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RESEARCH ARTICLE

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Seals exhibit localised avoidance of operational tidal turbines

Jessica Montabaranom | Douglas Gillespie | Emma Longden | Katie Rapson | Anhelina Holoborodko | Carol Sparling | Gordon Hastie

Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews, UK

Correspondence
Jessica Montabaranom
Email: jlm35@st-andrews.ac.uk

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Abstract

1. Tidally energetic habitats are used by a range of marine mammals, including pinnipeds. These areas are also important to the tidal energy industry, leading to an overlap between tidal developments and important habitats used by seals. The concerns around negative ecological impacts from tidal turbines derive primarily from the potential for fatal collisions between animals and the moving parts of the turbine (i.e. blades) and habitat exclusion from important areas.
2. We quantified the number of encounters of seals within close range (10s of metres) of the turbine and estimated the likelihood of seal presence over an annual cycle. Data were collected with two multibeam sonars monitoring an operational turbine in the Pentland Firth, Scotland, between May 2022 and June 2023. There were 704 seal encounters within close range of the turbine.
3. We used generalised additive models (GAMs) to investigate the temporal patterns of seal presence at the turbine site. Results showed that the probability of seal presence was significantly higher at slack water, at night and during the winter months (November–January: mean of ~4 seals a day). When comparing seal presence between periods of turbine operation and non-operation, the model predicted a decrease in presence during turbine operation in flow speeds of $\geq 2.3\,\mathrm{ms}^{-1}$ (mean reduction of 77% at the highest flow speed; 95% CI: 22%–93%).
4. *Synthesis and applications*. The result showing that seals exhibit avoidance of the turbine during operation is important for industry developers and regulators, as lower numbers of seals close to the turbine reduces the potential for fatal collisions and injuries. The modelled reductions in presence can be used directly as avoidance rates in collision risk models to predict the impacts of future turbine arrays and de-risk the consenting process for this industry.

KEYWORDS
active acoustics, behaviour, collision risk, environmental monitoring, marine mammals, multibeam sonar, renewable energy

1 | INTRODUCTION

As the effects of climate change are increasing, the renewable energy sector is expanding rapidly to meet net zero targets. Offshore resources are expected to contribute a significant portion of worldwide energy demands, and as tidal energy is a predictable resource, this industry is expanding (European Commission, 2020). It is estimated that 11% of the United Kingdom's current electricity demand could be fulfilled by tidal resources (Coles et al., 2021).

Tidally energetic environments are dynamic habitats and attract a variety of marine top predators such as seals (Hastie et al., 2016), harbour porpoises (*Phocoena phocoena*) (Palmer et al., 2021) and larger cetaceans (delphinids: Bailey & Thompson, 2010; baleen whales: Johnston et al., 2005). This attraction is likely a result of increased foraging opportunities or efficiency (Benjamins et al., 2015; Zamon, 2001); predator–prey interactions in these environments have been studied in razorbills (*Alca torda*), common guillemots (*Uria aalge*) (Waggitt & Scott, 2014), harbour seals (*Phoca vitulina*) (Hastie et al., 2018) and harbour porpoises (*Phocoena phocoena*) (Embling et al., 2010).

As the tidal industry expands, there will be increasing overlap between key habitats for marine predators and tidal turbines. One reason the expansion of the tidal energy industry has been limited is uncertainty around the environmental impacts of tidal devices, particularly on marine mammals protected under national (e.g. Marine Scotland Act 2010) and international legislation (e.g. EU Habitats Directive). Concerns derive primarily from the potential for injury or mortality as a result of collisions between animals and the moving parts of the turbine (i.e. blades) (Copping et al., 2023; Sparling et al., 2015). In particular, collisions between marine mammals and blades moving at speeds above ~5 ms^{-1} (95% CI: 3.2–6.6) are predicted to be fatal (Onoufriou et al., 2019). To assess the potential impacts of tidal energy developments, prior to installation, tools such as the encounter rate model (SNH, 2016) and collision risk model (Band et al., 2016) have been developed to predict collision rates. However, there is currently a lack of data on animal behaviour around these devices and whether they exhibit avoidance behaviours that would effectively reduce their risk of collision (Gillespie et al., 2022; Joy et al., 2018). This is a key data gap in terms of parameterising collision risk models for future assessments.

Previous studies have described avoidance behaviour exhibited by animals to anthropogenic structures at a range of spatial scales (Band, 2012; Cook et al., 2014). Cook et al. (2014) defined three scales of avoidance for seabirds: macro- (>500 m), meso- (10–500 m) and micro-avoidance (<10 m); these scales can also be applied to marine mammal avoidance of tidal turbines. Previous studies have measured cetaceans' avoidance of tidal turbines, with data showing harbour porpoise behavioural responses to tidal turbines at meso- (200–230 m; Tollit et al., 2019) and micro-spatial scales (0–150 m; Gillespie et al., 2021; Palmer et al., 2021). To date, seal behavioural response data are available only on a macro-spatial scale. For example, harbour seals (*Phoca vitulina*) in the Pentland Firth, Scotland, exhibited avoidance of a small array of tidal turbines up to 2 km away (Onoufriou et al., 2021). However, there is currently a lack of meso- and micro-scale data for seals, which needs addressing in order to quantify the frequency and nature of close range interactions.

The paucity of data on seal behavioural responses is partly due to the technological challenge of tracking seals underwater at meso-spatial scales (10s of m). However, multibeam imaging sonars are being used increasingly to study marine species, including fish and marine mammals (Francisco et al., 2022; Gonzalez-Socoloske & Olivera-Gómez, 2023; Sibley et al., 2023). Multibeam sonars provide a radar-like image of the ensonified region, providing accurate tracking of individual targets. Critically, Hastie, Bivins, et al. (2019) and Hastie, Wu, et al. (2019) showed that seals could be detected and tracked in high spatial (~1 m) and temporal (<1 s) resolution in tidal habitats and were able to monitor animal behaviour within 10s of metres of the tidal turbine over long periods of time (months).

This study reports on seal presence and behaviour within close proximity of an operational tidal turbine in the Pentland Firth, off the north coast of Scotland. Importantly, the two seal species in this area (grey seals (*Halichoerus grypus*) and harbour seals) are protected by national legislation and the latter has exhibited a significant local population decline over the last few years (Carter et al., 2020). The objectives of this study were to (1) describe temporal variation of seal occurrence around an operational tidal turbine relative to environmental co-variates and (2) investigate the nature of meso-scale interactions between seals and tidal turbine relative to operational status of the turbine.

2 | MATERIALS AND METHODS

2.1 | Data collection

The inner sound is a tidal channel in the Pentland Firth between the Scottish mainland and the island of Stroma. Tidal flow speeds in the inner sound regularly exceed 4 ms^{-1} (Goddijn-Murphy et al., 2013). An array of four 1.5 MW tidal turbines was installed by MeyGen, SAE Renewables and has been operational since 2017 (Figure 1); this study focused on the monitoring of one turbine. The monitored turbine has three blades of 9 m length, the rotor sits at 14 m above the seafloor. The turbine support structure (TSS) sits at a depth of approximately 33 m at peak low tide and 36 m at peak high tide. The turbine operates at tidal flow speeds above 1.2 ms^{-1} at rotation speeds increasing with flow from 6 to 14 rotations per minute (rpm) giving blade tip speeds between 5.6 and 13.2 ms^{-1}.

An underwater platform integrating active acoustics and passive acoustics (High Current Underwater Platform; HiCUP) was deployed alongside an operational tidal turbine. The system was connected to the tidal turbine via a subsea umbilical cable which provided power and communications. Data were transferred in real time to a PC onshore via fibre optics in the turbine export cable.

Data for this study were collected using two Tritech Gemini 720is multibeam sonars mounted on the HiCUP deployed on the seabed approximately 30 m north of the tidal turbine (Gillespie et al., 2022).

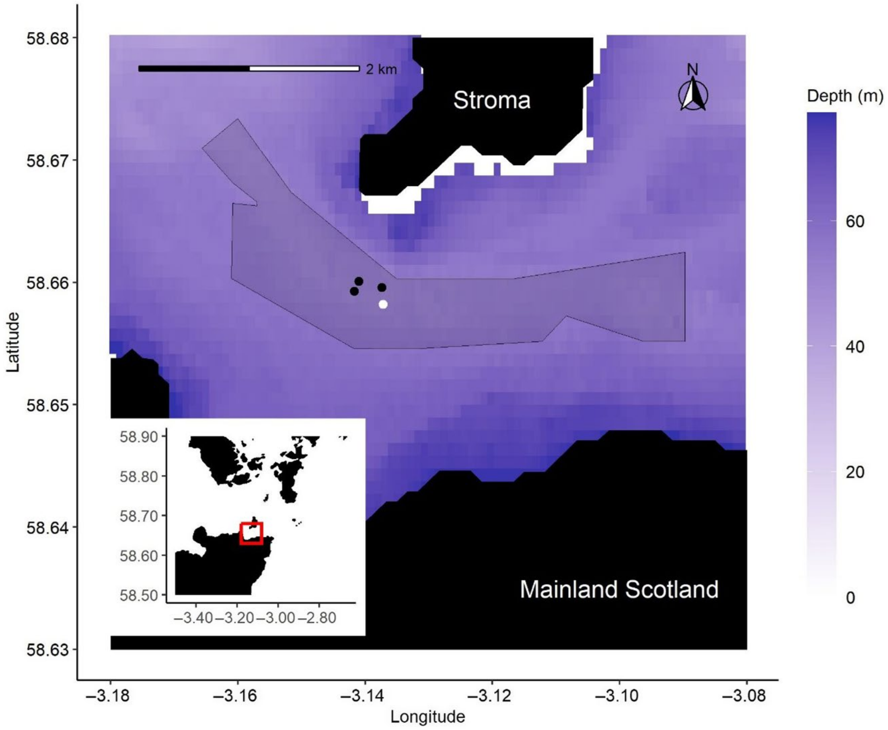

FIGURE 1 Map of the MeyGen lease area and the Phase 1 turbines. The shaded area represents the lease area, and the turbines are represented by the circles. The white circle represents the monitored turbine.

The sonars covered a 120° horizontal swath, with a vertical beam width of 20°. Both sonars were set to a maximum detection range of 55 m giving coverage to 15 m beyond the far side of the turbine blades. The 120° swath was covered by 512 separate beams with a separation of between 0.2° (close to the image centre) and 0.4° (at the edge of the image, i.e. at ±60°). However, the actual resolution of the sonar varied between 1° and 2°. At the maximum range of 55 m, this gave an image resolution of between 1 and 2 m across the image. The range resolution was approximately 3.3 cm at all distances. The two sonars were aligned horizontally and set at a 17° vertical offset from one another, which allowed for monitoring of the full height of the turbine. The nominal frame rate was five frames per second (fps), per sonar. As close interactions between seals and turbines were likely to be rare events, this set-up allowed for continuous 24/7 monitoring over many months. The monitoring period lasted from May 2022 to June 2023.

The platform also incorporated a tetrahedral cluster of hydrophones (Gillespie et al., 2022), which was used to help differentiate between vocalising cetaceans and seals, when an unidentified marine mammal was detected on the sonar.

Data were collected using the Tritech Genesis software (version 1.7.3.37), which archived all raw data to external hard drives; this was conducted offline due to limited internet access to the turbine site. Due to technological issues, the Genesis software would occasionally stop collecting data, or would collect data at a slow frame rate, which required a system reset. The sonars were actively collecting data over 338 days; only data collected at a rate of ≥3.3 fps were used for analysis, resulting in 240 days of usable data between May 2022 and April 2023. Data collected in May and June 2023 were not of sufficient quality (≤3.3 fps). The turbine's operational status was predominantly active, although there were intermittent periods of shutdown (see Appendix S1).

The algorithms and workflow used for the sonar data processing and track detection are described in Gillespie et al. (2023). A simple movement detector automatically identified candidate seal tracks. It additionally identified high numbers of non-seal tracks from fish and other objects moving in the water column, as well as false detections from movement of the turbine rotors and downstream turbulence from the rotating blades. Detection and annotation software was all built as plugins for the PAMGuard passive acoustic monitoring software (Gillespie, 2024; Gillespie & Macaulay, 2024) to benefit from its existing data handling and annotation systems.

2.2 | Data processing

Four experienced sonar auditors manually reviewed all detected tracks in 15-min windows, using the PAMGuard Viewer version 2.02.13. Although seals were the focus of this study, other species groups were also detected (e.g. diving birds, fish, porpoises). Tracks were assigned a classification (fish, bird, seal, porpoise, elasmobranch, unidentified) and a confidence score (CS) from 1 (low) to 5 (high). When the PAMGuard software identified tracks of interest, tracks could be presented as shorter, separate track groups. The reviewer would identify and group these as one track when the animal was visible in the underlying raw sonar data between each track group (Gillespie et al., 2023). A track was deemed a new animal when there was no overlap in time. Although sonar did not allow us to differentiate between individual seals, this would not impact subsequent statistical analysis as models were based on presence and absence rather than individual counts. Once a track was selected, a number of parameters enabled the selection of a confidence score, including shape, physical features (i.e. head and flippers), size, movement and swim speed of the animal. Seal tracks detected on a multibeam sonar from Hastie, Bivins, et al. (2019) and Hastie, Wu, et al. (2019) with confirmed visible sightings from observers were used as a reference training data set for seal tracks in this data set.

Three experienced auditors manually audited PAM data from the HiCUP, at times when a marine mammal CS of ≥2 was detected on sonar. This cross-referencing was to ensure the marine mammal target detected was a seal and not a vocalising cetacean. An encounter was defined as a minimum of 10 clicks and ended when no clicks were detected for 5 min as described in Palmer et al. (2021).

2.3 | Seal presence model

To examine the temporal variation in seal presence and determine whether turbine operation influenced the occurrence of seals, the sonar data were divided into 10-min windows. A binary 'presence' variable was created depending on whether there was a seal present (1) or absent (0) in each 10-min window. The majority (92%, $n=587$) of 10-min windows with seals present contained detections of a single seal; a small number (8%, $n=52$) contained more than one seal. We also compared models with different CS of seal tracks and found no significant difference in the results of the modelling for tracks with CS of ≥2. The final model included seal tracks with a CS of between 2 and 5 (out of 5). Seal tracks with higher CS (≥4) are likely to give the most robust data on occurrence patterns but are also likely to miss many animals. A lower CS may introduce higher uncertainty in the target ID but provides a more precautionary estimate of the total number of seals.

A binomial generalised additive model (GAM) with logit link function was fitted to the resultant time series of presence/absence using the function *bam* in the package *mgcv* (Wood, 2017) in R (4.2.2, R Core Team, 2024). GAMs allow modelling of complex non-linear relationships between explanatory variables and the response variable. Temporal and environmental variables that were investigated included Julian day, time of day (hour), tidal flow speed (ms^{-1}), illumination (days since new moon) and turbine operation (power generation in kW) (Table 1). Julian day and hour were fitted as a tensor smooth interaction, with cyclic cubic splines (cc) to account for their periodicity. Turbine operation was fitted as an interaction with flow speed and as a separate categorical variable. Auditor ID was also fitted to the model as a random effect, accounting for any possible differences in classification rates between auditors. By assessing the wiggliness of the smooth function, $k=6$ was chosen to allow a degree of flexibility to capture nonlinear effects without overfitting.

Model selection was based on Akaike's information criteria (AIC; Johnson & Omland, 2004). The reliability of the final model's coefficients was assessed through model validation checks including the *gam.check* function part of the *mgcv* package (Wood, 2017) and to confirm the chosen k value provided sufficient wiggliness without overfitting ($p>0.05$). Autocorrelation in the model residuals was checked by visually inspecting autocorrelation plots. The significance of parameters was assessed using Wald's test statistic (Wood, 2017).

The final model was used to predict the probability of seal presence around the turbine relative to all the retained temporal covariates and the two operational states (operational/non-operational). The mean percentage change in seal presence between the two operational states was estimated as a function of flow speed. Parametric bootstrapping was then used to generate 95% confidence intervals around the percentage change using the approach described by Palmer et al. (2021).

TABLE 1 Range of explanatory variables assessed as a predictor of seal presence.

Category	Variable	Description
Temporal	Julian day	Discrete variable (1–365) attributed to day of the year
	Hour	Discrete variable (0–23) attributed to hour of the day
	Days since new moon (illumination)	Discrete variable (0–29) indicating day of the lunar cycle
Tidal state	Flow speed	Continuous variable (0–4.2) in ms^{-1} rounded to the nearest 0.1 ms^{-1} indicating flow speed, at the given time start time of the 10-min window from a tidal model verified by Acoustic Doppler Current Profiler measurements at the turbine
Turbine operation	Power generation	Binary variable (0/1) indicating whether the turbine was generating power (>0 kW) and the blades were rotating, at the given time start time of the 10-min window

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2.4 | Ethics statement

All procedures and data collection were approved by the University of St Andrews School of Biology Ethics Committee (reference number SEC18014).

3 | RESULTS

3.1 | General overview of seal detections

Over the year of data collection, 240 days had data of sufficient quality for analysis, during which 704 seals (CS ≥ 2) were detected on the sonars. Of these, the majority were given a CS of 3 or above ($n = 588$), with 303 of the targets given a high CS (≥4). The mean detection rate was 2.93 seals per day (SD = 1.21; 95% CI: 2.12, 3.66), though this rate varied throughout the year. The highest seal detection rate was observed in January 2023 (mean 5.34 per day) and the lowest in July 2022 (mean 1.17 per day) (Figure 2).

3.2 | Seal presence

All tested co-variates except illumination were significant predictors of seal presence in the final model (Table 2). The results show significant temporal variation in the probability of seal presence around the turbine across both diel ($p < 2 \times 10^{-16}$) and annual cycles ($p < 2 \times 10^{-16}$). The final model explained 5.6% of the deviance in the response.

The model results showed significant variation in the presence of seals throughout the year with higher numbers of seals detected during the winter months (between November and January) (Figure 2). Seal presence was predicted to be higher at night; though this pattern varied slightly throughout the year, potentially reflecting the variation in daylight hours and peak presence occurring in hours of darkness (Figure 3).

The model also showed that the interaction between tidal flow and turbine operation was a significant predictor of seal presence ($p < 2 \times 10^{-16}$). The probability of seal presence exhibited a negative relationship with flow speed with the highest probability between 0 and 1 ms^{-1} both when the turbine was operational and non-operational (Figure 4). However, there was a significant difference in the probability of seal presence between turbine operational states at higher flow speeds; seal presence was markedly lower when the turbine was operational compared to when it was non-operational at higher flow speeds (Figure 4).

TABLE 2 Smoothed variables tested as predictors in the modelling for predicted probability of seal presence.

Variable	df	x_2	*p*
Te (Julian day, hour)	15.2	203.5	$<2 \times 10^{-16}$
Flow speed by turbine on	1.0	79.8	$<2 \times 10^{-16}$
Flow speed by turbine off	2.3	18.4	<0.05
Auditor	2.1	12.7	<0.05

Note: Variables that were not significant predictors of seal presence were not retained in the final model. Te produces a full tensor product smooth.

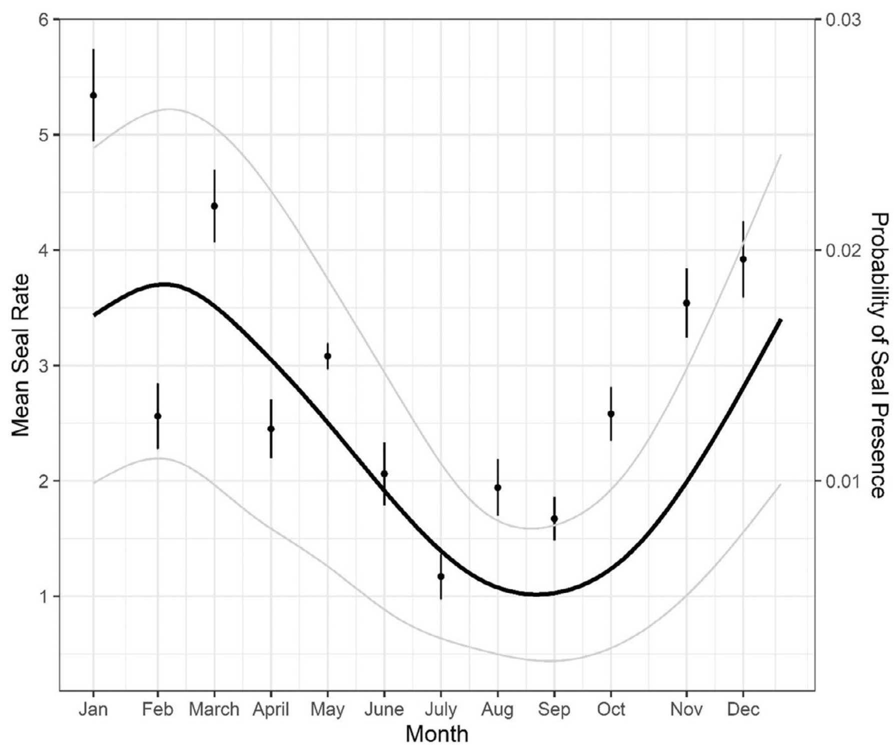

FIGURE 2 Daily mean seal rates per month (± standard error) overlayed by a GAM plot displaying the predicted probability of seal presence in a 10-min bin across the year, with a smooth (95% CI defined by grey lines). Median value for hour = 12, median value for speed = 1.9 ms^{-1}, across all auditors and operational status = 0.

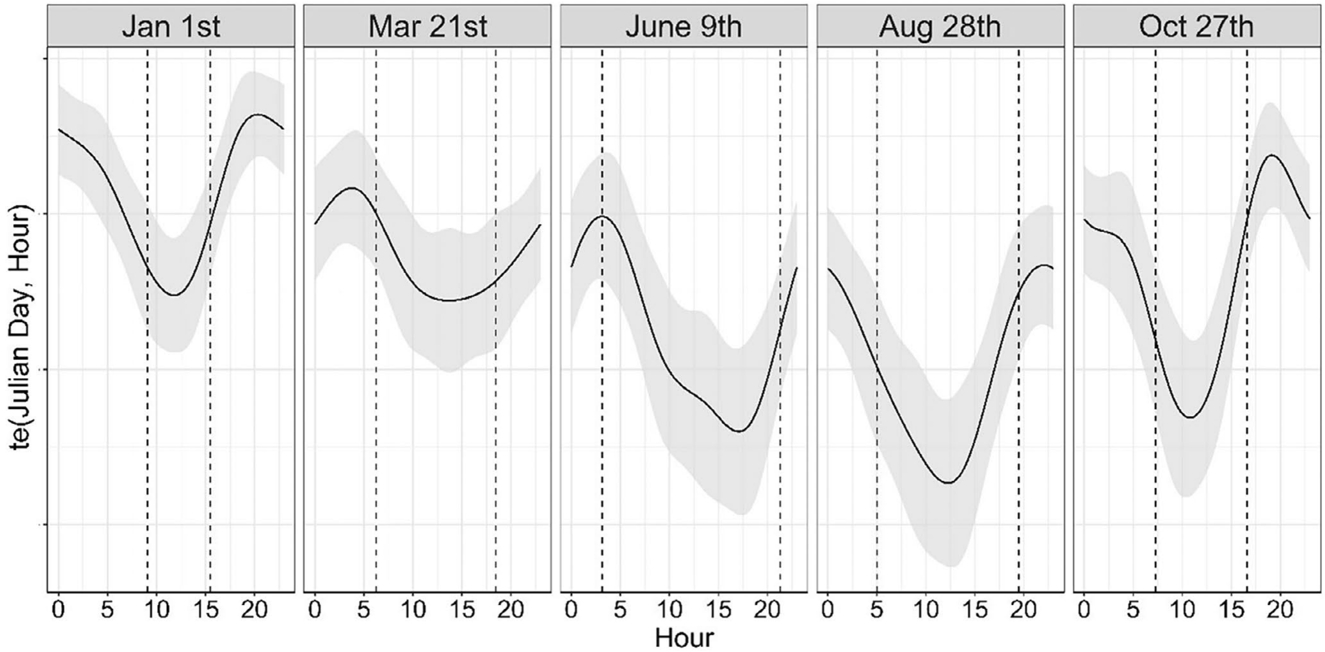

FIGURE 3 GAM plot displaying the variability of probability of seal presence in a 10-min bin across a 24-h time frame depending on the month, and sunrise and sunset times (dotted lines). The 95% CI are defined by the grey-shaded area. Median value for speed = 1.9 ms^{-1}, operational status = 0, across all auditors.

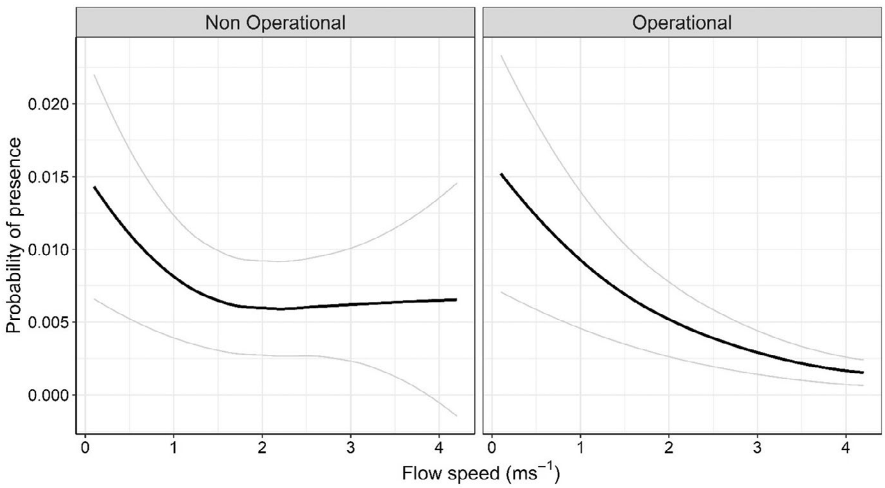

FIGURE 4 GAM plot displaying the probability of seal presence per flow speed rounded to the nearest 1 ms^{-1}, with a smooth (95% CI defined by grey lines). The left hand panel represents the probability of presence during non-operation of the turbine. Median hour = 12, median Julian day = 183, across all auditors.

3.3 | Avoidance rate analysis

The output of the final model was used to quantify the magnitude of the differences in the probability of seal presence (avoidance rate) as a result of turbine operation. The results indicated a significant reduction in seal presence during operation at flow speeds greater than 2.3 ms^{-1}, with a mean reduction of 77% (95% CI: 22%–93%) at the highest flow speeds (Figure 5).

4 | DISCUSSION

This study demonstrates that seals regularly swim within tens of metres of an operational tidal turbine. A mean of 2.93 seals were observed on a meso-spatial scale to the turbine per day (SD = 1.21; 95% CI: 2.12, 3.66) across the year. It also shows that there are significant daily, seasonal and annual patterns in seal presence at the tidal turbine. It has additionally demonstrated that the probability of seals being present near the turbine is lower at high flow speeds, irrespective of turbine operation. While the percentage of deviance explained by the model was relatively low (~6%), there was sufficient statistical power to identify a significant behavioural response to the operation of the turbine. It is not unusual for temporal models of marine mammal occurrence to explain a small portion of the deviance (Holdman et al., 2019). Importantly from an applied aspect, during operation, seal presence was further reduced by between 22% and 93% (95% CI) at higher flow speeds (≥2.3 ms^{-1}) (Figure 5).

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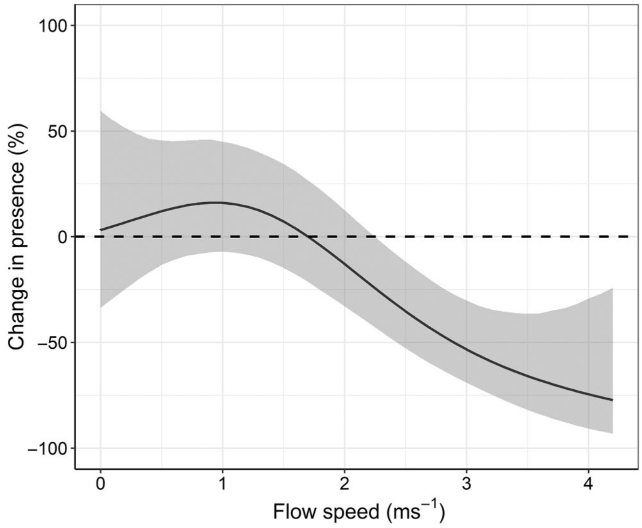

FIGURE 5 Mean percentage change in seal presence around the turbine between non-operational and operational periods, relative to flow speed. The grey-shaded area represents 95% confidence intervals. There is a marked decline in seal presence at flow speeds greater than 2.3 ms^{-1} with a mean decrease in presence of up to 77% (95% CI: 22%–93%) at the highest flow speed.

From a methodological perspective, the data collection and processing approaches were highly successful for detecting seals underwater around the operational turbine. The seabed platform allowed the collection of sonar data in a highly challenging environment almost continuously over a period of 12 months. Furthermore, the approach developed to detect and track seals (Gillespie et al., 2023) provided an efficient means of processing large volumes of sonar data and, although relatively user intensive, the manual post hoc auditing and confidence scoring of targets allowed the classification of seals in the data. Under half ($n=303$) of the classified seals tracks were assigned a higher CS (≥4). This highlights the uncertainty in species classification in sonar data and it is important to stress that there were no concurrent independent ground-truth data that might be used to confirm the classifications. For future monitoring studies collecting similar data, it will be important to further automate the classification steps. However, the automatic classification of marine mammal targets in multibeam sonar data is a challenging task. Hastie, Wu, et al. (2019) had some success classifying seals from other unknown targets in multibeam sonar data using Kernel support vector machines, and Cotter and Polagye (2020) used a random forest algorithm to classify seals, diving birds, fish schools and small targets, but only out to a range of 10 m, where the spatial resolution of the sonars was high. Despite this, using the current sonar system, the inherent limitations (e.g. low spatial resolution at higher ranges) mean that fully automated classification of targets is likely to be extremely challenging and some level of human validation will still be required. Nevertheless, improvements to classification to reduce volumes of data that need to be manually reviewed would be useful.

The results of the temporal modelling showed that seal occurrence varied significantly over the year with highest numbers during the winter (November–January) and lowest numbers during the summer (July–September) (Figure 2). Furthermore, there were consistent patterns in occurrence with time of day; higher numbers of seals were generally observed at night and lower numbers during the day (Figure 3). These results provide important ecological insights into seal usage of tidally energetic environments. Importantly however, due to the resolution of the sonar and the similarity in body size between grey seals and harbour seals, species differentiation was not possible. As both are known to occur within the study area (Carter et al., 2020), it is highly likely that both species were detected here and the data presented reflect a combination of grey and harbour seals.

Use of tidal channels and areas with high flow speeds by seals has previously been linked to foraging. For example, Hastie et al. (2016) showed that harbour seals in a tidally energetic channel showed a striking pattern in their distribution; all seals spent a high proportion of their time around the narrowest point of the channel during the flood tide. It was suggested that foraging on Atlantic mackerel (*Scomber scombrus*) was the primary driver of this spatial and temporal pattern. However, this species is not a significant component of either grey or harbour seals diets in Orkney, with the diet consisting primarily of gadoids and sandeels (Wilson & Hammond, 2019). Sandeel activity in the water column has been shown to peak in the spring and summer months in other areas (Winslade, 1974). This contrasts with when seal presence in proximity to the turbine was highest, which suggests they may either be attracted to the area to forage on other prey species more available in winter or may using this localised area for another reason. For example, the months with the highest occurrence of seals (November–January) are coincident with the end of the pupping period for grey seals in this area (Russell et al., 2019); the peak in detections may therefore simply represent high numbers of grey seal pups present in the water having left the breeding colonies close to the turbine (Russell et al., 2019).

The diel pattern in seal presence measured in the current study shows that the area around the turbine is used by seals primarily during periods of darkness (Figure 3). The underlying driver for this pattern is unclear, though potential reasons include diel cycles in foraging patterns or haul out behaviour. Although harbour seal haul out patterns are generally influenced by tidal cycles, with higher numbers of seals at sea during high tide periods (Thompson et al., 1997), diel cycles in harbour seal haul out patterns have been shown to be much stronger in rocky shore areas (such as this study area) where site availability is less influenced by the tidal cycle (Stewart, 1984; Thompson et al., 1989). This has been observed in a previous study of harbour seal behaviour in an area of Orkney relatively close to the current study area (Van Parijs et al., 1999).

These temporal patterns also have important implications for the prediction of encounter rates between seals and tidal turbines as the risk of collision will fluctuate over daily, seasonal and annual cycles. Specifically, most collision risk assessments assume static densities of animals when estimating encounter rates with turbines (SNH, 2016). Depending on the time of day or year that the underlying density data were derived, this could lead to an under- or over-estimation of numbers of animals exposed to the risk of collision. For example, density data for seals are often derived using a combination of haul out count data and distribution data from individuals tagged with GPS tags (Russell et al., 2017). For grey and harbour seals, tag data are generally only available during months out with the pupping and moulting seasons, which, in this study, has reported the highest numbers of seals. Future work should focus on measuring the variation in abundance of animals at proposed development sites across temporal cycles.

From an applied perspective, the result showing that seals avoid the turbine during operation are important in the assessment of collision risk. When operating, blade tip speeds varied between 5.6 and 13.2 ms^{-1}, all of which are above the 5.1 ms^{-1} threshold for serious injury derived by Onoufriou et al. (2019). However, at lower flow speeds, animals may have more time to react and move away after becoming aware of the turbine, and the possibility of moving between the turbine blades without collision also increases, so the avoidance at flow speeds above 2.3 ms^{-1} may reduce the overall risk of mortality.

From an impact prediction perspective, current guidance for marine mammals in Scotland recommends the use of a range of avoidance rates (between 0% and 99%; SNH, 2016), partly due to the lack of empirical data. Behavioural responses to renewable energy devices can be considered at a range of spatial scales, previously described by Cook et al. (2014): macro, meso and micro. To generate robust estimates of avoidance rates by seals to tidal turbines, it is useful to consider behaviour at each scale; these can then be combined to assess an overall cumulative avoidance rate to parameterise collision risk models. A previous study using data from individual seals tagged with GPS tags reported a mean macro-scale harbour seal avoidance of 27.6% (95% CIs: 11% and 49%) to the same tidal turbine array as the current study (Onoufriou et al., 2021). The results from the current study can usefully be considered as meso-scale avoidance and showed avoidance rates of up to 22–93% (95% C.I.) at flow speeds ≥2.3 ms^{-1}. Although good progress has now been made in understanding how seals respond to operating turbine at macro- and meso-scales, information on the micro-scale movements and avoidance behaviour (at a scale of metres) of individual seals around turbines remains the critical research gap with respect to deriving overall avoidance rates. Critically, further analysis of the individual seal tracks collected using the current sonar system could now be used to measure movements and quantify avoidance by seals at these micro-scales.

Although this study has shown significant avoidance by seals to an operating turbine, the stimulus that elicits the reduction in seal presence around the turbine is unclear. However, the acoustic emissions produced from this turbine are relatively high (range: 25 Hz–25 kHz) and are within the audible range of seals (Risch et al., 2023); it is therefore plausible that seals detect and respond to the noise of the turbine during operation. Hastie et al. (2018) carried out a series of acoustic playbacks of tidal turbine sounds and reported a macro-scale avoidance of a turbine acoustic signal; tagged harbour seals exhibited significant spatial avoidance of the sound which resulted in a similar mean reduction in the usage by seals of 27% (95% CI: 11%–41%) at the playback location. Furthermore, turbine noise levels increase with flow speed and the rotational speed of the blades (Hazelwood & Connelly, 2005), potentially explaining why there is a stronger avoidance response at higher flow speeds.

It is also possible that seals also use other sensory modalities such as vision to detect the operational turbine at ranges of tens of metres; if the turbine was visible underwater at higher ranges and seals exhibited avoidance at higher ranges during daylight hours, this may explain the lower numbers of seals detected during the day. Although harbour seals are sensitive to low light levels and are able to detect objects at depths greater than that of the turbine (>30 m) (Renouf, 1989), it is possible that seals use a combination of sensory cues to detect the moving blades. For example, seal whiskers (vibrissae) are highly sensitive to changes in flow disturbances (Zheng et al., 2021) and may allow them to detect and avoidance of the turbine. Understanding the specific stimuli that the seals are responding to is important when looking at the transferability of the results to other areas and different turbine designs.

The current study has provided new evidence to inform consenting of future tidal turbines. However, it is important to consider that the measured meso-scale avoidance responses were to a single turbine within a small array (four turbines). As the tidal industry develops, turbine array sizes will increase and understanding the interactions between wildlife and larger arrays will become important (Coles et al., 2021). This will require a monitoring of other prospective macro-scale impacts such as displacement of animals from large areas or barrier effects (Hemery et al., 2024). Importantly, there is already evidence to suggest there is a positive relationship between array size and avoidance rates by marine mammals; harbour porpoises' presence around the same array monitored in the current study was reduced to a greater extent when four turbines were operating relative to when just one was operating (Palmer et al., 2021). Future monitoring of animals at operational tidal developments should therefore be carried out to quantify impacts of larger arrays as they scale up. Although the methods used here were successful for measuring the presence and behaviour of animals within a localised area around a turbine, scaling these up to monitor each turbine in an array is unlikely to be practical or cost-effective. For seals, macro-scale behaviour could be studied through a behavioural study of individual seals using GPS movement tags (e.g. Hastie et al., 2018). This would allow investigation of potential displacement from large areas (e.g. Onoufriou et al., 2021) or barrier effects to important transit routes (e.g. Sparling et al., 2018). This is also now a relatively standard monitoring technique for renewable energy developments that would allow the comparison of behavioural data and avoidance from different sites to evaluate transferability of findings and aid in reducing the uncertainty around the estimated impacts.

AUTHOR CONTRIBUTIONS

Gordon Hastie, Douglas Gillespie and Carol Sparling led the conceptualisation of the study and designed the methodology. Douglas

Gillespie developed the algorithms and software. Douglas Gillespie, Gordon Hastie, Jessica Montabaranom, Emma Longden, Katie Rapson and Anhelina Holoborodko processed and annotated the data. Jessica Montabaranom and Gordon Hastie analysed the data. Jessica Montabaranom, Gordon Hastie and Douglas Gillespie led the writing of the manuscript. All authors contributed to drafts, the reviewing process and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

All authors declare they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available via the PURE University of St Andrews Digital Repository: https://doi.org/10.17630/0cb53061-4a53-47c1-8bd8-12775b894708 (Montabaranom et al., 2024). The PAMGuard software and plugins are available via Zenodo: https://doi.org/10.5281/zenodo.13951593 (Gillespie & Macaulay, 2024), and https://doi.org/10.5281/zenodo.13627798 (Gillespie, 2024).

ORCID

Jessica Montabaranom https://orcid.org/0009-0009-1909-7280
Douglas Gillespie https://orcid.org/0000-0001-9628-157X
Emma Longden https://orcid.org/0000-0002-2321-4656
Katie Rapson https://orcid.org/0009-0005-3018-4183
Anhelina Holoborodko https://orcid.org/0009-0002-5114-8008
Carol Sparling https://orcid.org/0000-0001-7658-5111
Gordon Hastie https://orcid.org/0000-0002-9773-2755

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1: Supporting information.

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