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# Water Currents, Drifter Trajectories, and the Estimated Potential for Organic Particles Released from a Proposed Salmon Farm Operation in Little Musquash Cove, Southern New Brunswick to Enter the Musquash Marine Protected Area

# Courants, trajectoires de bouées dérivantes et estimation de la probabilité que des particules organiques provenant d'un élevage de saumons proposé pour l'anse Little Musquash, dans le sud du Nouveau-Brunswick, pénètrent dans la zone de protection marine de la Musquash

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## ABSTRACT

A proposal to establish and to operate a finfish aquaculture site in the mouth of Little Musquash Cove, triggered questions about the potential for farm wastes to enter the Musquash Marine Protected Area (MMPA) that is a few kilometers to the east of the proposed site. In order to evaluate this question, new current meter and surface drifter observations were obtained from the area of interest. Calculations based on these and historical observations indicate that fish feed pellets and fish feces are unlikely to enter the MMPA and non-sinking and dissolved substances may intermittingly enter the mouth of the MMPA. DEPOMOD results suggest that the projected flux of sinking organics to the bottom exceeds 1 g $C{\bullet}m^{-2}{\bullet}d^{-1}$ in some areas. The drifter observations indicated that 32% of the non-sinking particles released within the boundaries of the proposed lease site on a flooding tide may enter the mouth of the MMPA. This percentage increases to 58% if near entries are included. If it is assumed the non-sinking particles released on an ebbing tide do not enter the MMPA, then the drifter data suggest that the total probability of non-sinking particles entering the MMPA is 16-29%, i.e. half of the flood tide probabilities.

## RÉSUMÉ

Une proposition relative à la création et à l'exploitation d'un établissement piscicole à l'embouchure de l'anse Little Musquash, a suscité des questions sur la possibilité que des déchets issus de l'exploitation pénètrent dans la zone de protection marine de la Musquash (ZPMM), qui se trouve à quelques kilomètres à l'est du lieu proposé pour l'exploitation. Afin de répondre à ces questions, on a effectué de nouvelles observations dans la zone visée à l'aide de courantomètres et de bouées dérivantes. Les calculs issus de ces observations et d'observations antérieures révèlent qu'il est très peu probable que les granulés de nourriture et les matières fécales des poissons pénètrent dans la ZPMM, et que les substances qui demeurent en suspension et les substances dissoutes peuvent, par intermittence, pénétrer dans l'embouchure de la ZPMM. Selon les résultats DEPOMOD, le rythme projeté du dépôt de matières organiques au fond de l'eau dépasse 1 g $C{\cdot}m^{-2}{\cdot}jour^{-1}$ dans quelques zones. Selon les observations faites à l'aide de bouées dérivantes, 32 % des particules en suspension relâchées dans les limites du site proposé à marée montante peuvent pénétrer dans l'embouchure de la ZPMM. Ce pourcentage passe à 58 % si on inclut les approches de l'embouchure. Si on suppose que les particules en suspension relâchées à marée descendante n'entrent pas dans la ZPMM, les données relevées grâce aux bouées dérivantes indiquent que la probabilité totale que des particules en suspension entrent dans la ZPMM est de l'ordre de 16-29%, c'est-à-dire la moitié de la probabilité calculée à marée montante.

## INTRODUCTION

A proposal to establish and to operate a finfish aquaculture site in the mouth of Little Musquash Cove, was received in January of 2008 by the New Brunswick Department of Agriculture and Aquaculture, the New Brunswick Department of Environment, and, subsequently, the Federal Department of Fisheries and Oceans (DFO). The proposal was prepared by Sweeney International Management Corp on behalf of Limekiln Fisheries (2000) Limited (SIMCorp 2008).

The proposed lease boundary dimensions are approximately 680 x 820 m, which is an area of about 49.1 hectares (SIMCorp 2008). Within this lease, the fish cages are proposed to be distributed between 2 grid systems, each with a 3 x 4 array of cages (12 cages for each array) for a total of 24 cages. Each of these cages is to be 100 m in circumference (a radius of 15.9m) and each grid cell is 55 x 55 m square. The nets on each cage would be 10 m in depth. The area covered by a single cage is, therefore, 795.8 $m^2$, and the area covered by the complete cage system would be about 19,099 $m^2$ (SIMCorp 2008). The water depth within the lease area varies from between about 10 and 30 m below mean low water with a mean depth of 17.9 m.

Each fish cage is proposed to be stocked with about 35,000 fish for a site total of about 840,000 fish. The fish will be placed into the cages at a size of about 75 to 100 g, and will be harvested at an average size of about 4.5 kg (SIMCorp 2008). The expected food conversion ratio for these fish is 1.2:1 (SIMCorp 2008).

The proposed site location (MF-0506; Fig. 1) is approximately 4 km to the east of Chance Harbour and 2 km to the west of Musquash Harbour, a designated Marine Protected Area (MPA). The nearest operating fish farm is located near the mouth of Haley's Cove, a distance of 3 km toward the west.

The proximity of the proposed site to the Musquash Marine Protected Area (MMPA) prompted the Oceans and Habitat Branch of the DFO Maritimes Region to request advice from DFO Maritimes Science Branch concerning the potential for operational wastes released from the proposed farm to be transported into the MMPA.

Unfortunately, there is little information available concerning the circulation in the geographic area of the proposed site. Tidal excursions in the area are suggested to be several kilometers (approximately 10 km) in length, a distance that traverses the distance between the proposed farm location and the MMPA (Forrester 1959, Chang et al. 2007). Hence, there is a suggested potential (see Appendix 1) for suspended particulates and dissolved substances, e.g. inorganic nutrients that would be released from the proposed farm to enter the MMPA. The potential for sinking particulates to enter the MMPA is less, since they would likely sink to the bottom well before reaching the MMPA.

This relative scarcity of information, coupled with the proximity of the proposed site to the MMPA and the possibility that at least some substances released from the proposed farm might enter the MMPA, contributed to the initiation of a field program undertaken by DFO Maritimes Science St. Andrews Biological Station staff during the spring and summer of 2008 to gather new information on the water currents and drift patterns from the area of interest. The work consisted of a series of current meter moorings, drifter releases, and model simulations.

The purpose of this report is to: 1) describe the specifics of the new observations, 2) use the information to better evaluate the displacement pathways for substances likely to be released from the proposed farm, 3) review the historical literature of relevance to this issue, and

4) synthesize the information in the context of the implications of the exposure of the Musquash Marine Protected Area to the transport of wastes that might be released from the proposed site.

## MATERIALS AND METHODS

### Current Meter Mooring

An RDI Workhorse Sentinel Acoustic Doppler Current Profiler (ADCP) was deployed near the middle of the proposed farm site (MF-506, 45.13148°N, 66.28615°W; Fig. 1) in the mouth of Little Musquash Cove for a period of approximately 35 days beginning on the 22nd of February 2008 and ending on the 27th of March 2008. The depth at this point was approximately 17.5 m below lowest normal tide; the average depth at the proposed site is 17.9 m below lowest normal tide.

The ADCP was configured to record the current speed and direction every 10 minutes at 1 m depth intervals, beginning at 3.61 m above the bottom and extending to 2.5 m below the sea surface. The current direction was measured by a magnetic compass housed within the ADCP body. The directions were adjusted for the local magnetic deviation so data output was relative to true North. The ADCP data was edited to remove weak signals and data from bins above the sea surface.

### Particle Transport Estimated from Current Meter Data

The transport and dispersal of a substance released from a fish farm is essentially a product of the water velocity ($V(x, y, z, t)$) in the dispersal area and the length of time the substance is in the water column ($\Delta t$). In other words, the distance a substance travels ($D$) is estimated as $D = V\Delta t$ . The complexity of this estimate increases as the details of spatial (horizontal ($x, y$) and vertical ($z$)) and temporal ($t$) variation in the water velocity increases and as the complexity of the substance behavior increases.

Water velocities ($V = Vt + Vr$) in the Bay of Fundy can be characterized as the sum of a periodic tidal flow ($Vt$) and a residual or time averaged flow ($Vr$). The periodic flow is referred to as the tidal current or tidal stream, and it is composed of the periodic flows generated by many tidal constituents. The dominant period of the tidal flows is 12.42 h, and is referred to as the M2 or principal lunar tide. The residual flow is composed of the observed flow minus the tidal flows. It consists of wind driven flows ($Vw$), density driven flows ($Vd$) and other unresolved components ($Vo$) of the flow, i.e. $Vr = Vw + Vd + Vo$. For the purposes of this Research Document, the tidal flow is considered to be all of the flows observed on time scales of 12.4 hours or less, and the residual flows to be the time averaged flows.

The transport time scales of relevance are determined by the length of time the effluents from the fish farm remain in the water column. The effluent considered in this report is the organic and inorganic effluent (i.e. dissolved nutrients). Organic effluents from fish farms primarily include various forms and sizes of feed pellets, fish feces, and associated fines. Order of magnitude sinking rates for these particles are 0.1 $m \cdot s^{-1}$ for the feed pellets, 0.01 $m \cdot s^{-1}$ for fish feces, and 0.001 $m \cdot s^{-1}$ for fines. For a fish farm moored in a location with a depth of about 20 m, feed pellets would take about 3 minutes and fish feces would take about 33 minutes to sink to the bottom. In the absence of vertical turbulence, fine particles would take about 333 minutes to sink to the bottom. However, vertical turbulence in the coastal zone usually keeps these fine particles in suspension. These time scales indicate that the transport and initial settlement of the effluents is dominated by the tidal currents. Substances such as therapeutants, which would be released into the water via waste, medicated feed, and fish feces, remain in the water column for time scales determined by the sinking rates of the feed pellets and feces. Hence, their initial transport is controlled primarily by the tidal circulation.

Other releases or losses from the farm, such as pieces of equipment including feed totes and pieces of rope, fish mucus including perhaps pathogens, fish oils, and equipment oils, are all buoyant and remain in the water column for periods of days to weeks or longer. Hence, their transport and dispersal is governed by tidal and residual circulation features. As the fish pellets and feces decompose, the chemicals will gradually be released into the environment and be transported and dispersed by the tidal and residual circulation features.

In this Research Document, the transport or displacement of the above particles is estimated using a series of increasingly complex versions of the flow field.

The simplest estimates are based on the assumption of a constant velocity, i.e. constant speed and direction, for the duration of the time scale, and that the estimated displacement is represented by the radius of a circular zone of displacement over a single tidal cycle. The displacement time scales for the feed pellets and fish feces were assumed as indicated above. The displacements of the non-sinking particles, the fines, and dissolved inorganics, were calculated using a time scale of 6.5 h, about half of the M2 tidal cycle. This assumes that the particle displacements would reverse themselves during the second half of the tidal cycle. The calculations were made using the maximum and median current speeds of the near-surface, mid-depth, and near-bottom, as well as the maxima and median current speeds estimated from the velocity records from all depths.

Although this simple calculation is likely to overestimate the displacement of farm effluents, it provides a quick estimate of the potential zone of exposure and, if this zone does not overlap with the boundary of the MMPA, it is unlikely that more refined calculations will result in an overlap.

A more complete, although still very simple, estimate of particle displacement was generated by assuming a particle was released at the beginning of every water velocity measurement. The displacements for feed pellets are estimated as $D_n = V_n \Delta t$, where $V_n$ is the recorded water velocity and $\Delta t$ is the time (3.3 minutes) for the pellets to sink through the depth of the water column. The displacements for feces are estimated as the sum of the displacements for the 3 sequential velocity records, i.e. $D_n = V_n \Delta t + V_{n+1} \Delta t + V_{n+2} \Delta t$, where the *V's* are the sequentially recorded water velocities and $\Delta t$ is the time interval (10 minutes) between water velocity records. The total time for the displacement is 30 minutes, which underestimates the time for the feces to sink through the depth of the water column (33.3 minutes) by 3.33 minutes. The displacements of non-sinking particulates were estimated as the sum of the displacements of 75 velocity records (750 minutes ≡ 75 velocity records). These calculations result in frequency distributions of particle displacements, whereas the simpler calculations described above resulted in single displacement estimates.

Both of the above approaches assume a single release point and a spatially homogeneous velocity field. Both of these assumptions are oversimplifications.

DEPOMOD

A third approach utilized the DEPOMOD, an aquaculture waste dispersal model developed in Scotland (Cromey et al. 2002). This model incorporates multiple release locations, i.e. the full array of cages, and takes multiple particle sizes and sinking rates into consideration. The model also assumes a spatially homogeneous velocity field. The model was run using the near-surface, mid-depth, and near-bottom time series of water velocities obtained from the current meter deployed at the centre of the proposed site. The assumed settling rates of organic particles were those used by Chamberlain et al. (2005) for testing DEPOMOD in British Columbia salmon farms: 11.0 $cm \cdot s^{-1}$ for feed pellets and 3.2 $cm \cdot s^{-1}$ for feces (± 1.1 $cm \cdot s^{-1}$). The model domain was a 2000 × 2000 m square centred on the proposed farm site. Deposition rates were calculated at grid points spaced 20 m apart. Contours were plotted using MapInfo Vertical Mapper (v. 3.0), using rectangular interpolation (default values).

The model was run using 2 feeding rates: 1000 $kg \cdot cage^{-1} \cdot d^{-1}$, which was typical of maximum feeding rates at some other farms using the same size cages and similar stocking densities; and half that rate (500 $kg \cdot cage^{-1} \cdot d^{-1}$).

The approach of using a full 3 dimensional and time dependent characterization of the flow field was considered to be beyond the scope of this report.

**Drifter Experiments**

Surface drift in the vicinity of the proposed farm was studied using Convertible Accurate Surface Tracker (CAST) drifters. The drifters were typically released in clusters of 6. Clusters were deployed in the vicinity of the proposed aquaculture site and the MMPA on 6 dates in July and August 2008. Drifters were recovered on the following day, about 17-24 h after release; although in some cases, the drifters had become stranded on shore within a few hours after release. A range and direction finder that detects the frequency specific to the ARGOS signal transmitted by each drifter was used to locate the drifters for recovery.

Each drifter consisted of a perforated barrel and an electronics package housed within a central water proof tube. The combination extends from the sea surface to a depth of 1 m (Fig. 2); hence, the drifters follow the top 1 m of the water column. The electronics were configured to record the drifter's Global Positioning System (GPS) position every 10-12 minutes and to begin transmitting to the ARGOS satellite system after 16-18 hours. Once the ARGOS transmission began, ARGOS positions were recorded at intervals of up to 146 min. All times were recorded in UTC (GMT), which was 3 h later than local time (Atlantic Daylight Time).

Upon recovery, the GPS positions recorded in the internal memory of each drifter were uploaded to a laptop. The uploaded data was edited to remove low quality and outlier position fixes, as well as position fixes that were recorded prior to drifter release and subsequent to drifter recovery. Maps of the edited drifter tracks were drawn using MapInfo software. Tracks were drawn as straight line segments connecting temporally sequential positions. The estimated positions along the drifter tracks at 1 hour intervals after release, as well as the positions after 1 tidal excursion (12.42 h after release) and the positions at the times of high and low tides at Musquash Harbour (tide times obtained from the Canadian Hydrographic Service website http://marees-tides.gc.ca/english/Canada.shtml) were also shown. For the few tracks that were of sufficient length, the position at the end of the second tidal cycle (24.84 h after release) was shown.

# RESULTS

## Current Meter Mooring

The ADCP mooring located near the middle of the farm site indicates there is little depth variation in the current speed statistics (mean, median, minimum, and maximum; Fig. 3).

The full time series and frequency distributions of current speed for the mid-depth (11.5 m below the surface; Fig. 4), near-surface (3.6 m below the surface; Fig. 5), and near-bottom (3.6 m above the bottom; Fig. 6) show the maximum current speeds are 61.8 $cm \cdot s^{-1}$ (near-surface), 61.7 $cm \cdot s^{-1}$ (mid-depth), and 59.4 $cm \cdot s^{-1}$ (near-bottom). The median current speeds are 29.6 $cm \cdot s^{-1}$ (near-surface), 34.8 $cm \cdot s^{-1}$ (mid-depth), and 27.7 $cm \cdot s^{-1}$ (near-bottom). The minimum current speeds are effectively zero, i.e. 0.1 $cm \cdot s^{-1}$ (near-surface), 0.6 $cm \cdot s^{-1}$ (mid-depth), and 0.2 $cm \cdot s^{-1}$ (near-bottom). The direction of the tidal currents at all depths (Figs. 7, 8, and 9) is along an east-north-east (approximately 70ºN) to west-south-west axis (approximately 250ºN) and the residual current at all depths is toward the northeast (Figs. 7, 8, and 9) at a rate of about 3-5 $cm \cdot s^{-1}$.

### Frequency of Low Velocities

Table 1 shows the number of records when the current velocity was low ($\leq$5 $cm \cdot s^{-1}$), as well as the number of instances, when 2 or more consecutive records were $\leq$5 $cm \cdot s^{-1}$. The current was $\leq$5 $cm \cdot s^{-1}$ for <5% of the time (2.8-4.4% of records near the surface, at mid-depth, and near the bottom). There were few extended periods when the current remained $\leq$5 $cm \cdot s^{-1}$: 2-6 periods of 40 min (4 consecutive records $\leq$5 $cm \cdot s^{-1}$) and 0-1 period of 60-80 min (6-8 consecutive records $\leq$5 $cm \cdot s^{-1}$) within the 35-d deployment (see also Figs. 4-6).

## Particle Displacements based on Current Data

### Displacements based on Constant Maximum and Median Velocities

Based on the assumptions of a constant velocity, the observed maxima at the near-surface, mid-depth, and near-bottom, order of magnitude sinking rates, and a typical water depth for the site (see Materials and Methods section for details), the radial displacements (Table 2) of feed pellets were estimated to be 123-131 m, and those of feces to be 1,228-1,314 m. The displacements for non-sinking particles were estimated to be 14.4-15.4 km. The circles associated with the non-sinking particles and the median and maximum currents observed in the near-surface are shown in Fig. 10. The estimated displacement circles associated for feed and feces, based on the median and maximum current velocities estimated from all of the velocity records, are shown in Fig. 11.

Given that the MMPA seaward boundary is approximately 2 km away from the proposed farm site, the calculations suggest feed pellets settle within the site boundary and are not transported a distance sufficient to enter the MMPA. Fish feces are indicated to be transported beyond the site boundary and of a sufficient distance that they come close to the MMPA boundary. Non-sinking particles are displaced a sufficient distance that they will likley enter the MMPA at times.

These estimates represent maximum displacements and are likey to over-estimate the displacement of particles released from the farm for two reasons. The water velocities do not persist at the maximum rate and in the same direction for an entire half tidal cycle, and the feces and feed pellet sinking rates are under-estimated by a few centimeters per second so the time scales are slightly over-estimated.

Similar calculations using the median current velocity values, resulted in the calculated radius of displacement of feed pellets being 58-70 m, the radius of displacement of feces being 578-702 m, and the radius of non-sinking particles, the passive tidal excursion radius, as 6.9-8.2 km. These calculations further suggest that feed pellets will not travel a distance sufficient to enter the MMPA and that the distance travelled by fish feces is now insufficient to enter the MMPA. The displacement of non-sinking fine particles is reduced by more than half, but the displacement is still large enough to suggest entry into the MMPA boundary.

Displacement based on the Full Time Series of Currents

The displacements of the fish pellet, feces, and non-sinking particulates based on the full time series of mid-depth water velocities is shown in Figs. 12-14. The particles are estimated to be scattered along an east-north-east to west-south-west axis. The frequency distribution of the feed pellet displacements indicates that the maximum displacement is 123 m, whereas the $75^{th}$ percentile and median displacements are 91 and 70 m, respectively (Fig. 12). The frequency distribution of fish feces displacements indicates that the maximum displacement is 1050 m, whereas the $75^{th}$ percentile and median displacements are 816 and 628 m, respectively, (Fig. 13). Finally, the frequency distribution of non-sinking particulates indicates that the maximum displacement is 6.6 km, whereas the $75^{th}$ percentile and median displacements are 3.7 and 2.8 km, respectively (Fig. 14).

As expected, the displacements generated from the full time series of data are somewhat less than those generated by the maximum currents alone. Hence, these slightly more complete calculations support the indication that feed pellets and fish feces will not travel a distance sufficient to enter the MMPA. The displacements of non-sinking fine particles, although reduced compared to the former, continue to be large enough to suggest entry into the MMPA boundary.

**DEPOMOD**

The results of the DEPOMOD runs are shown in Figs. 15 and 16. The figures show the proposed location of the farm cages within the lease and the estimated flux of carbon to the seafloor generated by the operation of the farm under two feeding scenarios – one with a feeding rate of 500 $kg \cdot cage^{-1} \cdot d^{-1}$ and one with a feeding rate of 1000 $kg \cdot cage^{-1} \cdot d^{-1}$. These rates were based on industry recorded feeding rates for cages of similar size and stocking density to those proposed for the Little Musquash site.

The feeding rate of 500 $kg \cdot cage^{-1} \cdot d^{-1}$, resulted in the maximum estimated carbon flux being 5.5 $g\ C \cdot m^{-2} \cdot d^{-1}$ with 96% of the carbon fluxes ≥1.0 $g\ C \cdot m^{-2} \cdot d^{-1}$ remaining within the site boundaries. When the feeding rate of 1000 $kg \cdot cage^{-1} \cdot d^{-1}$ was used, the maximum carbon flux was 11.2 $g\ C \cdot m^{-2} \cdot d^{-1}$ with 86% of the carbon fluxes ≥1.0 $g\ C \cdot m^{-2} \cdot d^{-1}$ confined within the site boundaries. This model suggests that an estimated 27 ha of the seafloor would receive ≥1 $g\ C \cdot m^{-2} \cdot d^{-1}$ (47% of the 49.1 ha site). A deposition rate of 1 $g\ C \cdot m^{-2} \cdot d^{-1}$ is considered to be the threshold between oxic and anoxic sediments (Chamberlain et al. 2005, Hargrave 1994). The DEPOMOD calculations did not include the displacements of non-sinking particles.

The length scales of the zone of exposure estimated from the DEPOMOD output are reduced compared to the zones estimated from the above simpler calculations. Once again, this is to be expected since the DEPOMOD approach used greater, and more accurate, sinking rate estimates for fish feed pellets and feces, the release of particles from all of the individual cages within the proposed cage array for the site and model outputs were contoured in terms of the concentration of settled particles, in units of carbon mass. The settling rates of feed pellets was assumed to be 11 $cm \cdot s^{-1}$ rather than 10 $cm \cdot s^{-1}$. This 10% increase in the settling rate results in a reduced sinking time and, hence, a reduced horizontal displacement by about 10% relative to the simple order of magnitude calculations. The settling rates of fish feces was assumed to be 3.2 $cm \cdot s^{-1}$ rather than 1 $cm \cdot s^{-1}$. This 300% increase in the settling rate results in a considerable reduced sinking time for fish feces and, hence, a reduced horizontal displacement by about 300% relative to the simple order of magnitude calculations. The DEPOMOD model also assumes that most of the waste from the farm is due to fish feces rather than feed pellets, so the settled concentration field is dominated by the dispersal of the feces.

### Drifter Releases

Six releases of drifter clusters were conducted. A summary of the date and time of release, the number of drifters released, the state of the tide during the release period, and the wind conditions during the drift period are given in Table 3. The drift trajectories recorded from each drifter and each release date are shown in Figs. 17 to 22.

<u>Drifter Release 22 July 2008 (Fig. 17)</u>

On 22 July 2008, a cluster of 6 CAST drifters was released, just after low tide (start of flood tide), from a point within the boundaries of the proposed aquaculture site near Little Musquash Cove (MF-0506). All drifters were released within minutes of each other and initially headed eastward, toward the mouth of Musquash Harbour. Drifters 60, 66, 68, and 69 entered MMPA Zone 2B (Gooseberry Cove) and hit the shore in the cove within 7 h after release. Drifters 49 and 64 entered MMPA Zone 2B, then changed directions after the high tide (5.9 h after release), moving southwest toward Little Dipper Harbour. They changed direction again after the next low tide (12.1 h after release) heading northeast, until they were picked up just outside of Little Musquash Cove (Drifter 49) and Haleys Cove (64), 16 h after release.

Only drifters 49 and 64 remained in the water for 1 tidal excursion (12.42 h). Drifter 49 travelled a total of 10.36 km during 12.42 h after release (straight line displacement = 4.23 km). Drifter 64 travelled a total of 11.13 km during 12.42 h after release (straight line displacment = 4.76 km).

Of the 6 drifters released all entered the MMPA.

<u>Drifter Release 24 July 2008 (Fig. 18)</u>

On 24 July 2008, a cluster of 6 CAST drifters was released near the middle of the proposed farm site at approximately 41 min after low tide (flood tide). All drifters initially moved northeast past the mouth of Musquash Harbour. All except Drifter 69 continued up the coast until the high tide (5.4 h after release), when they changed directions, moving southwest; they changed directions again at the next low tide (13.7 h after release), moving northeast until they were recovered after 17-18 h off the mouth of Haleys Cove. Drifter 69 hit the shore just east of the mouth of Musquash Harbour, just after high tide (5.4 h after release), then moved to the southwest with the falling tide, and stopped on the shore just east of Musquash Harbour, 10.8 h after release.

All except Drifter 69 remained in the water for 1 tidal excursion (12.42 h). The distances travelled in 12.42 h after release are as follows:

| Drifter | Distance along track (km) | Straight line displacement from release to end point (km) |
|---|---|---|
| 49 | 30.60 | 6.10 |
| 60 | 29.18 | 5.26 |
| 64 | 28.93 | 5.02 |
| 66 | 30.20 | 6.34 |
| 68 | 23.13 | 8.57 |

None of the drifters entered the Musquash Marine Protected Area.

Drifter Release 28 July 2008 (Fig. 19)

On 28 July 2008, a cluster of 6 CAST drifters was released at the same time, at high tide (start of ebb tide), from a point within the MMPA, at the northern boundary of Zone 2A. Drifters 49, 64, 68, and 69 initially moved southward, toward the mouth of Musquash Harbour; they then changed direction about 2 h before the change in tide and moved northward, hitting the shore in the western area of Zone 2A, within 7.3 h after release. Drifter 66 also initially moved southward, but moved further south initially (almost reaching Zone 3), changed directions at the change in tide, and then moved north toward the release point, hitting the shore 10.9 h after release. Drifter 60 initially followed the same track as Drifter 64, but after hitting the shore, reversed direction, moving south out of Musquash Harbour, and then continued southwest off the mouth of Haleys Cove; at the next low tide (18.9 h after release) it reversed direction and moved northeast back into Musquash Harbour, where it was recovered 27.5 h after release.

Only Drifter 60 remained in the water for at least 1 tidal excursion (12.42 h). It travelled a total of 6.42 km during 12.42 h after release (straight line displacement = 3.06 km). After 2 tidal excursions (24.84 h), it had travelled a total of 22.77 km (straight line displacment = 2.82 km).

None of the drifters from the MMPA entered the proposed farm site.

Drifter Release 30 July 2008 (Fig. 20)

On 30 July 2008, a cluster of 5 CAST drifters was released near the middle of the proposed farm site at approximately 17 min after high tide (start of ebb tide). Drifter 60 moved westward and stopped on a ledge near the shore just west of Little Musquash Cove, 1.9 h after release. All other drifters initially moved northwest, then north, into Little Musquash Cove, hitting the shore 3.5-4.2 h after release.

None of the drifters entered the Musquash Marine Protected Area.

Drifter Release 6 August 2008 (Fig. 21)

On 6 August 2008, 6 CAST drifters were released at the same time, just after low tide (start of flood tide), from a point within the boundaries of the proposed aquaculture site near Little Musquash Cove (MF-0506). All 6 drifters intially headed eastward. Drifters 47, 64, 68, and 69 hit the shore just east of the mouth of Musquash Harbour, 2.9-3.6 h after release. Drifters 48 and 59 did not hit shore just east of Musquash Harbour. Drifter 48 continued eastward about 4 km, until 1 hour after high tide, when it changed direction and headed southwest. About 1 hour after the following low tide, it changed direction again, heading northeast toward the mouth of

Musquash Harbour. About 1 hour before the next high tide, it changed direction again, heading westward until it hit the shore near its release point, about 20 h after release. The track for Drifter 59 was similar to that of Drifter 48, except it did not go as far eastward (beyond the mouth of Musquash Harbour), and, subsequently, did not go as far offshore in the southwesterly direction. As with Drifter 48, it hit the shore near its release point, 21.5 h after release.

Only drifters 48 and 59 remained in the water for 1 tidal excursion (12.42 h). Drifter 48 travelled a total of 21.01 km during 12.42 h after release (straight line displacement = 4.74 km). Drifter 59 travelled a total of 12.16 km during 12.42 h after release (straight line displacement = 2.57 km)

Drifter Release 20 August 2008 (Fig. 22)

On 20 August 2008, 5 CAST drifters were released at 2-3 min intervals, 16-25 min after low tide (flood tide), along a line starting just off the mouth of Chance Harbour, and ending within the proposed aquaculture site near Little Musquash Cove (MF-0506). All drifters initially moved eastward along the coast, and then changed direction at the change in tide (5.7 h after release), moving southwest away from the coast; at the next change in tide (12.0 h after release) they headed northwest, but remained offshore; at the next change in tide (18.1 h after release), they headed in a south-southwest direction further offshore; at the next change in tide (24.4 h after release) they headed a short distance to the northeast, until they were recovered in offshore waters, 25-28 h after release.

All drifters remained in the water for 2 tidal excursions (24.84 h). The distances travelled along the tracks, as well as the straight line displacements from the release points, during 1 and 2 tidal excursions are as follows:

| Drifter | Distance along track (km) | | Straight line displacement (km) | |
|---|---|---|---|---|
| | 1 tidal excursion | 2 tidal excursions | 1 tidal excusion | 2 tidal excursions |
| 47 | 33.66 | 60.00 | 12.44 | 25.22 |
| 48 | 30.12 | 61.60 | 10.93 | 20.85 |
| 59 | 35.77 | 62.29 | 13.79 | 26.30 |
| 64 | 35.63 | 65.92 | 12.68 | 23.16 |
| 68 | 31.18 | 58.93 | 11.43 | 22.94 |

**Particle Displacements based on Drifter Data**

The drifter data are most relevant to the displacements of non-sinking particulates. The estimates of the displacement of non-sinking particulates derived from both the current meter data and the drifter data suggest that these particulates may travel a distance sufficient to enter the MMPA. However, the drifter data indicate that all of the drifters that traverse the distance between the proposed farm site and the MMPA do not enter the MMPA. Many of the drifters travelled past the mouth of the MMPA. One of three clusters of drifters, released on a flood tide entered the MMPA, i.e. 33%, and these only entered the most seaward zone of the MMPA. Of the 24 individual drifters released within the boundaries of the proposed site, 19 were released on a flooding tide and 5 on an ebbing tide. Of the 19 released on a flooding tide, 6 (32%) entered the mouth of the MMPA. An additional 5 came very close to entering the MMPA. The combination of entries plus near entries results in 11 of 19 (58%) flood tide drifter releases entering the MMPA. The conditions that make entry into the MMPA were not identified in this study.

## DISCUSSION

### Tidal Current

The water velocities obtained as part of this study are consistent with the earlier perspective of circulation in this part of the Bay of Fundy.

The first systematic measurement of currents in the Bay of Fundy was made in 1904 and 1907, at a series of stations located in the main shipping lanes (Dawson 1908). Dawson's Station A, located in the middle of the Bay of Fundy between Saint John and Digby at a distance of more than 10 km from the proposed farm site, was the closest of Dawson's stations to the Musquash area. The maximum recorded tidal velocity at this location was 0.85 $m \cdot s^{-1}$ (1.7 knots). Dawson recognized that the dominant feature of the water current in the area was strong tidal periodicity, that near the coast current speeds are generally reduced relative to the offshore and vary on small spatial scales (10-100s of meters) due to local details in bathymetry (Dawson 1908).

The next series of current observations was obtained during the 1950s. Forrester (1959) summarized this current meter data, collected in the Passamaquoddy Bay and Bay of Fundy areas during 1957 and 1958 by the Canadian Hydrographic Service in association with the Atlantic Oceanographic Group. The data were collected as part of the International Passamaquoddy Fisheries Board investigation into the potential influences of a tidal power project on the water properties, circulation, and fisheries in the region. Information on the speed and direction of tidal and non-tidal or residual water flows were collected at stations located throughout the study area using an Ekman and/or a Gurley current meter and/or a C.B.I. Drag suspended from an anchored vessel. The instruments were deployed at approximately half hour intervals at 3 depths (5 m and 25 m below the surface and near the bottom) for consecutive time periods of 13, 25, or 72 h.

Two of Forrester's (1959) stations were in the vicinity of Little Musquash and Musquash Harbour. Station 1 of Forrester's study was located 1-2 km offshore of Point Lepreau, and velocity data was collected at the station on 4 July 1957. Station 46 was located 1-2 km offshore of Musquash Harbour, and the velocity data was collected on July 14, 1958. The tidal stream velocities at all depths at both stations were observed to rotate in a counter-clockwise direction around a major axis that is more or less parallel to the coastline along a northeast - southwest axis (Figs. 23 and 24). The Station 1 tidal stream velocities at 60 m are less rectilinear than those at 5 and 25 m. The maximum tidal stream velocities were 0.91, 0.99, and 0.76 $m \cdot s^{-1}$ at the respective depths of 5, 25, and 50 m. The residual velocities at 5, 25, and 50 m were, respectively, 0.08, 0.08, and 0.06 $m \cdot s^{-1}$ away from the coast. The maximum total velocities, i.e. tidal stream plus residual velocities, were 0.88, 0.95, and 0.76 $m \cdot s^{-1}$, at the same respective depths. The station 46 tidal stream velocities at 60 m are less rectilinear than those at 5 and 25 m. The maximum tidal stream velocities were 0.81, 0.91, and 0.62 $m \cdot s^{-1}$, at the respective depths of 5, 25, and 60 m. The residual velocities at 5 and 25 m were, respectively, 0.37 and 0.29 $m \cdot s^{-1}$ in a direction away from the coast. The residual velocity at 60 m was 0.12 $m \cdot s^{-1}$ toward the coast. The maximum total velocities, i.e. tidal stream plus residual velocities, were 1.16, 1.09, and 0.64 $m \cdot s^{-1}$, at the same respective depths.

In 1965, a current survey of the Bay of Fundy was conducted by C.J. Langford (Anon. 1966, Godin 1968). This survey focused primarily on the inner Bay of Fundy, but it did include a station (Station 60) seaward of Point Lepreau. Godin (1968) analyzed these data using a series of low digital filters and tidal harmonic analyses. These analyses indicated the M2 semi-diurnal tidal constituent is the dominant tidal frequency characterizing the current in the Bay of Fundy. For Station 60, the amplitude of the M2 current along its major axis was estimated as 1.30 knots

(0.65 $m \cdot s^{-1}$) and along the minor axis as 0.15 knots (0.075 $m \cdot s^{-1}$). The estimated maximum tidal current, the current generated by the sum of the velocities represented by all of major tidal constituents, was 2.04 knots (1.02 $m \cdot s^{-1}$) and the maximum observed tidal stream velocity was 1.88 knots (0.94 $m \cdot s^{-1}$).

McLaren Atlantic Limited (1975) reported on the current speeds and circulation patterns estimated from short term drogue studies conducted in the vicinity of Point Lepreau. Current speeds were found to range from 0.01 to 0.9 $m \cdot s^{-1}$ (0.03 to 3.0 $ft \cdot s^{-1}$). This work showed the presence of nearshore eddies with length scales of 100s of meters and an onshore-offshore horizontal gradient in current speed with weaker currents close to shore and significantly stronger currents within 300 m (1000 ft) further offshore.

McLaren Atlantic Limited (1977) reported on current speeds recorded by current meters at several near-shore locations around Point Lepreau. These records indicated small scale (100s m) alongshore and onshore-offshore spatial variability in speed, direction, and the duration of current speeds and directions. Nearshore current speeds typically reached maxima of 0.25 to 0.35 $m \cdot s^{-1}$, whereas offshore maxima were 0.50 to 1.00 $m \cdot s^{-1}$. Wind effects on the subsurface current were not noticeable unless the wind speed exceeded 60 $km \cdot h^{-1}$, and the effects were most pronounced near the shore. The strong winds increased the current speeds by 0.1 to 0.15 $m \cdot s^{-1}$ at times. Interestingly the maximum current speed did not increase during spring tides. Instead the duration of the peak current increased. The residual currents ranged from about 0.1 to 0.50 $m \cdot s^{-1}$ toward the west or south.

The current maximum speeds of approximately 0.60 $m \cdot s^{-1}$ observed at the proposed Musquash farm site are intermediate to those reported in the literature and are consistent with a gradient of strong offshore current speeds of about approximately 1 $m \cdot s^{-1}$ and weaker nearshore current speeds of <0.50 $m \cdot s^{-1}$.

The current observations described in this Research Document appear to be consistent with those predicted by a preliminary circulation modelling effort made by the University of New Brunswick (UNB) Ocean Mapping Group. http://www.omg.unb.ca/~haigh/musquach/musquash_model.html

### Residual Flow

The first recognition and description of a non-tidal residual flow was provided by a drift bottle study conducted in 1919 by Mavor (1921). As part of these studies drift bottles were released at a series of stations spread out along a transect running offshore from Cape Spencer and along the shipping route from Saint John to Digby. Returns from these drifters indicated a westward residual flow past Musquash of 0.1 to 0.2 $m \cdot s^{-1}$ (5 to 10 nautical miles per day; Mavor 1921).

Watson (1936) collected temperature and salinity data from several stations located along transects running perpendicular to the coast and originating offshore of Point Lepreau and Tiners Point, a location between Musquash and Saint John. The component of the residual velocity running parallel to the coast between these transects was estimated by Watson as 0.34 $m \cdot s^{-1}$ away from Saint John, i.e. toward the west.

The residual velocities estimated by Forrester from his current meter record located 1-2 km offshore of Musquash Harbour, his Station 46, were 0.37 and 0.29 $m \cdot s^{-1}$ parallel to the coast, at the respective depths of 5 and 25 m (Forrester 1959). The residual velocities at a location off Point Lepreau were estimated as 0.08, 0.08, and 0.06 $m \cdot s^{-1}$, in a direction away from the coast and at depths of 5, 25, and 50 m, respectively (Forrester 1959; Station 1). The estimated residual velocity at 60 m was 0.12 $m \cdot s^{-1}$ toward the coast. Godin (1968) estimated the residual velocity a few kilometers off Point Lepreau, at his Station 60, as being 0.21 $m \cdot s^{-1}$ (0.41 knots).

Bumpus and Lauzier (1965) synthesized the results from surface drift bottles released between 1948 and 1962, throughout the continental shelf off eastern North America from Newfoundland to Florida. In the Bay of Fundy, the directional pattern of the circulation remained constant throughout the year, but the rate varied seasonally. In the area between Point Lepreau and Saint John, the surface residual was consistently toward the west, out of the Bay of Fundy, with a rate ranging from 0.02 to 0.12 $m \cdot s^{-1}$. The mean (standard deviation) rate was 0.06 (0.03) $m \cdot s^{-1}$ (Table 4).

The bottom residual current in the area was first estimated from seabed drifters by Lauzier from a series of seabed drifters releases made between 1961 and 1965 throughout the Bay of Fundy, Gulf of Maine, Scotian Shelf, and Gulf of St. Lawrence (Lauzier 1967). In the Bay of Fundy, interpretation of the drifter recoveries suggested the presence of an onshore near-bottom flow along the New Brunswick coast to the west and east of Saint John. The estimated average rate of drift for the entire study area was 0.1 to 0.35 $m \cdot s^{-1}$ (0.2 to 0.7 nautical miles/day), and no seasonal variations in the bottom residual flow patterns were detected in the data.

### Particle Displacements

The displacement pathways of particles estimated from the current meter data and drifter releases reported on in this Research Document are consistent with estimates based on historical information.

The simple particle displacement calculations and DEPOMOD particle displacement runs reported here suggest that sinking particles released from the proposed farm site will not enter the MMPA and that some of the non-sinking particles and dissolved fractions will enter the MMPA. Thirty-two percent of the drifters released on a flooding tide entered the MMPA and 58% of these drifters either entered or nearly entered the MMPA. If it is assumed that particles released on an ebbing tide do not enter the MMPA, then the drifter data suggest that the total probability of non-sinking particles entering the MMPA is 16-29%, i.e. half of the flood tide probabilities. These probabilities could be refined by conducting additional drifter studies with the releases spread throughout the tidal cycle and over a wider range of wind conditions.

This information is consistent with the model results reported by Chang et al. (2007) for the displacement of non-sinking particles released from the nearby Haley's Cove farm site. These results were based on the outputs from the Quoddy_dry transport model. The model grid under-represented some of the topographic and bathymetric details in the region and the model was run using only M2 tidal forcing. The model runs did not include the influence of wind or fresh water inputs and, hence, they under-estimated residual flows in the Musquash area. In order to have more confidence in model simulations for the area, the model needs to be modified to include these features, as well as additional tidal forcing frequencies.

### Drifters

The drifter studies conducted as part of this Research Document are the first to resolve drift trajectories within a tidal cycle in the Musquash area, and the first to accurately record the time at which drifters reach the shoreline within the Musquash area. The results are consistent with the information derived from historical drifter studies, and the cumulative evidence from the present and historical drifter studies suggests that non-sinking particles released from the farm on a flood tide would enter the outer zones of the MMPA (especially zones 2 and 3) 32-58% of the time.

The historical evidence comes from the several drifter studies that have been conducted along the New Brunswick side of the Bay of Fundy over the past 100 years. These studies focused on delineating the residual circulation within the Bay and showed, that along the New Brunswick shore from Saint John to the Grand Manan, the residual flow was toward the west (Mavor 1919, Chevrier 1959, Bumpus and Lauzier 1965, Lauzier 1967, Bugden 1980). Perhaps of particular note are the Chevrier (1959) and Bugden (1980) studies. The Chevrier study released 10,000 drifters in the Quoddy Region, an area located well to the west of the Musquash area, in the 1950s. The releases were spread over all seasons of the year, and none were recovered as far east as the Musquash area (Chevrier 1959). The Bugden study released hundreds of surface drifters from a location off what is now the Point Lepreau Nuclear Power generating station. This location is much closer to, but also to the west of, the Musquash area of interest. The drifters were released on a daily basis from October 1978 to October 1979. The majority of the recovered drifters were found along the New Brunswick coastline to the west of Point Lepreau in the Quoddy Region or along the Nova Scotia coast to the east of Digby in the inner Bay of Fundy. Very few drifters were recovered along the New Brunswick coastline to the east of Point Lepreau.

The Bugden (1980) study suggested that the surface drift patterns were relatively independent of the local winds. The tidal currents in the area were considered to be sufficiently strong that typical wind speeds do not generate currents of sufficient speed to be easily detected in drifter recovery records or current meter records (Bugden 1980). This would suggest that the potential for transport of materials from the proposed farm site into the MMPA is not influenced by the typical seasonal variation in the wind, i.e. seasonal variations in the speed of the residual flow are associated mainly with the seasonal variations in the freshwater outflows from the Saint John River.

The new surface drifter work described in the present report distinguishes iteself from the previous work in that the releases were focused on the Musquash area and utilized technology that enabled high temporal and spatial resolution of the trajectories of the individual drifters. However, the study was relatively limited in terms of the number of releases; clusters of surface drifters were released from within the proposed fish farm site on four dates, a line of drifters that included a release within the proposed farm site was released on a single date, and a cluster of drifters was released within the MMPA on another date. Three of the releases from within the proposed farm were initiated on a flood tide and one was initiated on an ebbing tide. Drifters from only one of these releases entered the MMPA. In this release, all of the drifters entered the MMPA, but only into the outer Zones 2 and 3. Drifters from the other two flood tide releases moved eastward from the proposed site and drifted past the mouth of Musquash Harbour, without entering the MMPA. On both of these occasions, some of the drifters ran aground east of Musquash Harbour, while others returned to the vicinity of the proposed farm. The drifters from the transect release were also released on a flooding tide and, like the other flood tide releases, the drifters initially moved eastward along the coast. However, unlike the other flood tide releases, the drifters moved further offshore on the initial ebbing tide and further again during the second tidal cycle. This movement was associated with an offshore wind. The drifters from the ebb tide release all moved into Little Musquash Cove and grounded there within 4.2 h.

We also conducted one release within the MMPA, from the northern boundary of Zone 2, on the ebbing tide. All except one drifter remained within Musquash Harbour, eventually running aground within Zone 2. The other drifter left the MMPA entering the Bay of Fundy, before returning to the MMPA Zone 2. This suggests that on a time scale of 1 tidal cycle, there may be relatively little exchange of water from the middle of Musquash Harbour with the water outside of the MMPA. It also suggests that particles released offshore of the mouth of Musquash Harbour during a flooding tide may enter the Harbour.

Although the surface drifter information suggests some transport into the MMPA on tidal time scales, the historical evidence from bottom drifter studies (Lauzier 1967, Bugden 1980) and the estimated residual currents from near bottom current records (this report) also suggest there is a shoreward residual transport along the New Brunswick coast in the vicinity of the Musquash area. This is consistent with an estuarine flow in which the bottom flow is opposite to the surface flow, and it raises the possibility that once particles released from the farm settle on the bottom, they may slowly migrate toward the shore and mouth of the MMPA. Determination of the actual potential and time scales of this migration are beyond the scope of this report and would require further field research.

## CONCLUSIONS

This report addresses the question of whether materials released from the proposed finfish farm in the vicinity of Little Musquash Cove would be transported into the MMPA. The report does not include a detailed analysis of the temporal frequency and potential level (concentration) of exposure of the MMPA to prescribed releases of particular substances from the proposed fish farm. This would require a longer term research effort aimed at the development of calibrated and validated transport and dispersal models for the area.

1. The current data obtained during this study is consistent with historical observations.

2. The currents in the Musquash area, and, hence, the transport and dispersal of substances released from the proposed farm site, are dominated by tidally periodic currents and a strong residual flow.

3. Sinking fish feed pellets and fish feces are unlikely to be transported into the MMPA.

   Particles that sink will settle to the bottom well before they reach the mouth of the MMPA. Although the length scale of the particle displacements is sensitive to the sinking rate of the particles, the conclusion is robust to even the conservative order of magnitude sinking rates assumed in parts of this report.

4. The trajectory of floating particles released from the farm site during a portion of the flooding phase of the tidal cycle can cross into the mouth of the Musquash Marine Protected Area.

   The trajectories of surface drifters on the time scale of a single tidal period (12.42 h) is about 10 km, a distance that spans the distance between the proposed site and the MMPA. The drifter data also indicates that 26-58% of the drifters released on a flooding tide in the vicinity of the proposed farm site entered or nearly entered the MMPA. One of the three (33%) flood tide releases of drifter clusters conducted as part of this study resulted in drifters entering the MMPA.

   Whether this would be repeated every tidal cycle is unknown. The drifters tended to be released near the beginning of the flood tide and during the time of year when fresh water discharge and the rate of the westward residual flow is relatively low and the predominant winds are weak and from the southwest. This suggests that the surface flow out of the MMPA is relatively weak and the eastward tidal trajectories of particles may be relatively large, resulting in the potential for exchange into the MMPA perhaps being at a seasonal high. Releases during other times of the year, when the rate of westward flow is larger and winds are from the northwest, might result in fewer drift tracks entering the MMPA. This suggestion of seasonality in the drifter trajectories is consistent with the findings of Bumpus and Lauzier (1965) and Bugden (1980). A more detailed consideration of this probability will require more extensive field and modelling work focusing on the geographic area at the entrance to the MMPA.

5. The residual currents and the associated drift trajectories have a strong annual variation associated with the influence of seasonal variation in river discharge.

   Although the residual flow is consistently toward the west, the speed of this flow is enhanced during periods of high discharge and reduced during the periods of low river discharge.

6. The persistent westward residual flow results in the net displacement of most particles being progressively further toward the west.

7. There are likely to be small scale features of the circulation in the vicinity of the proposed site that have not yet been characterized.

   Historical wisdom and evidence from the nearby areas such as Duck Cove suggests the presence of a strong horizontal gradient in the current speeds along this coast, with the currents close to shore being reduced relative to those further offshore. Hence, the exact location of the proposed fish cages is likely to influence the transport and dispersal patterns associated with the site, as well as the fish production characteristics of the site. However, a detailed characterization of the circulation in the vicinity of the proposed farm site was beyond the scope of the present work, and such a characterization would require much more information. This information would provide more details on the transport and dispersal scales in the immediate area of the proposed farm site.

8. This report does not consider the particle displacements that might occur due to possible resuspension of particles.

   The possibility that a secondary movement of settled and resuspended materials toward the shore and the MMPA is suggested by historical bottom drifter data, the residual flows estimated from near-bottom current meter records, and the observation that the maximum speed of the flood current is greater than that of the ebb current. The time scale over which this transport might occur is unknown and sediment resuspension and transport models are not available to help assess the possibility of this transport. Hence, the likelihood of this material entering the MMPA was beyond the scope of this report.

9. The consequences to the MMPA resulting from the estimated potential for exposure to substances released from the proposed fish farm site was not addressed in this report.

10. As part of the need to develop and implement a long term monitoring program for the MMPA, the possibility of developing calibrated and validated transport and dispersal models for the area should be considered to help address both the frequency and level of exposure of the MMPA to potential releases of substances from areas in the vicinity of the MMPA.

    A preliminary effort in this direction has been made by the UNB Ocean Mapping Group (http://www.omg.unb.ca/%7Ehaigh/musquash/musquash_model.html ).

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Table 1. Frequency of low current velocities (≤5 $cm \cdot s^{-1}$). Current velocities were recorded at 10 min intervals.

| Depth | Total no. of records | No. of records ≤5 $cm \cdot s^{-1}$ | No. periods with 2 or more consecutive records ≤5 $cm \cdot s^{-1}$ | No. periods with 3 or more consecutive records ≤5 $cm \cdot s^{-1}$ | No. periods with 4 or more consecutive records ≤5 $cm \cdot s^{-1}$ | No. periods with 5 or more consecutive records ≤5 $cm \cdot s^{-1}$ | No. periods with 6-8 consecutive records ≤5 $cm \cdot s^{-1}$ | % of records ≤5 $cm \cdot s^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Near surface (3.5 m below surface) | 4576 | 156 | 33 | 9 | 2 | 2 | 0 | 3.4 |
| Mid-depth (9.5 m below surface) | 4879 | 213 | 59 | 22 | 6 | 2 | 1 | 4.4 |
| Near bottom (4.6 m above bottom) | 4898 | 136 | 35 | 16 | 4 | 1 | 0 | 2.8 |

Table 2. Estimated radii of tidal excursion areas for particles that do not sink and the horizontal displacement of sinking feed pellets and feces (see text for assumptions concerning sinking rates and water depths).

| Depth | Current speed ($cm \cdot s^{-1}$) | Estimated radius of tidal excursion (m) | Feed pellet displacement (m) (sinking rate 10 $cm \cdot s^{-1}$) | Feces displacement (m) (sinking rate 1 $cm \cdot s^{-1}$) |
|---|---|---|---|---|
| | | | | |
| **Maximum current** | | | | |
| Near surface (3.5 m below surface) | 61.8 | 14 461 | 124 | 1 236 |
| Mid-depth (9.5 m below surface) | 61.6 | 14 414 | 123 | 1 232 |
| Near bottom (4.6 m above bottom) | 61.4 | 14 368 | 123 | 1 228 |
| *All records* | *65.7* | *15 371* | *131* | *1 314* |
| | | | | |
| **Median current** | | | | |
| Near surface (3.5 m below surface) | 29.6 | 6 926 | 59 | 592 |
| Mid-depth (9.5 m below surface) | 35.1 | 8 213 | 70 | 702 |
| Near bottom (4.6 m above bottom) | 28.9 | 6 763 | 58 | 578 |
| *All records* | *31.7* | *7 413* | *63* | *634* |

Table 3. Date, time, location, number of drifters, tide, and wind conditions at time of drifter releases. All times are UTC (3 h after local time, Atlantic Daylight Time). Drifter release locations were in or near the proposed farm site (MF-0506) or in the Musquash Marine Protected Area. Tide information for Musquash Harbour is from the Canadian Hydrographic Service (http://marees-tides.gc.ca/english/Canada.shtml). Wind conditions from the nearest weather station, Point Lepreau (approximately 15.5 km west of the proposed farm site) are from Environment Canada (http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html)

| Date | Time (UTC) | Location | No. of drifters | Nearest tide (Musquash Harbour) | | Wind at release time (Point Lepreau) | |
|---|---|---|---|---|---|---|---|
| | | | | Type | Time (UTC) | Direction (degrees) | Speed ($km \cdot h^{-1}$) |
| 22 Jul 2008 | 12:21 | Farm | 6 | Low | 12:10 | 60 (NE) | 13 |
| 24 Jul 2008 | 14:18 | Farm | 6 | Low | 13:37 | 50 (NE) | 11 |
| 28 Jul 2008 | 11:12 | MPA | 6 | High | 11:11 | 170 (S) | 7 |
| 30 Jul 2008 | 13:36 | Farm | 5 | High | 13:19 | 250 (SW) | 9 |
| 6 Aug 2008 | 13:03 | Farm | 6 | Low | 13:06 | 320 (NW) | 6 |
| 20 Aug 2008 | 11:57 | Along the Coast to the east and west of the Farm | 5 | Low | 11:41 | 300 (NW) | 15 |

Table 4. Summary of surface residual current speed as estimated by Bumpus and Lauzier (1965) for the area seaward of the proposed farm site. All currents are toward the west. Rates were converted from miles per day to meters per second using 1 $mile \cdot d^{-1} = 0.02\ m \cdot s^{-1}$.

| Month | Rate | |
|---|---|---|
| | ($miles \cdot d^{-1}$) | ($m \cdot s^{-1}$) |
| | | |
| January | 3 | 0.06 |
| February | <1 | <0.02 |
| March | - | - |
| April | 3 | 0.06 |
| May | 5 | 0.10 |
| June | 3 | 0.06 |
| July | 5 | 0.10 |
| August | 2 | 0.04 |
| September | 3 | 0.06 |
| October | 3 | 0.06 |
| November | 6 | 0.12 |
| December | 2 | 0.04 |
| | | |
| Mean (standard deviation) | | 0.06 (0.03) |

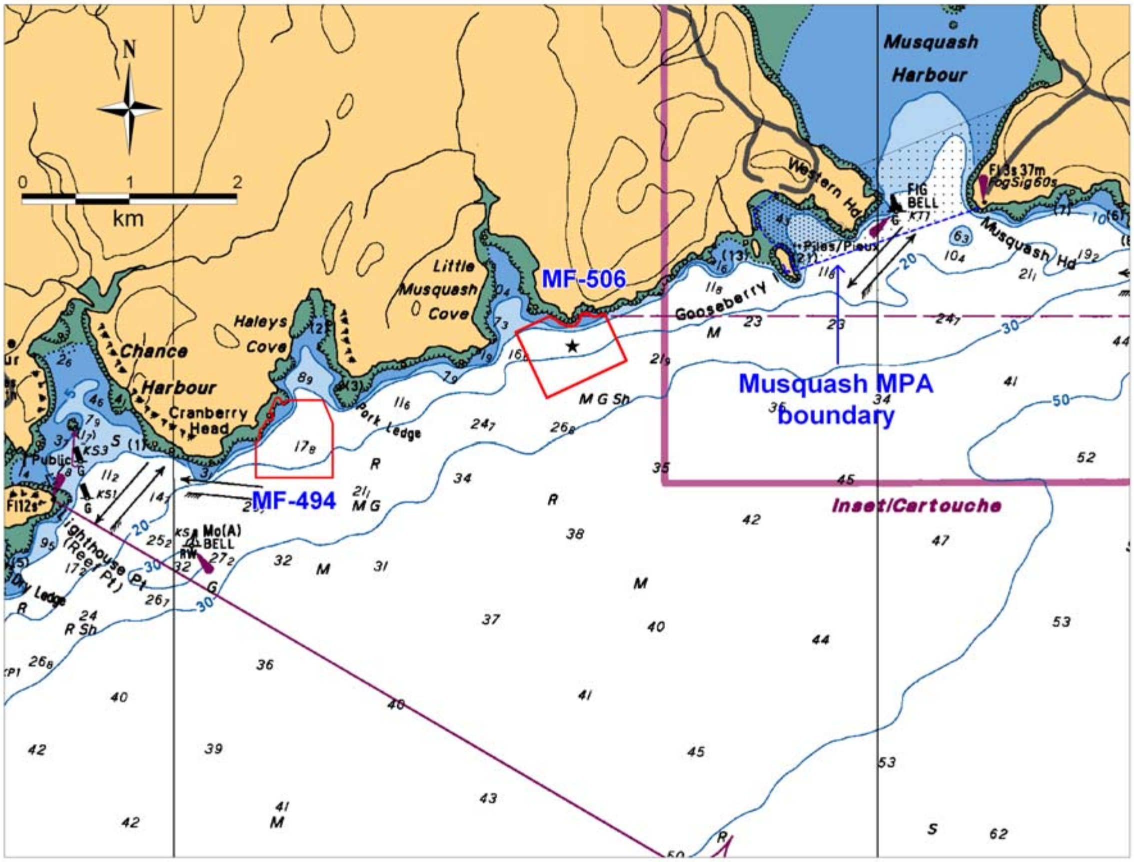


Fig. 1. Map showing the Musquash Marine Protected Area (MMPA), including the most seaward zone (Zone 3) within the MMPA, the location of the proposed finfish aquaculture site MF-506 (thick red polygon) near Little Musquash Cove, the location of the existing fish farm (thin red polygon) at the mouth of Haleys Cove (MF-494), and the location of the current meter deployment 22 February to 27 March 2008 (indicated by a star near the centre of the site).

Fig. 2. Convertible Accurate Surface Tracker (CAST) drifters out of the water (left) and in the water (right). The central orange cylinder contains the electronics package including the GPS receiver and the ARGOS transmitter.

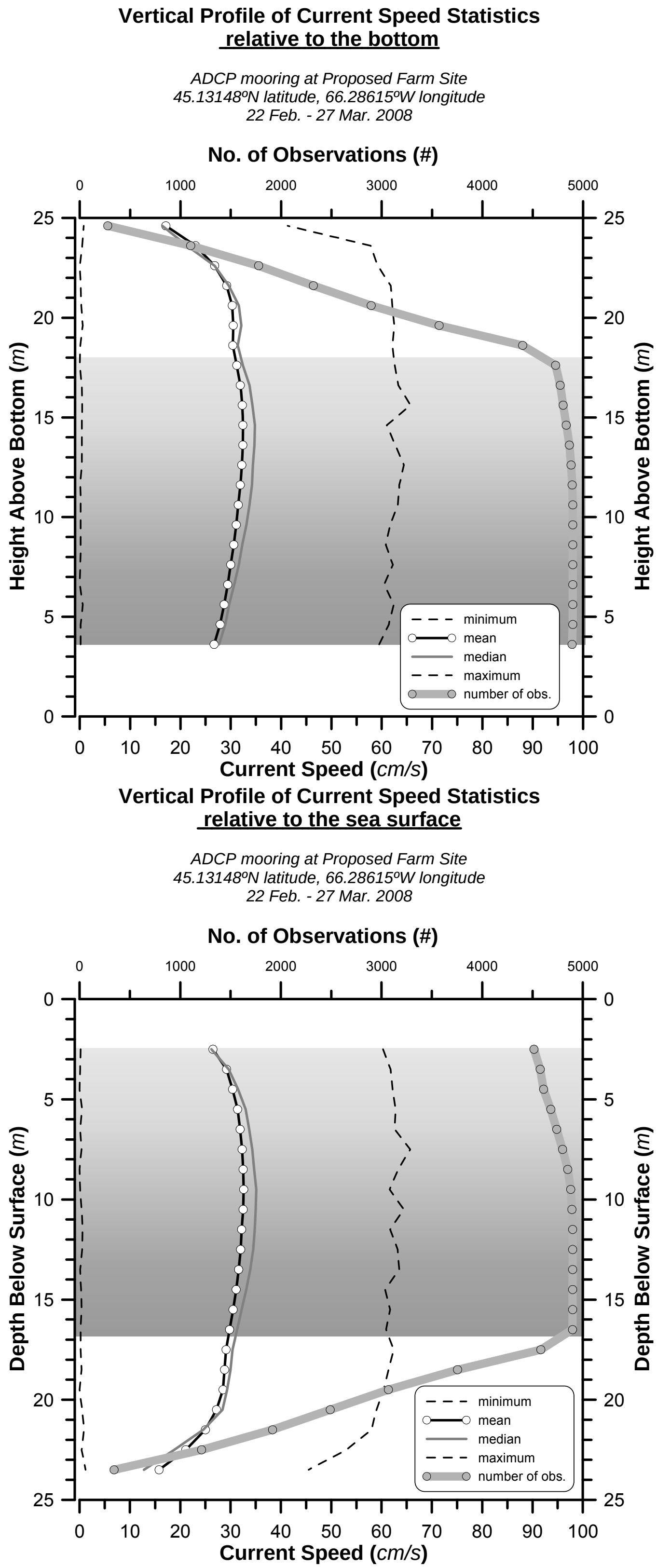


Fig. 3. Vertical profile of current speed summary statistics relative to height above the bottom (top panel) and depth below the sea surface (bottom panel).

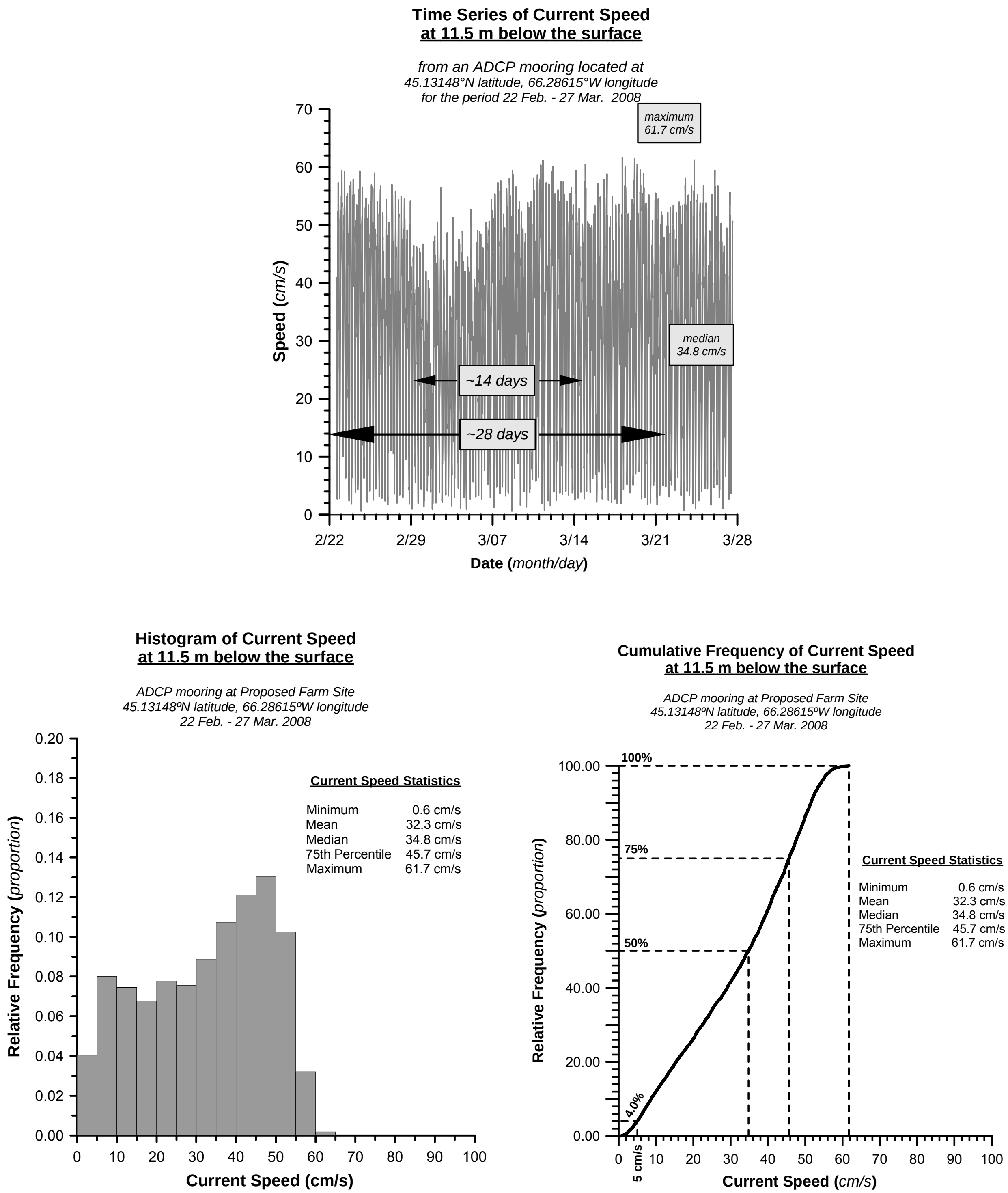


Fig. 4. Time series (top), frequency histogram (bottom left), and cumulative frequecy distribution (bottom right) of the current speed at a depth of 11.5 m below the sea surface as recorded by an ADCP moored from 22 February - 27 March 2008 at a location (45.13148ºN latitude, 66.28615ºW longitude) near the center of the proposed farm site (MF-506).

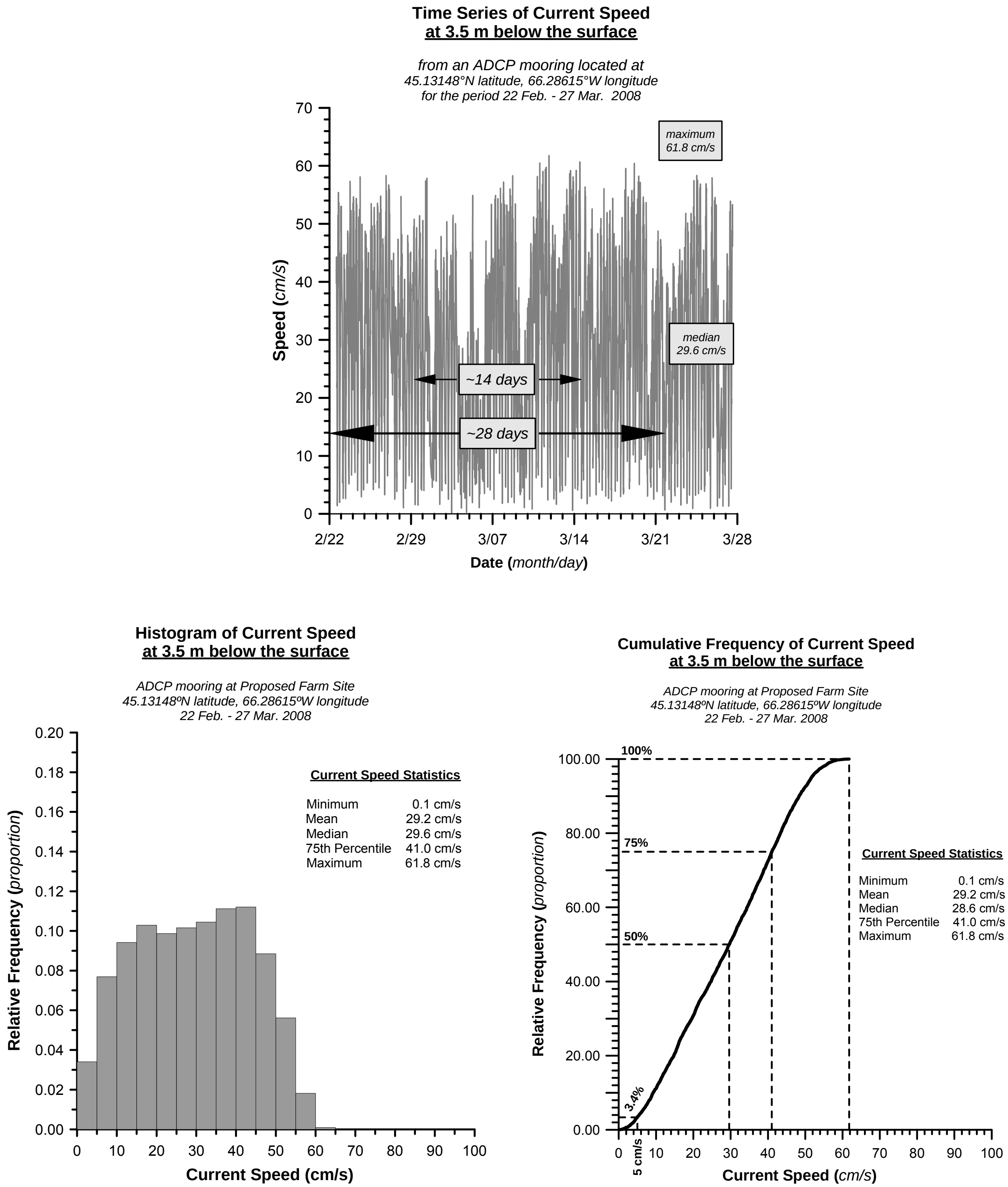


Fig. 5. Time series (top), frequency histogram (bottom left), and cumulative frequecy distribution (bottom right) of the current speed at a depth of 3.5 m below the sea surface as recorded by an ADCP moored from 22 February - 27 March 2008 at a location (45.13148ºN latitude, 66.28615ºW longitude) near the center of the proposed farm site (MF-506).

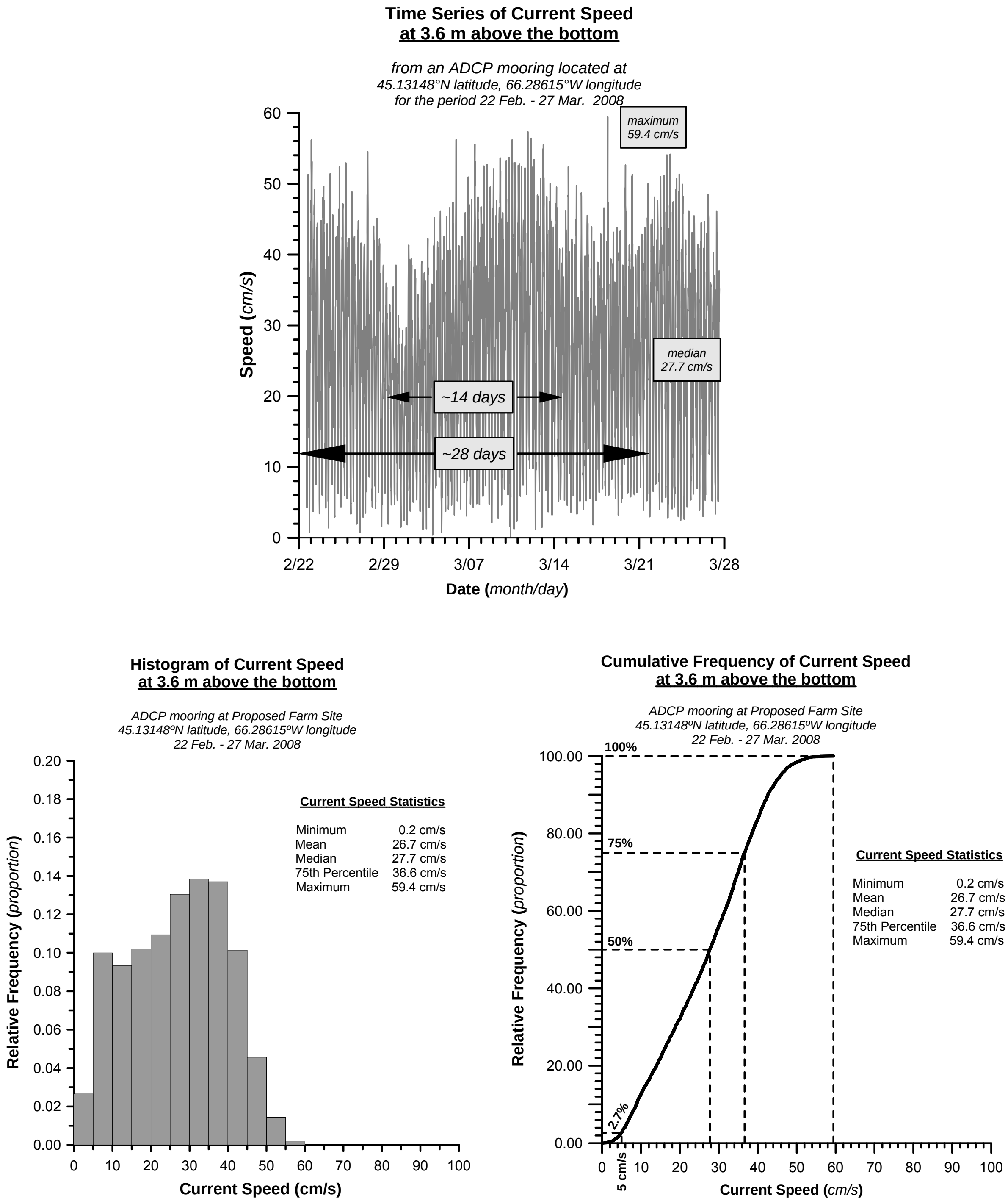


Fig. 6. Time series (top), frequency histogram (bottom left), and cumulative frequency distribution (bottom right) of the current speed at a depth of 3.6 m above the sea bottom as recorded by an ADCP moored from 22 February - 27 March 2008 at a location (45.13148ºN latitude, 66.28615ºW longitude) near the center of the proposed farm site (MF-506).

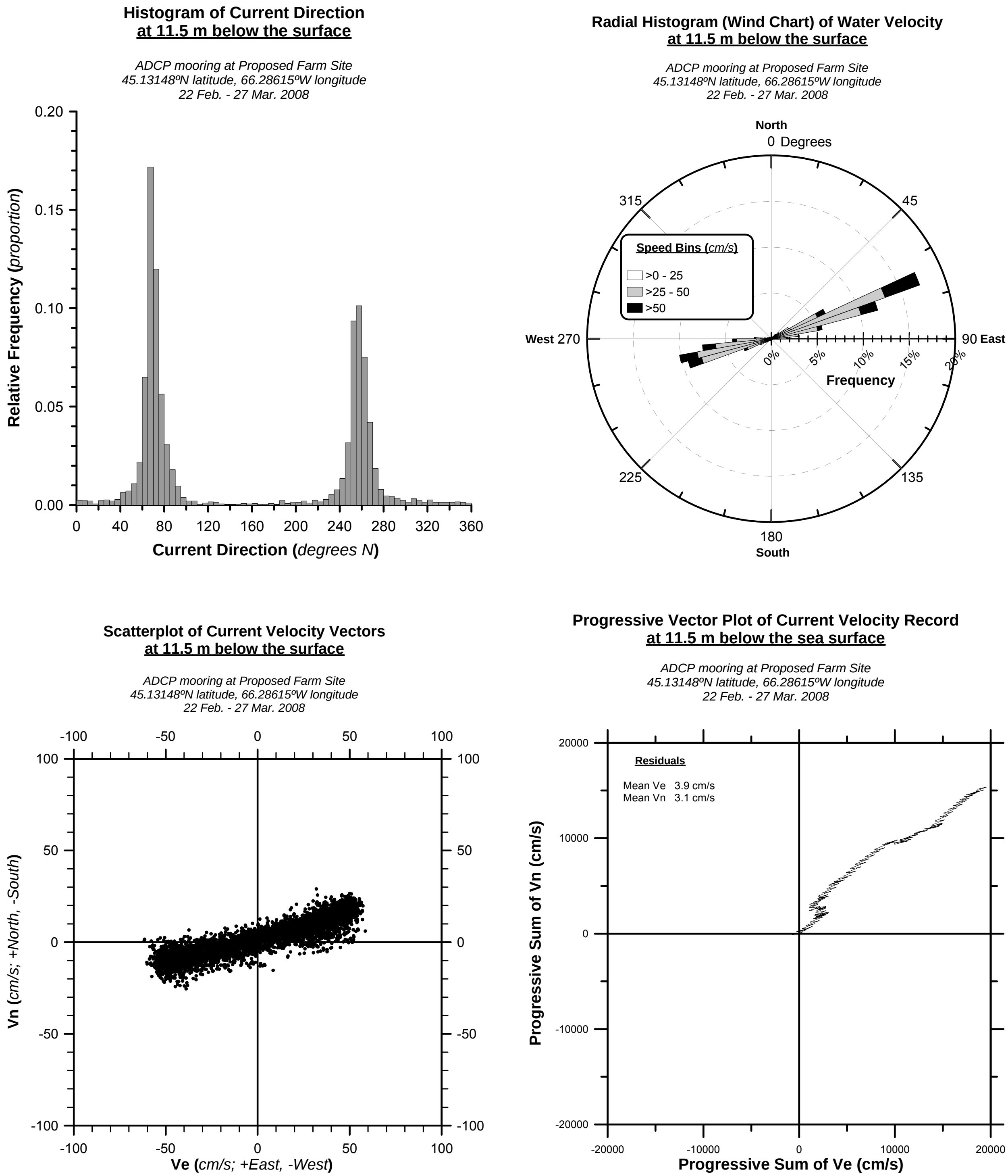


Fig. 7. Frequency histgram (top left) and a wind or radial frequency chart (top right) of the current direction, a scattergram (bottom left) and a progressive vector plot (bottom right) of the east (Ve) and north (Vn) velocity components at a depth of 11.5 m below the sea surface as recorded by an ADCP moored from 22 February - 27 March 2008 at a location (45.13148ºN latitude, 66.28615ºW longitude) near the center of the proposed farm site (MF-506).

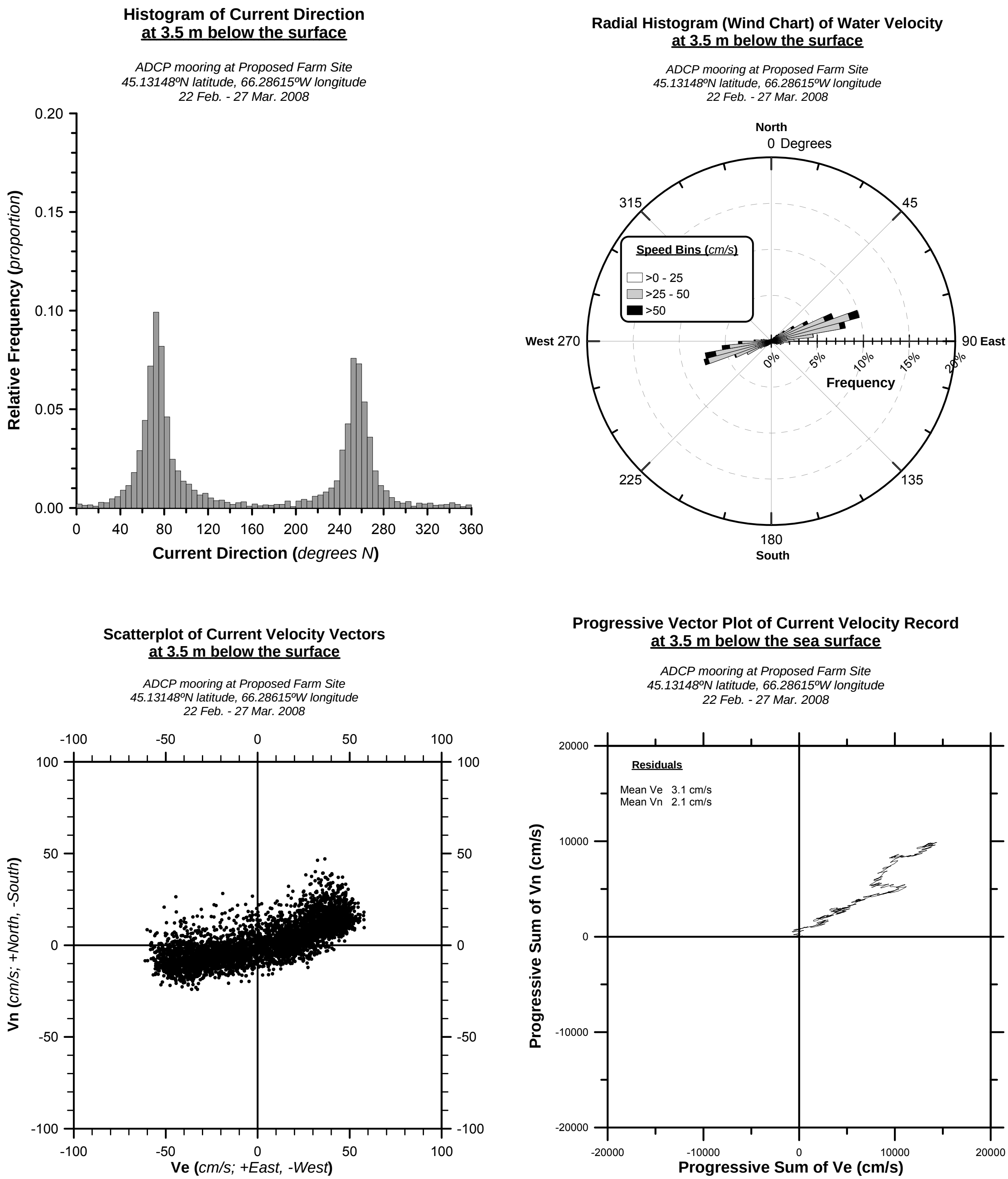


Fig. 8. Frequency histgram (top left) and a wind or radial frequency chart (top right) of the current direction, a scattergram (bottom left) and a progressive vector plot (bottom right) of the east (Ve) and north (Vn) velocity components at a depth of 3.5 m below the sea surface as recorded by an ADCP moored from 22 February - 27 March 2008 at a location (45.13148ºN latitude, 66.28615ºW longitude) near the center of the proposed farm site (MF-506).

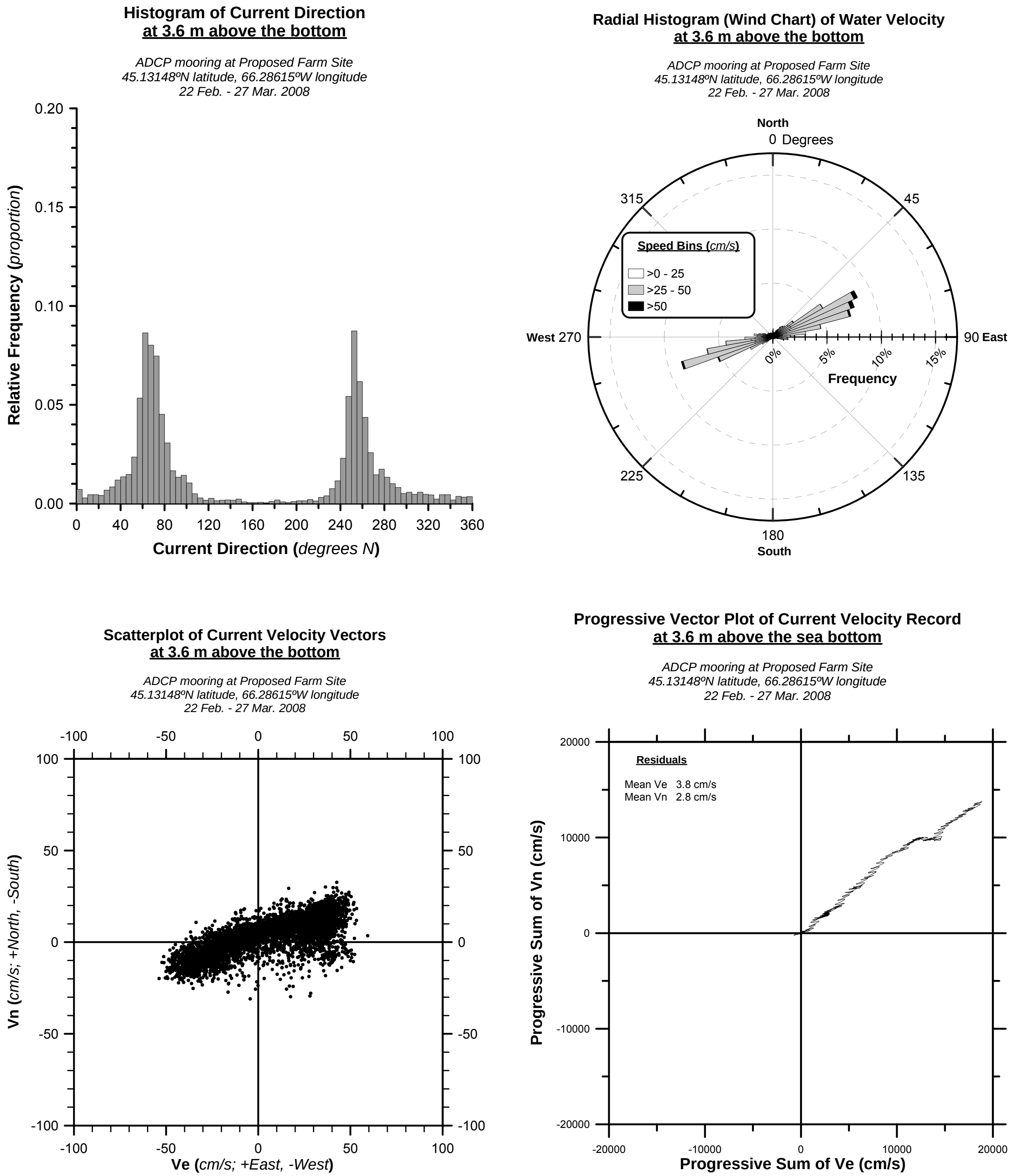


Fig. 9. Frequency histgram (top left) and a wind or radial frequency chart (top right) of the current direction, a scattergram (bottom left) and a progressive vector plot (bottom right) of the east (Ve) and north (Vn) velocity components at a depth of 3.6 m above the sea bottom as recorded by an ADCP moored from 22 February - 27 March 2008 at a location (45.13148ºN latitude, 66.28615ºW longitude) near the center of the proposed farm site (MF-506).

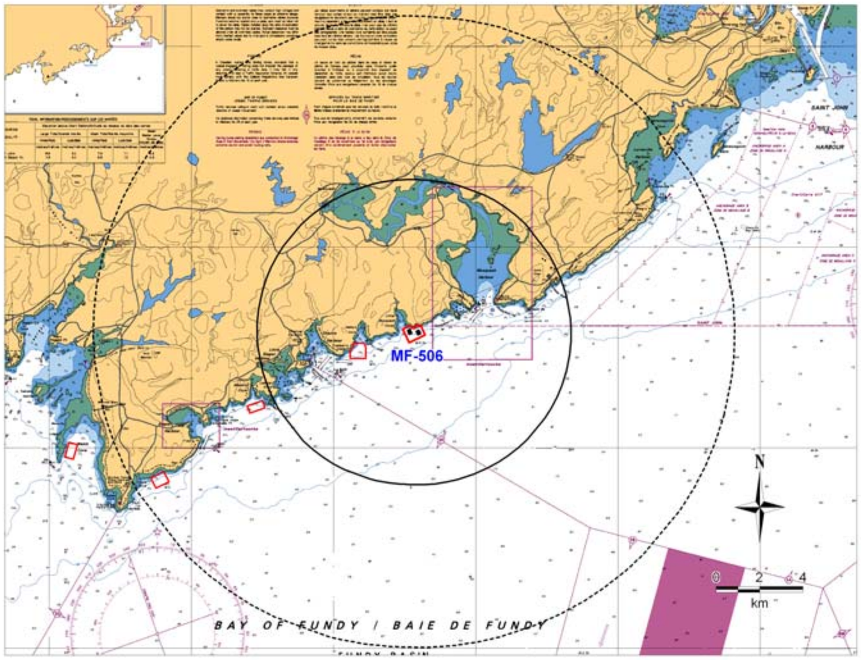


Fig. 10. Map showing estimated surface water zones of influence around the proposed aquaculture site MF-506, based on the near surface current meter data and non-sinking particles (see Table 2). The solid line is based on the median current speed (radius 6.9 km) and the dotted line is based on the maximum current speed (radius 14.5 km). The small red polygons represent aquaculture sites. The origin of each circle is the middle of the proposed site.

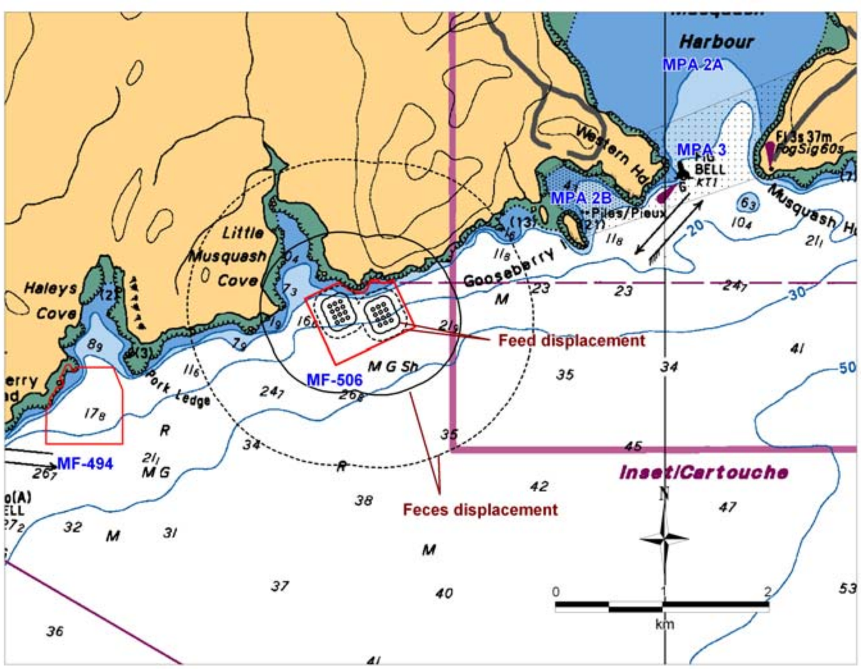


Fig. 11. Map showing estimated displacements of feces and feed around the proposed aquaculture site MF-506, based on the median (solid line) and maximum (dotted lines) current speeds estimated from all depths. The circles were drawn with origins at the center of each cage cluster.

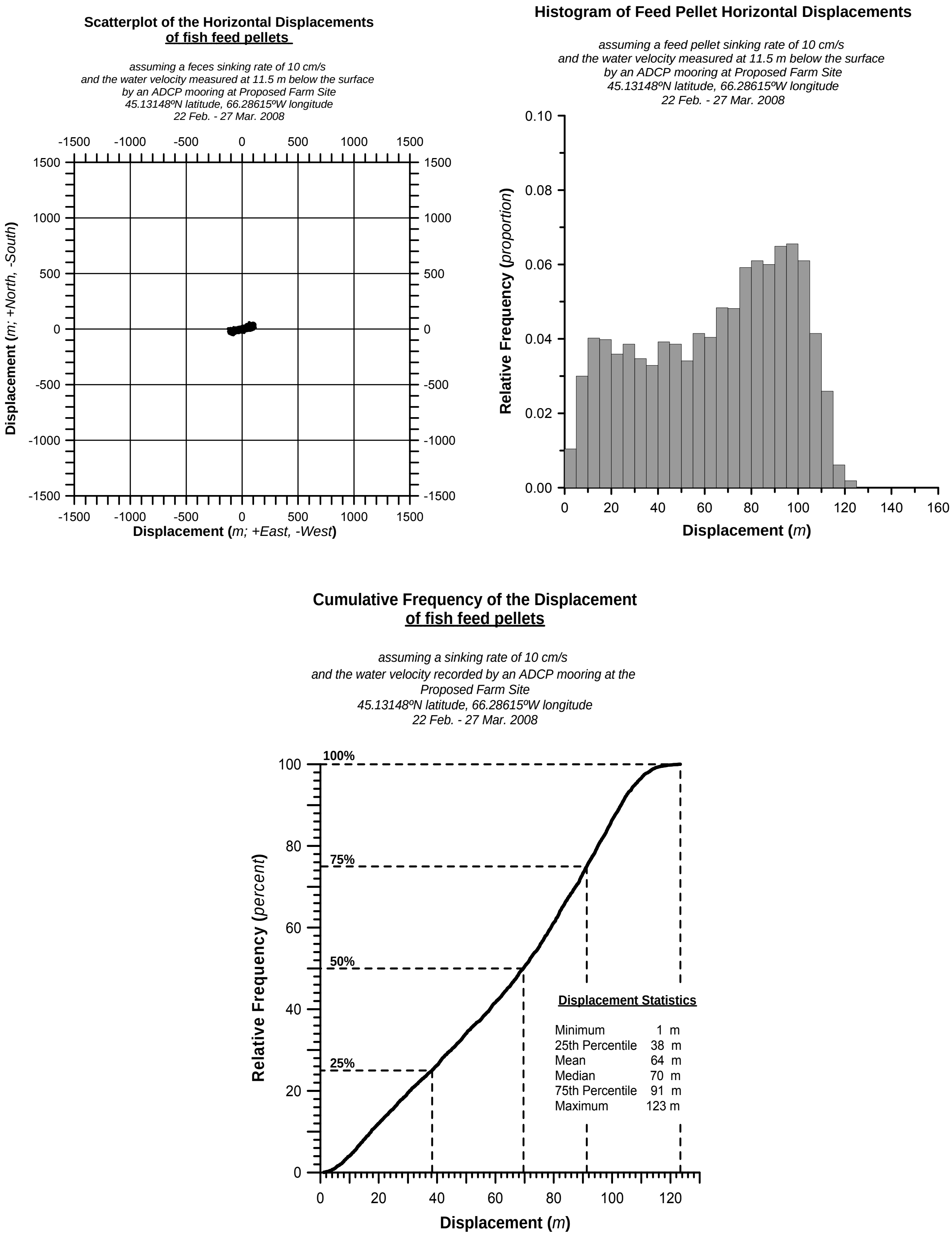


Fig. 12. Estimated displacement scattergram (top left), frequency histogram (top right), and cumulative frequency distribution (bottom) of feed pellet particle displacements from the proposed fish farm assuming a particle sinking rate of 10 cm·s$^{-1}$ and the water velocity recorded at 11.5 m below the sea surface by an ADCP moored from 22 February - 27 March 2008 at the approximate center (45.13148ºN latitude, 66.28615ºW longitude) of the proposed farm site (MF-506).

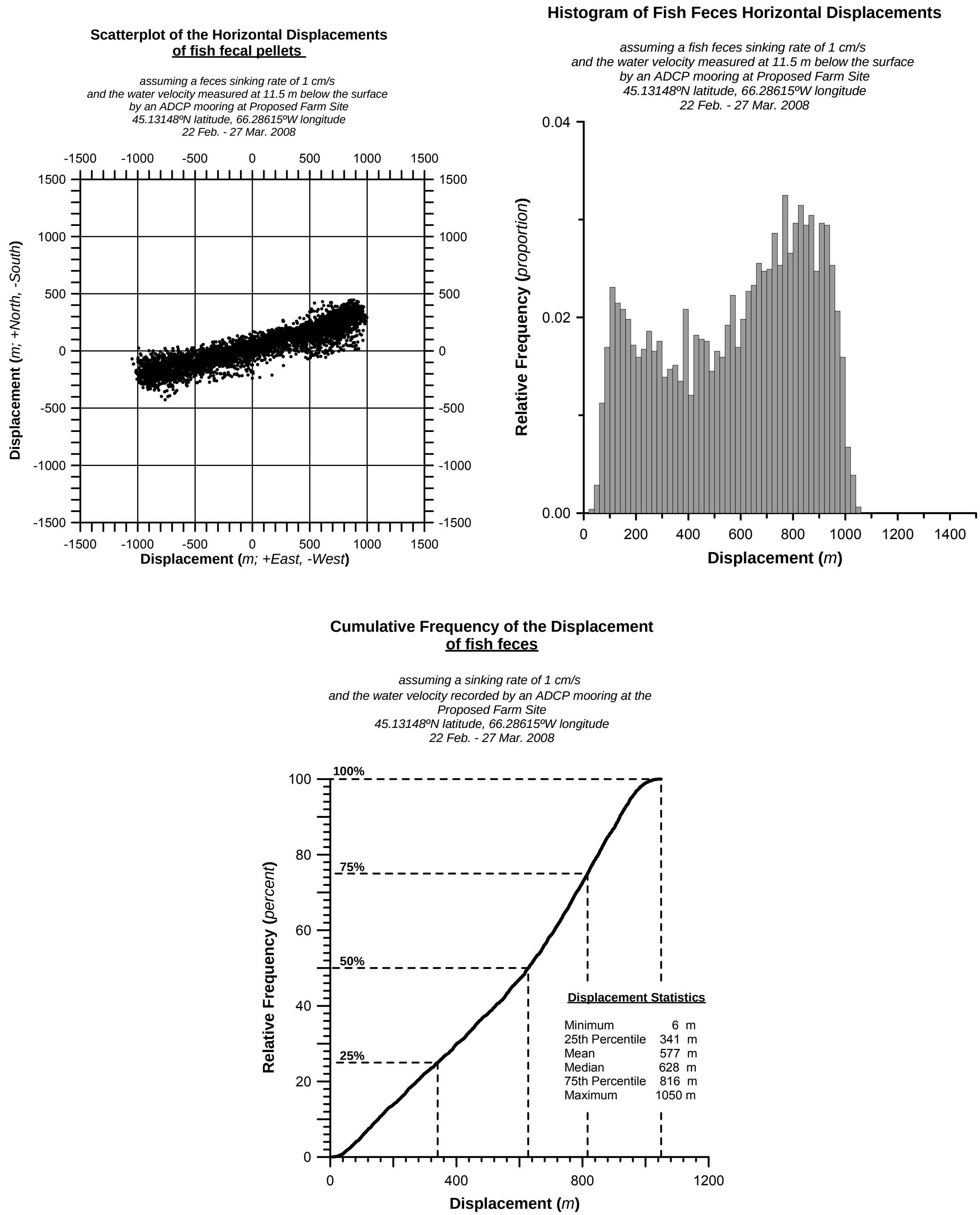


Fig. 13. Estimated displacement scattergram (top left), frequency histogram (top right), and cumulative frequency distribution (bottom) of fish feces displacements from the proposed fish farm assuming a particle sinking rate of 1 cm·s$^{-1}$ and the water velocity recorded at 11.5 m below the sea surface by an ADCP moored from 22 February - 27 March 2008 at the approximate center (45.13148ºN latitude, 66.28615ºW longitude) of the proposed farm site (MF-506).

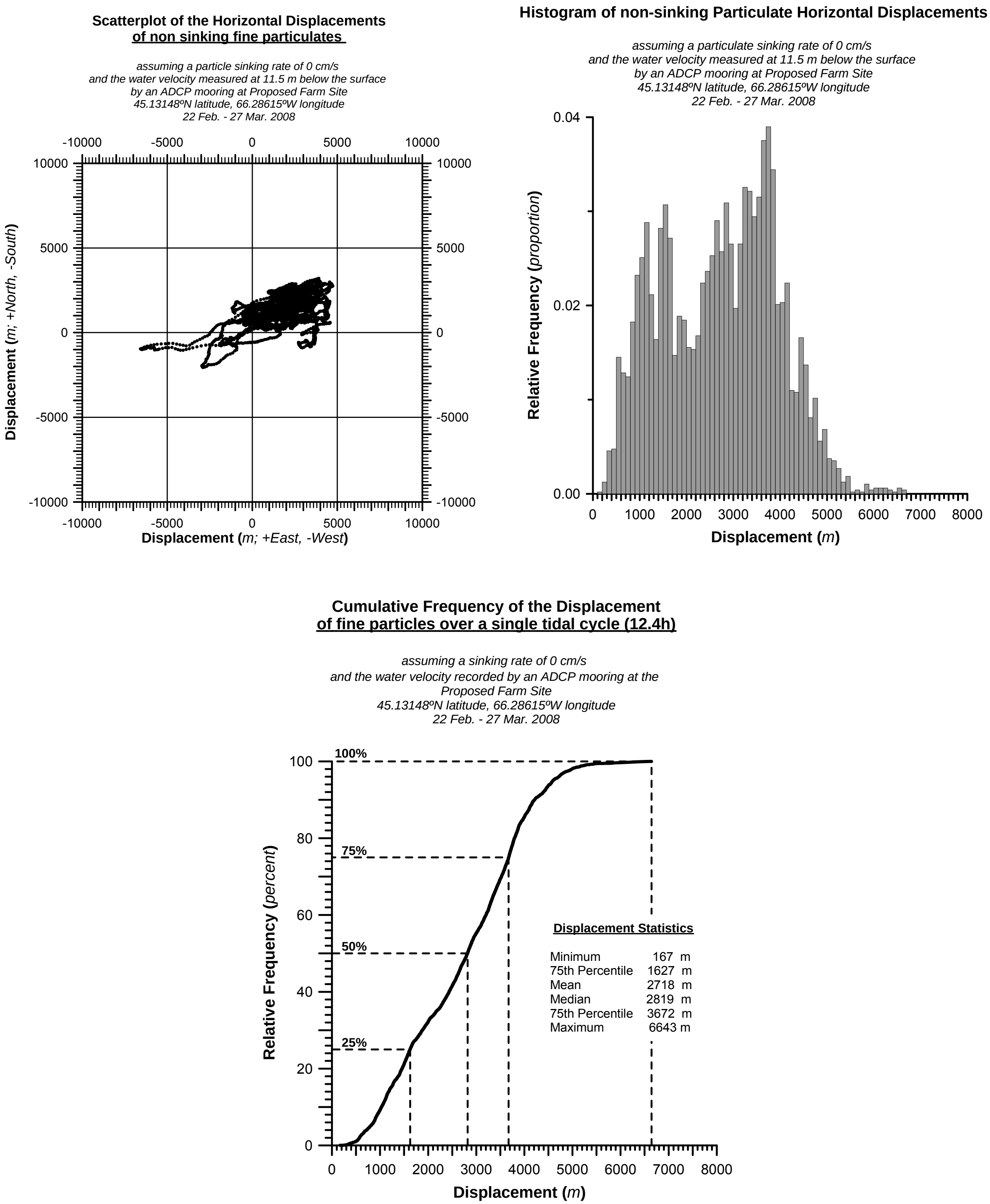


Fig. 14. Estimated displacement scattergram (top left), frequency histogram (top right), and cumulative frequency distribution (bottom) of non-sinking particles released from the proposed fish farm assuming the water velocity recorded at 11.5 m below the sea surface by an ADCP moored from 22 February – 27 March 2008 at the approximate center (45.13148ºN latitude, 66.28615ºW longitude) of the proposed farm site (MF-506).

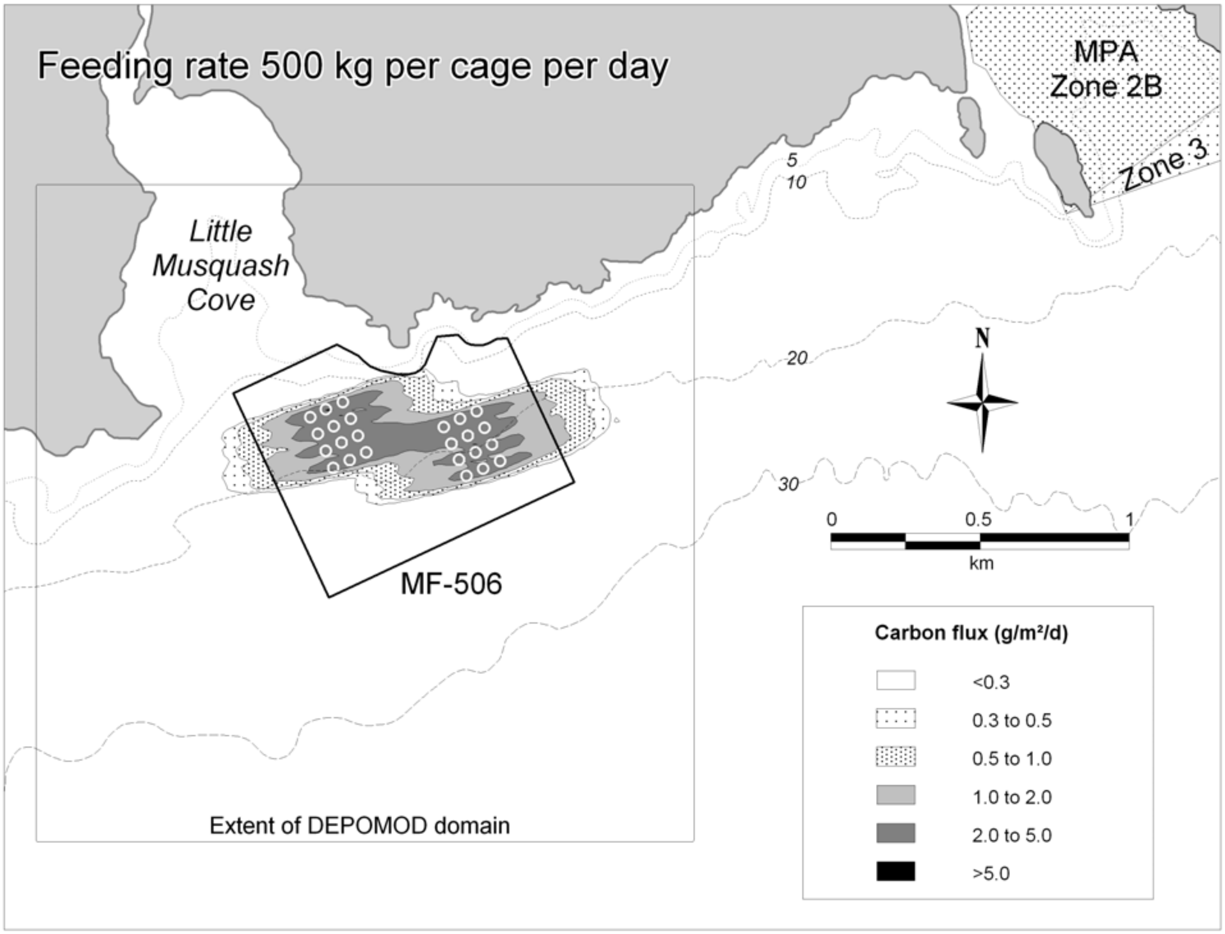


Fig. 15. Carbon fluxes to the seafloor at proposed aquaculture site MF-506, as predicted by DEPOMOD, using a feeding rate of 500 $kg \cdot cage^{-1} \cdot d^{-1}$. The larger square represents the model domain (2000 × 2000 m). Also shown are the proposed site's boundaries and cage locations. The Musquash Marine Protected Area is located at the top right.

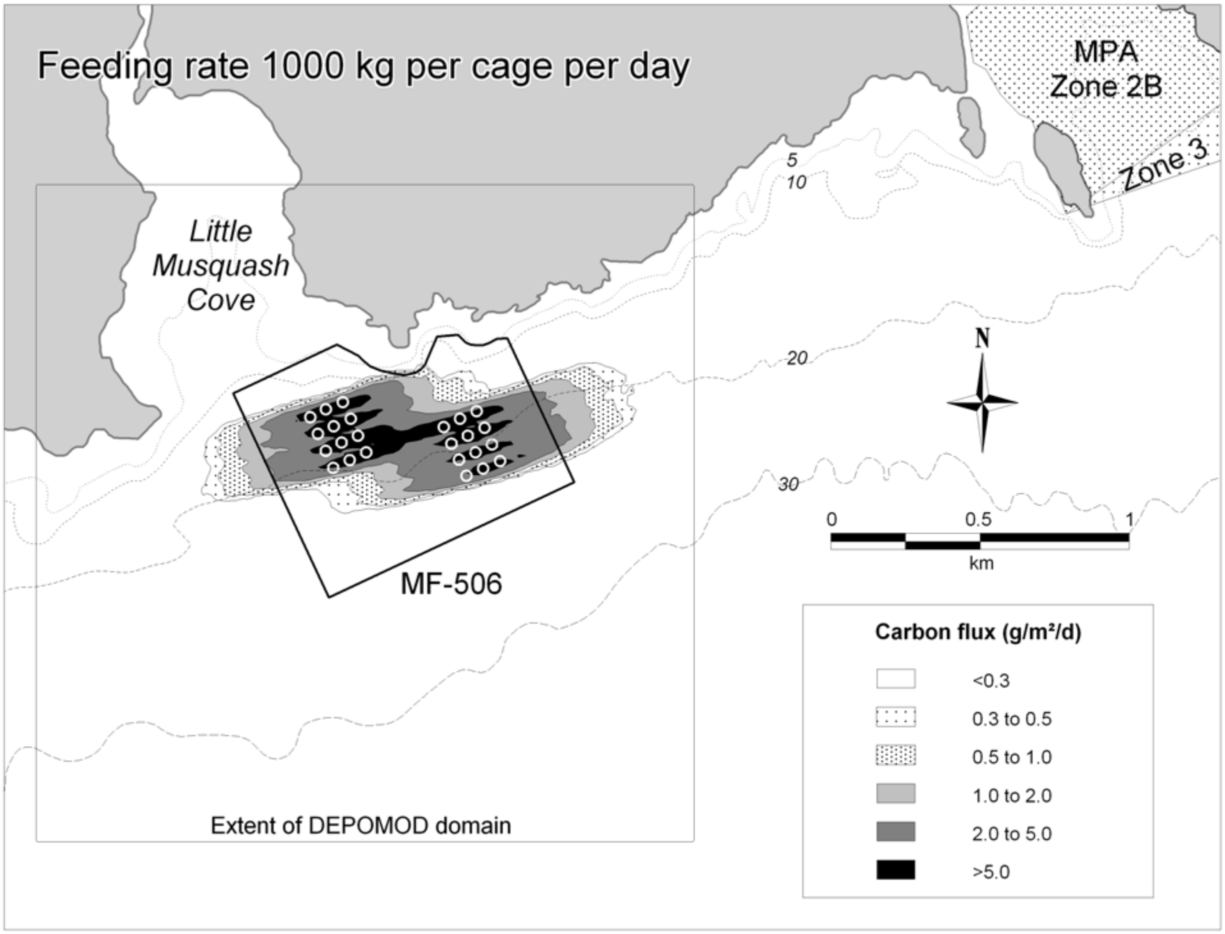


Fig. 16. Carbon fluxes to the seafloor at proposed aquaculture site MF-506, as predicted by DEPOMOD, using a feeding rate of 1000 $kg \cdot cage^{-1} \cdot d^{-1}$. The larger square represents the model domain (2000 × 2000 m). Also shown are the proposed site's boundaries and cage locations. The Musquash Marine Protected Area is located at the top right.

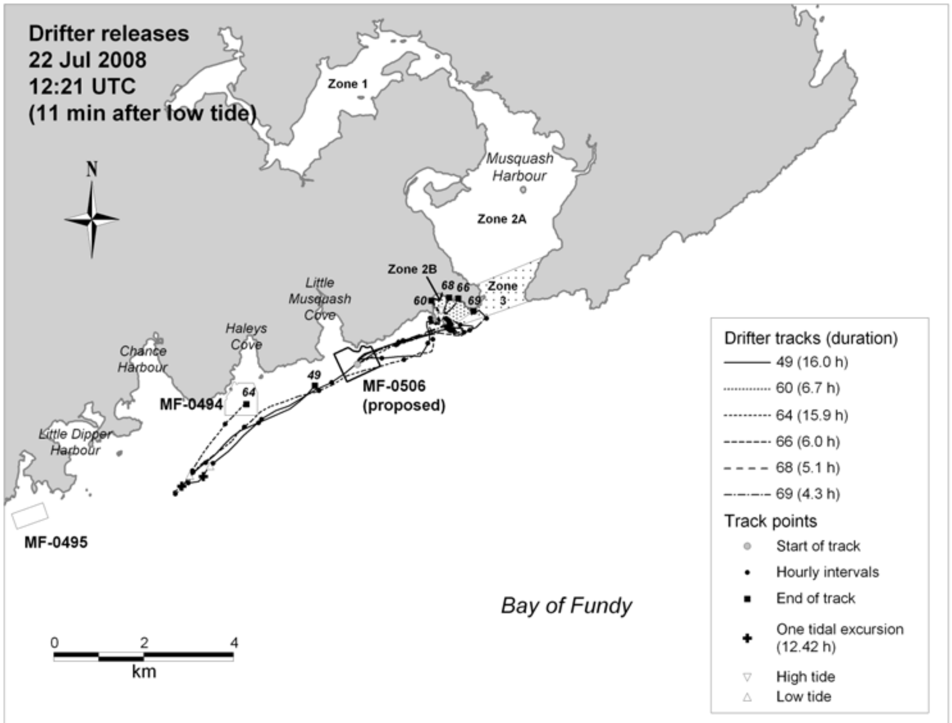


Fig. 17. Trajectories of drifters released from the proposed farm site (dark polygon) on 22 July 2008.

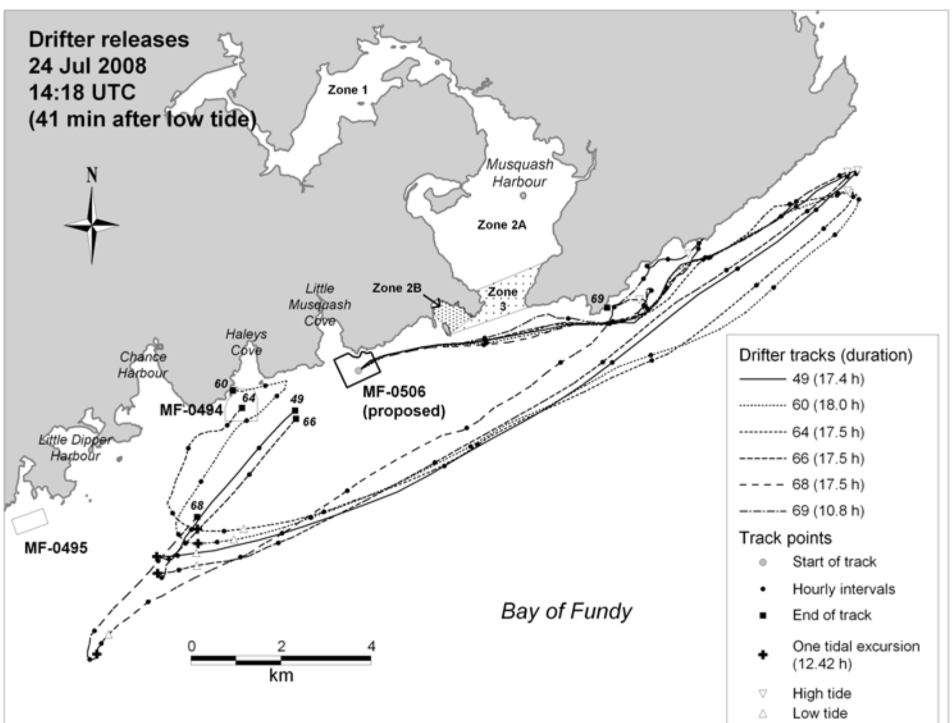


Fig. 18. Trajectories of drifters released from the proposed farm site (dark polygon) on 24 July 2008.

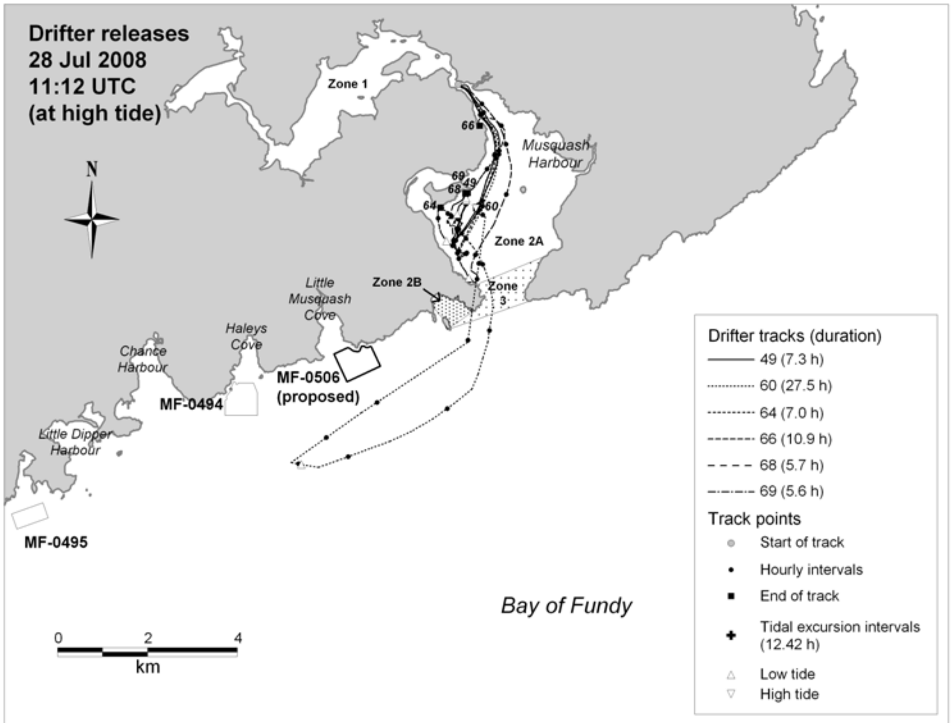


Fig. 19. Trajectories of drifters released from the Musquash Marine Protected Area (dark polygon) on 28 July 2008.

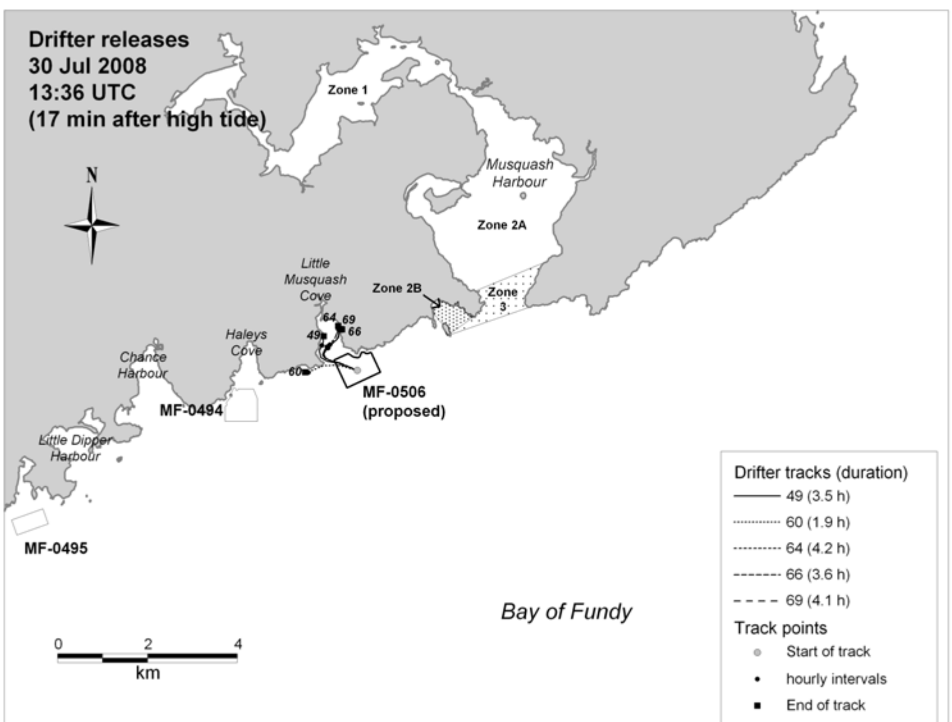


Fig. 20. Trajectories of drifters released from the proposed farm site (dark polygon) on 28 July 2008.

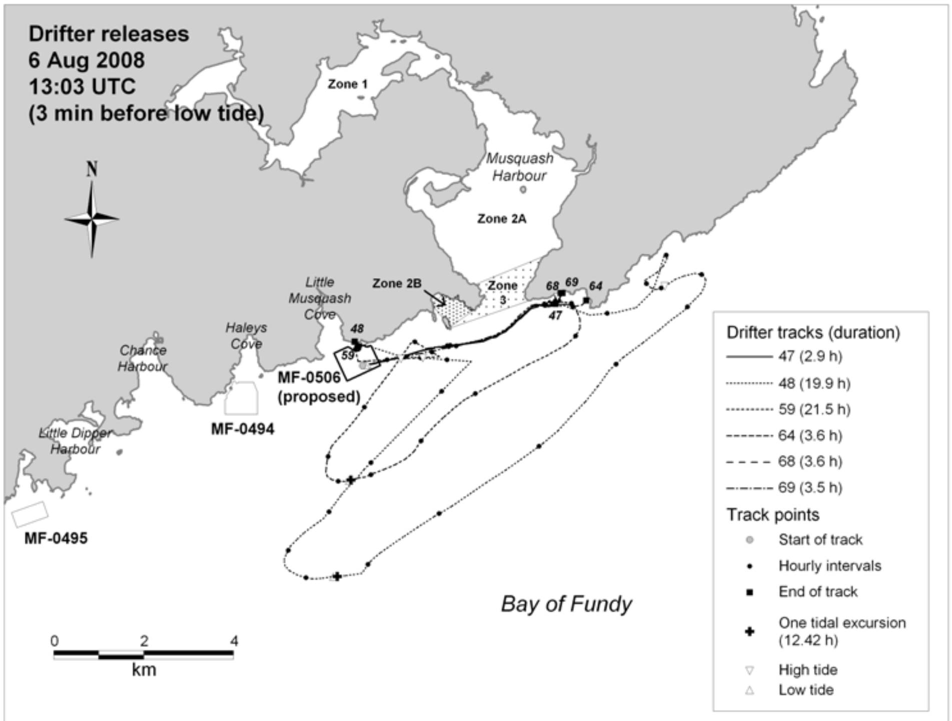


Fig. 21. Trajectories of drifters released from within the proposed farm site (dark polygon) on 6 August 2008.

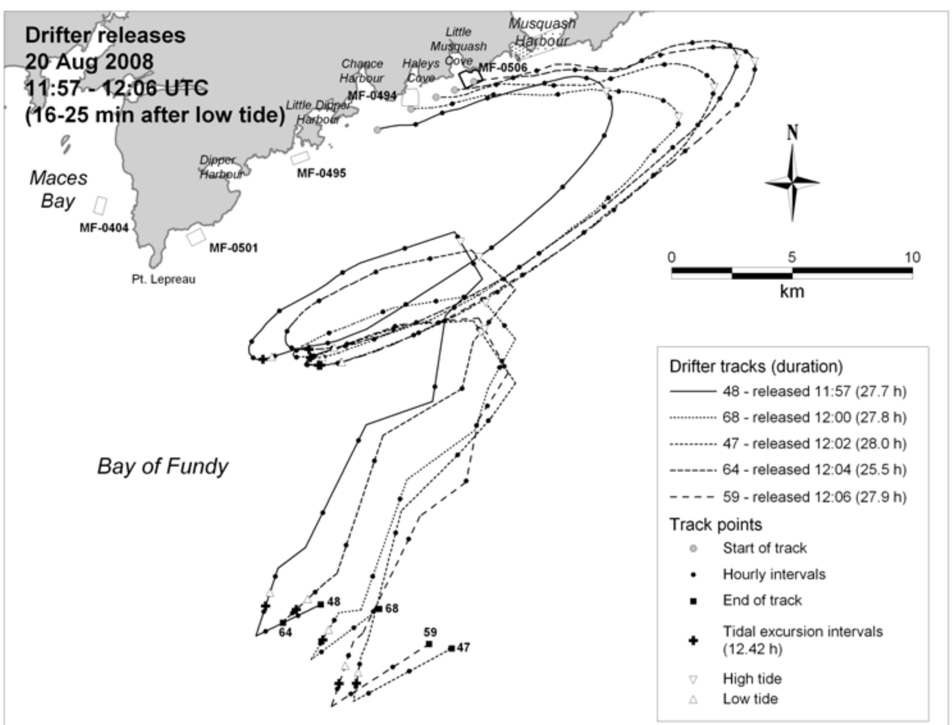


Fig. 22. Trajectories of drifters released from within and near the proposed farm site (dark polygon) on 20 August 2008.

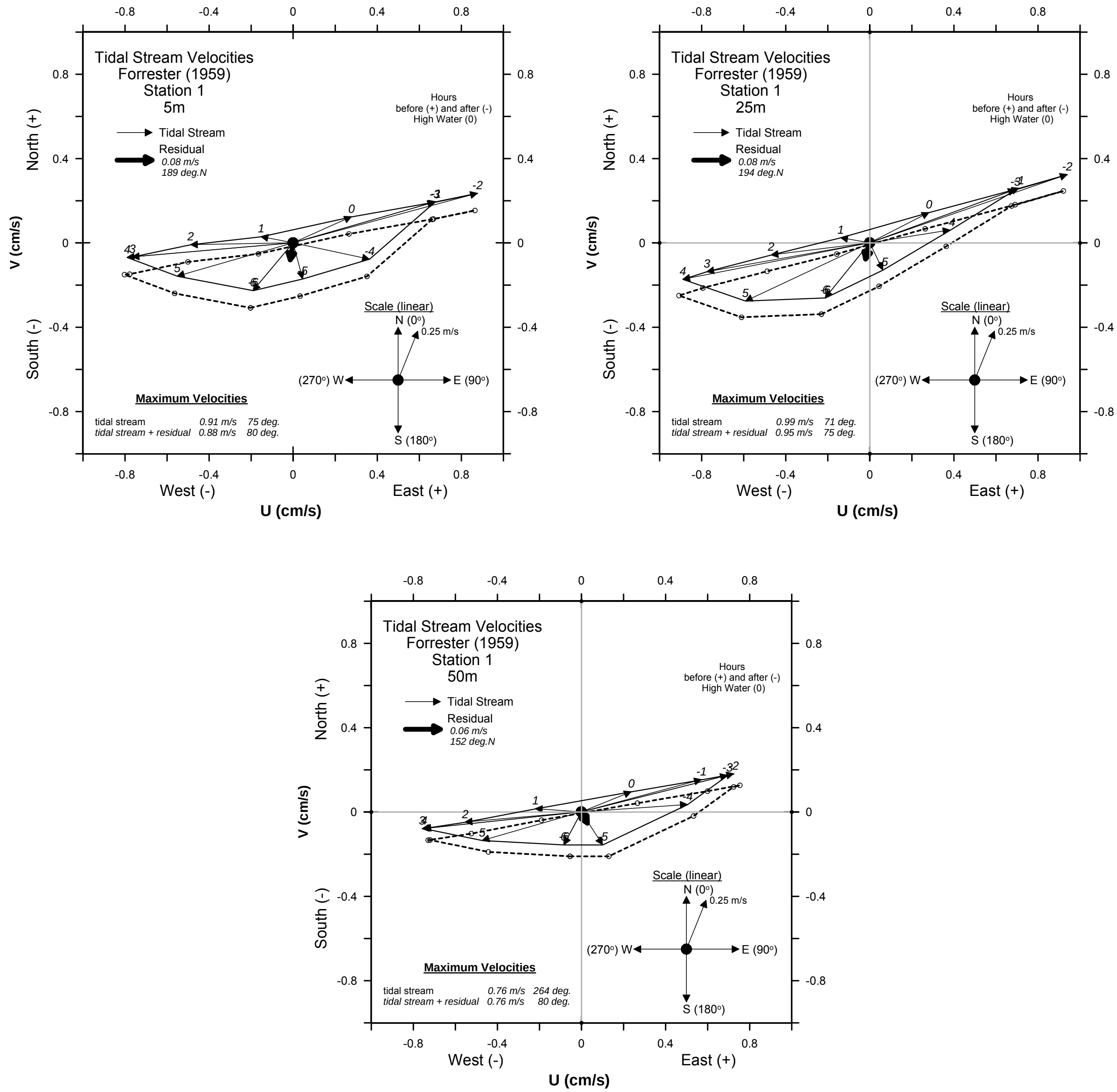


Fig. 23. Tidal stream (thin vectors) and residual (thick vector) current velocities at Forrester's (1959) Station 1 located 1-2 km seaward of Point Lepreau. The residual velocities are the vector time average of the estimated velocities at the station. The tidal stream velocities are the instantaneously observed velocity at a specific time minus the residual velocity. The tidal stream plus residual velocities are indicated by the dashed polyline. The numbers at the end of each tidal stream vector indicate the time (in hours) before (-) or after (+) high water (0).

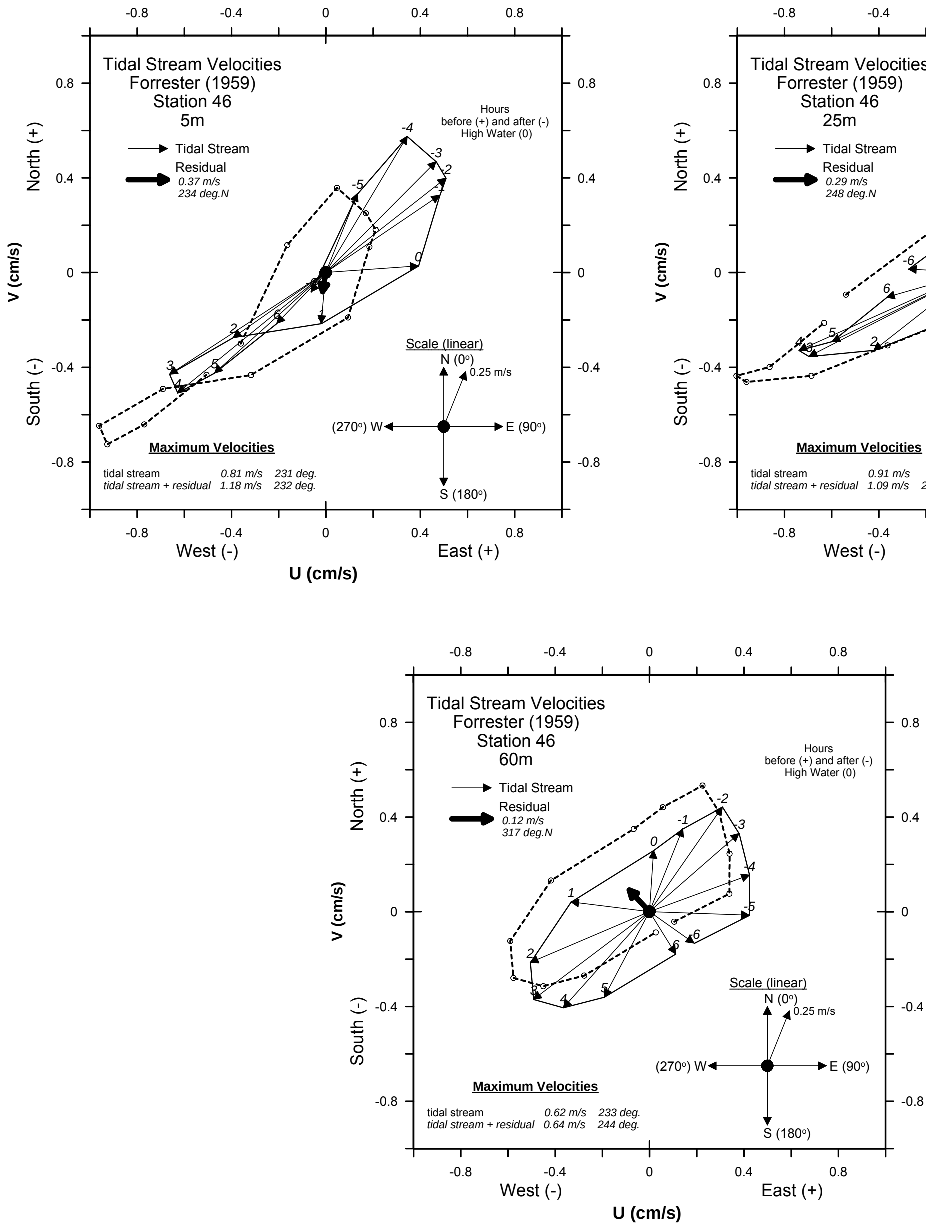


Fig. 24. Tidal stream (thin vectors) and residual (thick vector) current velocities at Forrester's (1959) Station 46 located 1-2 km seaward of Musquash Harbour. The residual velocities are the vector time average of the estimated velocities at the station. The tidal stream velocities are the instantaneously observed velocity at a specific time minus the residual velocity. The tidal stream plus residual velocities are indicated by the dashed polyline. The numbers at the end of each tidal stream vector indicate the time (in hours) before (-) or after (+) high water (0).

**Appendix 1. Displacement of Particles released from the Proposed Farm Site as Estimated from some Historical Information.**

The historical information on water flows enables some crude estimates of the transport and dispersal length scales to be made.

A crude estimate of the maximum distance travelled by particles released from the fish farm can be obtained by assuming the water flows at a constant rate for a period of 6.21 hours, i.e. half a tidal cycle. These particle displacements are referred to as tidal excursions. The direction of the excursion depends upon the time of particle release in relation to the phase of the tide. For example, particles released on a flood tide will tend to move in the direction of the flooding current, those released on an ebb tide will travel in the direction of the ebbing current, and those released at other times will move in directions dictated by the state of the current at the time. The spatial domain of the excursion will, therefore, depend upon the ellipticity of the current rosette and the pattern of spatial variation in the current within the excursion domain. A simple estimate can be made by assuming particles will be released at all phases of the tide and that the domain of tidal excursion can be represented by a circle centered on the release point with a radius of one tidal excursion. Another assumption could be that the domain of tidal excursions is aligned with the major axis of the tidal flow. The real domain probably lies somewhere in between these extremes.

Tidal excursion estimates such as the above apply to particles that move passively with the water and remain in the water column for the duration of the half tidal cycle. This assumption only applies to the very small sized particles. Fish feed pellets and well formed fish feces sink and only remain in the water column for a time period estimated by the depth of the water column ( $H$ ) divided by the particle sinking rate ( $w_s$ ), i.e. $T = H/w_s$ .

Several studies provide crude information about the potential magnitude of the water velocity in the area of interest. For example, Station 46 of Forrester's (1959) study was located 1-2 km offshore of Musquash Harbour, and velocity data was collected there on 14 July 1958. The tidal stream velocities at all depths rotate in a counter-clockwise direction around a major axis that is more or less parallel to the coastline along a northeast - southwest axis (Figs. 23 and 24). The tidal stream velocities at 60 m are less rectilinear that those at 5 and 25 m. The tidal velocities at 5 m, 25 m, and 60 m below the surface were estimated for a mean tidal range of 6.4 m (21 ft). The maximum tidal stream velocities at these depths were, respectively, 0.81, 0.91, and 0.62 $m \cdot s^{-1}$. The residual velocities at 5 and 25 m were, respectively, 0.37 and 0.29 $m \cdot s^{-1}$ away from the coast. The residual velocity at 60 m was 0.12 $m \cdot s^{-1}$ toward the coast. The maximum total velocities, i.e. tidal stream plus residual velocities, were 1.16, 1.09, and 0.64 $m \cdot s^{-1}$ at the same respective depths. The maximum tidal velocity estimated by Godin (1968) for a location off Point Lepreau was 1.02 $m \cdot s^{-1}$.

A typical maximum velocity for an estimate of particle displacement is, therefore, 1 $m \cdot s^{-1}$. When this velocity is assumed, the particle displacements range from ±0.3 to 22 km (Appendix Table 1) with the range generated by differences in the sinking rates of particles of different size and origin. The table also includes length scales of displacement for estimated pure tidal and residual current speeds.

The above estimates refer to the displacements of particles during the first tidal cycle after release of the particle into the water. Displacements of particles at depths of 5 and 25 m that moved several hundred meters offshore during the initial tidal cycle would progressively shift toward the southwest during subsequent tidal cycles. The particles drifting at 60 m depth would progressively move toward the coast.

The proposed fish farm is about 2 km from the seaward boundary of the Musquash Marine Protected Area. The above crude estimates of particle transport therefore suggest that it would only be the fine particulates and dissolved substances that have the potential to cross the seaward boundary of the Musquash Marine Protected Area (MMPA) and enter into the MMPA, and this would be only for some of those released during a flood tide.

The particle displacement estimates referred to above are only crude ball park estimations of exchange potential. They assume the current is horizontally and vertically homogeneous throughout the displacement area, and utilizes very limited information on current speeds that is not from the immediate area of interest. As others have cautioned before, this is not likely to be a good assumption. The currents off the coast of southwest New Brunswick are known to vary on small spatial scales (e.g. Dawson 1908), and extrapolation of current information over spatial scales of hundreds of meters or more must be treated cautiously (Loucks et al. 1974).

Appendix Table 1. Simple order of magnitude estimates of the distance or length scale of influence that a substance released from the proposed Musquash fish farm might be expected to travel.

| Particle Type | Particle Sinking Velocity | Water Depth at Proposed Site | Length of Time in the Water Column i.e. Time Scale | | Typical Horizontal Water Velocity | Distance Travelled, i.e. ±Length Scale of Influence | |
|---|---|---|---|---|---|---|---|
| | ($w$) | ($H$) | ($\Delta t = H/w$) | | ($V$) | ($D = V\Delta t$) | |
| | ($m \cdot s^{-1}$) | (m) | (s) | (h) | ($m \cdot s^{-1}$) | (m) | (km) |
| | | | | | | | |
| **Maximum Tidal Velocity** | | | | | | **Tidal Excursions** | |
| Feed Pellets | 0.1 | 30 | 300 | 0.1 | 1 | 300 | 0.3 |
| Fish Feces | 0.01 | 30 | 3,000 | 0.8 | 1 | 3,000 | 3.0 |
| Fine Particles | 0.001 | 30 | 22,360 [1] | 6.2 | 1 | 22,360 | 22.4 |
| Dissolved Substances | 0 | 30 | 22,360 [1] | 6.2 | 1 | 22,360 | 22.4 |
| **Residual Velocities** | | | | | | **Residual Displacement** | |
| Feed Pellets | 0.1 | 30 | 300 | 0.1 | 0.2 | 60 | 0.06 |
| Fish Feces | 0.01 | 30 | 3,000 | 0.8 | 0.2 | 600 | 0.6 |
| Fine Particles | 0.001 | 30 | 22,360 [1] | 6.2 | 0.2 | 4,400 | 4.4 |
| Dissolved Substances | 0 | 30 | 22,360 [1] | 6.2 | 0.2 | 4,400 | 4.4 |
| **Maximum Tidal Velocity in Flood Direction minus Residual [2]** | | | | | | **Displacement** | |
| Feed Pellets | 0.1 | 30 | 300 | 0.1 | 0.8 | 240 | 0.24 |
| Fish Feces | 0.01 | 30 | 3,000 | 0.8 | 0.8 | 2400 | 2.4 |
| Fine Particles | 0.001 | 30 | 22,360 [1] | 6.2 | 0.8 | 17,860 | 17.9 |
| Dissolved Substances | 0 | 30 | 22,360 [1] | 6.2 | 0.8 | 17,860 | 17.9 |

[1] - Since $\Delta t = H/w$ is greater than one half a tidal cycle (6.21 hours = 12.42 h / 2), the maximum drift time of 6.21 h (22,360 s) is used.

[2] - Since the MMPA is located to the east of the proposed farm site, this has been estimated as the maximum tidal velocity in the flood direction (eastward) minus the residual velocity which is westward.