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Concepts and Applications of Water Transport Time Scales for Coastal Inlet Systems

by Honghai Li

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) reviews concepts describing water transport time scales – flushing time, age, and residence time – and illustrates their use for coastal applications. As an example, a methodology to estimate residence time is presented for a constructed wetland cell in Chesapeake Bay, MD with the output of the Coastal Modeling System (CMS) and the CMS-driven Particle Tracking Model (PTM).

INTRODUCTION: Water transport time scales measure how a coastal system, such as an inlet, embayment, or estuary, responds to introduction of dissolved and suspended materials, and how fast water masses are replaced within the system. In general, the waterborne material can be conservative or non-conservative. Processes such as salinity (or freshwater), nutrients, passive larvae, and contaminants can be thought of as the tracer materials for the estimate of the time scales related to coastal advection and dispersion. This CHETN discusses the time scales described as flushing time, age or residence time of conservative materials in a first-order approximation of transport.

Coastal, estuarine, and ocean dynamics determine transport time scales of water within inlets, embayments or estuaries, which play a central role in water quality and bay ecology. Associated with navigation-related operation and maintenance projects, the transport time scales include the estimate of salinity change in response to channel modification and transport of fish larvae, fish eggs, and juvenile fishes into and out of an embayment through a coastal inlet. In addition, water and waterborne material transport can assist engineers and scientists in examining sustainability of wetland development through beneficial reuse of dredged material and to assess the consequence of dredging activities on water and material exchange processes and flushing of a coastal system.

TIME SCALES: Monsen et al. (2002) summarize the applications of water transport time scales in coastal, estuarine, lake, and riverine systems. Three basic time scales are commonly defined: flushing time, age, and residence time.

1. Flushing time: Flushing time, also known as turnover time, defines the amount of time required to replace a certain water mass or waterborne material, expressed as a scalar such as mass or volume, in a coastal system. For a well-mixed, steady-state system, a more quantitative description was presented by Geyer et al. (2000) as “the ratio of the mass of a scalar in a reservoir to the rate of renewal of the scalar.” Accordingly, Fischer et al. (1979) expressed the flushing time in a reservoir system:

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$$T_f = \frac{M}{F} \tag{1}$$

where T_f is flushing time, M is mass of the scalar in the reservoir, and F is mass flow rate of the scalar through the reservoir. An alternative way to calculate T_f is

$$T_f = \frac{V}{Q} \tag{2}$$

where V is total volume of water in a coastal system, and Q is volume exchange rate through the system.

Flushing time, as expressed in Equations (1) and (2), is essentially an integrated time scale under the assumptions made. It measures the average time required to flush a system. Based on the concept of a continuous stirred tank reactor (CSTR), an ideal embayment is designed and sketched in Figure 1. Total volume of the embayment is V, and tracer concentration in the embayment is C. Volume inflow and net outflow rates are represented by Q_i and Q, respectively, and inflow tracer concentration is C_i. The tracer mass balance in the embayment can be expressed by the following equation:

$$V\frac{dC}{dt} = Q_iC_i - QC \tag{3}$$

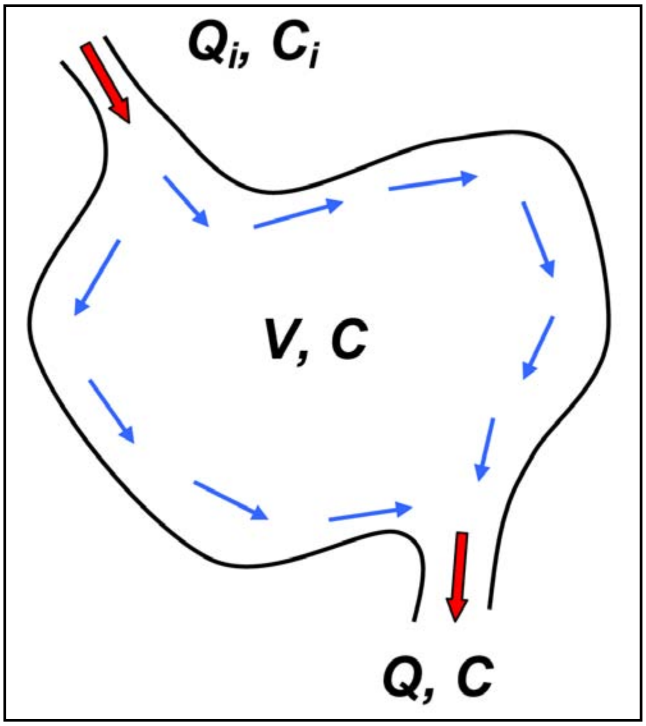

Figure 1. An ideal embayment.

Assuming that there is no net tracer mass inflow ($C_i = 0$), and that the initial concentration is C_0 is completely mixed and at the steady-state in the embayment, the solution of Equation (3) is

$$C(t) = C_0 e^{-\frac{Q}{V}t} = C_0 e^{-\frac{t}{T_f}} \tag{4}$$

Based on Equation (4), the temporal change in tracer concentration in the embayment is shown in Figure 2. At the end of the flushing time period ($t = T_f$), about 1/*e* (37%) of the initial tracer remains in the system or 63% of tracer is removed from the embayment, so the system is by no means completely flushed. Therefore, flushing time is often referred to as average residence time.

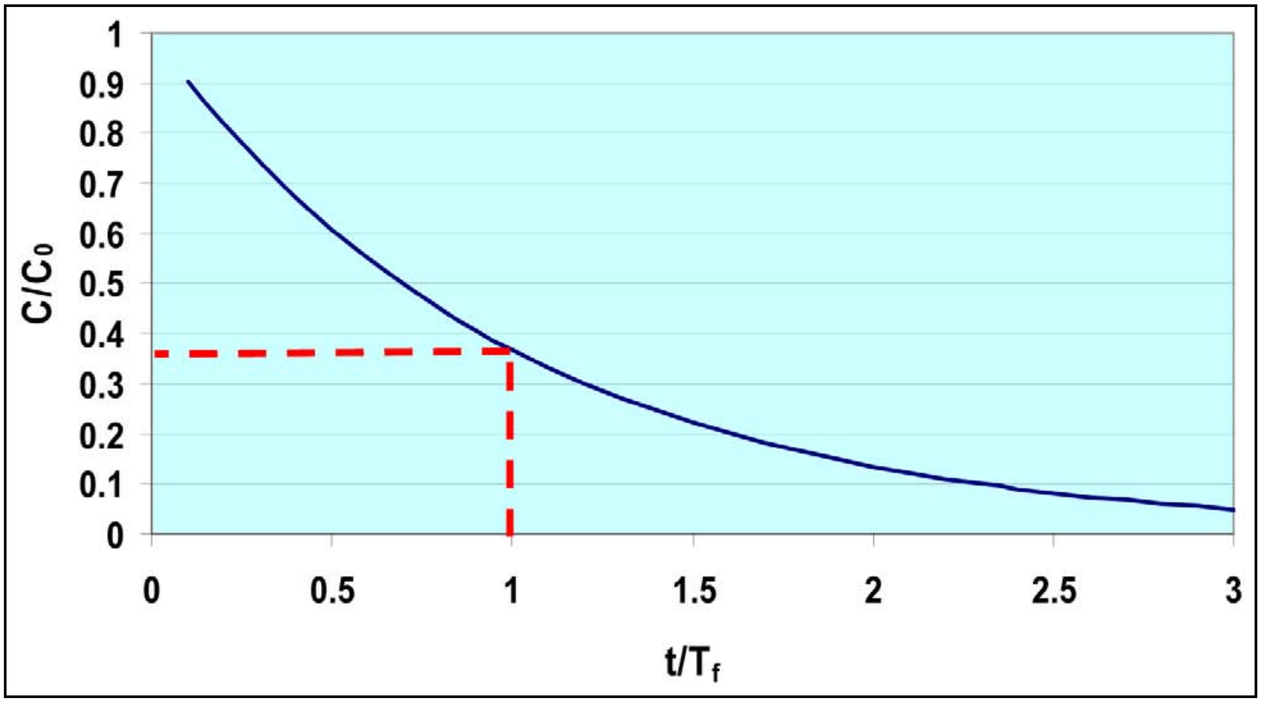

Figure 2. Temporal change in tracer concentration based on Equation (4).

In reality, a coastal system is not homogenous or in a steady state. Flushing time calculated by Equations (1) or (2), or by the CSTR solution in Equation (4) tends to underestimate the time that a water mass or volume stays in the system.

For an instantaneous material release in a reservoir, Takeoka (1984) associated the concept of average residence time with the remnant function that is calculated as the total mass of released material remaining in the reservoir at any given time *t*, *R(t)*, divided by the initial mass released, *R*(0). Based on this function, average residence time, T_f, is calculated as

$$T_f = \int_0^\infty \frac{R(t)}{R(0)} dt \tag{5}$$

The estimate of flushing time can become more complicated if the embayment (Figure 1) is a tidally influenced system. Water leaving a system with the ebb tide can be pushed back by the following flood tide. Sanford et al. (1992) developed a tidal prism model and presented the following equation to calculate flushing time with the introduction of an adjustable parameter, *b* (called the return flow factor),

$$T_f = \frac{V}{(1-b)Q} \tag{6}$$

where the volume exchange rate, *Q*, is obtained from dividing the tidal prism by the tidal period. The return flow factor, *b*, is the ratio, ranging from 0 to 1, of the inflow of returning ebb water to the total flood flow from the ocean.

Studies by Sanford et al. (1992) and Monsen et al. (2002) showed that flushing time is sensitive to the selection of the *b* value. The return flow factor, when increased from 0.25 to 0.75, can increase flushing time by a factor of 3.

2. Age: As described in the previous section, flushing time is an integrated time scale and a system-specific quantity. Age, on the other hand, is a water parcel specific quantity and is time dependent and spatially varying within a system. For a reservoir, Bolin and Rodhe (1973) defined the time that a water parcel has spent since it entered the reservoir as the "age," T_a, of the water parcel (Figure 3). By assuming that the water parcel moves from entrance to exit following the path in Figure 3, the same water parcel has a shorter age at locations near the entrance than those near the exit. If two water parcels enter a system at the same time and move to Location A at the same speed following Path P1 and P2 respectively, as shown in Figure 4, the water parcels have different ages in arriving at the same location A.

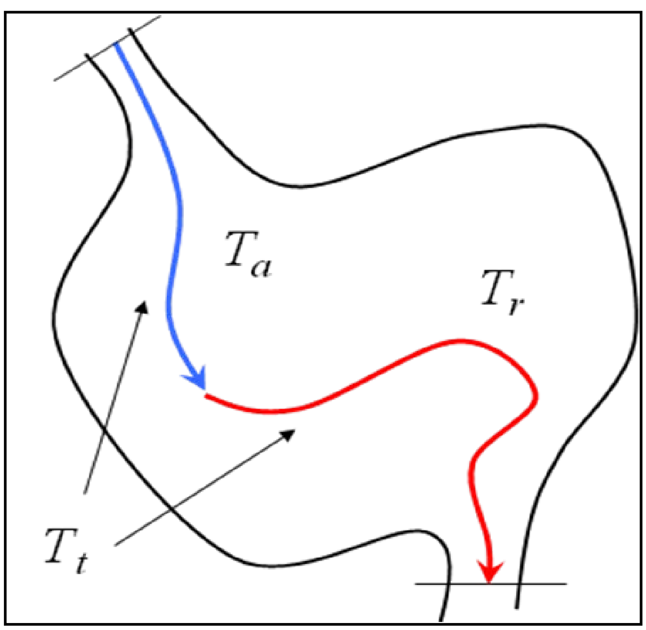

Figure 3. Age, T_a, residence time, T_r, and transit time, T_t, of a water parcel in an embayment.

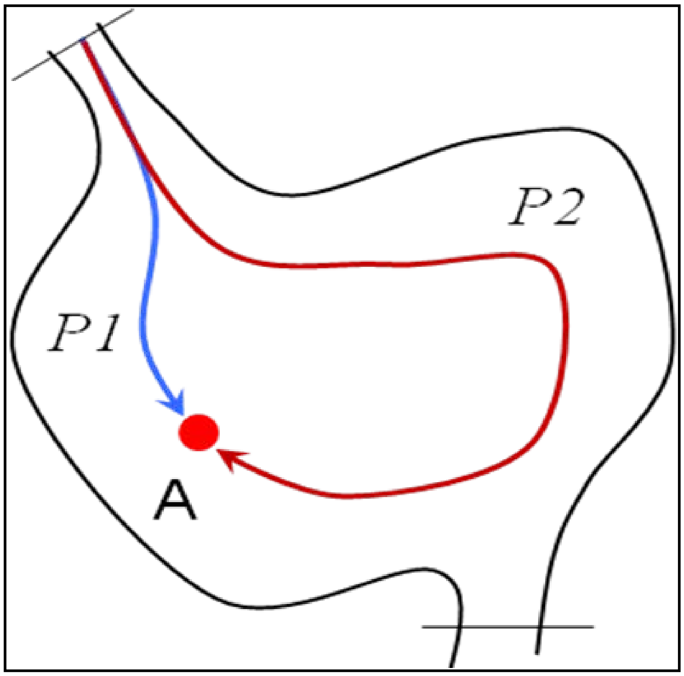

Figure 4. Two water parcels move from the entrance of the embayment to Location A through Path P1 and Path P2, respectively.

3. Residence Time and Transit Time: Residence time, T_r, is a water parcel specific time scale and is defined as the amount of time required for a water parcel at any given location of an embayment to leave through the embayment exit (Figure 3). Based on the definition, residence time is the compliment to age relative to a common location within a system. Therefore, age and residence time together measure the time interval that a water parcel travels from the entrance to the exit of the embayment. This transport time scale is the transit time, T_t, as described by Zimmerman (1976).

ESTIMATE OF FLUSHING TIME AND RESIDENCE TIME: The time scales defined above characterize water transport and mixing in a coastal system. Measurements of them require extensive survey and collection of data. The task becomes straight forward and simpler with numerical models.

Flushing time or average residence time can be obtained by calculating the average volume or mass fluxes into and out of a system through Equation (1) or (2). Assuming that the system has an instantaneous net outflow of q_i at time index i, average net outflow, Q, is calculated as

$$Q = \sum_{i=0}^{T} q_i / T \tag{7}$$

over a specific simulation period of T. For a tidally influenced system, Q would be replaced by the tidal prism. Total volume of the system, V, and surface area, A, are measured at Mean Sea Level (MSL), and T is the dominant tidal period in the system.

As expressed in Equation (5), the remnant function and the average residence time can be calculated by using a numerical model. The approach requires an initial placement of material or conservative tracer in an embayment. Absent additional material input, numerical simulations can be performed, and the total mass of placed material remaining in the system will be estimated at a specified time interval. Flushing time or the average residence time described by this method is equivalent to the *e*-folding time, *i.e.*, the amount of time required to remove about 63 percent of the initially placed material in the embayment (Knauss, 1978), which represents the average time to flush the material out the system.

An example is the beneficial use of dredged materials from a navigation channel for restoring wetland cells (Poplar Island) in Chesapeake Bay, MD. The Coastal Modeling System (CMS) (Buttolph et al. 2006) was established at the site to explore the interactions between estuarine circulation and the wetland restoration, and to evaluate the sustainability of the constructed wetlands (Figure 5). The CMS provided water level and currents, which were the input to the PTM.

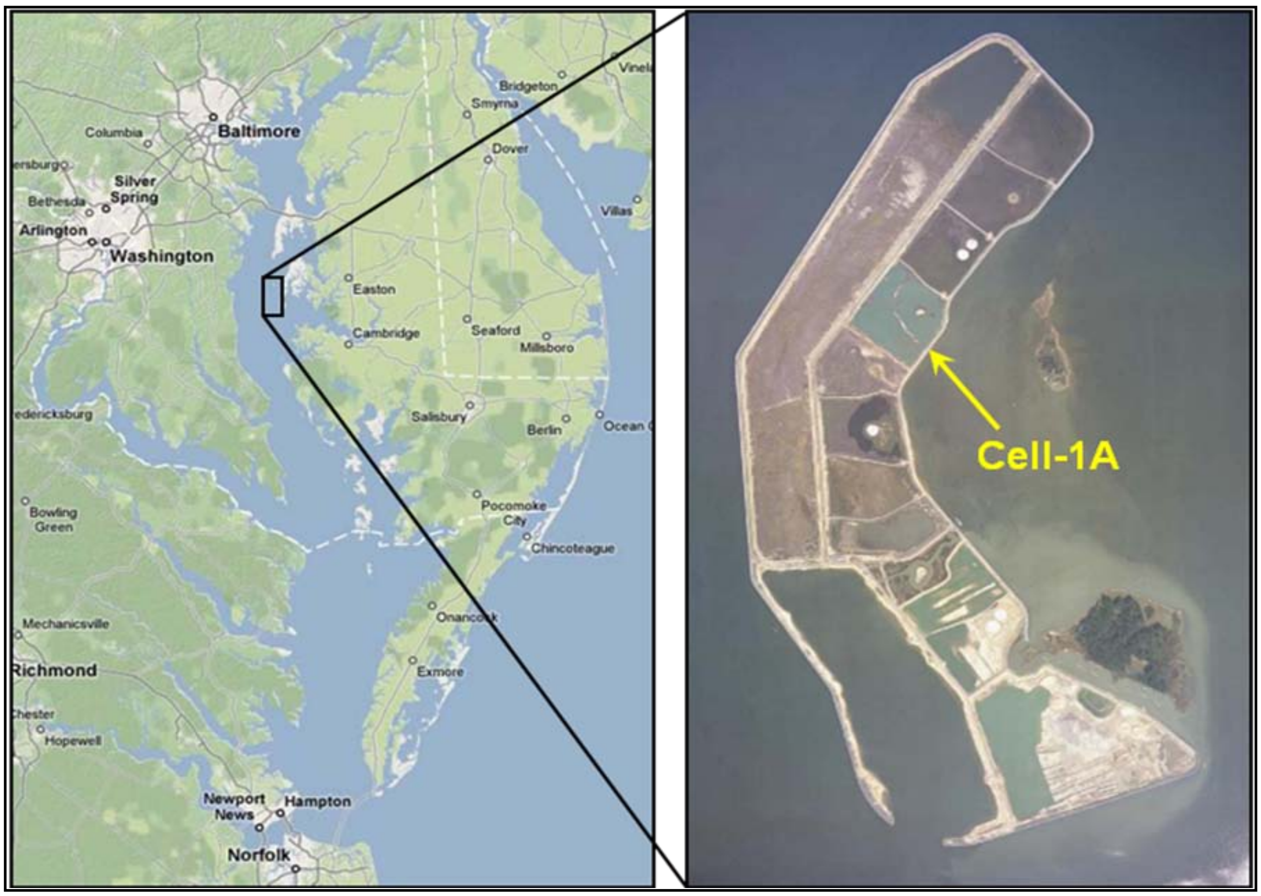

Figure 5. Wetland Cell-1A, Poplar Island, Chesapeake Bay.

Figure 6 shows the CMS-driven PTM computational domain, the detail of Cell-1A. The wetland cell domain is 600 by 450 m, and the CMS grid size is 1.8 by 1.8 m. Water depth in the domain ranges from 1.5 m outside the cell in Chesapeake Bay to 1.0 m above MSL surrounding the cell, and the mean water depth in the cell is 0.6 m relative to MSL. The surface area of the cell is 30,475 m^2. A narrow opening connects the wetland cell to Chesapeake Bay. Relatively deep channels with water depth of about 1.2 m were built inside the cell to enhance water exchange between the cell and the bay.

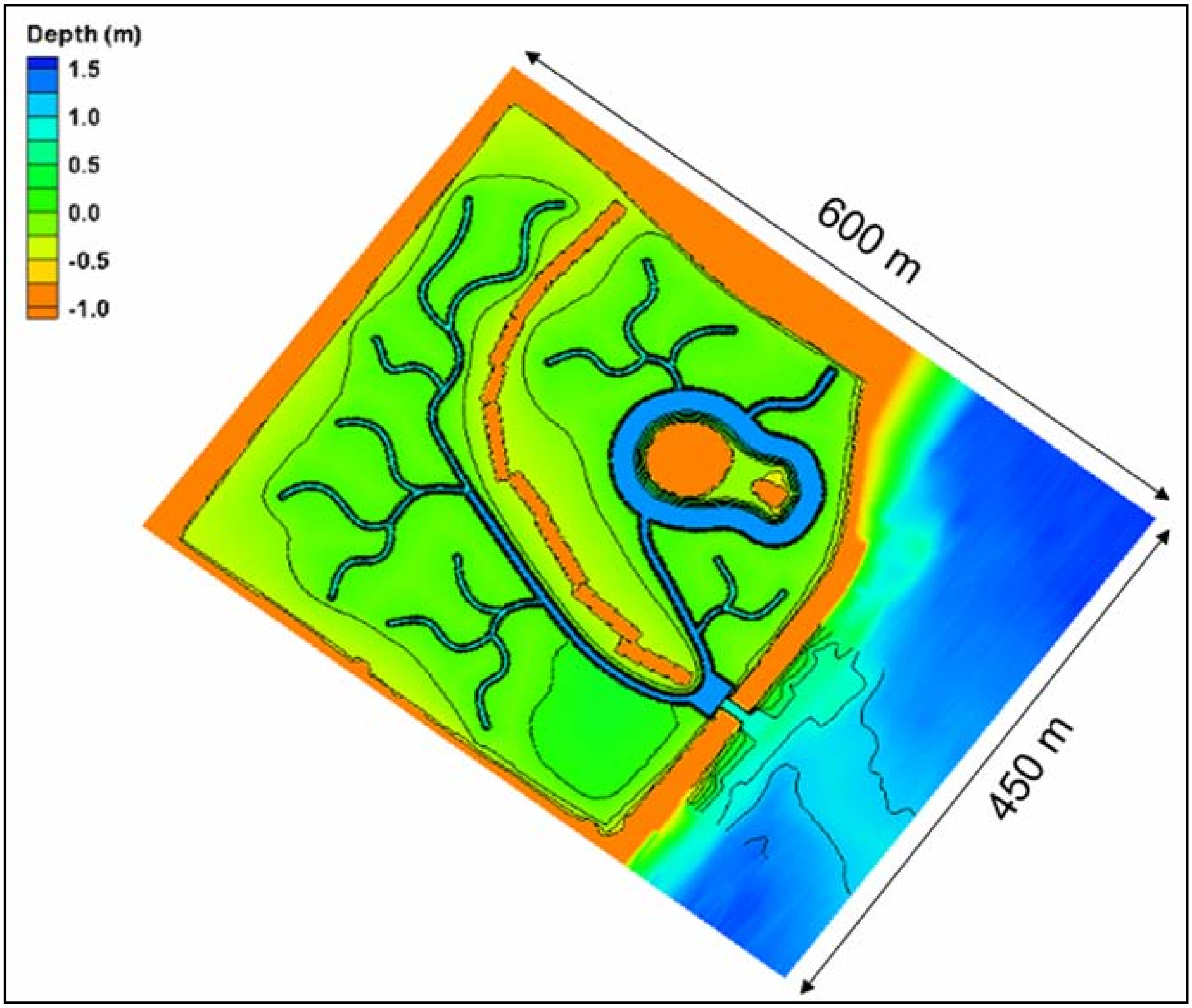

Figure 6. CMS-driven PTM computational domain.

The CMS was driven by the tidal boundary forcing as shown in Figure 7. The mean tidal range (mean high water – mean low water) is about 0.34 m. The dominant tide in Chesapeake Bay is M2 that has a period of 12.42 hr.

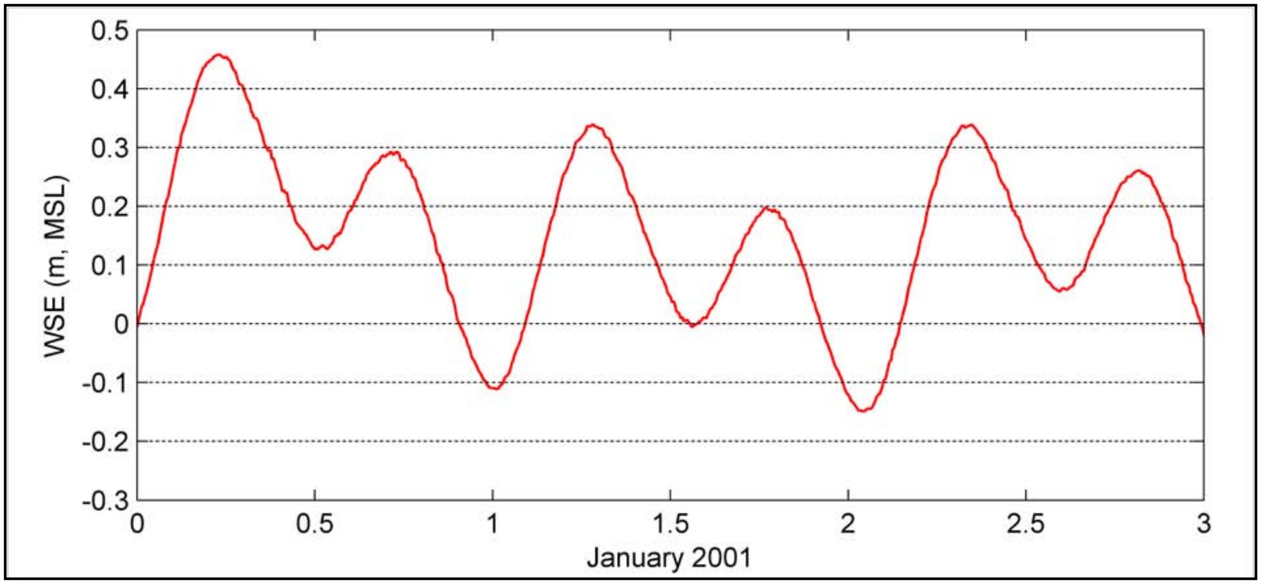

Figure 7. Water surface elevation at Poplar Harbor, Chesapeake Bay.

For this tidal flushing system, Equation (2) is used to estimate the flushing time of the wetland Cell-1A (Figure 5) as,

$$T_f = \frac{V}{Q} = \frac{VT}{P} = \frac{VT}{AR} \tag{8}$$

where *A* is the surface area, *P* is the tidal prism for the M2, and *R* is the mean tidal range outside the wetland cell. Based on the domain configuration presented above, the calculated flushing time of Cell-1A is 21.8 hr. Therefore, the average time required for tidal induced full exchange of water between the cell and the bay is approximately one day. With this exchange rate, suspended fine material, nutrients, and fish eggs in the water column are flushed out of the cell in less than one day.

Monsen et al. (2002) worked with a much larger system, Mildred Island, a tidal lake in California. Applying Equation (2) for the water body and considering only tidal flushing without the return flow factor, the flushing time is 61.4 hr (2.6 days). They also applied the CSTR tracer method, Equation (4), a continuous tracer loading method (Dronkers and Zimmerman, 1982), and a particle tracking method. The average residence time calculated from those methods ranged from 2.4 to 9.1 days.

Flushing time is an integrated measurement of water transport and exchange, and it is independent of local processes. This time scale is associated with continuous quantities in the water column, such as conservative tracers and dissolved materials. On the other hand, age and residence time are a water-parcel specific time scales and are associated with both continuous quantities and discrete quantities (water parcels). Because age and residence time are location and time-dependent, estimates of them quantify mixing and transport processes occurring in a specified region during a specific time frame (Monsen et al., 2002; Sheldon and Alber, 2002). In this regard, a Lagrangian particle tracking model can be a suitable tool to perform the task (Brooks et al. 1999; Monsen et al. 2002).

As defined, age is a transport time scale relative to system entrance and residence time to system exit, and age and residence time are complementary to each other. The ways to estimate these two time scales are similar. In the following application of a particle tracking model, only residence time is estimated.

The PTM was developed under the Coastal Inlets Research Program (CIRP) and Dredging Operations and Environmental Research (DOER) program, and it must be forced by a hydrodynamic model (Demirbilek et al. 2008). Herein, the PTM is driven with the Coastal Modeling System (CMS) to calculate residence time. The pathways of sediment particles or neutrally-buoyant particles can be calculated under the combined influence of tide, current, waves, and wind.

In the CMS-driven PTM, users can define a polygon area in the computational domain. In running the simulation with the polygon, the time that a particle enters or exits the area is recorded (Demirbilek et al. 2008). Placement of such a polygon permits the user to calculate the time required for a water parcel to travel from an initial parcel release location to the polygon. If the defined area is near the boundary of a study domain, the time estimated is the residence time of the tracked parcel starting from the initial location. In the Poplar Island example, the polygon was specified at the cell's only opening to Chesapeake Bay, and the residence time of any parcel starting from the locations inside the wetland cell was estimated as the parcel reaches to the polygon (the cell boundary) (Figure 8).

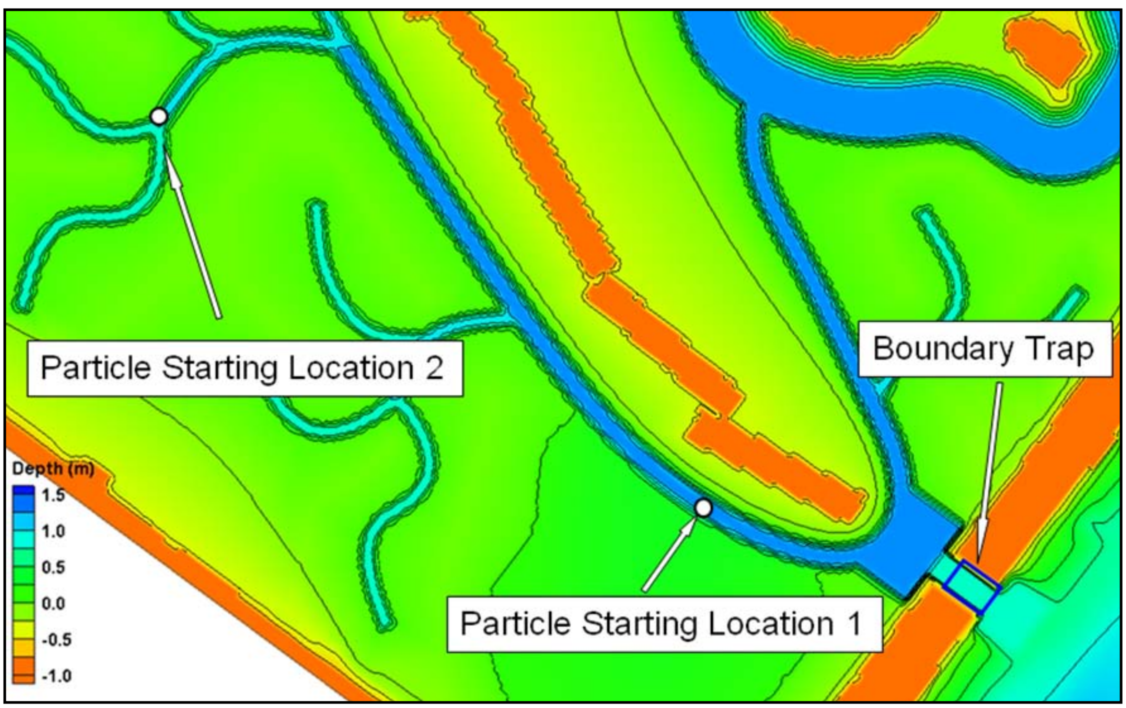

Figure 8. The PTM simulation to estimate the residence time in the wetland cell. White dots are the particle starting locations, and the blue rectangular area at the cell opening is a designated trap.

Statistically, the PTM analysis requires release of a large number of particles in a study. For demonstration in this example, 12 neutrally-buoyant particles, representing waterborne material such as salinity, fine-sized particles, fish larvae, and fish eggs, were released from the starting locations 1 and 2 at hourly intervals, (Figure 8). The CMS and PTM simulations started on 1 January at 03:00 GMT and ended on 4 January 2001 at 00:00 GMT. Figure 9 shows the release time for each individual particle that was tracked until the end of the simulation. Particles that remained inside the cell after the simulation would have a residence time of 58 to 69 hours, depending on particle release time.

PARTICLE	AREA	TIME RELEASED
1	1	2001/01/01 03:00:00
2	1	2001/01/01 04:00:00
3	1	2001/01/01 05:00:00
4	1	2001/01/01 06:00:00
5	1	2001/01/01 07:00:00
6	1	2001/01/01 08:00:00
7	1	2001/01/01 09:00:00
8	1	2001/01/01 10:00:00
9	1	2001/01/01 11:00:00
10	1	2001/01/01 12:00:00
11	1	2001/01/01 13:00:00
12	1	2001/01/01 14:00:00

Figure 9. Release time for twelve particles.

Figures 10 and 11 show the time when a particle entered the designed polygon in a standard CMS-driven PTM output file (the third column in the figures). The difference between this time and the particle release time (Figure 9) is the residence time for that particle.

PARTICLE	AREA	TIME IN	TIME OUT
4	1	2001/01/01 07:25:40.0	2001/01/01 07:27:10.0
5	1	2001/01/01 07:28:40.0	2001/01/01 07:30:10.0
2	1	2001/01/01 08:29:20.0	2001/01/01 08:30:30.0
3	1	2001/01/01 08:31:00.0	2001/01/01 08:32:10.0
6	1	2001/01/01 08:45:30.0	2001/01/01 08:47:50.0
7	1	2001/01/01 09:33:00.0	2001/01/01 09:34:00.0
8	1	2001/01/01 10:19:40.0	2001/01/01 10:21:00.0
9	1	2001/01/01 11:37:00.0	2001/01/01 11:39:40.0
12	1	2001/01/01 18:51:10.0	2001/01/01 18:52:20.0
11	1	2001/01/01 19:12:00.0	2001/01/01 19:13:00.0
10	1	2001/01/01 20:00:20.0	2001/01/01 20:01:40.0

Figure 10. CMS-driven PTM output file with a polygon specified in the simulation. All particles were released from Location 1 as shown in Figure 8.

PARTICLE	AREA	TIME IN	TIME OUT
3	1	2001/01/01 10:12:40.0	2001/01/01 10:14:10.0
7	1	2001/01/01 11:24:10.0	2001/01/01 11:26:30.0
6	1	2001/01/01 22:39:20.0	2001/01/01 22:42:10.0
2	1	2001/01/02 11:12:40.0	2001/01/02 11:18:20.0

Figure 11. CMS-driven PTM output file with a polygon specified in the simulation. All particles were released from Location 2 as shown in Figure 8.

As shown in Figures 9, 10, and 11, residence time spatially and temporally varies in the tidal environment. Location 1 is close to the cell opening, and nine released particles exited the system at the end of simulation. Particles released between 06:00 and 11:00 had the shortest residence time of less than two hours, which corresponded to ebb (Figure 7). Location 2 is placed further inside the cell. The residence time of the released particles was much longer. At the end of the 3-day simulation, only four particles exited the cell.

To estimate average residence time T_f at a specified location, particles should be released at certain time intervals through the tidal cycle, and the residence time obtained for each particle should be averaged. For Poplar Island, the time-average residence time starting from Locations 1 and 2 is about 8.4 and 46.1 hr, respectively. Particles released from Location 2 inside the cell stayed in the cell about five times longer than those released from Location 1, close to the cell's connection to Chesapeake Bay. Clearly, the particle-specific method presents spatial and temporal heterogeneity of the system. To estimate and compare the system-specific time scale using the particle-specific method to that by Equation (2), particles need to be released from each grid box of the wetland cell, and spatial and temporal averaging of residence time needs to be made.

The ebb tide could flush a particle into the bay and the flood tide could bring the same particle back to the wetland cell through the specified polygon at the cell opening. Because the polygon area in the PTM simulation has the capability to record multiple entrances of a particle, residence time estimated using the PTM automatically includes particle transport by tide-induced recirculation (tide return factor).

CONCLUSIONS: By using a coastal hydrodynamic model such as the CMS, and a coupled particle tracking model, the PTM, the integrated transport time scale, flushing time, the water element specific time scale, and residence time were estimated in an example of a constructed wetland cell. Flushing time is a system-dependent time scale, which tends to underestimate material transport and exchange time in a real system because of assumptions such as full mixing and steady-state conditions. Residence time is a water particle dependent, and has a spatially and temporally varying time scale. The CMS and the PTM provide a convenient modeling approach to estimate this transport time scale associated with local hydrodynamic conditions. It requires a system-wide, extensive particle tracking study to calculate flushing time of a system (average residence time) by a particle tracking model. A similar approach can be applied to calculate other particle specific time scales including age and transit time.

ADDITIONAL INFORMATION: This CHETN was prepared as part of the Coastal Inlets Research Program (CIRP) and was written by Dr. Honghai Li (*Honghai.Li@usace.army.mil*, voice: 601-634-2840, fax: 601-634-3080) of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL). Mitchell E. Brown and Alejandro Sanchez of CHL provided hydrodynamic model information for the Poplar Island example. The CIRP Program Manager, Dr. Julie D. Rosati (*Julie.D.Rosati@usace.army.mil*), the assistant Program Manager, Dr. Nicholas C. Kraus, the Chief of the Coastal Engineering Branch at CHL, Dr. Jeffrey P. Waters, Dr. Tahirih Lackey, and Gary L. Brown, Estuarine Engineering Branch, Coastal Processes Branch, CHL, reviewed this CHETN. Files for the example may be obtained by contacting the author. This CHETN should be cited as follows:

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