RESIDENCE TIME OF SMITH COVE, THAMES RIVER ESTUARY, USA

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ABSTRACT
Smith Cove is a small partially enclosed estuarine embayment along the western shore of the Thames River estuary. The residence time in this cove was estimated using current meter data collected in October 2001 and March 2002. Results showed a weak outflow from the cove that was modulated by local winds. Strong westerly winds, usually associated with the passage of cold fronts, increased the non-tidal flow out of the cove and reduced the water level in the cove. Northerly and easterly winds had the opposite effect. The estimated residence time based on tidal flushing is 4 days. However, due to the temporal variability in wind speed and direction, the estimated residence time varied between 2 and 8 days. Drifter data collected throughout the cove over several tidal cycles also showed a large velocity shear between the shallow regions and main channel within the cove. This will cause additional spatial differences in the residence time. The periodic pulses of flow out of or into the cove may influence the transport of sediment and suspended material between the cove and the adjacent Thames River estuary.

INTRODUCTION

Small coves and embayments along the shores of larger estuaries are often overlooked when considering the dynamics of the entire estuary; however, these areas may serve an important ecological function (e.g. Howell et al. 1999) as well as trap sediments and pollutants (Benoit et al. 1999a; 1999b). Such coves may receive some freshwater from local creeks but are generally shallow and have weak tidal currents. They may be separated from the main channel of the adjacent estuary by broad shoals. Along the northeastern USA coast the natural circulation in many of these coves has been modified due to the construction of railroads, which have partially closed off the coves isolating them from the adjoining larger estuary. For such coves, it is often assumed that the flushing has been significantly reduced, and that they are gradually being filled with sediment. This study examined the residence time in one such cove along the Thames River estuary in Connecticut.

The terms flushing time and residence time have been used variously by different authors and researchers. A detailed review of their use in estuaries can be found in Sheldon and Alber (2002). Flushing time is generally taken to be the "freshwater replacement time" or the time it takes the total freshwater inflow to

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14. ABSTRACT
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equal the amount of freshwater in the system (Dyer 1973). The residence time is broadly the amount of time a particle, or group of particles, will remain in the estuary or a particular reach or region of the estuary. This concept is more applicable to the shallow coves considered in this paper because their dynamics are primarily controlled by exchanges with the adjacent main estuary, rather than freshwater inputs. These exchanges may be driven directly or indirectly by the wind, or by tides. A study by Geyer (1997) of the shallow Childs River estuary on Cape Cod, USA, showed that the along-estuary winds altered the salinity distribution and effectiveness of the associated gravitational circulation in such a way that the flushing of water from within the estuary was either enhanced or retarded depending on the direction of the wind. There was a strong correlation between the flushing time (calculated by the fraction of freshwater method) and wind strength and direction. A similar connection between non-tidal currents and wind stress was previously observed in the Indian River lagoon (Smith 1983). Coastal and local winds may also play an indirect role in the flushing of shallow estuaries by modulating the water levels (Kjerfve et al. 1978) or the water surface slopes (Wong and Wilson 1984; Janzen and Wong 1998) in the embayment. In the absence of winds, small shallow estuaries or coves are still subject to regular and predicable flushing by tides. This residence time is usually calculated using the tidal prism method, which makes a number of simplifying, and somewhat limiting, assumptions. Recently this method was further refined to include differences in flood and ebb flows (Luketina 1998), and the fraction of water which leaves the estuary on the ebb but returns the following flood due to weak mixing and circulation in the adjacent waters (Sanford et al. 1992). This latter effect is expected to be important where shallow coves or embayments connect to shoal regions of the estuary rather than the main advective channel.

STUDY AREA
The Thames River estuary is aligned north-south between the eastern end of Long Island Sound and Norwich, Connecticut (Figure 1). The shoreline of the estuary is naturally indented and has high banks. Along both the western and eastern shores, there are railroads, constructed during the 1850's (CT Department of Environmental Protection 1982), which run almost the entire length of the estuary. As the railroads were built along an almost straight path, their construction effectively closed off many of the shoreline embayments. One of these is Smith Cove, located on the western bank 4.5 miles north of the mouth of the Thames River estuary.

The cove is divided into upper and lower reaches by a topographic constriction, spanned by a road bridge, which coincides with a change in shape and orientation of the cove (see Figure 1). The upper reach is generally less than 100 meters wide, has one narrow channel approximately 1.5 meters deep, bordered by shallow mudflats frequently exposed at low tide. It is oriented in a north-south to northwest-southeast direction. Small amounts of freshwater enter this reach via Hunts Brook and storm water drains. This study examined the lower section of

Smith Cove, which is 400 meters wide by 360 meters long with an average depth of 2.5 meters. Localized depths greater than 3 meters can be found along the channel, which is oriented in an approximately east-west direction between the road bridge (upstream entrance) and the outer entrance below the railroad bridge (see Figure 1). The tidal range is 0.8 meters and the tidal currents are generally very weak except through the entrance regions. The water column is generally well mixed with a weak horizontal salinity gradient between the upstream entrance and outer entrance. However, following large rain or wind events salinity gradients may be enhanced. Bottom sediments in the lower reach of Smith Cove trend from silt and clay in the northern shallow parts of the cove, to 60% sand in the channel region (Nolan 2002). The predominance of fine-grained sediments increases the possibility that metals and organic chemicals may accumulate within the cove.
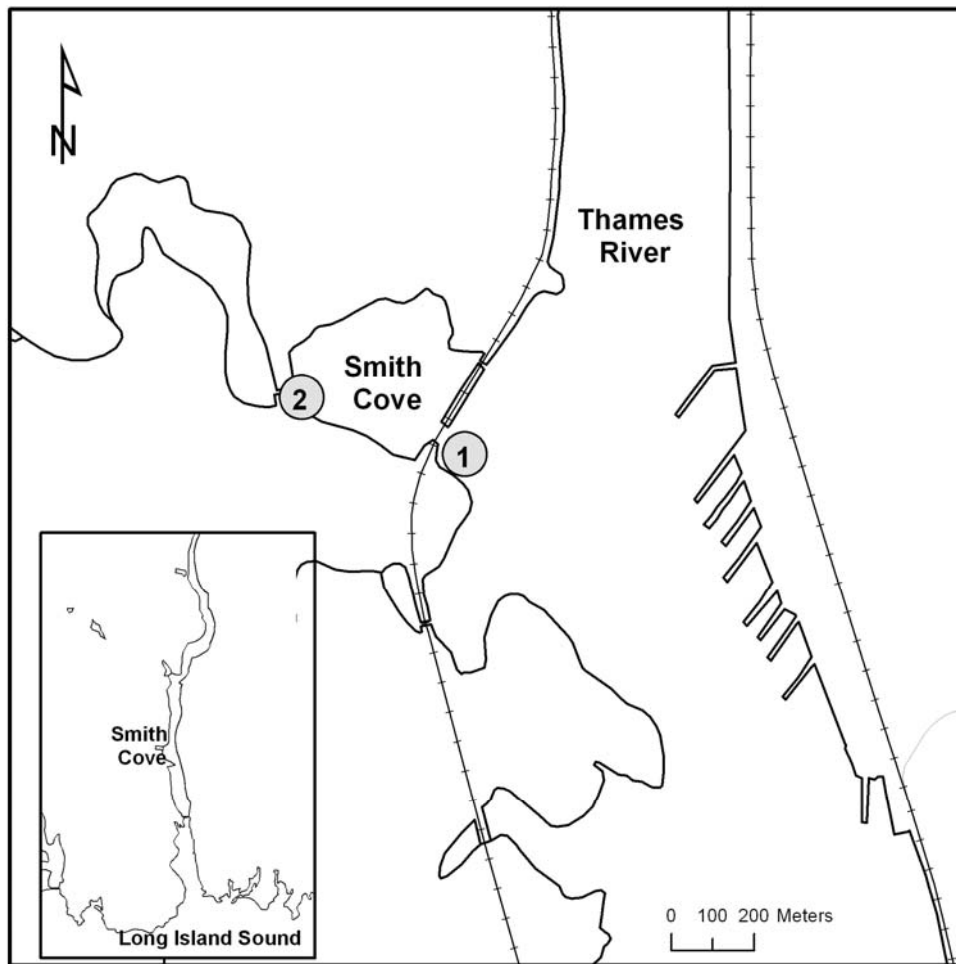

Figure 1 Location of Smith Cove in the Thames River estuary, CT. Current meters were moored at Stations 1 and 2, at the upstream and outer entrance to Smith Cove, during October 2001, and at Station 2 during March 2002.

The only water exchange between Smith Cove and the adjacent reach of the Thames River is under two small railroad bridges, one 20 meters long and one 7 meters long. This represents approximately 10% of the original interface with the Thames River and may limit the tidal flushing. However, the shallowness of this cove makes it very susceptible to wind-driven circulation. The purpose of this study was to investigate the residence time of water inside Smith Cove, and to determine the factors, or conditions, which control this residence time.

METHODS
This study utilized data collected by current meter moorings and surface drogues. Between 18 October and 1 November 2001 two current meters were deployed, one at Station 1, the outer entrance of Smith Cove at the railroad bridge, and one at Station 2, under the road bridge (see Figure 1 for station locations). Each meter was moored approximately 1 meter below the low tide level and recorded current speed and direction, salinity and temperature at 10 min intervals. Low tide water depth was 2.5 meters at Station 1 and 3.5 meters at Station 2. The current meter at Station 2 failed after only 2 days, but the meter at Station 1 provided a 2-week time series of currents and water properties at the outer entrance to the cove. Additional current data at Station 2 were collected between 7 March and 22 March 2002. As in the 2001 deployments, a single meter was moored approximately 1 meter below the surface. The current meters used in all deployments were Endeco 174 vector averaging current meters that recorded current speed and direction, plus water temperature, salinity and depth, every 10 minutes.

A series of drifter studies were conducted during October 2001 to determine the surface circulation throughout the cove. The drifters were constructed of two pieces of plywood, each 0.3 m by 0.6 m, arranged in a cross. A small surface float helped to locate the drogue but did not add any wind-drift to its movement. Drifters were set to follow the upper 1 m of the water, and were released at varying locations and times of the tidal cycle. Their position was tracked by coming along side the drifter in a small boat and using a hand-held GPS. Great care was taken to ensure that the boat did not interfere with the drifter movement. Hydrographic profiling along the channel was also conducted during October 2001. Wind data used in this study were collected at the University of Connecticut meteorological station in the lower Thames River. There is no measurement of the freshwater flow into Smith Cove; freshwater inflow events were approximated from rainfall data that was obtained from the University of Connecticut.

RESULTS

1. Current meter deployments

<u>Fall 2001</u>
In October 2001, data were collected at Station 1 over a 14-day period that started and ended with spring tides. Flow through the railroad bridge entrance was clearly bi-directional with an ebb/flood axis of 119°/299° (Figure 2a). The maximum ebb currents were generally stronger while the flood currents were more directionally variable.
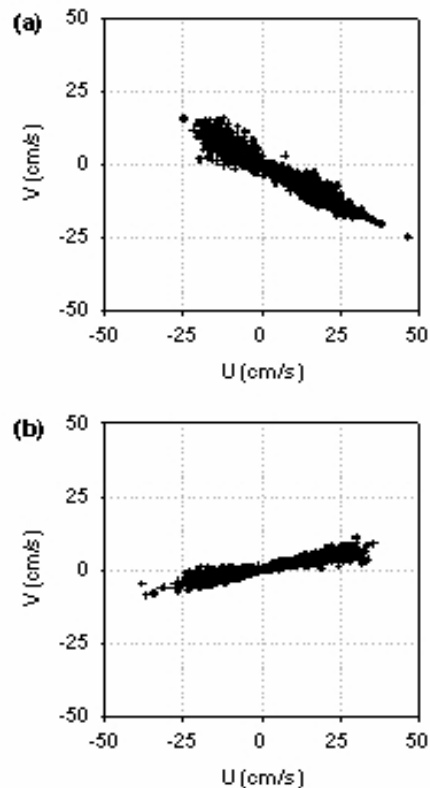

Figure 2   Scatterplots of currents measured at (a) Station 1, 18 October – 1 November 2001, and (b) Station 2, 7 – 22 March 2002. These plots use a standard oceanographic coordinate system: U is positive to the east and V is positive to the north. During both deployments, the flow was strongly bi-directional with a distinct ebb/flood axis.

The ebb/flood axis was used to rotate the measured currents to along (v) and across (u) channel components. The maximum along-channel velocities varied between 29 cm s^{-1} into the cove and 53 cm s^{-1} out of the cove (Figure 3a). The across-channel component was less than 8 cm s^{-1} at all times. The along-channel current speeds decreased to generally less than 20 cm s^{-1} during the neap tide, day 296 to day 300. At all times there was a distinct asymmetry to the flow. The velocity changed rapidly from maximum ebb to maximum flood, and then decreased more gradually from flood to ebb. On many days, a double ebb was observed which is consistent with other data collected in this section of the Thames River estuary (Huzzey 1998). The amplitude of M$_4$ constituent was the

second largest tidal harmonic and M_4/M_2 ratio was 0.24. The tidal mean current over the measurement period was 1.3 cm s^{-1} in the ebb direction, out of the cove.
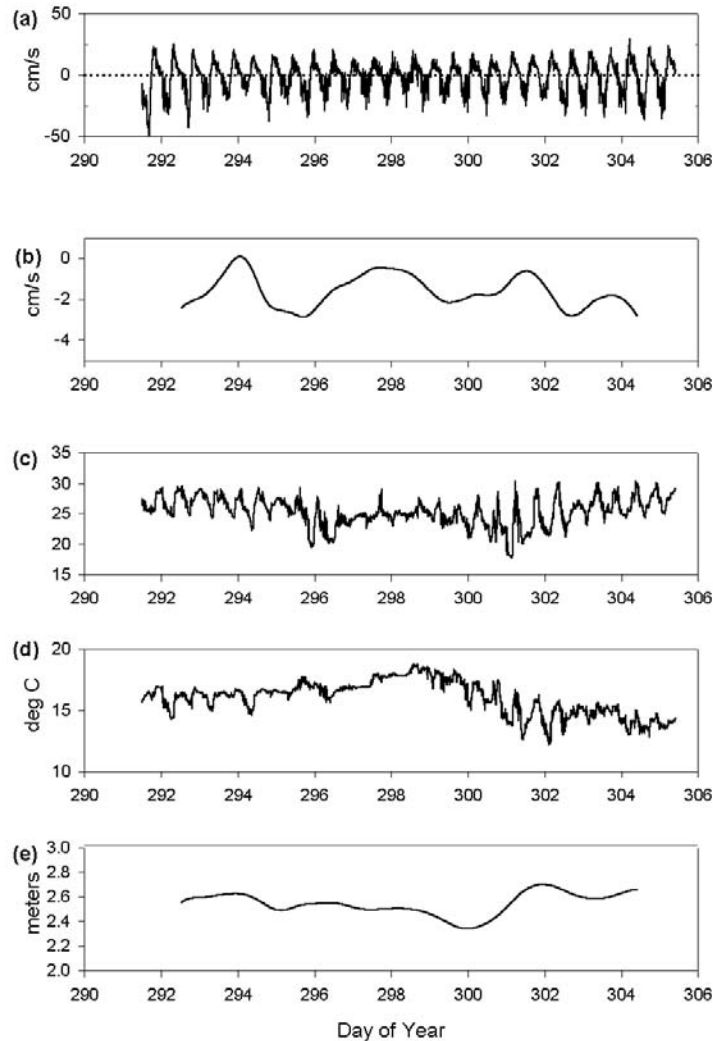

Figure 3: Time series of data collected at Station 1, 18 October – 1 November, 2001 (days 291-505): (a) along-channel velocity, (b) low-pass filtered along channel velocity, (c) salinity, (d) water temperature, and (e) low-pass filtered water depth

The non-tidal flow, calculated using a third-order Butterworth low-pass filter, was temporally variable but always out of the cove with speeds generally less than 5 cm s^{-1} (Figure 3b).The time-series of salinity at this location varied both tidally and in response to larger-scale events (see Figure 3c). For the first three days and the last two days of the deployment, the salinity varied semi-diurnally by approximately 4 psu, with a mean value of 27 psu; maximum and minimum vales of salinity lagged the maximum flood and ebb currents by as much as three hours. On days 297 to 300, during the neap tide, the mean salinity was 25 psu and there

was reduced tidal variability. Immediately before and after the neap tide, there were several days with greater salinity variations. On day 296, there was a strong pulse of low salinity (20 psu) water exiting on the ebb tides, which closely followed and corresponded with a period of enhanced non-tidal flow out of the estuary. Around day 301, there were several days with large semi-diurnal salinity oscillations. Tidal currents on these days were not especially strong, so the greater salinity range through the tidal cycle must reflect an increased longitudinal salinity gradient within the cove. This is supported by local rainfall data; several rainfall events were recorded over the previous few days. The water temperature over the deployment also varied tidally and showed a constant to slightly warming trend up to day 300 (Figure 3d). For days 300 to 302, the mean temperature decreased and the temperature changed tidally by as much as 5 °C, with the coldest water occurring at the end of the ebb. This is consistent with the salinity observations and further suggests that a fresher and colder water mass had entered the upper end of the cove at this time. The low-pass filtered water depth varied between 2.35 meters and 2.7 meters (Fig 3e).

Current data were also obtained at Station 2, the upstream entrance to the cove, for the first two days of the deployment. The flow was tidal and bi-directional, and the duration of each flood and ebb was almost equal. Maximum flood and ebb currents at the two locations were in phase, but the slack before ebb occurred 15 to 30 minutes earlier at Station 2. Maximum flood currents were similar magnitude at both stations, but the maximum ebb currents were at least 50% stronger at Station 1.

<u>Spring 2002</u>
Currents measured at Station 2 for two weeks in March 2002 were also strongly bi-directional and had an ebb/flood axis of 78°/258°. This alignment is in accordance with the direction of the channel as it passes under the road bridge (see Figure 1). The ebb/flood axis was used to rotate the measured currents to along (v) and across (u) channel components. Maximum flood along-channel current speeds were approximately 25 cm s^{-1} and max ebb speeds approximately 30 cm s^{-1} (see Figure 2b). The across-channel component was generally less than 5 cm s^{-1}. There was no distinct spring-neap variation in measured current speeds (Figure 4a) even though the deployment spanned a predicted weak spring tide. As was observed at this location in October 2001, the tidal flow was generally symmetrical with similar duration for each flood and ebb phase. In comparison with Station 1, there was no consistent double ebb or double flood and the M_4/M_2 ratio was only 0.10. The tidally averaged flow over the deployment period was 3.4 cm s^{-1} in the ebb direction. The low-pass filtered currents were always directed down-cove (Figure 4b); speeds were relatively constant around 4 cm s^{-1} with the exception of day 68 to 72.
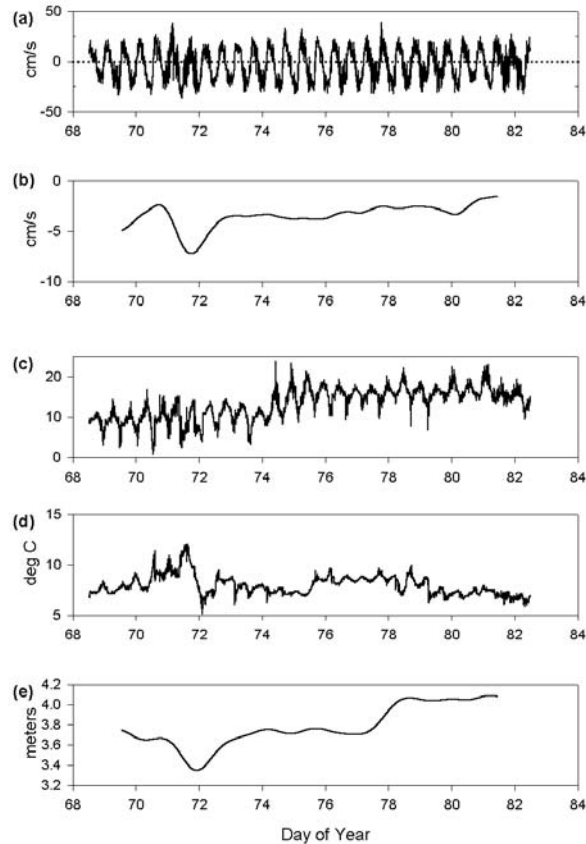
Figure 4   Time series of data collected at Station 2, 7 – 22 March, 2002 (days 68-81):
(a) along-channel velocity, (b) low-pass filtered along channel velocity, (c) salinity, (d)
water temperature, and (e) low-pass filtered water depth

Salinity varied tidally by as much as 10 psu. The maximum and minimum
salinities lagged the maximum flood and ebb currents by up to 3 hours.
Superimposed on this tidal oscillation was a marked increase in mean salinity on
day 72 (Figure 4c). During the first 6 days of the deployment, the mean salinity
was 9.6 psu but increased to 16.1 psu for day 73 to 80. Mean temperature values
were relatively constant over the deployment (Figure 4d), with the exception of an
increase, followed by a rapid decrease, on day 71. There was some tidal variation
in temperature and in general, the relatively warmer water corresponded with
lower salinity. This is the opposite of what was observed in October but is
consistent with the seasonal changes in water temperature noted in other areas of
the Thames River estuary (Huzzey 1998). The low-pass filtered water depth was
generally about 3.7 meters but decreased to 3.3 meters on day 72 and increased to
4.1 meters on day 78 (Figure 4e). These differences are indicative of changes in
total water volume in the cove.

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2. Surface drifters

Drifters were released on seven days during the current meter deployment in October 2001. The paths followed by drifters released during the flood and ebb portions of the tidal cycle on two of the days are shown in Figs. 5a and 5b respectively.
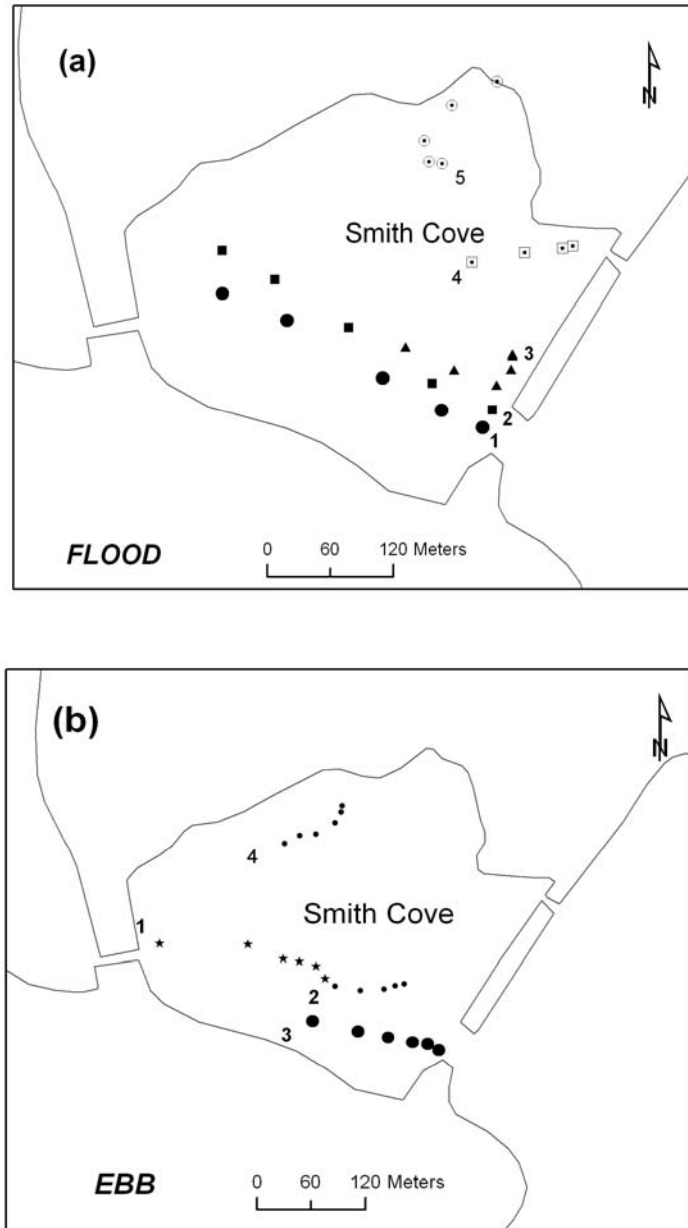

Figure 5   Paths followed by near-surface drifters showing typical patters of flow during ebb and flood tides. (a) 23 October, flood tide, winds 5-15 kts from the SE (b) 11 October, ebb tide, winds < 10 kts from W. Symbols along drifter paths indicate locations at 10 to 15 minute intervals; the release position for each drifter is adjacent to the drifter number.

Drifter paths on the other dates showed very similar patterns. Flow speeds were greatest in the channel. During the flood, drifters released near the outer entrance to the cove moved into, or remained in, the channel between the outer railroad bridge and the constriction at the road bridge (see drifter numbers 1, 2 and 3, Figure 5a). Drifter speeds along the channel in the cove were generally about 60% of the speed of the flow measured at Station 1, the entrance to the cove. The drifters released in the very shallow northern edge of the cove (drifters number 4 and 5, Figure 5a) moved very slowly and shoreward, often in a direction counter to the flood tide direction along the channel, suggesting that there is a broad eddy over the shallow northern shoal. In general, drifter speeds in the channel on 23 October were 3 to 4 times greater than those over the shallower shoals. During the ebb, drifters similarly showed faster speeds in the channel (see drifter numbers 1, 2 and 3, Fig 5b) and a northward and shoreward movement over the shoal (drifter number 4, Figure 5b). During the transition from flood to ebb tide, a brief clockwise eddy developed near the upstream entrance to the cove. The ebb current at Station 2 leads the current at the outer opening by 15 minutes. A distinct shear zone between water ebbing under the road bridge, but still weakly flooding within the cove, was observed on several occasions. At all times there was distinct difference is current speeds and directions between the channel and shoal areas within the cove.

DISCUSSION
The residence time in Smith Cove could be controlled by freshwater entering from the upper portion of the cove, tidal exchanges between the Smith Cove and the Thames River at the outer entrance, or wind acting either locally or remotely on the circulation. The bulk residence time of water in the cove can be estimated using the measured residual flows through the outer entrance (Station 1) and a measured value for the average volume of the cove. For these calculations any flux through the much smaller northern railroad bridge is neglected as the cross sectional area is only approximately 15 m^2 compared to 60 m^2 under the larger of the railroad bridges. The volume of the cove was obtained from a grid of depth soundings taken at mid tide; it was found to be 3.96 x 10^5 m^3. During the October 2001, the mean non-tidal current at Station 1 was 1.3 cm s^{-1} out of the cove. The current meter was moored at mid-depth in the central part of the entrance. As the boundary layer profile along the wetted perimeter if the opening was not measured, we applied the mean current speeds measured by the current meter uniformly to the entire cross sectional area, this gives a mean net flux through the entrance of 0.78 m^3 s^{-1}. Knowing the average volume of the cove and the net flux through outer entrance, the residence time was estimated as 3.96 x 10^5 m^3 /0.78 m^3 s^{-1} or 5.9 days. The observed residual flows during the October 2001 deployment varied between approximately zero and 3.5 cm s^{-1}. Assuming a constant volume of water in the cove, when the residual flow is 3.5 cm s^{-1} the residence time would reduce to 2.2 days.

The days with greater residual flows, and fluxes, through the entrance can be correlated to the local winds. The north-south and east-west components of the wind at the mouth of the Thames River are shown in Figure 6. During the October deployment, the wind was primarily out of the southwest with speeds less than 20 mph except for strong south southwesterly winds on day 295, and westerly to northerly winds on days 299 to 301 (Figure 6a).
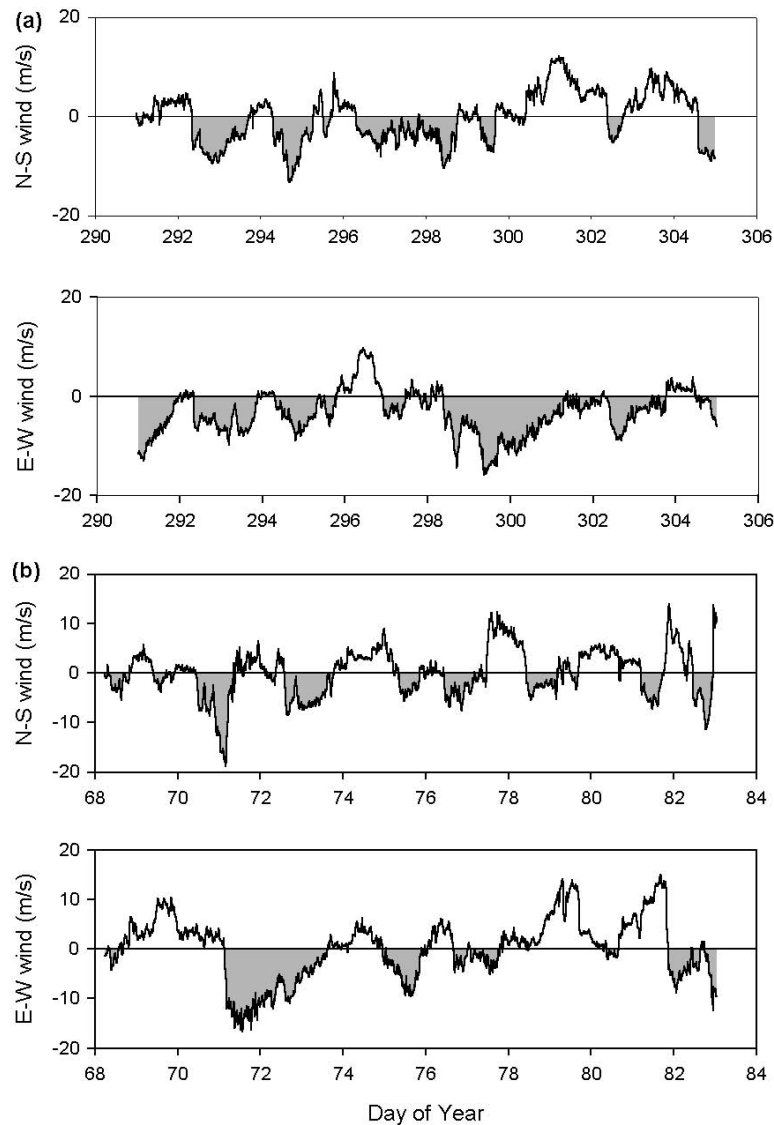

Figure 6   The north-south and east-west components of winds measured at the lower Thames River (Ledge Light) meteorological station maintained by the University of Connecticut Department of Marine Sciences during (a) October 2001 and (b) March 2002. Wind directions follow the meteorological convention; winds from the north and from the east are positive.

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This latter event was due to the passage of a cold front as evidenced in the air temperature and atmospheric pressure data collected at the same location. The south southwesterly wind on day 295 quickly changed to northwest; at that time non-tidal velocities through the entrance increased (Figure 3b) and a pulse of lower salinity water exited the cove on day 296 (Figure 3c). This was presumably water from the upper part of Smith Cove, upstream from the road bridge, which had been advected down into the main cove. Similar increases in flow out of the cove, and large tidal salinity oscillations indicative of more low salinity water reaching the entrance, occurred during the strong northwesterly wind event on days 299 to 301. During this event, which had more sustained and stronger westerly winds, the water level at Station 1 decreased to 2.3 meters (Figure 3e). Around day 298, which was during a neap tide, winds were very light and the residual flows very weak. Residual flows of less than 1 cm s^{-1} would increase the residence time to 7.6 days. The increase in water levels on days 302 and 304 correspond to days with strong northerly winds. Given the topography of the Thames River estuary, northerly winds could drive water onto the broad shoal outside Smith Cove, thereby altering water levels at the entrance to Smith Cove.

In March 2002, similar wind effects on the residual flows at the upstream entrance to the cove were observed. The strongest winds occurred on day 71 when the winds were from the south changing to the west at speeds of greater than 30 mph throughout the day (Figure 6b). Ebb current speeds were as much as 38 cm s^{-1}, the maximum value for the deployment. Later that day and during the following day there was a distinct pulse in non-tidal flow at Station 2, which reached maximum speeds of 7.2 cm s^{-1} (Figure 4b). There was also a decrease in the mean water level (see Figure 4e). Throughout the rest of the deployment, the non-tidal flow at this location was less than 4 cm s^{-1}. Two days after the pulse in down-cove flow the mean salinity at Station 2 increased by 5 psu. This can be attributed to a rebound effect as the cove re-filled, and higher salinity water from the Thames River entered. An opposite wind-induced disruption in flow and water level was observed on days 79 and 81 when there were episodes of 30 mph easterly winds sustained for several hours. Water levels at Station 2 increased by 0.4 meters during this time and there was a reduction in the down-cove non-tidal flow.

Freshwater enters Smith Cove from Hunts Brook, at the upstream end, and several storm water drains. Hunts Brook is less than 0.5 m deep; it is expected to have greater discharge during the winter and spring months or following large storm events. However, in general, freshwater inflows are very small and it is assumed that they would only control the residence time under extreme storm conditions. As can be seen in the data collected during this study, pulses of lower salinity water through the lower cove are connected to wind events and changes in non-tidal flows. More measurements are needed to determine whether the low-salinity water reaching the lower cove is a consequence or a cause of the changes in non-tidal flow.

Without winds or freshwater flows, and given the small size of Smith Cove relative to the tidal excursion, the residence time is most likely controlled by tidal exchanges between the Smith Cove and the Thames River. Commonly the time scale of such tidal flushing has been estimated using some version of the tidal prism method; that is, it is calculated using the known volume of the estuary divided by the tidal prism, or inter-tidal volume. This approach is flawed primarily because it assumes complete mixing within the estuary over the tidal cycle, and that none of the exiting water returns on the next tidal cycle. To account for this latter effect, Sanford et al. (1992) developed a modified tidal prism method where the residence time is given by:

$$T_R = \frac{VT}{(1-b)P} \tag{1}$$

Where V is the average volume of the estuary, T is the tidal period, P is the tidal prism, and b is a "return flow factor" which accounts for water entering each flood tide that had exited on the previous ebb tide. To obtain an accurate measurement of b requires knowledge of the flow field in the receiving waters and the size and location of the plume of water exiting from the cove. This is best obtained by dye studies. No such information is available for Smith Cove, but in this case b is expected to be large as Smith Cove empties into a broad shoal area of the Thames River estuary (see Figure 1) where the currents are generally less than 20 cm s^{-1} and directionally variable (L. Huzzey, unpublished data). This means that a significant portion of the water exiting Smith Cove on any ebb tide may re-enter the cove on the following flood tide, thereby reducing the effectiveness of the tidal flushing. A preliminary estimate of b for Smith Cove can be made using the residual flows through the outer entrance during the October 2001 deployment when the winds were very light (around day 298). The residual flows at this time were less than 1 cm s^{-1}. This gives a residence time of 7.6 days. Substituting this into equation 1 along with measured values of the volume (V) and estimated inter-tidal volume (P) and using a 12.4 hour tidal period, gives a value of $b = 0.7$. This value will be verified with further studies.

Data collected during these two deployments show that although tidal flushing may be the most repeatable and regular mechanism by which water is exchanged between Smith Cove and the Thames River, large wind events can cause water to be driven out of, or into the cove, and therefore further enhance or retard the flushing. These wind-driven flows will modulate the residence time on a synoptic scale. Of particular significance are the westerly winds associated with the passage of cold fronts. Observations in both October and March showed that strong westerly winds were accompanied by increased non-tidal flow down or out of the cove, and a decrease in water levels. The response of the cove to these wind events was within a day, implying that these westerly winds have a direct effect on the dynamics and enhance the removal of cove water, and its associated dissolved and suspended material, out of the cove into the adjacent Thames River estuary. In contrast, northerly or northeasterly winds increase water levels over the western shoal of the Thames River causing decreases in the residual flows out of the cove and increases in water levels within the cove. As with the westerly

winds, the response time was rapid and further illustrates the susceptibility of the cove to wind-induced modification of residence time.

Calculation of residence time simply based on flow through the entrances gives a bulk value that may significantly underestimate the residence time in some of the areas within Smith Cove. As the drifter data showed (Figure 5), tidal current speeds away from the channel region are very weak. Water exchanged through the entrance may primarily be the water located in the deeper, channel region. Water located in the shallower bordering shoals would have weaker tidal flushing, and thus a much greater residence time. Conversely, these very shallow areas may be more influenced by strong winds. More detailed current surveys are necessary to determine the magnitude the velocity shear across the cove under varying tidal and wind conditions. To be completely accurate, residence time calculations need to take into account this spatial variability.

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Source of unpublished materials

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