Marine Environmental Research 198 (2024) 106532

Contents lists available at ScienceDirect

Marine Environmental Research

journal homepage: www.elsevier.com/locate/marenvrev

Integrated survey methodologies provide process-driven framework for marine renewable energy environmental impact assessment

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ARTICLE INFO

Keywords:
Biophysical data collection
Environmental impact assessment
Habitat
Hydrodynamics
Marine renewable energy
Monitoring
Monitoring guidance
Seabirds
Survey methods
Uncertainty

ABSTRACT

Environmental interactions of marine renewable energy developments vary from fine-scale direct (e.g. potential collision) to indirect wide-scale hydrodynamic changes altering oceanographic features. Current UK Environmental Impact Assessment (EIA) and associated Habitats Regulations Appraisal (HRA) guidelines have limited focus on underlying processes affecting distribution and movements (hence vulnerability) of top predators. This study integrates multi-trophic ship survey (active acoustics and observer data) with an upward-facing seabed platform and 3-dimensional hydrodynamic model as a process-driven framework to investigate predator-prey linkages between seabirds and fish schools. Observer-only data highlighted the need to measure physical drivers of variance in species abundances and distributions. Active acoustics indicated that *in situ* (preferable to modelled) data were needed to identify temporal changes in hydrodynamics to predict prey and consequently top predator presence. Revising methods to identify key habitats and environmental covariates within current regulatory frameworks will enable more robust and transferable EIA and HRA processes and outputs, and at larger scales for cumulative and strategic-level assessments, enabling future modelling of ecosystem impacts from both climate change and renewable energy extraction.

1. Introduction

There is now a global recognition of a climate emergency and many nations are poised to begin rapid and very large-scale development of offshore renewable energy (European Commission, 2020; IRENA, 2019). The UK and Europe are taking advantage of widespread and convenient access to marine renewable energy resources *(Parsons and Gruet, 2018)*. While de-carbonisation of energy supply is a necessity, environmental impacts during this process must be limited to ensure sustainability of marine energy solutions *(*European Commission, 2020; Woolley, 2015). However, studies have suggested that aspects of UK environmental and conservation laws (Environmental, 2020; Scottish Government, 2010) are not coherent with renewable energy laws and policy objectives (Energy Act 2013; MacDonald, 2018), with little acknowledgement of environmental considerations within energy laws (MacDonald, 2014; Woolley, 2015). This lack of coherence between policy objectives appears widespread. Globally, marine plans envisage vastly increasing the number of marine renewable energy developments to help meet net-zero targets (IRENA, 2019), with significant concerns being raised that environmental legislation does not go far enough to prevent ecological harm (*Draft Sectoral Marine Plan for Offshore Wind Energy, 2019*; IEA, 2019; Woolley, 2015). Impact assessment methodologies must therefore evolve to progress the reliability and transferability of predictions of effects on protected marine species at individual and population levels.

A methodological framework which provides statistically powerful habitat and population assessment tools would enable improved assessment of marine energy developments. Such methods fit within the current environmental protection legislation (Benjamins et al., 2015; Elliott et al., 2014; Isaksson et al., 2020) and, with the correct selection of environmental covariates, could be used to take account of expected consequences of climate change (Declerk et al., 2023). This study describes survey methodologies and case study data that demonstrate how an improved survey framework can increase information available for quantifying interactions between renewable energy developments, marine habitat changes and animal behaviour. Utilisation of a range of complementary methodologies can better inform understanding of the

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https://doi.org/10.1016/j.marenvres.2024.106532
Received 18 January 2024; Received in revised form 20 April 2024; Accepted 28 April 2024

fundamental mechanistic links required to predict spatiotemporal changes in foraging habitat types and top predator population distributions (e.g., seabirds), and potentially reduce survey and environmental impact assessment costs. This proposed framework can provide improved information for industry and regulators to meet legislative requirements and ensure de-carbonisation of energy generation is as environmentally sustainable as possible.

1.1. *Assessment processes and scales*

Current worldwide approaches to assessing impacts of marine renewable developments focus on population-level consequences, either requiring numerical quantification or ensuring uncertainties are minimised regarding direct or indirect effects from a development (*See review in Chapter 11*, *Copping and Hemery, 2020*). In Europe (and the UK, while environmental laws remain a mirror of European legislation (Directive 2011/92/EU; Government, 2017)), impact assessments can cover spatial scales from the development area to much wider scales, for example in cumulative impact assessments of highly mobile species.

Strategic Environmental Assessments (SEA) operate at a sector and management area scale. The SEA, guided by policy, assesses likely sources of environmental impact, potential cumulative effects, and informs the development plan and subsequent EIAs. In the UK, Environmental Impact Assessments (EIA) and Habitats Regulations Appraisals (HRA) operate at the individual development (project application) and population scale. A developer is required to produce an EIA, guided by Statutory Nature Conservation Bodies (SNCBs), regulators, and other interested stakeholders (*European Commission, 2015*). The EIA is the primary document that identifies ecological features present within the development site, including protected species such as seabirds. Current practices prioritise distribution information on species present within the site, while generally less focus is placed on quantifying and monitoring habitat features which may underlie indirect species displacement. Alongside the EIA, the HRA requires consideration of "likely significant effect" on Natura sites as designated under the Birds and Habitats Directive (*Directive 92*/43/EEC *as amended*), or the Conservation of Habitats and Species Regulations 2017 under UK law.

Providing robust scalable methodologies, data analyses and interpretation from developed sites can improve understanding and guide SEA/EIA/HRA approaches in potential sites that have less data as the renewables industry develops and expands globally. However, there is an urgent need to close knowledge gaps and reduce the 'data-rich-information-poor' ('DRIP') outcomes of some current methodologies (Fox et al., 2018; Wilding et al., 2017). The diurnal, biweekly and seasonal variations within marine energy development areas mean statistical approaches to quantifying impacts may suffer from low power when only distributional information is collected (MacKenzie et al., 2017; Waggitt et al., 2020). Survey efforts collecting concurrent data (e.g. predators, prey, hydrodynamic habitat) can improve the models used to quantify impact (Couto et al., 2022; Scherelis et al., 2020). With growing recognition of the importance of understanding fine (Slingsby et al., 2021) to medium (Couch and Bryden, 2007; Cox et al., 2013) scale habitats (e.g. kolk boil to tidal front), concurrent spatial surveys, along with longer-term upward-facing seabed platform temporal datasets (Polagye et al., 2020; Viehman and Redden, 2018; Williamson et al., 2017) offer an efficient route to resolving uncertainties while remaining practical.

1.2. *Linking survey methods to assessment and populations*

Direct visual animal observations from at-sea and/or aerial surveys and tagging programs in the UK over the last 40–50 years have gathered detailed information on highly mobile top predator distribution (*Carter* et al., *2020*; Russell et al., 2017; *Waggitt* et al., *2020*; *Wakefield* et al., *2017*) and population dynamics (Woodward et al., 2019) to support population assessment models. However, colony/site-specific information on foraging behaviours and overwintering areas for year-round assessment is only just starting to be available, even for well-studied populations (Busch and Garthe, 2016; Daunt et al., 2020; Patterson et al., 2022; Ronconi et al., 2022; Woodward et al., 2019). Countries where the marine renewables industry is still in its infancy may not have long-term background ecological information and therefore require rapid, high data-quality approaches to informing potential impacts.

Many protected top-predator species forage in high-energy sites and are known to be associated with a range of fine-scale water column habitat and hydrographic features (upwelling, shear, tidal fronts, regions of high velocities, areas with high turbulent kinetic energy and specific locations with kolk-boils) which form, dissipate, or move, depending on tidal current velocities (Alonso et al., 2018; Benjamins et al., 2015; Hastie et al., 2016; Johnston et al., 2021; Lossent et al., 2018; Malinka et al., 2018; Nuuttila et al., 2018). An increasing amount of research is providing predictive relationships between hydrodynamic variables and mobile species distributions in high-energy areas (Couto et al., 2022; Lieber et al., 2018a, 2019; Slingsby et al., 2022; Waggitt et al., 2016; Whitton et al., 2020; Wiesebron et al., 2016). Alongside diel cycles, hydrodynamic conditions are therefore likely to be part of the underlying process behind species distributions and behaviour, with changes (hydrodynamic, species distributions, behaviour or the relationships between them) dependent on development location and scale (De Dominicis et al., 2018; Defne et al., 2011; Shields et al., 2011).

A process-based approach can utilise readily collectable biological and physical covariates which explain species usage of a site. For example, hydrodynamic conditions i.e., velocity, turbulence, upwelling can be quantified by both active acoustics and established 3D oceanographic modelling approaches (Lieber et al., 2018b; O'Hara Murray and Gallego, 2017a). Changes in hydrodynamic conditions due to tidal, wave or wind energy extraction may lead to shifts in benthic habitats such as sandbanks (critical habitat for important prey species such as sandeels) (Fairley et al., 2018; McIlvenny et al., 2016). These potential changes, as a consequence of energy extraction, could be the start of a process that causes changes at the population level of protected species, with different types of species sensitivity depending on foraging and prey characteristics (Wade et al., 2016).

Tidal stream energy sites are useful case studies to demonstrate process-driven methodologies, as the extremes of spatiotemporal variation in physical features appear over short time periods (semi-diurnal tidal cycles). Further, clear spatial patterns are generated at small scales which enable highly efficient and rapid collection of many replications of contrasting physical habitat data (*Slingsby* et al., *2021*). Concurrent collection of hydrodynamic habitat characteristics, with daytime observer surveys of seabirds, will provide robust datasets enabling predictive models for changes in foraging patterns. This approach will, in turn, assist in decreasing uncertainty of effects and help to meet the requirements for developments to be assessed at both the development (population) scale for EIA and HRA requirements, and wider ecosystem SEA requirements.

1.3. *Study aim*

The aim of this study is to demonstrate how integrating data collection methodologies can enable a habitat-focused, process-driven approach to understanding impact and cumulative assessments for marine renewable energy development sites. We do this with examples from the Pentland Firth, Scotland, at the MeyGen site (the world's first commercial scale tidal-stream array, 6 MW) (*Coles et al., 2021*). We show how utilising both ship-based surveys and autonomous upward-facing instrumentation platforms can robustly inform monitoring efforts of hydrodynamic habitats, prey presence and behaviour as well as top predator abundances and distributions. Outputs from three data sources are considered: (1) fine-scale 3D hydrodynamic modelling, (2) deployment of an upward-facing integrated seabed platform consisting of multiple active-acoustic instruments, and (3) ship-based surveys with similar downward-facing active-acoustics instrumentation along with wildlife observers. Combining these approaches in the correct sequence can provide high-quality information on fine-scale relationships between protected species and habitat usage. We aim to show how practical survey approaches can inform a more robust process-driven, predictive approach to impact assessments, fitting within and improving existing monitoring frameworks of interactions between marine renewable energy devices, environment, and top-predators.

2. Materials and methods

2.1. Study site

The MeyGen tidal turbine array (*Coles et al., 2021*) is located in the Inner Sound of the Pentland Firth, Scotland, UK, between the island of Stroma and the north coast of the Scottish mainland. The array consists of four 1.5 MW gravity-based turbines installed in Oct–Nov 2017. The Inner Sound is largely bare rock, with large sandbanks at the southeast and southwest ends. The site is characterised by flood and ebb tidal currents of >3 m s^{-1} on both the north and south coasts of Stroma Island. Current velocities and turbulence vary significantly through the semi-diurnal tidal cycle, as visualised in Appendix A (Figure A 1).

2.2. Hydrodynamic habitat comparisons

Five contrasting hydrodynamic habitat units of 600 × 600 m were selected around Stroma (Table B 1). Area size was based on the approximate survey width of a standard European Seabirds at Sea (ESAS) observer survey of 300 m on either side of a vessel *(Camphuysen et al., 2004*). The areas (Fig. 1) reflect either important locations (i.e. the site of the FLOWBEC-4D platform, see section 2.3) or contrasting areas of minimum, average and maximum current velocity across both ebb and flood cycles (Appendix A Figure A 1), and are likely to be directly or indirectly influenced by high levels of energy extraction and placement of structures (O'Hara Murray and Gallego, 2017b).

In this study, depth-averaged mean horizontal speed is used as a proxy for hydrodynamic habitat, as speed is linked to other hydrodynamic parameters used within species distribution modelling, such as turbulent kinetic energy or maximum shear (*Lieber* et al., *2018a*). For brevity, we only present speed and expand on this in the discussion.

The availability of top predator occurrence information from seabird data observed during the surveys and from previous tagging efforts of both seabirds (*Johnston* et al., *2021*), as well as ship survey routes, were considered during area selection. Area 1 is centred on the FLOWBEC-4D 2015 deployment (see *Section 2.3.1*). Area 2, to the southeast of Stroma, is within, and in the likely downstream effect of, planned future array developments, as well as informed by a priori information as a preferred area for black guillemot (*Cepphus grylle*) foraging due to increased prey abundance (sandeel, *Ammodytidae* spp. and butterfish, *Pholis gunnellus*) on the sandbanks (Johnston et al., 2021; Rollings et al., 2016). Areas 1 and 2 represent sampling from the Inner Sound. Area 3, to the northeast of Stroma, is an area of rapid changes in flow direction over the tidal cycle (Figure A 1). Area 4 to the northwest of Stroma is more representative of the central Pentland Firth and is the location of known strong shear generated by bathymetry around Stroma on the ebb tide (Figure A 1). Area 5 to the southwest of Stroma is close to seabird hotspots, as indicated from tagging data (Johnston et al., 2021). From here on, the areas are collectively referred to as 'habitat units'.

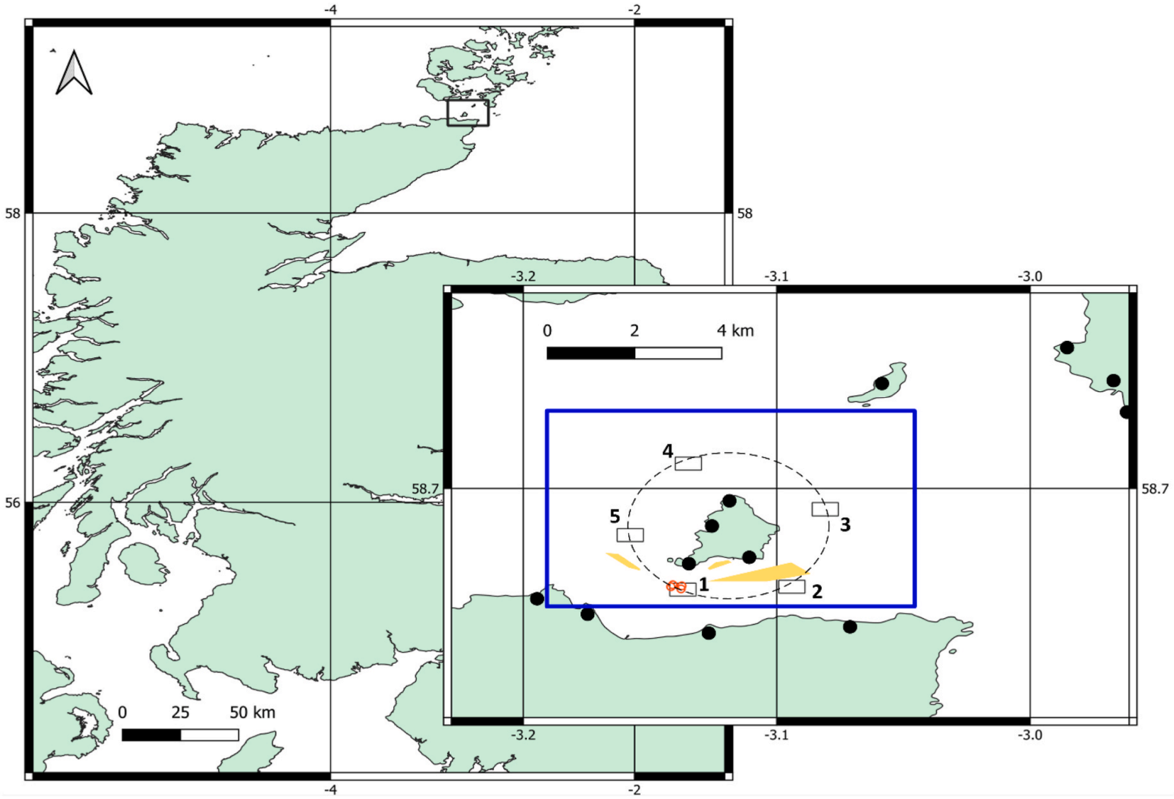

Fig. 1. Location of surveys around the island of Stroma on the north coast of Scotland. Blue box shows extent of distribution analysis. Smaller black boxes indicate hydrodynamic habitat units and their respective numbers. Dashed line indicates example ship survey route. Projected in WGS 1984. Black dots indicate seabird colony location, predominantly benthic and pelagic feeders, as identified in the Joint Nature Conservation Committee (JNCC) Seabird Monitoring Programme database. The location of the 4 tidal turbines (installed before the second ship survey in 2018) is marked with red circles and the location of sandbanks in the Inner Sound marked in yellow. https://marine.gov.scot/data/environmental-statement-meygen-tidal-energy-project.

2.3. Acoustics surveys/platform deployment

2.3.1. FLOWBEC-4D

The FLOWBEC-4D upward-facing platform was deployed 8th – 19th October 2015, collecting biological and physical data over a 265-hr period prior to installation of the MeyGen turbine array (in habitat unit '1'). The platform integrates a Simrad multifrequency EK60 echosounder (38, 120 and 200 kHz), Imagenex Delta T multibeam echosounder (260 kHz), Nortek Signature 1000 broadband Acoustic Doppler Current Profiler (ADCP) and an Acoustic Doppler Velocimeter (ADV). A custom ping synchronisation interface allows concurrent measurements across the different acoustic instruments (Williamson et al., 2016, 2017). After accounting for the transducer height and acoustic nearfield, the EK60 sampled from 2 m above the seabed upward to the sea surface in 0.2-m bins, sampling once per second at a pulse duration of 1024 μs. The ADCP has four slanted beams at a 25° angle, and one vertical beam, each with 2.9° beamwidth; ADCP measurements are in 1-m bins up to a maximum range of 30 m from the platform, with a 16 Hz burst for 1 s every minute. Horizontal bin length for the EK60 varied with water column horizontal speed. The limited range of the ADCP resulted in the top 4.5–7.6 m of the water column not being sampled depending on tidal phase. Only the ADCP and EK60 data are analysed here. The integrated platform allows concurrent collection of hydrodynamic and biological (fish school) data at very fine timescales and is one of several multi-instrument platforms recently developed for biophysical measurements within high energy sites (Polagye et al., 2020; Scherelis et al., 2020; Williamson et al., 2021). These outputs are hereafter referred to as 'platform' data. No concurrent observer data were recorded during the platform deployment.

2.3.2. Mobile acoustic surveys

Ship-based surveys collected spatial hydrodynamic habitat (ADCP) and biological (fish, EK60) data. Surveys on the Scottish Government Marine Directorate research vessel MRV *Scotia* covered two four-day periods in 2016 (22nd to 25th June, 56 h) and 2018 (21st to 24th July, 85 h). Each survey comprised repeated circular transects around the island of Stroma targeting the turbine locations within the Inner Sound to provide comparability with the FLOWBEC-4D data (specifically spatial comparison between the platform ADCP and ship ADCP). In 2016, technical issues meant no ADCP data were recorded. Exact spatial overlap was not always possible due to turbine maintenance works in 2018 that limited sampling of habitat unit 1 during two days of the survey. The 2016 survey was conducted closer to the spring tidal phase, while the 2018 survey was completed closer to the neap phase (Fig. 3).

Ship-based surveys used a Simrad multifrequency EK60 echosounder (38, 120 and 200 kHz) installed on a drop keel 2 m below the ship, i.e. approximately 7.5 m below the surface. The EK60 used a pulse duration of 1024 μs, transmitting on all frequencies simultaneously every second. Data outputs used 0.2 m vertical bins with horizontal bin length dependent on vessel speed which ranged from 2.5 to 7.7 m s^{-1} (GPS speed). Hydrodynamic measurements used a RDI 150 kHz broadband ADCP with a beam angle of 30°, sampling 2 m depth bins over a maximum of 30 bins, with measurements every 0.1 s, averaged over 3.1 s periods. The FLOWBEC-4D platform and *Scotia* EK60 echosounders were calibrated using a 38.1 mm tungsten carbide sphere following standard procedures (*Foote* et al.*, 1987*).

2.4. Observer data

Both the 2016 and 2018 ship surveys included two teams of two seabird observers (with the addition of a scribe in 2018) on two-hourly rotations from 0400 to 1900 UTC daily. Observers followed ESAS protocols (*Camphuysen* et al.*, 2004)* recording as close to species-level count data in 50 m bands up to 300 m from the ship. Seabird location was recorded at the point they passed abeam of the vessel, or in the case of flushed animals this was estimated, along with the distance band where the animal was last seen. The circuit surveys were conducted against the flow of the tide when passing through the Inner Sound, with target speeds throughout the survey within the range of recommended at-sea survey speeds of 2.5–7.7 m s^{-1} through the water. Surveys against the flow are recommended to minimise double sampling of the same individuals (by observers) and fish schools which may occur if the ship is moving with the flow (Waggitt et al., 2016). Observations north of Stroma were therefore with the flow so true sampling effort is reduced in these areas, though ship speed over ground was kept as constant as possible.

2.5. Data analysis

2.5.1. Hydrodynamic processing

The Finite Volume Community Ocean Model (FVCOM) Scottish Shelf Model for the Pentland Firth and Orkney Waters (hereafter referred to as "SSM") was used to produce horizontal velocity data for the habitat units around Stroma (Fig. 1), as described in *Section 2.2* (Chen et al., 2011; O'Hara Murray and Gallego, 2017b). The 3D hydrodynamic model consists of an unstructured triangular grid, with various environmental scalars (temperature, salinity etc.) and vector (turbulent kinetic energy, vertical and horizontal water velocities etc.) variables calculated at nodes and elements respectively, with vector grid size a minimum of 160 m within habitat units. The SSM uses ten equidistant depth bins, with outputs giving point-estimates of horizontal velocity, in 15-min time-steps, for each element within the five habitat units extracted by latitude and longitude (Table B 1). Set up information is available in Table B 2, with sampling information available in Table B 3. The SSM was run for two-week spring-neap periods on dates covering both surveys and platform deployment before sub-setting the data extraction and analysis to the respective survey periods. Depth-averaged easting and northing components of horizontal velocity were extracted and used to calculate depth mean averaged speed ($\overline{v}$) using *Equation 1*.

$$\overline{v} = \frac{1}{k}\sum_{i=1}^{k}\sqrt{(e-pe)_i^2+(n-pn)_i^2}$$

Equation 1 calculates depth-averaged mean horizontal speed, where the mean value of all depth bins of the water column is calculated. e = easting component, n = northing component of recorded velocity data with k = number of depth bins = 30 (FLOWBEC-4D), 30 (*Scotia*), 10 (SSM). "p" prefixes of e, n correspond to platform movement data (nominally zero for FLOWBEC-4D as a stationary platform and SSM).

ADCP data from FLOWBEC-4D 2015 and *Scotia* 2018 were recorded with earth coordinates for measurement correction during processing, velocity errors, vertical velocity, and false targets (RD Instruments, 2000). Data were converted to earth coordinates (eastward (*e*), northward (*n*), upward (*u*)) and ship-based measurements were corrected for platform speed on all three axes (*pe, pn, pu*), converting into a singular value representing true depth mean averaged speed ($\overline{v}$) per second (*Equation 1*). For FLOWBEC-4D platform correction values were zero as it is a static platform.

2.5.2. EK60 methods for fish school detection

EK60 data were processed following Fernandes (2009) protocols for fisheries acoustics analysis using Echoview 5.3 software. The protocol removes background noise by summing volume backscattering strength (S_v, in units dB re 1 m^{-1}) of all available EK60 frequencies for the data source and selecting only data above a given threshold (−200 dB). Outputs are then passed sequentially through a 3x3 median filter and 5x5 dilation filter, to ensure fish schools were fully delineated across all frequencies, and then finally a mask was applied. Due to instrument depth (drop keel 2 m below the hull), surface turbulence and instrument characteristics including the nearfield, the top 12 m of the water column were removed for the fish school analysis (see *Couto* et al.*, 2022*). The detection parameters used within the SHAPES algorithm (Barange, 1994) were a minimum total school length of 10 m, minimum school height of 1 m, minimum candidate school length of 5 m, minimum candidate school-height of 1 m, vertical-linking distance of 2 m, and maximum horizontal-linking distance of 15 m to detect regions (echo trace boundaries) that are likely fish schools (*Fernandes, 2009*), where the linking distance allows nearby candidate schools to be joined within the threshold distances. All regions were visually checked for validity. This inspection highlighted some schools which were subsequently removed from the FLOWBEC-4D dataset due to connectivity with surrounding turbulence. As these removed schools represented <4% of the total potential schools, no further filtering was applied. Ship survey fish detections did not suffer from this issue due to the instrument and deployment characteristics mentioned above. Due to the limited number of schools detected during the ship surveys, a direct comparison with schools detected at the FLOWBEC-4D deployment location was not possible; therefore, comparisons of detection were taken from the entire survey as well as the Inner Sound, defined as surveyed areas south of Stroma (Fig. 1).

2.5.3. *Seabird abundance and distribution*

Kernel density estimations were produced from seabird observer data from the 2016 and 2018 ship surveys. This provided the expected group sizes of birds across the site of three ecotypes based on their foraging characteristics: surface (*Fulmarus glacialis* and *Rissa tridactyla*), pelagic (*Alca torda* and *Fratercula arctica*) or benthic (*Uria aalge* and *Phalacrocorax aristotelis*). Less abundant species contributed <10% of total observations and are not included in the analysis. Kernel density estimation with island and mainland as barrier (hence referred to as KDE analysis) was performed using ArcMap 10.7 geographic information

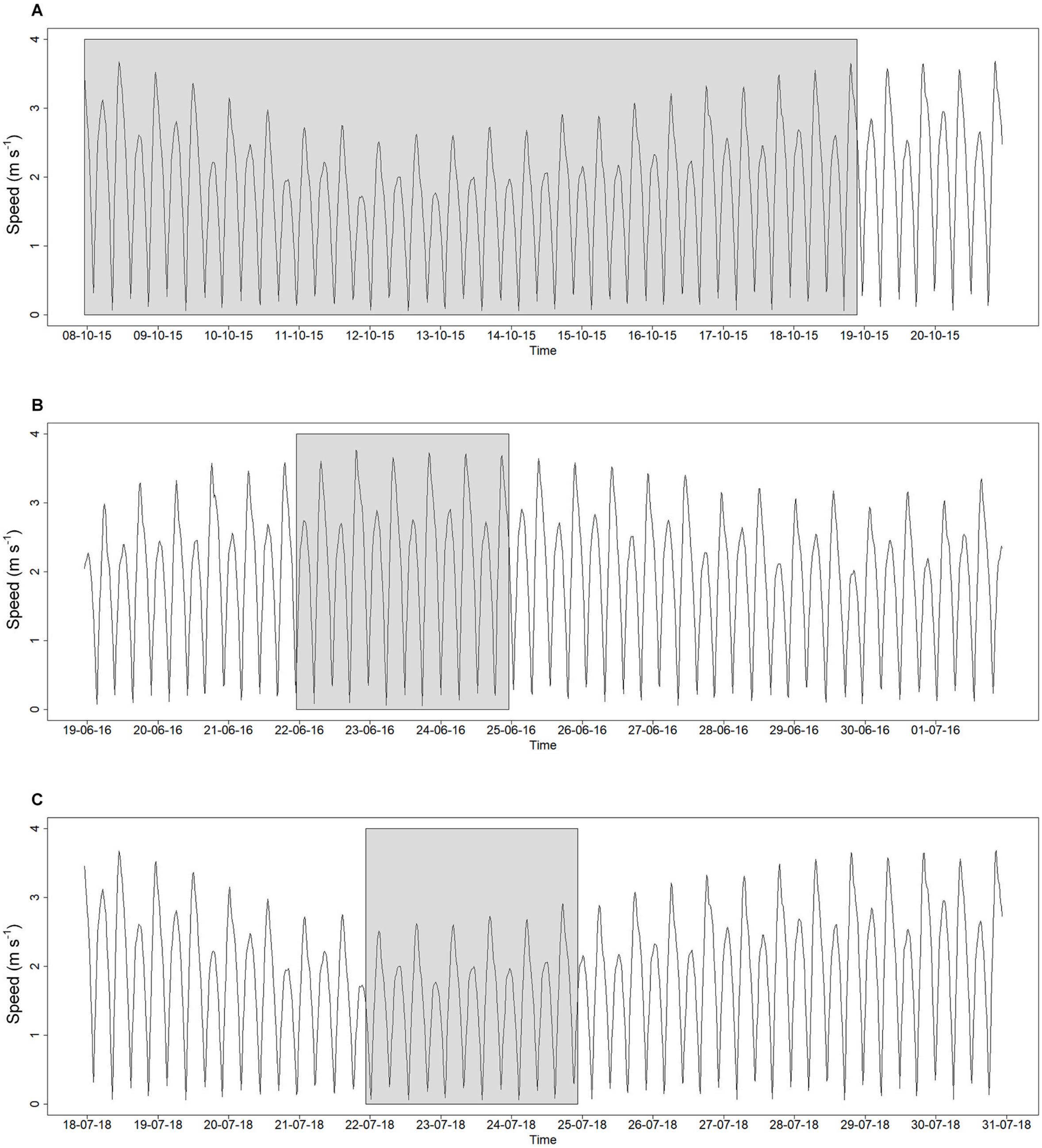

Fig. 2. Depth-averaged mean horizontal SSM speed outputs for the three survey periods. Grey boxes show the period of each survey. (A) FLOWBEC-4D 2015, (B) *Scotia* 2016, (C) *Scotia* 2018.

system software, weighted for number of birds observed in each group (*Silverman, 2002*). The estimation was constrained to a survey width of 300 m (survey range of the ESAS method) with a buffered area of 300 m either side of the survey track defining the spatial extent of the predictions. Spatial survey effort is shown in Figure B 1. Statistical comparisons between the survey years are also presented.

3. Results

The results are presented across the three different data types: (1) hydrodynamic data (depth averaged mean horizontal speed, hereafter referred to as 'mean speed') which compares outputs from SSM predictions against the FLOWBEC-4D platform deployment period in 2015, and the 2018 *Scotia* survey ADCP data, (2) compares fish school vertical (FLOWBEC-4D 2015, *Scotia* 2016 and 2018) with spatial distributions (*Scotia* 2016 and 2018), and (3) compares seabird spatial kernel density distributions between the 2 years of survey (*Scotia* survey periods within 2016 and 2018).

3.1. Hydrodynamic conditions and comparisons of modelled vs in situ data

SSM predictions of horizontal speed were compared against the field data collected within the selected Habitat Units by FLOWBEC-4D and *Scotia* ADCP (Figs. 2 and 3). The SSM estimates lower median values than *in situ* ADCP data for the equivalent FLOWBEC 2015 period/area, and for all areas except Habitat Unit 3 for the 2018 *Scotia* ADCP. Additionally, the SSM underestimates the upper extreme values when compared to all *in situ* data across all Habitat Units. With the 2016 survey conducted over the spring tides and the 2018 survey over neap tides, we would expect 2016 speed values to be higher than 2018. From the SSM outputs, this is only the case for three out of the five habitat units (Habitat Unit 2, 4, and 5). Habitat Unit 1 and 3 SSM outputs show slightly greater median velocities in 2018; however, have a similar range to 2016 outputs.

Comparing FLOWBEC-4D 2015 and 2018 ship data in Habitat Unit 1, the ship data does not return as high peak speeds as the FLOWBEC-4D data. This is thought to be partly due to the timing of the 2018 survey within the neap phase of the fortnightly tidal cycle, but also due to the ship instrumentation being unable to sample the top 12 m of the water column where tidal speeds are greatest.

3.2. Fish school detections

The FLOWBEC-4D platform EK60 detection rate for fish schools was 3.78 hr^{-1} (1007 schools) across the deployment period, compared to 1.00 hr^{-1} (56 schools) and 3.16 hr^{-1} (269 schools) for the 2016 and 2018 ship survey respectively (Table 1) The FLOWBEC-4D platform detected a greater rate of fish schools on the flood tide, with detections decreasing in both tidal phases during the night. However, fish schools in both ship surveys had the greatest detection rates on the ebb tide during the day and a lower detection rate during the night. During the night, the 2016 survey detected three times as many schools on the flood tide as on the ebb, with the 2018 survey having similar detection rates in each tidal phase. Within the Inner Sound, the FLOWBEC-4D platform had a higher detection rate during all day-night/tidal phases than either of the ship surveys. Highest detection rates were during the day on the flood tide (5.48 schools hr^{-1}), with lowest detection rate during the night on the ebb tide (0.33 schools hr^{-1}). Both ship surveys saw lower detection rates within the Inner Sound compared to the full survey route (Table 1). The 2016 ship survey detected more schools on the ebb tide during the day but showed no trend with tidal state during the night. The 2018 ship survey detected no schools on the ebb tide at any time of day, and a slightly higher detection rate on the flood tide during the day than during the night.

3.2.1. Vertical distribution

The 2015 FLOWBEC-4D platform data detected 75.9% of total detected fish schools within the top 12 m of the water column (Fig. 4, Table 2). The precautionary approach to fish school categorisation means these results are highly unlikely to be false positives (e.g. entrained air identified as schools). Detections from FLOWBEC-4D platform show a slightly bimodal vertical pattern of fish school occurrence with a secondary maximum of fish schools at around 18 m from the surface during both the day and night, similar to previous studies using the FLOWBEC-4D platform (Fig. 4B) (*Williamson* et al., *2019*).

Due to the lower detection rates within the Inner Sound from the ship surveys, Fig. 5 shows the vertical distributions for the complete circuits of the ship surveys. The 2016 survey showed similar vertical trends between day and night with fish on the ebb tide generally present higher in the water column. 59.1% of the 2018 schools were detected between 12 m and 18 m from the surface. However, due to the ship surveys having no detection at less than 12 m from the surface, it is unknown how this may compare to the bimodal trends observed in the platform data. 18% of the 2018 fish schools were detected in water depth of 42 m or more, meaning these detections were outside of the Inner Sound, most of which were during the ebb tide.

Fig. 6 shows the fish schools detected by the FLOWBEC-4D platform during the equivalent tidal phases of the two ship surveys. This indicates that there is a change in average school depth across the tidal phase, with spring phase fish schools (Fig. 6A) tending to be higher in the water column than during neap tidal phase (Fig. 6B), with a bimodal trend apparent in the neap phase. The spring phase shows the majority of fish in the top 10 m (Table 2), potentially partly explaining the lower detection rates of the overall 2016 *Scotia* fish school surveys when this upper part of the water column is not sampled by the ship.

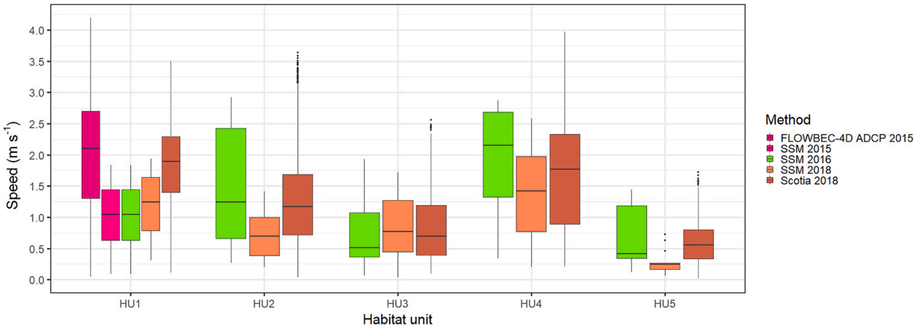

Fig. 3. Hydrodynamic data comparison. FLOWBEC-4D 2015 ADCP data was only collected in Habitat Unit 1 where is it compared to SSM model output during the same period. Other areas consist of comparing between 2018 survey periods of both *Scotia* ADCP data and SSM output as well as SSM 2016, though note this is from a different lunar tidal phase period (See Fig. 2).

Table 1

Data summary of daily and tidal detection rates for the three EK60 acoustic surveys.

	Full circuit (schools hr^{-1})				Inner Sound (schools hr $^{-1}$)			
	Day		Night		Day		Night	
	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood
FLOWBEC-4D 2015	–	–	–	–	3.05	5.49	0.33	1.19
Scotia 2016	0.79	0.32	0.22	0.69	0.32	0.08	0.15	0.15
Scotia 2018	0.95	0.62	0.36	0.38	0.00	0.11	0.00	0.09

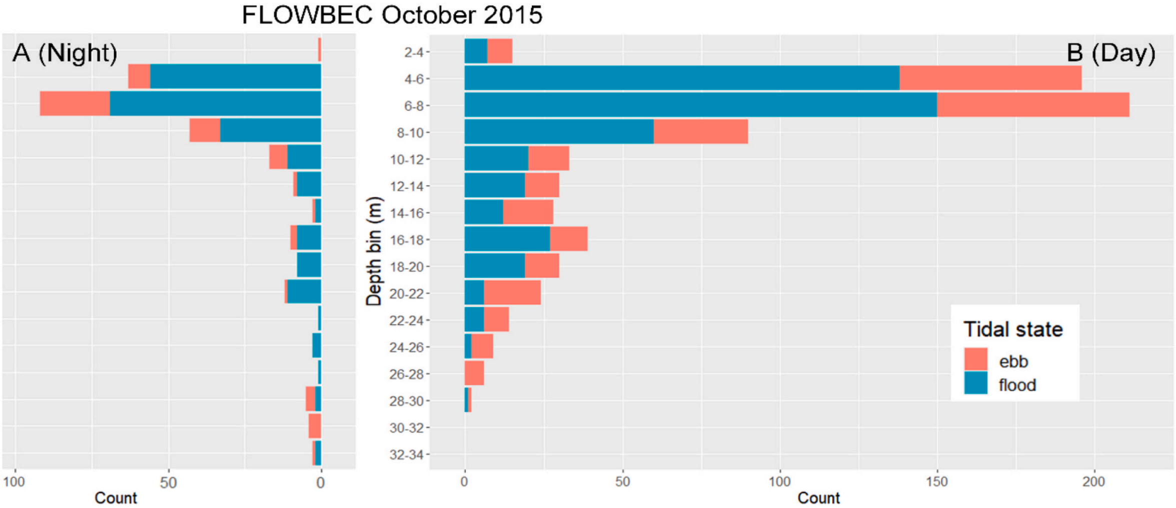

Fig. 4. Stacked bar graph of vertical EK60 fish school detection outputs for FLOWBEC 2015: (A) Night (n = 275) and (B) Day (n = 727).

Table 2

Percentage breakdown of fish school detections across depth bins for the overall *Scotia* 2016 (n = 56) and 2018 (n = 269) ship surveys. FLOWBEC-4D (n = 1002) was deployed in ~36 m of water, therefore there are no deeper detections. Detections from ship surveys deeper than 36 m are outside the Inner Sound. FLOWBEC-4D data recorded during the equivalent spring-neap tidal phase of the *Scotia* 2016 (n = 209) and *Scotia* 2018 (n = 290) are also shown.

Percentage breakdown of fish school detections (%)								
Depth bin (m)	0–6	6–12	12–18	18–24	24–30	30–36	36–42	42+
FLOWBEC-4D 2015	27.4	48.5	11.9	8.9	2.6	0.7	–	–
Spring (2016) period	23.5	64.6	7.7	3.4	0.4	0.4	–	–
Neap (2018) period	29.7	36.9	17.6	12.7	2.8	0.3	–	–
Scotia 2016	–	–	3.6	16.0	30.4	19.6	5.4	25.0
Scotia 2018	–	–	59.1	5.6	2.2	6.7	8.2	18.2

3.2.2. *Spatial distribution*

The spatial distribution of schools in the Inner Sound showed similar trends in both 2016 and 2018 ship surveys (Fig. 7), with schools regularly detected close to the planned or installed turbine location and across the sandbanks at the eastern and western entrances to the Inner Sound. Species-group-specific fish school analysis of these data is presented in *Couto* et al. *(2022)*. The majority of schools at either end of the Inner Sound are fish without swim bladders (e.g. sandeel-type species), likely utilising the large sandbank habitat present. In 2018, schools were only detected on the flood tide in the Inner Sound, while in both ship surveys, a greater percentage of schools detected to the north of Stroma were on the ebb tide. There were more detections over the south-eastern corner sandbank, with detections over the south-western sandbank less variable between years, though higher in 2018. Schools were detected along the eastern, northern, and western coasts of Stroma in both surveys, with the increase in 2018 school detections predominantly north and northeast of Stroma.

3.3. *Bird abundances and distribution*

Twice as many seabirds were recorded in 2018 (131 birds/hr) than in 2016 (64 birds/hr) across the full survey route (Table 3). The mean group size of pelagic feeders increased by around a third in 2018 compared to 2016 ($W = 2700513$, p-$value < 0.001$), with pelagic feeders remaining the largest ecotype, despite percentage share of observations decreasing from 84.8% in 2016 to 80.2% in 2018 (Table 3). Mean group sizes decreased for both surface ($W = 16482$, p-$value < 0.001$) and benthic ($W = 28022$, p-$value < 0.01$) feeders across the whole survey route in 2018 compared to 2016, with proportion of observed surface feeders increasing (7.2%–13.1%) while benthic feeders decreased (8.0%–6.6%) (Table 3). The overall percentage of surface feeders increased from 2016 to 2018 (7.2%–13.1%), though notably the percentage share decreased within the Inner Sound from 2016 to 2018 (54.7%–37.0%).

The 2018 survey saw a doubling of total numbers of seabirds across the site with a 12.5% increase in number of seabirds within the Inner Sound, predominantly increases in counts of surface and benthic feeders; however, the far greater increase in number of seabird observations outside of the Inner Sound meant that all ecotypes decreased relative usage of the Inner Sound compared to outside in terms of overall percentage use in 2018 (56.4%–30.7%, Table 3). Mean group size within the Inner Sound showed a similar trend to the whole survey, decreasing

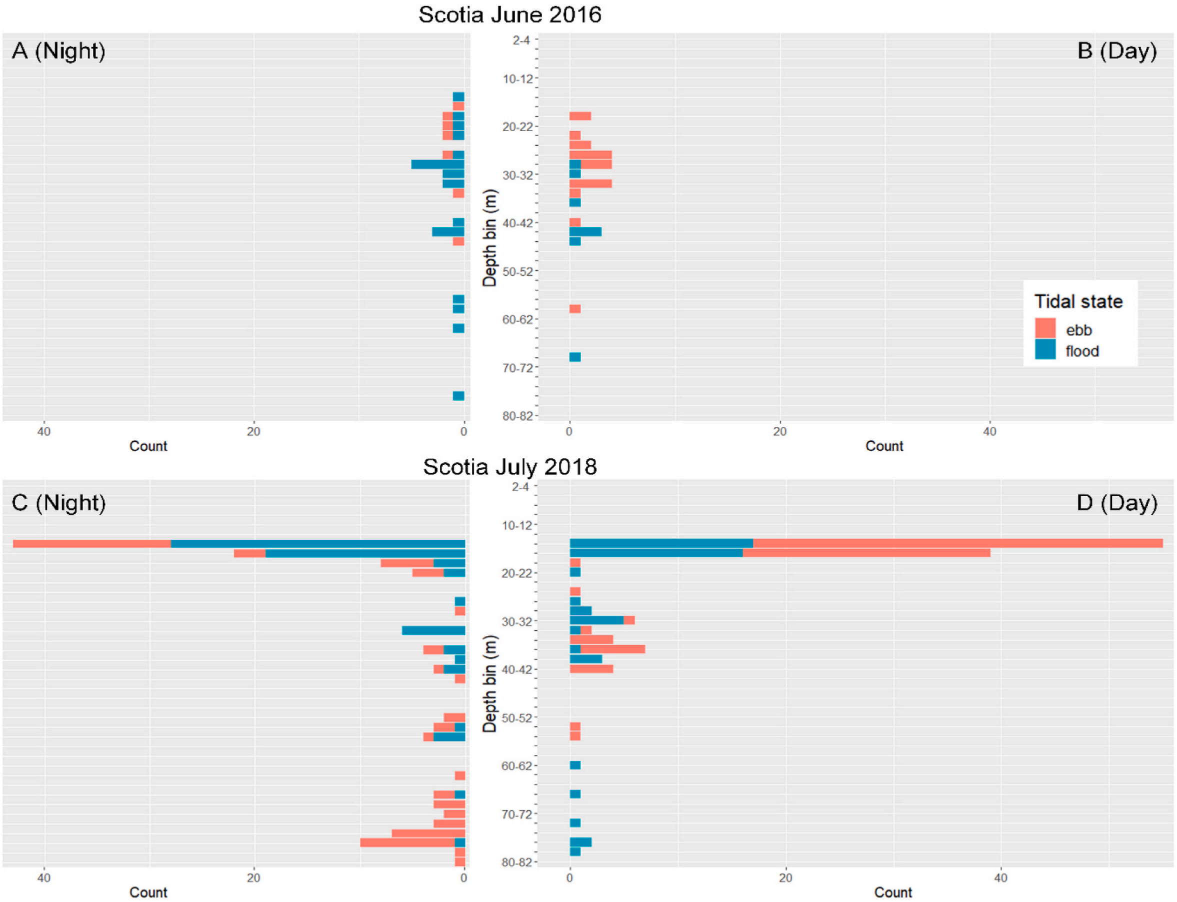

Fig. 5. Stacked bar graph of vertical EK60 fish school detection outputs *Scotia* 2016: (A) Night (n = 29) and (B) Day (n = 27); *Scotia* 2018, (C) Night (n = 135) and (D) Day (n = 134).

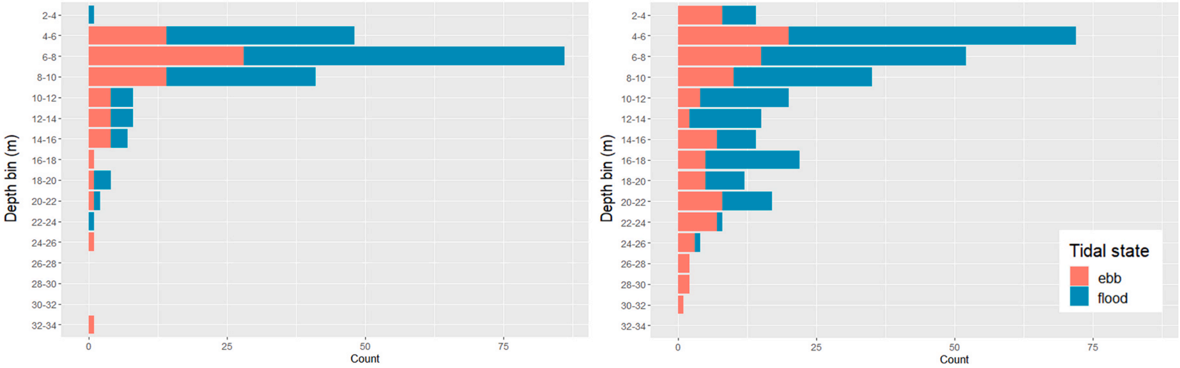

Fig. 6. Stacked bar graph of detections of fish schools from the FLOWBEC-4D October 2015 deployment subset to only representative tidal periods from during the (A) 2016, "spring" (n = 209) and (B) 2018 "neap" (n = 290) (See Fig. 2).

for surface and benthic feeders, with increases of pelagic feeders (Table 3).

Spatially, the ship surveys show that consistent high use areas across the tidal cycle are rapidly identifiable, but only for some ecotypes. Benthic feeders (Fig. 8C) showed clustering predominantly at either end of the Inner Sound in both years, with KDE outputs indicating higher densities in 2016 due to the increases in average group size despite more birds being observed in the Inner Sound in 2018 (Table 3). Fig. 8B and Table 3 show little change in pelagic feeder count and distribution within the Inner Sound; however, total counts and group size were much larger around the rest of the survey route in 2018 compared to 2016. Additionally, there are known colonies of pelagic seabirds on the western coast of Stroma, with higher densities around this area only detected during the survey in 2018. This suggests that proximity to colonies (colonies denoted in icons in Fig. 1) does not necessarily define consistent usage for pelagic feeders.

Surface feeders were sporadically observed in 2016, with the few larger groups observed causing highly varied KDE calculations for the surrounding survey area where no surface birds were seen. Surface feeders were observed in larger numbers to the north-eastern coast of Stroma in 2018, and were more continually observed around the survey route. Surface feeding birds proportionally decreased within the Inner Sound in 2018 despite more than double the raw counts in 2018 compared to 2016.

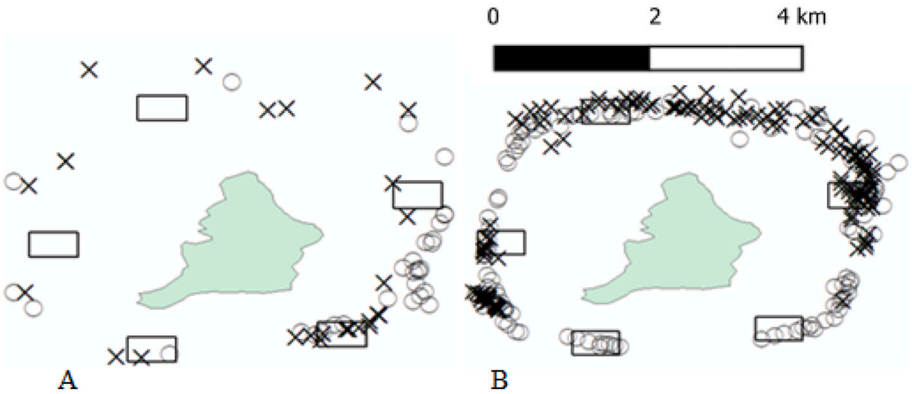

Fig. 7. Spatial distribution of fish school detections from (A) June 2016 *Scotia*, and (B) July 2018 *Scotia* ship surveys around Stroma Island. Schools were detected on Ebb = X and Flood = O. Black rectangles are areas used to contrast hydrodynamic data (See Fig. 1). Flood tidal phase is flow west to east.

Table 3
Summary of seabird observations from *Scotia* ship surveys with species ecotype of surface, pelagic, and benthic foragers. Total does not include species not listed in the three ecotypes. Inner Sound percentages are of total counted per ecotype (surface, pelagic, benthic) or overall total in that year's survey. Full circuit shows percentage of each ecotype from the total count. Superscript numbers indicate mean group size.

	Full Circuit	Inner Sound
Scotia 2016		
Surface	393 (7.2%)$^{2.0}$	215 (54.7%)$^{1.9}$
Pelagic	4650 (84.8%)$^{1.9}$	2515 (54.1%)$^{1.8}$
Benthic	443 (8.0%)$^{1.7}$	364 (82.2%)$^{1.7}$
Total	**5486**	**3094 (56.4%)**
Scotia 2018		
Surface	1488 (13.1%)$^{1.7}$	551 (37.0%)$^{1.2}$
Pelagic	9095 (80.2%)$^{3.1}$	2346 (25.8%)$^{1.9}$
Benthic	749 (6.6%)$^{1.2}$	585 (78.1%)$^{1.2}$
Total	**11,332**	**3482 (30.7%)**

4. Discussion

This case study set out to investigate whether using outputs from a process-driven approach, integrating multiple data-collection methods (3D oceanographic model output, upward-facing seabed platforms as well as ship-based downward-facing active acoustics that measure both fish and water column characteristics and standard top predator observations), can be more rapid and robust in reducing uncertainties in predicting potential impacts of offshore renewable developments compared to techniques which omit the underlying processes affecting distribution and movements (and hence vulnerability) of top predators. Using an example in a tidal stream habitat, before and after the deployment of four 1.5 MW tidal turbines, we have shown how two similar ship-based observer surveys can produce highly variable results; twice the total abundance of seabirds in one year vs the other, with large differences in spatial distributions in both surface and pelagic ecotypes, but not benthic. We discuss how, without appreciating the underlying mechanisms potentially causing this large amount of variation, there would be a high level of uncertainty of the effect of introducing tidal turbines if only the standard observer-based survey approach had been used. In this discussion we show, with outcomes from examples of this

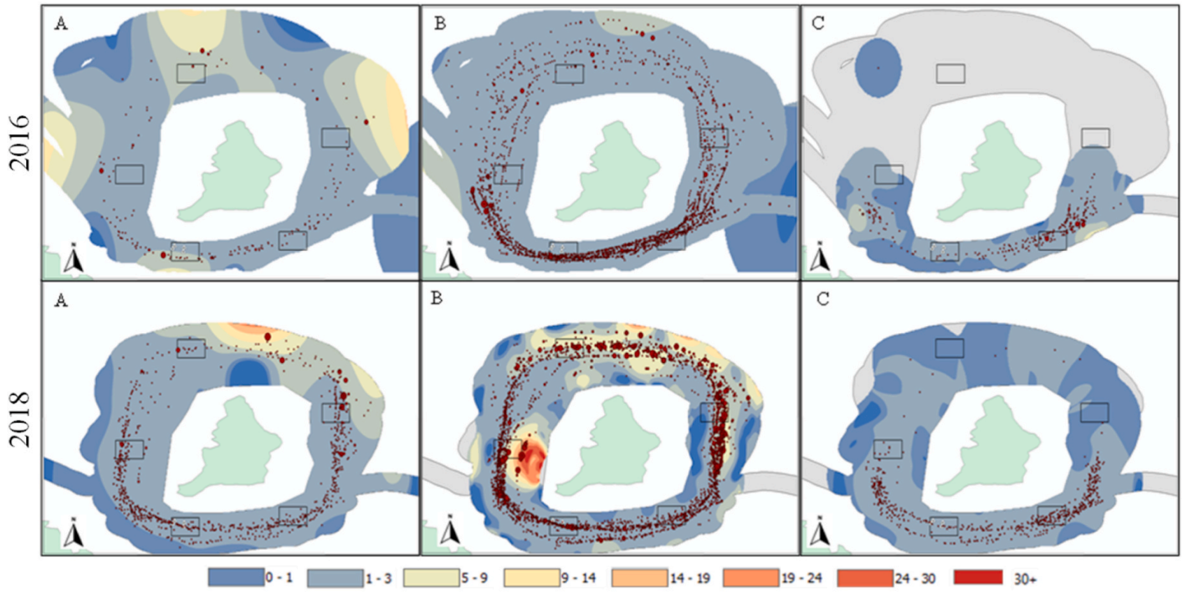

Fig. 8. Kernel density interpolation for expected group size for the 2016 and 2018 *Scotia* surveys. A = Surface, B = Pelagic, C = Benthic foraging seabirds. Interpolation was restricted to a 300-m buffer either side of the ship track to match observer survey width. Observation symbols (circles) are weighted by group size between 1 and 30+. Blue-Red classification indicates expected average group size for the survey period, broken by natural breaks. Grey fill indicates areas surveyed where no individuals were observed of the foraging group to inform the interpolation.

case study, firstly, how the use of 3D hydrodynamic models can help to identify areas of ecological importance and potential hydrodynamic (i.e. habitat) changes from the deployment of tidal devices (*De Dominicis* et al.*, 2017*). Secondly, how these contrasting areas of important ecological habitat (and/or habitat change) can be sampled at a high temporal resolution with the use of active acoustics on upward-facing seabed platforms providing water column information on fish abundance and behaviour as well as hydrographic characteristics. Thirdly, how fewer ship-based observational surveys of top predators are needed if they use downward-facing acoustics and can be compared to upward-facing platform data. Finally, we show how the combinations of this process-driven approach will more rapidly and accurately quantify impacts of marine renewables on habitats and species, informing a variety of legislative requirements within EIA and HRAs.

4.1. Use of 3D hydrodynamic models

2D and/or 3D hydrodynamic models such as FVCOM are already used by developers during site selection, scoping and development work to investigate optimal locations and array design of marine energy devices. Previous studies have shown that seabird and marine mammal use of marine energy sites is closely linked to many of the hydrodynamic variables that hydrodynamic models are capable of providing (e.g. horizontal and vertical velocity, turbulent kinetic energy, shear, wakes and highly ephemeral water column features such as kolk-boils) (Slingsby et al., 2021; Lieber et al., 2018b, 2019; Scott et al., 2010; Waggitt et al., 2016). Here, we used the FVCOM SSM (Figure A 1) to assess contrasting habitat sites (Fig. 1) of minimum, maximum and average current speed as well as the location of initial turbine deployment (and FLOWBEC-4D platform) and MeyGen phase 2 deployment (*Coles et al., 2021*). Our comparisons of *in situ* to model data from ADCP deployments from both the FLOWBEC-4D platform and the ship surveys showed that the SSM mostly captures the fine scale differences between habitat sites well (except site 5, Fig. 2) but that it consistently underestimates the maximum tidal speeds. These findings suggest that 3D models are suitable for identifying contrasting fine-scale water column habitats that are likely to be influencing foraging behaviours of mobile animals as referenced above. Also, that fine-scale surveys performed with ADCPs are valuable for model validation and refinement. We suggest that exploring water column habitat differences initially will also allow comparisons to any local or regional tagging study outputs (McIlvenny et al., 2021; Johnston et al., 2021; Onoufriou et al., 2021) or vantage point survey data (*Isaksson* et al.*, 2020*) which can rapidly highlight possible mechanistic reasons for hotspots of species foraging and more easily determine sites where upward-facing platforms would be most usefully deployed. We also suggest this point of investigation is an excellent opportunity for working directly with developers, who may have or are going to be, deploying ADCPs for better understanding of flow conditions. Setting up joint deployments of new instrumentation that combines ADCP and echosounders can reduce costs and speed up environmental impact studies (*Scherelis* et al.*, 2020*).

4.2. Upward-facing FLOWBEC-4D platforms

Once important hydrodynamic habitat locations are identified, depending on site characteristics, development-specific assessments may benefit from multiple locations of seabed platform deployments and ideally all of these areas would be surveyed using upward facing platforms so that the full water column (seabed to sea surface) can be surveyed for fish and concurrent physical features over fortnightly tidal cycles. Ideally, we suggest that multiple upward facing platforms should be deployed in all contrasting habitat sites at the same time and for long enough (and/or duty cycled) to capture seasonal differences and overlap with ship-based surveys. Insights into full spring-neap hydrodynamics and prey occurrence and behaviour are only practically obtainable from seabed-based platforms. Battery or turbine-connected platforms provide longer term, survey options across tidal cycles, further benefiting from only requiring single day deployment and retrieval costs (*Williamson* et al. *2021*). A goal would be the deployment of a platform in an area of known biologically important hydrodynamic features (i.e. turbulent wakes, kolk boil production, Leiber et al., 2019; Slingsby et al., 2021) that is predicted to change (using SSM) with array size or design (*De Dominicis* et al. *2017*). Increasing the spatial coverage via multiple seabed platform deployments will also likely better quantify and feedback to 2D or 3D hydrodynamic models any potential near-to-medium field hydrodynamic habitat changes, further benefiting cumulative impact assessments as the industry develops.

In this study, as we only had the opportunity to deploy FLOWBEC-4D once at the pre-deployment turbine site in October 2015, fish data are not directly comparable to either of the ship-based surveys in the summers of 2016 and 2018. However, what can be shown clearly is the fact that the highest fish density (Figs. 4–6, Table 2) and the highest water velocities are consistently found in the top 12 m of the water column, which only upward facing platforms can sample. Acoustic data collected from ships are not free of interference until well below the keel and the *MRV Scotia*, even though custom built for fisheries surveys, has no useful data across frequencies at less than 12 m from the surface. However, at water column depths that are directly comparable there are strong similarities between the FLOWBEC-4D data and the ship surveys, as consistently fewer fish schools are found in both data types at night vs the daytime and fewer during spring tides as compared to neap (Figs. 4–6, Table 2). These facts are picked up again at the end of the next section as they are important in demonstrating the importance and complementarity of the different survey techniques.

Expanding the use of platforms is likely to benefit from collaborative efforts on seabed platform design and instrumentation configurations. Other seabed platforms such as the Adaptable Monitoring Package (AMP) (*Polagye* et al.*, 2020*), and the Fundy Advanced Sensor Technology (FAST) platform (*Viehman and Redden, 2018*) take a similar approach as FLOWBEC-4D to whole water column, continuous, long-term data collection of biological and physical covariates. The High Current Underwater Platform (HiCUP) (Gillespie et al., 2022) focuses on marine mammal detection and uses only one type of active acoustics: multibeam sonar. We suggest that combining fine-scale data collection effort of top predators, fish (prey) and hydrodynamic habitat data will further aid impact assessment and monitoring processes, as it would provide process-based covariates to help predict protected species underwater behaviour. Understanding and therefore being able to predict fine-scale predator-prey and foraging relationships between protected species, changing hydrodynamic conditions, and prey early on in development planning can help better inform EIA/HRA decision making regarding cumulative assessments, especially as array and device sizes increase.

4.3. Ship surveys: Observations of top predators and concurrent use of active acoustics

Ship-based observational survey methods described here are the same as surveys already recommended within the UK for EIA purposes, and therefore our alteration of the use of vessels capable of concurrently collecting acoustic data on hydrodynamic features and fish abundance and behaviour is comparable with the current EIA framework (Camphuysen, 2006; Rollings et al., 2016). On their own, and as shown in the seabird distributions (Fig. 8), ship-based observations can provide a rapid snapshot of usage within the site. However, only collecting seabird observations offers little insight into mechanisms driving the underlying processes that led to the observed doubling of abundance and changes in distributions. It is a missed opportunity not to collect concurrent, high quality, explanatory information that can enable mechanistic understanding and therefore increased predictability of seabird site usage. The understanding of why seabirds are changing their foraging locations will lower risk by increasing the predictability of seabird reactions to subsequent changes in prey availability due to physical effects of introducing marine renewable developments. In our study, benthic-feeding seabirds showed little differences in distribution between years, staying relatively close to local colonies and nearby sandbank habitats that characterise the Inner Sound (Fig. 8). Conversely, pelagic feeders showed significant differences between the surveys, with increased count rates in 2018, forming larger aggregations throughout the survey route compared to the overall, approximately evenly distributed increases in benthic feeders between years. This increase indicates that pelagic feeders' use of the site is likely driven by very different factors than benthic feeders.

Without collecting concurrent data on fish presence, the observed high degree of variance in abundance and distribution would remain a source of uncertainty. It could be attributed to the difference in tidal state (neap vs spring), yearly (2016 vs 2018) or monthly (June vs July) variation or even to the addition of the four tidal turbines between the years. The addition of using a ship with active acoustic instruments (EK60 and ADCP) collecting concurrent hydrodynamic and fish data allows investigation of whether these variables are important in predicting seabird presence and abundance. This is indeed the case, as has been shown in our related study (Couto et al., 2022), showing that both velocity and fish school presence explains a high proportion of the variation in snapshot seabird distributions, but that fish school presence is more important than absolute velocity. So, the next obvious question is why were there more fish schools in 2018 than 2016? As we have the FLOWBEC-4D data over a full spring-neap cycle showing that more fish schools were also present during the neap phase (Fig. 6) and that this fish behaviour has been seen in other studies that have deployed acoustic instruments for two continuous weeks (Embling et al., 2013; Williamson et al., 2021) we can say with a higher level of confidence that it is most likely that more fish schools are present at neap tides. That also allows us to conclude that it is highly unlikely that the addition of the four tidal turbines could have caused such a change and that it is also unlikely to just be chance differences between years. Understanding fine-scale relationships between protected species, hydrodynamic conditions, and prey early on in development planning can help better inform EIA/HRA decision making regarding cumulative assessments, especially as array and device sizes increase.

5. Conclusions

This study has shown the benefits of concurrent data collection methods utilising a mobile and a static platform, both with active acoustic instruments, that can provide information on hydrodynamic conditions and fish schools, parameters that can greatly increase the information that can be used to explain variation in seabird distributions. Observer-only data highlighted the need to provide information on both the physical and prey drivers of variance in seabird abundances and distributions, as results showed different seabird ecotypes varied in how they responded to increases in fish-school presence. Results from active acoustics from both the upward-facing platform and ship observations indicated that collecting concurrent *in situ* biophysical data provides the information needed to identify temporal changes in hydrodynamic conditions to better predict mechanism for changes in prey and top-predator spatial densities. Combining ship and seabed-based platform methodologies can rapidly produce high-quality data on the environmental drivers of variation needed to robustly predict top predator use of and presence in marine renewable energy sites. In practice, these methods sit well within the scope of current regulatory practices, with the primary addition of seabed platforms having the potential to significantly contribute to future EIA site surveys, as they provide rapid between-site learning processes, providing robust, data rich, informative outputs helping to reduce uncertainties.

Funding

The analysis was funded as part of a NERC CASE PhD Studentship Project (NE/P010067/1) with Marine Scotland Science. FLOWBEC-4D platform development and deployment were funded by NERC and Defra grant (NE/J004308/1) and a KTP with MeyGen Ltd (KTP009812). This work was supported by the NERC VertIBase project (NE/N01765X/1) and the UK Department for Business, Energy and Industrial Strategy's offshore energy Strategic Environmental Assessment programme. Elements of this work were funded by PELAgIO (NE/X008770/1). PELAgIO is part of the 'The Ecological Consequences of Offshore Wind' (ECO-Wind) programme, funded by the Natural Environment Research Council (NERC), The Crown Estate through its Offshore Wind Evidence and Change Programme and is also supported by the Department for Environment, Food and Rural Affairs (Defra).

CRediT authorship contribution statement

James Chapman: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis. **Benjamin J. Williamson:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Ana Couto:** Writing – review & editing, Investigation, Formal analysis. **Arianna Zampollo:** Writing – review & editing, Software. **Ian M. Davies:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Beth E. Scott:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to the thank the FLOWBEC-4D development team as well as the observers and scientists of the MRV *Scotia 2016* (Marianna Chimienti, Helen Wade, Laura Williamson, Ewan Edwards, and Eric Armstrong) and 2018 (Tom Evans, Sarah Fenn, Ross Culloch, David Hunter and Adrian Tait) surveys. Additionally, thanks go to Paul Fernandes (University of Aberdeen) for guidance and reviewing of the acoustic fisheries analysis undertaken here.

Appendix

Appendix A. Visualised hydrodynamic flows around Stroma

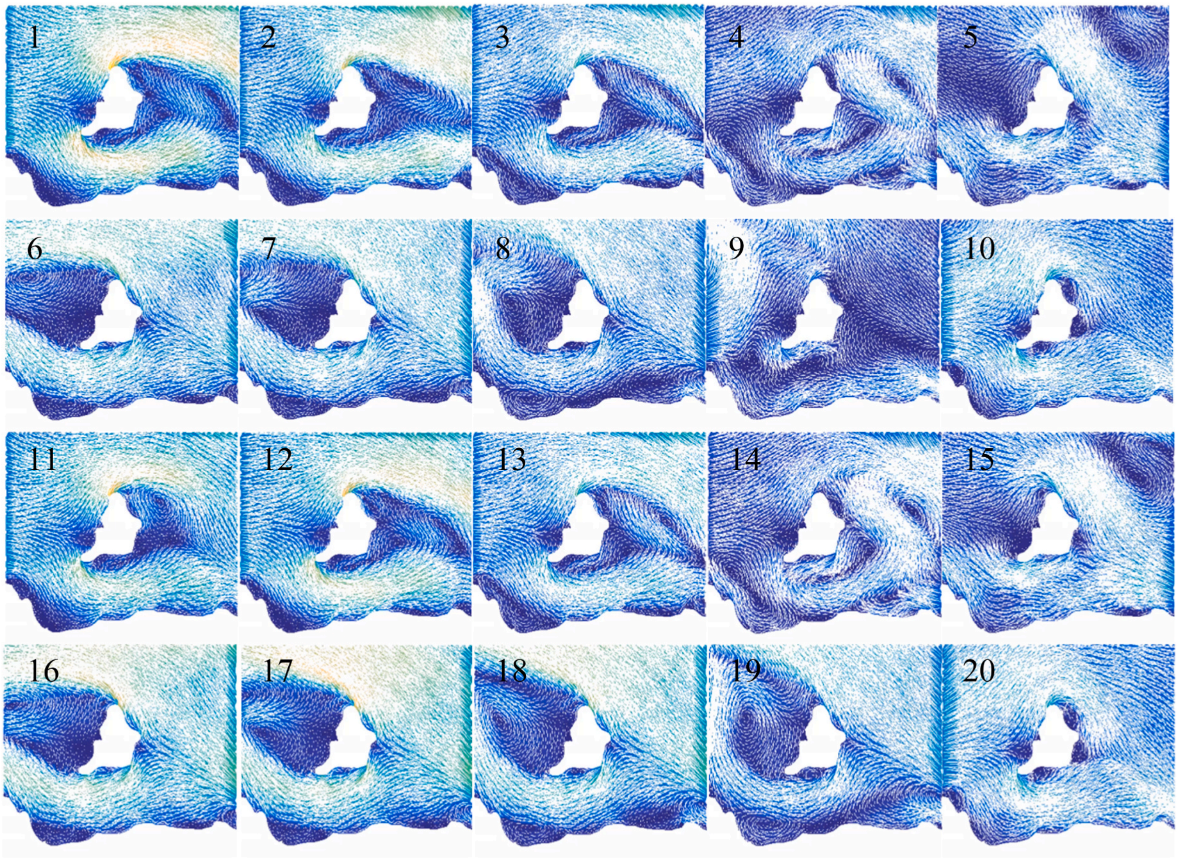

Fig. A 1. Hydrodynamic model flow prediction visualisation around the island of Stroma at hourly intervals. Yellow = highest flow, dark blue = lowest flow speeds. Numbers corresponding to tidal state: Flood tide to the east = 1–3, 9–13, 20; Ebb tide to the west = 4–8, 14–19. Colouring indicates tidal speed (dark blue = 0 m s^{-1}, yellow = 3.5 m s^{-1}). Credit: Shaun Fraser and Rory O'Hara Murray, from the Scottish Shelf Model.

Appendix B. Sampling information

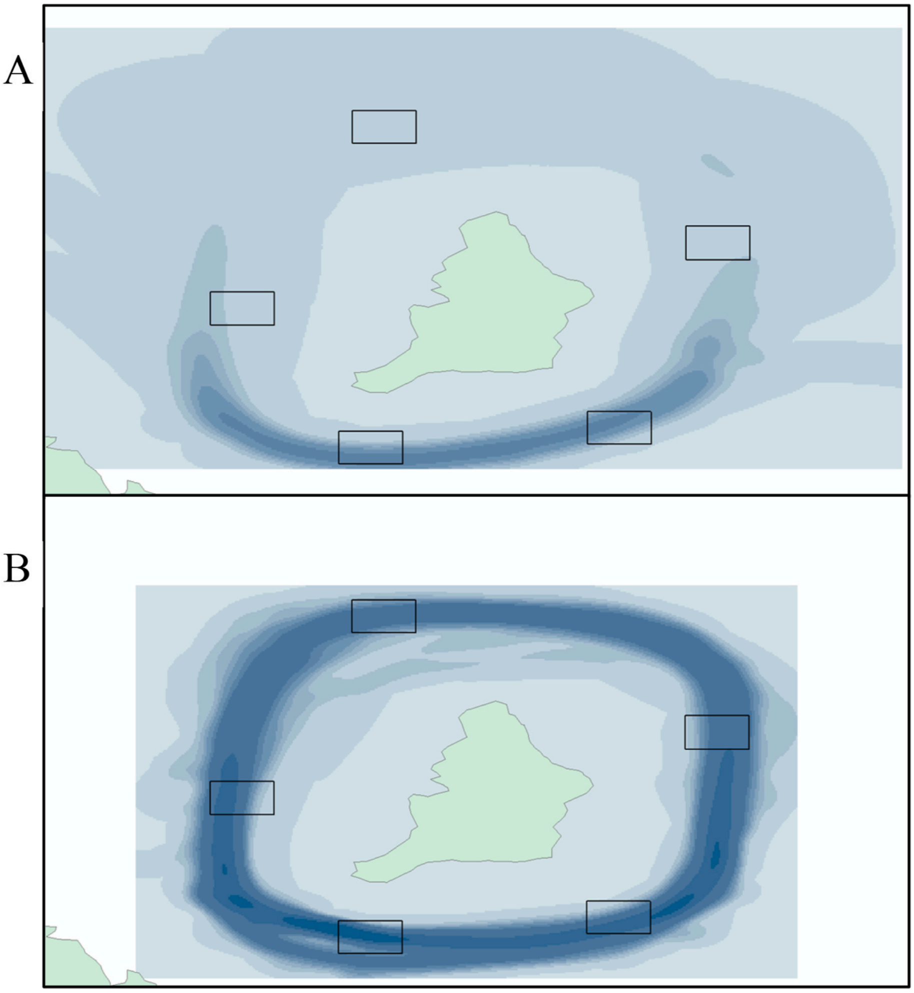

Fig. B 1. Indication of relative spatial survey effort for the MRV *Scotia* ship surveys in (A) 2016 and (B) 2018). Methods are replications of site survey efforts and are therefore considered fair comparisons in relation to EIA methodologies. Squares are the habitat unit areas compared during the hydrodynamic analysis. Projected in WGS84.

Table B 1
Habitat unit extents in decimal degrees and depths for SSM analysis.

Habitat unit	Extent				Depth (m)		
	North	East	South	West	Min	Mean	Max
1	58.660772	−3.131853	58.655385	−3.142187	39.23	32.97	26.97
2	58.661956	−3.088854	58.656569	−3.099188	36.16	32.54	28.46
3	58.694158	−3.075666	58.688613	−3.086000	75.57	70.17	60.16
4	58.713000	−3.129666	58.707613	−3.140000	73.87	68.18	64.42
5	58.683387	−3.152666	58.678000	−3.163000	49.90	45.19	38.48

Table B 2
FVCOM-SSM set up processing information. 2015 period information used as an example.

FVCOM Set up information	
Source	FVCOM_3.0
Run on	FLOWBEC 2015:25/03/2019; *Scotia* 2016: 25/03/2019; *Scotia* 2018: 19/03/2019
References	http://fvcom.smast.umassd.edu http://codfish.smast.umassd.edu
Conventions	CF-1.0
Coordinate System	Georeferenced
Coordinate Projection	None
Tidal Elevation Forcing	Off
River Forcing	113 Rivers in model
AMM7 Boundary Forcing	No Atmosphere

Table B 3
Number of samples of hydrodynamic information across the three surveys within each area.

		SSM 2015		*SSM 2016*		*SSM 2018*		*Scotia 2018*		*FLOWBEC 2015*
Area	SSM elements	Timesteps	Sample size	Timesteps	Sample size	Timesteps	Sample size	Number transits	Sample size	Sample size
1	16	1152	18,432	320	5120	344	5504	46	–	77,103
2	18	1152	20,736	320	5760	344	6192	33	–	–
3	23	1152	26,519	320	7360	344	7912	55	–	–
4	19	1152	21,888	320	6080	344	6536	44	–	–
5	16	1152	18,432	320	5120	344	5504	54	–	–

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