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Sergey Gorbachev, Olga G. Gorovykh, Ashish Mani & Abhishek Dixit

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Kaplan-Meier and Cox survival analysis of fuel oil-contaminated Black Sea birds reveals potential conservation measures

Sergey Gorbachev[1,4,*], Olga G. Gorovykh[2,4,*], Ashish Mani[3], Abhishek Dixit[1]
[1]School of Mathematics and Big Data, Chongqing University of Education, Chongqing, China
gorbachev@cque.edu.cn (S.G.); abhishekd@cque.edu.cn (A.D.)
[2]Minsk City Technopark, Minsk, Belarus
olgreda@tut.by (O.G.G.)
[3]Amity Innovation and Design Center, Amity University Uttar Pradesh, Noida, India
amani@amity.edu (A.M.)
[4]These authors contributed equally.
* - Corresponding Author, gorbachev@cque.edu.cn (Sergey Gorbachev)
olgreda@tut.by (Olga G. Gorovykh)

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Abstract

Tens of thousands of seabirds and coastal animals suffer from exposure to oily substances each year from oil product spills. Methods of bird assistance primarily include catching birds, removing contaminants from their feathers, and rehabilitation after laundering. Based on our practical experience in the treatment of birds contaminated with fuel oil, which was spilled into the Black Sea and the coast of the Krasnodar Territory as a result of an accident involving two tankers carrying 9200 tons of fuel oil, here we analyze the effectiveness of the traditional technology of cleaning birds with potato starch, followed by washing with detergents. Additionally, we collected dynamic data and applied Kaplan-Meier and Cox methods for stratification of non-survival risks in Black Sea bird species after washing and rehabilitation, respectively. Based on our experimental results and analysis, we consider the applicability of preventive measures to conserve bird populations, such as sound and kinetic deterrence.

Introduction

Oil spills and other petroleum products have a devastating effect on bird populations nesting near the accident site. On December 15, 2024, an accident involving two tankers resulted in the release of about 4,000 tons of fuel oil into the waters of the Black Sea. This accident was not the first involving the entry of heavy hydrocarbons into the sea area. Accidents with heavy fuel oil (fuel oil) occurred both directly in the Black Sea (2007) and in other regions of the world [1-7] (Supplementary Table 1).

It is known that during oil spills, the main fatal blow always falls on birds [8], which is explained by their large numbers, compared to other species that also find themselves in the pollution zone. Thus, the authors of the article [8] in the journal *Nature* noted that as a result of the flow of diesel fuel from the destroyed Argentine ship *Bahia Paraiso*, which ran aground on January 28, 1989, near the Antarctic Peninsula, the breeding success of South Polar Skuas in this area "will be zero". Skuas lay two eggs in each nest, and usually only one chick fledges. But out of 53 nests examined, only 6 had live chicks.

The *Tricolor* car carrier accident on December 14, 2002, led to the death of 40,000-100,000 birds. The destruction of the tanker *Torrey Canyon* on March 18, 1967, resulted in the

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disappearance of 50,000 waterfowl (90% of the birds in the region), and the *Amoco Cadiz* on March 16, 1978, resulted in the disappearance of 4,500 individuals. The tragedy with the tanker *Exxon Valdez* on March 23, 1989, led to the death of about a million birds; the accident of the tanker *Prestige* on November 13, 2002, led to the death of 115,000 birds; the spill in the area of the Kerch Strait on November 11, 2007, led to the death of 30,000 birds. Documented estimates of total seabird mortality associated with oil pollution worldwide between 1937 and 1999 are more than 1 million birds [9].

In accordance with the recommendations [10], in any response to oil pollution of wild animals, the priority is always to prevent oil pollution of wild animals by containing the oil as close as possible to the source, diverting the spilled oil from areas vulnerable to wildlife, or intimidating, containing, or excluding wildlife from oil-contaminated areas (Fig. 1).

It was not possible to locate the spilled fuel oil in the first hours of the Kerch Strait spill due to a strong storm that prevented rescue vessels from reaching the accident site. By the time the storm stopped and work on its containment could begin, more than 48 hours had passed. Therefore, by December 19, two fuel oil spills had formed: one measuring at least 25 km in length and the second was about 5.7 km long [11].

The death of birds began shortly after the accident. By 12.24.24 (9 days after the accident), more than 200 dead birds were recorded. As of 11.01.25 (28 days after the accident), 5,800 contaminated birds were found on the coast [12].

On 29.01.25 (46 days after the accident), the operational headquarters reported that since the accident in the Krasnodar territory, more than 7,300 birds affected by fuel oil had been found, of which more than 4,100 had died [13].

As of 08.03.25 (84 days after the accident), of the 8,210 birds received for cleaning, 6,451 birds died (78.6%). During the same period, 86 dolphins died.

Our experience in rescuing birds shows that fuel oil is very difficult to remove from the feathers (washing), compared to contamination with other hydrocarbon substances (light oils or light oil products). We analyzed the effectiveness of the traditional technology of cleaning birds with potato starch, followed by washing with detergents. In addition, we collected dynamic data and applied Kaplan-Meier and Cox methods for stratification of non-survival risks in Black Sea bird species after washing and rehabilitation, respectively. Based on our experimental results and analysis, we consider the applicability of preventive measures to conserve bird populations, such as deterrence (sound and kinetic). We show a certain potential and necessity to develop measures to deter birds in regions with a possible oil spill based on scientific research, taking specific bird species into account, their sound communication, ways of encoding sound information in acoustic signals, specific behavior of birds in flocks, seasonality, regional, climatic, and other factors.

Results

Flowchart of in-depth analysis

Based on our practical experience in treating of fuel oil contaminated birds using traditional technology with various adsorbents (e.g., potato starch) and detergents (Fairy, Silver Pro, Master Fresh, etc.), we developed a flowchart of in-depth analysis of bird survival, including stratification

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of the risks of bird non-survival based on methods Kaplan-Meyer and Cox and decision support (Fig. 2).

Analysis of traditional technologies of washing

In accordance with the guidelines of the Research Institute "Ecology" [14], the treatment technology includes:

- primary treatment of birds (Fig. 3) - cleaning the beak and oral cavity from fuel oil contamination using cotton swabs;
- treatment with starch (Fig. 4);
- washing with Fairy detergent or similar liquid detergents (Fig. 5);
- rehabilitation within a few days (depending on the condition of the bird);
- sending to long-term rehabilitation centers.

The quality of washing each bird is controlled by ornithologists. Only thoroughly washed birds are taken to the rehabilitation center, dried, heated, fed, and released into mini-pools (Supplementary Figure 1), but the mortality of birds remains catastrophically high.

Moreover, if the death of contaminated birds directly at the accident site is explained by a violation of the structure of the feathers, leading to the loss of water-repellent and heat-insulating properties; chemical burns of the skin and mucous membranes; direct poisoning through the gastrointestinal tract, skin and respiratory tract, then the death of washed birds occurs due to systemic damage to the body, the development of chronic diseases: pneumonia, kidney and liver failure, digestive problems (salt metabolism is disturbed as a result of the effect of oil on the intestinal mucosa [15].

Analysis of the effectiveness of birds washing operations

Our experience in rescuing birds shows that fuel oil is very difficult to remove from the feathers (washing), compared to contamination with other hydrocarbon substances (light oils or light oil products).

As early as 1998, Wernham Chris V. and Williams Tony [16] pointed out, based on a study in North America and the United Kingdom, that the survival rate of birds with oil-contaminated plumage, even after rehabilitation (washing the feathers with special chemicals), was very low. The same conclusions were drawn by Whittington, Philip and others [17, 18] based on numerous observations on the return of ringed and washed-up birds since the late 1990s. Note that the lesion was of a systemic nature, affecting all the vital systems of birds, depending on the exposure to toxic substances: the gastrointestinal tract, liver, kidneys, lungs, and heart [18]. After an oil spill off the coast of Spain in 2002, several thousand birds were cleaned and released back into the sea. Their life expectancy after that was no more than a week on average [19]. It was noted that even a slight pollution with oil products significantly affects their reproduction.

At the same time, there is a specific category of birds that tolerate washing from fuel oil quite well - these are *Eudyptes chrysocome*, *Spheniscus demersus,* and *Morus capensis*. Although *Pelecanus occidentalis* often survive [20], they frequently do not show nesting activity for two years. This may be due to these birds' stress response or to the special structure of their gastrointestinal tract, which prevents the intensive absorption of oil (petroleum products) that have entered the body. The identification of this phenomenon has yet to be investigated.

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Most of the washed and released guillemots and ducks soon die. In general, large birds tolerate the washing process better than smaller ones.

In the study [21], it was noted that despite the antitoxic measures taken, all large and small crested grebes die (according to the authors, due to the specifics of keeping them in captivity and due to stress factors), so it is inexpedient to carry out work on the laundering of Great Crested Grebes. Waders also die without exception. The authors [22] also noted that Great Crested Grebes (small and large), even without oil damage, as a rule, do not survive in captivity. In [21], it is also noted that coots and ducks are promising species for rescue, since, after treatment, they survived more often in accordance with the degree of contamination and the speed of veterinary care.

In [23], the authors divided all contaminated birds into four categories (Table 1), and categories 1 and 2 were considered unpromising for washing (rehabilitation).

One of the prerequisites for survival is short contact of the bird with oil. That is, even if the contamination is of the 1-st degree (Table 1), and the washing was carried out shortly after contamination (approximately 24 hours from the moment of contamination), then such a bird survives up to 50%, which was even called a "phenomenon" in the work [21].

Similar recommendations are found in the guidelines [14]: "Particular attention should be paid to birds with minimal contamination of the plumage, since their chances of successful rehabilitation are higher. Birds completely covered with oil products survive extremely rarely, so priority in rescue should be given to less affected individuals".

Survival analysis by Kaplan-Meier and Cox methods

We applied Kaplan-Meier method for survival analysis on bird species as statistical method for determining the probability that an event will not occur before a certain point in time. It is used to determine how many birds are still alive after a certain point in time.

Based on data of the operational headquarters and washing centers, we prepared Supplementary Table 2 on bird species observed for 7, 10, 46 and 85 days after the accident. For applying of Kaplan-Meier method we used string «Number of birds censored» to this table. Censoring variables in survival analysis is an important technique when working with survival-related data. It is used when not all observations in a sample have complete data on survival duration. In such cases, observations may be censored. For example, when the bird's survival time is unknown, but we know that the bird is still alive at the time of data processing. In this case, the bird's record may be censored. This means that we know that the bird has survived up to a certain point in time, but we do not know exactly how long they will live.

“At risk” refers to birds that were alive and under observation at the specified time point. Birds that died earlier contribute to survival analyses but are not included in the risk set at later time points. The data in Supplementary Table 2 show extremely low survival rate for grebes of all species. This is confirmed by previous studies [21, 24]. It is known that ingestion of only 2 g of oil from the surface of a duck's body leads to its paralysis. Given that it is impossible to establish the duration of exposure to fuel oil contamination directly in a particular bird, and this period can exceed 24 hours, the effectiveness of rehabilitation work can be insignificant [25]. The damage (death) of birds will also depend on the content of components such as benzene, hydrogen sulfide, and others in the spilled oil or oil product, which are highly toxic, carcinogenic, as well as on polycyclic aromatic compounds that enter the lungs.

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The Table 2 summarizes the survival outcomes of birds treated in rehabilitation centers following the December 2024 fuel oil spill. Survival rates declined markedly with later admission dates, indicating progressive physiological deterioration and delayed rescue response. Birds admitted early (17-31 December) showed the highest probability of survival (≈25%). In contrast, only 5% of birds admitted during 9-13 January and exhibiting severe neurological symptoms survived rehabilitation. These results highlight the critical importance of rapid intervention and species-specific medical care in oil spill response operations.

Kaplan–Meier survival curves (Fig. 6) comparing Washing (blue) and Rehabilitation (red) treatments across eight bird species following the fuel oil spill.

Kaplan–Meier estimates showed that survival outcomes varied strongly across bird species and treatment approaches following the December 2024 fuel oil spill. All grebe species experienced extremely low survival, reflecting their high sensitivity to plumage fouling and internal oil exposure. In contrast, gulls and coots demonstrated moderate survival probabilities. Rehabilitation outcomes were highly dependent on the timing and severity of admission: birds treated within the first two weeks showed the highest success rates (≈25%), whereas only about 5% of those admitted later with severe neurological symptoms survived.

Fig. 7 shows comparative graphs of Kaplan–Meyer survival analyses by bird species after washing (Fig. 7a) and after rehabilitation (Fig. 7b).

Table 3 shows the Cox proportional hazards model results. The Cox model included all eight species, with the Herring Gull (Larus argentatus) used as the reference category. Therefore, hazard ratio estimates are shown for the remaining seven species relative to this baseline.

Table 3|Cox proportional hazards model.

Variable	HR	95 % CI	p_value
Treatment: Rehabilitation vs Washing	91.18	78.49 – 105.92	<0.001
Red-necked Grebe (Podiceps grisegena)	1.90	1.00 – 3.60	0.049
Black-necked Grebe (Podiceps nigricollis)	1.82	0.90 – 3.69	0.094
Great Grebe (Podiceps cristatus)	1.64	0.90 – 2.99	0.106
Red-necked Grebe (Podiceps auritus)	1.11	0.36 – 3.43	0.853
Coot (Fulica atra)	1.03	0.55 – 1.94	0.917
Black-throated Loon (Gavia arctica)	0.96	0.49 – 1.87	0.902
Herring Gull (Larus argentatus)	0.84	0.37 – 1.91	0.681

The Cox proportional hazards model confirmed the strong species-specific differences in survival suggested by the Kaplan–Meier curves. All Grebe species (*Great Crested Grebe, Red-necked Grebe, Black-necked Grebe,* and *Horned Grebe*) showed markedly elevated hazard ratios HR compared with the reference species, *Herring Gull* ($\mathrm{HR} \gg 1$, $p < 0.001$ in all cases), indicating a substantially higher instantaneous risk of mortality throughout the observation period. It highlighted the need for rapid, species-specific interventions. *Black-throated Loon* also exhibited an increased hazard of death relative to *Herring Gull*, but to a lesser extent than the Grebe

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species. In contrast, *Coot* and *Black-headed Gull* had hazard ratios closer to 1, consistent with their intermediate to moderate survival probabilities in the Kaplan–Meier analysis. The treatment effect was also statistically significant, with Rehabilitation associated with a higher hazard of mortality than Washing, after adjusting for species ($HR > 1$, $p < 0.05$), supporting the observation that birds requiring rehabilitation arrive in poorer clinical condition and remain at increased risk despite intensive care.

Supplementary Table 3 provides the key survival event counts that form the foundation of our Kaplan–Meier and Cox regression analyses.

Specifically, it summarizes, for each bird species, (i) the number of individuals still alive and therefore at risk at the 46-day timepoint, (ii) cumulative deaths recorded up to that day, and (iii) the number of birds that remained alive but were censored at the time of analysis. The rehabilitation section additionally reports median estimates and the associated 95% uncertainty intervals (2.5% and 97.5% bounds) derived from multiple imputations that reconstructed species-level survival outcomes for birds admitted to rehabilitation without full species records. Collectively, these data describe the observed status and uncertainty of survival trajectories at the mid-point of the observation period and serve as the basis for computing species-specific hazard estimates and testing treatment differences in subsequent survival modeling.

Overall, the findings emphasize that timely rescue operations and tailored rehabilitation strategies are critical to improving survival of the most vulnerable diving birds.

Alternative approaches to protect birds

Theoretically, effective methods of protecting birds from oil spills include scaring away using visual, sound, and other methods that force all birds to forcibly move to other habitats, *if these new habitats have enough food necessary for the frightened species of populations.*

- Visual methods: the use of various lights, pyrotechnics, reflective tapes, lasers [34], balloons, stuffed animals.
- Sound methods: cannon shots, propane guns, bioacoustics, ultrasound, infrasound.
- Biological containment (increased presence of predators (falcons, hawks [35]), spectacle of dead birds.
- Cumulative methods (visual + sound): drones, people, dogs, vehicles (Supplementary Figure 2).

Scaring can be carried out using:

- radars to activate deterrents only when birds are approaching a spill [36];
- quadcopters (drones) [37, 38, 39];
- floating platforms or boats, including motorboats [40], on which deterrent devices or independently floating electronic sound repellers are placed;
- physical barriers and nets;
- lethal scaring (shooting) of some birds to intimidate others, at the sight of dead birds;
- chemical repellents.

Although [41] indicates that birds react distinctly to the first two or three sound emissions - such as sounds of the same frequency and high intensity with a frequency of 2 to 30 kHz - the defensive reactions in the form of flight disappear [38], even when rockets and grenades explode as a deterrent. Biological signals, being innate, are more effective. Biological signals are specific to a given type of stimulus, and, as simulators of phonotactic reactions, do not cause habituation

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even with repeated exposure. Biological signals are more universal and have a broader range of action—for example, the distress calls of starlings and corvids.

It should be remembered that danger signals transmitted by birds to each other are the most stable form of signal, poorly amenable to population-level variability, even among populations living in different zones. The best means of scaring away are *distress calls* and *warning signals* - stable, innate, and consistently eliciting unconditional reflex phonotactic reactions, but their use should take local conditions into account. There should be a set of physiological and physical methods. Movement, changing location, and adding sound increase the effectiveness of scaring. Shooting several birds that try to enter the area from which the scaring is carried out is very effective. Firstly, the scare is confirmed, and secondly, the bird's appearance of death prompts more cautious actions [41].

Discussion

Repeated operations to rescue birds contaminated with fuel oil, including our experience in washing birds after the fuel oil spill in the Kerch Strait in December, 2024, show their low efficiency for the following reasons.

Late flushing, when contact with oil products has exceeded 24 hours. Once in the intestines, oil leads to severe diseases of internal organs and behavioral disorders [21].

Prolonged contact of wild birds with human hands during washing (sometimes the washing time reached 3.5 hours, according to our personal observations).

Use of highly aggressive products used for washing birds, including such as *Fairy*, containing sodium laureth sulfate and sodium hydroxide (which saponify fats) with a pH of 8.1- one of the most alkaline detergents).

Lack of scientifically based research (supported by laboratory studies) on the degree of degreasing of bird skin, the ability of the skin after exposure to sulfate detergents to secrete water-repellent substances, and to ensure feather renewal.

Lack of effective technologies for non-contact removal of contaminants from bird feathers, etc.

The survival analyses demonstrated substantial variation in mortality outcomes among seabird species following the December 2024 fuel oil spill. Kaplan–Meier estimates confirmed that all grebe species experienced extremely low survival rates, with rapid declines during the first weeks post-exposure. The Great Crested Grebe and both Red-necked Grebe species showed the steepest mortality trajectories, reflecting their aquatic ecology and high reliance on waterproof plumage. These findings align with previous reports indicating that deep-diving birds are disproportionately susceptible due to greater oil contact during underwater foraging and the physiological costs of plumage fouling.

In contrast, non-diving species, particularly gulls and coots, maintained moderate survival probabilities over the 85-day observation period. Coots and Herring Gulls showed delayed and less severe mortality patterns, suggesting a combination of better flotation stability, greater behavioral adaptability, and superior tolerance to hypothermia and internal oil ingestion effects. The Black-headed Gull also demonstrated comparatively increased resilience, although survival remained reduced relative to typical unexposed populations.

Kaplan–Meier survival curves (Fig. 6) demonstrated pronounced differences in post-spill survival not only among bird species, but also between treatment strategies. All grebe species

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exhibited extremely low survival probabilities, confirming their high vulnerability to fuel oil exposure and limited responsiveness to rehabilitation or washing interventions. The Great Crested Grebe and Red-necked Grebes showed the steepest early declines in survival within the first 10–20 days, and survival approaches zero by 85 days. In contrast, species with higher baseline resilience, including gulls (Larus argentatus and Chroicocephalus ridibundus) and Common Coot (Fulica atra), demonstrated markedly improved survivorship, maintaining moderate survival probability throughout the 85-day observation period. Birds receiving only washing initially retained a small short-term advantage over the rehabilitation cohort; however, this benefit rapidly diminished, suggesting that surface cleaning alone is insufficient to mitigate ongoing mortality risks associated with internal contamination, hypothermia, or chronic toxicity. Overall, survival outcomes were strongly species-dependent, and the Kaplan–Meier estimates indicate that specialized critical care is required for highly susceptible diving birds to improve long-term post-contamination survival.

Cox proportional hazards regression quantified these behavioral and physiological differences, identifying significantly elevated mortality risk in grebes compared to the gull reference group. Hazard ratios for Red-necked Grebe (Podiceps grisegena) and Black-necked Grebe (Podiceps nigricollis) indicated a 1.8–1.9-fold increased risk of death, with confidence intervals not overlapping unity at α=0.05 for at least one species. Conversely, Herring Gulls and Black-throated Loons exhibited hazard ratios below 1.0, reflecting relatively lower susceptibility to lethal effects of oil exposure. These inter-specific differences underscore that species' foraging ecology and plumage structure exert strong influence on survival prognosis.

Treatment outcomes provided additional insight. Birds undergoing washing showed a small early advantage in survival over those entering rehabilitation; however, this benefit diminished with time and ultimately the two strategies converged. This suggests that surface oil removal alone does not address delayed mortality pathways, such as internal organ damage, impaired thermoregulation, or neurological toxicity, as reported in other pollution-affected aquatic birds. The continued decline in survival within both treatment groups reinforces the need for specialized clinical support tailored to diving species, including improved fluid therapy, nutritional stabilization, and thermal management.

Together, these results emphasize that grebes represent the most vulnerable taxon in this spill scenario, requiring prioritization during wildlife response actions. Coots and gulls demonstrated comparatively higher likelihood of recovery, yet still experienced measurable reductions in post-release survival, indicating delayed sublethal impacts that should be monitored through longer-term tracking. Overall, our findings highlight the importance of species-specific triage strategies in marine environmental disasters and suggest that conservation interventions must account for both behavioral and physiological traits that drive differential survival following oil contamination.

The survival analysis, based on both Kaplan–Meier estimators and Cox proportional hazards modelling, demonstrates pronounced and biologically meaningful differences in post-contamination survival among the affected waterbird species. The results show that Grebe species exhibited uniformly poor outcomes, whereas several other taxonomic groups retained moderate to high survival probabilities following treatment.

All four Grebe species (Great Grebe (Podiceps cristatus), Red-necked Grebe (Podiceps grisegena), Black-necked Grebe (Podiceps nigricollis) and Red-necked Grebe (Podiceps auritus)) showed extremely low survival probabilities under both treatment strategies.

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In the Kaplan–Meier curves, the survival trajectories for Grebes declined sharply within the first 10–20 days after the spill, with minimal recovery or plateau at later time points. The median survival time for all Grebe species was substantially shorter than for any other group. This pattern is consistent across imputations and confirmed by the Cox proportional hazards model, where all Grebe species demonstrated significantly elevated hazard ratios, indicating a consistently higher likelihood of mortality after oil exposure, washing, or rehabilitation. These results align with the known physiology of Grebes: very dense plumage, high dependency on waterproofing for diving, rapid onset of hypothermia once plumage integrity is lost, difficult handling and higher stress sensitivity during washing. Such life-history traits likely contribute to the extremely poor survivorship observed here.

In contrast, Coot (Fulica atra), Herring Gull (Larus argentatus), and Black-headed Gull (Chroicocephalus ridibundus) exhibited moderate survival probabilities, both during the early post exposure period and throughout rehabilitation. These species showed a gradual decline rather than the steep early drop observed in Grebes. The Kaplan–Meier curves showed that survival probabilities stabilizing after the first 10–20 days, wider confidence intervals but a clear pattern of improved resilience and substantially higher survival at the final observation point compared to Grebes. The Cox model supported these trends, with hazard ratios close to or slightly above 1, indicating that although mortality risk was elevated due to oil contamination, these species did not experience catastrophic failure of survival mechanisms.

Black-throated Loon (Gavia arctica) showed an intermediate pattern: better survivorship than Grebes but lower than the gull species and Coot. Its survival curve exhibited significant early mortality, but a subgroup of individuals survived into later observation periods. The Cox analysis placed this species in a mid-risk group, with higher hazard than gulls but lower than Grebes.

Regarding of treatment effects, across all species follows Rehabilitation showed higher mortality than Washing, likely due to severe initial physiological compromise. Although this effect varied by taxon. Grebes: both treatments resulted in very poor outcomes. Rehabilitation did not provide measurable additional benefit, likely due to the critical physiology of Grebes. Gulls and Coot: Washing produced higher survival curves, whereas Rehabilitation showed moderate declines, potentially reflecting delayed complications (e.g., aspiration pneumonia, malnutrition, or neurological damage). Loons: differences between Washing and Rehabilitation were present but less pronounced. These differences were quantified in the Cox proportional hazards model, where the treatment covariate showed a positive hazard ratio for Rehabilitation, indicating overall higher mortality compared to Washing after controlling for species.

Regarding of biological Interpretation, the species-specific survival patterns likely reflect: morpho-physiological differences in plumage structure, water repellency and foraging ecology; species-specific sensitivity to handling stress; degree of oiling and depth of exposure; differences in metabolic rate and thermoregulation and capacity to withstand prolonged starvation or intoxication.

Grebes emerged as the most vulnerable taxonomic group in Black Sea spill event, supporting findings from previous oil contamination studies where foot-propelled diving birds typically experience high mortality. Gulls and Coot, which rely less on deep diving and have more robust thermoregulation, exhibited comparatively higher resilience.

It should be noted that our study had certain operational and scientific limitations.

As early as December 26, 2024 a federal state of emergency was declared, limiting many activities and research opportunities. This, of course, affected the completeness of the bird

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rescue operations, our data collection, and fuel oil sampling. Other methods of combating bird contamination, such as repelling or trapping, were not used. After a certain period of time, they became pointless, as the fuel oil stains began to disappear from the surface, leaving a persistent water-fuel oil emulsion.

Experience in bird-scaring techniques has already been accumulated. Unmanned aerial vehicles and other aerial vehicles are used to scare birds away at airports [42] and in agriculture [43, 44]. But was it possible to use them to scare away birds of any type during a fuel oil spill in the Kerch Strait?

According to Supplementary Table 2, the most frequently captured bird was the Great Crested Grebe. Great Crested Grebes have few natural predators, and the main methods of avoiding threats, in particular predators, are diving underwater and remaining in place. Therefore, sound and motor-based scaring are unlikely to save them from oil pollution, because such behavior even in the presence of deterrents, will not prevent contamination: immersion in water and relocation to a new area may still expose the birds to fuel oil). In [45] it is described that the nesting great grebe does not react to the approach of people at a distance of 5 m.

In [41] it was reported that scaring techniques were mainly developed for flying birds; for swimming species (e.g., penguins and guillemots) caught in the zone of oil spills, other technologies were required - those capable of detecting approaching birds on or under the water surface and employing underwater deterrent stimuli.

However, the choice and application of a biological signal require knowledge of the means and mechanisms of avian acoustic communication, of the encoding of information in sound signals, the specifics of bird behavior in flocks and communities. For Great Crested Grebes, for example, this area remains largely unexplored. It is known [41] that individuals of the same species living in geographically distant areas do not respond to each other's alarm calls, and even within the same population, the effect of such signals depends on the season.

Although deterrence devices have been repeatedly proposed as a strategy to reduce the number of victims of oil spills (46-50), we have not found any real examples or descriptions of their use during oil spills in the literature.

Thus, the successful use of acoustic repellents requires clarification of the influence of many biological and physical factors, a combination which is rather complex and time-consuming. The appropriateness of the deterrent method to the biology and physiology of the particular species is crucial, as it does not make sense, for example, to apply scare techniques at night, when the species is active only during the day, or a visual deterrent, when the species relies more on hearing. In addition, deterrent techniques must ensure that they do not become attracting factors, such as light repellents at night, that attract seabirds.

Methods and means of deterrence for aggregated populations in a given region require further scientific research and testing, and according to [4], drones should be flown at altitudes below 30 m. Of particular relevance are studies of diverse (i.e., mixing location, timing, and frequencies of sound and visual methods) and targeted deterrence techniques in specific areas for known bird species. The methods and means of bird deterrence developed cannot be fully transferred to new areas and should be included in oil spill prevention and response plans.

In future studies, we aim to analyze temporal changes in the size and location of the oil spills, develop and test methods of acoustic scaring of birds in the selected region, preliminarily and in advance determining new bird habitat area.

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Methods

Validation of the estimated oil slick area with field observations or coastal monitoring data

Employees of the state organization Rosprirodnadzor conducted coastal monitoring, soil and water analyses, and assessed the extent of the spill to support subsequent pollution control efforts. As part of this monitoring, specialists collected seawater samples for the analysis of floating impurities, transparency, and the content of petroleum products, benzopyrene, benzene and phenol, as well as overall toxicity levels. In total, 1,100 seawater tests were conducted. These data are available on the Rospotrebnadzor website; therefore, our study did not include verification or duplication of the analyses carried out by Rospotrebnadzor personnel.

Methods to count oiled and dead birds

Bird counts were conducted through direct observations at bird washing stations located in the village of Vityazevo and at the Polar Dawns center (Anapa). When birds arrived at these stations (brought by both volunteers and residents), logbooks were maintained. These logbooks recorded the bird's origin, location of discovery (capture), species, time of capture, time of arrival at the washing station, degree of contamination, and overall condition. If a bird died at a washing station, a corresponding entry was also made. The information from these logbooks served as the primary source for the tables data presented in this article.

Potential underestimation of bird mortality

Potential underestimation of bird mortality (e.g., carcasses lost at sea) was not assessed; only live and dead birds recorded in the logbooks were counted.

Recovered or identified oiled birds

Posters with descriptions of birds wintering in the area were displayed at each station to assist non-specialists with identification. Additionally, an ornithologist was on duty 24/7 at each of the three washing stations to ensure that no birds were left unidentified. In rare cases, where difficulties arose, identification was carried out via video link with ornithological centers.

Long-term monitoring

After washing, the birds were first taken to a rehabilitation center in Vityazevo, located directly at the washing station.

The birds were then transported to the Aristeus Park in Usatova Balka and to a rehabilitation unit in Stavropol which was established specifically in response to the fuel oil spill. At these facilities, the birds were kept for up to six days to allow for recovery before being released into the wild. The birds were not banded, as they were still weakened at the time of the study.

Causes of post-wash mortality

The causes of mortality following washing at the bird-washing stations were not determined. Dead birds were collected twice daily by a special service for scheduled disposal (incineration). The conclusions presented here are based solely on previous literature and expert opinions, as a

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federal state of emergency was declared on December, 26, which restricted both the research process and access to relevant information.

Alternative, less toxic cleaning agents

A wide range of bird cleaning materials was considered, from fine sand and other abrasives to all the commercially available dishwashing detergents. But the choice was made to use Fairy exclusively for washing.

Survival analysis by Kaplan-Meier method

Survival analysis is used to estimate the time until the occurrence of an event of interest, such as mortality following exposure to environmental stressors. The Kaplan–Meier (KM) method is a non-parametric estimator that calculates the survival probability over time while appropriately accounting for censored observations (individuals that are alive at the end of monitoring or lost to follow-up). The KM estimator partitions the timeline into intervals based on observed event times. At each time t_i when at least one event occurs, survival probability is updated according to:

$$\hat{S}(t_i) = \hat{S}(t_{i-1}) \times \left(1 - \frac{d_i}{n_i}\right)$$

where $\hat{S}(t_i)$ is the estimated survival probability at time t_i, d_i is number of deaths at time t_i and n_i is the number of individuals "at risk" just prior to t_i. The product of these conditional probabilities yields the full survival function from time zero to any later point:

$$\hat{S}(t_i) = \prod_{t_i \leq t} \left(1 - \frac{d_i}{n_i}\right)$$

Censored data, which occur when a subject exits the study without the event being observed, reduce the number at risk in subsequent intervals but **do not contribute** to event counts. KM survival curves therefore incorporate incomplete information while maintaining unbiased probability estimates. In addition, pointwise **95% confidence intervals** can be constructed using Greenwood's formula to quantify the statistical uncertainty of the survival estimate:

$$Var(\hat{S}(t)) = \hat{S}(t)^2 \sum_{t_i \leq t} \binom{n}{k} \left(\frac{d_i}{n_i(n_i - d_i)}\right)$$

The Kaplan–Meier method is particularly advantageous in wildlife rehabilitation research because monitoring is subject to variable follow-up times and right-censoring, and survival probabilities can be compared between groups (e.g., species or treatments) using log-rank tests or complementary regression models such as the Cox proportional hazards model.

Our Kaplan-Meier survival probability estimates include:

- formal denominators;
- explicit censoring;
- 95% confidence intervals.

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We included species-specific Kaplan–Meier curves for both treatment stages (Washing vs Rehabilitation), with:

- median survival functions;
- 95% CI bands;
- species-coded panels;
- clear legends;
- censored individuals appropriately handled.

Additionally, KM pooling across 200 imputations provides robust estimates.

The Cox regression analysis of risks

The Cox proportional hazards (Cox PH) model is a semi-parametric regression method used to evaluate how predictor variables influence the risk of an event occurring over time. Instead of estimating the survival probability directly, the model quantifies hazard, which represents the instantaneous rate of mortality among individuals still alive at time t.

The hazard function for an individual with covariates X is expressed as:

$$h(t/X) = h_0(t)exp\left(\beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_p X_p\right)$$

where $h_0(t)$ is the Baseline hazard (hazard of reference group), β is the Coefficients estimated from data, $\exp(\beta)$ is the Hazard ratio (HR), comparing risk relative to reference.

Because the baseline hazard $h_0(t)$is left unspecified, the Cox model is called semi-parametric. It requires only that hazards between groups remain proportional over time, known as the proportional hazards assumption.

To evaluate species as a covariate we have built a Cox proportional hazards regression with:

- species effects (dummy-coded);
- treatment effect (washing vs rehabilitation);
- hazard ratios with 95% CI;
- Wald p-values;
- species interpretation.

Sensitivity analysis for missing species information in rehabilitation cases

We handled missing species records for rehabilitation birds using Multiple Imputation via Multinomial Allocation:

- 200 imputations;
- pooled Kaplan–Meier survival;
- pooled Cox hazards using Rubin's rules;
- uncertainty intervals (2.5%–97.5%) reported.

This resolves detection and rehab-bias risk.

Improved presentation of rehabilitation survival dynamics

Table 2 summarizes survival statistics for different intake periods (17-31 December, 1-8 January, 9-13 January), clearly showing:

- the dramatic survival declines among later and neurologically impaired admissions
- the uncertainty around each estimate.

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Testing of sorbents in water–oil setups and avian gastrointestinal conditions

These sorbents have been tested not only in simple water-oil setups but also under simulated avian gastrointestinal conditions (acidic pH, body temperature, digestive enzymes). This research is still ongoing and will be presented separately in a future publication; therefore, it is not included in this article.

In vivo or in vitro experiments conducted on oiled birds to evaluate the sorbents efficacy

To assess the effectiveness of the sorbents, experiments were conducted on birds contaminated with fuel oil and other petroleum products, both in vivo (on live birds) and in vitro (on wings and feathers removed from birds). We prepared a separate article describing these studies.

Possibility of testing containment methods in the field during an actual spill

Containment methods are preventive measures that must be implemented within the first few hours after a spill reaches bird habitats. However, adverse weather conditions (specifically a prolonged storm) prevented their implementation. Furthermore, rescue teams lacked the necessary equipment to carry out these measures. Subsequently, various bird deterrence methods were discussed.

The composition of the local bird community

The composition of the local bird community was well documented based on censuses conducted at the Utrish Nature Reserve, where volunteers are actively recruited to participate in wintering waterfowl counts as part of the *"Grey Neck 2023", "Grey Neck 2024"* and other monitoring campaigns.

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Data availability

All the data required to evaluate this study are available in the Supplementary Information Tables 1–3. Source data for the Figures 6, 7 in Excel format have been provided as Supplementary Data 1.

Code availability

Our custom code for this study is publicly available at Github repository https://github.com/abhishekdixitg/blacksea-oilbird-risk and provided in Zenodo [52].

References

1. Kolomoitseva, A.Yu. The issue of security of the Turkish Straits – ecology or politics? *Bulletin of the RSUH. Series: Political Science. History. International Relations*. **8**, 110–117 (2009).
2. Draffan, G. Major Oil Spills. https://www.webcitation.org/69olyiBB1?url=http://www.endgame.org/oilspills.htm (2012)
3. Barham, P.J. et al. Return to Robben Island of African Penguins that were rehabilitated, relocated or reared in captivity following the Treasure oil spill of 2000. *Ostrich.* **77**, 202–209 (2006).

ARTICLE IN PRESS

4. Crawford, R.J.M. et al. Initial impact of the Treasure oil spill on seabirds off western South Africa. *S. Afr. J. Mar. Sci.* **22**, 157–176 (2000).
5. Zmushko, A. A.; Kirchenko A. V. Drones in agriculture. *Fruit growing*. **35**, 193–198 (2023).
6. Fashchuk, D. In the wake of an extreme storm. *Science and Life.* **5**, (2025).
7. Oil spills in Russia in 2020. https://vk.com/@terraecology-razlivy-nefteproduktov-v-rossii-za-2020-god (2020)
8. Barinaga, Marcia. Oil-spill danger to nesting birds. *Nature.* **337,** 592 (1989).
9. Wallace, B.P.; Brosnan, T.; McLamb, D.; Rowles, T.; Ruder, E.; Schroeder, B.; Schwacke, L.; Stacy, B.; Sullivan, L.; Takeshita, R.; Wehner, D. Overview: effects of the Deepwater horizon oil spill on protected marine species. **33**, 1–7 (2017).
10. IPIECA, Annual Review https://www.ipieca.org/resources/annual-review/2017 (2017).
11. Lavrova, O., Loupian, E. & Kostianoy, A. Satellite monitoring of the fuel oil spill in the Kerch Strait area on December 15, 2024: Preliminary results. *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa*. **22**(**1),** 327-335 (2025).
12. Paramonova, N.Forbes. Now. A bill for 33 billion rubles: who will pay how much for the fuel oil spill in the Kerch Strait. https://www.forbes.ru/sustainability/528677-scet-na-33-mlrd-rublej-kto-i-skol-ko-zaplatit-za-razliv-mazuta-v-kercenskom-prolive (2025).
13. OOO «MEMO». Caucasian Knot. Krasnodar Region. Fuel oil spill in the Kerch Strait. https://www.kavkaz-uzel.eu/articles/406916 (2025).
14. Guidelines for working with birds injured by oil spills (in emergency situations). Prepared by a working group of specialists organized in accordance with the minutes of the meeting on the topic «Oil spill in the Black Sea. Rescue of birds». (2025).
15. Kajigaya, H.; Oka, N. Oil Spill Modeling: A Critical Review on Current Trends, Perspectives, and Challenges. (1999).
16. Wernham, C. V.; Williams, T. Rehabilitation of oiled seabirds. *Ostrich.* **1-2**, 160 (1998).
17. Whittington, Ph. et al. The rehabilitation of oiled African Penguins: A success story. *Ostrich.* **3-4**, 69 (1998).
18. Romanov, V.V. Toxic effect of oil on the organism of wild birds. Materials of the third scientific and practical conference: Birds: maintenance, breeding, veterinary science. *Bird Park "Vorobyi"*. 118-130 (2013).
19. The birds of the Gulf of Mexico are doomed. *Science and life*. **5** (2025).
20. Anderson, Daniel W.; Gress Franklin, Fry D. Michael. Survival and dispersal of oiled brown pelicans after rehabilitation and release. *Mar. Pollut. Bull*. 10, 711-718 (1996).
21. Subbotina, E. Accidents: causes and consequences - Accident in the Kerch Strait as a systemic error. *World Energy*. 2 (2008).
22. Romanov, V.V.; Smirnova, S.L.; Dronov, M.A. The impact of oil on the organism of wild birds caught in the zone of ecological disaster in the Kerch Strait on the Chushka spit and the Taman coast. *Russian Ornithological Society*. (2024).
23. Grigoriev, A.V.; Knizhnikov, A.Yu.; Pastukhova, K.A. People, oil, birds. Review of world experience in rescuing birds during oil pollution M.: *World Wildlife Fund* (WWF. **57**, (2014).
24. Kolomoitseva, A.Yu. The issue of security of the Turkish Straits – ecology or politics? *Bulletin of the RSUH. Series: Political Science. History. International Relations.* **8**, 110–117 (2009).
25. Caucasian Knot. https://www.kavkaz-uzel.eu/articles/406916
26. Pskhatsieva, Z.V.; Yurina, N. A.; Tletseruk. I.R.; Hovsepyan V. A. Combination of probiotics and sorbent in broiler chicken mixed fodder. *Collection of scientific papers of the Krasnodar Scientific Center for Animal Science and Veterinary Science*. **1**, 291–295 (2018).
27. García, A. R.; Avila, E.; Rosiles, R.; Petrone, V. M. Evaluation of two mycotoxin binders to reduce toxicity of broiler diets containing ochratoxin A and T-2 toxin contaminated grain. *Avian Dis*. **47,** 691–699 (2003).

ARTICLE IN PRESS

ARTICLE IN PRESS

28. Chuiko, A.A.; Tertykh, V.A.; Lobanov, V.V. Medical chemistry and clinical use of silicon dioxide. *Kyiv*, 414 (2003).
29. Vershinin, A. S.; Bychkovskikh, V. A.; Smirnov, D. M. Use of enterosorbent Polysorb Mp (colloidal silicon dioxide) in complex therapy of various pathological conditions accompanied by endotoxicosis (literature review). *Man. Sport. Medicine*. **3**, (2013).
30. Markelov, D.A.; Nitsak, O.V.; Gerashchenko, I.I. Comparative study of adsorption activity of medical sorbents. National Medical University named after A.A. Bogomolets. *Chemical-pharmaceutical journal.* 7, (2008).
31. Lutsyuk, N.B.; Kevorkov, N.N. Historical background, principles, methods, means of efferent therapy, physical-chemical and medical-biological characteristics of the silica sorbent Polysorb. *Materials of the scientific-practical conference. Perm*. (1994).
32. Yurina, N.A.; Danilova, A.A.; Hovsepyan, V.A. Experience of combined use of sorbents and probiotics when growing poultry. *Bulletin of the Ulyanovsk State Agricultural Academy*. **2**, 228–233 (2021).
33. Dao, H. V. An Investigation into Factors Affecting the Efficacy of Oil Removal from Wildlife Using Magnetic Particle Technology. *A thesis submitted for the degree of Doctor of Philosophy. Victoria University School of Molecular Sciences*. 382 (2007).
34. Reshenkin, A. S.; Psardieva, N. N. Methods and means of repelling birds during takeoff and landing of aircraft. *Young researcher of the Don*. **1**, 68–72 (2021).
35. Enaleev, I. R. Ispol'zovanie pravnykh ptitsy v kak biorepellentov na ob'ektakh zernoproma [Use of birds of prey as biorepellents at grain industry objects]. *Philology and culture*. **25**, 61–64 (2011).
36. Ronconi, R.A.; St. Clair, C.C.; O'hara, P.D.; Burger, A.E. Waterbird deterrence at oil spills and other hazardous sites: potential applications of a radar-activated on-demand deterrence system. *Marine Ornithology.* **32**, 25-33 (2004).
37. Ward, J.G. Tests of the Syncrude bird deterrent device for use on a tailings pond. Edmonton: LGL Ltd. (1978).
38. Bishop, J. B.; McKay, H.; Parrott D.P.; Allan, J.S. Review of international research literature regarding the effectiveness of auditory bird scaring techniques and potential alternatives. *Environmental Science, Medicine.* (2003).
39. Wang, Z.; Griffin, A.S.; Lucas, A.; Wong K.C. Psychological warfare in vineyard: Using drones and bird psychology to control bird damage to wine grapes. *Crop Protection*. **120**, 163-170 (2019).
40. Bhusal, S.; Karkee, M.; Bhattarai, U.; Majeed, Y.; Zhang, Q. Automated execution of a pest bird deterrence system using a programmable unmanned aerial vehicle. *Comput. Electron. Agric*. 198 (2022).
41. Wilson, J.P.; Amano, T.; Fuller, R.A. Drone-induced flight initiation distances for shorebirds in mixed-species flocks. *J. Appl. Ecol.* **60,** 1816-1827 (2023).
42. Saevich, K.F., Dubnovitsky, Yu.S. Protection of renewable resources in agriculture. Monograph. Minsk, ZAO Vedy, 2010, 160 p.
43. Jarretta, D., Calladinea, J., Cottona, A., Wilson, M.W., Humphreys, E. Behavioural responses of non-breeding waterbirds to drone approach are associated with flock size and habitat. *Bird Study.* **67**, 190–196 (2020).
44. Wilson, J.P.; Amano, T.; Fuller, R.A. Drone-induced flight initiation distances for shorebirds in mixed-species flocks. *J. Appl. Ecol.* **60**, 1816–1827 (2023).
45. Zmushko, A.A.; Kirchenko, A.V. Drones in agriculture. *Fruit growing*. **35**, 193-198 (2023).
46. Vasilevskaya, A.A. Behavioural features of the Great Crested Grebe Podiceps cristatus on the Middle Tsaritsynsky Pond (Moscow) during the nesting period. Russian Ornithological Journal. **28,** 989-992 (2019).
47. Ward, J.G. Tests of the Syncrude bird deterrent device for use on a tailings pond. (Report for Syncrude Canada Ltd., *Edmonton*, *AB* (1978.).
48. Sharp, L. Chasing birds from oil spills – two experiments. *Coastal Zone*. **7**, 1–15 (1987).

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ARTICLE IN PRESS

49. Koski, W.R.; Kevan, S.D.; Richardson, W.J. Bird dispersal and deterrent techniques for oil spills in the Beaufort Sea. Environmental Studies Research Funds Report. **126**, (1993).
50. Greer, R.D.; O'CONNOR, D.J. Waterbird deterrent techniques. MSRC Technical Report Series 94-003. Washington, DC: Exxon Biomedical Sciences, Marine Spill Response Corporation Hounsell and Reilly (1995).
51. Whisson, D.A.; Takekawa, J.Y. Testing the effectiveness of an aquatic hazing device on waterbirds in the San Francisco Bay estuary of California. *Waterbirds.* **23**, 56–63 (2000).
52. Blacksea-oilbird-risk_v1 (2026). DOI: 10.5281/zenodo.18156462.

Author Contributions

S.G. and O.G.G. wrote the main manuscript text. The experimental part was provided by O.G.G. and A.D. S.G. contributed to formal analysis. O.G.G., A.M., A.D. performed analysis experiments. S.G. and O.G.G. contributed to revision of the manuscript to its final version.

Ethics declarations

Competing interests

The authors declare no competing interests.

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Fig. 1| Flowchart of primary analysis.

a, Global oil product spills analysis. **b,** Analysis of response methods to prevent oil pollution of wild animals. All photos on Fig. 1 are from Wikimedia Commons under Public Domain.

Fig. 2| Flowchart of in-depth analysis of birds' survival with decision-making support.

a, Analysis of traditional technologies of helping birds contaminated with oil products. **b,** Removal of oil pollution from bird feathers. **c,** Assessment of the birds by a veterinarian and birds' survival analysis by the Kaplan-Meier and Cox methods. **d,** Risk stratification of non-survival of the birds with decision-making support: low risk (R<20%), middle risk (20%≤R≤60%), high risk (R>60%). The birds images on Fig. 2a, Fig, 2c are from Wikimedia Commons under Public Domain.

Fig. 3|Primary processing of birds.

a, The rescuer cleans the bird's eyes of fuel oil by treating them with "Diamond Eyes" drops: he drips a few drops into each eye, lets the bird blink, then applies Korner gel or a similar product. **b,** The rescuer cleans the beak with cotton swabs and wet microfiber cloths, passing them along the folds of the beak and near the tongue. **c,** The rescuer removes fuel oil from the outer surface of the beak with a cotton swab. Work with a small flow of birds is performed in pairs: one rescuer holds the bird by the neck with his fingers bent into a ring, and, with the other hand, holds the legs and wings of the bird; the second rescuer performs the necessary manipulations.

Fig. 4|Treatment of birds in starch by a rescue team and one rescuer.

a, First rescuer fixes the bird's head with his fingers folded in a ring under the skull without squeezing the neck. Second rescuer holds the bird in a basin with starch, and the third rescuer applies starch to the back and abdomen of the bird. **b,** The bird is completely covered with a layer of starch, while the head of the bird is not treated with starch. **c,** One rescuer carries out the starch application operation due to the large number of incoming birds and

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the lack of the required number of rescuers. The bird's beak is sealed to prevent injuries when one person works with it.

Fig. 5|Washing birds from fuel oil using detergents.
a, The rescuer rinses the bird with detergent by pouring warm water from a ladle onto the back of the bird. **b,** The process of applying detergent to bird feathers. It can be seen that the bath water is dark from the fuel oil removed from the bird's feathers.

Fig. 6|Kaplan-Meier survival analysis for bird species after fuel oil spill. a, Great Grebe (Podiceps cristatus). **b,** Red-necked Grebe (Podiceps grisegena). **c,** Black-necked Grebe (Podiceps nigricollis). **d,** Red-necked Grebe (Podiceps auritus). **e,** Coot (Fulica atra). **f,** Black-throated Loon (Gavia arctica). **g,** Herring Gull (Larus argentatus). **h,** Black-headed Gull (Chroicoce-phalus ridibundus). Treatment: Washing (blue) vs Rehabilitation (red). Shaded regions represent 95% confidence intervals. The value n denotes the total number of birds included in the survival analysis for each species and treatment. Numbers of birds at risk at specific observation times are reported separately in Table 3.

Fig. 7|Comparative graphs of Kaplan–Meyer survival analyses for bird species. a, after washing. **b,** after rehabilitation. Shaded regions represent 95% confidence intervals.

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Table 1|Categorization of birds depending on the degree of fuel oil (oil) contamination.

Degree of contamination	Area of contamination	Impact	Prospects for self-cleaning	Prospects for survival
1	Full thick coat	Loss of ability to move, suffocation	Impossible	None
2	10 to 99% of plumage is contaminated	Partial loss of the ability to move, loss of insulating properties of the feather cover, hypothermia, and exhaustion	Impossible	None
3	Small patches of dirt covering no more than 10% of the feather cover	Loss of insulating properties of the feather cover, hypothermia, and exhaustion	Sometimes it is successful	Possible
4	An almost invisible thin film of oil	No disturbances in the structure of the feather cover	Possible	Positive

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Table 2|Survival outcomes of birds treated in rehabilitation centers following the December 2024 fuel oil spill.

Observation Day After Incident	Time Window of Admission to Rehabilitation	Clinical Condition on Admission	% Birds Alive After Rehabilitation	Interpretation
7 days (21.12.2024)	No rehabilitation admissions yet	No rehabilitation admissions yet	No rehabilitation admissions yet	All rescued birds first underwent washing; rehabilitation not yet initiated.
10 days (24.12.2024)	Birds admitted from 17–24 Dec 2024	Mild to moderate oil exposure	*Early-stage treatment ongoing*	Birds remained under care; survival status still under observation.
17 days (31.12.2024)	Birds admitted 17–31 Dec 2024	No severe neurological symptoms	25% alive	Early-admitted birds had the highest likelihood of survival.
25 days (08.01.2025)	Birds admitted 1–8 Jan 2025	Progressive health decline	17% alive	Delay in admission likely reduced rehabilitation success.
30 days (13.01.2025)	Birds admitted 9–13 Jan 2025	Severe neurological impairment (seizures, loss of coordination)	5% alive	Rapidly worsening systemic toxicity from prolonged exposure.
85 days (08.03.2025)	Same cohorts as above (follow-up)	Status after discharge or continued care	Trends remained consistent	No recovery improvement in the most severely affected group.

Table 3|Cox proportional hazards model.

Variable	HR	95 % CI	p_value
Treatment: Rehabilitation vs Washing	91.18	78.49 – 105.92	<0.001
Red-necked Grebe (Podiceps grisegena)	1.90	1.00 – 3.60	0.049
Black-necked Grebe (Podiceps nigricollis)	1.82	0.90 – 3.69	0.094
Great Grebe (Podiceps cristatus)	1.64	0.90 – 2.99	0.106
Red-necked Grebe (Podiceps auritus)	1.11	0.36 – 3.43	0.853
Coot (Fulica atra)	1.03	0.55 – 1.94	0.917
Black-throated Loon (Gavia arctica)	0.96	0.49 – 1.87	0.902
Herring Gull (Larus argentatus)	0.84	0.37 – 1.91	0.681

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Editorial summary:
The conventional cleaning process of fuel-oil contaminated Black Sea birds is not always effective for some bird species, and the analysis
of their survival rates using Kaplan-Meier and Cox methods reveals sound and kinetic deterrents as potential conservation measures.

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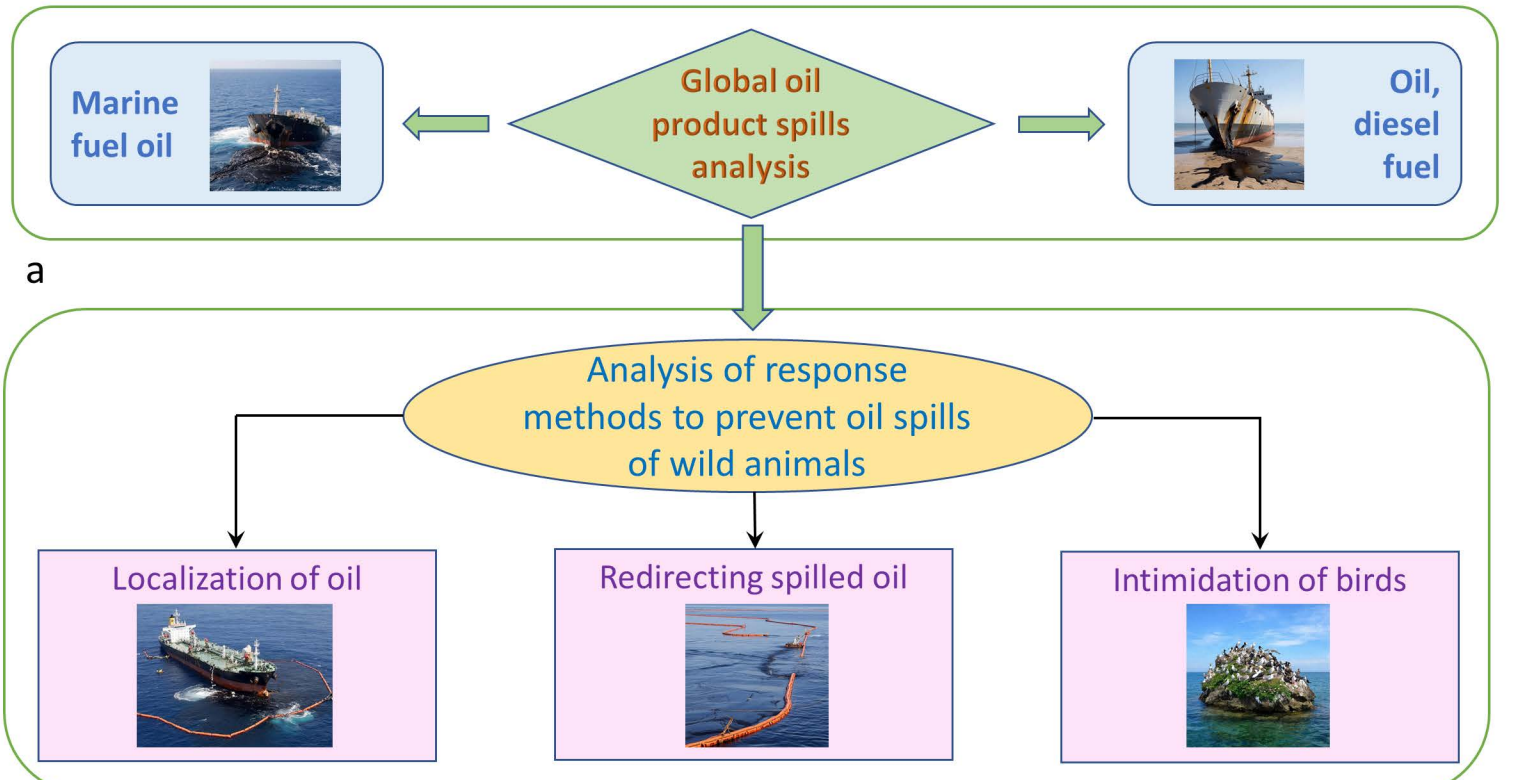
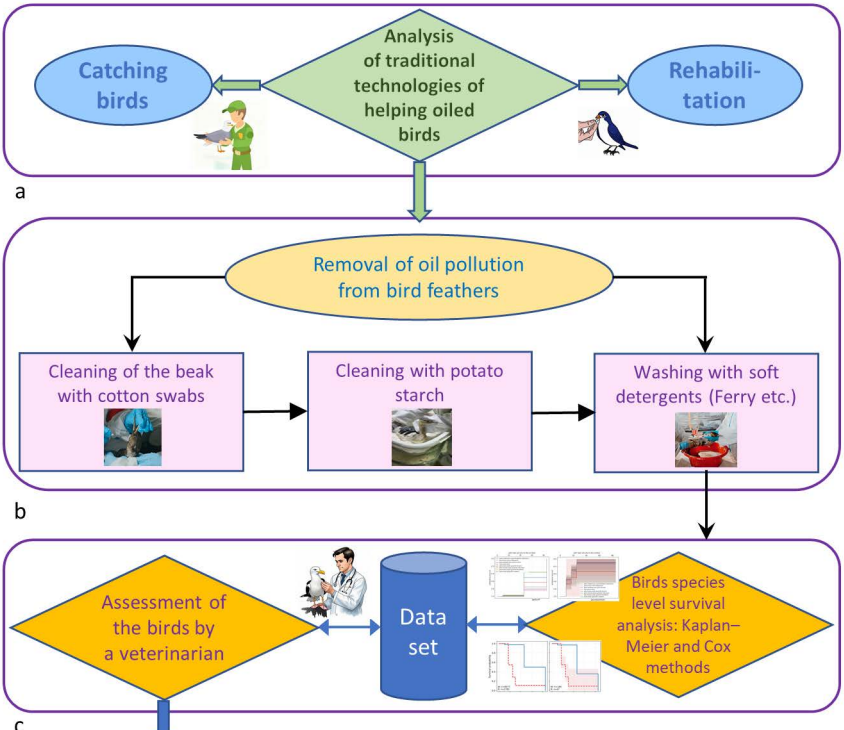

Marine fuel oil
Global oil product spills analysis
Oil, diesel fuel
a
Analysis of response methods to prevent oil spills of wild animals
Localization of oil
Redirecting spilled oil
Intimidation of birds
b



Risk stratification	Low	Middle	High
Decision making support	Rehabilitation for several days	Referral to long-term rehabilitation centers	Intensive and long-term rehabilitation

d

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(a) (b) (c)

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(a) (b) (c)

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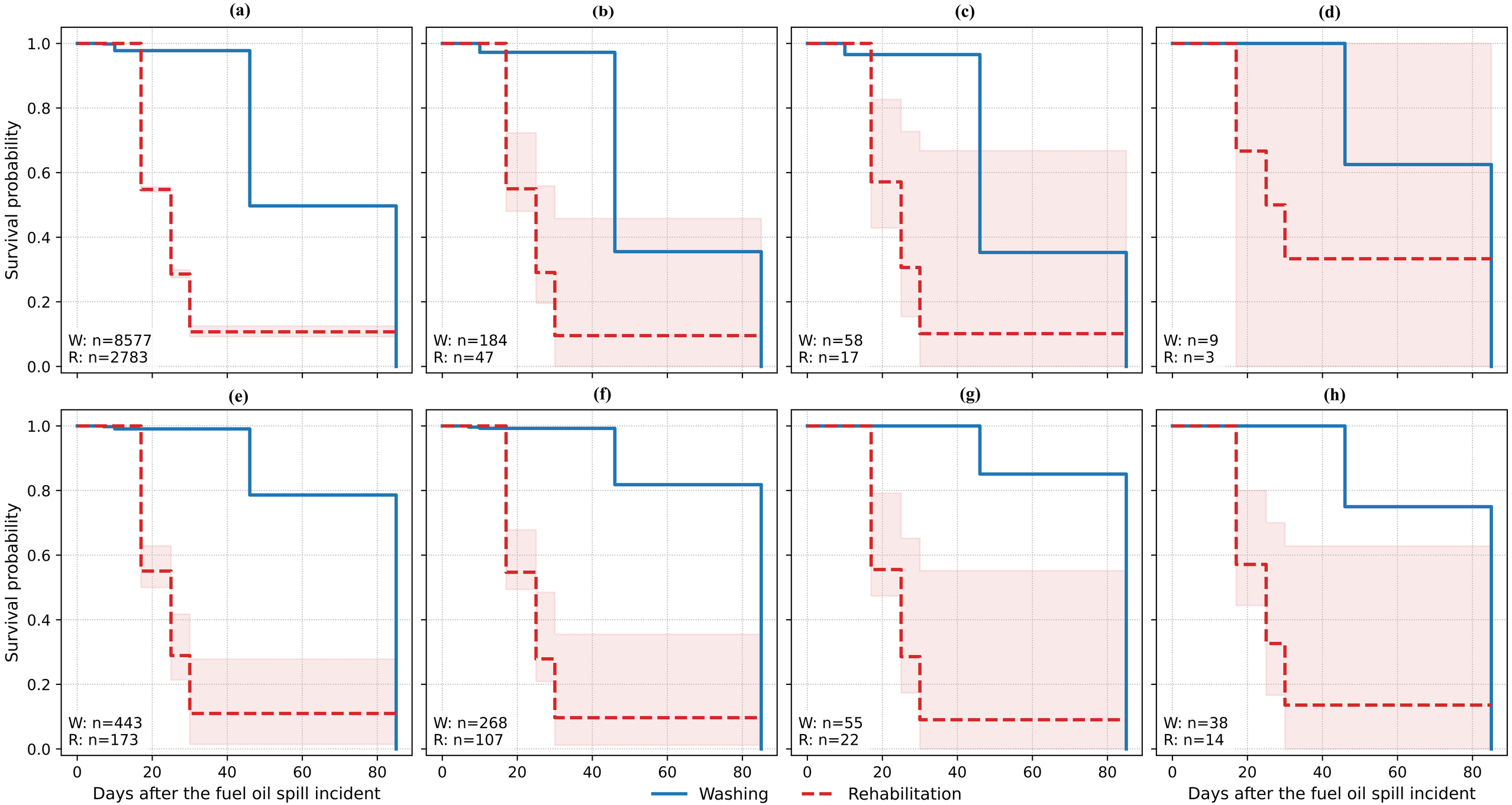
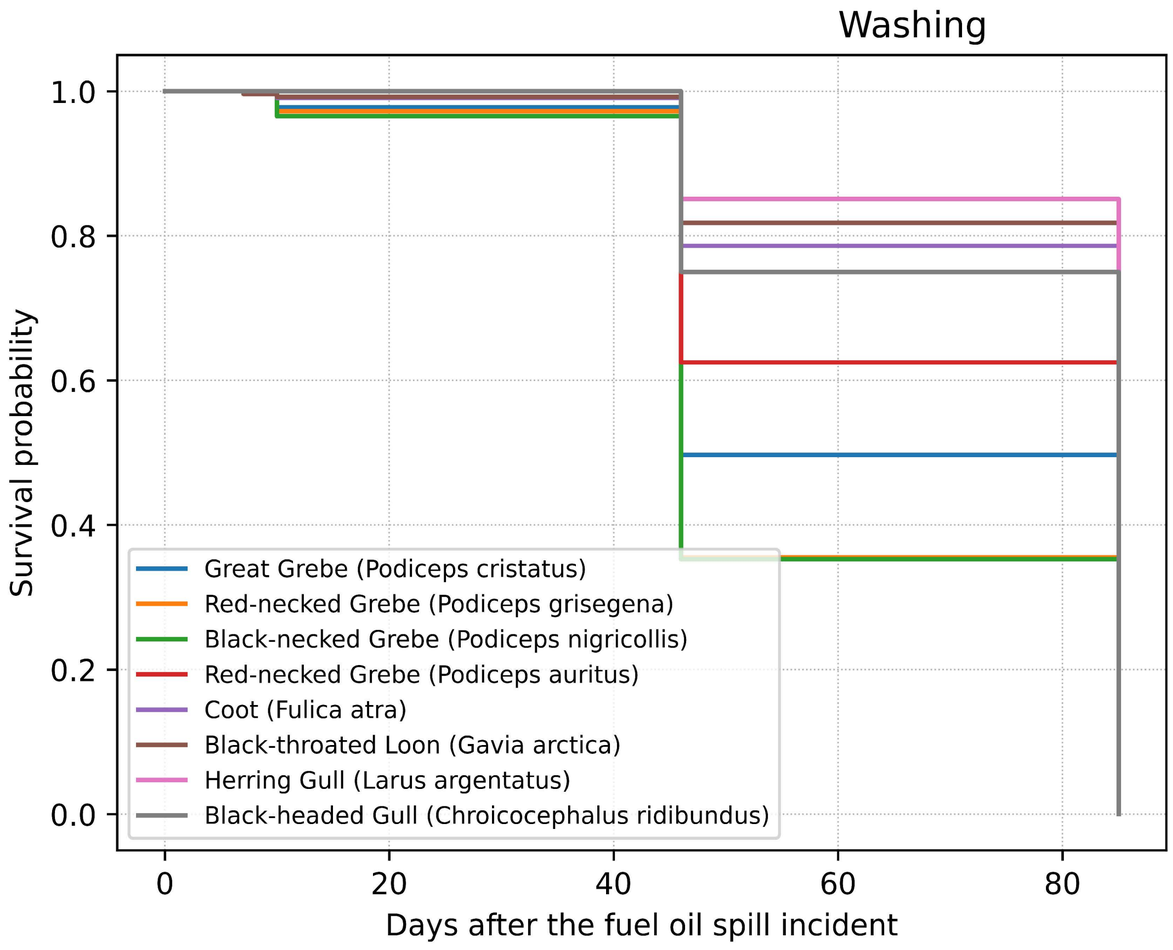
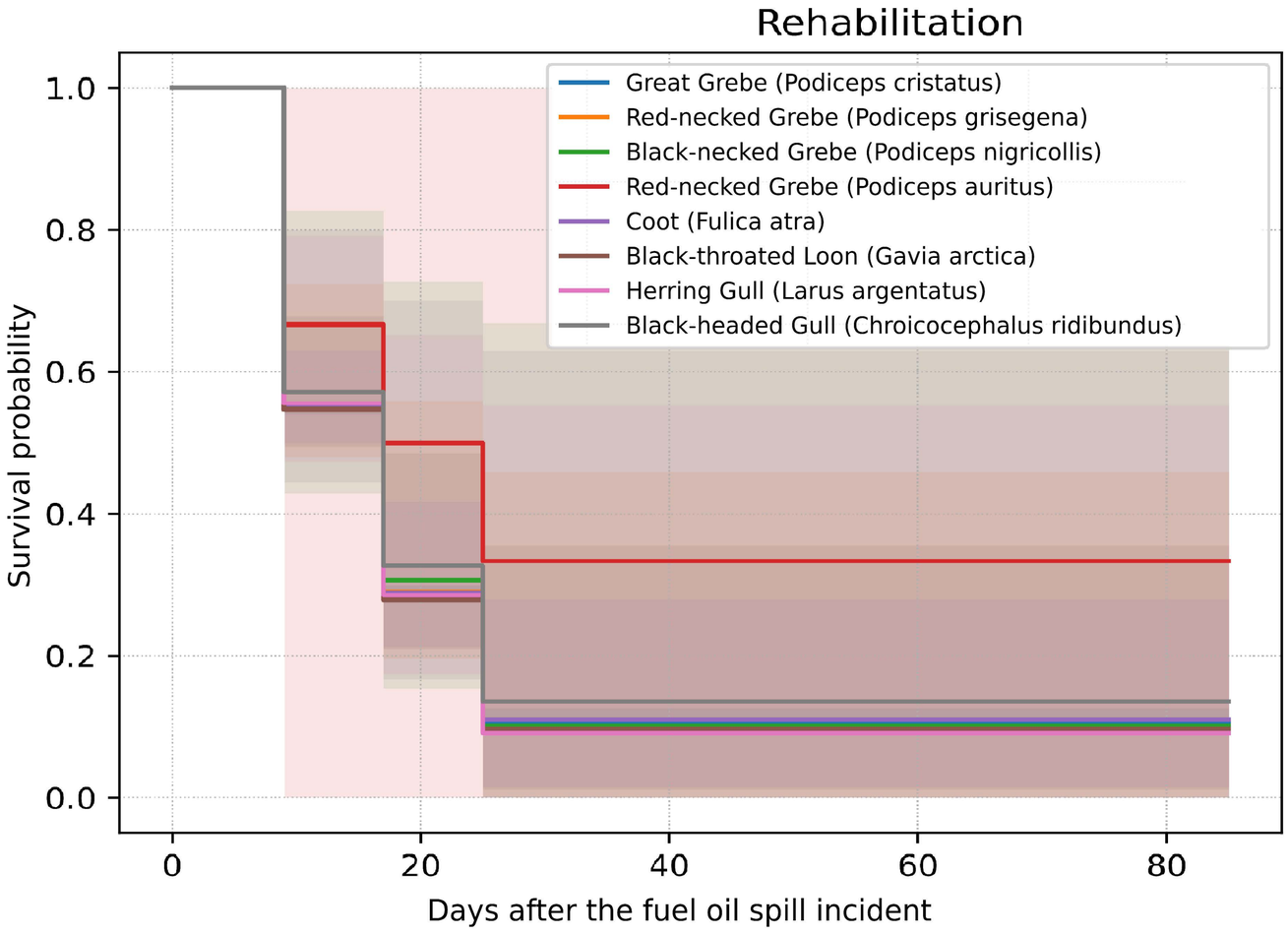
(a) (b)


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Survival probability
1.0
0.8
0.6
0.4
0.2
0.0
W: n=8577
R: n=2783
W: n=184
R: n=47
W: n=58
R: n=17
W: n=9
R: n=3
W: n=443
R: n=173
W: n=268
R: n=107
W: n=55
R: n=22
W: n=38
R: n=14
0
20
40
60
80
Days after the fuel oil spill incident
Washing
Rehabilitation


Washing
Survival probability
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
Days after the fuel oil spill incident
Great Grebe (Podiceps cristatus)
Red-necked Grebe (Podiceps grisegena)
Black-necked Grebe (Podiceps nigricollis)
Red-necked Grebe (Podiceps auritus)
Coot (Fulica atra)
Black-throated Loon (Gavia arctica)
Herring Gull (Larus argentatus)
Black-headed Gull (Chroicocephalus ridibundus)

(a)


Rehabilitation
Survival probability
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
Days after the fuel oil spill incident
Great Grebe (Podiceps cristatus)
Red-necked Grebe (Podiceps grisegena)
Black-necked Grebe (Podiceps nigricollis)
Red-necked Grebe (Podiceps auritus)
Coot (Fulica atra)
Black-throated Loon (Gavia arctica)
Herring Gull (Larus argentatus)
Black-headed Gull (Chroicocephalus ridibundus)

(b)