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Using a Stakeholder-Engaged Approach to Understand and Address Bacterial Transport on Soft-Shell Clam Flats

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Abstract

Small-scale fisheries, which are often distributed over large spatial scales and occur in rural settings, tend to lack financial resources and capacity to conduct research on local issues. One approach to overcome this challenge is to use relatively inexpensive environmental monitoring methods with stakeholder engaged science and participatory modeling. Here, we present a case study focused on water pollution impacts and tidal circulation in a mid-coast Maine (USA) estuary to develop a simulation model and a partnership approach that can support soft-shell clamming communities to effectively address water quality, namely bacteriological closures of mudflats. We deployed multiple low-cost drifter buckets, Lagrangian flotation devices that measured surface current speeds and provided validation data for a hydrodynamic model based on finite volume community ocean model (FVCOM). The drifter buckets resolved the influence of wind, tidal currents, and bathymetry on surface water circulation patterns between the main channel and adjacent mudflats, highlighting the impact of cross-estuary winds during slack tides on potential bacterial transport. We calculated residence time using the validated FVCOM model: in the prohibited area (~ 2.5 days), and the conditional area (~ 0.5 days). This information has already influenced local management decisions and helped shape new conservation projects. In addition to contributing new understanding about tidal patterns in this coastal region, our novel methodology of combining field techniques, FVCOM modeling, and stakeholder engagement helps show how engaged research approaches can improve regulatory outcomes for small-scale fisheries while also protecting public health.

Keywords Stakeholder engagement · Soft-shell clam · Bacteria pollution · Estuarine circulation · Lagrangian drifters

Introduction

The soft-shell clam (*Mya arenaria*) fishery plays an important role in the economy of coastal communities in the northeastern United States (US) and especially in Maine (Hanna 2000; Dow and Wallace 1961). In 2020, soft-shell clamming was the second largest fishery in the State by dollar value (Maine Department of Marine Resources 2020b). Further, Maine supplies 60% of the soft-shell clams in the US (Evans et al. 2016). However, there are many ongoing threats to the health and survivability of the soft-shell clam fishery. In 1977, Maine clammers harvested approximately 3500 annual metric tons while in 2020 clammers harvested approximately 600 annual metric tons (Congleton et al. 2006; Maine Department of Marine Resources 2020a). The major reduction in landings has been attributed to a combination of factors, including but not limited to invasive green crab (*Carcinus maenas* L.) population increases (McClenachan et al. 2015); climate change impacts, such as warming temperatures and ocean acidification (Siedlecki et al. 2021); and poor water quality (Floyd and Williams 2004; Hanna 2000).

Water quality has been identified as one of the most important issues facing the soft-shell clam fishery by multiple stakeholder groups (Evans et al. 2016; McGreavy et al. 2018). Freshwater can contain fecal coliforms, an indicator of fecal matter and therefore, fecal coliform bacteria. The presence of fecal coliforms near clam flats generates

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pollution closures. These closures can negatively impact landings by reducing access to potential harvesting areas (Evans et al. 2016). Importantly, ingesting fecal coliform bacteria can cause serious health hazards, such as food poisoning, sepsis, and other gastrointestinal problems. (McFeters et al. 1972; Parr 1939). The diverse nature of fecal coliform bacteria sources (i.e., surface runoff, combined sewer overflows, and point source discharges) compounds the problem (Auer and Niehaus 1993; Berkes et al. 1998). Water quality managers generally use area classifications to minimize public health risks. For example, the Maine Department of Marine Resources (DMR) follows the National Shellfish Sanitation Program (NSSP) federal guidance for water quality regulation as it relates to shellfish consumption, using four types of pollution classifications to mitigate human consumption of bacteria: prohibited, restricted, conditionally approved and open. No harvesting is allowed in prohibited areas due to high concentrations of bacteria, while restricted areas are only open to harvest with a special permit for depuration digging, where clams are treated before market. Open classifications are areas where pollution tests result in very low concentrations of bacteria, deemed safe by the NSSP. These areas can be harvested at any time. Conditionally approved areas are closed to harvesting when a particular meteorological or tidal condition is exceeded, which can result in an influx of bacteria from runoff. For example, most Maine clam flats are closed when rainfall meets or exceeds 5.08 cm (2″) in a 24-h period and are closed for 14 days. In some locations, there are unique sets of closure rules. For example, in the Medomak River estuary, conditionally approved areas are closed when rainfall meets or exceeds only 2.54 cm (1″) within a 24-h period and are closed for 9 days.

Conditional closures can result in large economic losses (Evans et al. 2016). The closure system is conservative because the public health implications, where leaving a clam flat open creates the potential for consumption of bacteria. Closures are also conservative because these highly distributed estuarine systems are information poor, so there is a lack of data to determine more accurate closure times. Better understanding of local scale watershed hydrology and estuarine hydrodynamics could result in less restrictive and more targeted closures (Evans et al. 2016). However, the nature of small-scale fisheries spread over an extensive coastline can make management and process-level studies at these scales difficult to manage (Stoll et al. 2016). Closure delineations are often contested by harvesters because these systems tend to be data-poor and are based on specific stations that may not accurately capture the variability of the hydrodynamics within a system. Limited resources, such as staff time, agency funding, and sampling supplies can keep regulatory agencies from sampling with enough frequency to open clam flats after rain events in a timely manner. This is especially true in a region like Maine where there are approximately 5600 km of tidal shoreline to monitor. Closure maps are distributed to clammers from the regulatory agency and are almost universally delineated with straight lines. These straight lines are determined based on long-term geometric mean bacterial counts from multiple stations and ease of enforceability. That is, the lines are drawn so that clammers and enforcement officials have clear boundaries. For example, straight-line closure boundaries around well-known navigational points are common. Since bacterial pollution is a serious public health risk, relatively conservative closures based on ease of enforcement generally take precedent over bacterial loading and receiving water residence time. However, by filling information gaps, new technology, such as numerical oceanographic models, can change the way conditional and prohibited zones are distributed and enforced. With these new tools, the wild clam fishery could make more informed closure decisions and reduce the economic and social impacts from unnecessary water quality closures. Importantly, these new tools could also determine that more stringent closures are necessary.

Another water quality information gap that can be filled by models is residence time. Residence time is generally defined as how long a water parcel takes to leave a fluid system (Luketina 1998). For our purposes, residence time is one component determining how long fecal coliform polluted water stays on clam flats. Fecal coliform laden waters are contained mostly in the surface layer of freshwater that extends into the estuary as bacteria rapidly decay in salt water (McFeters et al. 1972; Auer and Niehaus 1993). This layer is mixed downward towards the clam flats or left behind on outgoing tides, resulting in contaminated clams. In general practice, the closure time for a clam flat is supposed to account for the time water remains in the system plus the time harmful bacteria stay in the clam. These clams filter out bacteria laden waters after a few days depending on the number of clams in the area (Beal et al. 2018). Using oceanographic techniques, maps of residence time can highlight areas that are more susceptible to bacterial pollution and can also help public health agencies find areas that are in need of targeted sampling. By calculating residence times, the closure time may be shortened or lengthened in certain areas in an estuary (Wen 2017). Hydrodynamic effects on the residency of fecal coliforms can also be incorporated into closure designations. Incorporation of these effects could create a more targeted management scheme where areas that are flushed frequently could possibly be opened or given a more lenient closure type (Wen 2017).

Sustainability Science Methodology

Recognizing the need for more fine-tuned closure delineations and durations as well as the need to design our research to inform future decision making, we adopted a sustainability science approach. Sustainability science takes a collaborative and interdisciplinary approach to co-create a range of solutions to complex problems that occur at the nexus of the ecosystem, socioeconomics, and communities (Kates et al. 2001; Clark et al. 2016). While sustainability science offers diverse orientations to producing usable science, there are at least five commitments that are especially important for designing research. First, designing research questions so they align with questions and problems that decision makers and stakeholders are asking helps set the research on a course so it will be perceived as relevant (Norström et al. 2020; Cash et al. 2003). Second, it is essential to understand individual and group preferences for involvement in scientific processes to help ensure that they can participate in ways that work for them and do not create an undue burden on their time and resources (Lang et al. 2012). Third, research efforts need to be iterative where collaborators regularly meet to discuss research progress and make adjustments as needed (McGreavy et al. 2015; Lang et al. 2012). Fourth, making an effort to co-produce knowledge and combine multiple forms of expertise can foster credible science and also helps people form relationships and create the social structure in which the knowledge gets used (Lang et al. 2012). Fifth, researchers should be cognizant of the distribution of power and make deliberate changes to promote equity within the process (McGreavy and Hart 2017). This can help mitigate the risks of science contributing to and reinforcing unequal power and unjust conditions (Lang et al. 2012).

Following this five-part commitment to research design, we used an engaged case study methodology to conduct our research (Brewer et al., 2016; Yin 2013; Tellis 1997). This included engaged and collaborative research practices (Gillham 2010; Creswell 2009) and participatory tidal modeling (Ingram et al. 2018; Falconi and Palmer 2017; Tuler et al. 2017; van Eeten et al. 2002). We developed research-based partnerships with clam harvesters and other stakeholders in the region to co-design the study and develop and deploy this inexpensive sampling approach. The relatively low-tech approach to monitoring tidal patterns with drifter buckets was intentional, as this technique may help overcome difficulties faced by small-scale fishers who need easy, accessible, and affordable monitoring procedure approaches (Kaiser et al. 2019; Schemmel et al. 2016). This study represents a bottom-up participatory approach to sustainability science where stakeholders participate in a collaborative space throughout the scientific study, developing methods, research questions, and analyzing and disseminating results (Reed et al. 2018; Goodman et al. 2017).

Methods

Study Area

The Medomak River estuary (MRE; 44° 4′ 14.718‴, – 69° 21′ 45.42″) is home to some of the most productive soft shell clam flats in the US. The town of Waldoboro had the highest soft-shell clam landings in Maine between 2015 and 2017. The MRE fishery employs approximately 10% of all clammers in the state (~ 150 clammers out of ~ 1500). As a result, the MRE has been identified as a *place of interest* by the DMR, the Maine Department of Environmental Protection (DEP), and clammers located in nearby communities. The designation indicates that the MRE is of particular socioeconomic and ecological importance and is part of the justification for the Medomak Taskforce, a group of stakeholders from multiple state and municipal organizations focused on addressing water quality issues in the MRE. Importantly, there are no previous studies on hydrodynamics and ecosystem functioning in the published literature and no ongoing water quality monitoring programs outside of regulatory clam bacterial monitoring for this estuary. The geomorphology of the Medomak is clearly an important control on circulation and retention of particles and clam larvae. The estuary is 51.5 km long and widens from head of tide towards the mouth but then narrows (44° 1′ 30″, – 69° 22′ 48‴) before opening up to the adjacent Gulf of Maine. The estuary is centered around a relatively deep channel (6–20 m, Fig. 1) that spans the length of the estuary, and is anywhere from two to three times deeper than the surrounding clam flats (Fig. 1).

The central channel is one of the key geomorphological features controlling the hydrodynamics in the Medomak estuary since the strongest currents and mixing occur here (Valle-Levinson 2010; Fig. 1; Bouma et al. 2005). On a flood tide, the channel fills, and then spills out onto the clam flats and when the tide goes out, water from mudflats drains to the channel (Bouma et al. 2005). The average flow for the Medomak River is 2.5 $m^3 s^{-1}$ based on the watershed drainage size of 275 km^2 (Table 1; U.S. Geological Survey 2016).

Engagement, Interviews, and Outreach

We engaged in multiple forms of data collection and observation, including extensive time on clam flats observing harvesters, attending meetings, conducting semi-structured interviews, and used participatory mapping techniques (60 + h). From August 2016 to May 2019, we attended Medomak Taskforce meetings, Shellfish Advisory Council Meetings, Waldoboro selectboard meetings,

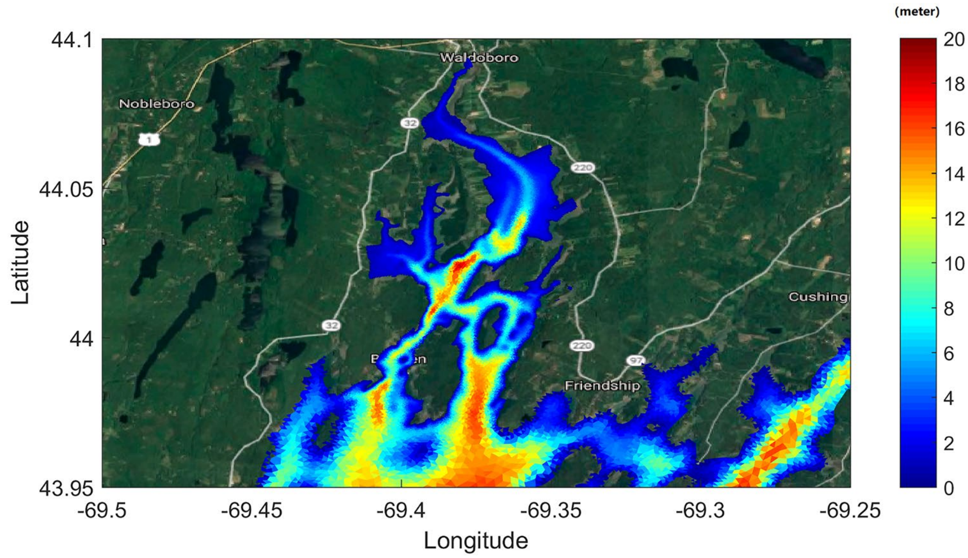


Fig. 1 Medomak estuary bathymetry map. The bathymetry in this river is mainly built from National Geophysical Data Center (NGDC) Northeast Atlantic 3 arc sec offshore bathymetry

and Waldoboro shellfish committee meetings throughout the research process. These meetings included harvesters, municipal managers, representatives from multiple state agencies, as well as interested community members. Following sustainability science commitments, initially we participated in meetings as active listeners, and observed conversations to identify the needs of the community. Later, as research progressed, we also presented multiple times to these groups, keeping the community informed of results and analysis (McGreavy et al. 2015; Lang et al. 2012).

To determine research questions and approaches to the drifter bucket methodologies, we also interviewed six key informants in Waldoboro, ME, who are participants or harvesters in the wild soft-shell clam fishery. We identified participants through personal contacts, attending Shellfish Advisory Council meetings, and by snowball and key informant sampling. Snowball sampling is a method where interview participants identify future participants from their community and key informant sampling includes the identification of key informants, or members of a community that could speak to larger processes and represent larger communities, who are asked to participate in the interview process (Corbin and Strauss 2014). Within the interview process, interviewees were asked to share environmental or socioeconomic concerns and, identify areas that were economically or culturally important, where they had seen declines in clam landings, and that were often closed often due to water quality issues. Extensive follow-up informal conversations with other clammers as well as observations across shellfish-related contexts outside of formal interviews corroborated that water quality and residence time were the primary concerns of the community. Through outreach, extended engagement, and initial interviews, we determined our research goals to be focused on improving residence time calculations for shellfish closures. This was the primary concern of all the key informant interviews.

To determine target areas for research, interview participants were also asked to identify the previously mentioned areas of significance on maps. This included areas interview participants recognized as historically productive and socially or economically important. Participants were asked to mark using an “X” or star specific locations of potential pollution sources as well as circle regions that were productive or important to the soft-shell clamming community. Participants’ maps largely agreed with each other, highlighting similar areas (Fig. 4). This, along with harvester observation on clam flats, determined release points for the Lagrangian drifter study. Drifters were released from those areas to better track the fate of water sourced from those areas (Fig. 2).

Each interview was digitally recorded and all interviews were transcribed and analyzed using an inductive coding process through NVivo 11 (Bazeley and Jackson 2013; Corbin and Strauss 2014). Interview protocols were reviewed and approved by the Institutional Review Board

Table.1 Physical and meteorological characteristics of the Medomak estuary, Waldoboro, ME. Data came from public USGS river gauge datasets (U.S. Geological Survey 2016)

Length of river	64 km
Watershed drainage size	275 km^2
Average river flow	2.5 m^3 s^{-1}*
Annual precipitation	114.8 cm year^{-1}
Average tide range	3.5 m

*Average flow was calculated using a USGS streamflow approximation based on watershed drainage size and nearby stream gauges.

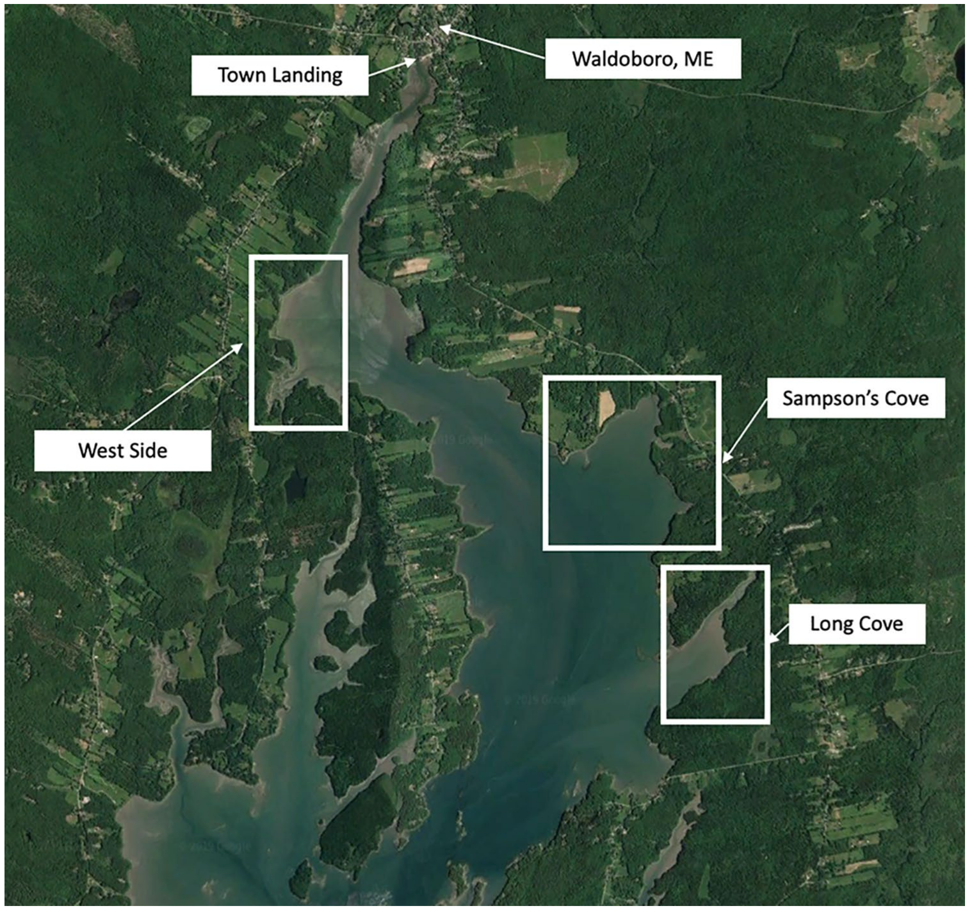


Fig. 2 Points of interest in Medomak estuary. This map highlights points of interest in Medomak estuary that will be referred to in this article, including the town landing, Waldoboro, ME, the West Side, Sampson's Cove, and Long Cove

for the Protection of Human Subjects (IRB) at the University of Maine (IRB: 2019–06-18).

Drifter Release

The drifters were based on the "super-bucket" design described by MacDonald et al. (2007). This relatively inexpensive approach targets surface water dynamics since fecal coliform bacteria can deteriorate rapidly in saltwater and are generally confined to the surface layer (Sabet and Barani 2011; McFeters et al. 1972; Auer and Niehaus 1993). Briefly, the drifter consists of a 0.03 m^3 plastic bucket, with a hole cut out of the bottom, and holes drilled in the sides (Fig. 3). The hole allows the bucket to sink after filling with water. Drifters were tested to determine the necessary flotation to remain upright and within the surface water currents. Counterweights were attached to the bottom of the bucket, and a buoy float was attached to the upper handle (Fig. 3). The design of the drifters allowed for a majority of the weight to be subsurface, so that they move with surface currents rather than being moved by surface winds (Spencer 2014; Sabet and Barani 2011).

Drifters were released three at a time from each stakeholder identified study point, as shown in Fig. 4. All three release points coincided with suspected pollution sources as well as areas that may be sources of clam seed or produced high landings (Fig. 4). In particular, clammers were interested in how pollution could flow from the town of Waldoboro into the larger estuary. They were also interested in possible mixing or transport of pollution at the boundary between the prohibited and conditional zones near the West Side (Figs. 2 and 4). Finally, they asked questions about the circulation pattern in Sampson's Cove (Figs. 2 and 4), a site described as important and closed often due to pollution. Importantly, clammers helped conduct the releases, often assisting to retrieve buckets after release and monitoring them during deployment. After 12–24 h, we released a second set of three drifters. Drifters were released during maximum ebb or maximum flood current speed and releases lasted for 12 to 24 h. After 12 to 24 h, drifters were retrieved. A satellite GPS tracker and a Garmin Hiking GPS XTrack were attached to each drifter. Satellite trackers were activated at the dock before deployment. Drifter tracks were mapped using MATLAB

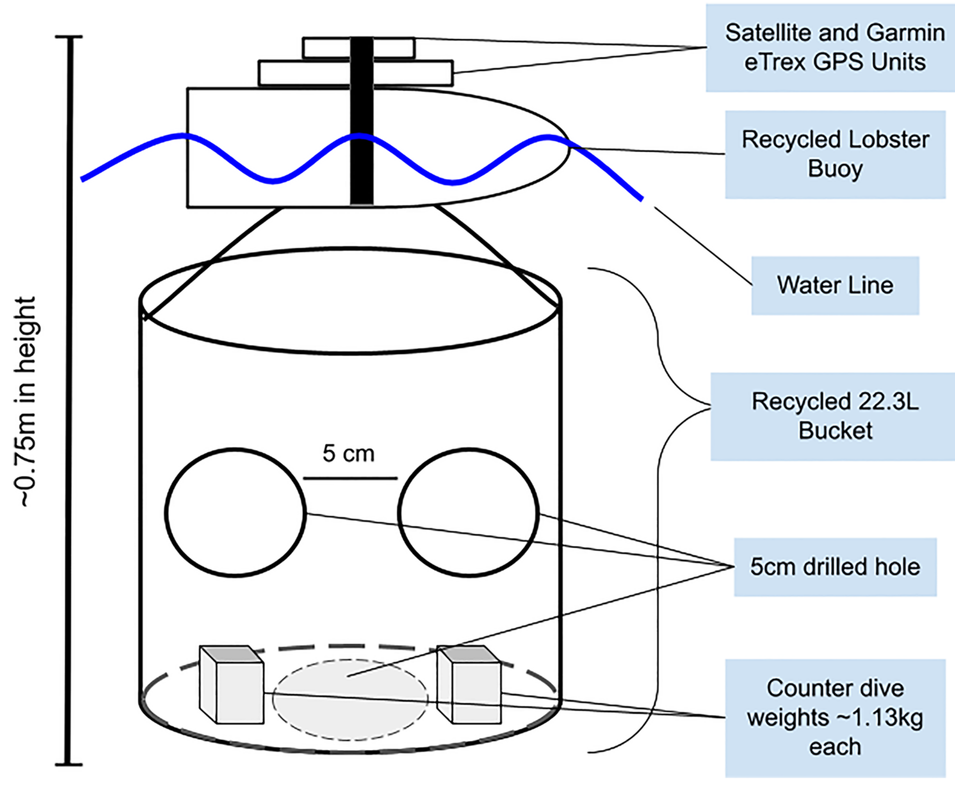


Fig. 3 Cross section of bucket drifter. Bucket drifters were built using mainly recycled materials. This provides a schematic. Some lines are dashed to provide a three-dimensional view of the drifter. Counter dive weight measurements and heights are averaged between all 6 drifters used

and Google Maps for both satellite and GPS datasets (MATLAB ver. R2018b). Displacement and the distance traveled was calculated for each drifter track as the change in distance between Garmin GPS marker points over time using regression analysis in Matlab® (Table 2).

Lagrangian Particle-Tracking Experiments in FVCOM

Drifter tracks are often used to improve numerical model simulations (Proehl et al. 2005; Xu et al. 2006; Chen et al. 2012). We utilized a realistic three-dimensional

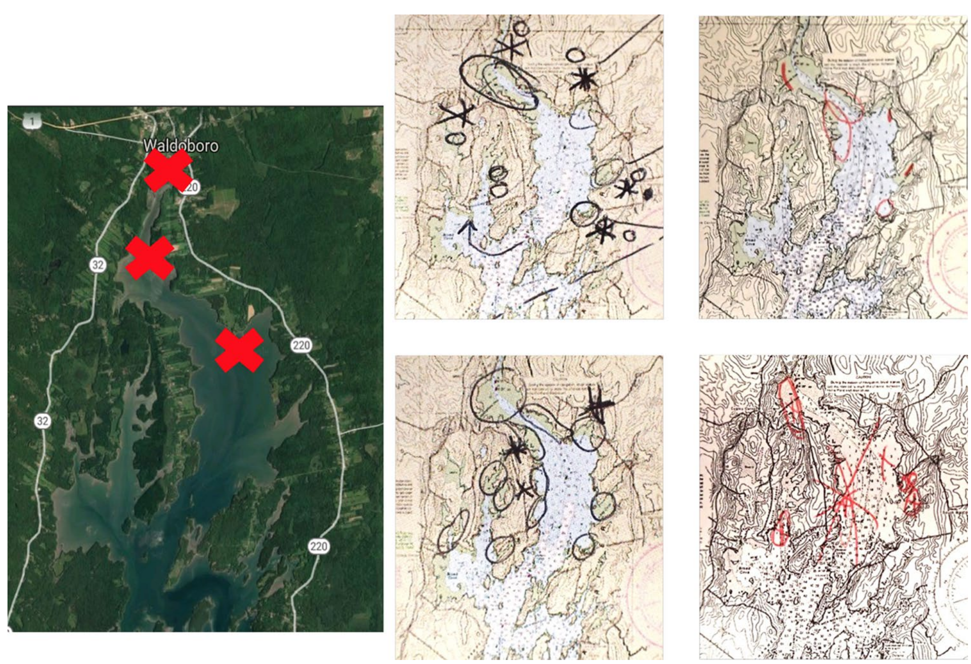


Fig. 4 Connecting clammers to site choice. Each clammer interviewed was asked to highlight areas on maps they identified as potential sources of pollution and/or clam seed. On the left, areas highlighted by stakeholders and used for drifter release areas are designated with an "X." On the right, four maps are shown which were drawn on by interviewees

Table.2 Drifter track summary data. Information on each drifter track and release. N refers to the number of drifters released at that time. Drifters released in July 2017 were used as a proof-of-concept test. Distance traveled was averaged across drifter buckets

Date	N =	Release tidal state	Distance traveled (km)	Time (h)
7/20/2017	6	Max ebb	3.701	12.1
7/26/2017	6	High tide	1.287	1.5
8/15/2017	6	Max ebb	3.541	4.3
8/16/2017	5	Max ebb	1.126	7.9
8/17/2017	5	Max flood	5.150	8.1
8/22/2017	5	Max ebb	2.575	17.2
8/23/2017	3	Max ebb	15.449	20.5
8/24/2017	3	High tide	13.357	23.5
9/14/2017	6	Max flood	16.737	31.5
9/20/2017	3	Max ebb	5.311	25
9/21/2017	3	Max ebb	2.575	5
10/5/2017	3	Max ebb	9.978	20.9
10/6/2017	3	Max flood	9.981	21
10/26/2017	3	Max ebb	7.581	26
10/27/2017	2	Max flood	6.278	21.5

hydrodynamic model for mid-coast Maine to simulate drifter tracks in the MRE. The model is an implementation of the unstructured-grid finite volume coastal ocean model (FVCOM), which has the advantage of accurately following complicated coastlines using unstructured triangle elements (Chen et al. 2006; Chen et al. 2003; Chen and Cowles 2004; Huang et al. 2008). The model domain covers a wide shelf area in the mid-coast of Maine and major estuaries including the Medomak River estuary. Like most hydrodynamic models, the model covers a large area but is only validated in a few locations due to the high cost of collecting validation data (Liberti et al., in press). One of the objectives of this project was to validate the output of an existing model in an information-poor location using low-cost drifter tracks. The unstructured grid allows for a large model domain while maintaining high spatial resolution in the fringing estuaries (e.g., ~ 10 m in the MRE). The model bathymetry was obtained from the 1/3 arc-second NOAA Digital Elevation Model (DEM) for Portland, Maine. The model was forced with offshore tides and river discharge from six major rivers including the Medomak River. The discharge of the Medomak River was estimated from USGS StreamStats. The regression equations used in StreamStats were developed through a process known as regionalization, which relates streamflow statistics computed for a group of selected stream gages (usually within a state) to the upland basin characteristics (https://www.usgs.gov/mission-areas/water-resources/how-streamstats-works).

Model results were validated using temperature, salinity, and current velocity data throughout the mid-coast region from the Sustainable Ecological Aquaculture Network (SEANET) and the Northeast Regional Association of Coastal Ocean Observing System (NERACOOS) buoy systems. However, it is important to note that no such assets have been deployed within the MRE and these drifter tracks represent the first estimates of current velocity in the estuary. To conduct Lagrangian particle-tracking experiments in our model, neutrally buoyant particles were released in the surface of the modeled velocity field. Their trajectories were qualitatively compared with drifter tracks.

Results

The major goal of the project was to employ an engaged approach to understand estuarine hydrodynamics using accessible techniques and computer-based simulations to produce both locally relevant and scalable knowledge about tidal dynamics and pollution circulation. Here, we describe: (1) results from semi-structured interviews and observations, (2) results from the drifter study, and (3) calculations of residence time and results from the FVCOM model.

Semi-structured Interviews

Bacterial closures were the primary concern of all clammers interviewed. This concern was corroborated by the relative emphasis on water quality during Waldoboro Shellfish Committee meetings as well as within the Medomak Taskforce meetings, where water quality closures were a frequent or primary topic. Water quality research was also the focus for a presentation, led by Glen Melvin (a local leader of the clamming community in the area), given at the Fisherman's Forum in 2017 (https://www.youtube.com/watch?v=qUSurzo9acU). There were other important environmental factors that clammers implicated in the deterioration of clam flats including the presence of eelgrass and green crabs. In multiple conversations, clammers cited expanded eelgrass beds as a cause for decreased settlement of clam larvae. It was also discussed how warming weather, and a lack of ice coverage for the river, was leading to an increased presence of both eelgrass and green crabs. However, when compared to these other factors, water quality was the primary challenge cited for the wild soft-shell clam fishery in this region. The quote below highlights this priority:

> *"Yes, financially, yes, our biggest enemy [pollution closures]. Yes, would be the green crabs and pollution. And when the green crab is not around, it's just the pollution. But, yes, definitely until recently, and it's getting better, pollution is our biggest enemy. That hurts the Medomak worse than anything else."* - Clam Harvester 1

There was also significant interest in understanding the MRE hydrodynamics, to better understand both the residence time of pollution, as well as circulation patterns that may impact settlement of soft-shell clam larvae. The first Medomak Taskforce meeting attended by the research team included an extensive discussion of research that had already been done by the group, where task force members highlighted a distinct lack of information about hydrodynamics. Additionally, when reviewing management practices, there was no mention of pollution transport across closure lines, flushing mechanisms, or residence time. Necessarily, the primary focus of water quality managers is on testing water samples for coliform bacteria since bacterial contamination presents a substantial public health risk. However, by focusing on water samples without incorporating hydrodynamic context, some management inefficiencies are created, such as shaping closure areas around navigable points, or assigning straight classification lines across curved estuaries. In the quote below, the harvester interviewee responds to questions about decreased productivity in previously identified areas:

> *"Well I think that has to do with river flow, I mean this spot right here used to be a real productive area, you know as soon as we dug them all out, there's nothing, no recruitment back in the mud, but up along the shore they're as thick as gravel, but they just don't settle out here in the mud. I don't know if it's cause it's too flat, and everything is being pushed, rolled across the mud and pushed up into the rocks and it's just not settling out here."* - Clam Harvester 3

Areas identified by the clamming community specifically for the purpose of understanding circulation were mapped out for the field protocol as release points (Figs. 2 and 4). All clammers identified two coves, Sampson's and Long Neck coves (Fig. 2), that were characterized as large productive clam flats impacted by pollution closures. This was also corroborated by the observation of clammers primarily harvesting in these areas over the summer and into the fall, unless the area was closed due to rainfall. The reason behind this productivity was related to the hydrodynamics of the area, known to clammers as the "East–West theory." Specifically, the clammers contend that clam productivity is higher in coves lateral to bends in the estuary channel due to increased water flow. Below, a clam harvester describes this theory, and consequently, identifies Long Cove and Sampson's Cove as productive areas.

> *"Alright so um, yeah I'm not sure, obviously all the shores and the first 50 feet off the banks is great everywhere in the Medomak. It's interesting... these coves here, where the river comes up are the most productive down here it would be Long Cove and Sampson's cove. So it's like the sea lays that way, then as the river goes straight, it appears the west side, where it makes the turn and goes up into the town, so it's like whatever the back cove is, as it makes a turn, are the most productive. Year after year."* - Clam Harvester 4

The interview results shaped our research goals and methodology. Our research questions focused on hydrodynamics, particularly current flow in economically valuable coves and areas, as that was the information gap identified by the community. We also shaped our deployments to cover areas that were identified as important by clammers, as corroborated with clam harvesting observation in the MRE.

Drifter Tracks

We released 3 drifters on 22 occasions over 4 months from July to October in 2017. The average distance traveled by the drifters in 6 h was ~ 5.63 km (3.5 miles). Drifter dispersion as measured by the average distance between three replicate drifters was most always minimal. Two major results were derived from the drifter study. As predicted, at specific geomorphological constrictions, flow velocities increased dramatically (Fig. 5). The first geomorphological constriction is west of Sampson's Cove, downriver from the West Side. The second major constriction is downriver from Long Cove (Fig. 5). As the drifters moved seaward in the estuary, there were spikes in flow velocities in these constrictions (Fig. 5). The geomorphological constrictions were important to clammers because if drifters did do not reach these constrictions on ebb tides, they were far more likely to remain in the upper estuary. The second result relates to retention. During flood tides, the drifters sped up, moving in eddies generated by increased tidal flow spilling over the channel located in the center of the estuary. However, drifters did not speed up as the tide ebbed, or went out, which may indicate that some of the freshwater deposited on the flats during flood tides does not completely flush out, but instead is retained in the upper estuary.

Examining the "East–West Theory"

Tidal transport is the most dominant forces in this estuary controlling residence time and other hydrodynamic characteristics (Wen et al. 2017; Yu et al. 2012; Fenster 1996; Hume 1988; Galloway 1975). In the Medomak River estuary, this is shown through tight coupling of velocity increases and tidal flooding. Nearby, the Kennebec River estuary, which has similar morphological characteristics but far more freshwater flow, has been proven to have an ebb dominated flow (Fenster 1996). However, in the Medomak, drifter speeds increased with the flood tide, showing a flood dominated estuary. As shown in Figs. 5 and 7, drifters released for ~ 24 h point towards this flood-dominant pattern,

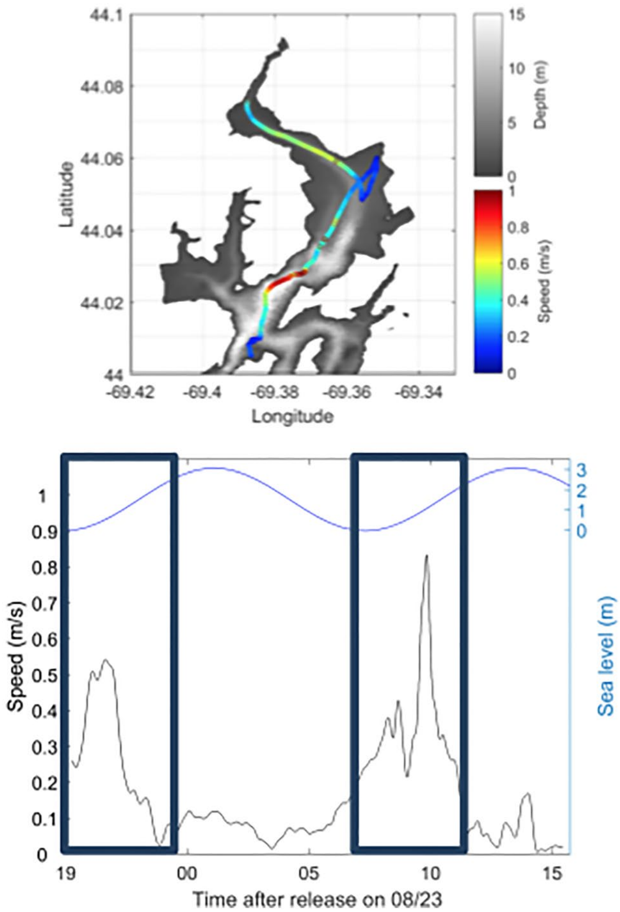


Fig. 5 Centrifugal forces. On the top: the map of one of the drifters released on 8/23/17 shows the large loop near Sampson's Hill (Fig. 2). Bottom: speeds in m/s in the black line, with tidal stage in m in the blue line

where drifters moved faster as the tide came in, rather than as the tide went out.

Eddies are generated through tidal currents shedding from the central channel. The circular rotating pathways of the drifters were caused by changes in bathymetry and wind patterns trapping water masses in coves adjacent to the main channel. In shallow estuaries, surface tidal flow around curvatures is known to create the lateral secondary flow away from the channel and into habitats like mudflats in this case (Vriend 1981; Figs. 5 and 7).

Bathymetry-Cross-sectional Area

Cross-sectional area varies from the head of the tide to the lower estuary. Near the head of the tide, where the Waldoboro town landing is located, cross sectional areas are between 30 and 75 m^2. Although the estuary widens significantly south of Waldoboro, the volume does not change radically as the estuary is still very shallow as indicated by the reduction in the overall cross sectional area. There is a constriction, shown by the decrease of ~ 20 m^2 in cross-sectional area below the conditionally approved line (Fig. 6), which affected drifter speed (Fig. 7). This constriction increased flows by contracting a large volume of water into a small area and generated momentum that pushed water past the curve of the channel into nearby coves like the Sampson's Cove and Long Cove (Fig. 2). The constriction was also important in transporting water masses onto the western shore, which has shown higher bacterial counts than the eastern side. As the estuary widens, the estuary also gets deeper, and the channel widens as well, showing the sharp increase in cross sectional area at around 44.06° north (Fig. 7). Here, drifters slowed and were more easily impacted by vorticity currents, as well as wind driven changes in direction. As shown in Fig. 6, the Medomak then again constricts, which could entrap waters from the upper estuary. This has a direct effect on residence and flushing time which was estimated and is discussed in later sections (Wen et al. 2017; Chapra 2011; Hume 1988).

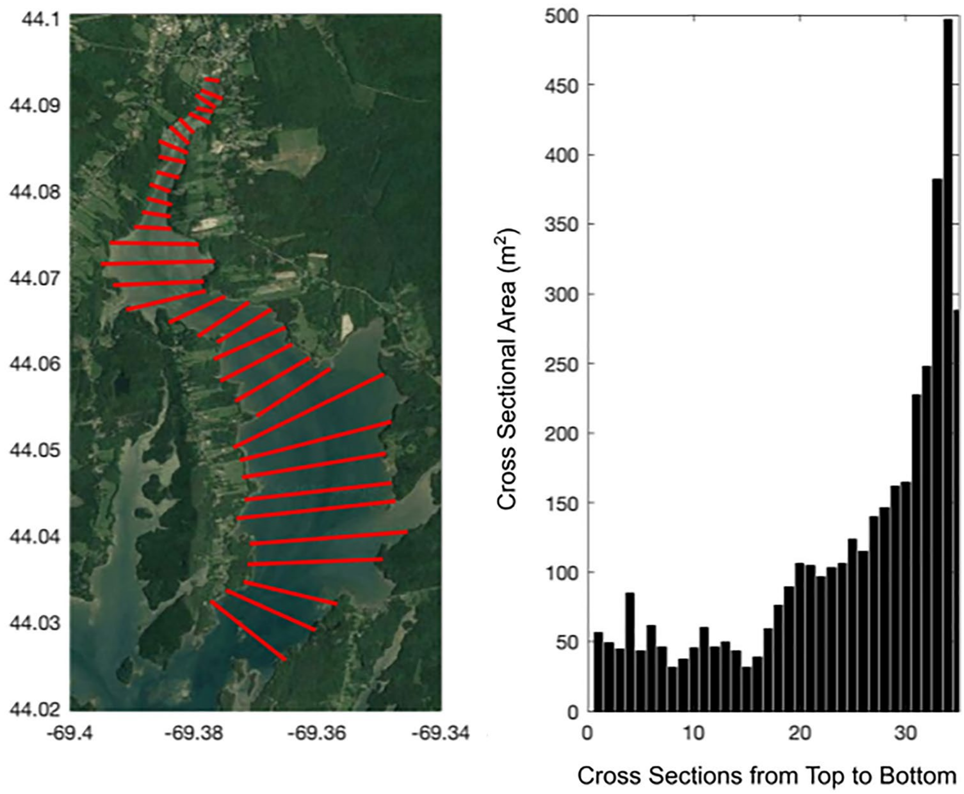
Wind Effects

During slack tides or when the drifters were not near cross sectional constrictions, drifter tracks showed a change in trajectory based on predominant wind direction in the estuary. Lagrangian tracks with low velocities, but distinct changes in direction, have been identified as being predominantly affected by wind (Fig. 8). Based on the drifter track maps differing directions of winds pushed water out of the channel. The wind either entrapped the water in the upper estuary, before the major constrictions pushed the water into the more open area, facilitating either entrapment in coves on the western side, or pushed the water along a path to escape this area of the estuary. When the predominant wind direction was perpendicular to the channel, drifters were pulled away from the channel, increasing retention (Fig. 8). When wind pushed flow away from the channel, vorticity forces entrapped parcels of water and moved them towards the coastline (Southwick et al. 2017; Fig. 8). These vorticity forces were generated by changes in bathymetry or salinity. These entrapped water masses could then be moved within these vorticity currents away from the channel and towards clam flats by the wind (Southwick et al. 2017; Xie et al. 2017).

Residence Time and Model Calculations

Drifter tracks were compared with virtual particle releases from a FVCOM model of the region. Briefly, the model domain consists of estuaries from the Kennebec River Estuary to the mouth of Penobscot Bay and includes the Medomak River estuary at a spatial resolution of

Fig. 6 Cross-sectional area transects. This map shows the transects chosen to calculate cross sectional area as part of the drifter analysis. On the right, the area including bathymetry data from NECOFS is shown in m^2, the x-axis is the number of sections from the highest transect upriver



approximately 10 square meters. The drifters were used to ground truth current velocity. Initial model experiments demonstrated that the modeled particles moved more slowly (~50% slower) than the drifters, which indicated the velocity was underestimated in the model. Thus, we adjusted the model to increase velocity, mainly by reducing bottom

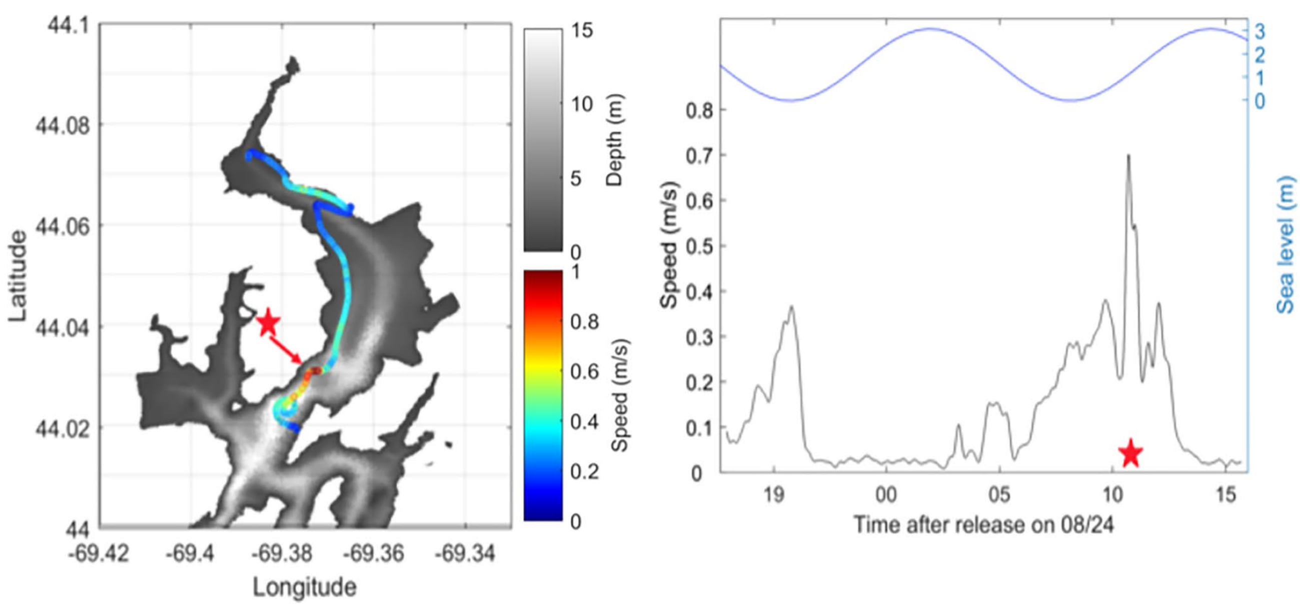


Fig. 7 Cross-sectional area effects. On the left: drifter track from 8/24/17 with a color bar showing speed in m/s. On the right: speed of drifter in a black line m/s, with sea level in a blue line in meters. The red stars are associated with a constriction in the river where velocities sharply increase regardless of tidal stage

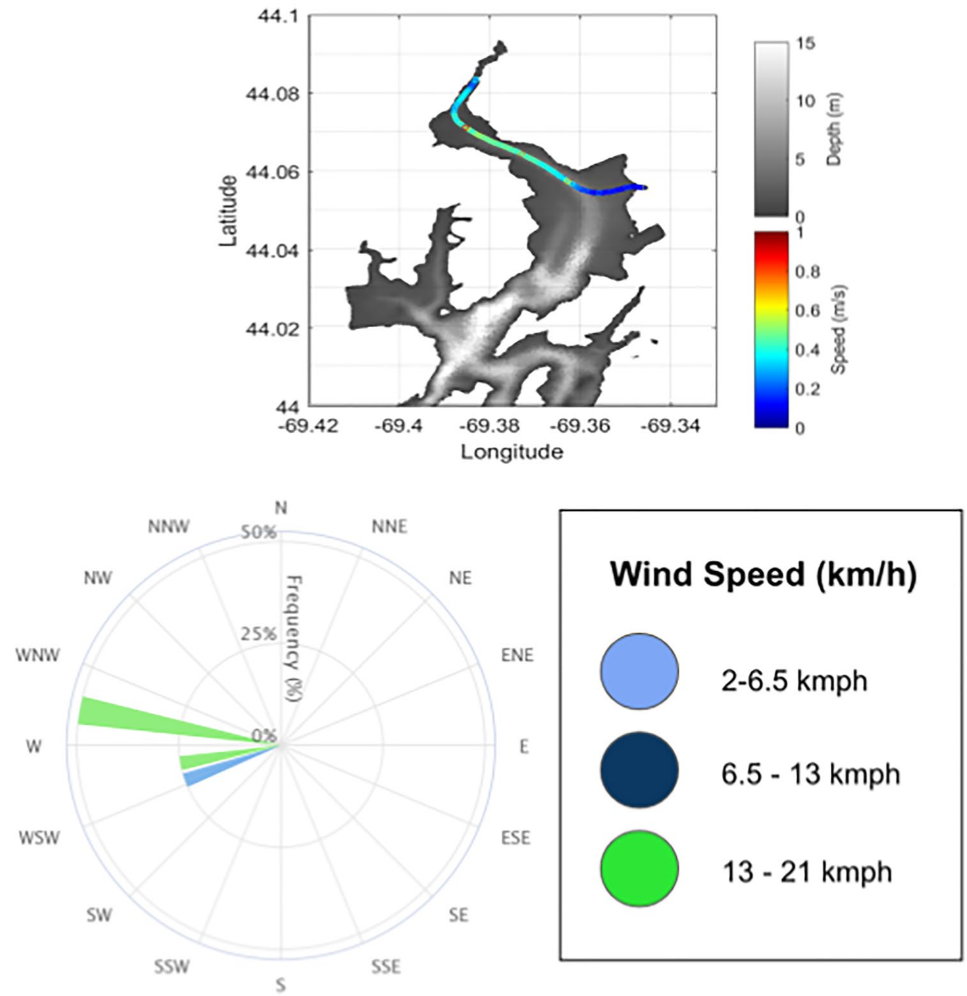


Fig. 8 Wind direction influences. Top: drifter track released on 8/17/17. Blue arrows show dominant wind orientation. Bottom: wind sundial showing prevailing winds from the west

friction and improving open tidal boundary conditions, which increased the overall incoming velocity of the estuary. The ultimate discrepancy between modeled and observed trajectories could be based on the duration deployed of the experimental Lagrangian particles, and that the model did not include a high-resolution wind field.

The adjusted modeled particle tracks showed reasonable agreement with the drifter tracks (Fig. 9). One area that the model had difficulty simulating accurately was the narrow head of the estuary near the largest town in the estuary and a likely source of fecal coliforms, Waldoboro (Fig. 9). More precise bathymetry and better head of tide boundary conditions may be necessary to accurately simulate this region. Another area for improvement would be the incorporation of wind dynamics. For example, we released the modeled particles in a relatively wide channel where model bathymetry had a high fidelity to actual bathymetry due to the relatively simple channel-shoal configuration. The drifter (black line) moved to the eastern shallow shore at the end presumably due to wind dynamics that were not incorporated into the model tracks since no high spatial resolution wind simulation was available to force the model over this time period (red line in Fig. 9).

One of the most relevant results to the original goal of the research was the residence time calculations, using salinity as a metric for how long freshwater remained in the prohibited and conditionally closed areas. The FVCOM model was used to model residence time using isohaline analysis, or using salinity changes in the estuary to understand the salt flux. The calculated salt flux is attributed to the movement of freshwater in and out of the estuary. As seen in Fig. 10, the residence time in the prohibited section was closer to 2.5 days, while in the conditional area it was less than 0.5 days, showing a remarkable difference between two adjacent areas of the Medomak River Estuary. This residence time was corroborated by the drifter releases, where drifters released at the southern end of the prohibited area remained for several hours without moving appreciably, while drifters released from the southern portion of the conditional area generally left in 4 h (Fig. 10).

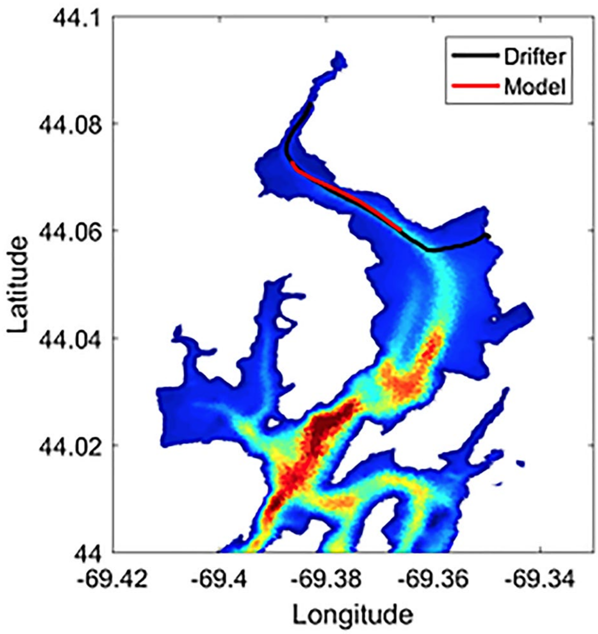


Fig. 9 Drifter data incorporation. The black line showing a drifter track, and a red line showing the particle trajectory within the model. This figure shows the differences between model and drifter track over bathymetry map

Discussion

In this section, we review our sustainability-science approach, implications of the drifter study, and recommendations for future management. Our approach cultivated a co-development of knowledge centered around the hydrodynamics of the MRE, as well as new collaborative spaces for future work in developing management strategies. The drifter study highlighted the connectivity between geomorphology, wind, tidal forcing, and residence time. Finally, this study resulted in three recommendations for state managers to better determine residence and closure time for water quality issues.

Sustainability Science Approach

Our sustainability science approach created the foundation for new community-led projects and policy recommendations that have directly informed decision making. Revisiting sustainability commitments listed above each of the research questions were identified and co-produced through semi-structured interviews, participation in community meetings, and active listening to partners (Kates et al. 2001; Clark et al. 2016; Lang et al. 2012; McGreavy et al. 2015). This process was continuous, where collaborators met and discussed the research progress and integrated new knowledge throughout the entire project and beyond. Hydrodynamic data collection and analysis were immediately shared with community partners so they could stay involved and informed as research moved from fieldwork to analysis. Finally, in recognition of his extensive contributions to fieldwork and support in analysis, Glen Melvin, the vice-president of the Waldoboro Shellfish Committee was invited to be a co-author. This invitation reflects his commitment to the collective work and promotes partner equity (McGreavy and Hart 2017). The approach facilitated long-lasting and productive partnerships that have resulted in management recommendations, and new collaborations on future projects (Clark et al. 2016; Lang et al. 2012). Follow-up studies are required to test the multiple environmental factors mentioned in our interviews; however, our oceanographic modeling coupled with this engaged research process serves to connect harvester questions with community driven science, as well as broaden baseline understanding of the circulatory patterns in the MRE for future work.

Drifter Study Implications

Our results showed relationships between geomorphologically driven tidal transport and pollution closures, as there were clear connections between transport patterns and pollution closures. We found that tidal forcing during running tides, wind forcing during slack tides, and cross sectional area of the estuary all had an impact on the flushing mechanisms within this estuary. However, the magnitude of each of these factors shifts depending on where the drifters were within the estuary. Retention, identified by the patterns of drifter releases and driven by tidal forcing, may explain the extent of mudflats in this area. Flood dominant estuaries tend to cause resuspension of sediment that settles out during the lower ebb tide flow. The relatively wide nature of the Medomak estuary south of Waldoboro which eventually narrows to a southern constriction also helps the system retain particles. But this type of circulation may also indicate that bacteria can remain in the estuary past one tidal cycle. Wind-driven transport and secondary flow at estuarine bends can relate to differing pollution issues found in these areas (Chant 2002). Polluted waters from upstream, depending on the direction of wind forces and helical flow around the bend in the estuary, could be trapped in areas like the West Side, Sampson's Cove, or Long Cove, areas where drifters tracked water masses pushed away from the channel (Figs. 2 and 8). The effects the cross-sectional area has on the estuary most likely means that water downstream of the southern constriction will be unable to re-enter the estuary. This is an important concept, as below this constriction, pollution from downstream areas may have little effect on this upper section of the Medomak River (Chapra 2011, Fig. 7).

By incorporating this data co-collected with clammers into a hydrodynamic model, we are improving our estimates

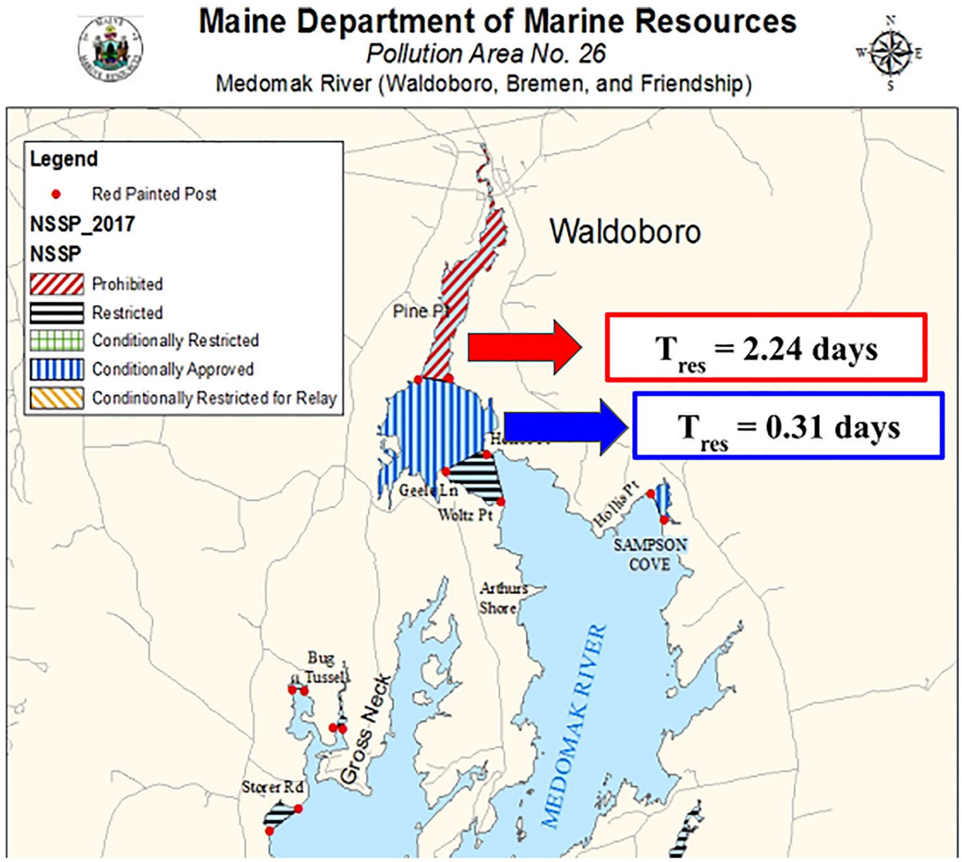


Fig. 10 Residence time calculation. Overlaying a map of the Medomak, there are two white boxes referring to the residence time of the prohibited (red) and conditional (blue) closed areas

of residence time for bacteria, and how it varies spatially. Estimates of residence time help identify areas of particular susceptibility to bacterial pollution (Fig. 10). Residence time is directly related to how long polluted water will remain in an area, impacting clam flats but this understanding will ultimately need to be linked to the residence time of bacteria in clams. With a better understanding of overall residence time, as well as the other hydrodynamic factors that relate to it (wind, tidal forcing, cross-sectional area) management has the ability to adapt more flexible and targeted bacterial closures. For example, the conditional closure time of nine days was developed through work done by the Medomak Taskforce and a clam meat study run by the DMR and could be repeated with shorter exposure times as supported by data collected in this study. From a management perspective, areas with a shorter exposure to pollution levels could have a shorter closure time, allowing for clam flats to be open more often.

Future Management

This research supported the development of three specific recommendations for state managers. First, focusing on wind conditions during 2.54 cm closures would allow stakeholders to explore seasonal wind shifts and how they interact with residence time. Second, managers should reexamine the sampling methodologies for bacteria laden waters, particularly focusing on taking samples at multiple depths to understand freshwater plume interactions with mudflats, and the timing with the tides. This would allow for stakeholders to explore how lateral mixing may play a part in the movement of bacteria toward the clamming areas. Finally, it would be valuable to recreate a clam meat study, where clams are exposed to polluted waters for periods of time corresponding to higher resolution residence time calculations. This would allow for a deeper understanding of how exposure time and purge time within the clam interact.

These recommendations have already informed decision making at the state agency level, where DMR representatives have agreed to keep wind direction data as part of their sampling methodology. There have also been discussions on increasing the number of weather stations nearby to get more accurate wind speed data for future model implementations using more highly resolved wind fields. Future talks are already scheduled to discuss new closure types based on hydrodynamic data. This type of meeting and continuous engagement is reflective of multiple aspects of sustainability science, particularly the commitment towards fostering structures where this knowledge is used through involvement (Clark et al. 2016).

Conclusion

Our engaged approach to tidal modeling research resulted in knowledge that extends understanding of hydrodynamics in the Medomak River estuary as well as knowledge that is useful for a range of potential decision-making applications for our partners and water and shellfish resource managers more broadly. Findings from this work have been shared between multiple state agencies, the Waldoboro Shellfish Committee, the Maine Shellfish Advisory Council, and the town management of Waldoboro, ME. The model predictions of current flows and particle releases are being used by clammers to inform their own community-led projects in the clamming industry which demonstrates saliency and credibility in the community. For example, in Waldoboro, ME Glen Melvin along with other leaders of the Waldoboro Shellfish Committee are seeding flats based on recommendations generated by our validated model. Recommendations were made by generating plots of residual currents in areas where the Shellfish Committee had implied they were productive in terms of landings, and that had been impacted by water quality closures. The Waldoboro Shellfish Committee determined the orientation and location of netted areas in Sampson's Cove based on the maps of the residual currents.

As a result of our collaboration and our attention to sustainability science commitments, the model output is more accessible and useful to the community. It has influenced decision-making on a local scale, highlighted by the development of this seeding project, and subsequent conversations for future community-driven work. On a regional scale, other large clamming communities such as Thomaston and Brooklin, ME are engaging in new and meaningful ways to build community-engaged projects centered on deploying drifters. The type of engagement demonstrated in this study may be a model for communities outside of the shellfish industry, including national and international communities that manage resources locally. The engaged approach and protocols presented can help disseminate costs and create a diversification of resources available for local managers. This could be particularly important in underprivileged or minoritized communities where financial and social resources may be more limited. Longer term partnerships created in a similar manner can also cultivate a diverse and responsive team that is able to both conduct research and help apply research to local management decisions. Moreover, if oceanographic and climate modeling efforts involve communities in multiple ways through a participatory approach, these models may also become more trustworthy and influence management (Ingram et al. 2018; Falconi et al. 2017; Tuler et al. 2017). Involving communities could include: inviting and collaborating with community contacts in ground truthing studies; sharing findings for weather scenarios related to water quality issues in the community; and making those models more accessible to a larger public base. Shellfish harvesting communities around the globe using more accessible and relevant model information can start to create more accurate water quality closures, therefore reducing economic and social impacts from closures and possibly making their shellfish safer for consumption. By using an engaged research practice as demonstrated above, scientists can create a more cooperative space between themselves and communities where results from scientific findings will be more effective in terms of real-world applications.

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