Surface currents in Eastern Bay – a dispersal mechanism for eelgrass (*Zostera marina*) seeds

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Surface currents are an important part of eelgrass restoration, as fronds bearing seeds float in surface currents. With a greatly expanded data set, we report an analysis of drift buoy recordings in Eastern Bay, showing that there is a net outward (eastward) flow. As part of this analysis, we present a new method for displaying a large (18K records) data set with 3 independent and 2 dependent variables.

Eelgrass (*Zostera marina* L.) reproduces both by rhizomes and by seeds. The latter are probably very important in the reestablishment of eelgrass beds in denuded areas. Seeds are produced on flowing stalks that detach and float off, carrying the seeds. When the stalks finally disintegrate, the seeds are dropped to the bottom[7]. Since 2007, we[2,3,4] have been restoring eelgrass by transplanting shoots into areas previously covered with eelgrass beds but currently denuded. For maximum efficiency, we desire to transplant flowering shoots into areas where the currents will carry the seeds to suitable substrate, which requires knowledge of the surface currents in our estuary. Prior information on these currents is limited to that previously reported[5]. We now report on a much larger data set, and with a new graphical method of presentation that can deal with the many variables. Methods of data collection are as previously presented[5]; in summary, one or two un-tethered buoys containing a GPS receiver and a telemetry transmitter were released during daylight hours, sending latitude and longitude information every 2 minutes to a network of receivers. The velocity (speed and direction) for that position is calculated for each pair of points and assigned to the recorded position and time in the tide cycle, which is calculated from GPS clock time and the time of high tide as determined from NOAA tide tables[6]. Data reduction was done by programs written in JustBASIC[8].

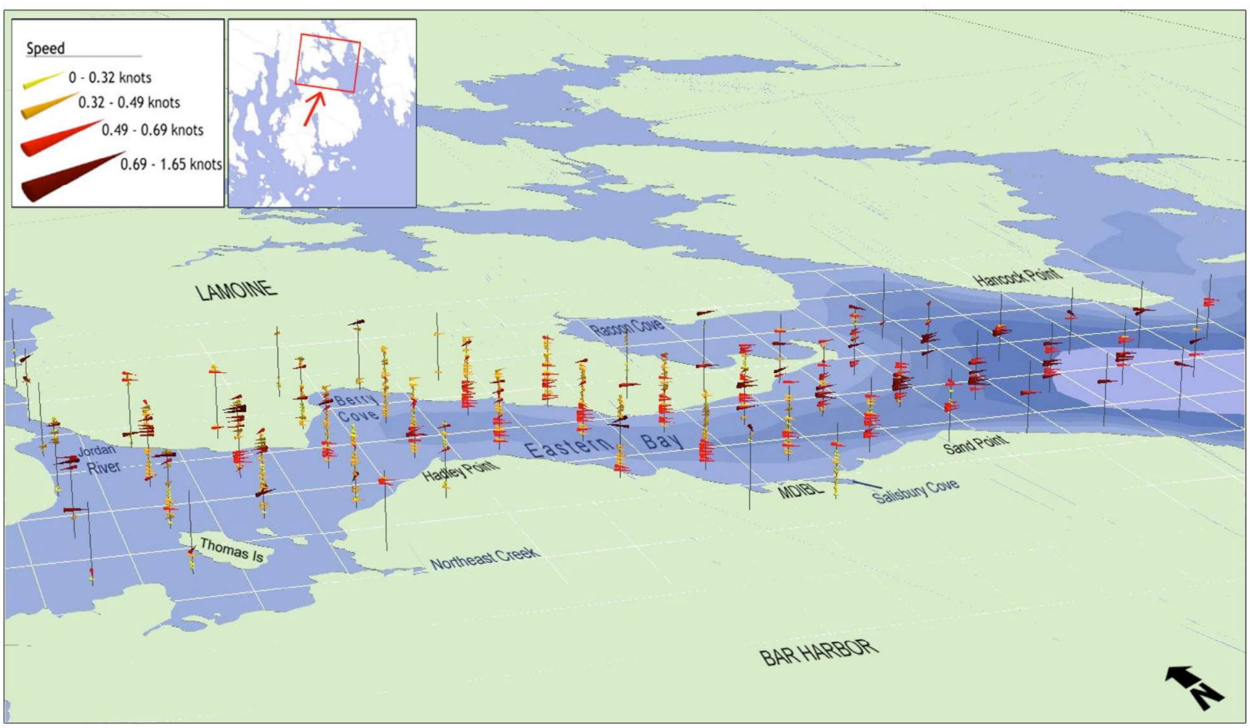

Figure 1. A three-dimensional plot of the entire data set, superimposed on a map of Eastern Bay. The grid represents the boundaries of the position rectangles (0.25 nm by 0.19 nm); the vertical lines are axes of the time after high tide, from 0 (bottom) to 12.5 (top) hours. Data apparently plotted on land are the result of position rectangles that include some water, from which the data were obtained. There are clearly some gaps in the coverage, especially toward the western end of the bay. It was not practical to include the number of observations with each arrow.

Half-hours after high tide	N	AVG SPEED	AVG DIR	EAST	SOUTH	WEST	NORTH	**EGV**
0	755	0.4	140.07	330	109	115	201	**0.260**
1	768	0.44	123.61	441	94	74	159	**0.369**
2	835	0.47	125.79	522	95	72	146	**0.383**
3	847	0.5	122.88	502	127	60	158	**0.421**
4	885	0.49	125.46	516	150	65	154	**0.402**
5	838	0.54	127.91	510	135	62	131	**0.423**
6	784	0.55	130.41	478	125	75	106	**0.421**
7	795	0.53	128.91	452	138	75	130	**0.412**
8	767	0.47	134.86	351	137	107	172	**0.331**
9	770	0.45	149.59	346	144	142	138	**0.228**
10	745	0.45	156.3	319	117	153	156	**0.180**
11	783	0.44	146.16	322	185	112	164	**0.247**
12	768	0.41	155.64	290	180	130	168	**0.168**
13	762	0.41	166.31	266	148	201	147	**0.097**
14	765	0.41	181.31	213	133	247	172	**-0.009**
15	692	0.41	182.48	179	135	218	160	**-0.018**
16	710	0.43	197.97	148	145	275	142	**-0.133**
17	821	0.47	206.15	165	162	337	157	**-0.207**
18	816	0.47	198.39	161	163	318	174	**-0.148**
19	849	0.44	204.27	131	183	343	192	**-0.180**
20	798	0.41	196.46	164	150	328	156	**-0.116**
21	813	0.41	194.82	190	158	291	174	**-0.106**
22	743	0.4	165.7	242	132	182	187	**0.098**
23	350	0.41	154.36	114	59	58	119	**0.176**
24	230	0.43	130.62	87	24	41	78	**0.326**
			Totals	**7439**	**3328**	**4081**	**3841**	

Table 1. Tabulation of data from 2009-2011, by half-hours after high tide. Number of observations, average current speed in knots, average current direction in degrees true. "EAST" through "NORTH" are the number in

The area of interest is a rectangle bounded by 44°24'30"N/68°12'30"W and 44°29'00"/68°22'00", covering Eastern Bay, Hancock Co., Maine. This area was divided into 200 grid squares, each 0.25 minutes (latitude or longitude) on a side, resulting in rectangles 0.25 nautical miles north-south and 0.1874 nm east-west. When empty squares were eliminated (mainly grid squares lying entirely over land), this resulted in 55 occupied grid squares. Averaged velocity data from within each square were assigned to the center of the square. Data were also divided into 30-minute periods following the last high tide; this resulted in 230 to 885 point-pairs for each tide period. (The smallest number represents a short period, since high tides repeat every 12 hours 26 minutes on average.) For each 30-minute tide period, each data point was assigned to its position block. Each grid square thus contains a number of points divided into 25 tide periods. To create Figure 1, a three-dimensional representation of Eastern Bay was created[1], a projection of the grid squares was overlaid on it, and the average data for that block and tide period were plotted against the block center on an apparent vertical axis, with half-hour tide periods (time after high tide) ranging from 0 (bottom) to 24 (top). Arrow length represents the speed of the current; arrow direction is the current direction. To further aid in discriminating between speeds, the arrows are colored according to the legend; in general, darker colors are higher speeds. Note the prevalence of eastward directed arrows, especially in the waters east of Hadley Point.

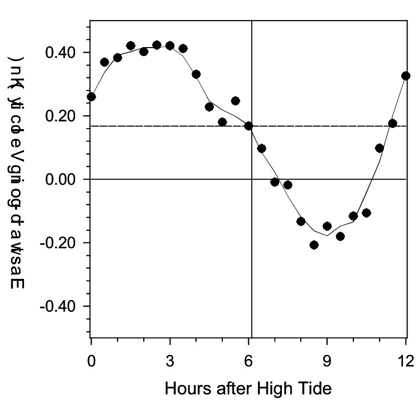

Figure 2. Eastward-going velocity (EGV) vs. tide stage, for all locations. While peak current speed occurs at the expected times (~3 hours from high tide), the current is not symmetrical around zero (solid line) but rather around 0.1677 (dashed line).

Another way to summarize these data is to divide the directions of movement into the 4 cardinal directions (East between 45° and 135°, etc.) and enumerate the instances of each. Table 1 gives this summary. Note that there are many more entries in the "East" quadrant than in any other. A better way of representing these data is to calculate the eastward-going velocity (EGV) by resolving all velocity vectors into their north-south and east-west components. This can be done easily by forming [sin(direction)](speed), which is the EGV. These values are listed in the last column of Table 1. If the currents were driven only by the tides, one would expect this average to be statistically not different from zero, as water moves symmetrically throughout the tide cycle. We find, however, an average eastward current of 0.1677 ± 0.00007 knots (mean ± SE for N = 18689 observations), for which $t = 20.04$; the probability this result could be chance alone is vanishingly small. This average current amounts to over 4 nautical miles per day.

If the only driving force moving the surface water were the tides, and if the tides were symmetrical, one would expect a symmetrical graph of EGV vs. tide stage, and the velocity would be symmetrical around zero. Figure 2 shows that this is not the case, and that there is more flow out of (eastward) then into Eastern Bay.

While there are still some gaps in the data set, particularly at the western end farthest from the laboratory, we can verify our previous preliminary conclusions. 1) There are often currents that could carry propagules from our oldest transplanted area west of Hadley Point toward the Lamoine shore, which seem to be the reason for the recent identification of young eelgrass beds at the latter sites[5]. We need to identify other trends to guide future transplantation efforts. 2) Averaged over the tide cycles, there seems to be a general eastward trend to the currents, as might be expected from the fresh water input to Eastern Bay (Northeast Creek, primarily) and the prevailing westerly winds. 3) Many records show a buoy movement that is circular or contrary to the assumed tidal current flow, which would lead to shoot fragments "stalling" in eddies. This may be very important for determining the locations of seeding in *Zostera marina*. 4) While the coast of Maine is subject to periodic shellfish closures due to red tide (*Alexandrium* sp.), there has never been a closure in upper Frenchman Bay. This has resulted in a concentration of shellfish harvesters during red tide events, with great damage to the eelgrass beds. We suspect that the failure of the red tide organism to enter the bay is due to the prevailing current, since an eastward flow in Eastern Bay translates to a southward flow in the main bay, which is the direction toward the open ocean. 5) The use of the pseudo-3D projections available in ArcScene[1] makes presentation of such a mass of data with so many variables a practical matter.

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