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Flushing Time Versus Residence Time for the Great Bay Estuary

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A White Paper from the Piscataqua Region Estuaries Partnership (PREP)

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Subjects Covered in this White Paper

- Why are these terms important?
- How do methods for assessing flushing time and residence time differ?
- Why use one method versus another for the Great Bay Estuary?
- What are the historical and most recent estimations of flushing time and residence time?
- Conclusions

Abstract

Note: In this article, the term "Great Bay" will be used to denote the sub-embayment portion of the Great Bay Estuary located south of Adams Point. The term "Great Bay Estuary" will be used to denote the entire estuarine system, from Portsmouth Harbor to the freshwater portions of the various tributaries that feed into the estuary.

The terms "flushing time" and "residence time" have cropped up often in discussions about water quality and eelgrass health in the Great Bay Estuary. Flushing time and residence time are not the same thing and should not be used interchangeably. Flushing time is defined as the time it takes to replace a certain water mass in a coastal system and is most often used as a general measurement of water exchange in an estuary used to relate water exchange from one estuary to another. The most recent estimates of flushing time (2013) for the Great Bay are between 2.5 and 7 days. Residence time describes how long a parcel, starting from a specified location within a waterbody, will remain in the waterbody before exiting; residence time is more often used to understand or predict chemical and biological processes for a particular system. The most recent estimate of residence time for the Great Bay (2005) is between 5 and 20 days.

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Why are these terms important?

"Flushing time" and "residence time" are two commonly used terms to talk about transport time in estuaries. Transport time is important for many things of interest to natural resource managers, including impacts of eutrophication or "nutrient over-enrichment." Transport time offers clues as to how long chemical components (such as nutrients) remain in a certain area within a water body and also relates to potential impacts of eutrophication such as the presence of phytoplankton (microalgae) and seaweed in both its attached and drift forms.

How do methods for assessing flushing and residence time differ?

While the term "flushing" can be used in a general context to describe water exchange, "flushing time" (sometimes referred to as "turnover time") is often used specifically to describe a spatially integrative measurement (i.e., not location specific) useful for general characterization of water exchange. Residence time, in contrast, is often used to denote a location specific metric that makes it useful for understanding the particulars of one estuary's unique conditions, chemical reactions and biological processes. Depending on the estuary, these different methods can produce similar estimates, or they can vary by as much as an order of magnitude. Therefore, it is important to use the most appropriate method, depending on the monitoring or research question at hand.

(Unfortunately, practitioners in the literature are not 100% consistent in how these terms are used, so readers must be careful to discern the methodological details and not simply rely on the terms used.) For the rest of this article, however, we will use "flushing time" to refer to the spatially integrative method and "residence time" to refer to the "local" or "spatially explicit" method.)

Flushing Time

Flushing time is most often defined as the time it takes to replace a certain water mass in a coastal system. In well-mixed estuaries with low freshwater inputs, flushing time is sometimes calculated from the mean tidal volume of the estuary and the mean volume of the tidal prism.

The basic mathematical operation involves dividing the volume of water in a system by the flow rate through the system. However, in an estuary, the volume and the flow rate are variable and quite dynamic. Therefore, to calculate flushing time, one has to assume that any introduction of mass is instantaneously and evenly mixed throughout the system. Then, it becomes possible to solve analytically for the concentration of a given substance in the outflow over time.

Most often, practitioners use an exponential decay function to come up with a final estimate of flushing. This is because, in this mathematical calculation, the water never completely flushes out. In most cases, practitioners declare the system "flushed" when 37% of the introduced substance remains in the system (Monsen et al. 2002; Li 2010; HDR/Hydroqual 2013) and 63% has exited the system. One example of this approach comes from the HDR/HydroQual hydrodynamic model calibration report (2013), based on the Great Bay Estuary. The report states: "One definition of flushing time is the time it takes to reduce the mass of the conservative substance to 0.37 (1/e) of the value at the beginning of the model simulation. Using this definition, the flushing time for the Great Bay is estimated at 7 days." Since this estimate is offered in the context of chemical and biological processes, it is important to remind readers that the introduced water may never completely leave the system and flushing is rarely 100% achieved. Flushing time only reflects the average amount of time the mass spends in a system (Monsen et al. 2002). Li (2010) notes that flushing estimates calculated in this way tend to underestimate the time that a water mass remains in a system.

Residence Time

In contrast with flushing time, residence time has a spatial component; it describes how long a parcel, starting from a specified location within a waterbody, will remain in the waterbody before exiting. Unlike flushing time, residence time defines finite transport times through the system (Monsen et al. 2002). Residence time is the more appropriate measure to use when attempting to understand chemical and biological processes in one specific estuary, rather than trying to compare one estuary to another (Monsen et al. 2002), because it considers the spatial particularities of each sub-embayment of an estuary (Li 2010).

There are a number of different methods for calculating residence time, including hydrodynamic computer models. In general, residence time is calculated by looking specifically at how long a particle of water stays in either a sub-embayment (e.g., the Great Bay or Little Bay) or for an entire system (e.g., the Great Bay Estuary). To assess residence time, practitioners must model many particles originating at many different locations within an embayment. Therefore, residence time is often expressed as a range of results, although mean residence times can also be given. Residence time models can also be used to generate maps to show which portions of an estuary have longer residence times, and are more poorly flushed as a result. Like flushing models, residence time calculations can be based on the saltwater or freshwater fractions of an estuary.

Note that residence time assesses how long it takes for a particle to exit the system; whether the particle re-enters the system is not taken into account. An additional term, "exposure time," is used to account for possibility of a substance, such as a nutrient or algal cell, exiting and then re-entering the system, due to changes in current direction because of tides, for example.

Why use one method versus another for the Great Bay Estuary?

Which calculation is more appropriate depends on the estuary, and what question is being asked. Residence time models are often used to understand or predict chemical and biological processes for a particular system. Monsen et al. (2002) note that: "Selection of the most appropriate transport time scale depends on the guiding question. If the question involves a comparison of general characteristics between different water systems, a system measure [e.g., flushing time] might be appropriate. However, if the question involves the importance of a chemical reaction or biological process in a sub-embayment of the domain, then a local transport estimate [e.g., residence time] might be necessary."

What are the historical and most recent estimations of flushing and residence time?

The most recent estimation of flushing time in the Great Bay Estuary comes from the 2013 HDR/Hydroqual Calibration report, based on a three-dimensional model. This report assessed the flushing time of the Great Bay to be between 2.5 and 7 days, depending on the tidal stage when the model was run. For estimates before 2013, it is useful to consult Trowbridge (2007), which contains a review of research on the Great Bay Estuary related to flushing and residence time. In 2005, a two-dimensional model assessed the Great Bay flushing time at between 5 and 30 days (Bilgili et al. 2005), depending on the tide and river discharge states involved. (High river discharge and spring tides caused the shortest flushing times.) In 1980, using a one-dimensional model and the tidal prism method—a different approach for assessing flushing time—Brown and Arellano (1980) estimated mean flushing times between 2 and 6 days, depending on what portion of the Great Bay proper was being considered.

The most recent estimation of residence time in the Great Bay Proper comes from a two-dimensional model implemented in 2005 (Bilgili et al.) In that study, water particles that began in the Great Bay remained in that sub-embayment between 5 and 20 days. These same water particles remained in the larger system (the Great Bay Estuary) for an average of 25 days (range of approximately 20 to 30 days). In other words, water particles may exit the Great Bay proper but continue to move around in Little Bay and the Piscataqua River for additional time before exiting over the ocean boundary.

Please see the various papers referenced above for more specifics for the entire estuary as well as each sub-embayment (e.g., Little Bay, Great Bay, Upper Piscataqua, Portsmouth Harbor).

Conclusions

The terms “flushing time” and “residence time” have cropped up often in discussions about water quality and eelgrass health in the Great Bay Estuary. Flushing time and residence time are often measured with different methods and should not be used interchangeably. In general, flushing time is a general measurement of water exchange in an estuary used to relate water exchange from one estuary to another. The most recent estimates of flushing time (2013) for the Great Bay are between 2.5 and 7 days.

Residence time usually denotes a local assessment that considers the particularities of the estuary in question; this approach is generally recommended for dealing with questions of water quality and biological processes. The most recent estimate of residence time (2005) for the Great Bay is between 5 and 20 days.

Relative to other estuaries, the Great Bay Estuary has a high rate of water exchange, whether you measure using flushing time or residence time. Understanding the specifics of how a high rate of exchange affects our estuary is complicated and includes consideration of a number of factors and issues. Of particular interest to PREP are the biological indicators affected by exchange rates including seaweed, phytoplankton and eelgrass. The 2018 State of Our Estuaries Report (PREP 2017) points out that seaweed abundance has increased since 1980 and may be a factor in eelgrass health. We are observing that even with a high rate of water exchange, seaweeds are often not flushed out with the tide because they are either attached to a rock or shell or, if they are drift algae, they are often caught up in eelgrass or other habitats.

With regard to phytoplankton the report points out that, while there are no statistically significant phytoplankton trends in the Great Bay Estuary, chlorophyll-a levels at certain locations periodically exceed 20 ug/L, considered a sign of “poor” water quality by EPA and NOAA. Phytoplankton reproduce at various speeds, depending on the species. While some phytoplankton can double once a day, others require three days to reproduce. Therefore, even if the residence time of the Great Bay was the same as flushing…that is, 2.5 to 7 days, that would still be enough time for phytoplankton to affect water clarity.

The PREP report notes that eelgrass health has been declining due to multiple factors, so evaluating conditions related to exchange rate that may be impacting eelgrass health continues to be important. The presence of seaweeds, phytoplankton and epiphytes all impact water clarity and eelgrass health. Because seaweeds, phytoplankton and epiphytes grow more when there are higher levels of nitrogen in the water column, PREP and external experts from other regions advise continued efforts to address nitrogen loading and especially non-point source loading, which is exacerbated by the increasing frequency of storms with heavy rainfall (PREP 2017; Kenworthy et al 2017).

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