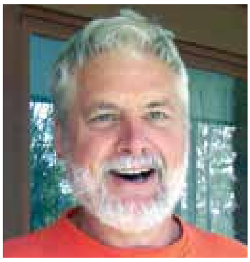
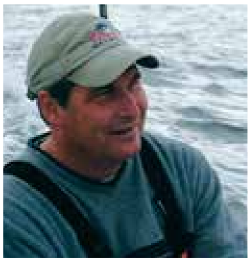
Drifting on the surface



Dr. Brian Sanderson



Dr. Michael Stokesbury

Dr. Anna Redden

Sanderson, Stokesbury, and Redden use surface drifters in a tidal energy development site to determine how fish might interact with tidal turbines.

Who should read this paper?

This paper is of interest to anyone concerned with the practicality of obtaining renewable energy from tides in order to replace fossil fuels without causing new ecological harms. Tidal power developers and marine engineers will be interested in the relatively low collision probability of drifting objects with turbines at the Minas Passage test site. Marine ecologists and environmental regulators will be interested in the implications for fish-turbine interaction. Physical oceanographers may be tantalized by circumstances that cause abrupt transition between relatively stable classes of drifter trajectory.

Why is it important?

Previous work acoustically tagged fish and then attempted to measure how those animals moved within their habitat and sometimes passed through the tidal energy development site. Such fish tracks are poorly resolved. The essential innovation is to regard well-resolved drifter tracks as an approximation of fish trajectories where currents are fast. By suspending acoustic receivers beneath the drifter, we also demonstrate a methodology to address the extent to which tagged fish are moving with the tide. In principle, probability that tagged fish encounter a turbine at the tidal energy development site can be obtained using moored receivers at the site. The drifter work enables such probabilities to be confirmed and to be understood in terms of broader habitat usage. The ocean community will benefit by better understanding how renewable energy development interacts with fish.

About the authors

Dr. Brian Sanderson is a physical oceanographer with interests in drifter trajectories, ocean mixing, and computational fluid modelling. He has also published on a variety of marine ecology topics and has recently turned his attention to fish and harbour porpoises at marine tidal power development sites. His objectives are to quantify encounter probability of marine animals with turbine installations in order to inform ecologically responsible development of marine renewable energy. **Dr. Michael Stokesbury** is a professor in the Biology Department of Acadia University. He has published over 60 primary research studies on diadromous and marine species including migration and behavioural research on Atlantic salmon, Greenland sharks, and Atlantic bluefin tuna. The focus of his research program is to quantify how anthropogenic disturbances in coastal ecosystems impact the spatial behaviour of fishes covering small to large spatial and temporal scales, may inflict mortality, and how such knowledge can be used to mitigate the negative effects of such activities on fish populations. **Dr. Anna Redden** is a marine ecologist and professor at Acadia University and has significant marine life monitoring expertise and experience in the upper Bay of Fundy. She has authored or co-authored over 90 primary publications, technical reports, and review papers. Since 2010, her research with colleagues and research students includes acoustic tracking of several fish species through the Minas Passage and studies (in collaboration with SMRU Ltd.) involving moored hydrophones to assess year-round marine mammal activity in the Minas Passage and FORCE demonstration area.

USING TRAJECTORIES THROUGH A TIDAL ENERGY DEVELOPMENT SITE IN THE BAY OF FUNDY TO STUDY INTERACTION OF RENEWABLE ENERGY WITH LOCAL FISH

Brian G. Sanderson[1], Michael J.W. Stokesbury[2], and Anna M. Redden[1,2]
[1]*Acadia Centre for Estuarine Research, Acadia University, N.S., Canada*
[2]*Biology Department, Acadia University, N.S., Canada*

ABSTRACT

A tidal energy development site has been designated in Minas Passage (Bay of Fundy, Nova Scotia, Canada) for testing in-stream turbines and producing renewable energy. Concern remains that turbines might harm local populations of marine animals as they sweep by within a fast-flowing water mass. Drifters approximately track a water mass and can support instrumentation for detecting fish that carry an acoustic tag. A tagged Atlantic salmon tracked sufficiently similarly to the drifter for it to be continuously within detection range for three intervals of up to 56 minutes over a 21-hour period. The same fish was briefly detected near the drifter five days later. Two types of quasi-stable drifter trajectory were found to make many transits through the fast-flowing waters of Minas Passage, with tidal excursion extending far beyond the passage. Drifter trajectories characterize water areas that are likely to be influenced by fish-turbine interaction over the tidal timescale. One quasi-stable trajectory is associated with accumulations of floating debris that may interfere with tidal energy devices. Most drifter tracks passed south of the tidal energy development site. Less commonly, drifters passed through the development site during flood tide and these tracks are associated with northerly extremes of quasi-stable trajectories. Few drifter tracks passed through the development site on the ebb tide and those that did quickly transitioned to quasi-stable trajectories that mostly pass south of the development site. Regardless of drifters mostly bypassing the development site, the monthly probability of drifter collision with a 500 kW near-surface tidal energy device was estimated to be 0.18. Collision probability for fish is argued to be lower.

KEYWORDS

Drifters; Quasi-stable trajectories; Fish motion; Tidal turbine; Collision probability

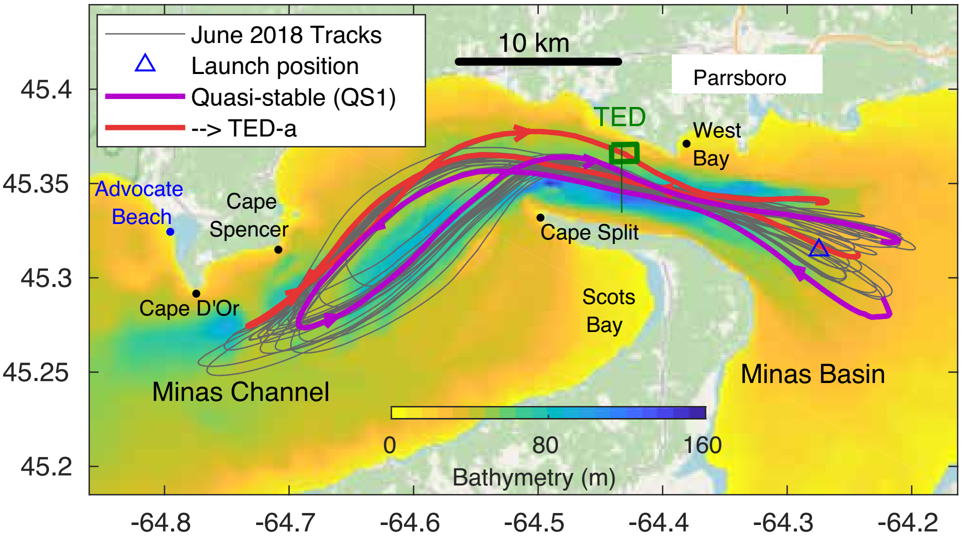


Figure 1: Track plotted from June 11-23, 2018, (grey) generally follows a quasi-stable trajectory (magenta). The drifter passed through the Fundy Ocean Research Centre for Energy tidal energy development (TED) site on two flood tides (red). The drifter was swept south of the TED site by the other 21 flood and 23 ebb tides.

INTRODUCTION

To explore the possibility of obtaining large-scale renewable energy from tides, Canada has established a tidal energy development (TED) site in Minas Passage, Bay of Fundy (Figure 1), where tidal currents can exceed 5 m/s [Karsten, 2011]. The TED site is managed by the Fundy Ocean Research Centre for Energy (FORCE). To date, three gravity-base, open-centred tidal turbines (up to 2 MW) have been tested within the FORCE TED site and it is anticipated that devices operating nearer the sea surface will be tested in future [Ajdin, 2020; Davie, 2019]. One motivation for development of renewable energy is depletion of accessible fossil fuels [Price, 1995]. A second motivation is the desire to prevent ecological disruptions like those attributed to the use of fossil fuels by a large and growing human population [May, 2010]. For tidal energy development to be beneficial, devices must be sufficiently effective as to displace use of fossil fuels and to do so without causing undue ecological harm.

Interaction of populations of anadromous fish with tidal turbines is one matter of ecological concern. Ideally, such interaction might be known if fish could be accurately tracked over a wide range of scales, from the scale of their habitat to a turbine at the TED site. In practice, this has not been achieved, although a large field effort has sporadically located acoustically tagged fish as they passed within detection range of moored receivers that are fixed relative to the seafloor [Keyser et al., 2016; Stokesbury et al., 2016]. Presently we report results from a modest project that tracked surface drifters that were drogued to move with near-surface waters. Modern technologies enable relatively accurate and complete measurements of drifter tracks as compared to a tagged fish being infrequently detected by receivers that are sparsely distributed [Keyser, 2015] relative to both tidal excursion and the extent of fish habitat.

In the fast currents in and near the FORCE TED site, Broome [2014] and Keyser [2015] considered travel times of acoustically tagged striped bass (*Morone saxatilis*) as they moved between pairs of moored receivers. Given measurement uncertainty, the resulting transit velocities could not be discriminated from the running tide, indicative of tidal current dominating usual swimming speed of striped bass in Minas Passage. The present current-tracking drifter measurements are, therefore, anticipated to be useful for understanding the interaction of fish with tidal turbines.

Prior turbine installations at the FORCE TED site included monitoring equipment, specifically hydrophones and an imaging sonar, but these proved inadequate for addressing turbine interaction with marine animals [Emera, 2019]. At Cobscook Bay, Maine (a less energetic location), the response of fish to tidal turbines could be observed with imaging sonar [Viehman and Zydlewski, 2015]. At the FORCE TED site, useful environmental measurements have been obtained from instruments mounted to stand-alone moorings and small bottom platforms. Much of this work has involved the detection of fish with acoustic tags (transmitters) implanted within their body cavity. Stokesbury et al. [2016] document seasonal presence and depth distribution of Atlantic sturgeon (*Acipenser oxyrinchus*) at the TED site. Keyser et al. [2016] found that striped bass were frequently detected at the TED site during winter, when cold water temperatures may make them sluggish and vulnerable to turbines. Those striped bass belonged to a genetically distinct local population and the probability that an individual will encounter a turbine has been estimated [Sanderson and Redden, 2016]. Tollit et al. [2019] detected year-round echolocation vocalizations by harbour porpoises (*Phocoena phocoena*) and reported variations in their presence at the TED site.

In Minas Passage, high ambient sound levels and pseudo-sound hindered the detection of echolocation vocalizations [Tollit et al., 2019]. Acoustic signals from nearby tags are reliably detected near slack water but detection becomes increasingly compromised as current speed increases, particularly during spring tides [Broome et al., 2015; Keyser et al., 2016; Sanderson et al., 2017]. Adams et al. [2019] demonstrated that some of the signal-detection difficulties that were experienced by Tollit et al. [2019] could be circumvented by attaching hydrophones to a drifter. Those measurements also draw attention to the large tidal excursion of water masses that pass quickly through the TED site within an ebb or flood tide. Interpretation of detections of fish as they briefly pass the TED site will, therefore, be assisted by the presently reported measurements of drift tracks through, and near, the TED site.

Bousfield and Leim [1958] reported an extensive accumulation of flotsam in Minas Channel (Figure 1). Flotsam commonly drifts through Minas Passage and we have observed fast-flowing flood tides to carry large logs through the TED site, which might cause concern when tidal energy devices operate near the sea surface. Such accumulation of floating debris also leads us to consider the possibility that a drifter might serve as a convenient instrumentation platform that reliably passes back and forth through Minas Passage over many tidal cycles.

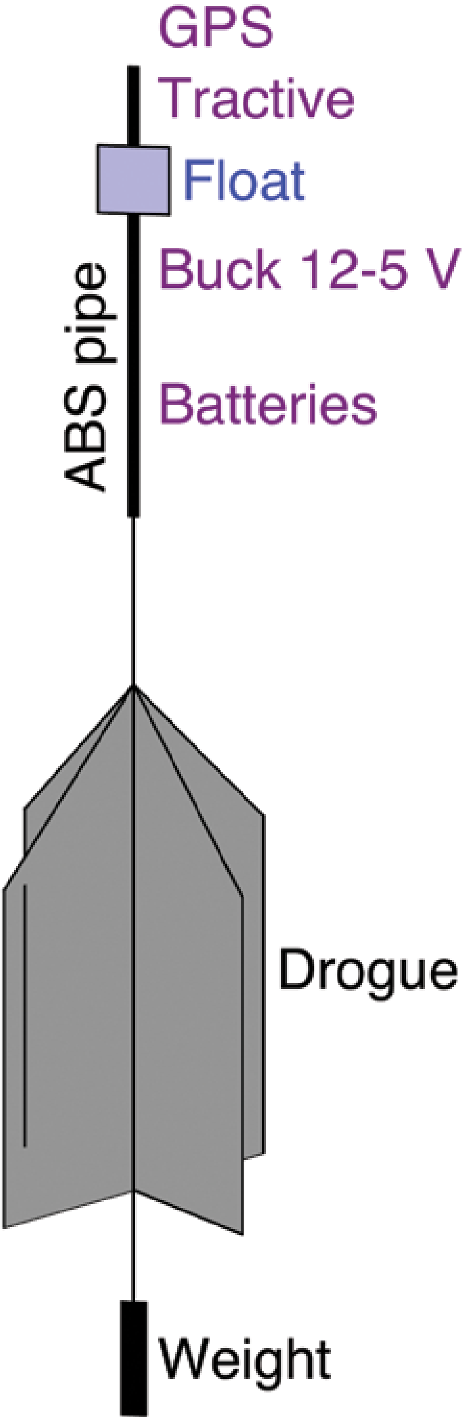


Figure 2: Schematic of the drifter with cross-vane drogue. The upper edges of the drogue are angled to minimize possibility of entanglement with commercial fishing gear. The ABS pipe contains primary electronic parts that are labelled in magenta.

Three drifter studies conducted over three years are presently reported. We document and discuss features of the drift tracks that are judged relevant to tidal energy development in Minas Passage, with particular attention to interaction of fish populations with tidal turbines. Present measurements also inform our understanding of fish tracks compared to drifter tracks. Utility of drifters as a measurement platform will be discussed. Probability of drifter collision with a tidal turbine installation is considered with respect to fish-turbine interaction. Efficacy of drifter-based monitoring is described and discussed.

MEASUREMENTS

Surface drifters (Figure 2) were constructed from 38 mm diameter ABS pipe and common plumbing fittings with flotation fashioned from 50 mm foam board insulation (extruded polystyrene foam). Drogues were attached beneath drifters so the unit would approximately move with the horizontal components of tidal currents. Wind driven currents, wave forcing, and wind drag on the surface float all cause departures from the fast tidal motion. Available wind and wave information are insufficient to accurately quantify such departure. Battery stacks, an epoxy-potted buck 12 V to 5 V converter, and a Tractive® GPS dog tracker were fastened to an ABS backing frame which was then slid inside the ABS pipe. The Tractive® uses a 3G network to report position at irregular intervals that depend upon drifter movement and connectivity to the network. A drifter moving fast near a 3G network might provide a GPS fix every few minutes whereas there may be an hour or two between fixes during stormy conditions when the drifter is far from a 3G transceiver. The Tractive® has an active tracking mode which can be operated from a smart phone to aid drifter recovery. Drifters were configured with additional instruments according to the requirements of each experiment.

2018 Experiment

A Columbus V-990 GPS logger was used to obtain position at 1 s intervals, with data downloaded from the recovered drifter. A Tractive® was used for recovery. As a backup for recovery, a GlobalStar GPS satellite transmitter was attached external to the drifter float. The GlobalStar measured positions at nominal intervals of 20 minutes with data uploads to a U.S. National Oceanic and Atmospheric Administration web site every two hours. A cross-vane drogue (1.22 m by 1.24 m) was constructed from plywood and attached 5 m below the sea surface. The drifter was deployed June 11, 2018 (Figure 1, blue triangle), and recovered in good condition on June 23, 2018. Both deployment and recovery were at high tide at the juncture of Minas Basin with Minas Passage.

2019 Experiment

The objective was to test the drifter as a measuring platform for scientific instrumentation. The drifter housed a Tractive® for position fixing and to facilitate recovery. A GlobalStar GPS satellite transmitter was attached and set to obtain hourly position, thus augmenting tracking when the Tractive® could not connect to a 3G network. A 0.5 m^2 cross-vane drogue was attached at 6.4 m below the water surface. Drogue area was reduced from that of the previous year with the expectation that storm conditions might sometimes displace the drifter from the singular quasi-stable trajectory measured during the 2018 drift (Figure 1). A Vemco VR2W-180 kHz receiver was attached 15 m below the sea surface to detect any nearby fish that had an acoustic tag implanted within its body cavity. Depth of the bottom weight was 17.5 m. The drifter was launched at high tide September 10, 2019, at the juncture of Minas Basin with Minas Passage (Figure 3, blue triangle). On October 10, the drifter grounded seaward of the low tide level, offshore from Halls Harbour, and was in good condition upon being recovered by boat on October 15, 2019.

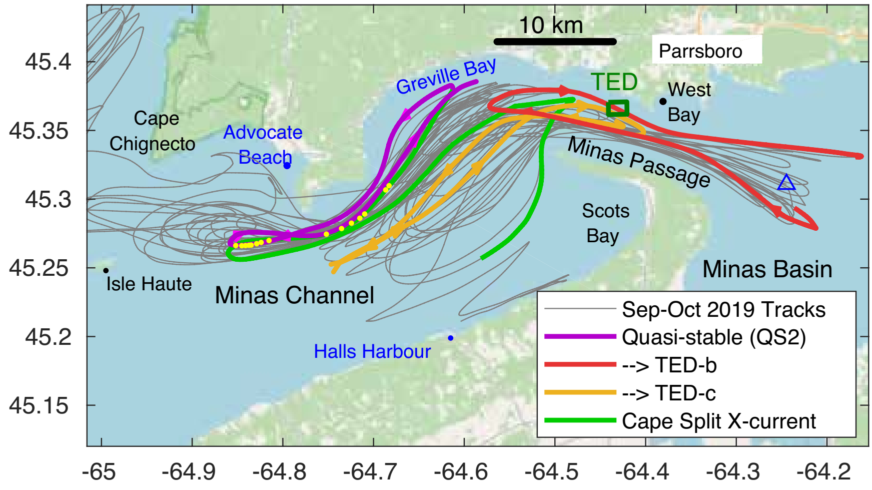


Figure 3: Track plotted from September 10 to October 10, 2019. The drifter passed through the Fundy Ocean Research Centre for Energy tidal energy development (TED) site on two flood tides but was swept south of the TED site on 14 flood and 17 ebb tides. Yellow dots show drifter position at every fourth detection of an acoustically tagged Atlantic salmon kelt.

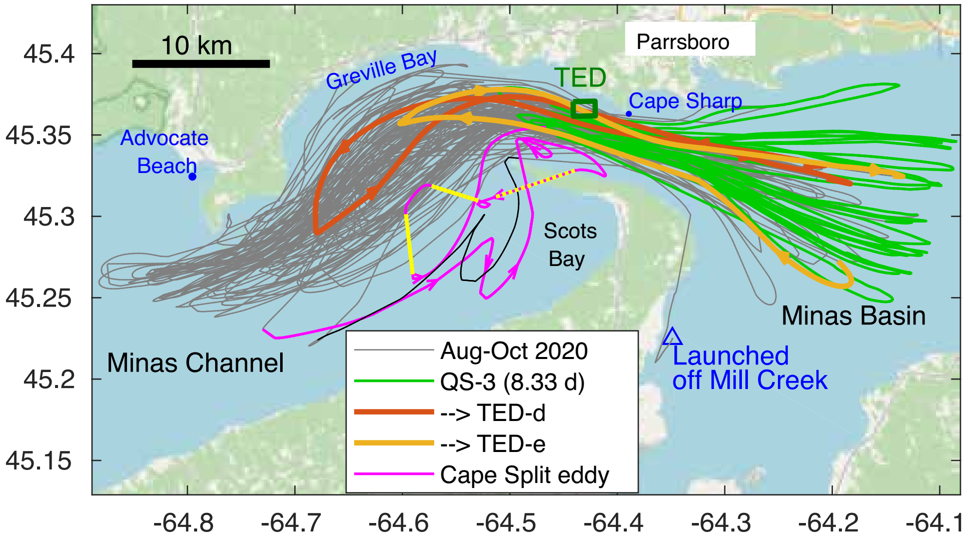


Figure 4: Track plotted from September 18 to October 8, 2020. The drifter passed through the Fundy Ocean Research Centre for Energy tidal energy development (TED) site on nine flood tides and two ebb tides but swept south of the TED site on 58 flood and 66 ebb tides. Yellow dots on the magenta track indicate interpolation where GPS measurements were not obtained.

2020 Experiment

Boat availability was restricted in 2020. As there seemed to be little chance that the drifter could be recovered, it only carried a Tractive® for navigation; the smaller instrument load enabled the drifter to be configured with less area exposed to wind than for the drifters used during the previous two years. The drifter was configured with a 0.8 m^2 drogue at 3 m below sea surface and a weight extending to 5 m. Having the drogue nearer the sea surface makes the drifter track more influenced by wind-driven current and wind waves. The reduced depth of the weight grants a possibility that the drifter might eventually wash into the intertidal zone where a boat may not be needed for recovery. The shallow depth of the weight also enabled deployment by wading the drifter out from the beach near Mill Creek at low tide on August 18, 2020 (Figure 4, blue triangle). The drifter operated until becoming grounded near Cape Sharp on October 11 and was recovered from the intertidal zone on October 15. While in the rocky intertidal zone, storm conditions broke one vane off the drogue and cracked the edge of an ABS fitting, causing the o-ring seal to leak a few drops of seawater. The buck converter and Tractive® were confirmed to be in good working order upon washing with fresh water and drying. Measurements spanning August 18 to October 8, 2020, were used for the present study.

Definitions

The mid-longitude of the FORCE TED site is -64.4329° (Figure 1). A drifter crossing this longitude will be said to have "passed the TED site." The TED site extends from a latitude 45.3615° to 45.3708°, a distance of 1 km. A drifter that passes the TED site between those latitudes will be said to have "passed through the TED site." A drifter that passes the TED site to the south of 45.3615° will be said to have "passed south of the TED site." Given the latitudinal extent of the TED site, a drifter passing between n and n-1 km south of the southern edge of the TED site will be said to "pass through Sn" (i.e., S1, S2, S3, S4; Figure 7).

The above definitions avoid the ambiguity of trajectories that pass through a corner of the two-dimensional TED site but also pass through the S1 site. Theoretically, there is a site (N1) to the north of the TED site but none of the present drifter tracks passed north of the TED site.

RESULTS

2018 Trajectories

During the 2018 drift (Figure 1), the drifter was twice sighted while undertaking other field work. On each of these two occasions, and during drifter recovery, the drifter was sighted nearby, or within, an extensive field of flotsam which included large logs and various debris. Over the 12 days of tracking, the drifter approximately followed a quasi-stable trajectory (QS1) as typified by the magenta path in Figure 1. During the ebb tide, QS1 corresponds to fast westward flow through the deeper waters in Minas Passage which then extends as a very turbulent jet into more shallow waters in Minas Channel. From the tail of the ebb tide to early flood tide, QS1 more slowly loops counterclockwise (cyclonic) in Minas Channel. The trajectory deflects northwards as the drifter enters Minas Passage on the flood tide before relaxing back towards mid-Passage. From one high tide to the next, a quasi-stable trajectory does not return to the identical position in Minas Basin and, within a quasi-stable type, trajectories are considered to approximate geometric similarity.

On two flood tides, the northwards deflection carried the drifter through the TED site. Such trajectories (labelled 'TED-a' in Figure 1) were generally to the northern edge of QS1 and did not exhibit the counterclockwise loop in Minas Channel. High tide start/end positions are variable in the north/south sense so the two trajectories through the TED site are not on consecutive flood tides – being separated by a QS1 trajectory that passes south of the TED site at 0121 UTC on June 13, 2018.

2019 Trajectories

The 2019 drift began with QS1 trajectories until the early flood loop in Minas Channel became larger. A larger loop corresponds to slower moving water which delays the time at which the drifter passes Cape Split. The green trajectory in Figure 3 shows the drifter passing Cape Split shortly before high tide, so the ebb tide jet carried the drifter beyond the westward limit of QS1. This soon placed the drifter on what turned out to be another type of quasi-stable trajectory (QS2 in Figure 3). Eventually, the QS2 trajectories penetrated too far westwards switching to a back and forth track in Chignecto Bay before eventually switching back into Minas Channel and Minas Passage. Details of these complex switching mechanisms are outside the scope of present work, except to observe that strong westerly winds coincided with the return from Chignecto Bay to Minas Channel.

2020 Trajectories

The 2020 drift began with a beach launch off Mill Creek (Figure 4) on August 18 during a spring tide. This involved wading out into chest-deep water at low tide. After about 4 m of rising tide, the drifter was lifted and dragged a little southward. On the following

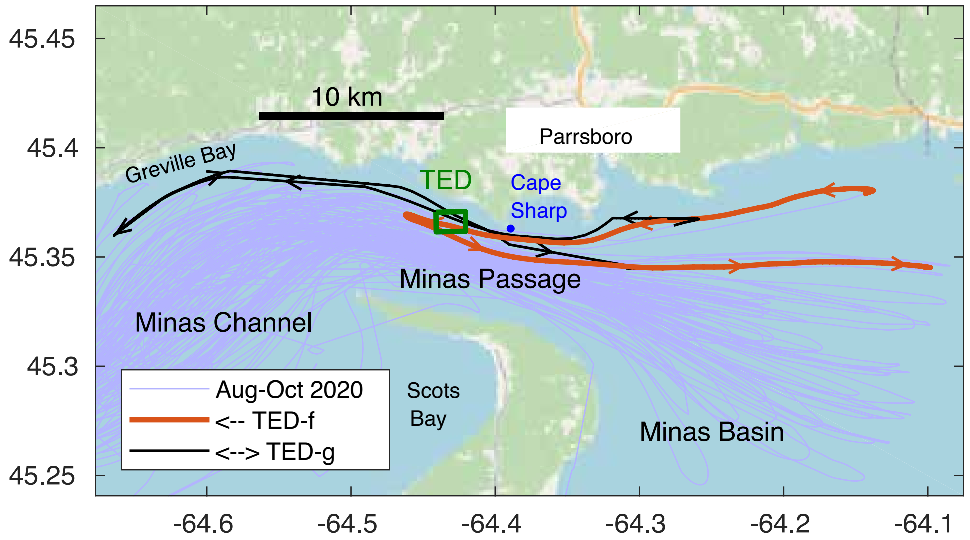


Figure 5: Tracks that cross the Fundy Ocean Research Centre for Energy tidal energy development (TED) site on the ebb tide during the 2020 experiment.

ebb tide, the drifter was swept through Minas Passage and into Minas Channel, after which it settled into QS1 motion for nine days. On August 28, the drifter transitioned to QS2 movement for 13 days. A southwards deflection within Minas Channel on September 12 delayed drifter entry into Minas Passage until the next flood tide (black line, Figure 4) after which the drifter moves with a QS1 pattern for 10 days.

On September 23, 2020, the flood loop in Minas Channel extends far south and into Scots Bay. The track from 0238 September 23 to 0533 September 24 is coloured magenta in Figure 4, with yellow dots indicating linear interpolation over portions of the track for which GPS positions were not obtained. On the next flood tide, the drifter grazes by Cape Split and is caught in a clockwise headland eddy. The following ebb tide carries it back into Scots Bay. Still one flood tide later, the drifter enters Minas Passage earlier than for QS1 trajectories and settles into QS3 trajectories for the next seven days. At low tide, QS3 trajectories are usually south of the TED site, being near mid-channel within Minas Passage. At high tide, QS3 trajectories can fan out to the north or south (Figure 4).

The 2020 drift passes the TED site on 67 flood tides and nine of these pass through the TED site. Of the nine flood passes through the TED site, five are characterized by TED-d trajectories and three by TED-e trajectories (Figure 4). The TED-d trajectories are like QS1 trajectories displaced a little northward from usual. Thus, five of the flood tide trajectories in 2020 are essentially the same as the two passes through the TED site in 2018.

There were only two ebb tide passes through the TED site (Figure 5). Both correspond to a position on the previous high tide that is close to the northern shoreline. The TED-f trajectory passes through the TED site at low speed (1.35 m/s) because it begins far to the east. The TED-g trajectory begins less eastward and

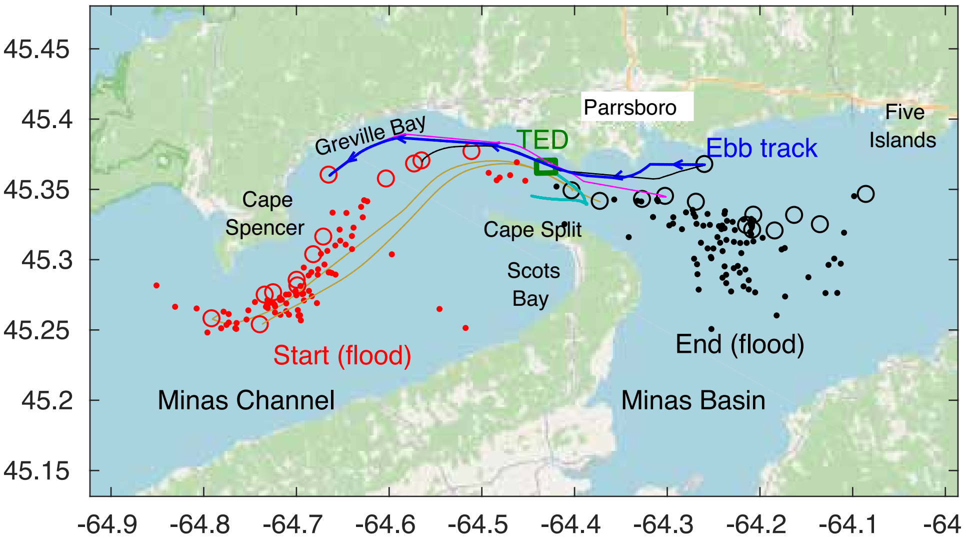


Figure 6: Start (red) and end (black) locations of flood tide trajectories passing the Fundy Ocean Research Centre for Energy tidal energy development (TED) site at speeds ≥1.5 m/s. Trajectories passing through the TED site are indicated with open circles and those passing south of the TED site are marked with dots. A flood-ebb-flood trajectory segment is drawn with black-blue-magenta lines. Two flood tracks (gold) through the TED site begin far to the east and reach to the middle of Minas Passage.

passes through the TED site at 2.53 m/s on the ebb and at 3.12 m/s on the flood. Assuming largely collimated current through Minas Passage, drift through the TED site on an ebb tide would require the drifter to be to the east and close to the north shore on the previous high tide. The drifter seldom (only twice) reached that position, and when it did, both the TED-f and TED-g trajectories culminated in a southward displacement and the TED-g trajectory was followed by QS1 trajectories that seldom go through the TED site. Thus, two lines of evidence indicate that trajectories passing through the TED site on the ebb tide are unstable with respect to subsequent ebb tide passes through the TED site.

Passing the TED Site, All Experiments

Summing over all three experiments, drifters passed through or south of the TED site 214 times, which is 60% of the number of passes that would result if drifters were always on a QS1 trajectory. In-stream turbines are thought to pose less danger to fish when current speed is low [Broadhurst et al., 2014], so the present focus is on drifters passing the TED site at speeds greater than 1.5 m/s. Circles in Figure 6 show start and end points for the 13 times that the drifter passed through the TED site on a flood tide. Dots in Figure 6 show start and end points for the 82 times that the drifter passed south of the TED site on a flood tide. Generally, trajectories that pass through the TED site have the more northerly start and end locations.

Two trajectories that do not conform to the northern endpoint generalization are plotted gold in Figure 6. Start points for these trajectories are far to the west and both trajectories end part way through Minas Passage, south of Cape Sharp. Near high tide, a cross-passage jet is observed to exit West Bay at Cape Sharp. This jet is apparent in Google Earth images and we have visually observed

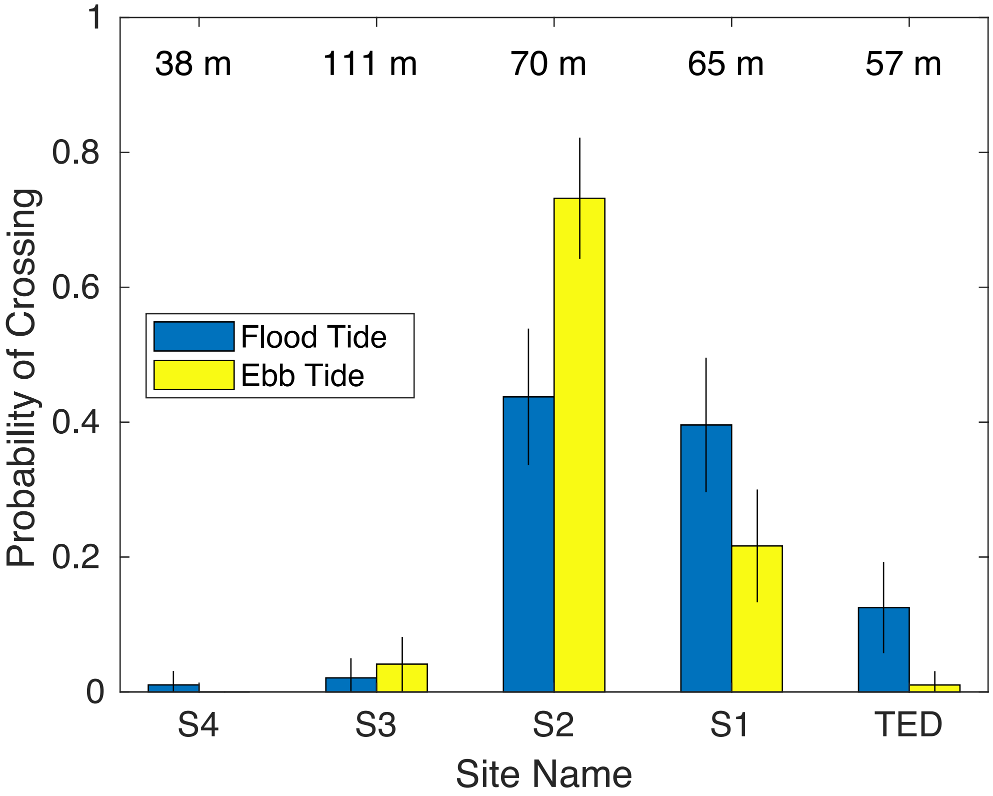


Figure 7: Probability of the drifter passing, with speeds ≥1.5 m/s, through the 1 km latitudinal extent of the tidal energy development (TED) site or through equal cross-passage widths (S1, S2, S3, S4) to the south of the TED site. Whiskers indicate 95% confidence intervals. Water depths are indicated for each site.

it from a small boat on June 12, 2018, as we measured a short drifter track (Figure 6, turquoise) being deflected southwards near the tail of the flood tide.

Only one ebb tide trajectory passes through the TED site at speed greater than 1.5 m/s, and its track is well to the north (Figure 6, blue line). This ebb trajectory begins when the previous flood trajectory (black line) passes through the TED site and terminates far to the north. The next flood trajectory (magenta line) also passes through the TED site but then deflects southwards.

Figure 7 compares the number of passes through the TED site with the number of passes through sites to the south. Drifter trajectories are much more likely to pass through sites S2 and S1 than through the TED site. Water column depth at these sites is not so different as to account for the drifter seldom passing through the TED site. Similarly, mean flood speed through TED is 3.5 m/s (SE 0.2 m/s), which is not different from the mean flood speed south of TED 3.5 m/s (SE 0.1 m/s). It follows that present measurements must miss some common type(s) of water mass movement through the TED site. Nevertheless, the present drifter measurements do find the origin of some water masses that pass through the TED site. Most of the flood tide water passing through the TED site likely comes from Greville Bay, from the red circles (Figure

Location	Time (UTC)	Day Month	Speed (m/s)
Minas Channel	1319-1406	14 Sept	2.1 to 3
Minas Channel	2152-2248	14 Sept	-0.6 to -1.1
Minas Channel	1012-1014	15 Sept	-1.1
Chignecto Bay	1307-1310	20 Sept	0.2

Table 1: Times at which an acoustically tagged Atlantic salmon kelt was detected during drift 2, 2019. Current speed is positive for flood tide and negative for ebb.

6) and northward. Measurements to date find no evidence of quasi-stable trajectories that predominantly pass through the TED site.

Probability of Drifter-Turbine Collision

Davie [2019] reports plans to install a floating platform that supports six turbines side by side at the FORCE TED site. If each turbine rotated through radius 3.15 m and had 20% efficiency, then such a system would produce about 500 kW from the power density [Karsten et al., 2008] of a 3 m/s current. It is of interest to calculate the probability of drifter collision with such an installation, assuming drifters have trajectories such as those presently measured.

Of all drifter trajectories, there were 15 passes through the TED site over a period of 92.6 days, or 4.86 through-passes/month. The near surface turbines (set of six) proposed for testing span a width of 37.8 m, which is 3.78% of the width of the TED site. The probability of a single drifter colliding with a turbine during a one-month period is, therefore, about 0.18. Such collision probability is relevant for the safe conduct of drifter measurements when turbines are operating. The monthly collision probability is similarly relevant for ecologically safe turbine operation, to the extent that present drifter tracks might represent movement of a fish. It is also relevant for turbine mechanical safety given that floating logs and other large debris move similarly to a drifter.

Detected Fish

The 2019 drifter suspended a VR2W-180 kHz receiver, which detected an acoustic tag that had been implanted into the body cavity of an Atlantic salmon kelt (*Salmo salar*) captured at Gaspereau River in spring 2019. Figure 3 indicates three clusters of signals that were received while the drifter was on QS2 trajectories in Minas Channel. The same kelt was detected while the drifter was in Chignecto Bay. (An Atlantic sturgeon was also detected at 1015-1019 UTC on September 19, 2019, when the drifter passed by Advocate.) Table 1 shows that the salmon kelt was intermittently detected over a time span of six days. The longest contiguous sequence of kelt detections lasted 56 minutes. Even in 2.1 to 3 m/s currents, contiguous detections spanned 47 minutes.

The drifter moved 4 km during the first set of contiguous detections whereas the detection range was about 200 m [Sanderson et al., 2017]. It follows that the kelt can be considered within 200 m of the drifter while the drifter moved 4 km along a QS2 trajectory. For 8 hours, the kelt was beyond detection range, only to return to within detection range of the drifter that had continued on a QS2 trajectory. The kelt then moved out of range for 11 hours before returning close to the drifter, which had continued along a QS2 trajectory. Thus, the kelt was in and out of detection range for over 21 hours while the drifter moved with the tide over a distance of 91 km.

Periods without detection are expected given the nature of horizontal mixing by turbulent eddies associated with tidal current. Eddies typically cause nearby pairs of drifters to separate over time [Sanderson and Booth, 1991], but sometimes turbulent flow field singularities [Okubo, 1970] can bring drifters closer together. Even a kelt that moves like a drifter (no swimming but maintaining depth) can be expected to move in and out of detection range of the drifting receiver. The most straightforward interpretation of the present measurements is that the kelt was nearby the drifter for at least 21 hours, sometimes approaching within detection range. Five days and 468 km later, the same kelt was again within detection range of the same drifter.

DISCUSSION

Trajectories of local anadromous fish are fundamental to understand and quantify interaction with tidal turbines. Many moored receivers have been deployed in Minas Basin and Minas Passage [Keyser, 2015] but their coverage has been insufficient for obtaining much information about trajectories taken by acoustically tagged fish. In contrast, trajectories of drogued drifters can be measured in detail. The following discussion is, therefore, developed under subheadings, as follows. First, a consideration of drifter tracks as an approximation to fish tracks. Second, elementary kinematic and dynamic properties of measured drifter tracks are discussed and considered relative to computational hydrodynamic models. Third, probability of drifters encountering a tidal turbine installation is related to the problem of fish-turbine encounters. Fourth, consideration is given to the influence of current-turbine effects on fish-turbine encounters. Finally, drifters are discussed as a monitoring platform.

Drifter Tracks as an Approximation to Fish Tracks

Drifters used in the present study are constrained to move in the horizontal plane, being moved by horizontal components of currents at about 5 m subsurface. Atlantic salmon gulp air to fill their swim bladder and cannot achieve neutral buoyancy when more than 21-24 m below the sea surface [Macaulay et al., 2020]. To a first approximation it might be expected, therefore, that Atlantic salmon also move in the horizontal plane of near-surface waters. Given detection range of the VR2W-180 kHz receiver [Sanderson et al., 2017], present measurements show an Atlantic salmon kelt remaining within about 200 m of the drifter for intervals of almost one hour. An Atlantic salmon post-smolt has also been recorded for 57 minutes on June 16, 2017, near a hydrophone drifting at 2.1 m/s in Minas Passage (unpublished data). Such observations are consistent with directed swimming being slow compared to current speeds in the study area. The primacy of tidal current over swimming is also indicated during six days when the kelt reappeared near the drifter from time to time. Post-smolt Atlantic salmon are capable of sustaining swimming speeds of about 0.8 m/s for several hours [Hvas and

Oppedal, 2017], but present measurements indicate volitional directed speed of order 0.1 m/s over time spans of about one hour.

The case for striped bass approximating movement in the horizontal plane is strengthened by them being narrowly distributed in the upper water column, particularly at winter water temperature [Keyser et al., 2016]. Broome [2014] and Keyser [2015] measured down-tide displacements of striped bass in Minas Passage that were dominated by the running tide which is consistent with critical swimming speed [Freadman, 1979] often being less than current speed and energy cost increasing rapidly with swimming speed [Castro-Santos and Haro, 2005]. Fish swimming behaviour near fishing trawls [Hammar et al. 2015; Wardle, 1986] is consistent with swimming no faster than the requirements of the moment.

Typical swimming speed need not be particularly slow for the trajectory of a fish to approximate that of a drifter. Consider, for example, a striped bass swimming at v=0.5 m/s in order to obtain the respiratory advantage of ram gill ventilation [Freadman, 1979], perhaps while searching for prey. Assume swimming direction only remains correlated for an integral timescale τ=60 s. For long times $t \gg \tau$, the random displacement by such swimming will scale as $v\sqrt{(2\ \tau\ t)}$ [Taylor, 1921] and would average about 800 m during one tide (t=6.21 h) – which is much less than the tidal excursion through Minas Passage.

Detailed swimming velocity of striped bass is unknown in Minas Passage. McLean et al. [2014] measured trajectories of Atlantic sturgeon in the intertidal zone of Minas Basin and found that trajectories were mostly winding with average speeds 0.3-0.5 m/s. About 20% of trajectories had average speed 0.78 m/s, but it must be kept in mind that these measurements represent the vector sum of both swimming velocity and current velocity. In principle, the "apparent swimming velocity" of acoustically-tagged fish in Minas Passage could be measured using a drifting array of synchronized hydrophones. Apparent swimming velocity results from both swimming and turbulent fluctuations of tidal current displacing the fish relative to the drifter. For present purposes, displacements of fish trajectories from a drifter trajectory is a function of apparent swimming velocity, not just swimming velocity.

Presently we have reported a low-cost and effective method that provides more information about fish tracks than was previously possible in the strong tidal currents of Minas Passage. While the preliminary result is consistent with other lines of evidence, further drifter measurements of tagged fish would be advantageous.

Properties of Drifter Tracks

Drifters sometimes settle into quasi-stable trajectories that approximately repeat themselves for many tidal cycles. Three types of quasi-stable trajectory (QS1, QS2, QS3) have been identified to sweep water masses through large tidal excursions in Minas Passage. At locations like Cape Split, the time-varying tidal current also has strongly hyperbolic spatial variation which can cause Lagrangian chaos [Ridderinkhof and Zimmerman, 1992; Kirwan et al.,

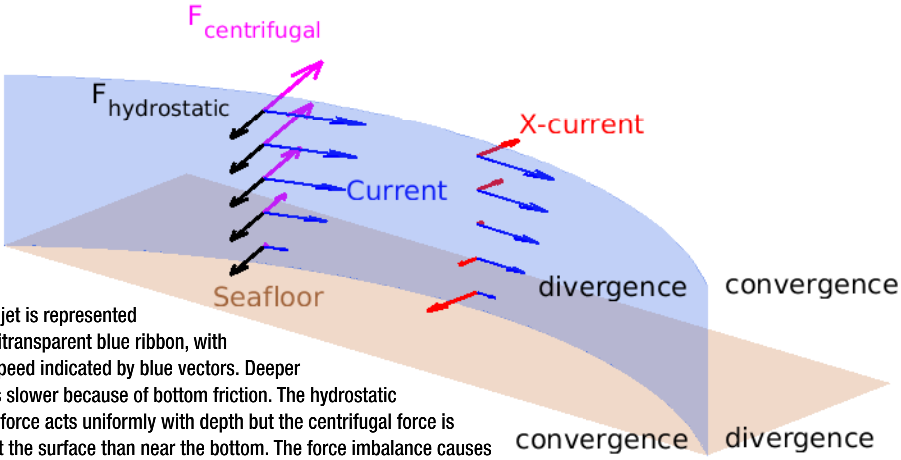


Figure 8:
A curved jet is represented as a semitransparent blue ribbon, with current speed indicated by blue vectors. Deeper current is slower because of bottom friction. The hydrostatic pressure force acts uniformly with depth but the centrifugal force is greater at the surface than near the bottom. The force imbalance causes cross-jet current (red) and thus regions of convergence and divergence on either side of the jet.

2007] whereby a small difference in initial drifter position causes a large change in the subsequent path.

Reasons for the quasi-stable trajectories require investigation. Long established theory [Thomson, 1876] relates three-dimensional secondary circulations to two-dimensional current along curved paths and this may be at least one factor that contributes to convergence of a drifter onto a QS1 track. Drifter tracks enter Minas Passage on the flood tide as a strongly curved jet (Figures 1, 3 and 4). Given the large external Rossby radius (about 200 km) and brief transit time through the bend compared to the tidal period, the jet is expected to have cyclostrophic dynamics. Consider the horizontal gradient of hydrostatic pressure to balance centrifugal “force” of the vertically-averaged current (Figure 8). This hydrostatic pressure gradient acts uniformly at all depths, but bottom friction causes current speed to be lower near the seafloor and faster near the sea surface. Thus, centrifugal force varies with depth and the partial imbalance of forces drives secondary (cross-jet) circulation (Figure 8). In the upper water column, the outer side of the curved jet is a convergence zone whereas the inner side becomes a divergence zone (opposite near the seafloor). Floating drifters tend to be collected by surface convergence zones [Okubo, 1970]. Drifters (and near-surface fish) may, therefore, be more commonly found on trajectories favoured by convergence.

A convincing validation test for a computational hydrodynamic model [Karsten, 2011] would be to replicate the quasi-stable trajectories that have presently been measured. Achieving such validation would provide a means for diagnosing the dynamics and kinematics of trajectories beyond the three-dimensional qualitative analysis above. Such diagnostics provide a means for understanding the prevalence of the QS1 trajectory and, therefore, why drifters so commonly pass to the south of the FORCE TED site.

It would be desirable to more fully measure trajectories through the TED site, particularly those that are likely to subsequently become unstable, because few such measurements have presently been obtained. On the flood tide, Figure 6 indicates investigation of trajectories that begin from a low tide position in Greville Bay so they later pass through the TED site. On the ebb tide, further work might explore ebb tide tracks that begin nearer the northern coastline and to the east of the TED site.

Drifter Tracks Related to Probability of Fish Encounter

Keyser et al. [2016] reported that VR2W-69 kHz receivers moored in Minas Passage recorded acoustically-tagged striped bass at all phases of the tide. This is consistent with tidal excursion illustrated by the present drifter study. A QS1-type trajectory extends from Minas Channel into Minas Basin and takes fish through Minas Passage mid-late flood tide and early-mid ebb tide. On the other hand, a QS3-type trajectory (between Minas Basin and Minas Passage) places fish in Minas Passage early-mid flood tide and mid-late ebb tide. When a trajectory too closely approaches some locations, Lagrangian chaos can shift the trajectory from one quasi-stationary state to another. Drifters sometimes depart Minas Passage for several days (e.g., a shift into a QS2-type trajectory) and later return into modes of movement through Minas Passage. This is consistent with the intermittent and clustered distribution of times at which individual striped bass were recorded in Minas Passage [Keyser et al., 2016]. From spring through late summer, Atlantic sturgeon were also recorded intermittently in Minas Passage and were also found to swim pelagically, 15-45 m subsurface [Stokesbury et al., 2016].

Drifter tracks through the TED site were much less common than drifter tracks that passed a little to the south (Figure 7). Keyser et al. [2016] recorded striped bass also passing mostly to the south of the TED site during the 2012-2013 winter. A lower fraction of passes through the TED site must lower the chances that fish in Minas Passage will encounter a turbine. Nevertheless, present measurements indicated that there was a monthly probability of 0.18 that a drifter would encounter a hypothetical 500 kW near-surface turbine installation. Sub-adult and adult life stages of striped bass have lower probability of encounter with a near-surface turbine installation because they are typically distributed at 20-40 m below sea surface during daylight, although they do undertake diel vertical migration to nearer the surface at nighttime when water temperatures are above 2°C [Keyser et al., 2016]. Buoyancy considerations [Macaulay et al., 2020] suggest that Atlantic salmon might be more exposed to a near-surface turbine installation.

An additional factor that influences probability of encounter for fish relative to probability of encounter for drifters is how commonly a fish from a local population will be on a trajectory that goes through Minas Passage, as opposed to having trajectories that remain in Minas Basin for a flood or ebb tide, for example. Neither Keyser et al. [2016] nor the present drifter measurements sufficiently address this additional factor although both provide an indication. Present drifter tracks go through Minas Passage on 60% of tides, consistent with the drifters being deployed at times and places from which trajectories through Minas Passage might be expected. In winter 2012-2013, six out of 17 tagged striped bass (35%) were detected at some time by receivers in Minas Passage [Keyser et al., 2016]. The same study also reported detection in Minas Passage of at least one of the six striped bass on 81.8% of measured days, corresponding to an average probability 0.247 for each of these fish having at least one trajectory through Minas Passage during a day. This indicates that individual striped bass less commonly pass through Minas Passage than the drifters of the present study – so this also causes probability of encounter to be less for a striped bass than for a drifter.

Current-Turbine Effects

A tidal turbine impedes current. At the Betz limit [Betz, 1966], about 33% of the approaching flow is diverted around the turbine and thus fish-turbine encounter should be similarly reduced. Turbines generate low frequency sound and near-turbine pressure vibrations to which fish might respond by swimming around the turbine [Hammar et al., 2015]. By Newton's third law, moving turbine blades create reactive current flow so that fish passing through the turbine might deflect from harmful contact with blades [Castro-Santos and Haro, 2015].

The Drifter as a Monitoring Platform

Minas Passage is a challenging location for monitoring interactions of marine animals with tidal turbines [Emera, 2019]. Optical visibility is poor and compounded by biofouling. Strong turbulence and bubbles limit the utility of active acoustic devices [Viehman et al., 2017], as well as the passive reception of acoustic signals [Sanderson et al., 2017; Tollit et al., 2019; Adams et al., 2019]. To date, most measurements have been made with instruments fixed relative to the seafloor, either by tethered floats or on gravity base platforms. Wilson et al. [2013] and Adams et al. [2019] found acoustic reception to be better when instruments were mounted to drifters. Presently, we observe that a drifter-mounted VR2W-180 kHz receiver sometimes detected a sequence of acoustic signals from a tagged fish for almost an hour, whereas tidal currents in Minas Passage can sweep a tagged fish past the detection zone of a moored receiver in the time between tag signals [Keyser et al., 2016; Sanderson et al., 2017]. Drifting platforms are suited to detection of acoustic tags that transmit infrequently while moored platforms require frequent transmissions which shorten tag lifetime. Recently, Vemco developed 170 kHz high resolution (HR) acoustic technology [Guzzo et al., 2018] which, for a given energy cost, enables shorter time between signals, thereby improving the odds of a passing tag being detected by fixed HR receivers in fast currents [McLean et al., 2019].

Wilson et al. [2013] observe that a drifter can be a relatively inexpensive instrument platform as compared to bottom-fixed moorings/platforms. Moored systems are also heavy and require larger vessels with substantial machinery for deployment and recovery. Large tidal range restricts large vessels to high tide for departure from, and return to, port. Adams et al. [2019] found it convenient to manually deploy and recover drifting instrument platforms from a relatively small, and fast, rigid hull inflatable boat which can be launched from the beach of West Bay at any tide. Quasi-stable trajectories make the drifter a more convenient monitoring platform at and near Minas Passage than at other sites, but drifters can still stray. A boat and personnel may be more frequently required to tend a drifting platform than a fixed system, and the chance of collision may make drifting platforms problematic when near-surface turbines are operating. Drifter deployment from shore has been demonstrated. The subsurface depth of the drifter's weight constrains stranding. Stranding was observed in the intertidal zone when the weight was set at half the tidal range below the surface float. Setting the weight deeper kept the 2019 drifter further from shore.

Most tidal energy devices operate at a fixed position so it is necessary to make measurements from a fixed platform when considering their interactions with fish. To a first approximation, many fish move with the strong tidal currents and so measuring on a drifting platform addresses the question of how fish come to be in the vicinity of a tidal turbine. Information obtained from one type of platform makes information from the other more complete.

The excursion of quasi-stable drifter tracks gives an indication of the zone within which fish may be found that have some probability of encountering a turbine during a tidal cycle. (It is also an indication of the zone within which the existence of flotsam, including logs, may impede tidal energy devices that operate near the sea surface.) For the TED site in Minas Passage, the excursion extends from Minas Channel to Minas Basin. Progress has been made to measure the distribution of striped bass within Minas Basin [Broome 2014; Keyser 2015] by using bottom-fixed VR2W-69 kHz receivers. Recently, fixed VR2W-180 kHz receivers have similarly recorded alewives (*Alosa pseudoharengus*) as they passed through Minas Basin during their post-spawn migration [Tsitrin, 2020]. On the scale of Minas Basin and Minas Passage, it is impracticable to moor enough receivers to resolve the trajectory of a tagged fish. Augmenting tagging studies with drifter releases near preferred habitat in Minas Basin would help quantify connectivity to the FORCE TED site. It is anticipated that drifter tracks might help fill in the gaps when tagged fish are infrequently detected by receivers that are moored at widely separated locations.

Exploitation of renewable tidal energy is being considered at other sites in the Bay of Fundy. If other sites are not characterized by quasi-stable trajectories, then that might substantially change the concept of "local fish population" from that which applies for Minas Passage. When trajectories pass through a development site but subsequently travel far away and seldom return, then a possibility is raised that the fish population of interest is distributed over a vast area, with individuals typically having a low co-occurrence with a turbine (at that site).

CONCLUSIONS

Quasi-stable drifter trajectories are associated with movement of migratory fishes in the vicinity of the FORCE TED site in Minas Passage. To date, measured trajectories tend to pass south of the TED site rather than through the site, particularly during ebb tides. Monthly probability is 0.18 that a drifter will encounter a 500 kW near-surface turbine installation at the TED site. Individuals from local fish populations are expected to have a much lower probability of encounter than a drifter, depending upon fish distribution in the water column and the extent to which fish utilize habitat that keeps them from taking trajectories through Minas Passage. Trajectory measurements have identified the distributions of water masses within which fish might interact with tidal turbines during the tidal cycle.

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