

Velocity skew controls the flushing of a tracer in a system of shallow bays with multiple inlets

I. Palazzoli^{1,2}, N. Leonardi³, A. M. Jiménez-Robles^{1,4}, S. Fagherazzi¹

Highlights:

- Wind currents and differences in tidal phase and amplitude along the inner shelf are an effective mechanism for flushing tracer out of a coastal bay with multiple inlets
- Velocity skew at the inlets directly controls the tracer flushing time
- A simple, single-parameter exponential model is used to determine the decrease in tracer mass in the coastal bays

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14 Key Points:

15 • Wind currents and differences in tidal phase and amplitude along the inner shelf are an
16 effective mechanism for flushing tracer out of a coastal bay with multiple inlets

17 • Velocity skew at ~~the~~ inlets directly controls ~~the~~ tracer flushing time

18 • A simple, single-parameter exponential model is used to determine the decrease in tracer mass
19 in the coastal bays

20

21

22 **Abstract**

23 The exchange of dissolved constituents between a shallow bay and the ocean is governed by
24 regular tidal fluxes as well as by wind generated storm surges and currents. These mechanisms
25 regulate the rate at which pollutants and nutrients are removed from the lagoons. Here we
26 determine the main hydrodynamic drivers controlling the removal of a conservative tracer from a
27 bay with multiple inlets. The transport of the tracer is simulated using the numerical model
28 Delft3D in a system of shallow lagoons along the coast of the Delmarva Peninsula, Virginia. The
29 tracer flushing time is evaluated using the Eulerian approach and the decay of the tracer
30 concentration in time is approximated with an exponential curve. We assess the influence of tidal
31 amplitude, local winds, and time of release of the tracer with respect to the tidal cycle on
32 flushing time. Results show that wind-driven fluxes are a prevailing factor controlling the tracer
33 transport and, therefore, the tracer concentration within the lagoons. Variations in tidal phase and
34 amplitude along the inner shelf also promote the flushing of the tracer out of the bays, while the
35 time of tracer release with respect to the tidal phase has been found to play a relatively negligible
36 role. The tracer flushing time is proportional to a velocity skew index, accounting for the
37 asymmetry of the ebb-flood velocities at the inlets, while the tidal prism has minimal effect on
38 flushing time. Our simulations revealed that the average flushing time of these bays is around 24-
39 27 days, decreasing to 21 days if favorable wind conditions exist. Finally, a simplified approach
40 is presented to compute the decay of tracer concentration in time as a function of hourly variable
41 wind characteristics as well as seasonal changes in meteorological conditions, without the need
42 of large scale simulations.

43 **1 Introduction**

44 Estuaries and bays are affected by the release of pollutants and nutrients that deteriorate water
45 quality and put ecosystems at risk (e.g. Cavalcante et al. [2012]). Therefore, there is a need to
46 determine the fate of these pollutants and quantify how long it takes for the pollutant to be
47 exported to the open ocean. The decay rate and the flushing time of contaminants injected into a
48 bay is regulated by coastal hydrodynamics [Braunschweig et al., 2003].

49 Fugate et al. [2006] estimated the spatial distribution of residence time in Hog Island Bay,
50 located at the center of the Virginia Coast Reserve (USA). Residence time in the lagoon was
51 found to be sensitive to variations in wind, tidal range, and tidal stage. Moreover, their results

52 revealed that in lagoons regulated by shallow friction the residence time has low values near the
53 inlets, while it becomes higher near the mainland. Safak et al. [2015] found that the residence
54 time near the inlets is influenced by the tidal phase at the moment of particles release, whereas it
55 is affected by wind in the inner parts of the bay. Finally, the exchange of water volume in the
56 same bays was derived from remote sensing images and in situ tracers by Allen et al. [2011].
57 They found that about half of the water volume is flushed out of the bay during each tide cycle,
58 while the other half is left inside the system and it is exported at a slower rate.

59 However, a comprehensive and systematic analysis of all processes determining the flushing of
60 a tracer is still lacking. The main purpose of this study is to understand the hydrodynamic
61 conditions under which a tracer is flushed out at the fastest rate. Particular attention is devoted to
62 water circulation induced by wind and variations in tidal phase and amplitude along the shelf,
63 which are shown to be the most effective processes flushing this system.

64 We compute the flushing time of the bays in order to compare different physical drivers.
65 Flushing time, water age, exposure time, and residence time are timescales that describe the
66 exchange and transport of water and dissolved materials in a coastal sea [Rayson et al., 2016;
67 Monsen et al., 2002; Takeoka, 1984]. The residence time quantifies the retention time of water
68 within a defined control volume, and it is a frequently used metric to evaluate the transport of
69 substances [Braunschweig et al., 2003] and to determine the ability of tides to remove pollutant
70 from a semi-enclosed water body [Patgaonkar et al., 2012]. This parameter depends on tidal
71 range, bathymetry, stratification, wind, and freshwater runoff and is considered to be a local
72 measure that varies in time [Choi and Lee, 2004]. Another commonly used transport time scale is
73 the flushing time which measures the average time that water and its constituents spend within a
74 reservoir before being flushed out [Du et al., 2018]. Flushing time is a bulk parameter that
75 quantifies the overall flushing of the system, and it only describes the renewal capability of a
76 waterbody without taking into account the physical processes that regulate the exchange of
77 material and their spatial distribution [Du et al., 2018; Rayson et al., 2016; Monsen et al., 2002].

78 The second goal of the paper is to determine whether tidal prism and variations in tidal phase
79 and amplitude at the inlets control the flushing time of the bays. A **higher** tidal prism during
80 spring tides or wind setup increases the exchange of water between bays and the ocean, likely
81 exporting more tracer. Tidal phase differences along the coast lead to asymmetric fluxes,
82 promoting tracer flushing. This is because a tidal phase lag between inlets produces surface

83 water gradients in the bays that drive residual circulation. This residual circulation decreases
84 flushing time [Herring and Winter, 2015].

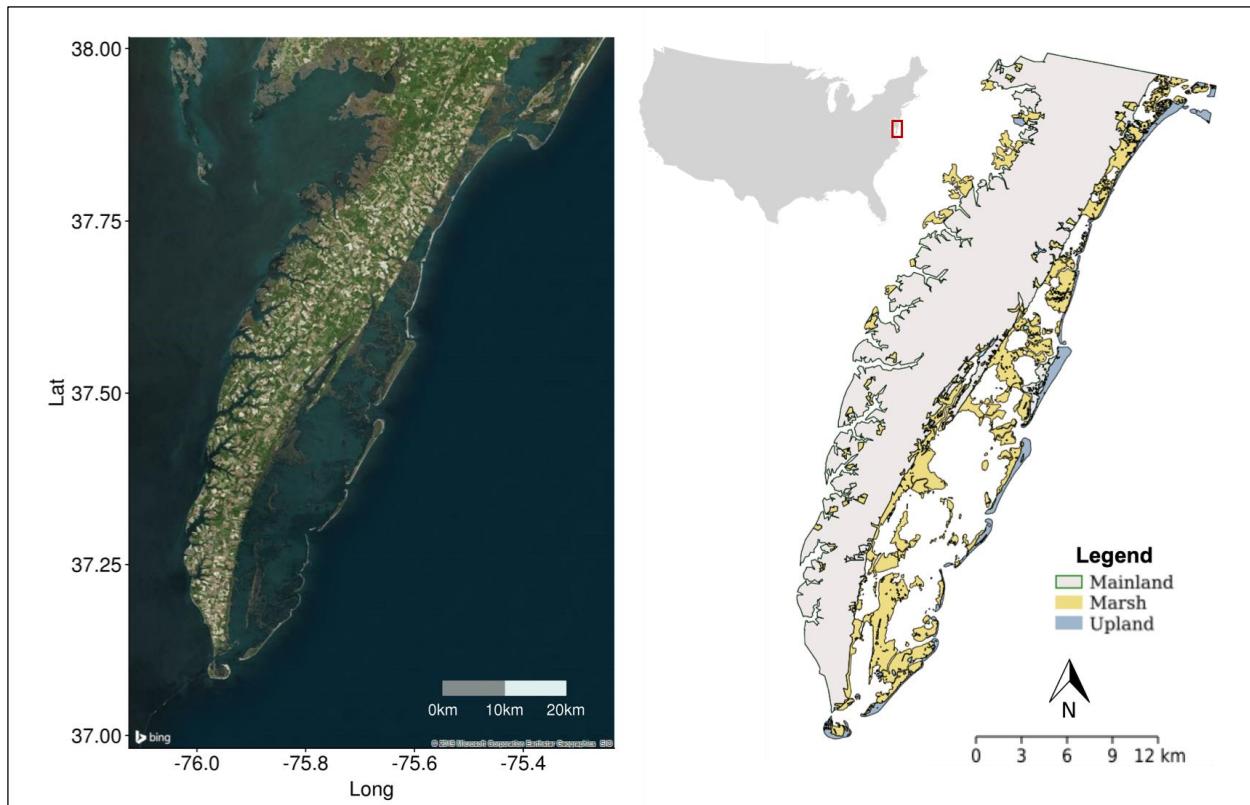
85 The third goal of this paper is to reduce the description of the system dynamics to a single-
86 parameter model, in order to facilitate the comparison of flushing time values under different
87 external agents. A single-parameter model allows the fast determination of flushing time as a
88 function of tidal and wind conditions without the need of expensive 2D simulations. Lagrangian
89 (particle tracking) and Eulerian (tracer patch) methods are typically used to analyze transport
90 time scales in estuaries. The Lagrangian approach explicitly simulates the trajectories of
91 individual tracer particles and registers the time when they leave the domain providing spatial
92 and temporal variations in residence time; the residence time is defined for each water parcel,
93 and this approach is thus frequently employed to relate the time-varying position of particles to
94 the point of their initial release [Rayson et al., 2016; Andutta et al., 2013; Braunschweig et al.,
95 2003; Monsen et al., 2002]. On the other hand, the Eulerian approach might be more suitable for
96 the residence time evaluation in the entire domain [Aikman and Lanerolle, 2004]. Eulerian
97 formulations can be more easily translated into a single-coefficient parametrization to describe
98 the decay of mass within a lagoon [Cucco et al., 2009]. Moreover, the Eulerian approach
99 properly models the advection and diffusion processes [Deleersnijder et al., 2001]. Flushing time
100 can also be estimated with the freshwater fraction method. This approach involves the
101 calculation of the total volume of freshwater found in an estuary and it estimates the flushing
102 time as the time taken to replace the existing freshwater in the estuary at the same rate of the
103 freshwater input [Guo and Lordi, 2000; Williams, 1986; Dyer, 1973]. The application of the
104 Lagrangian and Eulerian methods to study the hydrodynamics of lagoons and the relationship to
105 particle residence time has been presented in several studies. Safak et al. [2015] used the
106 Lagrangian particle tracking method to evaluate both the residence time of neutrally buoyant
107 particles and their exchange between the bays of the Virginia Coast Reserve system. The
108 residence time obtained with this approach was low, varying from a few hours to a few weeks
109 depending on the release location; this result was probably due to a relatively short simulation
110 period (two months), and to the fact that residence time estimates the time particles need to reach
111 the boundary of the domain without reentering once they exit the inlets. Defne and Ganju [2014]
112 employed a Lagrangian model for the analysis of particle trajectories and employed different
113 methods for the evaluation of the residence time in an estuary. They found that, when the

114 simulation period is too short, the residence time given by ensemble averaging the residence time
115 of each particle in the domain does not account for the particles that remain in the domain.
116 Burwell et al. [2000] compared the Eulerian and Lagrangian methods in predicting the residence
117 time of neutrally buoyant particles in a bay. The Eulerian method gave a good description of the
118 residence time variations in the bay, but it was affected by diffusion which produced lower
119 residence times compared to those produced by the Lagrangian method. In addition, the
120 Lagrangian approach was better suited to describe the spatial distribution of residence time, but it
121 presented limitations due to its sensitivity to the number of particles simulated in the model and
122 the eddy diffusivity value, which is set a priori and it is assumed to remain constant in time.
123 Delhez and Deleersnijder [2006] developed an Eulerian procedure that is equivalent to the
124 Lagrangian method and allows estimation of residence time as a function of space and time. This
125 adjoint method presents the advantage of delineating the fine spatial distribution of the particles
126 in the domain in space and time, while reducing the difficulties associated with the Lagrangian
127 representation of a spatially variable diffusivity.

128 Herein, we follow results from Cucco et al. [2009] who state the Eulerian approach is more
129 suitable to investigate the long-term flushing of substances from a tidal embayment. We evaluate
130 the fluxes of a conservative tracer within a system of shallow coastal bays along the Atlantic
131 coast of the USA, in the Virginia Coast Reserve (VCR). The transport of the tracer and its
132 flushing time are examined under different external forcing conditions, such as of tides and wind
133 induced currents. The tidal flow and the circulation of water and tracer are simulated using the
134 hydrodynamic model Delft3D-FLOW [Lesser et al., 2004; Roelvink and Van Banning, 1994].
135 The Eulerian method is applied to evaluate the time evolution of the spatially-averaged flushing
136 time.

137 **2 Study area**

138 The Virginia Coast Reserve (VCR) is a system of shallow coastal bays that extends for 100 km
139 along the Atlantic Coast of the southern portion of the Delmarva Peninsula, USA (Figure 1).



141
142 **Figure 1.** On the left, Virginia Coast Reserve along the Delmarva Peninsula. On the right, main
143 land cover types found in the study area (<https://www.vcrler.virginia.edu/home2/>).

144
145 The peninsula is bounded by Chesapeake Bay to the West and by the Atlantic Ocean to the
146 East. VCR includes 14 barrier islands protecting bays of different size. The small watersheds
147 found in the upland part of the study area supply a negligible amount of fluvial freshwater and
148 sediment to the lagoons [Nardin et al., 2018; Wiberg et al, 2015; Fugate et al., 2006], and the
149 water fluxes among different bays as well as the connection between bays and the ocean varies
150 significantly within the system [Wiberg et al., 2015]. The shallow bays present an average depth
151 of 1.0 m below mean sea level and are connected to the Atlantic Ocean by a network of channels
152 which have a mean depth of 5 m and become more than 10 m deep at the inlets [Nardin et al.,
153 2018, Mariotti et al., 2010]. Tides are semidiurnal and the mean tidal range is about 1.2 m [Safak
154 et al., 2015]. The principal wind directions are from SSE-SSW and N-NE and the highest wind
155 speeds are observed during the winter season [Fagherazzi and Wiberg, 2009].

156 Freshwater inputs to the VCR bays are minimal, and measurements of freshwater discharge in
157 three representative streams (out of 54) indicate an average discharge of $0.03 \text{ m}^3/\text{s}$ in each stream

158 [Anderson et al., 2009], so that the estimated total freshwater flux to the bays is less than 0.3%
159 the tidal prism. As a result, salinity variations in the bays are negligible. Salinity measurements
160 along two transects that run from the inlet to the mainland in the southern part of the Delmarva
161 Peninsula indicate average salinity of 31.0 ± 1.7 and 31.0 ± 1.1 ppt at the inlets, and 29.7 ± 2.7
162 and 29.0 ± 3.8 ppt at the landward shore of the bay [McGlathery et al. 2018]. Tidal exchange
163 dominates transport processes in these bays and it has been the subject of previous studies [e.g.
164 Wiberg et al., 2015; Fagherazzi and Wiberg, 2009; Fugate et al., 2006], but many mechanisms,
165 such as those responsible for the flushing of pollutants and temporal variations in flushing time,
166 remain unclear.

167 **3 Methods**

168 **3.1 Model description**

169 The hydrodynamic model Delft3D-FLOW [e.g. Lesser et al., 2004; Roelvink and Van
170 Banning, 1994] was used to reproduce the hydrodynamics and transport of tracers in the VCR
171 bays under tidal and wind forcing. The domain of the study area was delineated by a numerical
172 grid of dimension 459x200, and cell size of 250x250m. Three open boundaries were defined
173 along the East (Atlantic Ocean), South, and North sides of the domain (Figure 2). Given that
174 VCR has no significant fluvial sources of freshwater and the salinity is overall uniform, the
175 domain of the study area was composed of one vertical layer (2D), as in several other previous
176 studies conducted over the same region [Nardin et al., 2018; Wiberg et al., 2015; Mariotti et al.,
177 2010].

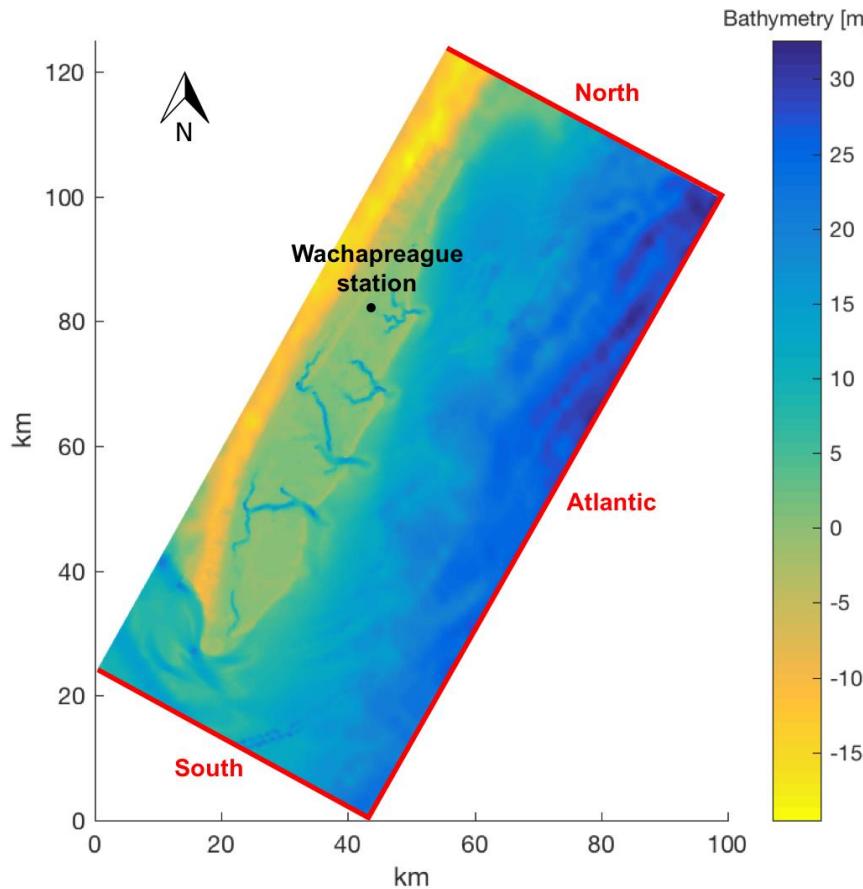
178 The water level was defined on all open boundaries by superimposing the various tidal
179 harmonics with their corresponding phases and amplitudes. In a first set of simulations we used
180 as boundary conditions the tidal harmonics obtained from the NOAA Wachapreague Station
181 (8631044, Wachapreague, Virginia, USA). The amplitude and phase were adjusted to account
182 for the propagation and amplification/dissipation of the tide in the lagoons and to properly
183 reproduce the measured tides at the location of the Wachapreague station.

184 In a second set of simulations the phase and amplitude were assumed to vary along the open
185 boundaries in order to account for spatial differences of the tidal signal in the Middle Atlantic
186 Bight. These differences were small, but they can affect residual tidal currents. Specifically, the
187 North and South boundaries (Figure 2) were divided into five segments, while the Atlantic

188 boundary was split into 10 segments. The amplitude and phase of the end points of each segment
189 were derived from the ADCIRC Tidal Database for the Atlantic Ocean [Mukai et al., 2002], and
190 then linearly interpolated by Delft3D so that the model could reproduce the regional tidal
191 forcing.

192 The presence of vegetation was accounted by means of a spatially varying Chezy coefficient
193 for bed roughness. The coefficient was set equal to $65 \text{ m}^{1/2}/\text{s}$ in the marshes and $45 \text{ m}^{1/2}/\text{s}$ in the
194 rest of the grid [Safak et al. 2015; Wiberg et al. 2015]. The tracer introduced in the model was
195 non-active and had no settling velocity. Sediment transport processes, as well as possible
196 morphological changes were neglected. The initial tracer concentration was equal to one at every
197 grid cell of the domain inside the lagoons and to zero for ocean and upland cells, with a clamped
198 condition (zero tracer concentration) at the boundaries.

199 When wind is present, a spatially constant wind speed was applied to the entire domain. The
200 wind exerts drag that was implemented as a surface shear stress term in the momentum
201 equations. The magnitude of the shear stress was computed as $\tau = \rho C_d U_{10}^2$, where U_{10} is the wind
202 speed 10 meter above the free surface, ρ the density of air, and C_d the wind drag coefficient,
203 which was assumed not to vary with wind speed and to be equal to 0.00723.



204
 205 **Figure 2.** Bathymetry, boundaries of the domain of the study area, and location of NOAA
 206 Wachapreague station (8631044, Wachapreague, Virginia, USA).

207 3.2 Model validation

208 Following Cunge [2003], model calibration relies on careful adjustment of the tidal boundary
 209 conditions. This is consistent with the results of Abbott and Cunge [1975] who showed that
 210 adjusting the boundary conditions, rather than adjusting friction, was a more reliable approach to
 211 the calibration of estuarine models. The same approach was adopted by Wiberg et al. [2015] and
 212 Mariotti et al. [2010] for the VCR bays. The calibration of the boundary conditions was done by
 213 comparing simulated water levels with water levels measured at Wachapreague station, for the
 214 period from April 1st (time 00:00:00) to April 5th, 2015 (time 00:00:00). The model performance
 215 was evaluated with two statistics: the model efficiency, ME, and the root mean squared error,
 216 RMSE [Mariotti et al., 2010]. Both phase and amplitude at the boundaries were varied until
 217 reaching the maximum model efficiency. The values calculated were 0.97 for ME and 0.26 m for
 218 RMSE. The amplitude and phase at Wachapreague station before (observed values) and after the

219 calibration (calibrated values) are presented in Table S1.

220 To test the reliability of the model we computed the difference in amplitude and phase between
221 the main harmonic constituents measured by NOAA at the Wachapreague station and the
222 harmonic constituents simulated by Delft3D with the ADCIRC boundary conditions (Figure S1).
223 The extraction of the harmonic constituents from the modeled water level was carried out using
224 the T_tide Harmonic Analysis Toolbox [Pawlowicz et al., 2002]. The model validation gave
225 excellent results, with amplitude differences of less than 2 cm and phase differences of less than
226 12 degrees (*VARYING TIDE* scenario, Figure S1). For comparison, we also plotted the difference
227 in amplitude and phase using the modified Wachapreague tidal signal along all boundaries
228 (*SPRING&NEAP* tide scenario, Figure S1). This model performed very well, although it led to
229 slightly higher phase errors due to the neglect of phase variations along the Atlantic boundary.

230 3.3 Simulation scenarios

231 The performed simulations are meant to explore whether the flushing time and the decay of the
232 tracer can be altered by one the following: i) differences in the time of release of the tracer with
233 respect to the tidal cycle, ii) tidal amplitude, iii) variations in tidal phase and amplitude along the
234 inner shelf, iv) shelf currents and varying tide along the boundaries, and v) wind conditions.

235 To study whether differences in the time of release affect the flushing of the tracer, a base
236 scenario, called standard simulation (*STD*), was run based on the average values of tidal
237 amplitude and frequency of the first six harmonics (M2, S2, N2, K1, M4, O1) at the open
238 boundaries. The same simulation was run twice, once starting from ebb conditions (*STD EBB*)
239 and once starting from flood conditions (*STD FLOOD*). For both cases, the initial water level
240 was around mean sea level. In a second set of simulations the tracer was released in
241 correspondence of high (*HIGH WL*) and low tide (*LOW WL*) at the open boundaries.

242 To determine whether tidal amplitude affects flushing time, we ran a simulation with the
243 smallest amplitude associated to the N2 constituent, called *N2 AMPLITUDE*, and another
244 simulation with tidal amplitude equal to the sum of the amplitudes of the harmonic constituents,
245 combined to obtain the maximum tidal amplitude (*MAX AMPLITUDE*). Tidal amplitudes that
246 are much different from the measured ones are unrealistic. However, we chose to run these
247 hypothetical scenarios in order to expand the parameter space of the simulations, so that we can
248 better understand the processes controlling the flushing of a tracer. Other two simulations were

249 run by accounting for the gradual alternation between the spring and neap tide, given by the
250 combination of the first six harmonics (M2, S2, N2, K1, M4, O1). In one of these, the tracer was
251 released during spring tide (*SPRING&NEAP*), and in the other the tracer was released during
252 neap tide (*NEAP&SPRING*).

253 To account for the spatial variation of the amplitude and frequency of each harmonic
254 constituent along the Virginia shelf we simulated the tracer mass decay under the effect of a
255 realistic tidal forcing (*VARYING TIDE*). To determine the effect of currents on flushing time, we
256 **run a** simulation (*CURRENT*) where we added a shelf current of 3 cm/s moving from northeast to
257 southwest along the shore. The current velocity was imposed perpendicular to the north and
258 south boundaries and was derived from field measurements of circulation over the Middle
259 Atlantic Bight continental shelf [Lentz 2008].

260 To determine the effect of wind on flushing time, we **run** twenty-one simulations with a wind
261 **with** constant speed and direction. Eight wind directions (every 45°, with north equal to 0°), and
262 four values of wind speed, 5, 6, 10 and 12 m/s, were considered. The convention used to name
263 each of the simulations that involve the wind effect is the following: the first part of the name is
264 determined by the direction (e.g. the wind blowing from south is called *S*, and the wind coming
265 from south-east is called *SE*), while the second part of the name is the wind speed in m/s (e.g. the
266 wind blowing from north-west with a velocity of 5 m/s is labeled as *NW5*). *No Wind* indicates the
267 scenario without wind. The characteristics of all the scenarios simulated in this study are
268 described in Table 1. Wind constantly blowing from one direction for several weeks is
269 unrealistic. Similarly to Scully et al. [2013], we also ran two simulations including wind data
270 observed at the NOAA Wachapreague station during the winter and summer seasons of 2015
271 (*WINTER WIND* from December 21st, 2014 to March 20th, 2015, and *SUMMER WIND* from
272 June 21st to September 23rd, 2015). The measured wind data (Figure 3) in the summer period
273 included a block of missing values from September 1st to September 9th and these data were
274 ignored in the evaluation of the decay parameter. No wind was prescribed during such period.
275 All of the above simulations started at mean sea level during ebb, with the exceptions of the low
276 and high water level ones.

277

278
279**Table 1.** Parameters of the scenarios simulated with Delf3D.

Simulation ID	Initial time	Final time	Amplitude and Phase	Wind direction [°]	Wind speed [m/s]
STD EBB	01/04/2015	01/08/2015	Average amplitude*, null phase	-	-
	03:18 (MSL, ebb)	03:18m			
STD FLOOD	01/04/2015	01/08/2015	Average amplitude*, null phase	-	-
	21:19 (MSL, flood)	21:19m			
HIGH WL	01/04/2015	01/08/2015	Average amplitude*, null phase	-	-
	00:12 (High tide, ebb)	00:12 m			
LOW WL	01/04/2015	01/08/2015	Average amplitude*, null phase	-	-
	06:19 (Low tide, ebb)	06:19m			
MAX	01/04/2015	01/08/2015	Sum of amplitudes**, null phase	-	-
AMPLITUDE	04:24 (MSL, ebb)	04:24m			
N2 AMPLITUDE	01/04/2015	01/08/2015	N2 amplitude, null phase	-	-
	03:13 (MSL, ebb)	03:13m			
SPRING&NEAP	18/04/2015	18/08/2015	M2, S2, N2, K1, M4, O1	-	-
	17:23 (MSL, ebb)	17:23m			
NEAP&SPRING	12/04/2015	12/08/2015	M2, S2, N2, K1, M4, O1	-	-
	05:48 (MSL, ebb)	05:48m			
VARYING TIDE	01/04/2015	01/08/2015	M2, S2, N2, K1, M4, O1 from ADCIRC	-	-
	02:47 (MSL, ebb)	02:47m			
CURRENT	01/04/2015	01/08/2015	M2, S2, N2, K1, M4, O1 from ADCIRC	-	-
	02:47 (MSL, ebb)	02:47m			
SE6	01/04/2015	01/08/2015	Average amplitude*, null phase	135	6
	03:08 (MSL, ebb)	03:08m			
SE12	01/04/2015	01/08/2015	Average amplitude*, null phase	135	12
	02:29 (MSL, ebb)	02:29m			
SW6	01/04/2015	01/08/2015	Average amplitude*, null phase	225	6
	03:19 (MSL, ebb)	03:19m			
SW12	01/04/2015	01/08/2015	Average amplitude*, null phase	225	12
	03:28 (MSL, ebb)	03:28m			
NO WIND	21/06/2015	23/09/2015	M2, S2, N2, K1, M4, O1	-	-
	00:00 (MSL, ebb)	23:00m			

N5	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	0	5
N10	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	0	10
NE5	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	45	5
NE10	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	45	10
E5	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	90	5
E10	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	90	10
SE5	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	135	5
SE10	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	135	10
S5	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	180	5
S10	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	180	10
SW5	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	225	5
SW10	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	225	10
W5	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	270	5
W10	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	270	10
NW5	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	315	5
NW10	21/06/2015 00:00 (MSL, ebb)	23/09/2015 23:00m	M2, S2, N2, K1, M4, O1	315	10
WINTER WIND	21/12/2014 00:00 (MSL, ebb)	20/03/2015 23:00m	M2, S2, N2, K1, M4, O1	Observed data	Observed data

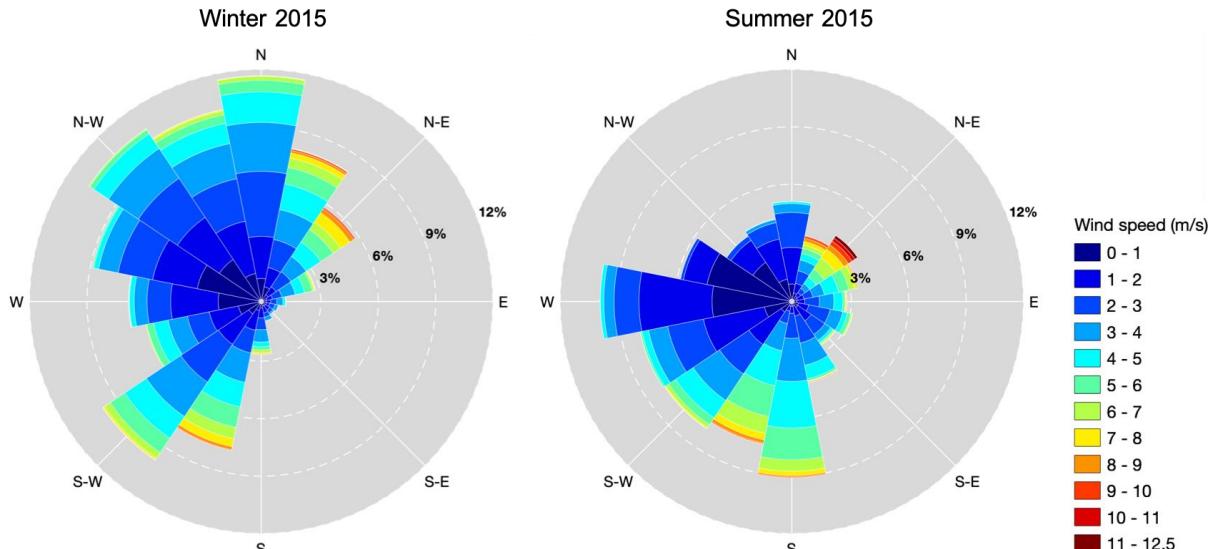
SUMMER WIND 21/06/2015 23/09/2015 M2, S2, N2, K1, M4, Observed Observed
00:00 (MSL, ebb) 23:00m O1 data data

* Average value of the amplitudes of the first six harmonic constituents, equal to 0.139425 m

** Sum of the amplitudes of the first six harmonic constituents, equal to 0.83655 m

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283



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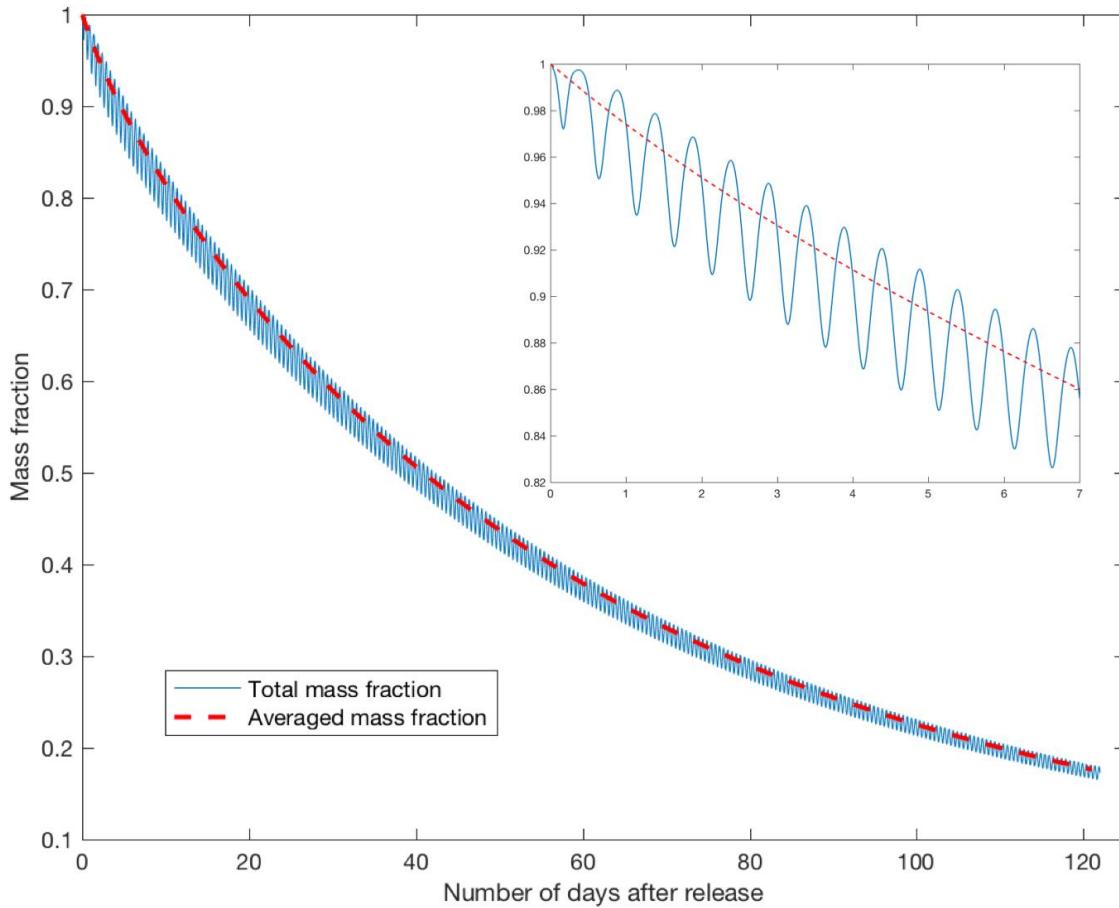
285 **Figure 3.** Distribution of wind speed and direction observed at NOAA Wachapreague station,
286 Virginia, USA (tidesandcurrents.noaa.gov). On the left, the winter season from December 21st,
287 2014 to March 20th, 2015. On the right, the summer season from June 21st to September 23rd,
288 2015. Colors indicate the wind speed, as specified in the legend. The radial axis shows the
289 frequency expressed as percentage of the total measurements of each combination of wind speed
290 and direction.

3.4 Decay of tracer concentration and flushing time

The flushing time is a system-level measure that quantifies the effectiveness of tidal flushing in removing a dissolved substance from a water body through its open boundaries and provides a single value for the whole system [Choi and Lee, 2004]. A water body connected to the sea, such as a coastal embayment, is characterized by a flushing time that is well approximated by a double-exponential decay curve [Defne and Ganju 2014; Periñez et al. 2013; Choi and Lee, 2004]. In this study the time variation of the tracer mass fraction that remains in the lagoon in the absence of wind was approximated with a double-exponential function as it presents higher

299 correlation coefficients compared to a single exponential curve. The interpolation was
 300 implemented on the curve obtained by averaging the mass fraction within the system of bays
 301 every tidal cycle, as shown in Figure 4.

302



303

304 **Figure 4.** Mass fraction decay for the *STD EBB*. The blue line represents the decaying mass
 305 fraction calculated as integral over the entire bay. The red line is the corresponding average. In the
 306 smaller panel a magnification of the first simulation days is reported.

307

308 The decay function is made of two exponential terms, and is defined by the three parameters
 309 a, b, c :

310

311
$$\frac{m(t)}{m_0} = ae^{-bt} + (1 - a)e^{-ct} \quad (1)$$

312

313 where $m(t)$ is the tracer mass at time t , m_0 is the tracer initial mass. This function describes a
 314 decay process that is faster at the beginning and gets slower with time [Defne and Ganju, 2014].
 315 The corresponding flushing time, T_f , was determined using the following equation [Choi and
 316 Lee, 2004]:

317

318
$$T_f = \frac{a}{b} + \frac{1-a}{c} \quad (2)$$

319

320 When a strong, constant wind is included in the model, the flushing process is faster, and the
 321 flushing time obtained from a single-exponential curve is similar to the value obtained from a
 322 double-exponential curve (Table S2). Therefore, in the simulations including wind, the decay of
 323 the tracer mass was interpolated with a simple exponential curve:

324

325
$$\frac{m(t)}{m_0} = ke^{-\lambda t} \quad (3)$$

326

327 where k (≈ 1) and λ are the parameters of the exponential function. In this case, the decay rate λ
 328 was employed to evaluate the flushing time, T_f , of the tracer [Choi and Lee, 2004]:

329

330
$$T_f = \frac{1}{\lambda} \quad (4)$$

331

332 An example of the different interpolations of the mass decay produced by the single and double
 333 exponential functions for the *STD EBB* scenario can be found in Figure S2.

334

3.5 Velocity skew at the inlets

335 In order to determine what process is responsible for the flushing of the tracer, the flushing
 336 time computed from Equations 2 and 4 was compared to the monthly averaged tidal prism of the
 337 bays and the velocity skew at the inlets. The tidal prism accounts for the total amount of water
 338 exchanged in a tidal cycle between the bays and the ocean. A larger tidal prism means larger
 339 fluxes and possibly a decrease in flushing time. The velocity skew at each inlet however
 340 accounts for the asymmetry of the tidal flow. Ebb velocities greater than flood velocities would
 341 prevent the return of the tracer into the bays, reducing the flushing time. This is particularly true

342 for a bay with several inlets, in which water can enter from one inlet during flood but then exits
 343 from a different inlet during ebb. Following Nidzieko and Ralston [2012], the velocity skew is
 344 computed as:

345

$$346 \quad S = \frac{\int_0^T v^3 dt}{\left(\int_0^T v^2 dt\right)^{3/2}} \quad (5)$$

347

348 where v is the maximum velocity in the inlet and T is the tidal period.

349 We also defined a total skew index, which accounts for the combined skew of each inlet and
 350 provides a metric of asymmetry for the entire complex of bays:

351

$$352 \quad S_{tot} = \sum_1^n |S_i| \quad (6)$$

353

354 where S_i is the velocity skew of one inlet and n is total number of inlets.

355 3.6 One-dimensional model for computing flushing time under different wind conditions

356 Simulations with constant wind speed and direction were used to construct a polynomial
 357 function that allows the determination of the exponential decay of the tracer mass using the least
 358 number of parameters. The goal of this method is to collapse complex, time-consuming 2D
 359 simulations in a simple point model based on a parameterized polynomial. This simple point
 360 model can then be effectively used to rapidly determine the flushing time of the system as a
 361 function of wind conditions.

362 In the presence of wind, the decay parameter λ was evaluated as a function of wind direction
 363 and wind speed. Specifically, the wind speed, v (m/s), and direction, θ (rad), and the
 364 corresponding decay rate, λ , for the exponential curve (Equation 3) were related using the
 365 following polynomial regression function:

366

$$367 \quad \lambda(\theta, v) = p_1 + p_2\theta + p_3v + p_4\theta^2 + p_5\theta v + p_6v^2 + p_7\theta^3 + p_8\theta^2v + p_9\theta v^2 + p_{10}\theta^4 + p_{11}\theta^3v + p_{12}\theta^2v^2 \quad (7)$$

368

369 where $p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8, p_9, p_{10}, p_{11}$, and p_{12} are the coefficients of the
 370 interpolating function. This polynomial model presents 4 degrees in the θ variable and 2 degrees

371 in the v variable, and is the regression function that gave the best fit. Results from these
 372 ensemble simulation runs with eight different constant directions and two constant wind speeds
 373 were used to determine the coefficients of Equation 5. Specifically, for each simulation a value
 374 of λ was determined for the given values of θ and v ; these points were then used to fit the
 375 polynomial surface represented by Equation 7.

376 Since the decay exponent was calculated as a function of wind speed and intensity (Equation
 377 7), we could simulate the mass decay for any time period characterized by a variable wind speed.
 378 Specifically, we divided the time period in constant intervals, Δt , and for each interval we
 379 computed the decay exponent assuming an average wind speed. Then we compounded the results
 380 for the whole period. Note that because the decay was exponential, the decay of concentration in
 381 time was simply obtained by adding all the exponents:

382

$$383 \frac{m(n\Delta t)}{m_0} = k e^{-\sum_1^n \lambda_i \Delta t} \quad (8)$$

384

385 where n is the number of time intervals, λ_i is the decay exponent during the interval $i\Delta t$,
 386 $(i+1)\Delta t$.

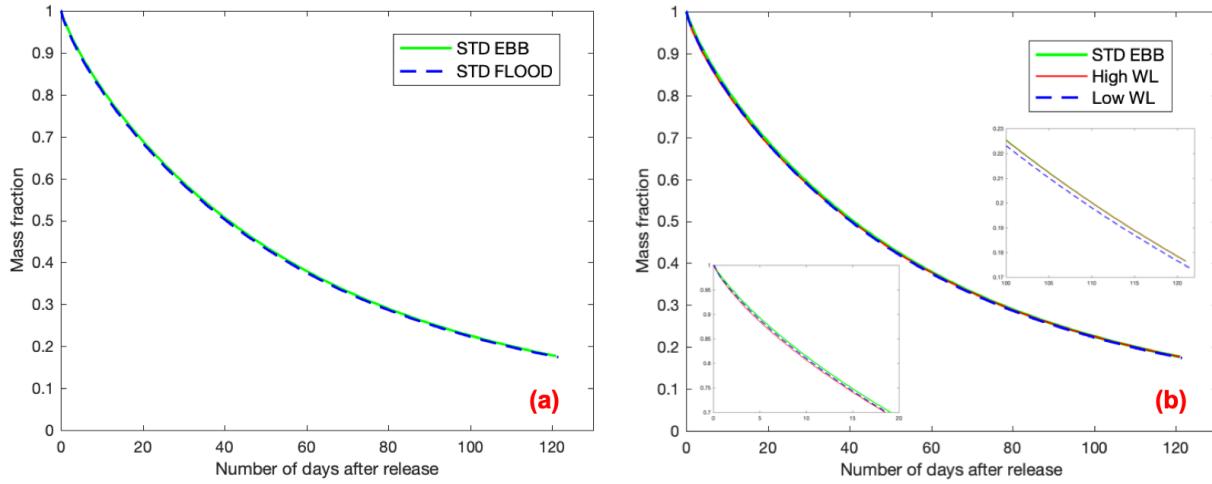
387 This equation allowed us to reproduce the time-varying mass decay produced by observed
 388 values of wind direction and speed. Even if the decay rates for different wind speeds and
 389 directions were obtained assuming a constant wind within every time interval, in our model each
 390 decay rate is used for only few hours, mimicking the natural wind variability of the Virginia
 391 Coast Reserve.

392 To test the model (Equation 8) we used wind data observed every hour at the Wachapreague
 393 station from 21st June to 23rd September 2015 (Figure 3). We derived two additional wind data
 394 sets from the hourly observed wind data, by averaging the data every 12 and 24 hours and
 395 applying Equation 8 with the same time interval of 12 and 24 hours. The obtained exponential
 396 curves were compared to the mass decay determined by a full scale Delft3D simulation during
 397 the same time period using the observed water levels and wind data registered at the
 398 Wachapreague station.

399 **4 Results**400 **4.1 Factors influencing the flushing time of tracer**

401 To determine whether the timing of the tracer injection is important, two standard simulations
 402 were carried out, one starting at mean sea level during ebb (*STD EBB*) and one starting at mean
 403 sea level during flood (*STD FLOOD*). These two simulations presented a similar decay of the
 404 tracer mass (Figure 5a).

405



406

407

408 **Figure 5.** (a) Comparison between the mass fraction decay in the simulation for scenarios
 409 starting at mean sea level during ebb (*STD EBB*, green line) and at mean sea level during flood
 410 (*STD FLOOD*, blue dashed line). (b) Comparison between the mass fraction decay in the
 411 simulation starting from mean sea level during ebb (*STD EBB*, green line) and tracer injected
 412 during high (*High WL*, red line) and low water level (*Low WL*, blue dashed line). In the inset
 413 panels we present a magnification of the first and last days of simulation.

414

415

416 **Table 2.** Values of the coefficients of the double exponential function and flushing time for each
 417 simulation without wind. In bold are highlighted simulations that used realistic tide conditions for
 418 the VCR bays.

419

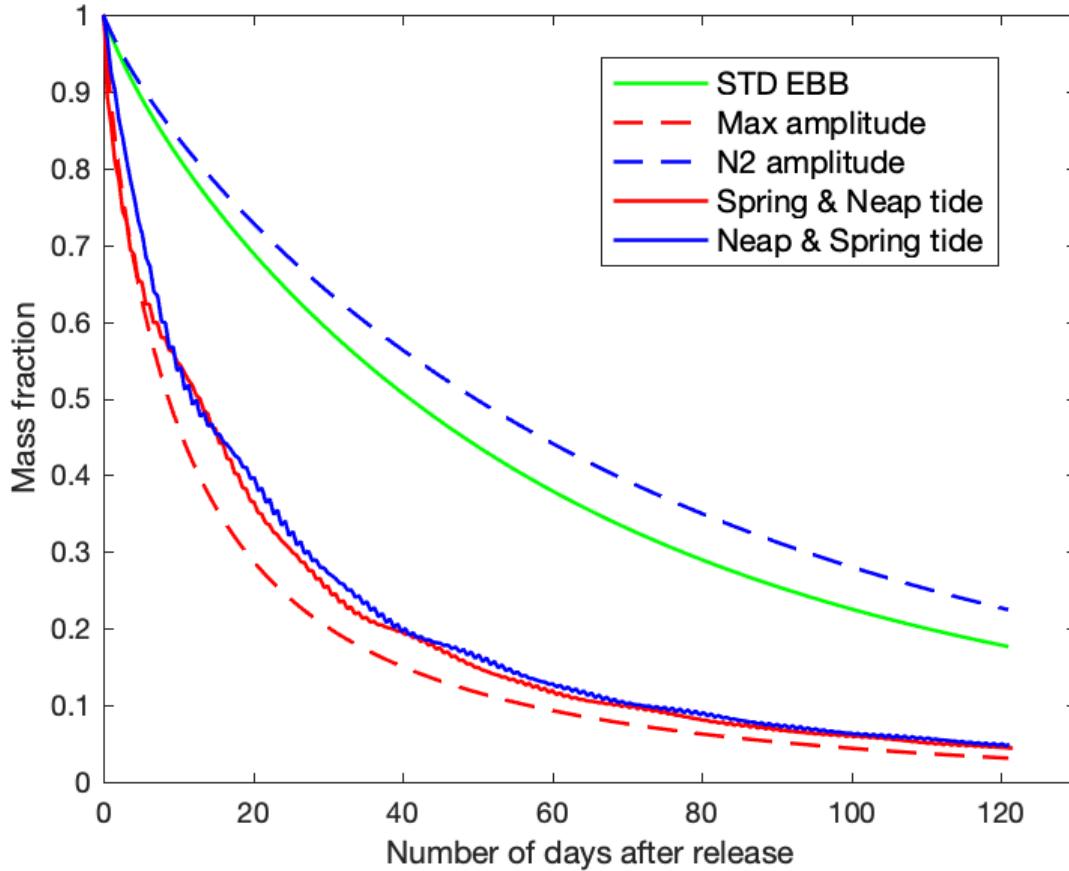
Simulation ID	a	b	c	Flushing time
	(days ⁻¹)	(days ⁻¹)	(days ⁻¹)	(days)
STD EBB	0.18102	0.05950	0.01294	66.33
STD FLOOD	0.17953	0.06395	0.01306	65.63
HIGH WL	0.16253	0.07537	0.01319	65.68
LOW WL	0.28679	0.03676	0.01175	68.50
MAX AMPLITUDE	0.61253	0.14127	0.02301	21.17
N2 AMPLITUDE	0.12571	0.07032	0.01139	78.55
SPRING&NEAP	0.43649	0.17282	0.02500	25.06
NEAP&SPRING	0.52961	0.10923	0.02091	27.34
VARYING TIDE	0.64422	0.08857	0.02089	24.30
CURRENT	0.63233	0.08474	0.01960	26.22

420

421 Both simulations had a flushing time of about two months, 66.33 days for *STD EBB* and 65.63
 422 days for *STD FLOOD* (Table 2). This result suggested that there is no significant difference
 423 whether a tracer is added to the system during ebb or during flood. In the next two simulations, the
 424 initial release of tracer was set to occur during high water level (*HIGH WL*) and low water level
 425 (*LOW WL*). Also in this case the flushing time did not show relevant differences (Figure 5b). In
 426 addition, the flushing time was similar to the one obtained for the standard simulation starting at
 427 mean sea level during ebb; a relatively small (two days) increase in flushing time occurred for the
 428 scenario starting at low water level.

429 Three simulations were then used to investigate the effect of tidal amplitude, and to see
 430 whether different tidal ranges influence the flushing time. In the *MAX AMPLITUDE* scenario,
 431 the decay of the tracer mass within the lagoon was faster than in the *N2 AMPLITUDE* scenario
 432 (Figure 6). The flushing time in the *N2 AMPLITUDE* simulation was about 79 days,
 433 approximately 60 days longer than the flushing time computed during the *MAX AMPLITUDE*
 434 scenario. Two more simulations were carried out to determine the difference in flushing time
 435 under Spring-Neap alternation: in one the tracer was released during a neap tide followed by a
 436 spring tide (*NEAP&SPRING*); in the second it was released during a spring tide followed by a
 437 neap tide (*SPRING&NEAP*). In this case the comparison presented a less pronounced

438 divergence. The difference in flushing time values was less than 2 days, further demonstrating
 439 that the timing of tracer injection had no significant impact in the flushing process (Figure 6).
 440

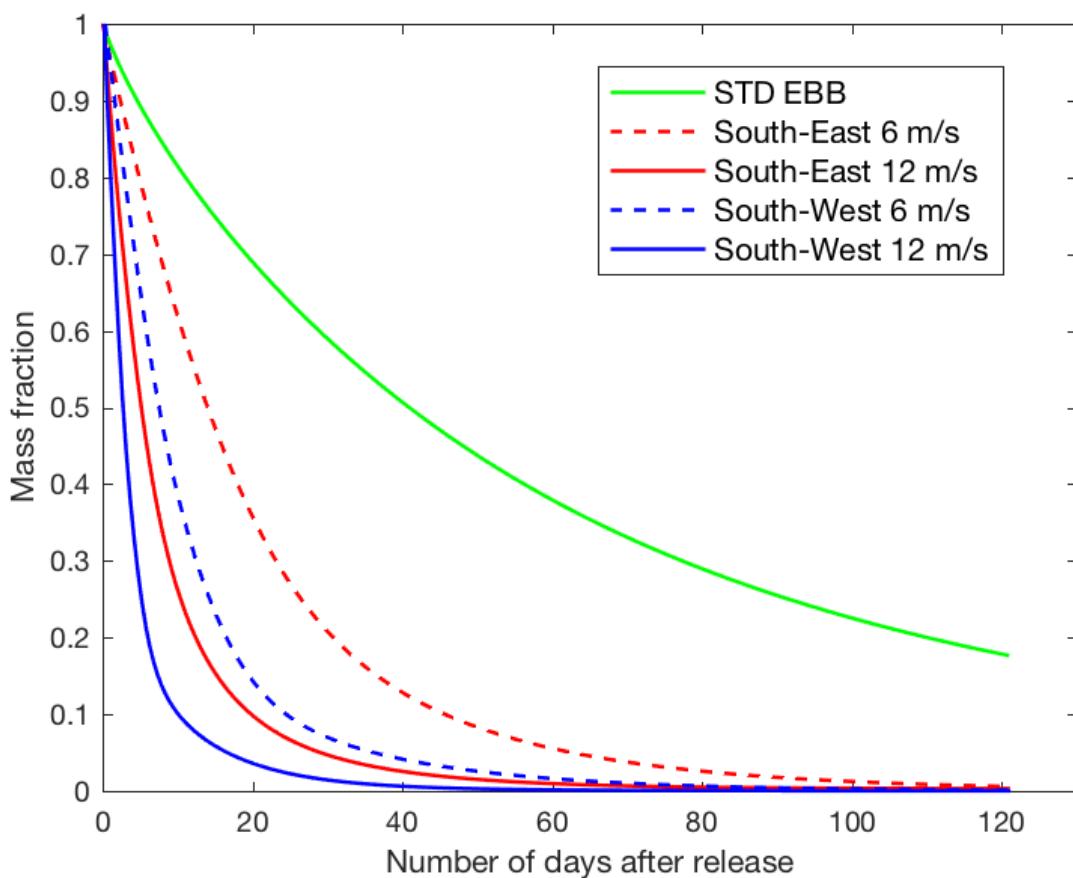


441
 442 **Figure 6.** Comparison between the mass fraction decay in the standard simulation and scenarios
 443 including Spring and Neap tides. The mass fraction is plotted after one full tide.
 444

445 To determine the effect of wind on tracer dispersion, hypothetical simulations with constant
 446 wind speed and direction were run. We considered the combination of two wind speeds and two
 447 wind directions, one perpendicular and one parallel to the inlets (Figure 7). We chose the two
 448 wind directions that produce the maximum (SW) and minimum effect (SE), in order to capture
 449 the full variability of this process. In these simulations the decay of the tracer mass fraction
 450 resulted to be faster than in the scenarios without wind, indicating that wind might be a strong
 451 driver of water exchange in the system. The decay of mass fraction due to the effect of wind can
 452 be interpolated with a simple exponential curve, since the use of a double exponential

453 interpolation yields the same values of flushing time and the correlation coefficient is high in
 454 both cases (Table S2). Table 3 shows the values of the flushing time evaluated for each
 455 simulation using a single exponential function to interpolate the decay. In particular, the
 456 simulations with the highest wind speed (12 m/s) were the most effective at flushing the system,
 457 and in the case of south-west wind the flushing time reached its lowest value (less than 4 days).
 458 Regardless of direction, as the speed doubles its value to 12 m/s, the flushing time decreases and
 459 becomes less than half the flushing time obtained when the velocity is 6 m/s.

460



461

462 **Figure 7.** Comparison between the mass fraction decay in the standard simulation and scenarios
 463 including wind coming from south-east and south-west directions and with a velocity of 6 m/s and
 464 12 m/s.

465

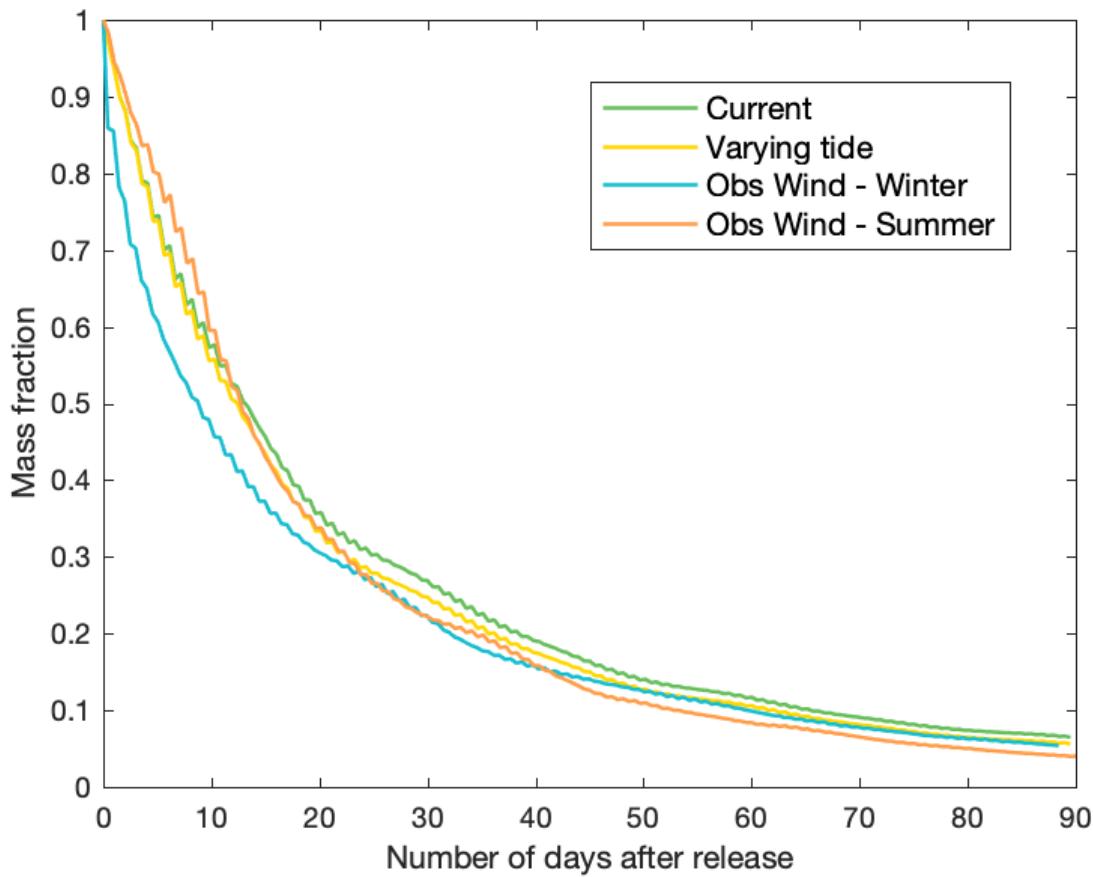
466 However, note that a constant wind lasting for several days is uncommon at the Virginia Coast
 467 Reserve, and more realistic conditions with variable wind should also be tested. Two simulations

468 were run with variable wind conditions measured at Wachapreague (Figure 8). When the
469 variability of wind speed and direction was taken into account, the flushing time increased
470 (Table 3, *WINTER WIND* and *SUMMER WIND* simulations). This is because most of the time
471 the wind is weak (Figure 3). The flushing time computed with winter winds is similar to the
472 flushing time without winds (25.06 days, see Table 3), whereas the flushing time decreases with
473 summer winds to 21.07 days. This is likely due to strong winds from northeast that were present
474 in Summer 2015 (Figure 3).

475 In the simulation with tidal phasing along the boundary (*VARYING TIDE*) the decay of the
476 tracer concentration in the bays was fast (Figure 8). The flushing time (24.3 days) decreased with
477 respect to *NEAP&SPRING* simulation with a constant phase (27.34 days, see Table 2). This is
478 likely due to subtidal circulation triggered by differences in tidal phase among the inlets. In fact
479 the residual Eulerian velocity enters the bays in the northern inlets, where the tidal signal arrives
480 first, while the velocity exits the bays in the southern inlets, where the tidal signal arrives with a
481 delay (Figure S3). Moreover, at each inlet the residual velocity is segregated in very distinct
482 flood and ebb paths. Both processes increase the dispersion of tracer when it exits the bays,
483 reducing the flushing time.

484 In the *CURRENT* simulation we considered a current along the shore from northeast to
485 southwest, mimicking the mean shelf circulation over the Middle Atlantic Bight. The flushing
486 time did not further decrease, and instead increased to 26.22 days (Figure 8, Table 2). The four
487 scenarios *VARYING TIDE*, *CURRENT*, *WINTER WIND*, and *SUMMER WIND* used realistic
488 boundary conditions and therefore the corresponding flushing time is more representative of the
489 system.

490



491
492 **Figure 8.** Comparison between the mass fraction decay in the scenario with a shelf current, the
493 scenario with varying tides along the boundaries and the observed wind data in the winter and
494 summer seasons of 2015.

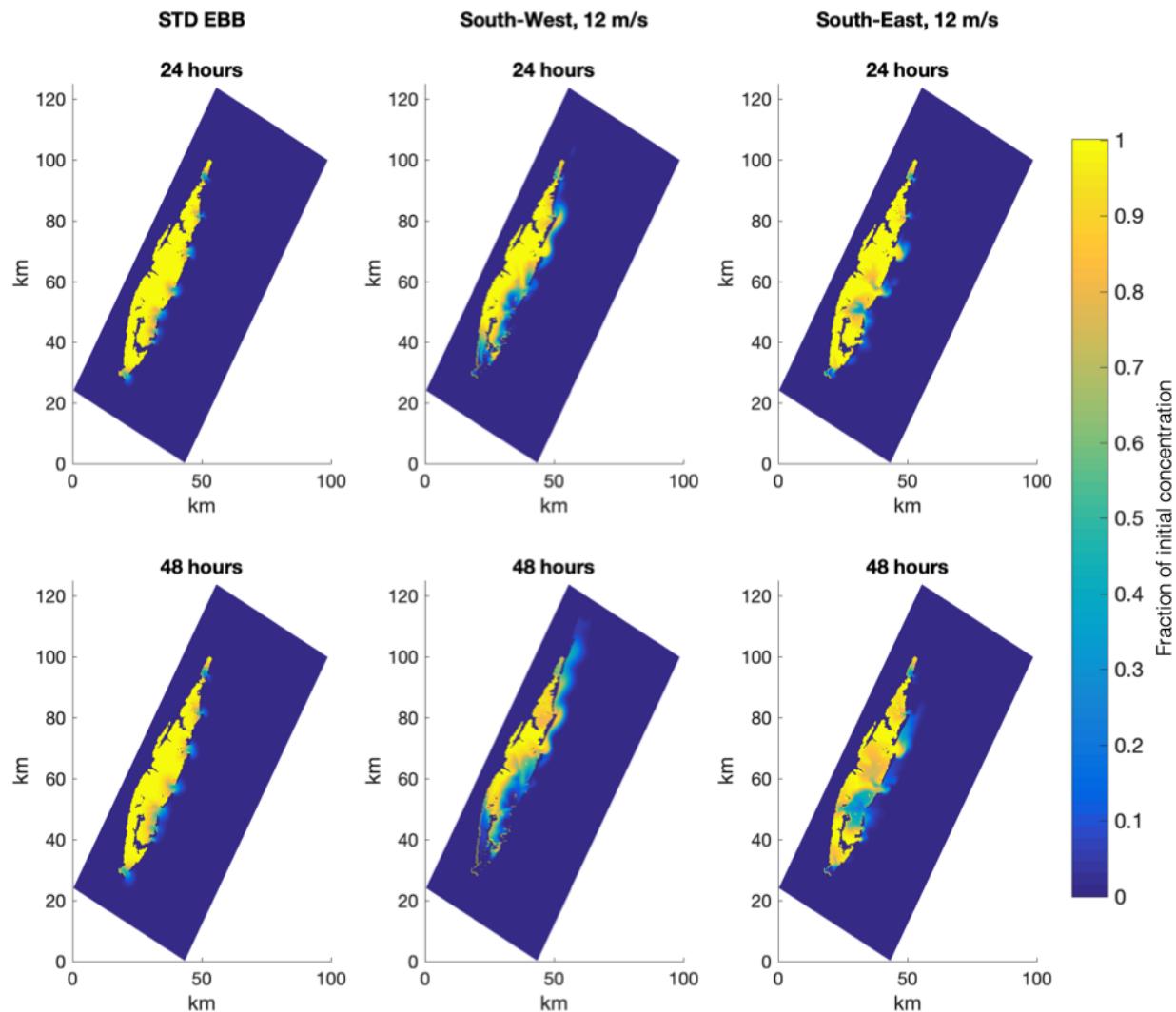
495
496
497 **Table 3.** Values of the coefficients of the single exponential functions, flushing time, and
498 adjusted R^2 and RSS of the interpolation for each simulation including wind. In bold are highlighted
499 simulations that used realistic wind conditions for the VCR bays.

Simulation ID	K	d (days ⁻¹)	Flushing time (days)	Adjusted R^2	RSS
SE6	1.0160	0.05112	19.56	0.9990	0.0136
SE12	0.9967	0.12600	7.94	0.9950	0.0420

SW6	1.0360	0.09545	10.48	0.9972	0.0278
SW12	1.0230	0.25000	4.00	0.9921	0.0392
WINTER WIND	0.7568	0.03991	25.06	0.9632	0.2266
SUMMER WIND	0.9718	0.04745	21.07	0.9874	0.1295

501 Figure 9 shows the fraction of total concentration of the tracer during the first time steps of the
 502 simulation (after 24 and 48 hours on the first day of simulation) in the scenarios without wind
 503 (STD EBB) and with wind (south-west 12 m/s and south-east 12 m/s). Both comparisons
 504 demonstrate that wind pushes the tracer outside the lagoons and prevents the return of water and
 505 tracer inside the lagoons. Therefore, the concentration of tracer remaining in the lagoons
 506 decreases if wind is included in the simulation, and as time passes the concentration of tracer
 507 decreases faster than in the scenario without wind.

509



510

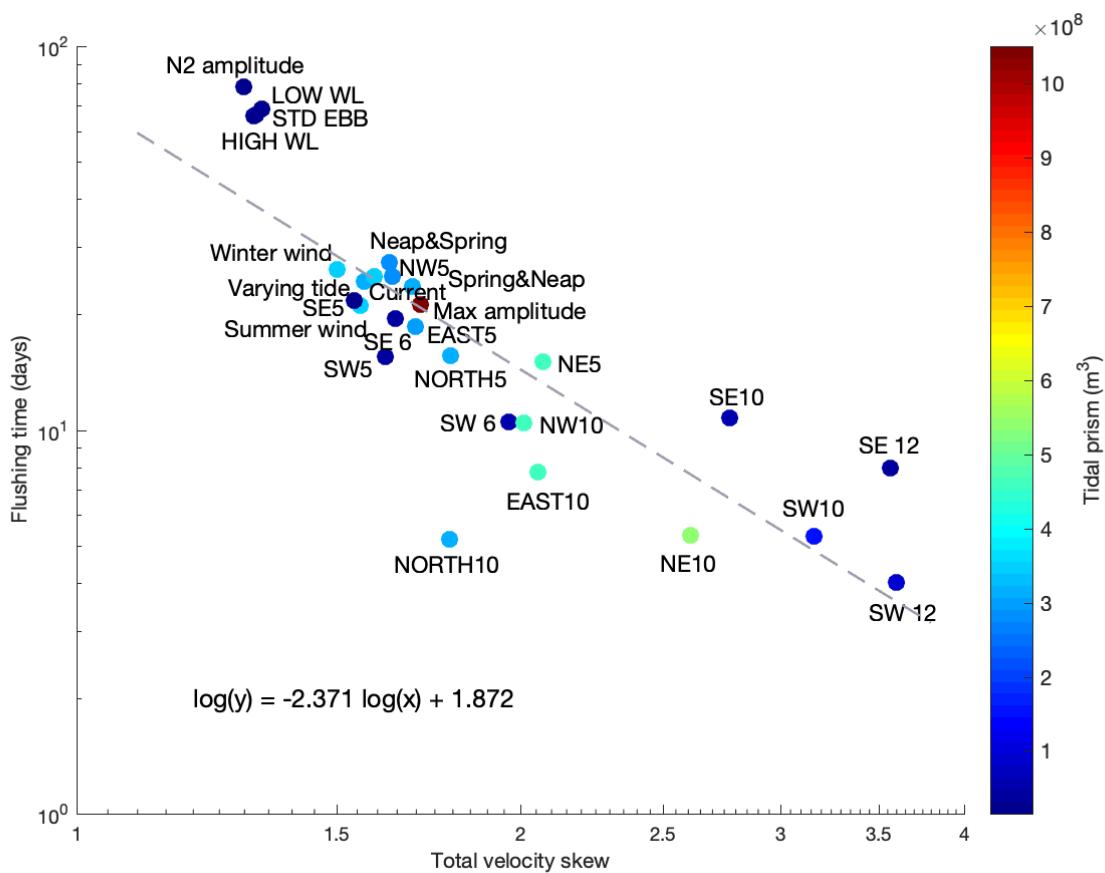
511 **Figure 9.** Fraction of total tracer concentration in the lagoon after the first 24 and 48 simulation
 512 hours in the scenario without wind (*STD EBB*), and in the scenarios with strong wind (*South-West*,
 513 *12 m/s*, and *South-East, 12 m/s*).

514 4.2 Relationship between velocity skew at the inlets and flushing time

515 We then determined whether tidal prism or velocity asymmetry at the inlets affect the flushing
 516 time of tracer in the bays using the results of all simulations. Flushing time is significantly
 517 correlated to total skew index (Kendall's tau = -0.73, $p < 0.05$), but not to tidal prism (Kendall's
 518 tau = -0.26, $p = 0.06$, Figure 10). Moreover, a multiple linear regression model between the
 519 logarithm of the flushing time (response), and the logarithm of the total velocity skew and of the

520 tidal prism (predictors) has an adjusted R^2 of 0.77 and a *p-value* of 9.88e-09. Specifically, the
 521 adjusted R^2 for a linear regression model between the logarithm of the flushing time and the
 522 logarithm of the total velocity skew is 0.70 with a *p-value* of 3.37e-08 (see equation in Figure
 523 10). On the contrary, the adjusted R^2 decreases to 0.13 when we analyze the correlation between
 524 the flushing time and the tidal prism. These results suggest that the total velocity skew explains
 525 70% of the variance in flushing time in log-log space (Figure 10), while the tidal prism can
 526 capture only the 13% of the variance in flushing time; together they explain 77% of the variance
 527 in flushing time. The high total skew for the simulations with wind indicates that some of the
 528 water entering the system from one inlet exits from a different inlet.

529



530

531 **Figure 10.** Flushing time of tracer as a function of tidal prism and total velocity skew. The grey
 532 line is the linear interpolation of the flushing time as a function of the total velocity skew. The
 533 equation of the linear model is indicated in the left bottom corner. Both x and y axes are in
 534 logarithmic scale.

535 4.3 One-dimensional model for computing flushing time under different wind conditions
 536 Previous results refer to the most frequent conditions in terms of wind speed and direction.
 537 However, since wind appears to be an effective forcing for flushing, additional simulations were
 538 carried out for increments of wind speed of 5 m/s and every 45 degrees of wind direction (Table
 539 4).

540
 541 **Table 4.** Values of the coefficients of the single exponential function, flushing time, and R^2 and
 542 RSS of the interpolation for the simulations including wind (simulations used for the polynomial
 543 fit).

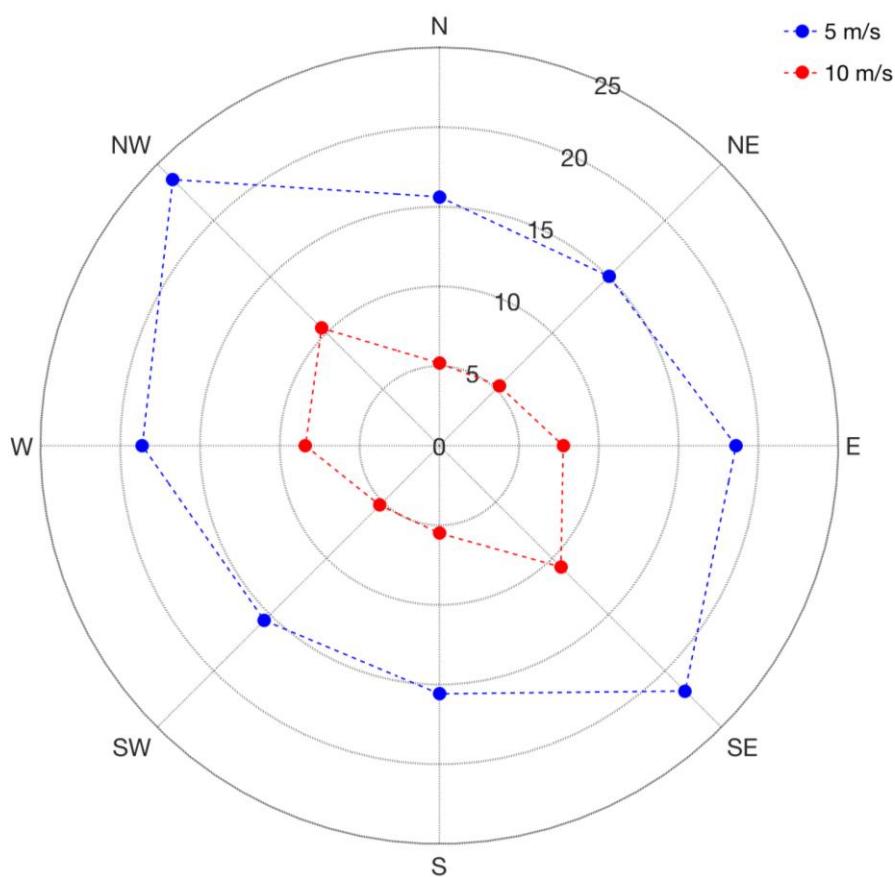
544

Simulation ID	K	λ	Flushing time (days)	Adjusted R^2	RSS	Variance of residuals
		(days ⁻¹)				
No Wind	0.92330	0.03421	29.23	0.9795	0.1975	1.0000e-03
N5	1.02000	0.06403	15.62	0.9990	0.0102	5.8072e-05
N10	1.03200	0.19320	5.18	0.9980	0.0104	4.7768e-05
NE5	1.01700	0.06653	15.03	0.9991	0.0092	4.9934e-05
NE10	1.02400	0.18840	5.31	0.9990	0.0054	2.4527e-05
E5	1.00400	0.05378	18.59	0.9992	0.0085	4.5660e-05
E10	1.01600	0.12890	7.76	0.9993	0.0048	2.6462e-05
SE5	0.98530	0.04592	21.78	0.9985	0.0166	8.8675e-05
SE10	1.02700	0.09284	10.77	0.9994	0.0054	3.0003e-05
S5	1.02200	0.06421	15.58	0.9990	0.0112	6.1717e-05
S10	1.03900	0.18190	5.50	0.9983	0.0093	4.3930e-05
SW5	1.01400	0.06447	15.51	0.9990	0.0103	5.5191e-05
SW10	1.04400	0.18940	5.28	0.9984	0.0086	4.3941e-05
W5	1.00900	0.05372	18.61	0.9989	0.0123	6.5706e-05
W10	1.02000	0.11910	8.39	0.9995	0.0039	2.1251e-05
NW5	0.97810	0.04234	23.62	0.9974	0.0286	1.4887e-04
NW10	1.05000	0.09581	10.44	0.9985	0.0141	7.7408e-05

545

546 For each simulation, the mass fraction of the tracer inside the lagoons is fitted using a single
 547 exponential decay, as in the previous simulations including wind (Table 3). The decrease of mass
 548 fraction inside the lagoons becomes more rapid as the wind speed increases (Figure 11), with the
 549 fastest decay reached when the velocity is equal to 10 m/s and the wind is blowing in the
 550 direction parallel to the coast (northeast and southwest). Conversely, when the wind blows
 551 perpendicular to the barrier islands (northwest and southeast), it facilitates the reintroduction of
 552 the tracer that has left the lagoons through the inlets. The mass fraction decay triggered by winds
 553 from southwest and northeast presents an analogous exponential trend. Similarly, winds blowing
 554 from southeast and northwest yield a similar flushing time.

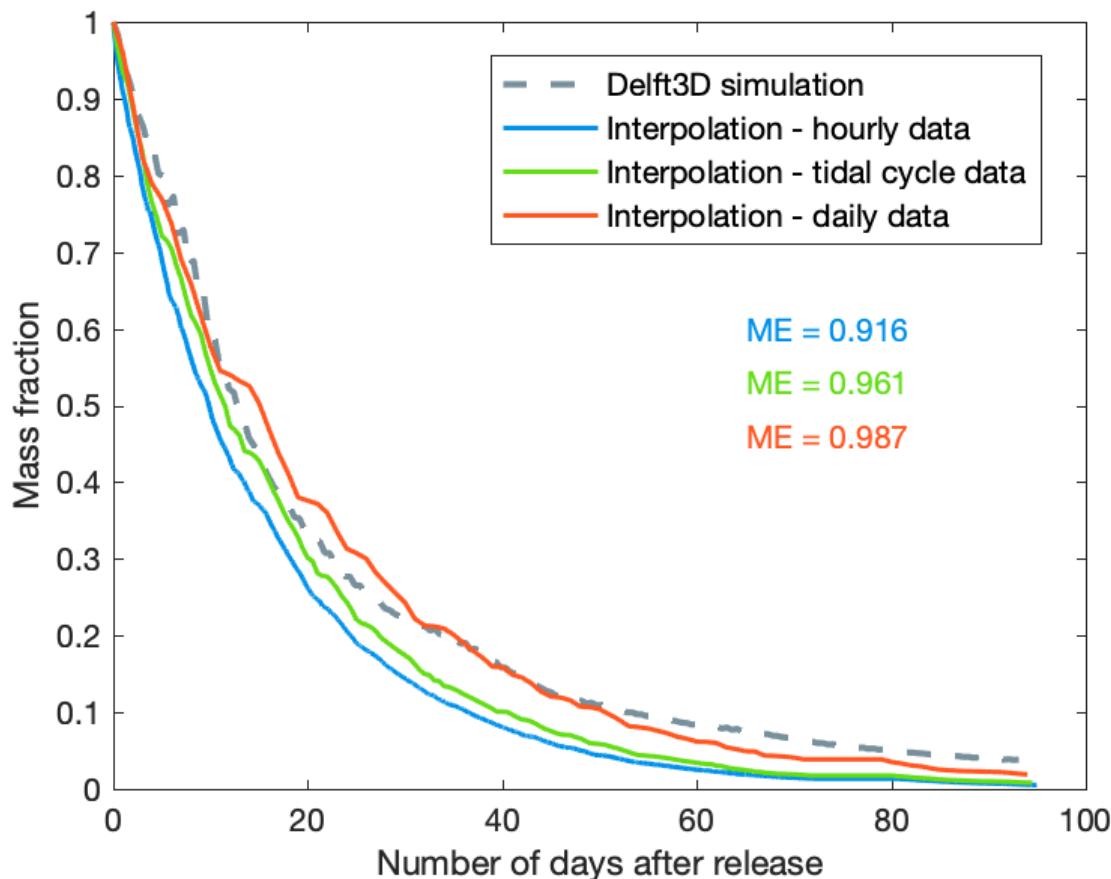
555



556

557 **Figure 11.** Flushing time distribution (days) as a function of the wind speed (in blue and red)
 558 and direction for the simulations with constant wind.

559



560

561 **Figure 12.** Comparison between the mass fraction decay derived from the Delft3D simulation
 562 and the mass fraction decay derived from the application of the polynomial function to the hourly,
 563 tidally and daily averaged wind data in the summer season of 2015.

564

565 The analytical method based on Equations 7 and 8 successfully reproduces the general mass
 566 decay behavior simulated by Delft3D (Figure 12). It is observed that the mass fraction retained in
 567 the system at the end of the simulation is better reproduced by the interpolation made with the
 568 daily averaged wind data, while tidally averaged, and hourly wind data are found to better
 569 interpolate the decay in the first days. The decay function varies depending on the interval over
 570 which the wind is averaged (one hour, one tide, one day) because the interpolating polynomial
 571 function is not linear.

572 **5 Discussion**

573 In the scenarios with Neap and Spring tides and without wind (Table 2, *SPRING&NEAP* and
574 *NEAP&SPRING*) the Eulerian approach adopted in this analysis produced a higher flushing time
575 than the values obtained with the Lagrangian method in Safak et al. [2015]: from 10 to almost 28
576 days in the case of the bays closer to the inlet. The reason for this is that the approach followed
577 by Safak et al. [2015] does not consider that a significant amount of particles that leave the
578 system during ebb can reenter the bays during flood, resulting in an underestimation of the actual
579 flushing time. On the other hand, coastal processes might facilitate the removal of the tracer once
580 it reaches the nearshore area outside the inlets, and thus, determine a faster decay of the tracer
581 mass. Here some of these processes, such as waves and wave-driven longshore currents, are not
582 included in the simulations and this might cause a change in flushing time. There is a difference
583 of approximately two days between the flushing time observed after the tracer is released during
584 high and low water levels, and this result seems to be in accordance with the median flushing
585 time evaluated in Safak et al. [2015] for almost all the bays having a direct connection to an inlet.
586 Also, the decrease in flushing time when wind is included in the model is in agreement with
587 Safak et al. [2015], and the magnitude of the decrease is a function of the velocity and direction
588 of the simulated wind. Specifically, the flushing time was lower during the summer of 2015
589 because a storm brought strong winds from northeast, a wind scenario that favors flushing
590 (Figure 11).

591 The particle tracking approach adopted by Safak et al. [2015] allows the evaluation of the
592 spatial distribution of the flushing time at each location, and shows that the parts of the bays
593 located near the inlets are more sensitive to tidal phase than wind forcing [Safak et al., 2015;
594 Fugate et al., 2006]. Here the Eulerian method provides a single value that defines the overall
595 flushing time of the tracer for all bays, regardless of the point of release. The entire system of
596 lagoons is more sensitive to wind forcing and differences in tidal phase along the coast than to
597 instant of release, indicating that the global flushing time is more affected by the flushing time
598 associated with the bays found in the interior region of the domain rather than in the areas
599 located near the inlets.

600 Defne and Ganju [2014] analyzed the influence of tides, coastal, riverine, and meteorological
601 processes on flushing time. They found that the percentage of particles removed from the domain
602 increases with the progressive addition of forcings to the scenario with only tides. However, in

603 that study the effects of each single factor were not investigated, and it is difficult to determine
604 what mechanism caused the greatest reduction in flushing time. Defne and Ganju [2014]
605 concluded that remote coastal forcings (i.e., tidally averaged water levels and currents added to
606 the tidal oscillations at the open boundaries) and meteorological forcings (surface air pressure,
607 wind speed and direction) were the most effective in the removal of particles.

608 In the scenarios of this study including the meteorological forcing, i.e. wind conditions, it has
609 been observed that as wind speed increases the mass decay occurs at a faster rate, and therefore
610 the flushing time of the tracer decreases. This is because wind-driven circulation produces
611 asymmetric fluxes of water between the lagoon and the ocean. Note that our synthetic scenarios
612 assume a wind speed that is constant in intensity and direction for an unrealistic long time, so the
613 resulting mass decay should be seen as a theoretical value. On the other hand, in our proposed
614 simplified model (Equation 7 and 8) the decay rate is changed every few hours to account for
615 wind variability in a realistic manner.

616 Given the highest wind speed (12 m/s), the most effective wind direction in the removal of
617 tracer particles is observed to be the southwest direction, corresponding to the direction parallel
618 to the inlets of the lagoons. In this scenario the tracer leaving the lagoons is not able to re-enter
619 into the system because the wind-generated currents **are moving** northwest. Moreover, the
620 Ekman transport facilitates the exchange of water and particles when the wind blows parallel to
621 the coast, increasing storm surges and extreme low tides [Fagherazzi et al., 2010]. Fagherazzi et
622 al. [2010] indicate that Ekman transport can increase the water level in the VCR lagoons by 0.2-
623 0.4 m, which roughly corresponds to an increase in tidal prism between 15% and 30%, and
624 therefore an increase of the fluxes in and out the system. These fluxes also vary across the inlets,
625 producing velocity asymmetry in flood and ebb and tracer dispersion (Figure 10).

626 On the other hand, in the scenario with a wind direction blowing landwards perpendicular to
627 the coastline (southeast direction), the particles exit and re-enter the system several times through
628 the inlets, producing a slower decay of the tracer concentration inside the lagoons. In addition,
629 the tracer that remains in the lagoons is pushed toward the northern bays of VCR, where the
630 inlets are smaller, and thus, the exchange of the tracer particles between the bays and the open
631 ocean takes place at a lower rate.

632 A wind perpendicular to the barrier islands but blowing from land towards ocean (northwest
633 direction) increases at first the flushing of the tracer by producing a setdown and a large outward

634 discharge. However, for continuity, a sizable water flux will also occur during the next flood
635 phase to replenish the lagoons with the water lost during the setdown. This phenomenon was also
636 observed by Fagherazzi and Priestas [2010] in the Louisiana coast. Wind blowing perpendicular
637 to the coast increased the flux of sediment toward the ocean at first, but then the sediment re-
638 entered the system during the following tidal cycle. The overall effect of a wind perpendicular to
639 the shore is an increase in water fluxes in and out of the system and a slight velocity skew in the
640 inlets, moderately increasing the flushing of the tracer.

641 A wind parallel to the shore produces instead a strong asymmetry in circulation, with flow
642 exiting the bays from one inlet and re-entering from a different one so that most of the tracer
643 exiting the system does not return (Figure 9). Field measurements and numerical simulations
644 carried out by Li [2013] in a bay with three inlets and wind blowing parallel to the shore indicate
645 that a net outward flow takes place at the downwind inlet, while a net inward flow occurs at the
646 inlet located upwind. As a result, fluxes during ebb are not rebalanced by symmetric fluxes
647 during flood within the same inlet, dramatically increasing the overall tracer removal from within
648 the lagoons.

649 When the variability in wind direction is accounted for, the flushing time becomes more
650 similar to the simulations without wind (Table 3). This is because most of the time the wind is
651 weak (Figure 3). We do notice a sharp decrease in flushing time with summer winds. While on
652 average the measured winds were higher in winter, in the summer of 2015 a storm occurred that
653 triggered winds above 10 m/s (Figure 3). The maximum wind blew from northeast, along the
654 shallow bays, which we showed being one of the directions more favorable for tracer flushing
655 (Table 4). Of all the simulations with realistic tidal and wind conditions, the one with summer
656 winds led to the lowest flushing time (21.07 days). We therefore conclude that winds do exert
657 control on the flushing of the system, but only if they blow along the bays and not
658 perpendicularly to them. Moreover, infrequent events with high wind speed are more important
659 than average wind conditions.

660 We conclude that processes triggering asymmetric fluxes between the bays and the ocean, such
661 as wind-driven subtidal circulation, and differences in tidal phase and amplitude along the shore
662 are the most successful at flushing tracer. Processes that augment the fluxes of water in and out
663 the bays, such as wind driven storm surges and setup caused by Ekman transport, also enhance
664 tracer flushing, but to a lower degree and partly through an increase in velocity skew.

665 Some of these results might be only valid for coastal bays with multiple inlets. In fact, if only
666 one inlet is present, subtidal circulation driven by wind is likely absent, since all the water is
667 entering and exiting from the same inlet. Wind can still trigger surges and Ekman transport, thus
668 increasing the volume of water exchanged with the ocean and therefore flushing, but the lack of
669 asymmetric flows will increase the overall flushing time of the tracer.

670 In this study we have not considered wind generated waves and long-shore currents. Based on
671 our findings, it seems likely that wave-driven long-shore currents would favor the dispersion of
672 tracer by creating asymmetric fluxes at the inlets, similarly to what wind-driven currents do.
673 More research is needed to determine the role of wave-breaking and long-shore currents on
674 tracer dispersion.

675 **6 Conclusions**

676 Semi-enclosed water bodies, such as bays and lagoons, host ecosystems sensitive to the release
677 of nutrients and pollutants due to human activities along the coast. Therefore, understanding the
678 decay and flushing time of tracers has important environmental consequences. Given a system of
679 bays, the mean flushing time associated to the entire area can be evaluated by using
680 hydrodynamic models and an Eulerian based approach. In this paper, the transport of a tracer
681 within the system of shallow bays in the VCR has been simulated using the hydrodynamic model
682 Deflt3D. The decrease in time of the tracer mass follows an exponential decay function.
683 Specifically, a double exponential function was found to better approximate the tracer decay
684 when the effect of wind is neglected, while a single exponential function is a good approximation
685 when the wind effect is included in the simulations. We further identified factors producing the
686 shortest flushing time of the tracer within a system with multiple inlets. We show that asymmetry
687 in ebb-flood velocity at the inlets is responsible for the rapid decay of the tracer mass in the
688 lagoons. These asymmetries, computed with a velocity skew index, are generated by differences
689 in tidal phase and amplitude along the inner shelf and by wind-driven circulation under non-
690 storm conditions.

691 In general, the average flushing time of the VCR bays is around 25-27 days. When the
692 difference in tidal phase along the Atlantic coast is accounted for, the flushing time decreases to
693 24 days, due to asymmetric tidal fluxes at the inlets. Winds can also decrease the flushing time,
694 but only if they are strong and blow along the bays (from southwest or northeast). In the summer

695 of 2015, strong winds reduced the flushing time to 21 days. Currents triggered by shelf
696 circulation do not seem to affect the flushing of the system.

697 A simple exponential decay function using wind-dependent parameters calculated with a
698 polynomial regression (Equation 7 and 8) can be used to estimate the decay in concentration
699 without the need of a hydrodynamic model. This function well predicted the tracer mass decrease
700 during the summer months of 2015 in the VCR bays. This result demonstrates that the average
701 flushing time of tracer within the entire system of bays in the Virginia Coast Reserve can be
702 estimated from the evaluation of a single parameter, which controls the exponential decay of the
703 tracer mass inside the lagoons.

704 **Acknowledgments, Samples, and Data**

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707

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Continental Shelf Research Journal

Supporting Information for

Velocity skew controls the flushing of a tracer in a system of shallow bays with multiple inlets

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Contents of this file

Tables S1 and S2, Figure S1 to S3.

Introduction

This supporting information provides data that were used to set up the simulations in the Delft3D-FLOW model and results that were obtained from the simulations in the Delft3D-FLOW model. Specifically, Table S1 shows the values of the amplitude and phase of the tidal harmonics observed at Wachapreague station before and after the calibration. These data were employed to reproduce the water level at the open boundaries of the domain. The manual calibration was done by comparing the water level observed at Wachapreague station and the water level reproduced by the model at the same location. Table S2 compares the coefficient of correlation, R^2 , the error sum of squares, RSS , and the variance of residuals for the interpolation of the decay of the tracer mass fraction using a single and a double exponential function.

Figure S1 shows the difference in amplitude and phase between the main harmonic constituents measured by NOAA at the Wachapreague station and the harmonic constituents simulated by Delft3D with the ADCIRC boundary conditions at the Wachapreague location. Figure S2 shows the difference between single and double exponential fit for the STD EBB scenario. Finally, Figure S3 shows the residual velocity in the main inlets of VCR obtained from the *VARYING TIDE* simulation.

Table S1. Amplitude and phase of the harmonic constituents before and after the calibration carried out at Wachapreague station.

Constituent #	Name	Description	Observed values		Calibrated values	
			Amplitude [m]	Phase [deg]	Amplitude [m]	Phase [deg]
1	M2	Principal lunar semidiurnal constituent	0.48675	241.8	0.486750	241.8
2	S2	Principal solar semidiurnal constituent	0.08415	273.2	0.084150	273.2
3	N2	Larger lunar elliptic semidiurnal constituent	0.10395	234.7	0.103950	234.7
4	K1	Lunar diurnal constituent	0.06930	128.7	0.069300	128.7
5	M4	Shallow water overtides of principal lunar constituent	0.02500	291.9	0.020625	291.9
6	O1	Lunar diurnal constituent	0.08700	146.9	0.071775	146.9

Table S2. Values of the adjusted coefficient of determination, R^2 , the residual sum of squares, RSS , and the variance of residuals of the double and single exponential function for each simulation with and without wind.

Simulation ID	Single exponential			Double exponential		
	<i>Adjusted R²</i>	<i>RSS</i>	<i>Variance of residuals</i>	<i>Adjusted R²</i>	<i>RSS</i>	<i>Variance of residuals</i>
STD EBB	0.9963	0.0429	1.7530e-04	0.9998	0.0026	1.0450e-05
STD FLOOD	0.9953	0.0623	2.4832e-04	0.9997	0.0033	1.3377e-05
HIGH WL	0.9960	0.0459	1.8768e-04	0.9997	0.0039	1.6015e-05
LOW WL	0.9968	0.0400	1.6256e-04	0.9999	6.1386e-04	2.4955e-06
MAX AMPLITUDE	0.9554	0.3703	0.0013	0.9987	0.0111	4.5982e-05
N2 AMPLITUDE	0.9970	0.0318	1.3068e-04	0.9999	0.0013	5.1807e-06
SPRING&NEAP	0.9666	0.3742	0.0014	0.9929	0.0793	3.3051e-04
NEAP&SPRING	0.9684	0.3069	0.0012	0.9976	0.0231	9.8742e-05
VARYING TIDE	0.9764	0.2439	8.5070e-04	0.9993	0.0067	2.8694e-05
CURRENT	0.9759	0.2512	8.9710e-04	0.9991	0.0094	4.0337e-05
SE6	0.9990	0.0136	4.7807e-05	0.9988	0.0165	5.5712e-05
SE12	0.9995	0.0420	1.1907e-04	0.9993	0.0059	2.4291e-05
SW6	0.9972	0.0278	8.4867e-05	0.9975	0.0250	1.0514e-04
SW12	0.9921	0.0392	1.3950e-04	0.9968	0.0155	6.5896e-05
WINTER WIND	0.9632	0.2266	0.0012	0.9947	0.0322	1.8824e-04
SUMMER WIND	0.9874	0.1295	6.1193e-04	0.9970	0.0306	1.6880e-04

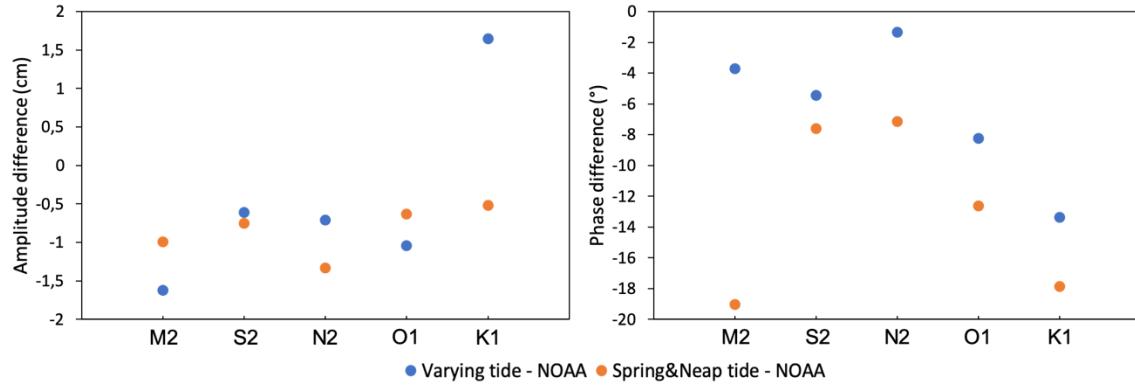


Figure S1. Difference between the amplitude and phase of M2, S2, N2, O1, and K1 harmonics observed at NOAA Wachapreague station and derived from Delft3D simulations of the *VARYING TIDE* and *SPRING&NEAP* tide scenarios.

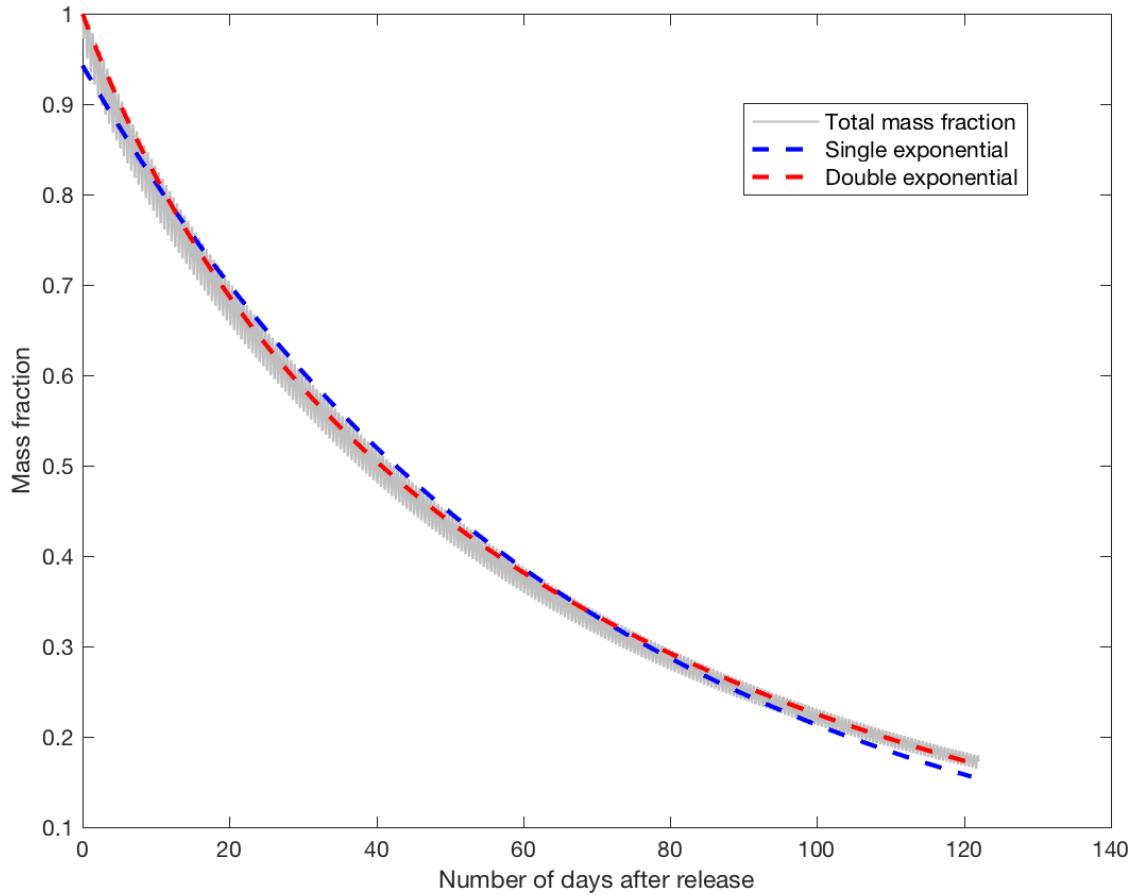


Figure S2. Comparison between single and double exponential fit for the *STD EBB* simulation (standard conditions, ebb starting point). The grey line represents the decaying mass fraction calculated as integral over the entire bay. The blue dashed line represents the single exponential fit to the mass fraction decay, as in Equation 3, whereas the red dashed line is the double exponential fit of Equation 1. Adjusted R^2 , RSS and Variance of residuals can be found in Table S2 of the Supporting Information.

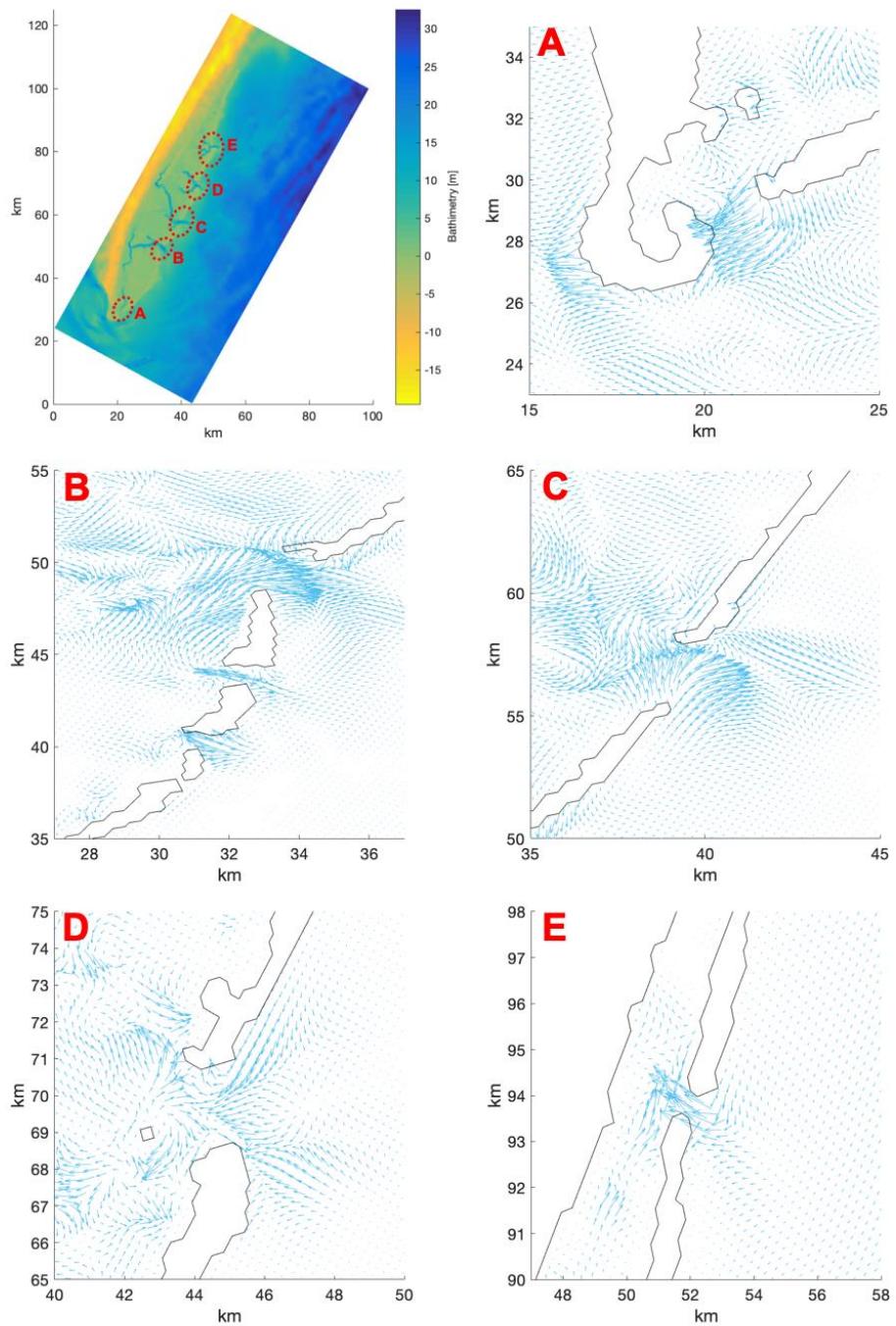


Figure S3. Residual velocity in the main inlets of VCR obtained from the *VARYING TIDE* simulation.

Conflict of Interest Statement

Manuscript title: *Velocity skew controls the flushing of a tracer in a system of shallow bays with multiple inlets*

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

Bologna, 10/09/2019

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