pour déterminer la mortalité des oiseaux marin qui tient compte de la densité et du comportement des oiseaux marin et de l'ampleur du déversement. Nous avons atteint trois objectifs principaux : (1) créer un modèle qui permet de simuler les mouvements des oiseaux marin par rapport à une nappe d’hydrocarbures simulée, (2) obtenir des renseignements sur les activités de vol et de nage des guillemots dans les aires d’hivernage en utilisant des enregistreurs de données électroniques et (3) intégrer ces renseignements dans le modèle pour prévoir la mortalité des guillemots et ensuite valider les résultats en utilisant les estimations de la mortalité du déversement survenu à Terra Nova en 2004.

Le modèle pour déterminer le mazoutage des oiseaux marin a indiqué que 5 987 (95 % CI de 1 421 à 10 952) sont morts pendant le déversement de 2004. Nous avons conclu que le modèle pour déterminer le mazoutage des oiseaux marin a permis d’obtenir une estimation de la mortalité plus valide sur le plan scientifique par rapport aux estimations disponibles puisqu’il n'a pas été nécessaire de formuler des hypothèses sur le risque de mazoutage pour les guillemots en vol. On pourrait améliorer davantage le modèle en intégrant des modèles plus précis des mouvements des oiseaux de mer, des estimations plus précises de la densité des oiseaux marin obtenues des enquêtes en mer et des modèles plus complexes de la trajectoire de la nappe d’hydrocarbures et en analysant d’autres espèces, surtout les mergules nains.

1 Introduction

Offshore petroleum exploration and production activities have been ongoing on the Grand Banks and Scotian Shelf since the 1970s. Subsequently, the number of production and exploration licences as well as significant discoveries within these regions have increased. In Newfoundland and Labrador, there are current production and/or exploration licences for portions of the northern Grand Banks, Orphan Basin, Flemish Pass, Laurentian Sub-Basin, Sydney Basin, west coast of Newfoundland and the Labrador Shelf (Figure 1). In Nova Scotia, licences exist on the Scotian Shelf near Sable Island, the Scotian Slope and on much of the Canadian section of Georges Bank (Figure 2). The activities related to oil exploration, development and associated marine traffic in areas frequented by seabirds increase the potential for seabird mortality due to accidental release of hydrocarbons. Consequently, there is a critical need to monitor seabirds at sea to ensure associated impacts are properly quantified and potentially mitigated.

As a nutrient rich ecosystem, the Grand Banks are home to a diverse assemblage of seabirds. An estimated 30 million seabirds utilize Eastern Canadian waters each year and up to 10 million murres winter on the Grand Banks (Lock et al. 1994). In comparison to other seabirds, alcids - the family which includes murres (*Uria* spp.) and dovekies (*Alle alle*) - are highly vulnerable to oil pollution (Wiese and Ryan 2003). They have proportionally small wings for their weight (Spear and Ainley 1997a) and therefore spend much time on the water, making them particularly vulnerable. In the late 1990s, approximately 300,000 birds died off the coast of Newfoundland each year as a result of chronic oil pollution caused by illegal dumping by passing vessels; 67% of these birds were thick-billed murres (*Uria lomvia*) (Wiese and Robertson 2004). Murres, like other alcids, are sensitive to anthropogenic disturbances because of their life history strategies, which include delayed maturity and low fecundity; this means their populations are slow to recover from losses. Murres wintering off Newfoundland and Labrador are also the target of hunting and are caught as by-catch in commercial fisheries (Chardine et al. 2008; Benjamins et al. 2008; Piatt and Nettleship 1987). It is estimated that between 160,000 and 190,000 murres are taken in the annual hunt (Chardine et al. 2008), and another 5,000 to 10,000 are caught in gill-nets (Benjamins et al. 2008). These factors place the murres among the groups of species of greatest concern when assessing the effects of oil spills on seabirds in Newfoundland waters.

Despite their vulnerability and much research, predicting the impacts of accidental oil releases on seabird populations remains a difficult task (French-McKay 2009; Burger 1993). During the spill from the Terra Nova Floating Production, Storage, and Offloading (FSPO) vessel, oil was visible on the water for approximately six days, during which time it changed position and size daily. Wilhelm (2007) estimated that during these six days, the spill swept an area of 793 km^2. This enabled them to produce an estimate of seabirds at risk of oiling by multiplying densities of birds in air and on water by the area swept by the spill (Schneider 2002). They compared this estimate to a mortality estimate based on spill volume. Many knowledge gaps were identified during the assessment of seabird mortality from the spill (Wilhelm et al. 2007). They were potentially limited by (1) the assumption that no birds from outside the immediate spill area flew into the spill, (2) the inability to predict what proportion of birds flying within the spill area would land and become oiled, (3) the assumption that all birds in oil-free patches within the spill area would eventually become oiled, and 4) a lack of extensive detection-corrected seabird density data.

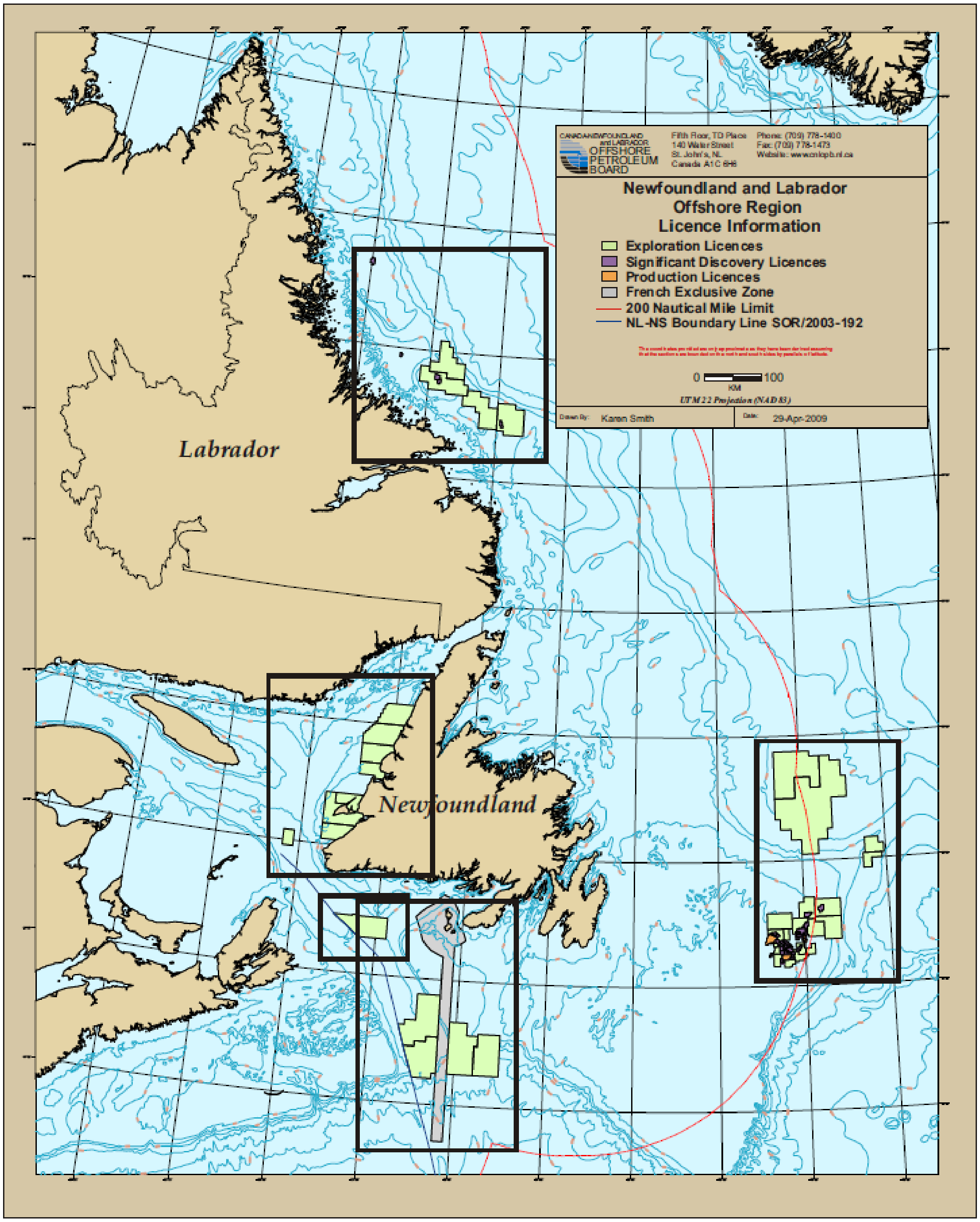


Figure 1. Offshore Newfoundland and Labrador petroleum licenses 2009 (*http://www.cnlopb.nl.ca/maps/onl_2009.pdf*).

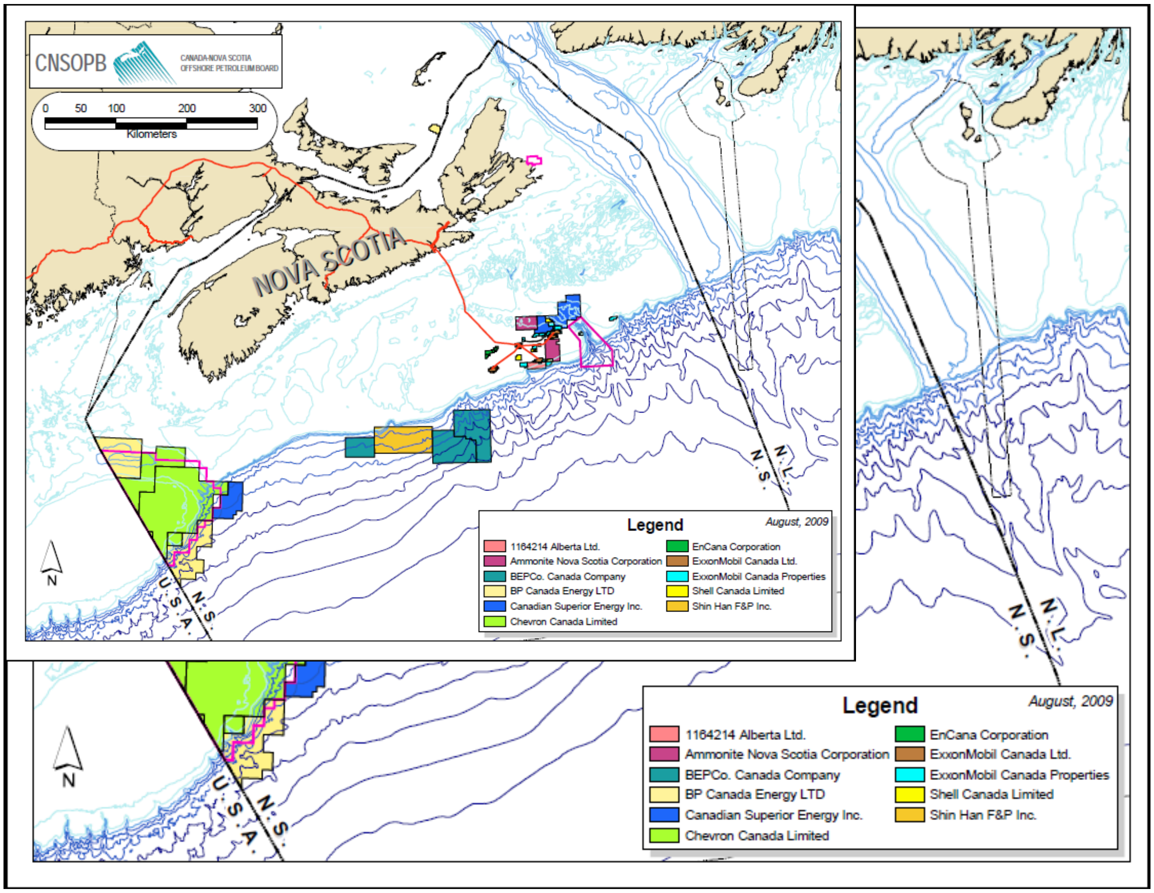


Figure 2. Offshore Nova Scotia Petroleum Exploration Licences, 2009 (*http://www.cnsopb.ns.ca/pdfs/web_map_full_size.pdf*)

Wilhelm et al. (2007) assumed that all birds on water within the spill area were at risk of being oiled and then considered 3 scenarios for flying birds (no flying birds at risk, ½ flying birds at risk, all flying birds at risk), leading them to estimate that between 1,975 and 31,173 murres and dovekies were at risk of oiling. The estimated number of murres at risk was between 1,975 and 8,755 birds. This estimate could be more scientifically defensible by (1) employing at-sea density estimates from more extensive surveys that take detection probability into account, (2) collecting information on seabird flight behaviour at sea, and (3) incorporating both of these into an oiling model that predicts seabird mortality based on seabird movement over the life of the spill.

Since 2006, extensive at-sea surveys sponsored by the ESRF and the Canadian Wildlife Service's (CWS) Eastern Canada Seabird At Sea (ECSAS) program have been conducted in the vicinity of the northeast Grand Banks production area. These surveys employ a modern protocol that includes distance sampling to account for varying seabird detectability (Gjerdrum et al. 2010; Buckland et al. 2001). Data from these surveys was analyzed recently as part of the final report for the ESRF Offshore Seabird Monitoring Project, making new density estimates available (Fifield et al. 2009).

The ability to address the question of how seabirds use their marine environment has improved recently due to the development of bird-borne microelectronic geolocators that record activity and rough position. In the past several years, these devices have been used effectively to study migration patterns and habitat usage in a variety of species (Stutchbury et al. 2009; Kubetzki et al. 2009; Shaffer et al. 2006). With daily time budget information summarizing how seabirds allocate their time on the water and on the wing, impact models can be better refined and ultimately lead to more scientifically credible estimates of the number of birds at risk from an oil spill.

In this study, we employed geolocators to quantify the at-sea flight and swimming behaviour of common (*Uria aalge*) and thick-billed murres in order to increase the confidence in model predictions of seabird mortality from offshore oil spills. We attempted to achieve three main goals: (1) create a simple seabird oiling model which incorporates seabird density and behaviour to estimate oil spill mortality, (2) determine overall trends and variability in flight and swim activity of murres, and (3) validate the model by combining murre activity data and at-sea density estimates to model an estimate of murre mortality during the November 2004 Terra Nova spill and compare this estimate with the estimates of birds at risk and the mortality estimate in Wilhelm et al. (2007).

2 Methods

2.1 Seabird Oiling Model

The ultimate goal of the project was to create a seabird oiling model. Specified model inputs included spill date, position, size, and duration, bird density, initial proportion of birds in flight, and flight and swim behaviour. Summary statistics on mortality rates and affected areas were to be produced. The model needed to be flexible yet simple to use and run on a variety of computer platforms.

2.2 Murre Winter Behaviour

The Canadian Wildlife Service (CWS)-Atlantic Region collaborated with researchers from other Environment Canada regions, Memorial University, and the University of Winnipeg to study murre behaviour at sea as part of a larger study on migration and over-wintering ecology. The study was carried out on murres from three colonies in Newfoundland and Labrador, and four in the Canadian Arctic (Figure 3).

Geolocators manufactured by the British Antarctic Survey were used to investigate murre behaviour. These featured two gold contacts that acted as a wet/dry switch, differentiating flight from periods on water. Three models that recorded activity at one of two levels of precision were used. Mk7 “fine-scale” devices weighed 3.6 g (about 0.4% of the mass of an adult thick-billed murre) had a temporal resolution of 3 seconds and recorded every period of wet and dry that was ≥ 6 seconds in duration (Figure 4). The Mk5 and the smaller Mk13 were “coarse-scale” devices that weighed 3.6 g and 1.8 g respectively. These recorded the number of 3-second samples that were wet at 10-minute intervals – thus these would be able to give a percentage of time in flight for each 10-minute period. All models recorded the maximal light value every 10 minutes which was used to ascertain day length and sunrise/sunset. Day length from these light level data provides an estimate of latitude, and time of local noon/midnight (calculated from local sunrise/sunset times) provides an estimate of longitude (Hill 1994).

No information on murre winter flight durations was available to guide the choice of an appropriate device. Fine-scale devices would provide the best temporal resolution, but device memory might be exhausted before birds even reached their wintering grounds. Coarse-scale devices would likely last through the winter, but would limit the temporal scale of the analysis. A hybrid scheme was chosen and 65 devices (25 fine-scale and 40 coarse-scale) were procured and deployed on murres for the winter of 2007-2008. During 2008-2009, 120 devices were purchased by collaborators as part of the larger study, and 30 were redeployed from the previous year. Of these, 31 were fine-scale and 119 were coarse-scale devices. Devices for the second year needed to be procured in advance of the field season to ensure they were available for deployment at the colony in 2008 when the first-year devices were being retrieved. This meant that no data from the first year of deployment was available to guide device selection for the second year. Coarse-scale devices thus predominated in the second year due to the availability of the newer, smaller Mk13 favoured by collaborators for the larger study.

Subsequent analysis of fine-scale devices indicated that typical murre flight durations were less than 10 minutes and that the fine-scale Mk7 devices had recorded the entire winter's activity. A total of 22 fine-scale datasets (11 for each year) were used for behavioural analysis (Table 1). Given the lack of large-scale variability in the flight time distributions across species, years, and sites (see Section 3.2), these 22 birds provided abundant data for our purposes. While the data from the Mk5 and Mk13 coarse-scale devices was not used for this report, it was used as part of the much larger study on migration and over-wintering ecology (Hedd et al. 2011; Gaston et al. 2011).

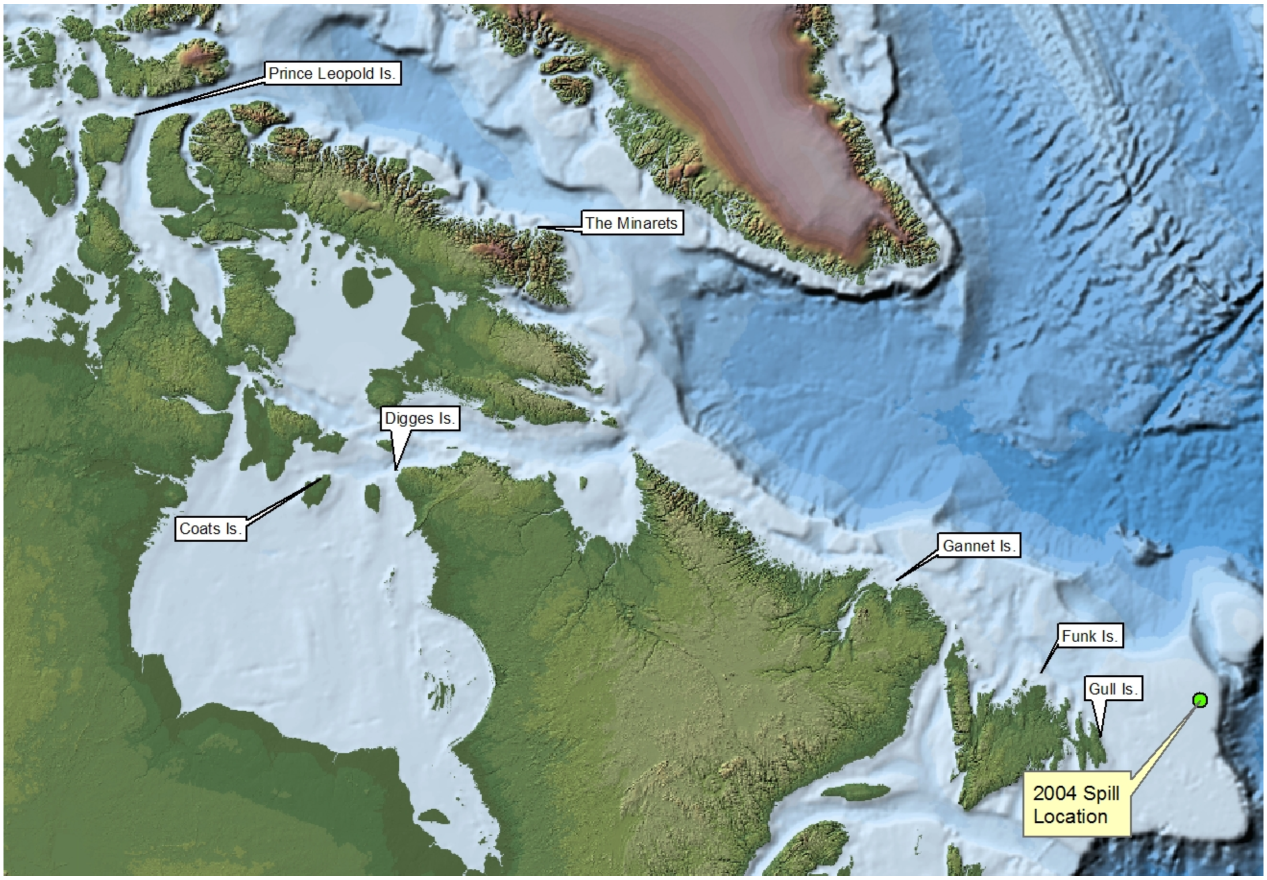


Figure 3. Map showing locations of colonies where geolocators were deployed and the location of the 2004 Terra Nova spill.

Table 1. Geolocator deployments and retrievals in 2007 – 2009. Shaded rows indicate devices analyzed for this report (Mk7).

Species	**Site**	**Deployment Year**	**Device Model**	**Number Deployed**	**Datasets Retrieved**	**Device Numbers**
Common Murre	Funk Is, Newfoundland	2007–2008	Mk5	14	7	
Common Murre	Funk Is, Newfoundland	2007–2008	Mk7	6	2	4234, 4240
Common Murre	Funk Is, Newfoundland	2008–2009	Mk5	5	0	
Common Murre	Funk Is, Newfoundland	2008–2009	Mk7	5	0	
Common Murre	Funk Is, Newfoundland	2008–2009	Mk13	10	0	
Common Murre	Gull Is, Newfoundland	2007–2008	M7	5	0	
Common Murre	Gull Is, Newfoundland	2008–2009	Mk5	10	2	
Common Murre	Gull Is, Newfoundland	2008–2009	Mk7	5	2	4408, 4412
Common Murre	Gull Is, Newfoundland	2008–2009	Mk13	10	1	
Common Murre	Gannet Is, Labrador	2008–2009	Mk5	5	3	
Common Murre	Gannet Is, Labrador	2008–2009	Mk7	3	2	4410, 4411
Common Murre	Gannet Is, Labrador	2008–2009	Mk13	8	5	
Thick-billed Murre	Gannet Is, Labrador	2008–2009	Mk5	5	4	
Thick-billed Murre	Gannet Is, Labrador	2008–2009	Mk7	2	1	4406
Thick-billed Murre	Gannet Is, Labrador	2008–2009	Mk13	7	2	
Thick-billed Murre	Coats Is, NU	2007–2008	Mk5	13	13	
Thick-billed Murre	Coats Is, NU	2007–2008	Mk7	7	5	4236, 4239, 4247, 4252, 4256
Thick-billed Murre	Coats Is, NU	2008–2009	Mk5	5	3	
Thick-billed Murre	Coats Is, NU	2008–2009	Mk7	5	2	4397, 4416
Thick-billed Murre	Coats Is, NU	2008–2009	Mk13	10	5	
Thick-billed Murre	Minarets, NU	2007–2008	Mk5	13	10	
Thick-billed Murre	Minarets, NU	2007–2008	Mk7	7	4	4241, 4243, 4253, 4254
Thick-billed Murre	Digges Is, NU	2008–2009	Mk5	22	7	
Thick-billed Murre	Digges Is, NU	2008–2009	Mk7	9	0	
Thick-billed Murre	Prince Leopold Is, NU	2008–2009	Mk5	10	8	
Thick-billed Murre	Prince Leopold Is, NU	2008–2009	Mk7	5	4	4355, 4404, 4405, 4413
Thick-billed Murre	Prince Leopold Is, NU	2008–2009	Mk13	9	2	

Figure 4. Thick-billed murre (*Uria lomvia*) on the Gannet Islands equipped with an Mk5/Mk7 style geolocator manufactured by the British Antarctic Survey.

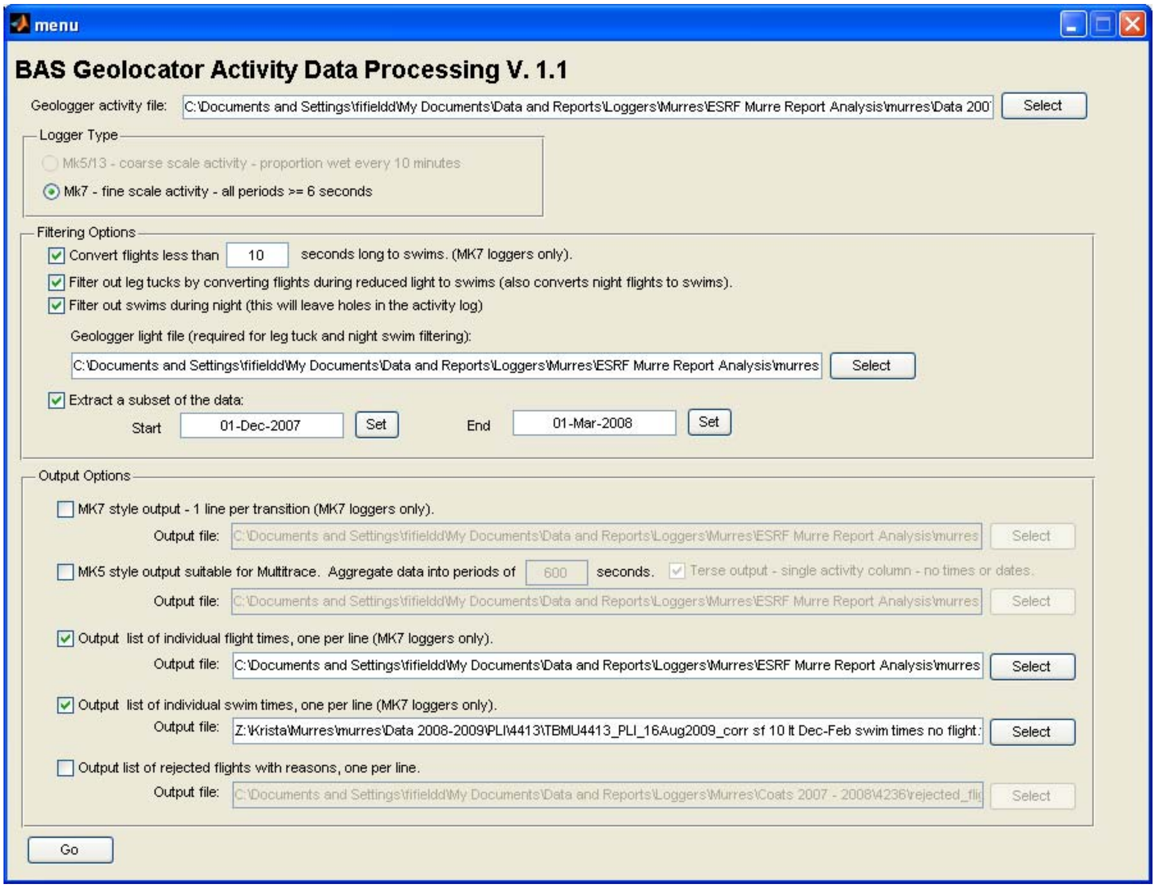
2.2.1 *Data Extraction and Filtering*

All devices were ground-truthed (for positional accuracy) prior to deployment at a known location. MultiTrace software (Jensen Software Systems) was used to generate twice-daily positions for the deployment period and maps were inspected to ascertain periods of residency on wintering grounds. Inspection of the wet/dry switch data showed long periods (i.e. many hours) of dry during the night.

It is extremely unlikely that these were periods of flight, but were caused instead by murres tucking their legs into their feathers for warmth during long periods on the water. Several lines of evidence strongly support this conclusion and are discussed in Section 4.2. This raised the question of whether all daytime dry periods were actually flights or were some related to leg-tucking as well? Examination of the activity data revealed that some daytime “flights” coincided with a temporary drop in light level. The light sensor in these devices is very sensitive and registers full-scale at the dim light levels that typically surround a leg dangling in the water. Murres fly with legs extended, so if these periods were flight, there would not be a drop in light level. Instead, these daytime dry periods with attenuated light levels were indicative of periods of leg-tucking while on the water.

Based on these observations, activity data were filtered using a software tool constructed in Matlab v.7 (The Mathworks, Inc.) (Figure 5). All dry periods that were accompanied by a drop in light level (and those at night) were reassigned as time on water (hereafter called “swims”) and merged with temporally adjacent swim periods. After filtering for leg-tucking, a large number of very short dry periods remained; many as brief as 6 seconds, the device’s minimum recording period. These were likely caused by device exposure to air when birds rolled onto their sides to preen or by leg tucks that were too brief to affect the light record. To account for this, all dry periods of less than 10-seconds duration were converted to time on the water.

Frequency distributions and summary statistics for daytime flight and swim times for each bird and the total population combined were produced. These were inspected for differences between individuals, species and colonies, and were ultimately combined into a single data set for input to the oiling model.



BAS Geolocator Activity Data Processing V. 1.1

Geologger activity file: C:\Documents and Settings\fifieldd\My Documents\Data and Reports\Loggers\Murres\ESRF Murre Report Analysis\murres\Data 200

Logger Type

○ Mk5/13 - coarse scale activity - proportion wet every 10 minutes

● Mk7 - fine scale activity - all periods >= 6 seconds

Filtering Options

☑ Convert flights less than 10 seconds long to swims. (MK7 loggers only).

☑ Filter out leg tucks by converting flights during reduced light to swims (also converts night flights to swims).

☑ Filter out swims during night (this will leave holes in the activity log)

Geologger light file (required for leg tuck and night swim filtering):

C:\Documents and Settings\fifieldd\My Documents\Data and Reports\Loggers\Murres\ESRF Murre Report Analysis\murres

☑ Extract a subset of the data:

Start 01-Dec-2007 End 01-Mar-2008

Output Options

☐ MK7 style output - 1 line per transition (MK7 loggers only).

Output file: C:\Documents and Settings\fifieldd\My Documents\Data and Reports\Loggers\Murres\ESRF Murre Report Analysis\murres

☐ MK5 style output suitable for Multitrace. Aggregate data into periods of 600 seconds. ☑ Terse output - single activity column - no times or dates.

Output file: C:\Documents and Settings\fifieldd\My Documents\Data and Reports\Loggers\Murres\ESRF Murre Report Analysis\murres

☑ Output list of individual flight times, one per line (MK7 loggers only).

Output file: C:\Documents and Settings\fifieldd\My Documents\Data and Reports\Loggers\Murres\ESRF Murre Report Analysis\murres

☑ Output list of individual swim times, one per line (MK7 loggers only).

Output file: Z:\Krista\Murres\murres\Data 2008-2009\PLI\4413\TBMU4413_PLI_16Aug2009_corr sf 10 lt Dec-Feb swim times no flight:

☐ Output list of rejected flights with reasons, one per line.

Output file: C:\Documents and Settings\fifieldd\My Documents\Data and Reports\Loggers\Murres\Coats 2007 - 2008\4236\rejected_fli

Figure 5. Screenshot of Matlab software created for activity extraction and filtering.

2.3 *Terra Nova Spill Mortality Estimate*

The seabird oiling model was validated by employing it to estimate murre mortality during the 2004 Terra Nova spill, using flight and swim behaviour extracted from geolocators and the parameters listed in Table 2. A small number of preliminary simulations were run over a 1,000 x 1,000 km area to investigate the appropriate scale of analysis, which led to the selection of a 400 x 400 km simulation area (see Section 3.3 for details). Estimates of the spill surface area during the six days that oil was visible on the water ranged up to 50 km^2, and this value was used to estimate an upper bound on the number of oiled murres.

Two murre density scenarios were modelled. First, a murre density estimate based on surveys conducted at the time of the spill was used (Wilhelm et al. 2007). Estimates for murres on water (3.46 ± 0.49 birds/km^2) and in flight (3.44 ± 1.62 birds/km^2) were summed to obtain

6.90 ± 1.69 birds/km^2. Second, a more recent winter (Nov. – Feb.) murre density estimate of 6.65 ± 2.83 birds/km^2 was obtained from at-sea surveys (2006 – 2009) supported by the ESRF and the ECSAS program (Fifield et al. 2009). For each scenario, 1,000 model runs were executed, each simulating a six-day period. Summary statistics for the estimated number of birds oiled, populations size, and affected area were produced.

2.4 *Effect of Spill Size*

The effect of spill size on murre mortality was also investigated. The model was run 50 times each for spills of 10, 25, 50, 100, 250 and 500 km^2 with a murre density of 6.65 birds/km^2. A 30 day trial was also run to investigate the change in oiling rates over time for a 50 km^2 spill with a density of 6.65 birds/km^2.

Table 2. List of parameters that are adjustable within the model and values used in simulations.

Parameter	**2004 Density Estimate**	**2009 Density Estimate**
Bird density (birds/km^2)	6.90	6.65
Bird density standard deviation	1.69	2.83
Initial proportion in flight	0.499	0.451
Longitude of simulation area centre (decimal degrees)	48.4	48.4
Latitude of simulation area centre (decimal degrees)	46.4	46.4
East-west size of simulation area (km)	400	400
North-south size of simulation area (km)	400	400
Centre of oil slick along east-west axis (km)	200	200
Centre of oil slick along north-south axis (km)	200	200
Oil slick radius (km)	3.9894 (50 km^2)	3.9894 (50 km^2)
Flight speed (km/hr)	65.0	65.0
Start date and time (UTC)	2004/11/21 10:30:00	2004/11/21 10:30:00
Number of simulation trials	1000	1000
Simulation time (hr)	144 (6 days)	144 (6 days)

3 Results

3.1 *Seabird Oiling Model*

A model was created to estimate the number of birds oiled during a spill. The model was implemented using the Java programming language because of its cross-platform compatibility and was tested under Windows XP and Linux using the Java Runtime Environment version 1.6. This section provides a generic description of the model operation, while Section 3.3 provides an example of its use.

During a model run, a simulation area of specified dimensions is created and a circular oil slick of a specified radius is placed at a given location. In the current implementation, the oil slick remains stationary during the simulation and the oil is assumed to be uniformly dispersed on the surface within the circle. The dimensions of the simulation space are specified by the user, and must be large enough not to unduly limit the maximum distance from which birds might arrive during the simulated time frame. These dimensions can be based on modelling experience and knowledge of the distribution, as well as flight speed and behaviour of the species of interest, if known. Additionally, the size of the simulation space can be guided by experimentation; a number of test simulations with varying dimensions can be run to investigate the distance from which birds originate before eventually becoming oiled.

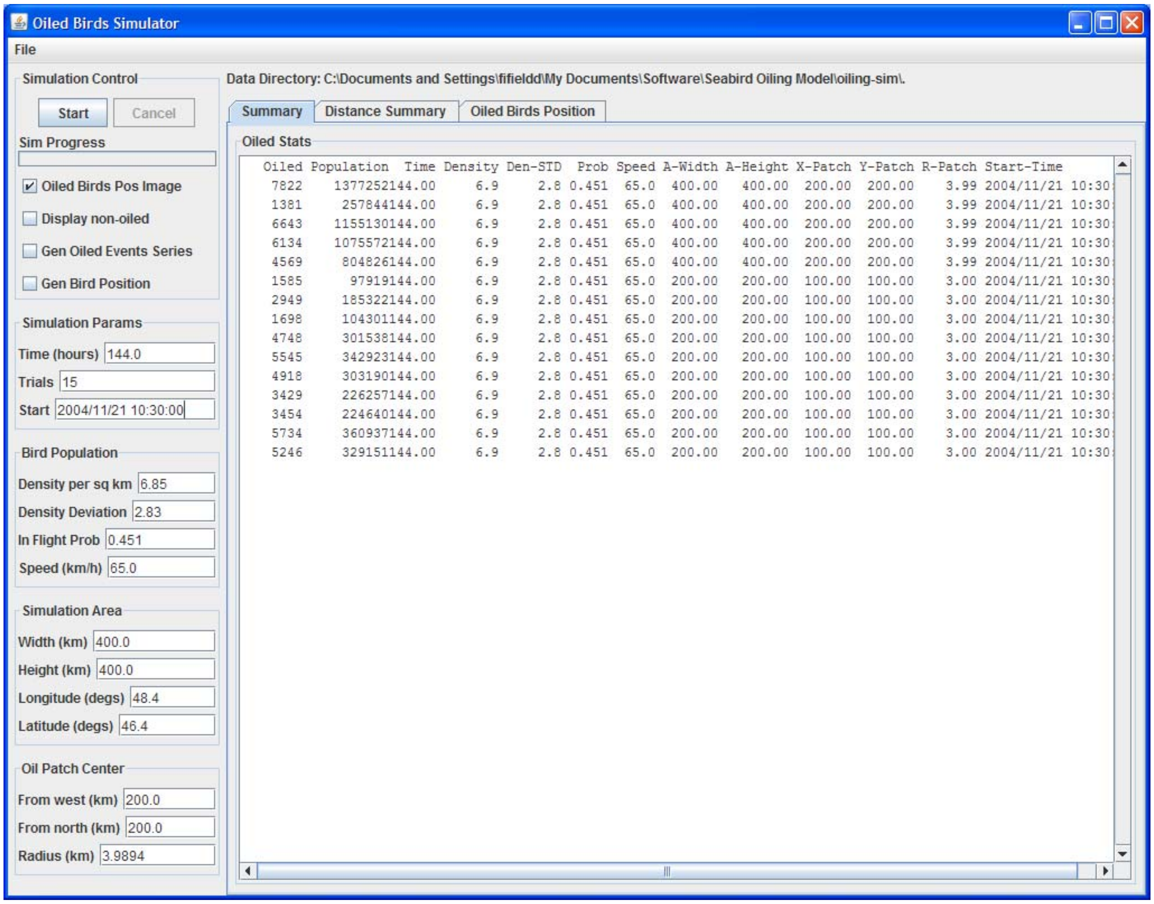
Before the start of each simulation run, the program randomly places birds in the simulation area. The number of birds initially placed depends on the density of birds requested and the size of the area. Bird density is specified by a mean ± SD (allowing uncertainty in density to be taken into account), and the specific density for each model run is drawn from a normal distribution with this mean and standard deviation. These density parameters can be estimated from surveys at sea during a spill, or (preferably) from an at-sea monitoring program in place before any spill takes place. The initial proportion of birds in flight and on water is adjustable and should be based on at-sea observation data.

The model proceeds for a user-specified time period during which it moves birds around the simulation area. Birds are moved through a series of simulated flights interspersed by time on the water. The length of each flight or swim period is randomly drawn from a list of representative flight and swim times provided to the model. For the example described in Section 3.3, flight and swim times were extracted from geolocator data (see Section 3.2). Flight speed is specified by the user, and direction for each flight is drawn randomly (i.e. the birds follow a random walk; Kareiva and Shigesada 1983). If a bird lands within the area covered by oil, it is considered to be dead.

The simulation area is a closed space; i.e. birds neither leave nor enter the area during the simulation. Yet, in the real world, birds at the periphery likely fly out of the area and other birds fly into the area from the outside. Over time, the number of birds entering the area from the outside would equal the number leaving, assuming that the study area neither attracts nor repels them. The model takes this into account simply by having birds that leave the simulation area immediately re-enter at the same location. In the current implementation, swimming birds are considered stationary. Since the model was designed with murre behaviour in mind, birds are assumed to be on the water at night and flying birds are forced to land at sunset (see discussion in Section 4.2.2). Daylight period is calculated based on the time of sunrise and sunset at the centre of the simulation area on the simulation date.

A number of statistical and graphical outputs can be produced for any of the individual model runs. Statistics include the initial population size, the number of oiled birds, and the distance from original positions to the point of oiling. The latter is useful to illustrate the “area of influence” of the spill and can be shown as a map. A graph showing the number of oiled birds as a function of time is optionally produced. Summary statistics for all runs combined include the number of oiled birds and distance from start positions to oiling.

A graphical user interface is provided that facilitates the modification of various parameters and displays the results (Figure 6). Parameters can be adjusted to adapt the model to various species, changing conditions, increasing knowledge, and/or different output needs (Table 2).



☑ Oiled Birds Pos Image

☐ Display non-oiled

☐ Gen Oiled Events Series

☐ Gen Bird Position

Simulation Params

Time (hours) 144.0

Trials 15

Start 2004/11/21 10:30:00

Bird Population

Density per sq km 6.85

Density Deviation 2.83

In Flight Prob 0.451

Speed (km/h) 65.0

Simulation Area

Width (km) 400.0

Height (km) 400.0

Longitude (degs) 48.4

Latitude (degs) 46.4

Oil Patch Center

From west (km) 200.0

From north (km) 200.0

Radius (km) 3.9894

Data Directory: C:\Documents and Settings\fifieldd\My Documents\Software\Seabird Oiling Model\oiling-sim\.

```
 Oiled Population  Time Density Den-STD  Prob Speed A-Width A-Height X-Patch Y-Patch R-Patch Start-Time
  7822   1377252144.00     6.9     2.8 0.451  65.0  400.00   400.00  200.00  200.00    3.99 2004/11/21 10:30
  1381    257844144.00     6.9     2.8 0.451  65.0  400.00   400.00  200.00  200.00    3.99 2004/11/21 10:30
  6643   1155130144.00     6.9     2.8 0.451  65.0  400.00   400.00  200.00  200.00    3.99 2004/11/21 10:30
  6134   1075572144.00     6.9     2.8 0.451  65.0  400.00   400.00  200.00  200.00    3.99 2004/11/21 10:30
  4569    804826144.00     6.9     2.8 0.451  65.0  400.00   400.00  200.00  200.00    3.99 2004/11/21 10:30
  1585     97919144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
  2949    185322144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
  1698    104301144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
  4748    301538144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
  5545    342923144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
  4918    303190144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
  3429    226257144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
  3454    224640144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
  5734    360937144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
  5246    329151144.00     6.9     2.8 0.451  65.0  200.00   200.00  100.00  100.00    3.00 2004/11/21 10:30
```

Figure 6. User interface for the seabird oiling model showing a summary of 15 model runs.

3.2 Murre Winter Behaviour

Visual inspection of the maps for each bird (see Figure 7 for an example) revealed that murres over-wintered on the Grand Banks, on the Labrador Shelf, in the Labrador Sea, and along the west coast of Greenland. All birds reached their over-winter areas by December and stayed until at least February.

3.2.1 Flight Behaviour

A total of 13,255 flights were recorded between December and February during the winters of 2007-2008 and 2008-2009 (Table 3). The majority of flights were relatively short (Figure 8). The mean flight time was ~ 4 mins with a median of only ~ 2 mins, and flights longer than 1 hr were rare (n = 23 of 13,255). At an average flight speed of 65 km/h, this equates to mean and median per-flight distances of 4.3 and 2.2 km respectively. The maximum flight duration was 297.5 mins (~ 5 hrs) and was recorded on February 6, 2009 by a thick-billed murre from the Gannet Islands.

Although the results varied slightly between individuals, they all followed the trend illustrated in Figure 8; a predominance of short flights and very few long flights. There were no differences detected between years, species, or breeding sites. The flight durations also did not change during the winter (see Figure 9 for an example). Flight duration frequency distributions for individual murres can be found in Appendix 1.

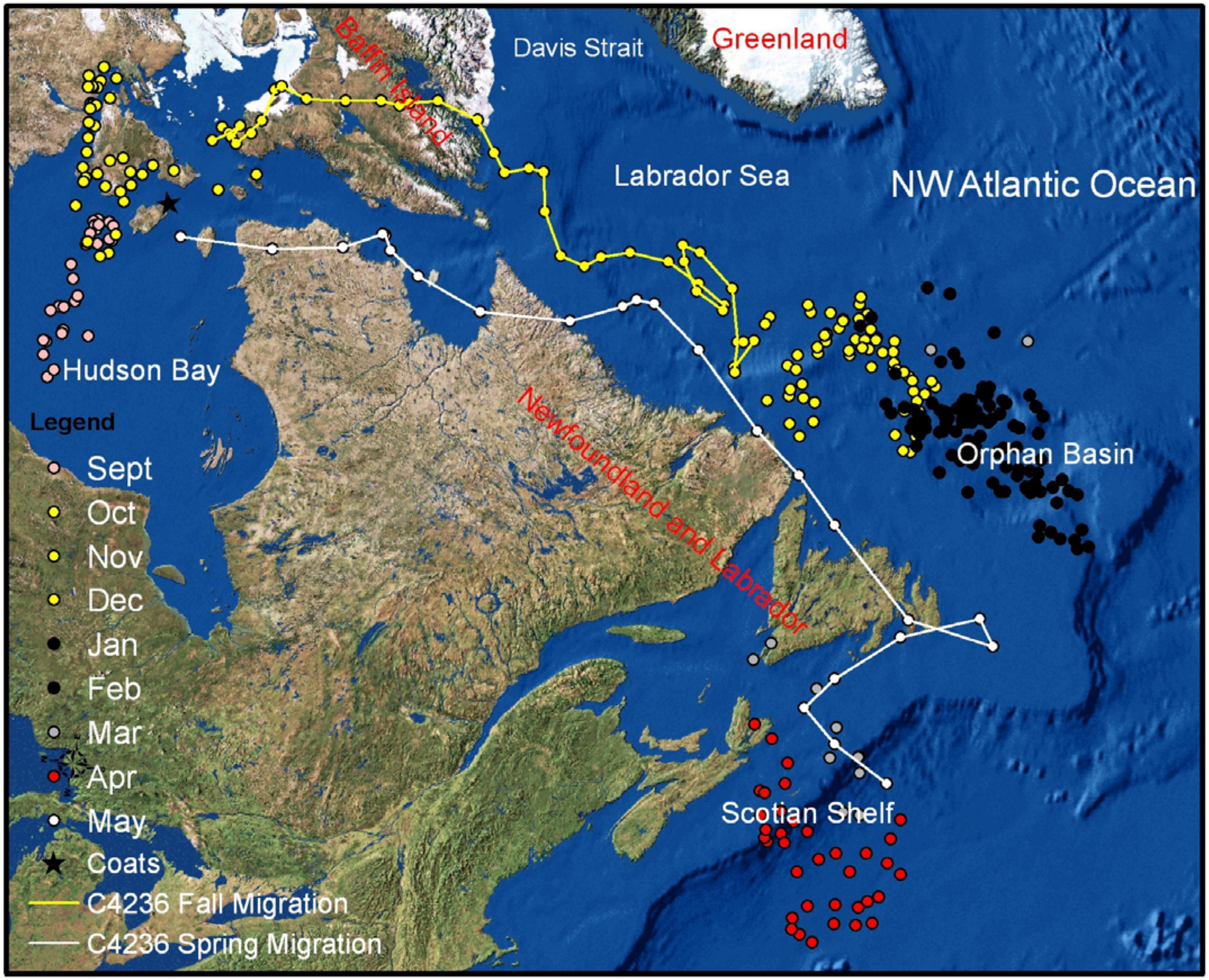


Figure 7. Example map of a thick-billed murre (*Uria lomvia*) (number 4236) showing migration routes and winter residency on the southern Labrador Shelf and Orphan Basin

Table 3. Summary of flight durations recorded by geolocators deployed on thick-billed (*Uria lomvia*) and common (*U. aalge*) murres between December and February, 2007-2009

Individual	**n**	**Mean Flight Duration (min)**	**Median Flight Duration (min)**	**Maximum Flight Duration (min)**
4234	812	4.1	2.4	49.6
4236	465	4.3	3.1	37.0
4239	489	3.2	2.1	42.1
4240	238	2.8	0.7	47.9
4241	526	3.4	2.1	32.5
4243	535	2.6	0.8	102.7
4247	658	4.4	2.9	67.8
4252	346	4.9	2.5	80.7
4253	716	2.7	1.1	70.5
4254	498	2.7	0.6	40.6
4256	577	4.0	2.5	44.6
4355	175	3.4	1.9	26.7
4397	673	4.5	3.2	40.3
4404	824	3.0	1.7	93.8
4405	366	4.7	3.1	31.8
4406	539	6.5	2.5	297.5
4408	1,104	3.2	1.3	131.5
4410	1,455	4.4	1.1	84.8
4411	774	4.7	5.7	64.8
4412	422	4.0	3.1	21.8
4413	610	4.2	2.7	37.6
4416	453	5.9	3.9	46.7
All birds combined	13,255	4.0	2.1	297.5

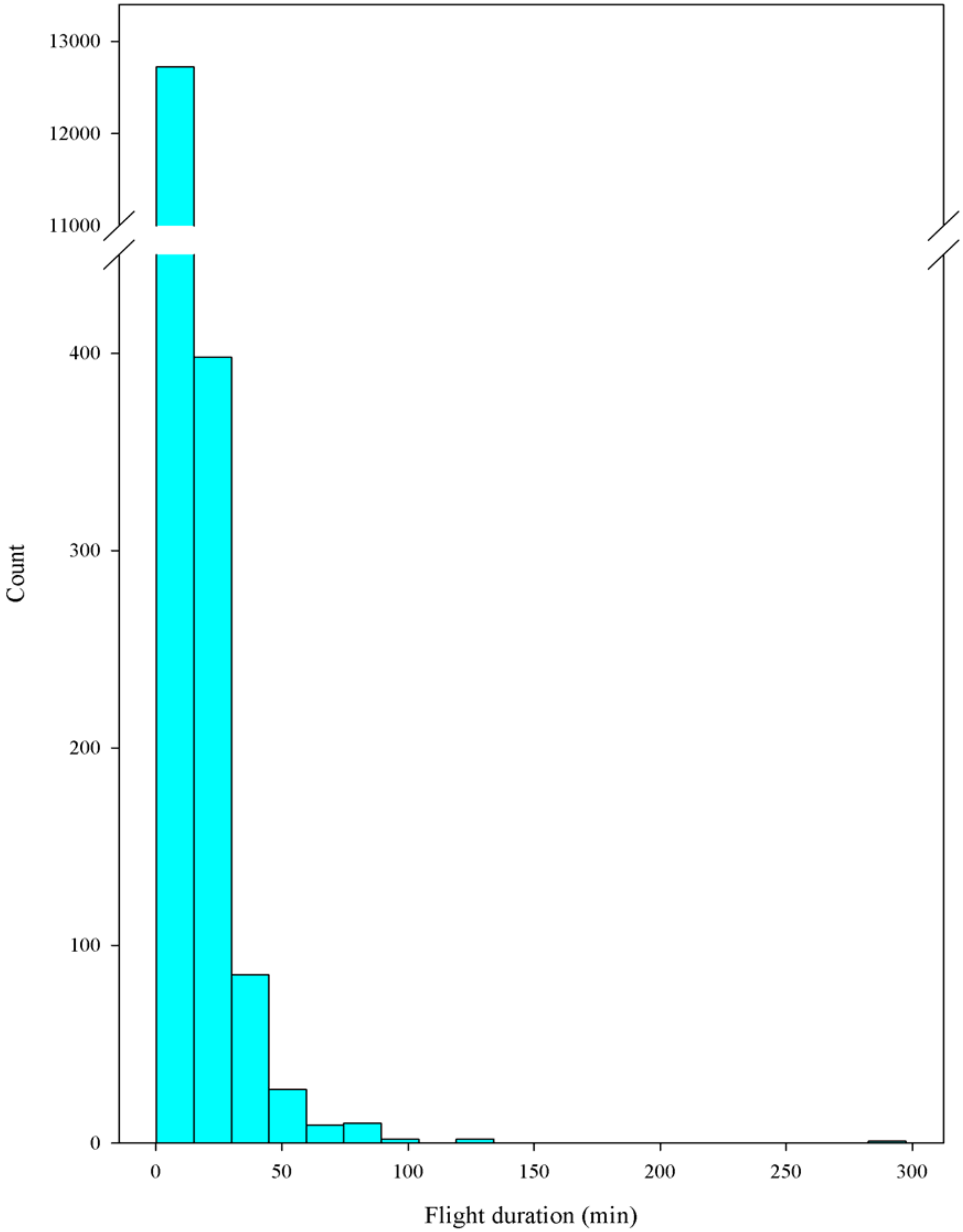


Figure 8. Combined frequency distribution of flight durations (min) from geolocators deployed on thick-billed (*Uria lomvia*) and common (*U. aalge*) murres between December and February, 2007-2009

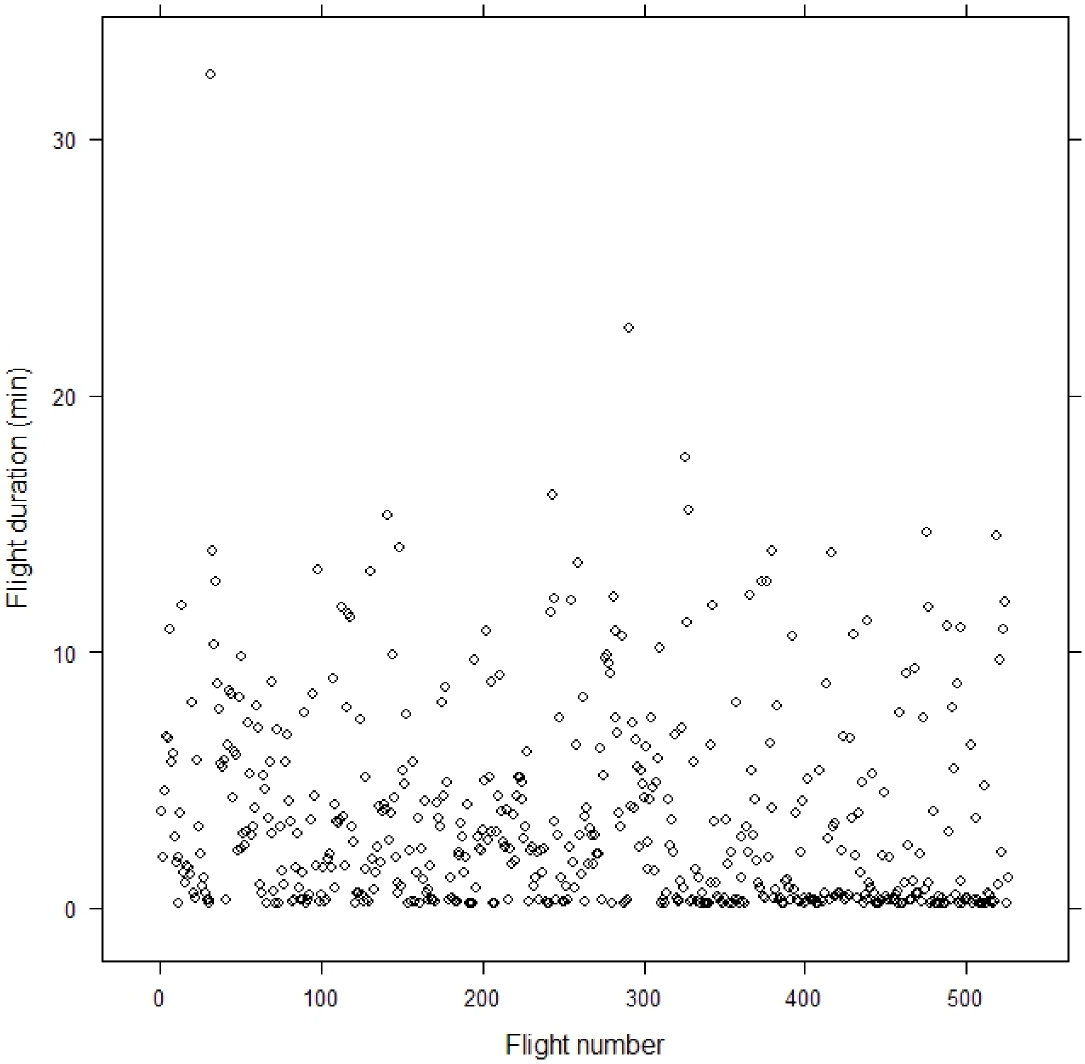


Figure 9. Flight durations (min) for a thick-billed murre (number 4241) for the period of December to February, 2007-2008 in relation to ordered flight numbers showing a consistent pattern of flight durations over time.

3.2.2 *Swim Behaviour*

A total of 15,094 daytime swim periods were recorded by the 22 murres and ranged in duration from 6 secs to ~11.5 hrs (median: 17 mins, mean: 65.5 ± 112.2 mins) (Table 4). The maximum swim duration was recorded on February 18, 2009 and February 25, 2009 by the same thick-billed murre which also held the record for the maximum flight duration.

The distribution of swim durations was strongly right skewed (Figure 10), but murres spent much longer periods swimming than flying and many swim periods were over 1 hour in length (n = 4,209 of 15,094). The results from individual murres varied slightly but the overall trend was similar between birds. The trend remained consistent between species, year, and breeding sites. The swim periods also remained consistent during the period of December to

February (Figure 11). Frequency distributions of swim durations from individual murres can be found in Appendix 2.

Table 4. Summary of daytime swim periods recorded by geolocators deployed on thick-billed (*Uria lomvia*) and common (*U. aalge*) murres between December and February, 2007-2009

Individual	N	Mean Swim Duration (min)	Median Swim Duration (min)	Maximum Swim Duration (min)
4234	903	57.1	16.0	600.0
4236	556	93.0	44.2	660.0
4239	580	78.2	34.7	680.0
4240	248	21.3	2.0	454.0
4241	624	81.5	18.4	650.0
4243	628	83.0	107.8	610.0
4247	749	58.8	73.8	524.0
4252	437	102.6	46.8	680.0
4253	804	62.3	9.3	680.0
4254	589	92.4	13.7	680.0
4256	668	69.7	21.1	640.0
4355	186	27.0	9.6	358.4
4397	763	63.2	24.7	680.0
4404	914	38.7	13.1	422.0
4405	457	111.3	48.2	630.0
4406	629	81.8	14.3	690.0
4408	1194	43.2	6.7	550.0
4410	1545	31.9	1.7	670.0
4411	864	59.6	12.9	660.0
4412	512	99.3	36.8	594.3
4413	701	68.0	21.0	660.0
4416	543	91.4	36.6	553.7
All birds combined	15,094	65.6	17.0	690.0

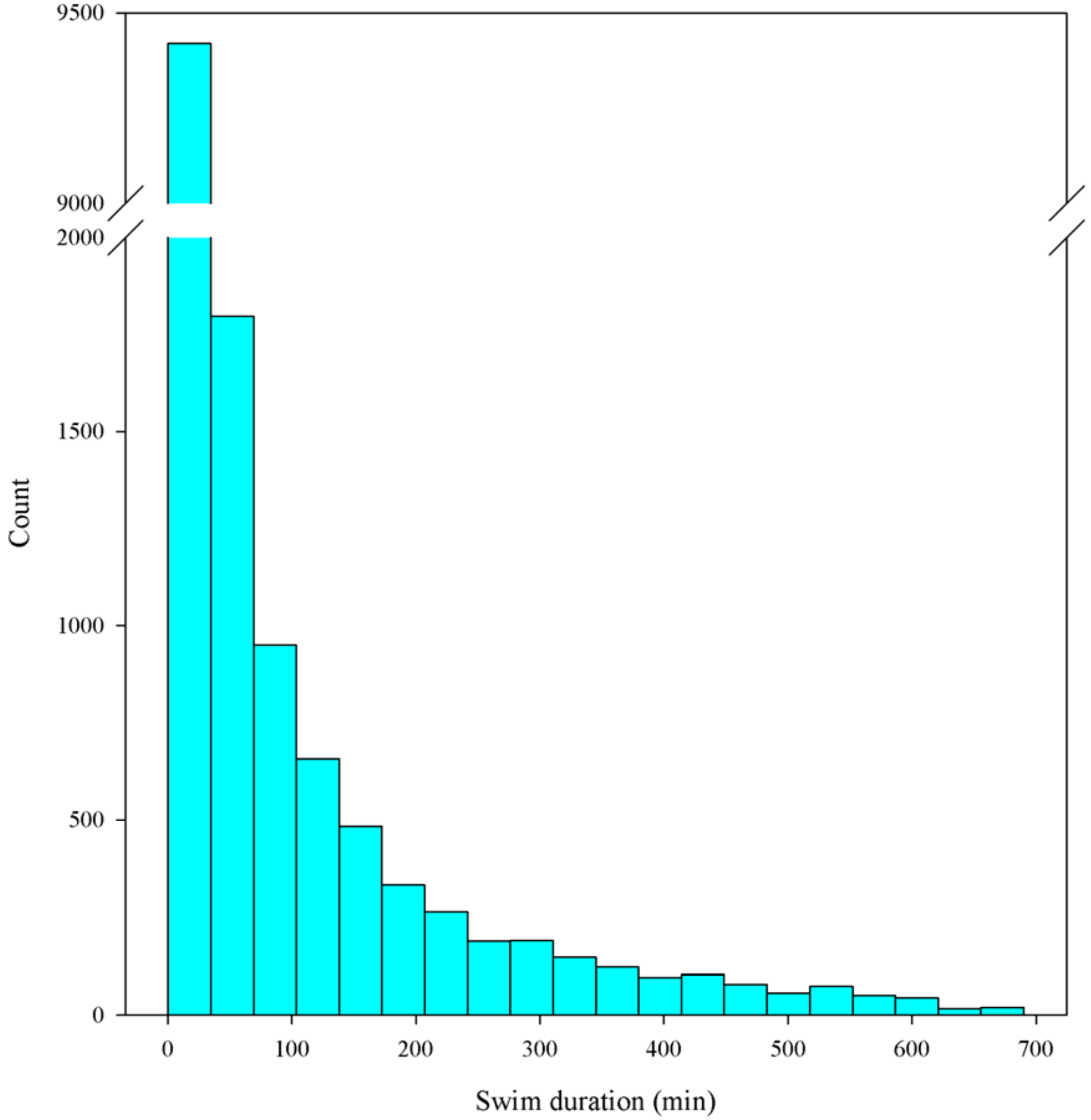


Figure 10. Frequency distribution of daytime swim durations (min) collected from geolocators deployed on thick-billed (*Uria lomvia*) and cCommon (*Uria aalge*) murres between December and February, 2007-2009

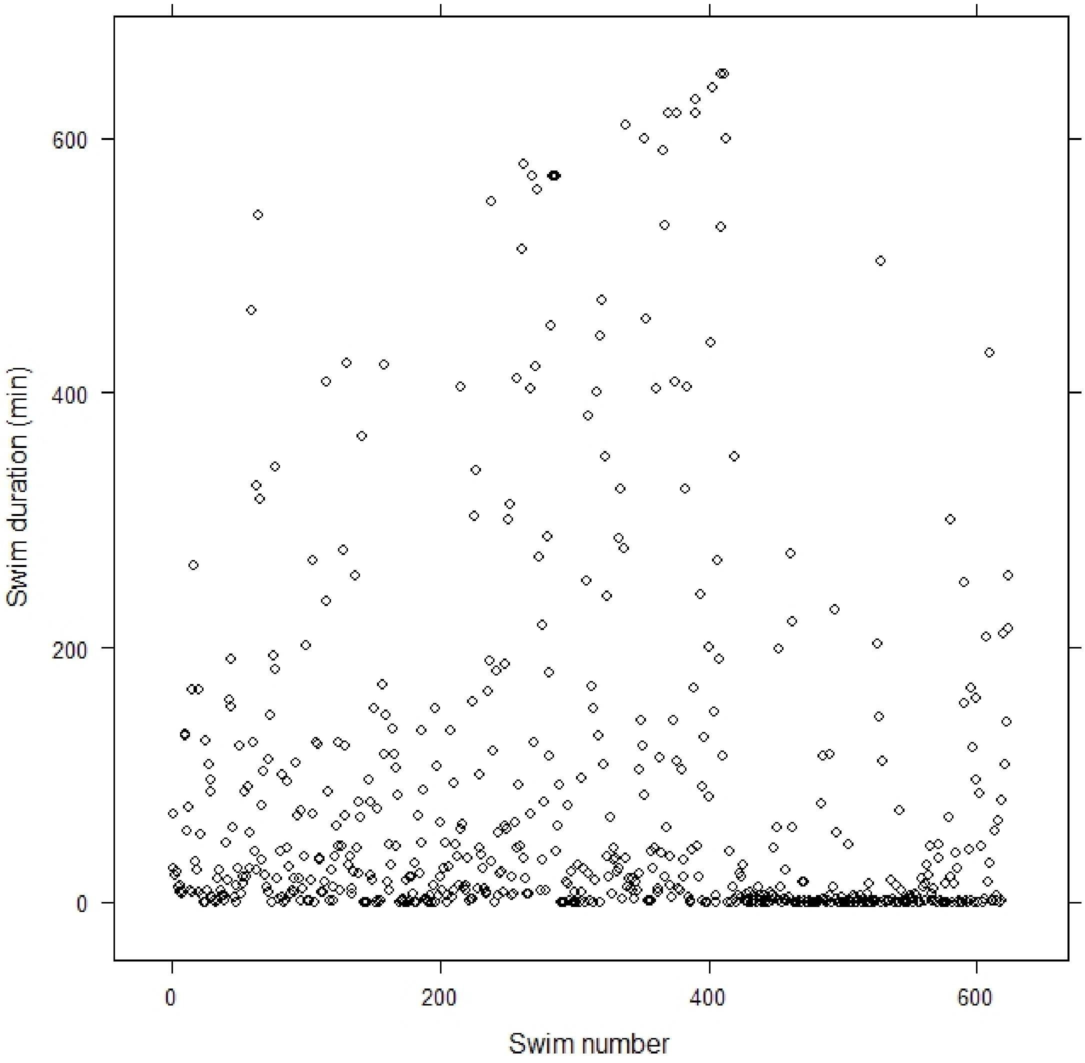


Figure 11. Daytime swim durations (min) for a thick-billed murre (number 4241) for the period of December to February, 2007-2008 in relation to ordered swim numbers, showing a consistent pattern of swim durations over time.

3.3 *Terra Nova Spill Mortality Estimate*

Murre mortality estimates were produced based on characteristics of the 2004 Terra Nova oil spill. Preliminary simulations for a 1,000 x 1,000 km area indicated that very few oiled birds (2 of 2,615) came from > 200 km away (Figure 12), so a 400 x 400 km grid was used. From the 2004 density estimate, the mean number of oiled murres was 6,263 (SD = 1,477, 95% CI: 3,441 – 9,206). This represented 0.57% (SD = 0.01) of the simulated population within the 400 km x 400 km area. Using the 2009 murre density estimate, the mean number of oiled murres was 5,987 (SD = 2,326, 95% CI: 1,421 – 10,952) (Table 5). Again, this corresponded to 0.57% (SD = 0.01) of the simulated population. The frequency distribution of numbers of oiled birds from the 1,000 trials using the 2009 density estimate was centered close to the mean value, and oiling estimates ranged from 10 to 13,499 birds from populations of 2,980 to 2,377,119 (Figure 13).

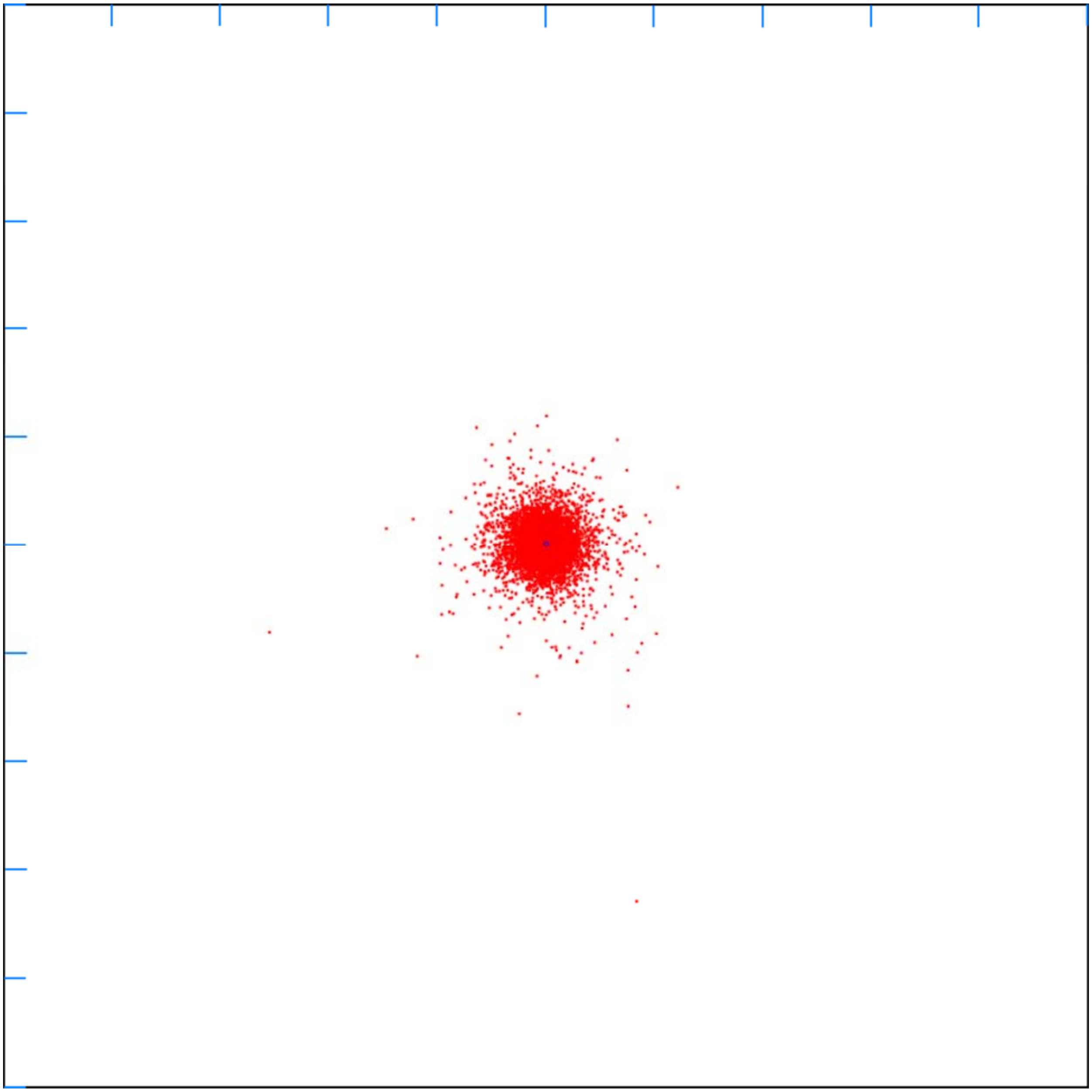


Figure 12. Initial positions of 2,615 oiled murres (population size: 2,938,271 birds), based on the simulation of a 50 km^2 spill (central circle) in a 1,000 x 1,000 km area for 6 days with 6.65 ± 2.83 birds/km^2. Only 2 oiled birds came from > 200 km from the spill centre. Axis tick marks are 100 km apart.

Table 5. Model estimates of murre mortality from 1,000 simulations of the November 2004 Terra Nova oil spill.

	Modelled Mortality		**Murres At Risk (Wilhelm et al. 2007)**
	2004 Murre Density Estimate	**2009 Murre Density Estimate**	
Mean number of oiled birds (SD)	6,263 (1,477)	5,987 (2,326)	2,744[1] 4,108[2] 5,472[3]
95% CI of mean number oiled birds	3,441 – 9,206	1,421 – 10,952	1,975 – 3,513[1] 2,082 – 6,134[2] 2,189 – 8,755[3]
Bird density (SE)	6.90 (1.69)	6.65 (2.83)	3.46 (0.49) – on water 3.44 (1.62) – in flight 6.90 (1.69) – total
Mean population size (SD)	1,107,242 (261,140)	1,058,096 (411,017)	NA
Mean percent of population oiled (SD)	0.57% (0.01)	0.57% (0.01)	NA

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[1] Assuming no birds in flight were at risk of oiling.
[2] Assuming 50% of birds in flight were at risk of oiling.
[3] Assuming 100% of birds in flight were at risk of oiling.

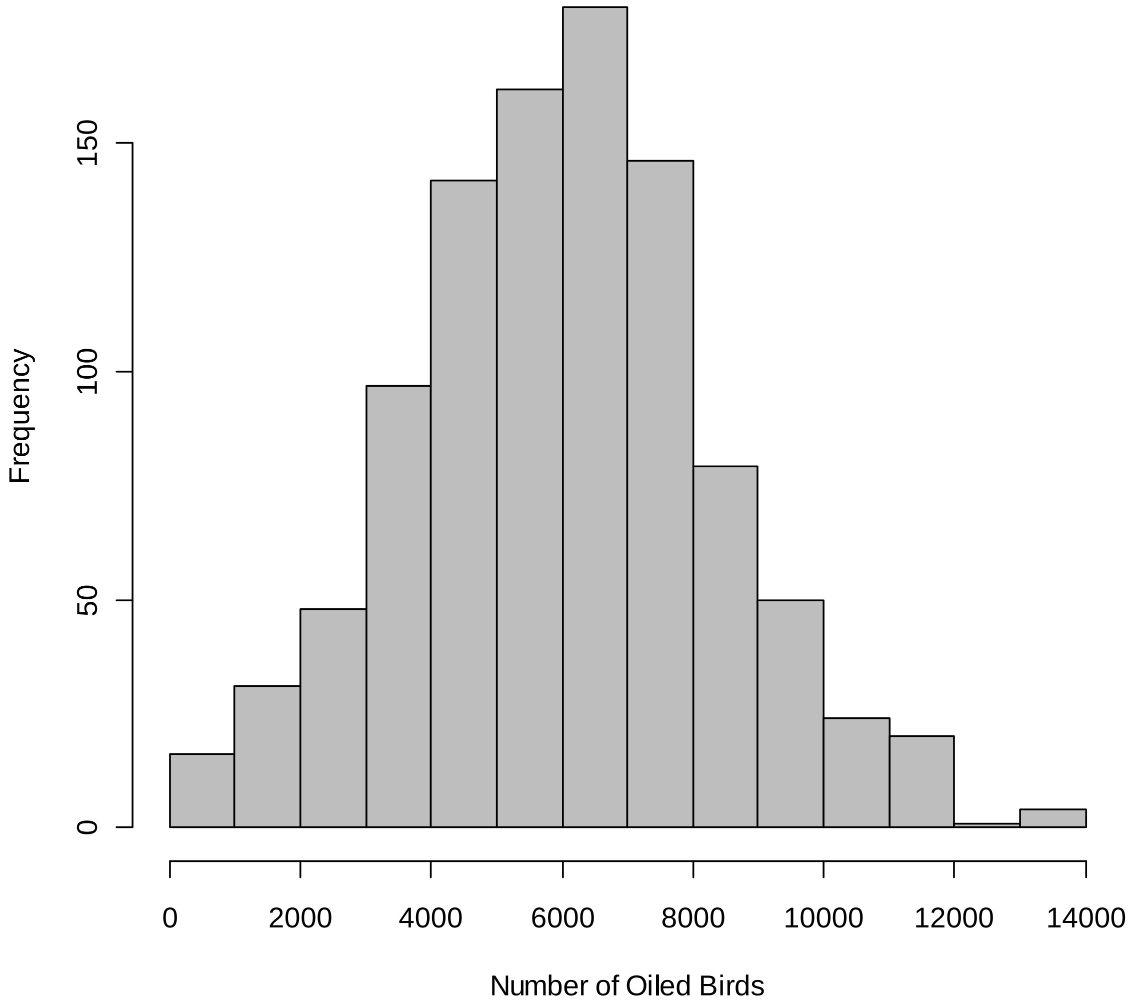

Figure 13. The distribution of oiled murre estimates for 1,000 model simulations of a 50 km^2 slick in a 400 x 400 km area containing 6.65 birds/km^2 (SD = 2.83)

The number of oiled birds increased at a relatively consistent rate during daylight hours and remained constant at night over the 6-day simulation (Figure 14). A closer examination of a single day from this simulation revealed an increased oiling rate immediately after sunrise and a less pronounced increase at dusk – visible only when zooming in on Figure 14. The increased oiling rate at dawn is due to the bird's beginning to fly after having been stationary on the water overnight, while the increase at the end of the day is due to birds in flight over the oil landing in the slick at sunset. A similar pattern was observed during a 30-day trial using the same parameters, except that the oiling rate showed a slow decline as time passed (Figure 15).

The distance between the initial bird position and the oiling site was relatively short for most birds (mean: 35.1 ± 28.3 km, over 1,000 runs) (Figure 16) indicating that most birds that were oiled came from relatively near the spill. However, the most distant bird that was oiled came from 207 km away; this is more than half the distance from the spill to the east coast of Newfoundland (Figure 3), showing that a spill can affect individual birds over a large distance.

3.4 Effect of Spill Size

A series of simulations for spills of 10, 25, 50, 100, 250 and 500 km^2 in a 400 x 400 km area containing 6.65 $birds/km^2$ revealed that modelled mortality increased with spill size (Figure 17). However, mortality was not a linear function of the spill area, it scaled in relation to the spill perimeter (or equivalently diameter).

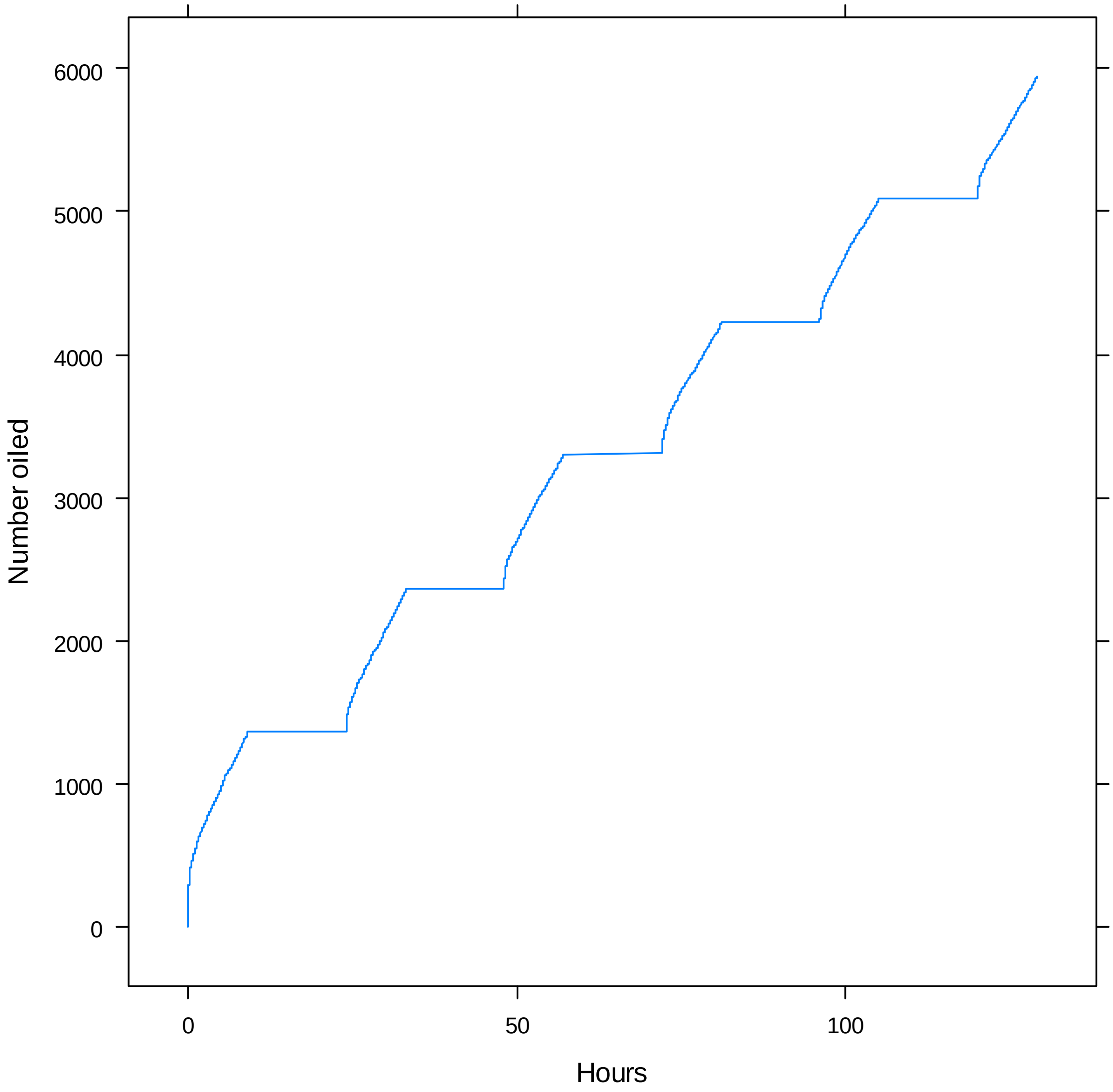

Figure 14. Example of the change in the number of oiled murres during 6 days, based on one simulation trial of a 50 km^2 spill in a 400 x 400 km area. For this model trial, 5,940 individuals were oiled out of a population of 1,064,000 murres (0.56%)

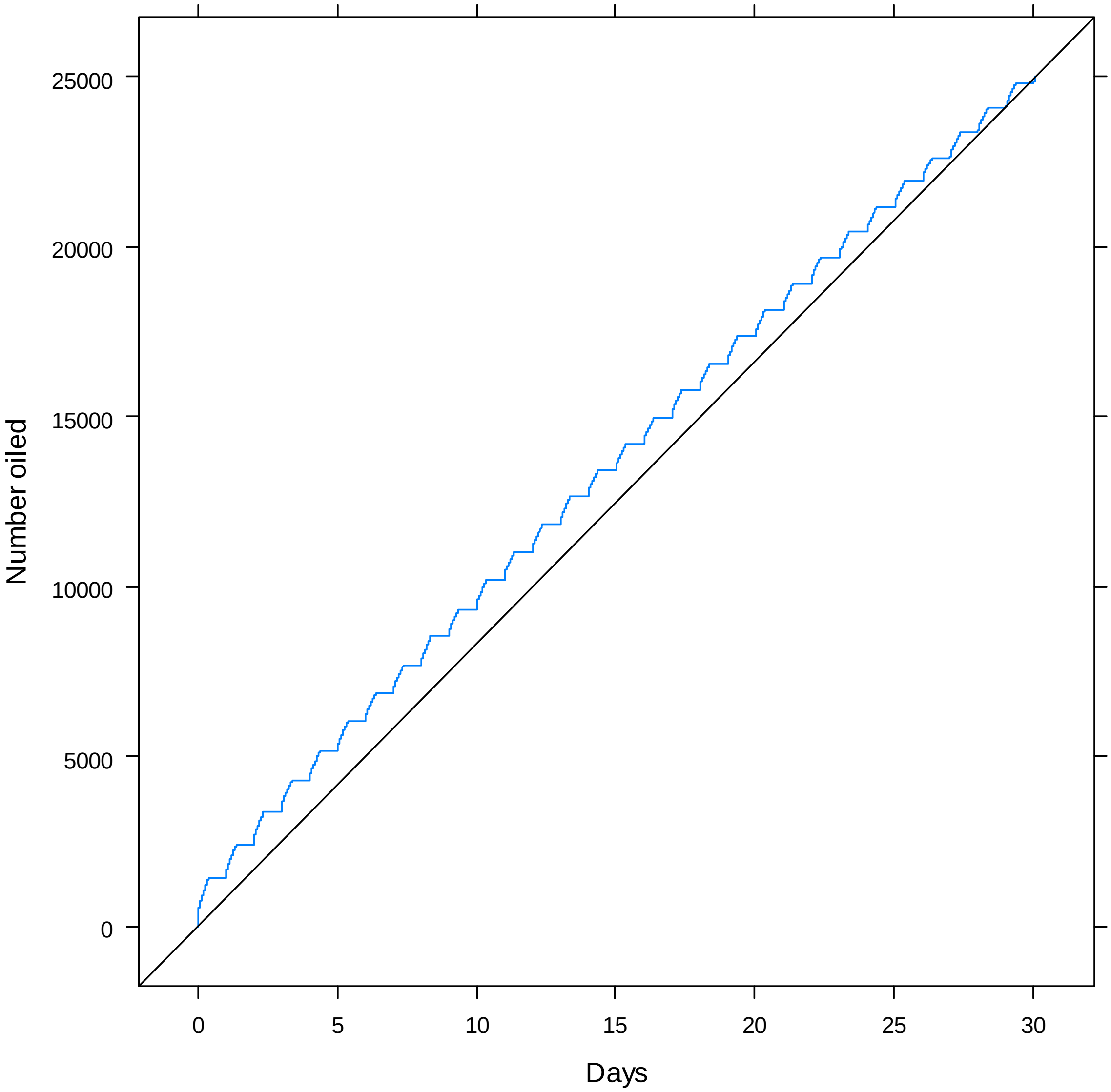

Figure 15. Results of a 30-day simulation of a 50 km^2 spill in a 400 x 400 km area with 6.65 birds/km^2 to investigate the change in oiling rate over time. The modelled number of oiled murres (blue) in relation to a 1:1 line (black) indicates a slow decline in the oiling rate over time.

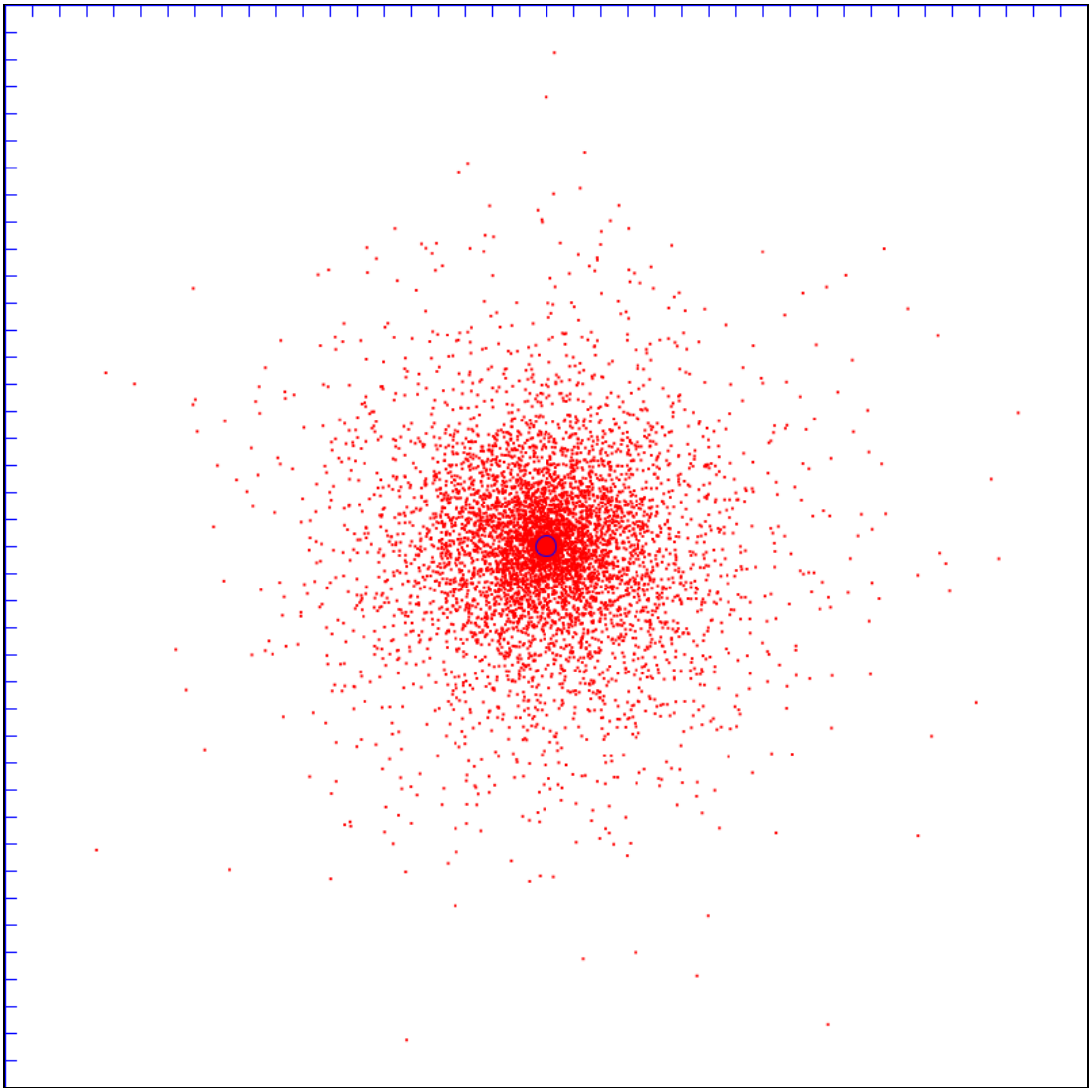

Figure 16. Initial positions of oiled murres that eventually became oiled based on one simulation trial of a 50 km^2 spill (blue circle) in a 400 x 400 km area with 6.65 birds/km^2. Mean distance from initial position to oiling for the 5,940 oiled birds out of a population of 1,064,000 individuals was 35.1 ± 28.3 km and the maximum distance was 207 km. Central circle represents the oil slick, axis tick marks are 10 km apart.

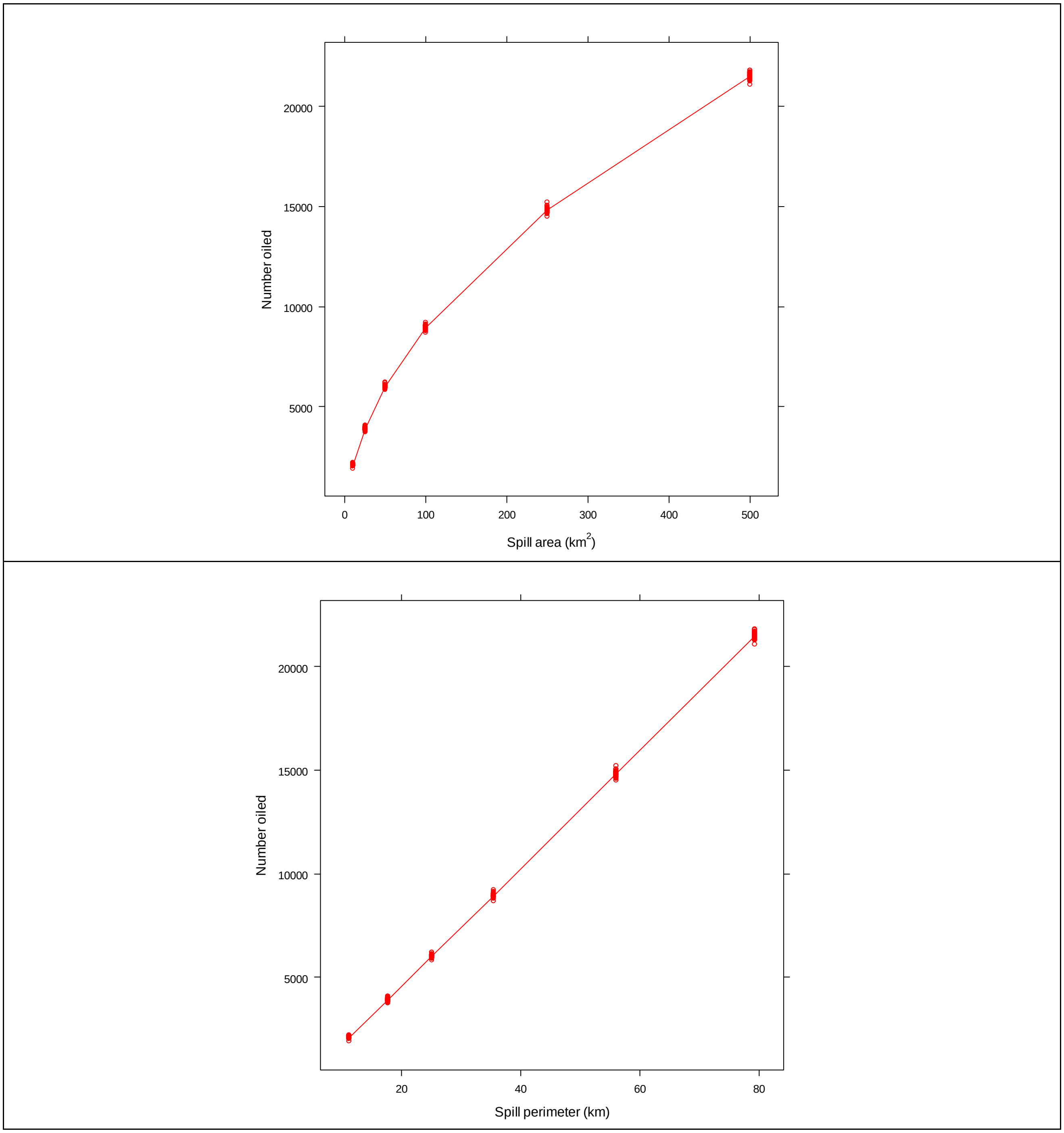

Figure 17. Effect of spill size on modelled mortality for 50 trials of 10, 25, 50, 100, 250 and 500 km^2 spills (red circles). Modelled mortality was more sensitive to spill area (i.e. increased more quickly) at small spill sizes (top) but scaled linearly with perimeter (bottom). Bird density was 6.65 birds/km^2 in a 400 x 400 km area.

4 Discussion

4.1 Seabird Oiling Model

Many oil spill models exist, yet few focus on assessing the impacts on wildlife (French-McKay 2009). Previous models relied on shoreline carcass counts (Wiese and Robertson 2004; Heubeck et al. 2003; Page et al. 1990), spill volume (Schneider 2002; Burger 1993) or seabird behaviour generalized at the scale of species guilds (French-McKay 2009). While recent models incorporate complex spill trajectory, weather and fate models, as far as we are aware, the seabird oiling model described herein is the first to incorporate such fine-scale seabird behaviour into an impact model.

The model places individual birds singularly at random at the start of a simulation run, based on a density parameter. It is common knowledge that most species are not distributed randomly at a given density throughout the ocean but instead aggregate into flocks at small spatial scales. The characteristics of seabird flock dynamics (i.e. rate at which flocks form, dissolve, join or split, and the movement of individuals between flocks) are currently unknown. Based on these uncertainties, we felt it was better to place birds singularly at random. Ideally, the model might include a flock aggregation sub-model that incorporates these variables. Inclusion of such a sub-model could be important if flocks are large in relation to the size of the areas of oil interspersed with open water that typically form as a slick weathers.

At-sea surveys have revealed that seabird density changes in response to a variety of biophysical and oceanographic drivers at larger spatial scales (Gjerdrum et al. 2009; Fifield et al. 2009). The model currently accepts a single density parameter (± SD) for the entire simulation area. The ability to specify multiple densities across the simulation area would add more realism.

The model currently assumes that birds do not fly at night. Although this may be true for some species of seabirds at some times of the year (eg. murres during winter), it is not universally true. For example, some albatrosses can spend many weeks on the wing without landing. The model also only moves birds while they are in flight and not while they are on the water. This restriction resulted from a focus on murre behaviour in the first implementation. Although murres do swim, their surface swimming speed is an order of magnitude less than their flight speed, and thus they cover relatively little ground while swimming, especially with mean and median swim times of only 66 and 17 mins, respectively.[†] More importantly, bird movement while on the water may be strongly affected by wind and currents, the same forces which affect patches of oil. Thus, it is possible that birds on the water would simply move with the oil without changing their position relative to it. Moreover, a murre would have to be very close to the oil patch in order to swim into it and become oiled. Thus a very narrow ring of area surrounding the oil patch could contain birds that might swim into the oil (depending on swim direction), and failing to model this movement may have biased the number of oiled birds towards slightly lower values. This bias is likely to be very low in the example presented here for two reasons. First, the number of birds that could occupy such a ring is quite small at the densities modelled, and second, birds on the water at the edge of the oil have a high likelihood of becoming oiled on their next flight anyway, thus mediating any potential bias. That said, the addition of options to allow for night flight and swimming movement would extend the general applicability of the model to a greater variety of species and situations.

[†] This is especially true since they undertake long periods of leg-tucking, which likely precludes swimming, except in circles.

The flight times used in the model were selected from a user-specified list of flight times, but flight directions were selected at random. Randomly directed flights are likely appropriate for murres during winter (when birds are not limited to flying along regular feeding or migration routes), and over short time frames (French-McKay 2009). But, incorporation of more complex theoretic flight models (e.g. correlated random walks or Lévy flights, Reynolds and Rhodes 2009; Kareiva and Shigesada 1983) into the oiling model could improve the accuracy of mortality estimates.

As an oil slick weathers over time, wind and wave action tend to create fingers of oil interspersed by leads of oil-free water. Whether birds that land in oil-free regions within a slick eventually become oiled and die is unknown. The model currently assumes that all birds landing within the boundary of a slick during the simulation period are oiled. The model could account for slick weathering by implementing a variable probability of oiling based on percent coverage within the slick.

During a 6-day simulation of the 2004 spill event (Figure 14), the number of oiled birds continued to rise. Knowing that the model lacked a facility to model slick weathering prompted the question of whether the number of oiled birds would continue to rise at the same rate if the model was run for a longer period. During a simulation with oil present for 30 days (Figure 15), the modelled number of oiled murres continued to rise, but the oiling rate did show a slow decrease over time. This is because, as time moves forward, the number of birds close to the spill drops due to oiling, creating an area of lowered bird density surrounding the spill and thus fewer birds are available nearby to become oiled. It then takes longer for more distant birds to reach the area and become oiled, resulting in a decreasing rate. The number of birds oiled after a 30-day simulation run (25,702) was a small proportion of the initial population of 1,096,000 murres in the simulation area, indicating that plenty of birds remained that could eventually enter the oil if the simulation continued. This implies that unless the supply of birds within flying distance is depleted, then more birds will continue to get oiled as long as the slick is on the water.

Oil slicks move and change size and shape in response to wind and currents. For example, the oil slick from the 2004 spill moved south to the shelf edge, then returned north over a six-day period before it dissipated. For simplicity, the virtual oil slick created by the model is circular, stationary, and of constant size. This requires the modeller to choose a single representative slick size for the duration of the simulation. Ultimately, more accurate estimates may be achieved by incorporating more realistic models of slick dynamics. This highlights the need for accurate information on slick size, shape, movement, and percent coverage during the life of the spill. Integrating the oiling model with a spatially explicit model of slick dynamics in a GIS environment would likely help facilitate such improvements.

4.2 Murre Winter Behaviour

4.2.1 Flight and swim speed

Most of the information on murre flight speed was collected during the breeding season but little is known of speed during winter. Croll et al. (1991) found that thick-billed murres could reach speeds up to 75 km/h over short distances. Common murres are known to fly up to 78 km/h (Vaughn 1937) but their speed changes substantially in relation to wind strength and direction (Spear and Ainley 1997b). Thick-billed and common murres were treated as a group species for the purpose of our simulations and were assigned a more conservative flight speed of 65 km/h based on observations of thick-billed murres near breeding sites (Benvenuti et al. 1998).

The ability to specify a range of flight speeds would improve the model. This is especially important for birds that undertake longer flights, since the impact (on position) of flight speed variations increases as flight time increases.

4.2.2 Leg-tucking and night flight

An examination of the night-time activity data consistently showed extensive dry periods (sometimes all night) night after night throughout the winter for all birds. These were interpreted as periods of leg-tucking as opposed to flight. Several lines of evidence strongly support this conclusion.

If these dry periods were actually flight, they should have resulted in extensive nightly movements of hundreds of kilometres (or more) which were not observed in the positional data. If instead these were periods of leg-tucking, they should result in a coincident rise in temperature when the device is held inside the feathers close to the birds' skin. Murres have a normal body temperature of *ca.* 37ºC which is markedly different from the water temperature on their wintering grounds. Unfortunately the geolocators we deployed were designed to measure sea temperature and only record temperature when the device is submerged, so no temperature data was available from these devices. Fortuitously, subsequent to this study, Temperature-Depth Recorders (TDRs; Lotek LAT1500) were deployed on Coats Island thick-billed murres during the winter of 2009-2010. These devices recorded temperature and depth every 2 minutes throughout the winter whether or not the device was submerged (KH Elliot and AJ Gaston, unpubl.). Data from these devices clearly distinguish time with leg in the water (constant low temperature), flight (variable low temperature), and leg-tucking (high temperature). Examination of data from these birds (n = 3) clearly showed long periods of > 30º C during the winter, confirming the habit of leg-tucking (Figure 18). Furthermore, no flights were recorded at night during the entire winter. This evidence indicates that our characterization of the night time geolocator activity switch data as leg-tucking (and not flight) was warranted.

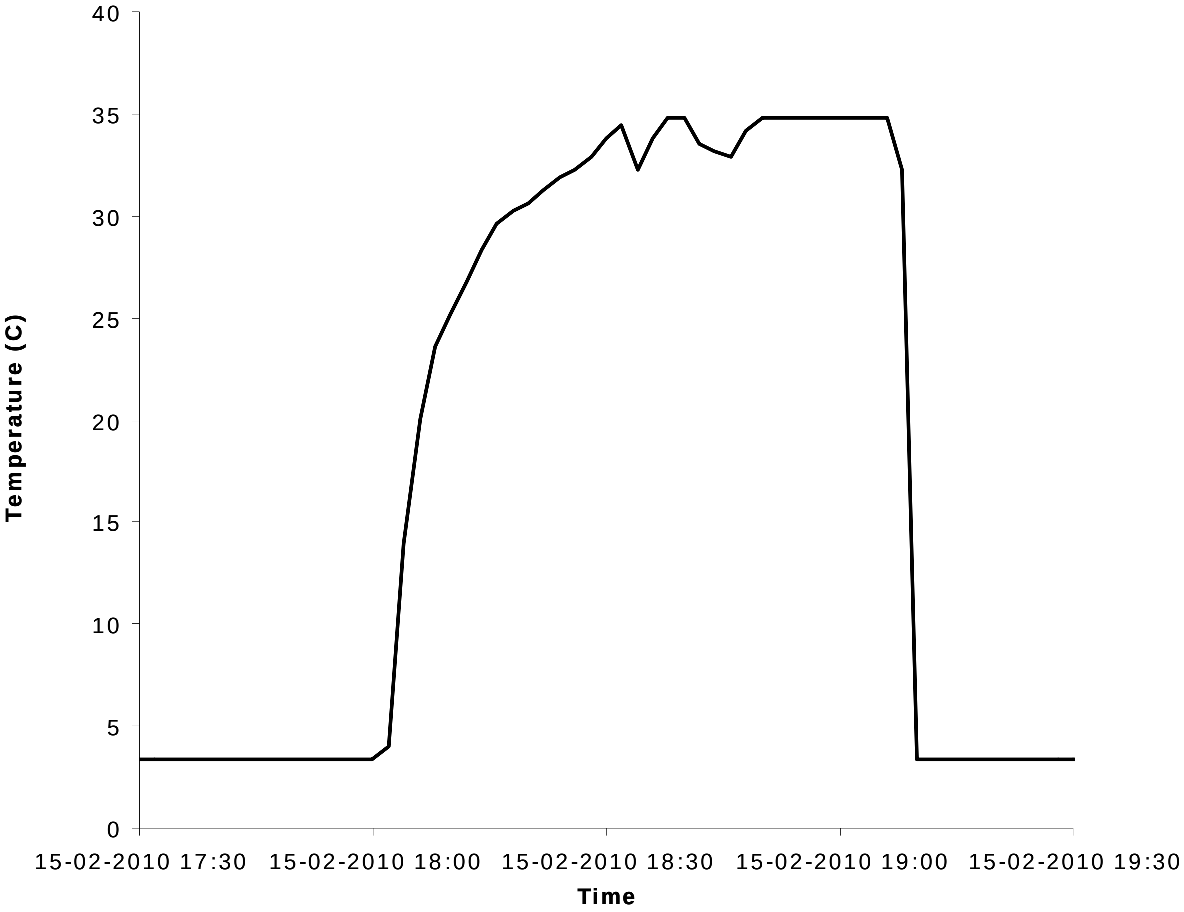

Figure 18. Example of a typical leg-tucking event during February, detected by the temperature sensor of a Time-Depth Recorder (TDR). The temperature rose quickly and remained high for more than an hour while the leg was tucked into body feathers. Ambient water temperature at the time was less than 5º C.

After filtering for leg-tucking, a high proportion of the remaining dry periods were equal to 6 seconds – the shortest dry interval these devices can measure. The authors have thousands of hours of combined murre observation time at breeding colonies and at sea, and flights of such short duration are rarely, if ever, observed. It is possible that these were periods of leg-tucking were too brief to affect the light data (since the devices only recorded light level as the maximum value during each 10 minute interval) and thus were not removed by filtering. Alternatively, short periods of dry time could occur when murres roll onto their sides during preening (a common occurrence in these species), exposing their legs to air (the device must be completely submerged in order to record wet). It is also possible that the sensor registered dry as birds skittered across the water's surface during aborted take-off attempts (also common in these species). It is likely that these very short dry periods were thus not flights and we arbitrarily chose to convert all dry periods of less than 10 seconds to periods on the water.

In general, although we feel confident that we correctly removed many false flights from the data, the fine-scale temporal accuracy of some of the remaining short periods of flight and swim remains uncertain. Temperature-Depth Recorders (TDRs) that measure temperature on a fine scale (seconds) would help resolve remaining questions regarding short flights. Until more precise measurements can be made, these results are the best available information for murre flight behaviour on their wintering grounds.

4.3 The Terra Nova Spill

Daily slick size and coverage estimates were available during the six days that oil was visible on the water during the November 2004 Terra Nova spill. Reports indicate that it started small and reached a maximum of around 50 km^2. Wilhelm et al. (2007) estimated that the slick swept an area of 793 km^2 during the six days, based on a bounding box drawn around the locations of daily slick sightings. They calculated an "instantaneous" estimate of murres at risk of oiling based on this area and murre density calculated from at-sea surveys conducted at the time. Lacking a dynamic model of murre flight, they were unable to quantify whether murres in flight were likely to land in the spill or fly over it. Instead, they assumed that all birds on water within this area were at risk and that 0, 50 or 100% of birds in flight were also at risk. They concluded that 2,744, 4,108, and 5,472 murres were at risk of oiling, for each scenario respectively, with overall confidence limits of between 1,975 and 8,755 murres. They also produced a mortality estimate of 4,688 murres (95% CI: 1,905 – 12,480) based on spill volume.

We modelled a 50 km^2 slick for six days using the density estimate from Wilhelm et al. (2007) and estimated that 6,263 (95% CI: 3,441 – 9,206) murres were oiled. Our estimate is higher than the three estimates of birds at risk and the mortality estimate in Wilhelm et al. (2007), but quite similar to their highest value and still well within their confidence limits. Our estimate likely represents an upper bound on murre mortality, since the slick was unlikely to cover the full 50 km^2 during the entire six days although it was modelled as such. The confidence interval for our estimate is somewhat smaller than the overall range they presented, likely due to the removal of uncertainty regarding the proportion of flying birds that become oiled.

A more recent murre density estimate from at-sea surveys conducted from 2006 to 2009 (Fifield et al. 2009) was also modelled. This density was very similar to the one from 2004, except that it was associated with a greater degree of uncertainty (6.65 ± 2.83 in 2009 vs 6.90 ± 1.69 in 2004). This resulted in an estimated 5,987 murres oiled (95% CI: 1,421 – 10,952). Not surprisingly, the two modelled mortality estimates are very similar, except the confidence interval is considerably wider when using the more recent survey data. This is because the more recent data was more variable than the data obtained at the time of the spill in 2004 (Table 5), since it was based on a greater number of surveys over a larger time frame that more accurately captured the natural variation in murre density. Variation in the number of oiled birds across multiple simulation trials was largely driven by the difference in population size in each trial. Variation in bird population size from trial to trial is dependent solely on the precision of the user-specified density estimate. This highlights the relationship between the precision of murre density estimates and the precision of predicted oiling mortality and underscores the importance of seabird surveys. More precise density estimates from seabird surveys will result in a smaller range of modelled mortality estimates.

The modelled number of oiled murres increased at a relatively steady rate during each simulated day with peaks in oiling rates at dawn and dusk (Figure 14). The model assumed all birds were on the water at night and began to fly at dawn. Murre flights are typically short, and those birds on the water and close to the slick during the night had a high probability of landing in the oil on one of their first flights in the morning. This led to an increase in the oiling rate after sunrise. Likewise, the model forced birds in flight to land at nightfall and those over the slick became oiled, briefly increasing the rate.

4.4 Effect of spill size

Not surprisingly, modelled mortality increased with spill area although not at a linear rate. The slope of this relationship was greatest for spills in the range of 10 to 50 km^2, implying that the model is more sensitive to changes in spill area at this scale. Mortality did, however, scale linearly with the spill perimeter in agreement with existing empirical data (Wilhelm et al. 2007; Burger 1993). This highlights the importance of accurately modelling changes in spill size and shape. Integrating the seabird model with a more complex model of spill dynamics has the potential to produce more accurate mortality estimates.

5 Conclusions

A modelling environment was implemented which simulates seabird movement in relation to an oil spill and estimates mortality. This model incorporates species-specific flight and swim behaviour at a finer scale than previous models. By specifically deriving a mechanistic empirical model with flight and swim behaviour, we have incorporated the uncertainty regarding the fate of birds in flight (Wilhelm et al. 2007) in order to produce more scientifically credible mortality estimates.

This is the first study in which electronic loggers were used to quantify murre flight behaviour during the entire non-breeding season. Geolocators were successfully used to collect data on murre behaviour on their winter grounds. This information was required as input for the oiling model. Thousands of representative flight and swim times were extracted indicating that most flight periods were quite short. Filtering of flight data to remove an unforeseen complication involving leg-tucking was successful in removing many tucking events. Yet, the filtering was unlikely to have removed all such events and thus there remains some uncertainty as to the true distribution of short flight times. The effect of this uncertainty on model predictions is unknown. Time-depth recorders from another study allowed us to confirm our suspicions of leg-tucking and the lack of night flight, but lacked the temporal resolution to help resolve questions of the distribution of flight times. Newer devices with greater temporal precision are now available to resolve this issue.

The model was used to estimate the number of murres oiled in the 2004 Terra Nova spill. The model estimated that 5,987 (95% CI: 1,421 – 10,952) murres were oiled during the spill, based on the most recent/extensive murre density estimate for the spill area (Fifield et al. 2009). Although slightly higher than the estimates of murres at risk (and an estimate of murre mortality) in Wilhelm et al. (2007), it is well within the confidence limits of those estimates (and vice versa). Using the density data available at the time of the spill, our model produced a more precise mortality estimate than the estimate of birds at risk in Wilhelm et al. (2007), likely due to the direct incorporation of flight and swim behaviour. Since the more recent/extensive at-sea survey data provides a more variable density value, the final modelled mortality estimate cited above has a similar confidence interval to that in Wilhelm et al. (2007). This underscores the importance of obtaining the most accurate and precise at-sea bird abundance estimates possible. Despite the significant methodological differences between this study and Wilhelm et al. (2007), the relative concordance of our model outputs with their estimates of mortality and birds at risk is encouraging.

Many tradeoffs were necessarily made to balance this initial model's realism against the resources available for its implementation. A number of possible improvements to the model itself and in the quality of the behavioural and density data provided to it have been discussed, and a number of recommendations were made. Ultimately, increased accuracy and precision in estimates of mortality due to oil spills can be achieved by marrying more realistic models of seabird behaviour and density with improved oil trajectory and fate models.

6 Recommendations

The following recommendations will improve both the accuracy and precision of modelled seabird oil spill mortality estimates. See the discussion in Section 4.

Recommendation 1
The oiling model should be extended to include a more accurate (perhaps species-specific) movement model which takes into account the distribution of flight directions, bird flocking behaviour, night flying, movement while swimming, and variable flight speeds.

Recommendation 2:
More accurate and defensible flight and swim time data should be collected for murres.

Recommendation 3
Flight and swim data should be collected for additional species, particularly Dovekies, in order to model their mortality in spills.

Recommendation 4
Improved models of seabird abundance and distribution in space and time should be extracted from continued at-sea survey programs.

Recommendation 5
Improved spill modelling should be incorporated to account for variation in spill size/shape/coverage/position over time.

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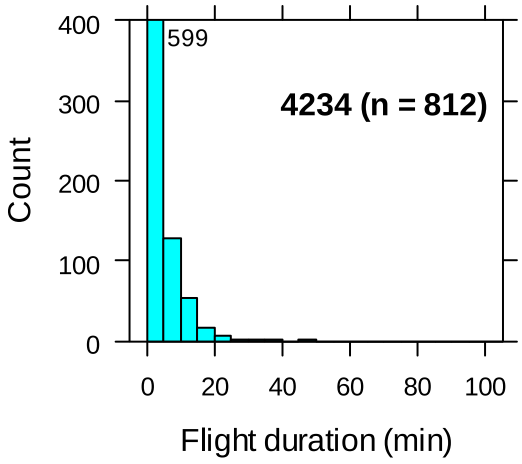
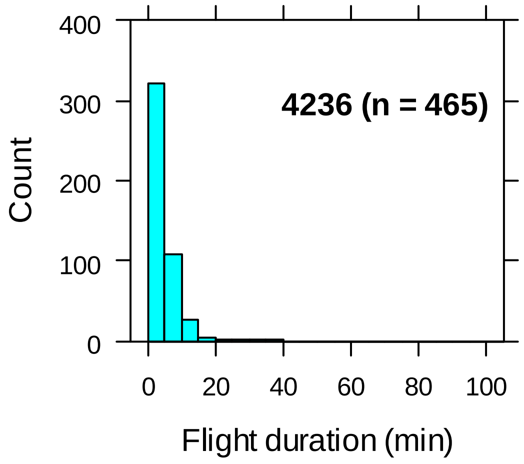
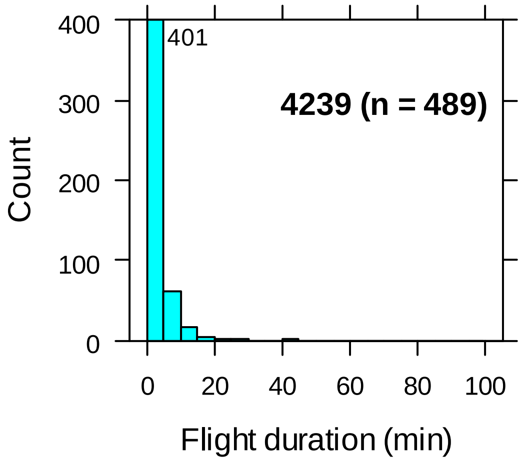
8 Appendices

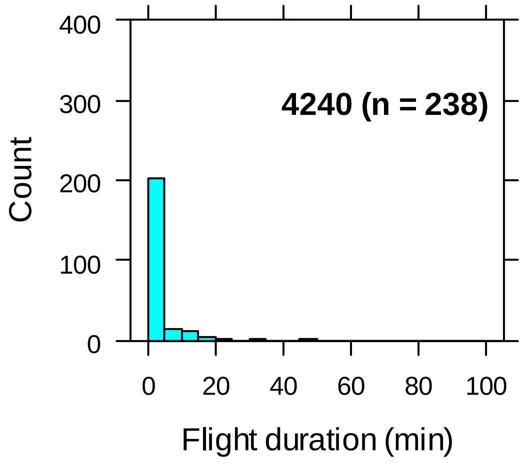
8.1 Appendix 1. Flight duration frequency distributions of individual murres.

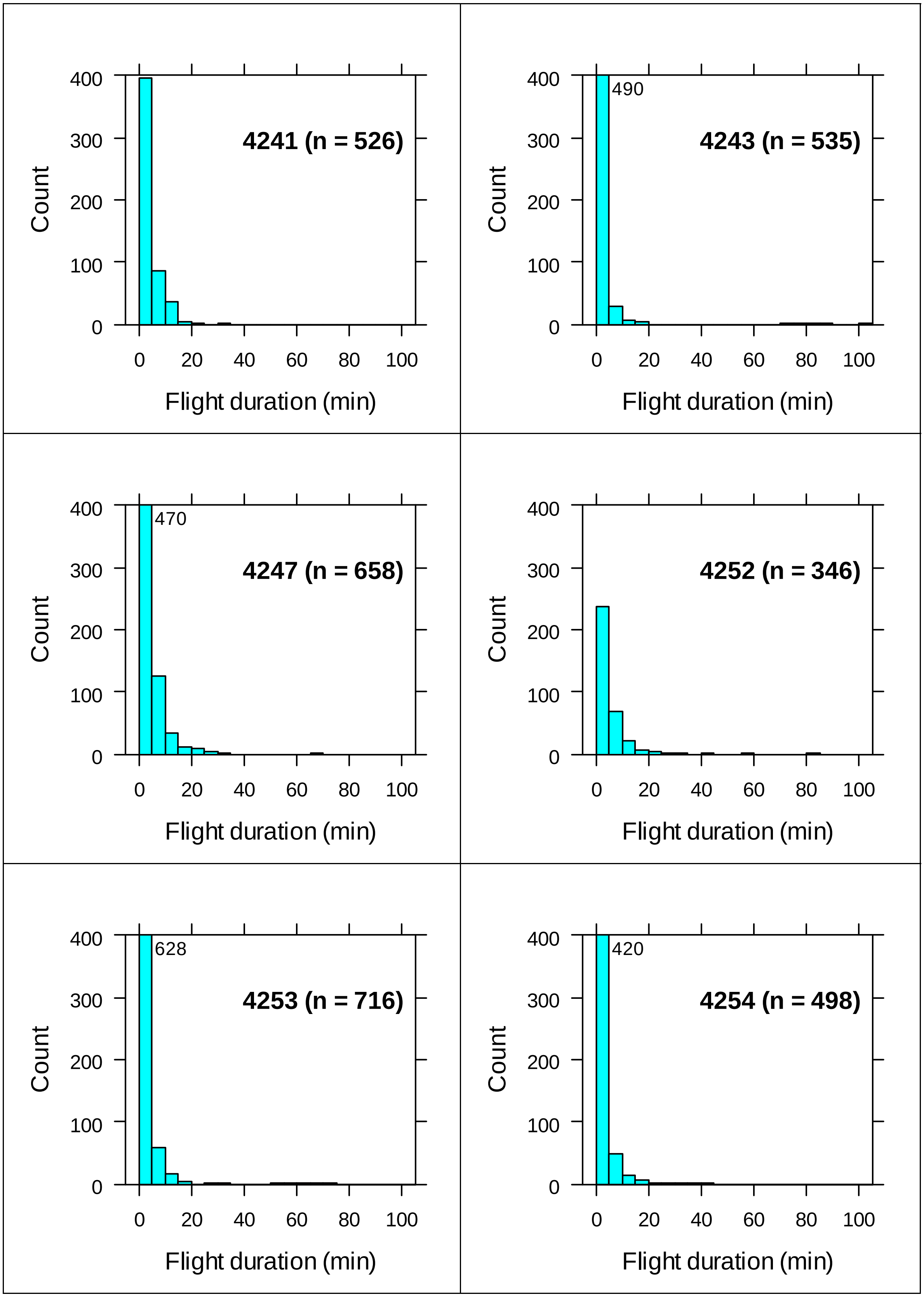
The following histograms depict the distribution of flight times between December and February for each individual murre. Each plot is labelled with the bird's device number as well as the number of flights (n). The y-axes are scaled to adequately portray the details of the distributions and in some cases the height of the first bar extended beyond the top of the plot, in which case the height of the first bar is indicated with text. Behaviours are typified by many short flights (< 5 min) and far fewer longer flights.







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4243 (n = 535)
490
4247 (n = 658)
470
4252 (n = 346)
4253 (n = 716)
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4254 (n = 498)
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Count
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100
200
300
400
Flight duration (min)
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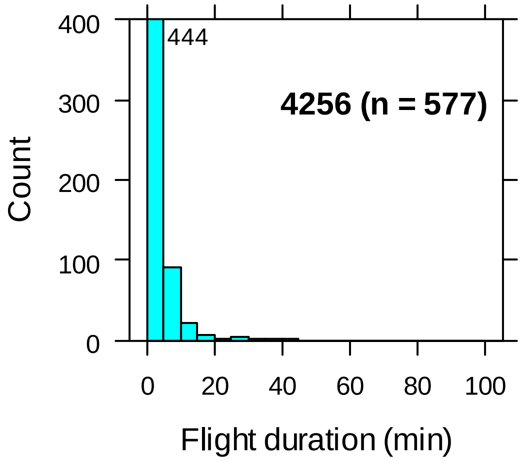
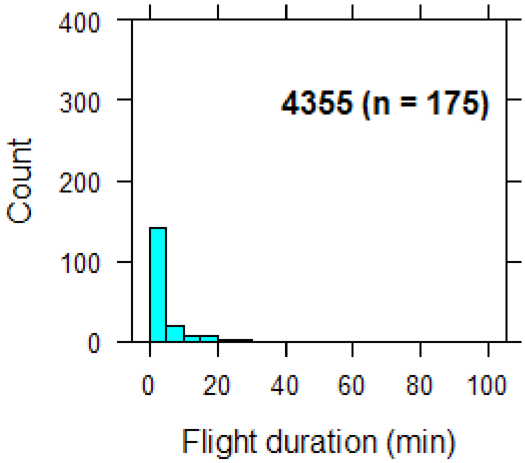
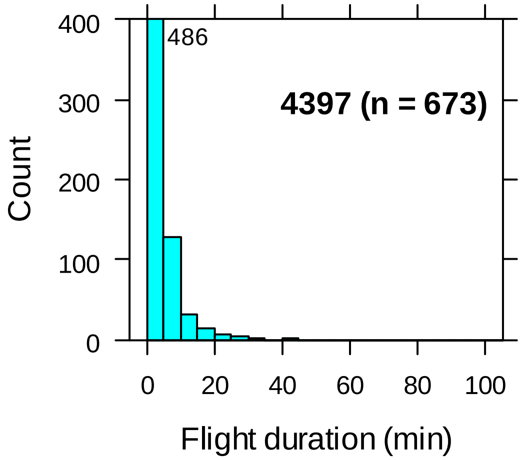
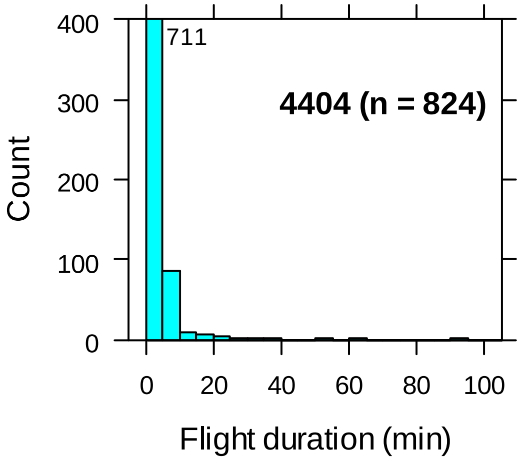
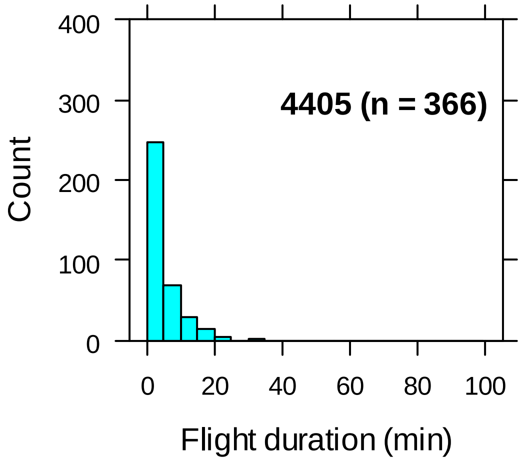
40
60
80
100











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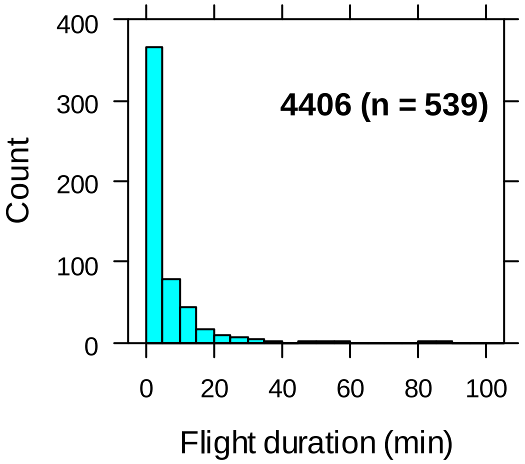

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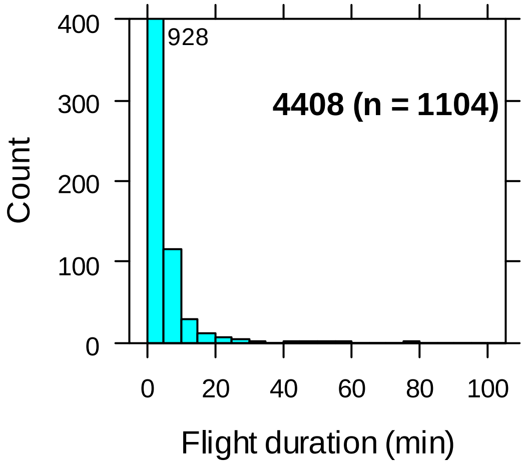
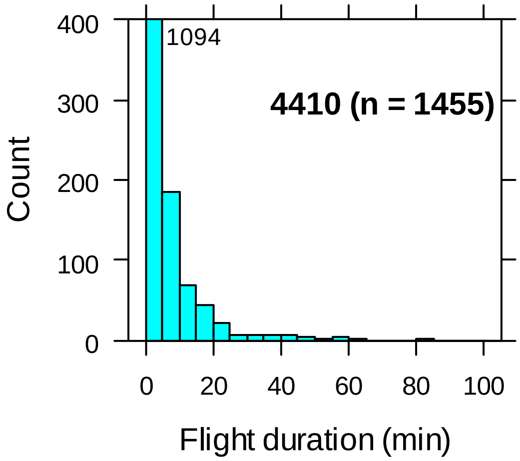
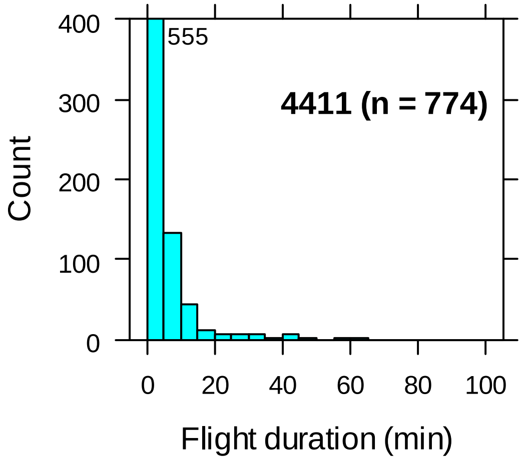
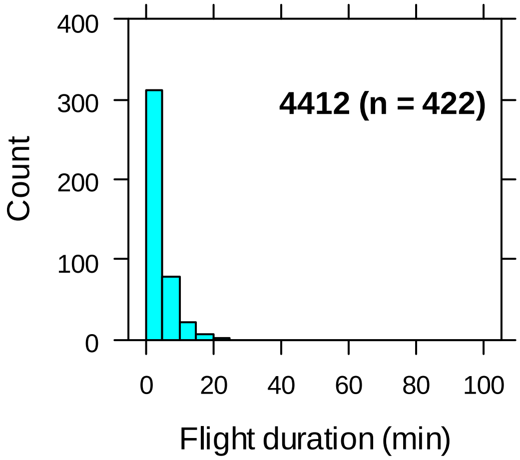
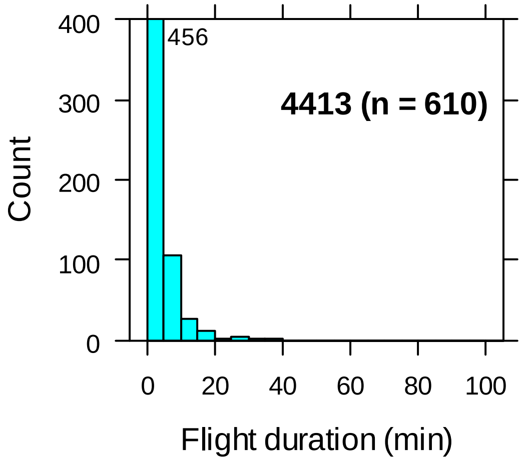
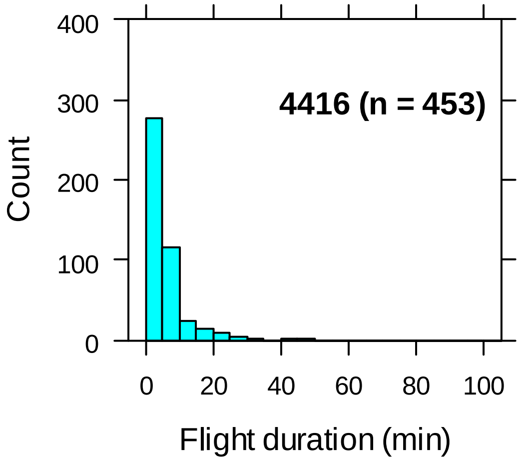






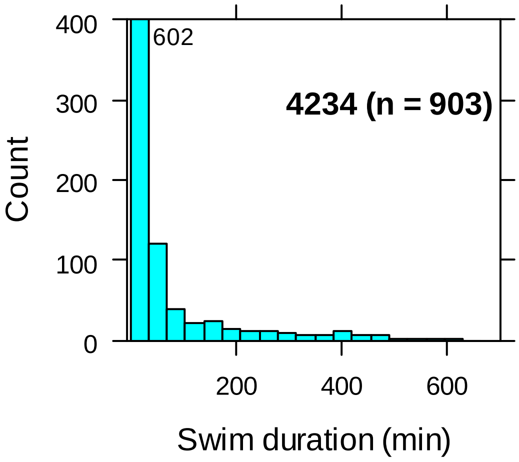


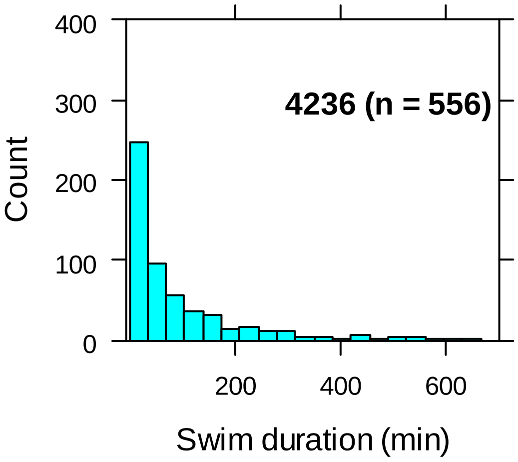


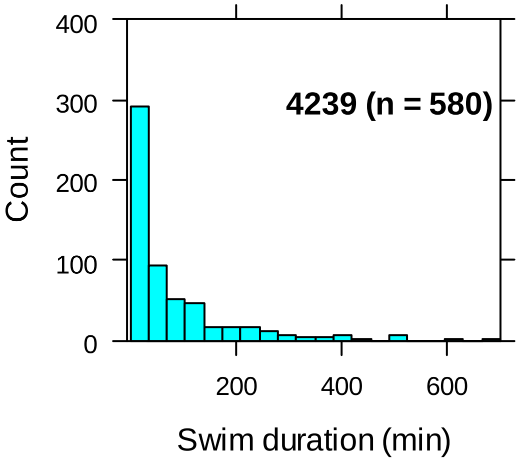


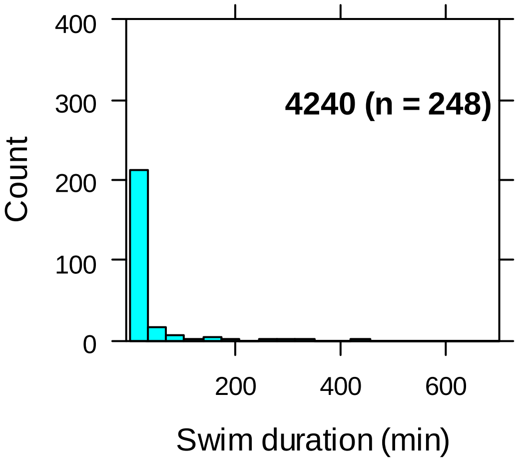
8.2 Appendix 2. Swim duration frequency distributions of individual murres.

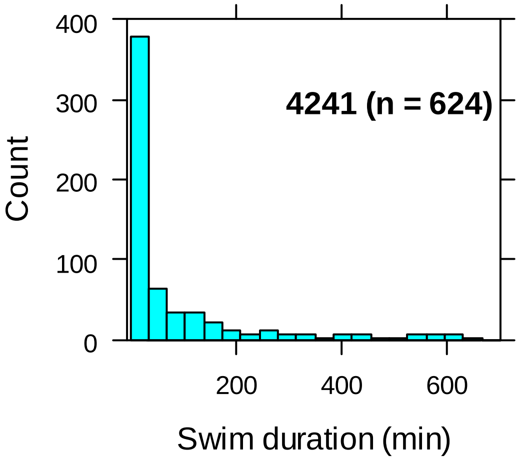
The following histograms depict the distribution of swim times between December and February for each individual murre. Each plot is labelled with the bird's device number as well as the number of swims (n). The y-axes are scaled to adequately portray the details of the distributions and in some cases the height of the first bar extended beyond the top of the plot, in which case the height of the first bar is indicated with text. Behaviours are typified by many short flights (< 35 min) and fewer longer swims.







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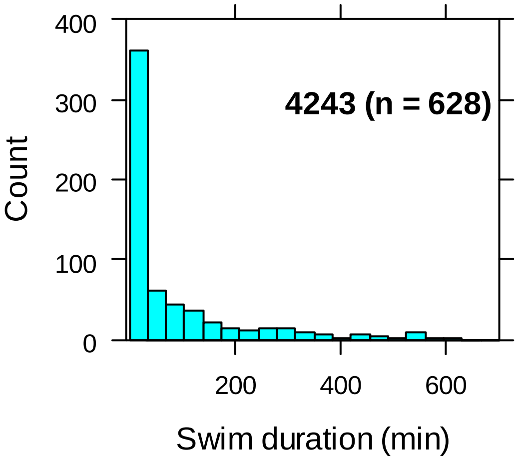
200
400
600
Swim duration (min)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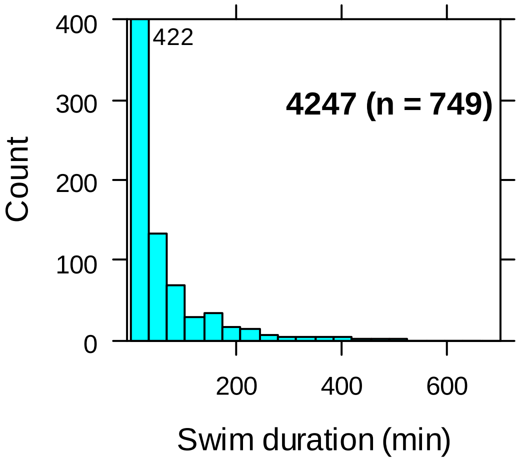
Swim duration (min)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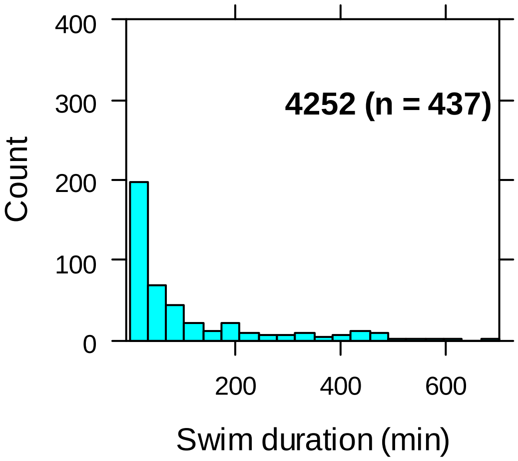
0
200
400
600
Swim duration (min)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Count
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300
200
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0
200
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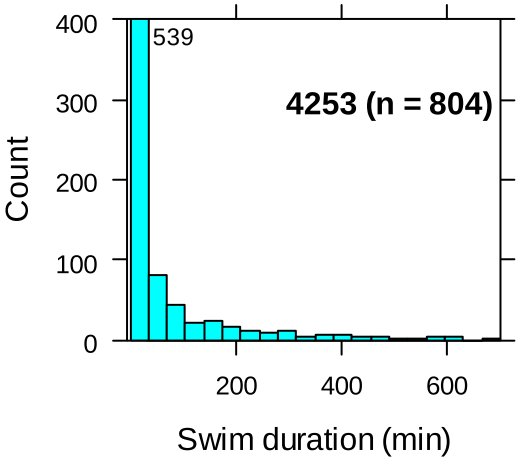
600
Swim duration (min)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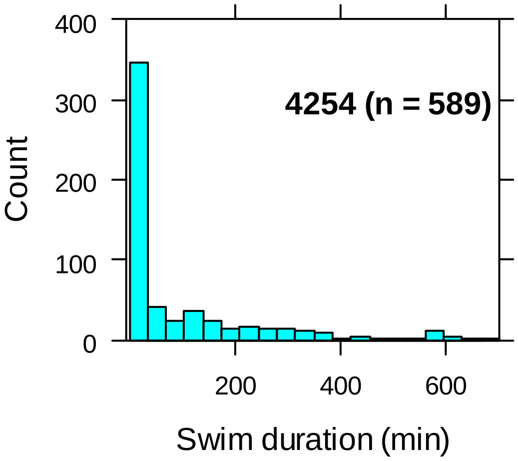
200
400
600
Swim duration (min)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Count
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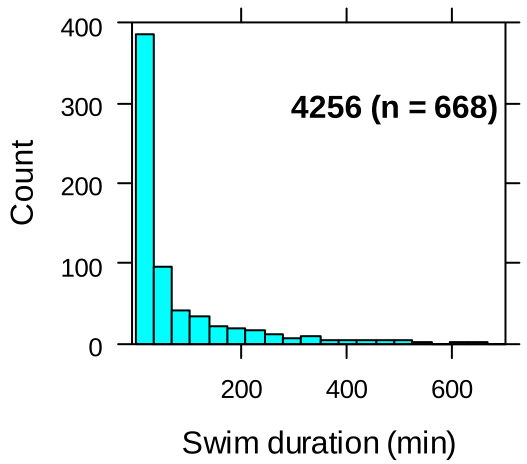
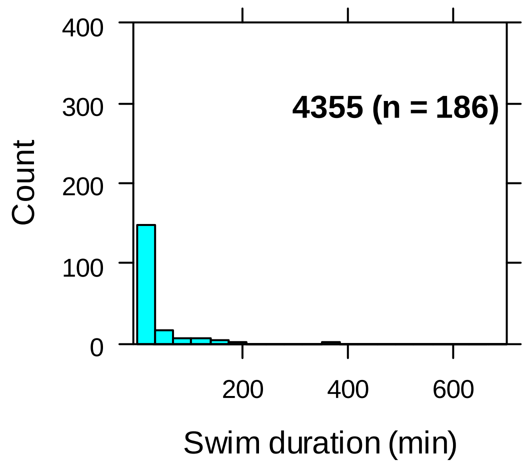
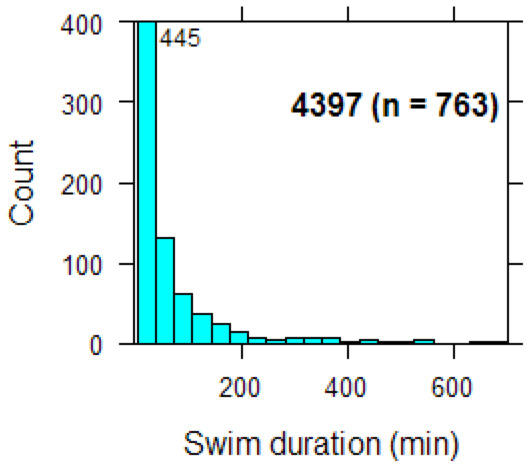
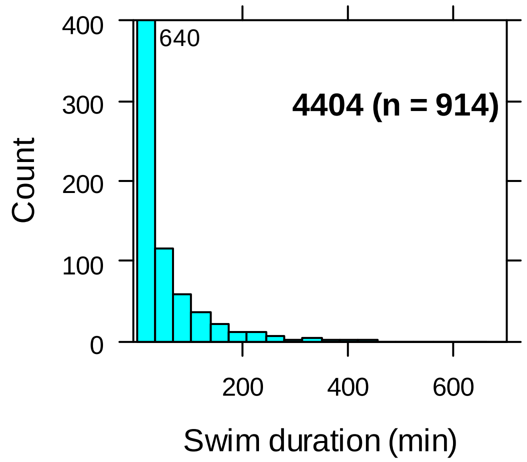
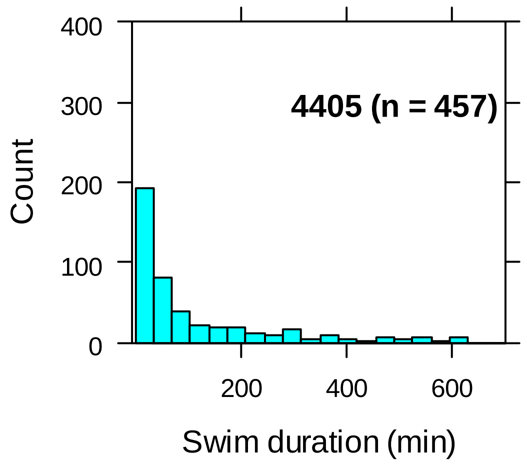
200
100
0
200
400
600
Swim duration (min)

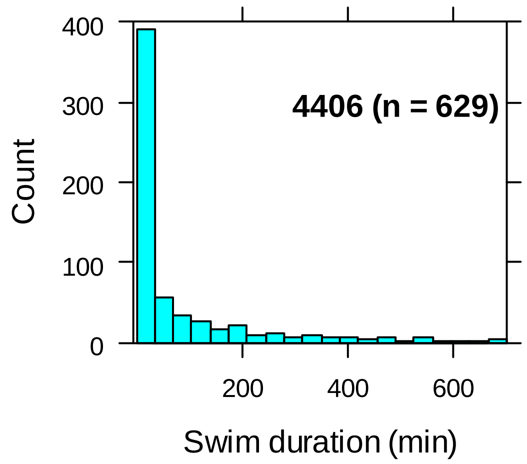

4256 (n = 668)
Count
400
300
200
100
0
200
400
600
Swim duration (min)

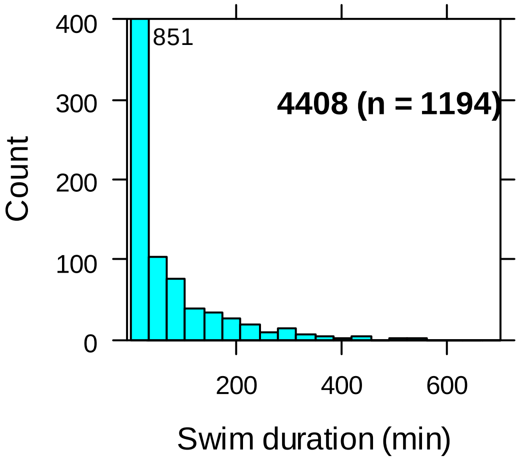

4355 (n = 186)
Count
400
300
200
100
0
200
400
600
Swim duration (min)

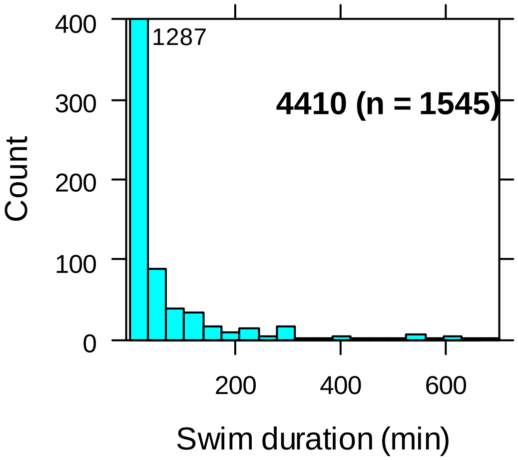

445
4397 (n = 763)
Count
400
300
200
100
0
200
400
600
Swim duration (min)

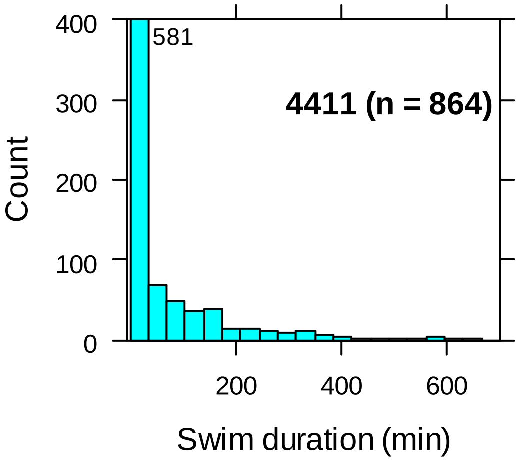

640
4404 (n = 914)
Count
400
300
200
100
0
200
400
600
Swim duration (min)

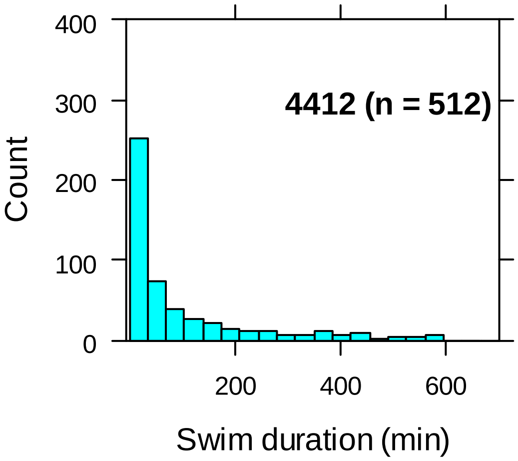

4405 (n = 457)
Count
400
300
200
100
0
200
400
600
Swim duration (min)

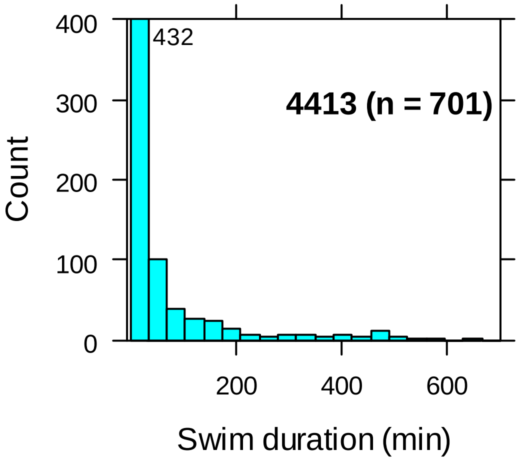

4406 (n = 629)
Count
400
300
200
100
0
200
400
600
Swim duration (min)

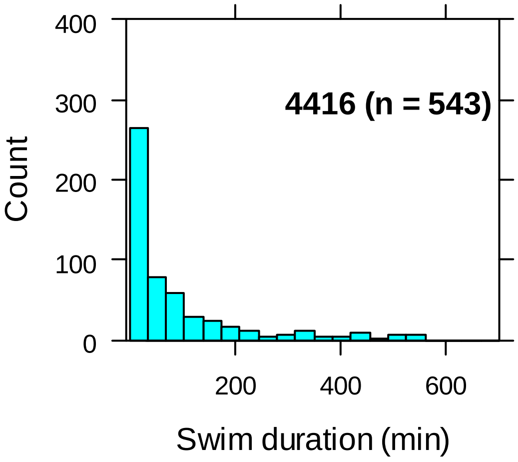

4408 (n = 1194)
851
Count
0
100
200
300
400
200
400
600
Swim duration (min)


4410 (n = 1545)
1287
Count
0
100
200
300
400
200
400
600
Swim duration (min)


4411 (n = 864)
581
Count
0
100
200
300
400
200
400
600
Swim duration (min)


4412 (n = 512)
Count
0
100
200
300
400
200
400
600
Swim duration (min)


4413 (n = 701)
432
Count
0
100
200
300
400
200
400
600
Swim duration (min)


4416 (n = 543)
Count
0
100
200
300
400
200
400
600
Swim duration (min)