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Developing bird-strike risk assessment models for open-water restorations

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Abstract: Mineral extraction sites that are restored to open water can increase bird-strike risk if they are planned near airports. This can generate conflict between the minerals industry and safeguarding authorities. To help resolve this potential conflict, it would be useful to predict how new restorations affect local water-bird populations so that mineral deposits can be exploited and restored in safeguarded zones without compromising flight safety. Bird abundances and movements at new restorations can be estimated with statistical models that use the environmental characteristics of restoration schemes as predictor variables. These models can improve guidance in safeguarding, provided that they comprise parameters that can be quantified or conceived at the planning stage. In this paper, we present suitable models based on bird counts conducted during 2004–2006 at 256 open-water restoration sites. We used the morphology of the restorations, their geo-spatial relationships, ecological characteristics and usage as explanatory variables in regression models that describe water-bird abundances, the likely presence of geese and gulls, and the frequency of bird movements in the nonbreeding and breeding seasons. The models that can best be used as predictive tools were selected using multi-modal inference techniques. We demonstrated how their application can provide objective data on the likely impact a restoration design will have on bird-strike risk.

Key words: bird strike, England, geese, gulls, human–wildlife conflicts, mineral extraction, predictive models, restorations, risk assessment, water birds.

Collisions between aircraft and birds (Dale 2009, Dove et al. 2009, Bernhardt et al. 2009) and mammals (Peurach et al. 2009, DeVault et al. 2009, VanCauteren et al. 2009) pose a risk to flight safety and cause significant economic loss (Allan 2002, Cleary et al. 2006). In recognition of these risks, the U.K. government conforms to International Civil Aviation Organization recommendations (ICAO 2000) and has set up an airport safeguarding process. Any development within 13 km of a safeguarded civil or military airport must be assessed to determine whether it may cause an increase in bird-strike risk.

This process often generates conflicts between the safeguarding authorities and the minerals industry, especially when open-water restoration schemes that attract wildlife are planned for mineral extraction sites near airports. These conflicts arises primarily due to the types and numbers of water birds that these restoration schemes may attract. Water birds, particularly waterfowl and gulls, are a major threat to air safety on account of their size and behavior (Rochard and Horton 1980, Allan 2006).

Some 44% of the land area in England that encompasses many potential mineral deposits falls within safeguarded zones around airfields (Henney et al. 2003). Mineral aggregates are an important strategic resource, and, in the United Kingdom, restorations of extraction sites that enhance wildlife also contribute to biodiversity action plans (Bate et al. 1998, Green Balance and Aquatic Environments Research Centre [AERC] Ltd. 1998). It would be useful to predict the likely outcome of restorations on local bird populations so that mineral deposits in safeguarded zones can be exploited and restored without compromising aviation safety.

The environmental characteristics of open water restorations that affect the abundances of water birds have been identified in various quantitative distribution models (e.g., Sillén and Solbreck 1977, Stoecker et al. 1982, Tuite et al. 1984, Bell et al. 1997). Some of these characteristics are quantifiable at the planning stage of development and could be used to assess the potential impact a new design of open water restoration may have on bird-strike risk.

We derived statistical models of water-bird abundances and movements at open water restorations from the environmental characteristics of the restorations, their usage, and their geo-spatial relationships. We used multi-modal inference techniques to identify the best approximating model for estimating (1) total water-bird abundance in the nonbreeding and breeding seasons, (2) the likely presence or absence of geese and gulls (the most hazardous species), and (3) the frequency of radar-tracked movements of water birds in the nonbreeding season.

Methods

Study area

We gathered data from 256 restorations between October 2004 and September 2006. These restorations were concentrated in 2 areas, the Thames valley and the Humber catchment, including sites in the basins of the Trent and Ouse rivers. We obtained bird counts and geospatial data from all the restorations. We collected more detailed characteristics from a subset of 97 of the sites. Restorations were allocated to this subset using a selection procedure that ensured key features remained represented within the subset of data. To achieve this, we constructed a matrix based on the initial relationships that were identified between the number of water birds and the area of open water by Robinson et al. (2004), as well as possible geospatial effects caused by the number of adjacent restorations (Brown and Dinsmore 1986, Fairbairn and Dinsmore 2001). The matrix grouped the restorations according to each site's area of open water (either <6, 6–15, or >15 ha) and its proximity to others (either ≤2 restorations, 2–10 restorations, or >10 restorations). A maximum of 10 restorations was allocated per group; we discarded extraneous restorations by random selection where groups were over populated.

Measuring the environmental features of the restorations

We geo-referenced the location and outline of all the restorations with a geographic information system (GIS), ARCview 9.0 (ESRI 1999), and used this software to accurately measure the restorations, geo-spatial and morphological features. All the restorations were grouped into one of 3 regions—the North, Midlands, or South of England—to account for any regional variation in bird numbers (Table 1). We also grouped the restorations into clusters according to their proximity to adjacent sites. Restorations >0.5 km apart were allocated to separate clusters. This acquisition was important because mineral extraction sites rarely occur in isolation, and the presence of other adjacent sites may influence bird numbers and their movements (Brown and Dinsmore 1986, Fairbairn and Dinsmore 2001, Tiner 2003). Grouping the data in this way also enabled us to take account of differences in the water-bird populations among clusters of restorations and to identify the importance of individual restorations both within clusters, as well as within the whole data set. We allocated 45 clusters; the number of restorations within each cluster varied between one and ninety-eight, defining both isolated water bodies and extensive complexes of open water (Table 1).

From the subset of 97 restoration sites, we obtained data about the biology, water chemistry, and usage of each site. At these restorations we quantified the number of waterside habitats using Phase 1 Habitat Surveys (JNCC 2004). The number of waterside habitats can influence the diversity and abundance of water-bird populations (Sillén and Solbreck 1977, Bell et al. 1997). We recorded a maximum of 5 habitats around the restorations, and we investigated the effect of habitat as a 5-tiered factor in the models (Table 1). We also included as a continuous variable the percentage of shoreline that was composed of emergent reed beds. We included the presence of short grass as an additional factor in the models because large numbers of geese may gather at restorations where there is short grass (Tuite et al. 1984, Allan 1999).

We also recorded the presence of artificial rafts and fish stock, noting whether restorations were stocked with game fish (e.g., salmonids) or coarse fish (e.g., cyprinids). Rafts placed on restorations can attract birds by providing a platform for nesting gulls, terns, or waterfowl, as well as safe loafing sites (Andrews and Kinsman 1990). Presence of fish can reduce water-bird abundance through competition for food (Giles et al. 1989, Barnard 1990). There is also evidence that stocking with game fish has a greater impact on water-bird abundance than stocking with coarse fish (Giles 1992).

We recorded the pH, potassium content, and general hardness of the water in each restoration using a standardized testing kit, and we used these data as continuous variables

Table 1. The list of parameters we used to describe the geo-spatial relationships, morphology, biology, and use of the mineral extraction site restorations (*n* denotes the sample sizes obtained for each parameter). We used Subset 1 parameters as predictors of the bird abundances that were recorded at all 256 sites. We used Subset 2 parameters as predictors of the bird abundances at 97 sites where additional data on restoration features were collected. We used Subset 3 parameters as predictors of bird movements that we tracked by radar at 26 restoration sites. (n. a. = not applicable)

Function	Parameters	Scale	Transformation	n	Subset
Geo-spatial	Cluster group	Factor 1–45[a]	n. a.	256	*
	Region	1 = North, 2 = Midlands, 3 = South	n.a.	256	1,2
	Number of pits in the cluster	Continuous 1–98	none	256	1,2
	Total area of open water in the cluster	ha	none	256	1,2
	Total length of shoreline in the cluster	m	none	256	1,2
Site morphology	Area	ha	$\log_{10}$	256	1,2,3
	Perimeter or shoreline	m	$\log_{10}$	256	1,2,3
	Sinuosity[e]	Circumference of circle or perimeter	none	256	1,2,3
	Presence-absence of islands	0 = absent, 1 = present	n. a.	255	1,2,3
	Number of islands	0–30	none	255	1,2,3
	Area of islands	ha	none	189	2
Site biology	Habitat diversity	Factor 1–5[b]	n. a.	97	2
	Presence/absence of short grass	0 = absent, 1 = present	n. a.	97	2
	Reed abundance	%	none	97	2
	Presence-absence of rafts	0 = absent, 1 = present	n/a	97	2
	Additional fish stock	1 = none, 2 = coarse, 3 = game	n/a	97	2
	Water pH	pH 1–12	none	96	2
	Potassium hardness	Tetra °dh	none	96	2
	General hardness	Tetra °dh	none	96	2
Site use	Recreational usage	Factor 1–5[c]	n/a	97	2
	Public access group	Factor 1–4[d]	n/a	95	2

[a]The clusters (and site number) were included in the linear mixed effects models of bird abundances as random effects (see Methods).
[b] The number of National Vegetation Classification Phase 1 vegetation types adjacent to the bank (a range of 1 to 5 was recorded).
[c] 1 = fishing, 2 = nature reserve, 3 = None, 4 = sailing, 5 = water sports.
[d] 1 = members only with full bank access to fishing permit holders or sailing club members, 2 = private with normally no access without owners permission, 3 = restricted to hides with no public access directly to the bank, 4 = unrestricted public access.
[e] Sinuosity = the shape of the shoreline relative to a circle, calculated as the ratio of the site perimeter to the perimeter of a circle of equal area (Gibbs et al. 1991).

in our models. Water chemistry may affect bird abundances and assemblages through its impact on the aquatic animal and plant communities (Andrews and Kinsman 1990, Hoyer and Cranfield 1994, Bell et al. 1997).

We also categorized the restoration sites according to their use and amount of public access to account for the impact of human disturbance on water-bird abundance (Tuite et al. 1984, Ward and Andrews 1993, Bell et al. 1997, Evans et al. 1997). We designated 5 types of recreational use and 4 types of public access as factors in the models (Table 1).

Water-bird counts

We obtained bird counts from all of the 256 restoration sites. The subset of 97 restorations was visited every 4 to 6 weeks between October 2004 and September 2006. We obtained a mean of 14.5 counts (range 9–23 visits) from the subset of 97 sites and a mean of 4.1 counts from the remainder of sites (range 123 visits).

We counted all water birds encountered on the water or in the waterside habitats located within clusters of restoration sites in the shortest time period possible to minimize the risk of double counting. Our surveyors circled each restoration site wherever possible to ensure that all water birds were seen. We also grouped species into guilds, based on their feeding behavior; these guilds included geese, dabbling ducks, diving ducks, diving species, grazers, piscivores, and waders (Pöysa 1983). Counts conducted at dawn and dusk were likely to be higher than at other times, and to account for this possible variation, we designated these counts separately as peak counts in the analyses.

Movements of water birds

We employed bird detection radar to quantify the scale and frequency of bird movements at restoration sites. The radar was based on marine S-band surveillance radar and was capable of detecting birds to a distance of 6 nautical miles. We tracked, plotted, and counted bird echoes using GIS (ArcView GIS 9.1, ESRI, Redlands, Calif.). We counted only the numbers of bird tracks that started or ended in each water body. This process eliminated most non-water-bird movements from the analyses and enabled us to assess how the properties of different water bodies influenced the numbers of birds utilizing them. All data were limited to those sites with good radar coverage.

Data analyses

We performed analyses for total water-bird abundance, abundances of the species guilds, the abundances of mallards (*Anas platyrhynchos*) and tufted ducks (*Aythya fuligula*), frequency of bird movements, presence of geese, and presence of gulls. Only the models for total water abundance, bird movements, and presence of geese and gulls are reported here.

We divided all the count data between the breeding (April–July) and nonbreeding seasons (August–March) and analyzed these data separately. This division aided the analyses by removing the seasonal variation in the data caused by migratory behavior and possible differences in the use of restorations by water birds between the nonbreeding and breeding seasons (Pöysa 1984, Owen et al. 1986).

Total water-bird abundances were $\log_{10}$+1 transformed prior to analyses to achieve homoskedasticity. We then used linear mixed-effect regression analysis to build models using the restoration site parameters of interest.

Distributions of the geese and gull counts were highly skewed. However, transforming the counts did not achieve homoskedasticity because geese and gulls were absent from many of the restorations. Therefore, we modeled the distribution of geese and gull counts by 2 methods. First, to model the abundances, we omitted the sites where they were absent from the analyses. In this way, the abundance data could be $\log_{10}$ +1 transformed to achieve homoskedasticity and models of their abundances could be constructed using linear mixed-effect regression analysis. Second, to predict the probability of presence or absence, we constructed generalized linear mixed models using restricted likelihood estimation and assuming a binomial distribution.

We used the mixed-effect models to account for possible correlations between the repeated counts at each site and correlations between the counts from sites within the same clusters. Thus, site nested in cluster was the random effect model fitted.

Two subsets of the data on restoration

site features were used to model the bird abundances and presence (see Table 1). Subset 1 was composed of the geo-spatial and morphological features that we measured using GIS software. It comprised data from all 256 restorations. Subset 2 was composed of the parameters concerning the biology, water chemistry, and use of the restorations, as well as the parameters from Subset 1. It comprised data from the subset of 97 restorations where we had collected the additional data. For both data subsets, we investigated each restoration site feature and their interactions during model building.

For the linear mixed effect analyses of abundances, we used a multi-modal inference approach with Akaike's Information Criterion (AIC) to identify the best supported models (Burnham and Anderson 2002). We then assessed the best-supported models in each subset of the data by comparing the Akaike weights (Rushton et al. 2004) and R2 values (Magee 1990, Xu 2003). Favored models were the least complex and made the most intuitive ecological sense. We then reran the most suitable pairs of models using restricted likelihood estimation to generate unbiased parameter estimates (Pinheiro and Bates 2000).

For the general linear mixed-model analyses for the probabilities of presence, we judged the assessment of the importance of individual predictive parameters using Wald statistics (Welham and Thompson 1997), residual diagnostics, and complexity. This allowed us to identify the best-supported models.

We obtained good coverage of radar-tracked bird movements from 26 restorations that were located within 4 clusters of sites in the Thames valley. These data were sufficient to model which restoration features affected bird movements. We analyzed the data using a third subset of the restoration site features (Subset 3) as predictors of the total number of tracked movements, Table 1. Prior to analysis, we transformed the movements using $\log_{10}$ + 0.1 to achieve homoskedasticity. We derived linear regressions using each restoration feature, combination of features, and their interactions as explanatory variables in separate models. We then used a multi-modal inference approach to identify the best-supported model(s) as described above.

Results

Predicting water-bird abundance

The models for total water-bird abundance explained more variation than the other models of abundance (Appendix 1). Here, we present these models as the best predictive tools for estimating abundances in the breeding and nonbreeding seasons. The following Subsets 1 and 2 models were selected and can be used to predict total water-bird abundance in the nonbreeding and breeding seasons.

Subset 1, nonbreeding season model. $\log_{10}$ (total water-bird abundance +1) = 1.091+ 0.946 ($\log_{10}$ area of open water) - 0.003 (number of adjacent sites) + 0.017 (number of islands) + 0.112 (if in region 2) + 0.059 (if in region 3) + 0.142 (number of islands if in region 2) – 0.017 (number of islands if in region 3).

Subset 2, nonbreeding season model. $\log_{10}$ (total water-bird abundance +1) = 0.546 + 1.392 ($\log_{10}$ area of open water) – 0.006 (number of adjacent sites) + 0.581 (if category 2 public access) + 2.280 (if category 3 public access) + 0.751 (if category 4 public access) – 0.146 (if islands are present) + 0.392 ($\log_{10}$ area of open water if islands are present) – 0.166 ($\log_{10}$ area of open water if category 2 public access) – 2.068 ($\log_{10}$ area of open water if category 3 public access) – 0.597 ($\log_{10}$ area of open water if category 4 public access).

Subset 1, breeding season model. $\log_{10}$ (total water-bird abundance +1) = 0.978 + 0.695 ($\log_{10}$ area of open water) + 0.041 (number of islands) + 0.080 (if islands are present) + 0.011 (if in region 2) – 0.080 (if in region 3) + 0.175 (number of islands if in region 2) – 0.040 (number of islands if in region 3).

Subset 2 breeding season mode. $\log_{10}$ (total water bird abundance +1) = 0.730 + 0.596 ($\log_{10}$ area of open water) – 0.011 (number of adjacent sites) + 0.296 (if category 2 public access) + 0.526 (if category 3 public access) + 0.267 (if category 4 public access) + 0.046 (if 2 vegetation types are adjacent to bank) + 0.159 (if 3 vegetation types are adjacent to bank) + 0.743 (if 4 vegetation types are adjacent to bank) + 0.294 (if 5 vegetation types are adjacent to bank) + 0.188 (if short grass is adjacent to bank) + 0.163 (if islands are present) + 0.007 ($\log_{10}$ area of open water × the number of adjacent sites).

The area of open water, the presence and number of islands, as well as regional effects and the type of public access were important

Table 2a. Parameter estimates from the Subset 1 and Subset 2 models selected to predict total waterbird abundances during the nonbreeding season. (Refer to Table 1 for definitions of each parameter.)

Model	Parameters	Effect	SE	*t*-value	*P*-value
Subset 1	Intercept	1.091	0.122	8.917	<0.001
	Area of open water	0.946	0.069	13.648	<0.001
	No. of sites in the cluster	− 0.003	0.002	− 2.103	0.018
	No. of islands	0.017	0.024	0.710	0.239
	Region 2	0.112	0.135	0.824	0.205
	Region 3	0.059	0.119	0.501	0.308
	Region 2 × No. of islands	0.142	0.057	2.471	0.007
	Region 3 × No. of islands	− 0.017	0.026	− 0.669	0.252
Subset 2	Intercept	0.546	0.181	3.021	0.001
	Area of open water	1.392	0.159	8.737	<0.001
	No. of sites in cluster	− 0.006	0.002	− 3.202	0.001
	Public access 2	0.581	0.257	2.262	0.012
	Public access 3	2.280	0.607	3.756	<0.001
	Public access 4	0.751	0.201	3.736	<0.001
	Islands present	− 0.146	0.188	− 0.779	0.218
	Area of open water × Islands present	0.392	0.191	2.058	0.020
	Area of open water × Public access 2	− 0.166	0.273	− 0.609	0.272
	Area of open water × Public access 3	− 2.068	0.726	− 2.849	0.002
	Area of open water × Public access 4	− 0.597	0.195	− 3.058	0.001

Table 2b. Parameter estimates from the Subset 1 and Subset 2 models selected to predict total waterbird abundances in the breeding season. (Refer to Table 1 for definitions of each parameter.)

Model	Parameters	Effect	SE	*t*-value	*P*-value
Subset 1	Intercept	0.978	0.121	8.093	<0.001
	Area of open water	0.695	0.068	10.164	0.000
	No. of islands	0.041	0.034	1.212	0.113
	Islands present	0.080	0.067	1.185	0.118
	Region 2	0.011	0.132	0.086	0.466
	Region 3	− 0.080	0.118	− 0.681	0.248
	Region 2 × No. of islands	0.175	0.058	3.026	0.001
	Region 3 × No. of islands	− 0.040	0.034	− 1.176	0.120
Subset 2	Intercept	0.730	0.142	5.149	<0.001
	Area of open water	0.596	0.126	4.719	<0.001
	No. of sites in cluster	− 0.011	0.003	− 3.479	<0.001
	Public access 2	0.296	0.111	2.655	0.004
	Public access 3	0.526	0.127	4.156	0.000
	Public access 4	0.267	0.091	2.949	0.002
	Habitat diversity 2	0.046	0.093	0.490	0.312
	Habitat diversity 3	0.160	0.116	1.376	0.085
	Habitat diversity 4	0.743	0.211	3.532	<0.001
	Habitat diversity 5	0.294	0.189	1.556	0.060
	Short grass present	0.188	0.082	2.284	0.011
	Islands present	0.163	0.076	2.161	0.016
	Area of open water × No. of sites in cluster	0.007	0.003	2.415	0.008

Table 3a. Parameter estimates from the Subset 1 and Subset 2 models that can be used to predict the probability of geese occurring at new restorations during the nonbreeding season. (Refer to Table 1 for definitions of each parameter.)

Model	Parameters	Effect	SE	*t*-value	*P*-value
Subset 1	Intercept	−2.601	0.445	−5.851	<0.001
	Area of open water	1.958	0.303	6.459	<0.001
	Islands present	0.972	0.243	4.005	<0.001
	No. of sites in cluster	−0.013	0.005	−2.530	0.006
	Region 2	0.752	0.429	1.754	0.040
	Region 3	−0.303	0.372	−0.813	0.208
Subset 2	Intercept	−14.725	3.302	−4.460	<0.001
	Perimeter	3.705	0.979	3.784	<0.001
	Potassium hardness	0.293	0.110	2.670	0.004
	During peak count times	0.503	0.242	2.083	0.019
	Short grass present	1.096	0.524	2.090	0.019
	Additional fish stock present	−1.035	0.527	−1.963	0.025

Table 3b. Parameter estimates from the Subset 1 and Subset 2 models that can be used to predict the probability of geese occurring at new restorations during the breeding season. (Refer to Table 1 for definitions of each parameter.)

Model	Parameters	Effect	SE	*t*-value	*P*-value
Subset 1	Intercept	0.107	0.662	0.162	0.436
	Islands present	1.430	0.291	4.908	≤0.001
	Length of shoreline in the cluster	-0.1×10^{-3}	0.1×10^{-4}	−3.189	0.001
	Area of open water	0.9320	0.465	2.007	0.023
	Region 2	−0.4619	0.615	−0.751	0.226
	Region 3	−1.3679	0.546	−2.507	0.006
	Area of open water × Length of shoreline in the cluster	0.3×10^{-4}	0.1×10^{-4}	2.897	0.002
Subset 2	Intercept	−8.329	10.403	−0.801	0.212
	Perimeter	4.383	1.180	3.714	<0.001
	Potassium hardness	0.602	0.184	3.268	0.001
	Reeds (%)	−0.027	0.011	−2.430	0.008
	No. of sites in cluster	−0.078	0.036	−2.165	0.016
	No. of islands	0.821	0.382	2.147	0.016
	Region 2	−3.077	1.574	−1.956	0.026
	Region 3	−4.416	1.660	−2.661	0.004
	Water pH	−0.591	1.257	−0.470	0.319
	No. of sites in cluster × No. of islands	−0.010	0.005	−2.126	0.017
Subset 2	No. of sites in cluster × Region 2	0.026	0.045	0.580	0.281
	No. of sites in cluster × Region 3	0.084	0.038	2.244	0.013

parameters in all the models. Habitat diversity and the presence of short grass also explained significant variation in total water-bird abundance in the breeding season (Tables 2a and 2b).

Example of model implementation. Using the Subset 1 model for a new restoration located in southern England with open water covering 3 ha, 5 islands and 10 adjacent restorations total water-bird abundance during the nonbreeding season can be estimated as:

$\log_{10}$ (total water bird abundance +1) = 1.571
Total water bird abundance = 36.27.

The estimated 95% confidence intervals calculated using the restricted likelihood analyses variance-covariance matrix (not shown) are 25.85 and 50.64 birds.

Predicting the occurrence of geese and gulls at new restorations.

We selected the following models derived from Subsets 1 and 2, and these can be used to estimate the probability that geese and gulls will occur in the nonbreeding and breeding seasons.

Subset 1, nonbreeding season models. Logit (probability of geese occurrence) = −2.601 + 1.958 ($\log_{10}$, area of open water) + 0.972 (if islands are present) − 0.013 (number of adjacent sites) + 0.752 (if in region 2) − 0.303 (if in region 3).

Logit (probability of gull occurrence) = − 1.632 + 2.011 ($\log_{10}$ area of open water) −0.014 (number of adjacent sites).

Subset 1 breeding season models. Logit (probability of geese occurrence) = 0.107 + 1.430 (if islands are present) − 0.1 × 10^{-4} (summed perimeter of all adjacent sites) + 0.932 ($\log_{10}$ area of open water) − 0.462 (if in region 2) − 1.368 (if in region 3) + 0.3 × 10-5 ($\log_{10}$ area of open water × summed perimeter of all adjacent sites).

Logit (probability of gull occurrence) = − 3.127 + 1.941 ($\log_{10}$ area of open water) + 0.003 (number of adjacent sites).

Subset 2 nonbreeding season models. Logit (probability of geese occurrence) = −14.725 + 3.705 ($\log_{10}$ perimeter) + 0.293 (potassium hardness) + 0.5032 (if calculating peak numbers at dawn or dusk) + 1.096 (if short grass adjacent bank) - 1.035 (if additional fish stock).

Logit (probability of gull occurrence) = -2.311 + 2.998 ($\log_{10}$ area of open water) − 1.074 × 10^{-5} (the summed perimeter of all adjacent sites) − 0.558 (area of islands) + 0.455 (if category 2 usage) − 0.926 (if category 3 usage) − 0.497 (if category 4 usage) + 0.193 (if category 5 usage).

Subset 2 breeding season models. Logit (probability of geese occurrence) = -8.329 + 4.383 ($\log_{10}$ perimeter) + 0.602 (potassium hardness) − 0.027 (% reed abundance) − 0.078 (number of adjacent sites) + 0.821 (number of islands) − 3.0771 (if in region2) − 4.4159 (if in region 3) – 0.591 (water pH) + 0.026 (number of adjacent sites if in region 2) + 0.084 (the number of adjacent sites if in region 2) - 0.010 (the number of adjacent sites × number of islands).

Logit (probability of gull occurrence) = -30.864 + 6.117 ($\log_{10}$ perimeter) + 10.080 (if in region 2) + 14.292 (if in region 3) + 8.230 (number of islands) - 0.015 (number of adjacent sites) + 1.407 (if category 2 access) + 1.396 (if category 3 access) - 0.682 (if category 4 access) + 0.023 (number of adjacent sites × number of islands) - 4.514 (sinuosity if in region 2) - 7.710 (sinuosity if in region 3) − 2.644 ($\log_{10}$ perimeter × number of islands).

In the nonbreeding season, the size of a restoration (especially the amount of shoreline), number of adjacent sites, presence and number of islands, presence of additional fish stock, short grass, and some differences between regions were important determinants of geese occurrence. Reed cover also was important during the breeding season (Tables 3a and 3b). Area of open water, number of adjacent restorations and their shape, size of islands, and site usage had important effects on gull presence in the nonbreeding season. In the breeding season, gull presence differed among regions and was also affected by the number of islands, restoration shape and type of public access (Tables 4a and 4b).

Example of model implementation. Using the Subset 2 model of geese occurrence, a new restoration with a 600-m perimeter, with no additional fish stock, short grass present, and a potassium hardness of 5 odh gives a likely geese presence at dawn or dusk (i.e., at peak count time) in the nonbreeding season as:

Logit geese occurrence

$$= -14.725 + 3.705(\log_{10}600 + 0.293 \times 5 + 1.096 + 0.503$$
$$= -1.368$$

Probability of geese occurrence

$$= \frac{\exp(-1.368)}{1 + \exp(-1.368)} = 0.20.$$

Therefore, the predicted probability of geese occurrence is 20%. The estimated 95% confi-

Table 4a. Parameter estimates from the Subset 1 and Subset 2 models that can be used to predict the probability of gulls occurring at new restorations during the nonbreeding season. (Refer to Table 1 for definitions of each parameter.)

Model	Parameters	Effect	SE	*t*-value	*P*-value
Subset 1	Intercept	−1.632	0.246	−6.634	<0.001
	Area of open water	2.010	0.250	8.048	<0.001
	No. of sites in cluster	−0.014	0.004	−3.214	0.001
Subset 2	Intercept	−2.311	0.426	−5.430	<0.001
	Area of open water	2.998	0.514	5.829	<0.001
	Length of shoreline in the cluster	-0.1×10^{-4}	0.4×10^{-5}	−3.036	0.001
	Area of islands	−0.558	0.237	−2.353	0.009
	Site usage 2	0.455	0.380	1.197	0.116
	Site usage 3	−0.926	0.416	−2.223	0.013
	Site usage 4	−0.497	0.660	−0.753	0.226
	Site usage 5	0.193	0.619	0.312	0.377

Table 4b. Parameter estimates from the Subset 1 and Subset 2 models that can be used to predict the probability of gulls occurring at new restorations in the breeding season. Refer to Table 1 for definitions of each parameter.

Model	Parameters	Effect	SE	*t*-value	*P*-value
Subset 1	Intercept	−3.127	0.490	−6.376	<0.001
	Area of open water	1.941	0.399	4.864	<0.001
	No. of sites in cluster	0.003	0.013	0.274	0.392
Subset 2	Intercept	−30.864	7.300	−4.228	<0.001
	Perimeter	6.117	1.727	3.541	<0.001
	Region 2	10.080	4.799	2.101	0.018
	Region 3	14.292	5.033	2.840	0.002
	No. of islands	8.230	4.201	1.959	0.025
	No. of sites in cluster	−0.015	0.011	−1.346	0.090
	Public access 2	1.407	0.716	1.965	0.025
	Public access 3	1.396	0.855	1.633	0.052
	Public access 4	−0.682	0.705	−0.968	0.167
	No. of sites in cluster x No. of islands	0.023	0.010	2.420	0.008
	Region 2 x sinuosity	−4.514	2.546	−1.773	0.039
	Region 3 x sinuosity	−7.710	2.740	−2.814	0.003
	Perimeter x No. of islands	−2.644	1.265	−2.091	0.019

Table 5. Parameter estimates from the predictive model of radar-tracked bird movements per hour.

Parameters	Effect	SE	*t*-value	*P*-value
Intercept	−1.071	0.186	−5.770	<0.001
Area of open water	1.397	0.209	6.701	<0.001

dence intervals calculated using the restricted likelihood analyses variance-covariance matrix (not shown) would be 8% and 44%.

Predicting water-bird movements

The most suitable model comprised a simple linear regression that used the area of open water as the only predictor of the number of bird movements per hour (area of open water, F1–24 = 44.9, R2 = 0.637, $P < 0.001$; Table 5), where, $\log_{10}$ (bird movements/hour + 0.1) = −1.071 + 1.397 ($\log_{10}$ area of open water).

Example of model implementation. For a new restoration with 8.5 ha of open water, the model gives an estimated number of bird movements as:

$(\log_{10} + 0.1)$ *bird movements/hour*
$= -1.071 + 1.397 (\log_{10} 8.5 \text{ ha})$
$= 0.23$
Bird movements/hour $= 10^{0.22817} - 0.1$
$= 1.591102$.

Therefore, the predicted number of movements is 1.59 birds per hour. The estimated 95% confidence intervals calculated using the restricted likelihood analyses variance-covariance matrix (not shown) would be 1.02 and 2.46 birds per hour.

Discussion

The predicted impacts that new developments may have on bird-strike risk are rarely quantitative or testable, partly because of the paucity of historical bird-strike data, but also due to a lack of quantitative analyses available in environmental impact assessments (Floater 2002). Current bird-strike risk assessments are subjectively based on the anticipated change a new development will have on local bird populations and their movements (Milsom and Horton 1995, Allan 2001). Now, by using the mathematical models presented here, it is possible to predict hazardous bird abundances and movements for open-water designs of restoration.

We suggest that all predictions for new restorations be based on a comparison of the results obtained from the Subset 1 and Subset 2 models. The highest values predicted by either model in both the nonbreeding and breeding seasons should then be used to help guidance in safeguarding issues.

Although the abundance models can provide broadly accurate estimates, their accuracy is limited to the predictive power of the restoration features that can be quantified at the planning stage. Substantial variation in the data was unexplained by our models. Water depth was an additional factor that was not recorded in our surveys but could be conceived at the planning stage and may have helped explain more variation in our data. Further, unexplained variation in the data may have also concerned differences in the ecological requirements among each bird species or guild.

Our predictions of likely bird movements per hour were based on a model derived from a limited data set. Consequently, the model's application should be speculative; it should be used in conjunction with existing knowledge of local bird movements. The model's predictions should be ground-truthed by field surveys and compared to observed records. The results should be viewed with the following caveats: (1) all predictions only apply to the nonbreeding season; (2) a new restoration's depth, planned use, and the amount of public access may affect the accuracy of the model's predictions; and (3) the predicted frequency of movements may apply only to established mature restorations and, therefore, may be inaccurate for new restorations.

All the models can be applied throughout England but must be limited to the type of restorations that were sampled in our study. These restorations comprised predominantly open-water sites and preclude shallow-water restorations comprising extensive reed beds, mud flats, or other features with little or no areas of open water. More data are needed to better understand how far away from an airport a particular restoration can be before it ceases to have an impact on bird-strike risk.

Management implications

It is of interest to the minerals industry, flight safety, and local planning authorities to understand the likely outcome of site restorations on local bird populations. Often the anticipated change that a new development will have on bird-strike risk can be perceived only subjectively, and, as a result, safeguarding decisions can generate conflict between the developers and safeguarding authorities. The decision-making process could be improved if more objective data were available. Our models can provide the objective data that are needed. Although these models are applicable only in England, the methods used to derive them can be applied anywhere. Our models can help safeguarding authorities protect flight safety without making unnecessary objections to new restorations or the exploitation of mineral resources.

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Alison Colyer (photo unavailable)

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