Estimation of Residence Time in a Shallow Back Barrier Lagoon, Hog Island Bay, Virginia, USA

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Abstract

Hog Island Bay, Virginia, is a shallow back barrier lagoon that is subject to seasonal inputs of inorganic nitrogen and related episodes of hypoxia. Numerical simulations were carried out to estimate the importance of physical flushing times relative to biochemical turnover times known to be a few days or less within the system. A 2D vertically averaged finite element hydrodynamic model, which was designed to accommodate regular flooding and dewatering of shallow flats and marshes, was coupled with a particle tracking model to estimate median lagoon residence time and the spatial distribution of local residence time in the lagoon. The model was forced with observed tidal elevations and winds from the end of the growing season when hypoxia tends to occur. The median residence time estimated by numerical modeling is on the order of weeks (358 hours), and variations in tidal stage, tidal range and wind produced deviations in median residence time on the order of days. Residence times near the inlets were very short, while those near the mainland were long, showing that (i) horizontal mixing in the Bay is insufficient to successfully apply integral methods to obtain residence times, and (ii) residence times near the mainland are long compared to timescales of biologically driven chemical transformations.

Introduction

Hog Island Bay, Virginia, is a shallow back barrier lagoon located behind Hog Island, one of the 100 km long chain of barrier islands on the Eastern Shore of the
Delmarva Peninsula, USA (Fig. 1). The lagoon system includes numerous relic oyster shoals, salt marshes, and mudflats, and is dissected by deep channels leading to the inlets. Freshwater runoff into the system is minimal and the water column is vertically well-mixed. Agriculture in the surrounding watershed leads to seasonal inputs of organic and inorganic nitrogen into the Bay. These nutrients support the growth of macroalgae (Gracilaria sp., Ulva lactuca), and microalgae as the primary producers in the system. Senescence and microbial degradation of the algal mats at the end of the growing season in late summer periodically cause hypoxia in the water column (Havens et al. 2001; Tyler et al. 2001). Nitrogen uptake and turnover by primary producers and bacteria typically occur on time scales of minutes to a few days (Anderson et al. 2003; Tyler et al. 2003), although nitrogen can be retained in macroalgal biomass for weeks (Tyler et al. 2001).

In order to determine the importance of physical flushing relative to biologically mediated transformations, we performed an analysis of water residence times in Hog Island Bay using a numerical model. A variety of time scales, such as residence time, transit time and average age, have been used to characterize the degree of mixing and flushing in estuaries (Geyer and Signell 1992; Vallino and Hopkinson 1998; Monsen et al. 2002; Bilgili et al. 2003a). We will use the concept of median residence time, which is the length of time required to replace half of a group of labeled or “tagged” water particles inside the bay with new water from the outside of the bay. Previous analytical estimations of water residence time in Hog Island Bay have yielded short time scales of flushing. Brumbaugh (1996) measured volume flux at the inlets of the lagoon system and used the tidal prism method to estimate a mean residence time of about 5 tidal cycles or about 60 hours (median residence time would be a factor of 0.7 less).
The tidal prism method calculates residence time in units of tidal cycles by dividing the volume of the lagoon at high tide by the volume of water which passes through the tidal inlet over the course of a representative flood tide. This method assumes that each tide replaces entirely old water with entirely new water and that the new water is immediately mixed to the back of the lagoon. Oertel (Oertel 2001) also applied the tidal prism method to the region, but employed high resolution bathymetry and the tidal range to estimate a mean residence time of only 1.85 tidal cycles. The tidal prism method is inadequate for describing residence times in estuaries of significant size because it assumes the horizontal distance a water particle travels over a tidal cycle to be the same order as the length of the estuary. Furthermore, traditional integral methods largely neglect spatial and temporal variations in tidal amplitude, wind stress, and horizontal mixing (Geyer and Signell 1992; Oliveira and Baptista 1997).

Numerical models can account for the factors which limit other methods that are used for estimating flushing rates and have successfully estimated residence time in basins with complex geometry (Hofmann et al. 1991; Oliveira and Baptista 1997; Vallino and Hopkinson 1998; Smith et al. 2001; Bilgili et al. 2003a). In this study, we coupled a 2D finite element hydrodynamic model, called BELLAMY, that was developed by Ip et al (1998) and others with a particle tracking module, DROG3DDT (Blanton 1995), to perform a series of LaGrangian drifter experiments in Hog Island Bay. The model was forced by observed wind and water elevation data that were collected for over 50 tidal cycles at the end of the growing season.
Model Description

The lagoon system associated with Hog Island Bay (Fig. 2) has extensive tidal flats and marsh which emerge during low tides but continue to slowly drain groundwater while emerged. A common numerical scheme used to model alternately dry and flooded regions is to “turn off” elements which become dry (Jelesnianski et al. 1992; Hervouet and Janin 1994). The reconfiguration of the grid required by this method comes at a computational cost, can create an unrealistic step-like response in the hydrodynamics near the drying boundary, and does not represent soil drainage at low tide. Another approach developed by Ip et al. (1998) solves these problems by allowing water to continue to flow through a porous sublayer after the element becomes dry. The principal momentum balance in many shallow tidal embayments is between the pressure gradient and bottom stress (Swift and Brown 1983; Friedrichs et al. 1992). The diffusive nature of this force balance allows straightforward coupling to an equation for Darcian diffusion of groundwater in an underlying porous sublayer (Ip et al. 1998). The governing equations of the original model depended only upon this balance of forces. To accommodate deeper channels and meteorological forcing, the model has since evolved to include local acceleration, wind stress, and the opportunity to include a depth dependent bottom friction coefficient in the governing equations (McLaughlin et al. 2003). When the water elevation in a given element reaches below a threshold level of 0.5 m, local acceleration is ignored, significantly speeding the computation where grid spacing is smallest.

The shallow bathymetry and minimal freshwater input of Hog Island Bay allow the utilization of a two dimensional vertically averaged model. The model solves for the
state of the system based on tidal forcing and wind stress. The non-linear system of
governing equations of the model is solved iteratively at each time step. In the shallowest
areas, pressure gradient and bottom surface stress are balanced:

\[ \frac{\partial H}{\partial t} + \nabla \cdot \mathbf{Q} = 0 \]

\[ gH \nabla \zeta + \frac{C_d}{H^2} \mathbf{Q} \mathbf{Q} = \mathbf{W} \]

where \( H \) is total depth of the water column, \( \mathbf{Q} = HV \) is the volumetric flux, \( V \) is the depth
averaged velocity, \( g \) is gravitational acceleration, \( \zeta \) is surface elevation relative to mean
sea level, \( C_d \) is the bottom drag coefficient, and \( \mathbf{W} \) is the kinematic wind stress (see also
McLaughlin et al., 2003). These equations may be rearranged to eliminate \( \mathbf{Q} \) and
produce a nonlinear diffusion equation. The addition of a porous layer below the open
channel using a Darcian approach yields:

\[ S \frac{\partial \zeta}{\partial t} - \nabla \cdot (D_o + D_p) \nabla \zeta = -\nabla \cdot \frac{D_o \mathbf{W}}{gH_o} \]

where \( D_o \) and \( D_p \) are the diffusion parameters for the open channel and porous medium,
and \( S \) is the storage coefficient, which varies between the open channel and the porous
medium. In deeper channels, local acceleration is added to the momentum balance:

\[ \frac{\partial \zeta}{\partial t} + \nabla \cdot \mathbf{Q} = 0 \]

\[ \frac{\partial \mathbf{Q}}{\partial t} + gH \nabla \zeta + \frac{C_d}{H^2} \mathbf{Q} \mathbf{Q} = \mathbf{W} \]

The flooding and drying module in this model study is not an attempt to accurately
describe the flow in the Darcian layer but rather a natural way of incorporating into the
model the volume of fluid displaced during the filling and emptying of tidal flats. This is
necessary due to the fact that the hydrodynamics in the main channel and other non-
drying areas are directly affected by the water storage on drying basins. The model is discussed extensively and is proven to be numerically robust and to successfully reproduce tidal constituents and morphological features in the Great Bay Estuary, New Hampshire in: (Ip et al. 1998; Inoue and Wiseman 2000; Erturk et al. 2002; Thompson et al. 2002; Bilgili et al. 2003b; McLaughlin et al. 2003).

Particle, or drogue, tracking was done with DROG3DDT (Blanton 1995) which was implemented with only one vertical layer in order to accommodate the 2D vertically averaged hydrodynamic model. The tracking model is forced by the velocity field generated by the Bellamy model and solved using a fourth order Runge-Kutta integration scheme. Particles are treated as passive drifters in this model.

Computational Setup

The primary region of interest within the lagoon system is Hog Island Bay, a Long Term Ecological Research site of ongoing nutrient flux analyses. The open water boundaries of the entire modeled region lie offshore in the ocean at least 18 km away from Hog Island Bay to avoid boundary effects, and to avoid the necessity of estimating forcing conditions along the many inlets within the system. Detailed bathymetry of the Machipongo watershed was obtained from the Virginia Coast Reserve/Long Term Ecological Research (VCR/LTER) webpage (Oertel et al. 2000). Additional bathymetry was obtained from NOAA nautical charts and the NOAA GEODAS database. Drogue release positions were limited to the areas of the Bay in the Machipongo watershed where
high resolution bathymetry was available, so that residence times may be simulated most accurately.

The modeled region was gridded using the BatTri 2D Finite Element Generator (Smith and Bilgili 2003). The model mesh was configured to have a minimum angle constraint of 25 degrees and to satisfy a Courant condition of 1000 with a time step of 149 seconds. An offshore zone of coarser resolution was defined beyond the 18 meter contour. These grid constraints and data produced a finite element grid of 29,900 nodes and 32,400 elements (Fig. 3).

Bottom roughness is incorporated into the drag coefficient via the definition $C_d = g n^2 H^{-1/3}$ (e.g., Henderson, 1966), where $n$ is the Manning’s roughness coefficient, and $n$ (in mks units) is specified as a linear function of instantaneous water depth according to: 

$$n = 0.040 - 0.000492H.$$  

The porous medium thickness is set to 1 m, and the hydraulic conductivity within the medium is set to $3.16 \times 10^{-4}$ (Bilgili et al. 2003b). Sensitivity analyses by Bilgili et al. (2003) indicated that changes in the porous medium parameters result in no significant change in the hydrodynamics of the open-water channel, which is the area of interest. Since the lagoon is almost entirely enclosed by land, a wind drag coefficient of 0.004 was used in accordance with the results for offshore directed winds from Friedrichs and Wright (1998).

Forcing data for the model were obtained from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS). Hourly water elevations from Wachapreague, near the northern end of the modeling domain, and Kiptopeke, near the southern end at the mouth of the Chesapeake Bay, were distance weighted along the 146 open water boundary nodes. Hourly wind velocities were obtained from the Kiptopeke
station. The model is forced with tidal elevations at the open water boundaries from the period of August 2 to September 16, 2000 (Julian day 214-259, Fig. 4). Wind stress forcing is derived from the wind velocities over the same period and applied uniformly across the grid.

The model was set to run at time steps of 149 seconds, or about 300 time steps per tidal cycle. Drogue tracking was started after the first six tidal cycles to allow time for the hydrodynamic model to reach dynamic equilibrium. The median residence time is estimated as the length of time required for half of the modeled drifters to exit through one of the inlets. Once they exit, it is assumed that the predominantly Southward alongshore current carries them away so that they do not reenter (Finkelstein and Ferland 1987).

Model Validation

The entire record of tidal elevations that were obtained from the CO-OPS data archive for Kiptopeke from August 2, 2000 to September 16, 2000 are shown in Fig. 4b. Note the variation in tidal range and synoptic variations in mean water level. The tidal elevations at Wachapreague are similar, but with about 0.3 m larger tidal range. Wind velocities for the same time period are variable and moderate (Fig. 4a). Mean predicted peak flood currents at Machipongo Inlet were 0.6 m s$^{-1}$. Although not measured at the same time, these results are consistent with the mean peak flood currents of 0.6 m s$^{-1}$ obtained by Brumbaugh (1996) on July 15-16, 1993 at Machipongo Inlet. Tidal ranges at the open boundaries for the simulation period varied from 0.62 m to 1.30 m with a mean
of 0.95 m. The modeled tidal prisms within this region for this period ranged from $0.4 \times 10^8$ m$^3$ to $1.5 \times 10^8$ m$^3$ with a mean of $0.8 \times 10^8$ m$^3$. This compares favorably with the tidal prism estimate of Oertel (2001) of $1.8 \times 10^8$ m$^3$, considering that he assumed a 1.5 m tidal range.

A more rigorous opportunity to validate the model came, subsequent to the initial residence time analysis, in November 2002, when an upward looking Acoustic Doppler Profiler (ADP) was deployed by P. Wiberg and S. Lawson near Rogue Island in Hog Island Bay (Fig. 1) in support of the VCR/LTER site. Without any adjustment of the model parameters, the model was rerun using observed tidal elevations and winds from that period. Figure 5 compares the model predictions and the ADP observations of vertically averaged currents. Although the model misses some peaks in velocity, there is a generally good match. The mismatch at the peaks biases the root mean square difference of 0.09 m s$^{-1}$ between the predicted and observed current speeds, while the root median square difference gives a more typical mismatch value of 0.06 m s$^{-1}$.

Particle Spatial Resolution Sensitivity

The lowest spatial resolution of drogue positions that also gives robust estimates of residence time maximizes the computational efficiency of the model. To determine the optimal spatial resolution, three runs were performed over 59 tidal cycles using the same tidal elevation and wind stress data. Regular matrices of drogues were established within the Machipongo watershed area with three different spatial resolutions. Drogues were spaced 500, 750, and 1000 meters apart, resulting in 488, 217, and 121 drogues in
each of the three respective configurations. Spatial distributions of the resulting residence times were qualitatively similar for each of the three runs. Median residence times were, 524, 525, and 537 hours for the 500, 750 and 1000 meter spacing respectively. It was therefore determined that drogue configurations with a spatial resolution higher than 750 meters did not give meaningfully significant differences in the results, and so this configuration was used in the following experiments (Fig. 6).

Error Estimation

For each model simulation, there is an error in the estimated median residence time that is associated with variations of the particle trajectories within the region of interest. The method of choosing a grid of evenly spaced particles within the region is a type of random systematic sampling of the modeled region with a regular interval (750 m) and a random start point. In order to estimate the error associated with variation of potential particle trajectories within the region, ten simulations were performed with the same forcing conditions and sampling interval, but with different random start locations. Each new starting position of the sampling mesh was placed 75 meters eastward from the previous starting position. The resulting standard error of the median residence time for these ten simulations was only 2.6 hours, suggesting that the estimation of the median residence time is not significantly affected by small scale spatial variations within the model simulation.
Median Residence Time

An important source of variation of median residence time in real estuaries is the variation of tidal elevations and wind velocities. The magnitude of these variations over synoptic time scales at the end of the growing season was estimated by performing separate model simulations with different starting times. The beginning of each simulation was lagged an arbitrary synoptic timescale of 3.5 tidal cycles from the previous one. Nine separate simulations were performed on the summer/fall 2000 period before there was insufficient water level data available to continue further in the year. The nine simulations were run for 18,000 - 9600 time steps or approximately 60 - 32 tidal cycles, of which the first 6 cycles were not used for particle tracking. The mean bay residence time from the five simulations is 358 +/- 39 hours (Table 1) and the range of bay residence time is 333 hours, showing that changes in tidal amplitude and wind velocities result in changes in bay residence time on the order of days. Mean bay residence times of drogues released during flood were on average 95 +/- 29 hours longer than those released 3.5 tidal cycles later during ebb. Particles initiated on ebb have systematically shorter residence times because the first half tidal cycle is directed seaward rather than landward.

The spatial distributions of the local residence times are similar for each of the above described simulations (Fig. 7). Local residence time is generally a function of distance from the inlets and proximity to the deep channel, except in cases where there is an elevated marsh around which residence times are high, for example, Rogue Island, which is just north of the inside of Machipongo Inlet. Many drogues that were originally
located near the mainland never made it out of the Bay during the simulated time period.

Figure 8 shows a typical drogue path. Animation of the wind velocity and the drogues show that drogue movement is influenced by the stronger tidal velocities in the deep channels, while in the shallower regions wind forcing is more important. When the model is run without wind forcing, the median residence time is too long to calculate because over half of the particles never leave the Bay. The wind not only provides a natural forcing on the water, it also acts as a horizontal diffuser. It is possible that adding random-walk type diffusion to the hydrodynamic model may further decrease the estimated median residence time. The overall distribution of residence times and the general pattern of the drogue paths indicate that the new water introduced at each flood tide pushes the water that is resident during low tide up and away from the inlets. Moderate wind induced horizontal mixing disperses the drogues and allows them to eventually exit with the ebbing tide.

The above particle tracking method for estimating median residence time is somewhat biased toward shallow regions in that, upon initial release, the drogues are equally spaced in terms of lagoon surface area, but not equally spaced in terms of the lagoon water volume that each initial drogue position represents. A more rigorous volume residence time can be calculated by weighting each drogue by the water depth at its initial release location. A slightly lower median residence time then results for the lagoon as a whole. Taking this approach results in the following median residence time: 324 +/- 39.
Conclusions

Numerical modeling has shown that the median residence times in Hog Island Bay at the end of the growing season are on the order of weeks instead of the few tidal cycles previously estimated using the tidal prism method. Numerical modeling not only accounts for limited horizontal mixing and changes in tidal amplitude and wind forcing, it allows the release of orders of magnitude more drogues than field operations allow and improves the statistical significance of the results. The spatial distribution of the residence times and general water movement within the Bay do not support the assumption of complete horizontal mixing that is required by integral methods of residence time estimation. Instead, the results suggest that in shallow friction dominated lagoons, new water from the incoming tide piles the old water up and away from the inlets. Residence times near the inlets are consequently very short, while away from the inlets water may reside for many weeks. Thus, in marshy areas and tidal creeks near the upland, biologically mediated reactions with turnover timescales of minutes to a few days are likely to control the fate of nutrients, while near the inlet, physical flushing dominates. One possible exception in Hog Island Bay may be the physical advection of nutrients tied up macroalgal biomass. It should be noted that the estimates nearest the inlets are conservatively short. Should the assumption of no returning old water be incorrect, then the amount of time a given parcel of water resides near the inlet is underestimated. The strong response of the drogues in shallow water to wind forcing suggests that during the winter, when algal growth is slow and winds are high, that residence times may be shorter due to a higher degree of horizontal mixing.
Acknowledgements

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Literature Cited


Brumbaugh, R. D., 1996. Recruitment of Blue Crab, Callinectes sapidus, postlarvae to the back-barrier lagoons of Virginia's Eastern Shore, Old Dominion University, Norfolk, VA.


Table 1. Variation in Median Residence Times over Synoptic Time Scales

<table>
<thead>
<tr>
<th>Time lag from Julian Day 214 (Tidal Cycles)</th>
<th>Median Residence Time, Median Depth Weighted Residence Time (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (flood)</td>
<td>534, 522</td>
</tr>
<tr>
<td>3.5 (ebb)</td>
<td>478, 417</td>
</tr>
<tr>
<td>7 (flood)</td>
<td>435, 386</td>
</tr>
<tr>
<td>10.5 (ebb)</td>
<td>381, 356</td>
</tr>
<tr>
<td>14 (flood)</td>
<td>334, 309</td>
</tr>
<tr>
<td>17.5 (ebb)</td>
<td>244, 206</td>
</tr>
<tr>
<td>21 (flood)</td>
<td>398, 337</td>
</tr>
<tr>
<td>24.5 (ebb)</td>
<td>219, 182</td>
</tr>
<tr>
<td>28 (flood)</td>
<td>201, 200</td>
</tr>
<tr>
<td>Mean +/- s.e.</td>
<td>358 +/- 39, 324 +/- 38</td>
</tr>
</tbody>
</table>
Figure Captions

Fig. 1. Map of Hog Island Bay, Virginia, USA. The ‘X’ marks the spot where the ADP was deployed.

Fig. 2. Hog Island Bay bathymetry, 1,2,5,10 and 15 m contours.

Fig. 3. Finite element grid of Hog Island Bay and surrounding region.

Fig. 4. Tidal elevations and wind velocities from Kiptopeke used to force the model.

Fig. 5. Observed and predicted vertically averaged current speeds near Rogue Island.

Fig. 6. Initial configuration of particle locations.

Fig. 7. Spatial distribution of local residence times for particles released during flood.

Fig. 8. Selected particle path over channel and shallow regions.
Horizontal Distance from West to East, $x$ (m)
Vertical Distance from South to North, $y$ (m)

Initial Position

Exit