Tidal Flushing Characteristics in Virginia's Tidal Embayments

Final Report submitted to:
Virginia Coastal Zone Management Program
Virginia Department of Environmental Quality

Submitted by:
Center for Coastal Resources Management
Virginia Institute of Marine Science
College of William and Mary
Gloucester Point, Virginia 23062

Authors:
Julie Herman, Jian Shen, Jie Huang

November, 2007

This research project was funded by the Virginia Coastal Zone Management Program at the Department of Environmental Quality through Grant #NA06N0S4190241 of the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, under the Coastal Zone Management Act of 1972, as amended. The views expressed herein are those of the authors and do not necessarily reflect the views of the U.S. Department of Commerce, NOAA, or any of its subagencies.

Tidal Flushing Characteristics in Virginia's Tidal Embayments

ABSTRACT

This project evaluated water bodies in the Virginia coastal zone using several water quality models to calculate residence times. Results were grouped into tidal flushing categories (quickly, intermediately, and slowly flushed) that reflect a relative time frame in which a water body is flushed.

INTRODUCTION

Tidal flushing (the movement of water in and out of a water body due, in part, to tidal processes) has important water quality implications that are known to affect numerous estuarine management issues. Some of these issues include siting for shellfish growing and aquaculture (which require regular tidal exchange to cleanse water and replenish food resources), low dissolved oxygen levels, and nutrient inputs.

Tidal flushing also is an important consideration for local government planners who wish to expand waterfront development in a community where economic growth relies on water-dependent activities. The ability to maintain a balance between ecological function and economic development is essential. The physical environment can lend important insight if certain characteristics such as flushing can be identified in advance. Presently, there is no resource for local government planners to consult for information on flushing characteristics across the Virginia coastal zone.

The objective of this project was to perform a combination of water quality modeling analyses that evaluated individual systems for general flushing characteristics. Residence times were calculated for each tidal creek and tributary, which then were classified using simple designations based on modeling output (ie. quickly flushed, intermediately flushed, slowly flushed). The initial focus was on shellfish growing areas (DSS, 2007) which constitute a large proportion of the coastal zone. Results were tabulated in a geographic information system (GIS) data layer that delineates the embayments and has an attribute file with the residence times and flushing categories.

METHODS

Different tidal flushing models are needed depending upon the complexity of the water bodies. In this study, three different models were used: a simple equation method; a tidal prism model, and a three-dimensional model. It is important to understand clearly the terms being used in the models. Note that ‘flushing time’ and ‘residence time’ are not the same (e.g. Monsen and others, 2002). Flushing time is a bulk parameter that describes general exchange characteristics of a simple water body. Residence time is the average length of time that a parcel of water remains in an estuary. These terms are discussed further in the following sections. In this report both are called residence time, in order to distinguish them from ‘flushing categories’, which are residence times grouped into qualitative categories (quickly, intermediately, and slowly flushed) that reflect a relative time frame in which a water body is flushed.

Tidal Flushing Models

Simple Equation Method

For a small water body, with simple geometry, the first-order description of transport is often expressed as **‘flushing time’**. The flushing time (T_f) is a bulk or integrative parameter that describes the general exchange characteristics of a water body without identifying the underlying physical processes, the relative importance of those processes, or their spatial distribution (Monsen and others, 2002). The water body is assumed to be well-mixed. The flushing time can be calculated as follows:

$$T_f = \frac{V}{Q_b} \quad (1)$$

where V is the mean volume of the water body and Q_b the quantity of mixed water that leaves the bay on the ebb tide that did not enter the bay on the previous flood tide (m^3 per tidal cycle).

In a steady-state condition, the mass balance equations for the water can be written as follows:

$$Q_b = Q_f + Q_o \quad (2)$$

where Q_f is total freshwater input over the tidal cycle (m^3) and Q_o is the volume of new ocean water entering the embayment on the flood tide, which can be determined by the use of the ocean tidal exchange ratio β as:

$$Q_o = \beta * Q_T \quad (3)$$

where Q_T is the total ocean water entering the bay on the flood tide, ie. Q_T = water surface area * tidal range. For additional information, see MDE, 2004.

The land surface areas of the subwatersheds draining to each water body were used to estimate Q_f.

The simple equation method was used for a majority of the water bodies (Fig. 1). Water body parameters and residence times are listed in Appendix A.

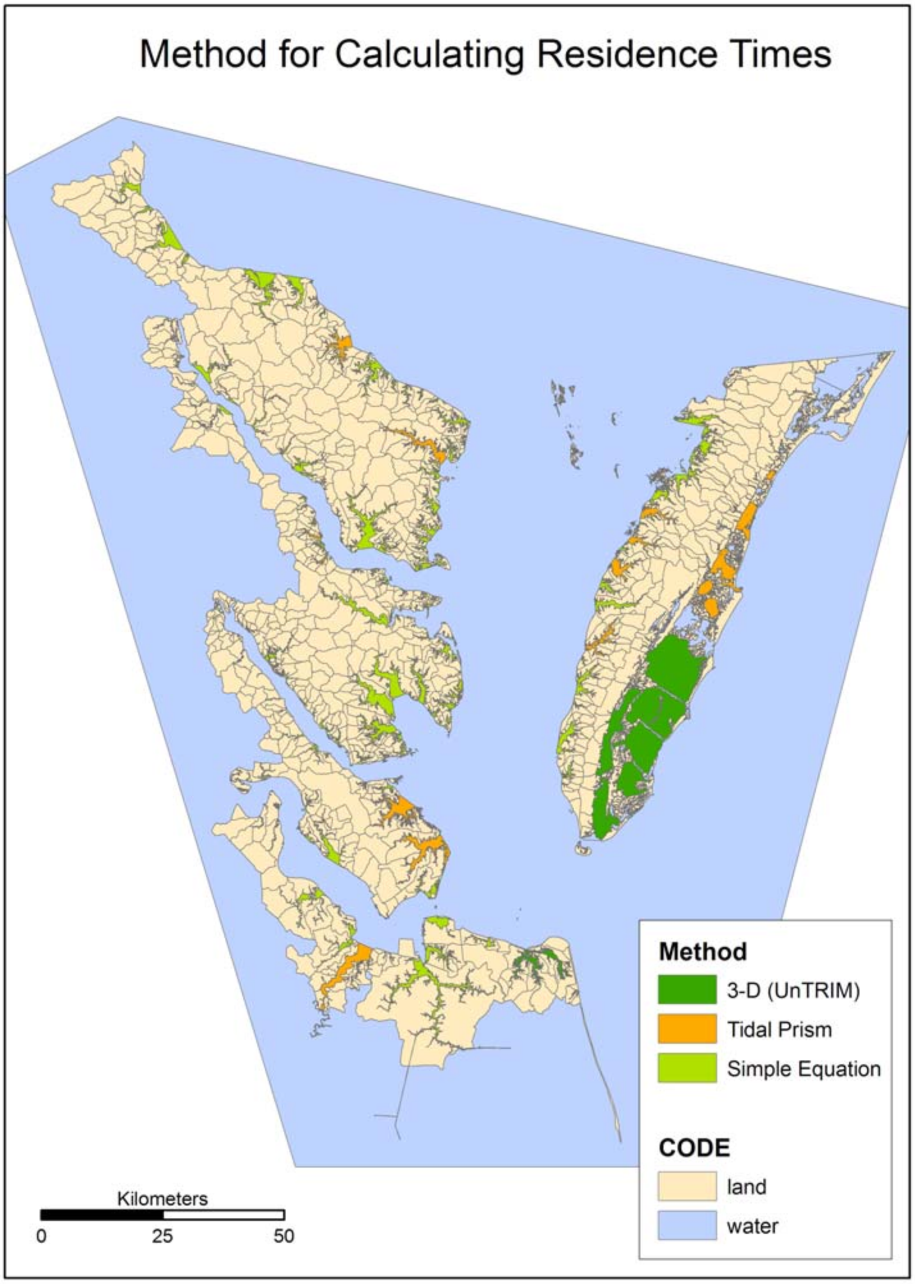

Figure 1. Methods used to determine water body residence times. The land is divided into subwatersheds, outlined in gray, for each water body. The water is divided into individual water bodies, color coded by the method used to calculate residence times.

Tidal Prism Model

For more complex coastal embayments (Fig. 1), the influence of tide needs to be considered. Therefore, the tidal prism method is often used which can be written as:

$$T_f = \frac{VT}{(1-b)P} \tag{4}$$

Where T is tidal period, P is tidal prism (the volume between high and low tide), and b is the return ratio that is the fraction (0.0 – 1.0) of ebb water returning to the embayment during flood.

The assumption that a water body is well mixed is not always valid. To account for spatial variability, salinity can be used to estimate the fraction of freshwater in an embayment. The flushing time can be calculated as:

$$T_f = \frac{fV}{Q} \tag{5}$$

where Q is river inflow and *f* is the mean fractional freshwater concentration in the estuary, given by:

$$f = \frac{1}{V}\int \frac{S_0 - S}{S_0} dv \tag{6}$$

where S_0 and S are the sea water salinity and the salinity in the estuary, respectively.

'Residence time' is the time it takes for a water parcel to leave the system through its inlet (Zimmerman, 1976). Consider a parcel of material in a reservoir at time t = 0. Let the amount of the material at t = 0 be R_0, and the amount of the material which still remains in the reservoir at time t be R(t). The residence time distribution function can be defined as:

$$\phi' = -\frac{1}{R_0}\frac{dR(\tau)}{d\tau} \tag{7}$$

It can be further assumed that:

$$\lim_{\tau \to \infty} R(\tau) = 0$$

The average residence time (τ_r) of the material is defined as:

$$\tau_r = \int_0^\infty \tau \phi'(\tau) d\tau \tag{8}$$

Integrating equation (7) by parts gives:

$$\tau_r = \int_0^\infty \frac{R(\tau)}{R_0} d\tau = \int_0^\infty r(t) d\tau \tag{9}$$

where $r(t) = R(t)/R_0$ is called the remnant function (Takeoka, 1984). Equation (9) is used to compute the residence time. For additional information see Shen and Haas, 2004. Residence times are listed in Appendix A.

Three-dimensional model

The Unstructured, Tidal, Residual Intertidal, and Mudflat model (UnTRIM) was used for the complex water bodies on the ocean side of the Eastern Shore. The UnTRIM model (Casulli and Walters, 2000; Casulli and Zanolli, 1998) is a general three-dimensional model. The model domain is covered by a set of non-overlapping convex triangles, or polygons. Each side of each polygon is either a boundary line or a side of an adjacent polygon. A center point exists in each polygon such that the segment joining the centers of two adjacent polygons is orthogonal to the side shared by the two. The model preserves all the advantages of the previous TRIM model, but uses an orthogonal, unstructured grid with mixed triangular and quadrilateral grids (Cheng et al., 1993; Cheng and Casulli, 2002). The z-coordinate is used in the vertical. The Eulerian-Lagrangian transport scheme was used for treating the convective terms and a semi-implicit finite-difference method of solution was implemented in the model (Casulli and Zanolli, 1998). Since the Eulerian-Lagrangian transport scheme is implemented in the model, a large model timestep can be used. Thus, very fine model grid cells can be used to represent the model domain without reducing computational efficiency. Detailed model descriptions can be found in the references above.

The model grid used for the Eastern shore consists of 16714 horizontal elements (Fig. 2). The bathymetry obtained from NOAA 3 minutes Coastal Relief Model and NOAA charts. For those shallow area without bathymetric data, 0.3 m - 0.5m were specified based on NOAA charts. The model grid resolves large waterbodies and deep channels connecting marshes and inlets. Because the depths in these water bodies are very shallow, one vertical layer is used for the model simulation. The model simulates both tide and salinity. The model was forced at its open boundary by 9 tidal constituents, namely M_2, N_2, S_2, K_1, O_1, Q_1, K_2, M_4, and M_6, which were obtained from the U.S. Army East Coast 2001 database of tidal constituents (Mukai et al., 2002), and the long-term mean salinity. The model was calibrated for the tide. The timestep used for the model is 300 seconds.

Equation (9) in the previous section is used to compute the residence time.

The ocean side of the Eastern Shore water was divided into 6 sub-water bodies (Fig. 1). A dissolved passive tracer is used to compute the residence time. Since the residence time in the area is about 4 to 30 days, the model simulation period is about 100 days for each water body. The initial condition of the tracer at water body j can be expressed as:

$$C(t=0, \mathrm{x}_i) = 100; \qquad x_i \in S_j \qquad for \quad j = 1, . \quad . \quad ., 11 \tag{10}$$

$$C(t=0, \mathbf{x}_i) = 0; \qquad for \quad other \quad \mathbf{x}_i \tag{11}$$

where C(t, **x**) is the concentration of the passive tracer and S_j is the set of the model cell (i,j,k) index within the j^{th} water body (j = 1 to 6). Other model boundary conditions, including tide and salinity, are the same as those used for the tide and salinity simulation.

The UnTRIM model also was used for Lynnhaven and Broad Bays in Virginia Beach. See Li (2006) for details.

Residence times are listed in Appendix A.

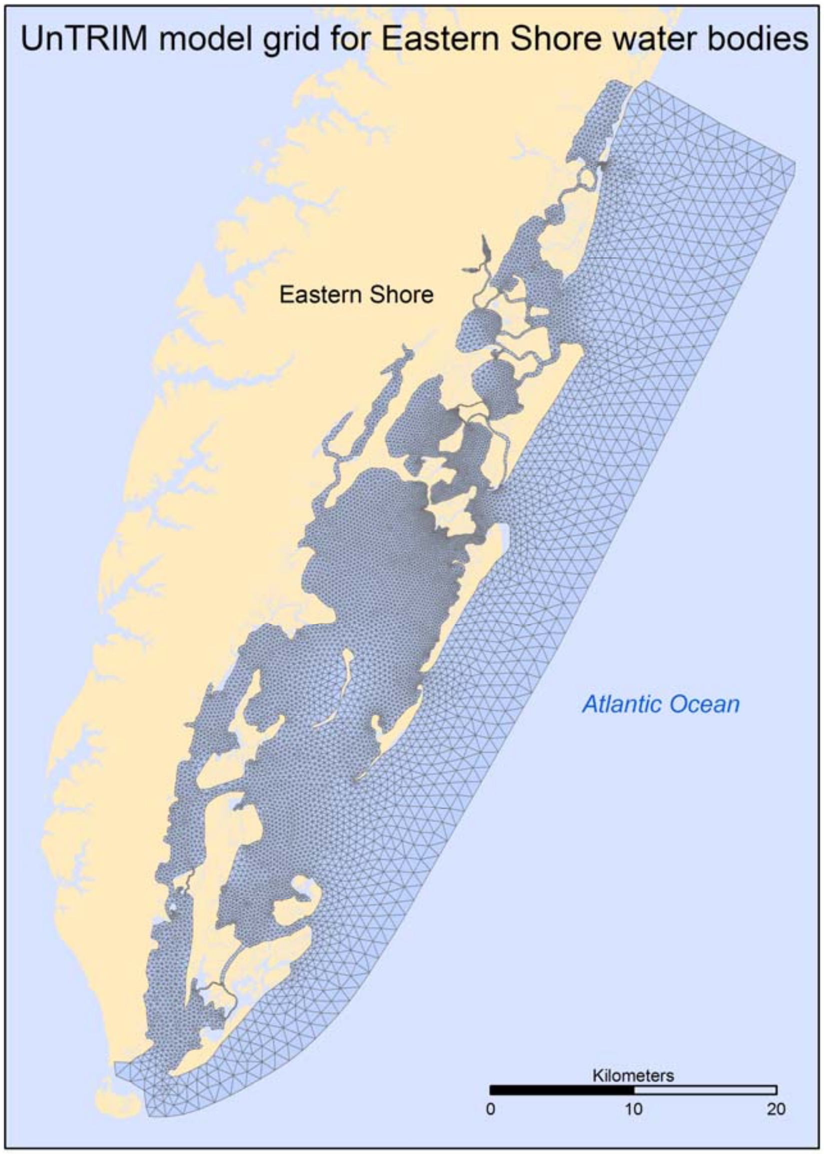

Figure 2. UnTRIM model grid for water bodies on ocean side of Eastern Shore.

Tidal Flushing Categories

The parameters used to calculate residence times for each water body included water body volume, watershed area, and tidal range. Additional water body parameters consisted of water body perimeter, river (water body) length, and mean depth (water body volume/water body area).

Several approaches, including descriptive and multivariate statistics (principal components analysis), were investigated to group residence times into flushing categories. Microsoft Excel and Minitab Statistical Software were used for the analyses. Appendix A lists all of the water body parameters and the flushing categories.

GIS

The parameters listed in Appendix A were joined to a GIS shapefile that delineates all the water bodies. The shapefile and associated metadata file are included as Appendix B.

RESULTS AND DISCUSSION

Residence Times

Residence times are mapped in Figure 3. Residence times range from 0.1 to 29 days, and one value of 72 days. General observations on the geographic distribution of residence times include:

- Most smaller water bodies off the main rivers (James, York, and Rappahannock) have shorter residence times (0-3 days). This may partly be due to larger tidal ranges (tidal heights increase upstream because of decreasing channel widths).
- Water bodies off the Potomac River are larger and more complex, and tend to have residence times around 4-8 days.
- Water bodies on the bay side (west side) of the Eastern Shore mostly have residence times of 3-5 days. The water bodies are not overly large or complex, but freshwater input may be lower.
- Residence times on the ocean side of the Eastern Shore vary widely, probably because of their unique geometry (very shallow bays with multiple inlets) and the difference in methods used to calculate residence times.
- The residence time for Broad Bay in Virginia Beach (waterid=71 in Appendix A) is 72 days based on the UnTRIM model. The water body geometry is unusual in that it has a very long narrow opening that empties into an adjacent bay, which in turn has a somewhat restricted opening to Chesapeake Bay. The residence time is much longer than the next longest time of 29 days, therefore it was considered an outlier for this project and not included in the graphs and calculations for tidal flushing categories.

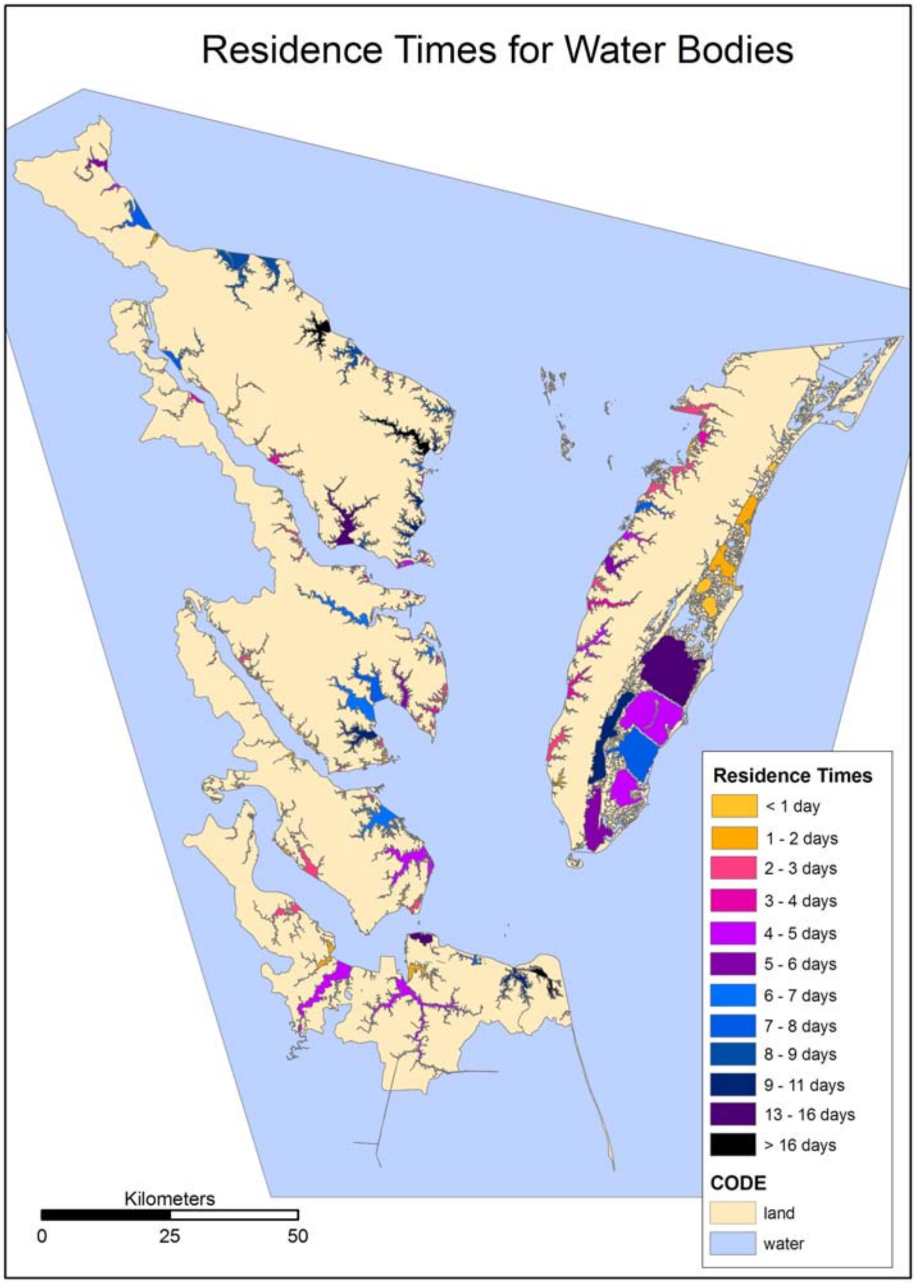

Figure 3. Residence times for each water body.

Results show that the simple method underestimates residence times for most water bodies (Fig. 4), because it does not incorporate the more complex aspects of water body geometry. However, there is insufficient detailed data to perform a tidal prism or 3D hydrodynamic model for every water body, and is beyond the scope of this project.

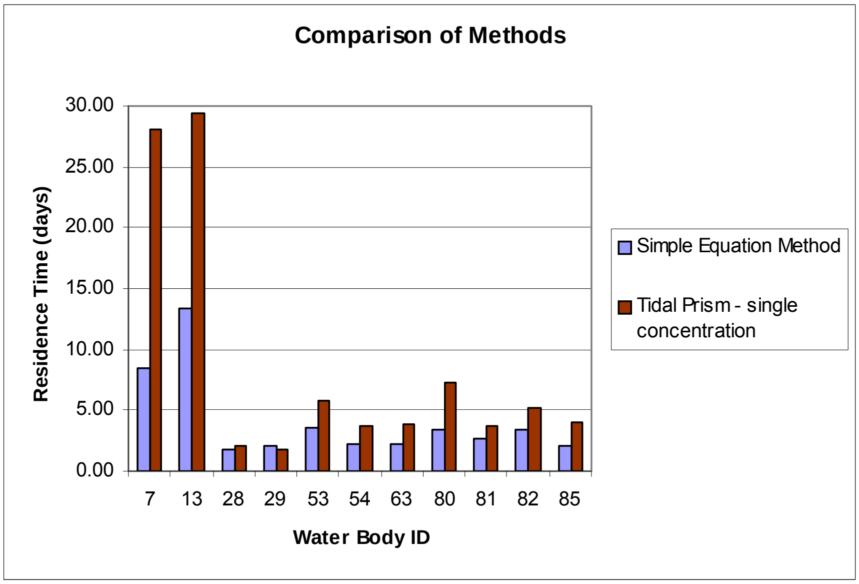

Figure 4. Simple Method vs. Tidal Prism Model residence times (days) for select water bodies.

Tidal Flushing Categories

Both descriptive statistics and a multivariate statistic, principal components analysis (PCA), were used to investigate a method for grouping the residence times and water bodies into tidal flushing categories, consisting of quickly flushed, intermediately flushed, and slowly flushed. A PCA was run several times on different groups of the parameters used to calculate residence times (e.g. water body volume, watershed area, and tidal range). No clear patterns were discernible, and the results from the descriptive statistics below provided meaningful categories.

Figure 5 shows the frequency distribution of residence times.

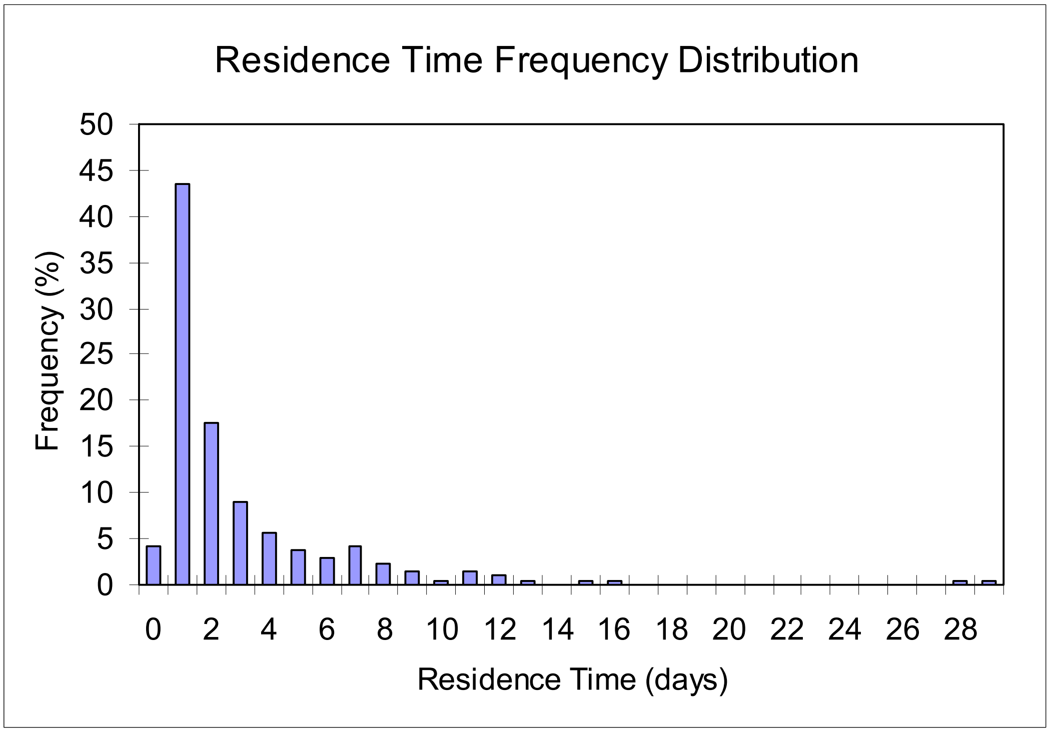

Figure 5. Frequency of residence times. Values for residence times were rounded before grouping. A residence time of 0 days means less than ½ day.

Residence times are less than 3 days for about 65% of the water bodies. About 80% of the water bodies have estimated residence times less than 5 days.

Graphs of residence time vs. water body parameter (e.g. residence time vs. water body volume; residence time vs. water body area, etc.) were examined. All the graphs had relatively small R^2 values. The graph of residence time vs. mean depth (Fig. 6) had the highest R^2 value, and conceptually was a reasonable parameter to use for flushing categories.

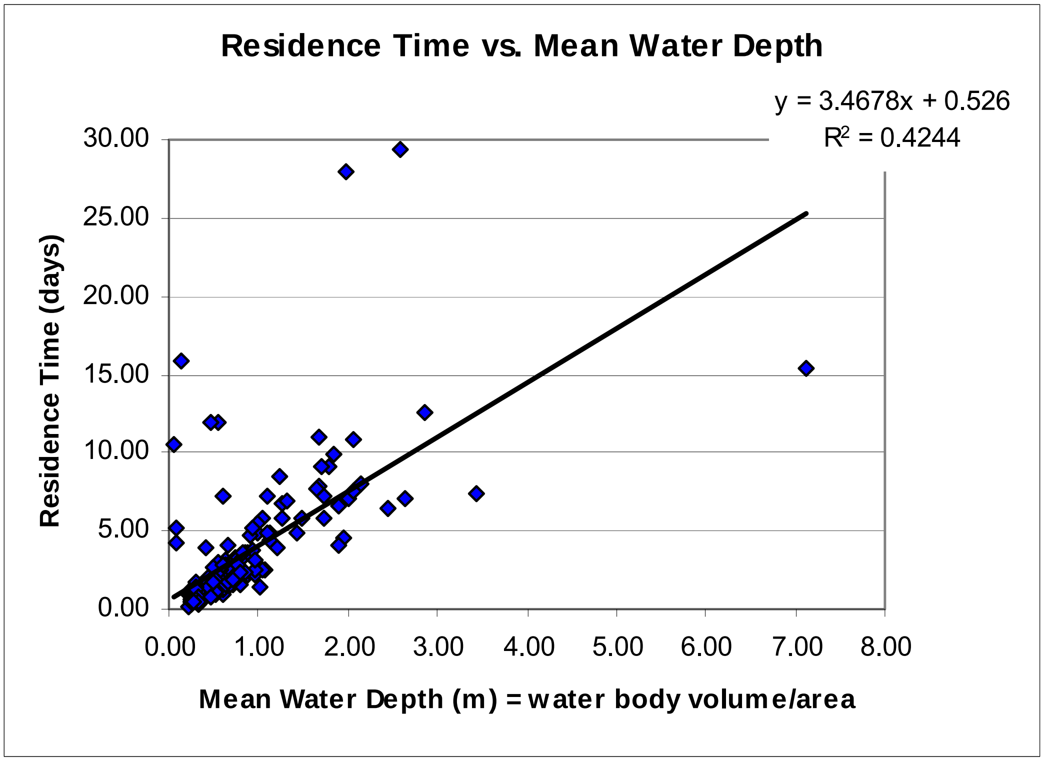

Figure 6. Residence time vs. mean water depth.

According to the regression, deeper water systems tend to have longer residence times than shallower water systems. A probable explanation is that, in a given unit of time, more energy (e.g. higher velocity) is needed to replace existing water with incoming ocean water in a deeper system. However, no clear divisions for the tidal flushing categories are evident in this graph.

If the frequency of the mean depths is plotted (Fig. 7), groupings for tidal flushing categories are more apparent, with quickly flushed = mean depth < 1m, intermediately flushed = 1m ≤ mean depth< 2m, and slowly flushed = mean depth ≥ 2m.

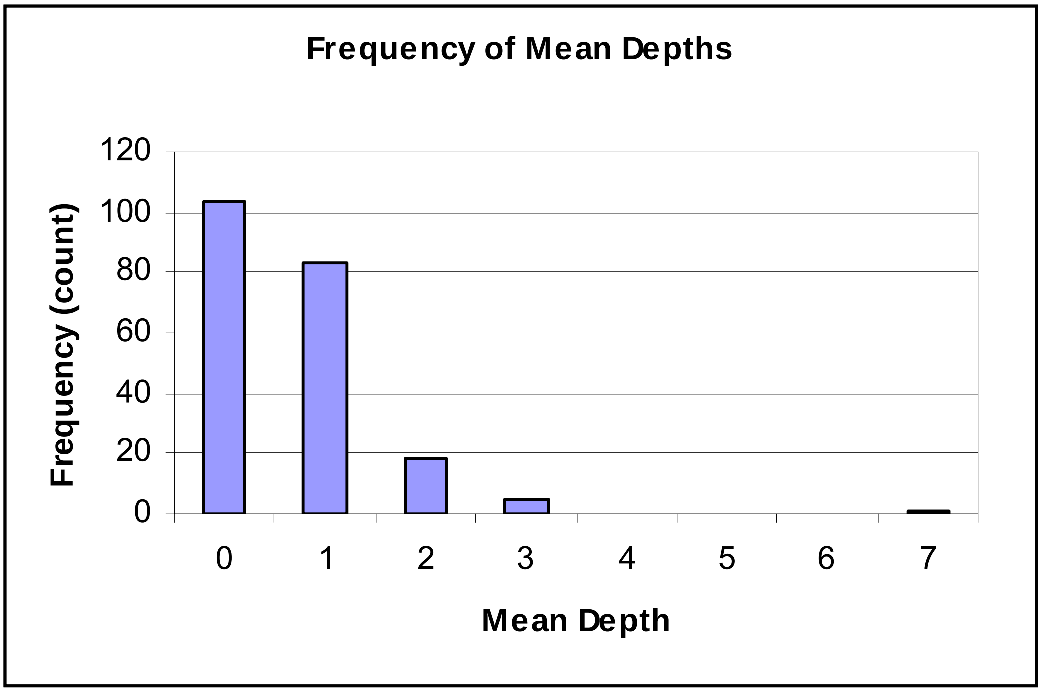

Figure 7. Frequency of mean depths. Tidal flushing categories are mean depth < 1 (i.e. bar = 0) is quickly flushed, mean depth ≥ 1m and < 2m (i.e. bar = 1) is intermediately flushed, and mean depth ≥ 2 (i.e. bar = 2 or higher) is slowly flushed. Values for mean depths were rounded before grouping.

Figure 8 shows a map of the tidal flushing category for each water body.

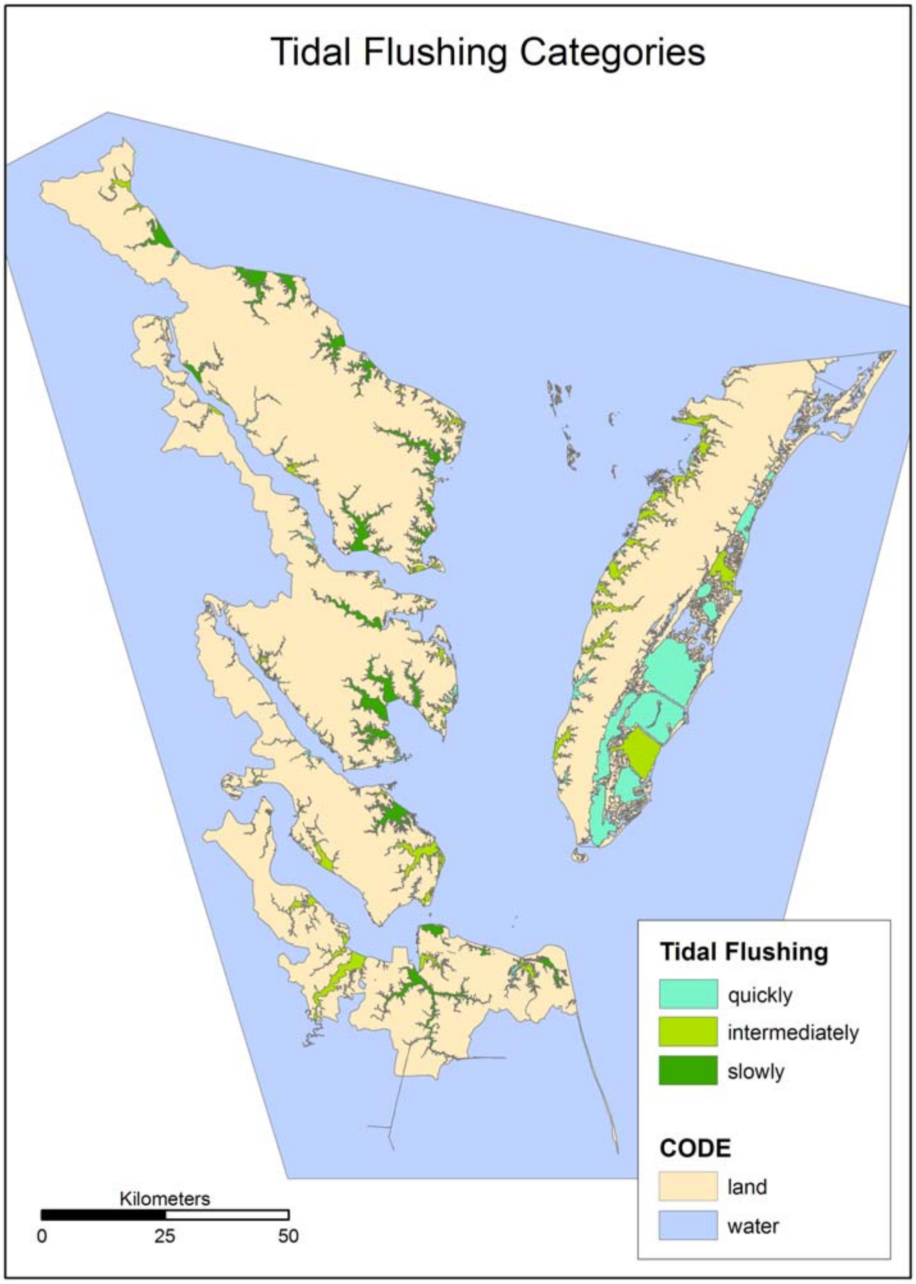

Figure 8. Tidal flushing category for each water body.

The geographic distribution of flushing categories shows that regardless of location, in general small, simple water bodies flush quickly and complex water bodies flush slowly. The large bays on the ocean side of the Eastern Shore flush quickly because they are shallow and have multiple inlets for water exchange.

Using mean depth to define the tidal flushing category means that the flushing category is independent of the residence time. Intuitively this makes sense because a long residence time for a small water body implies that it is slowly flushed, but that same residence time for a large water body suggests that it is quickly flushed. Figure 9 shows that tidal flushing categories contain a range of overlapping residence times.

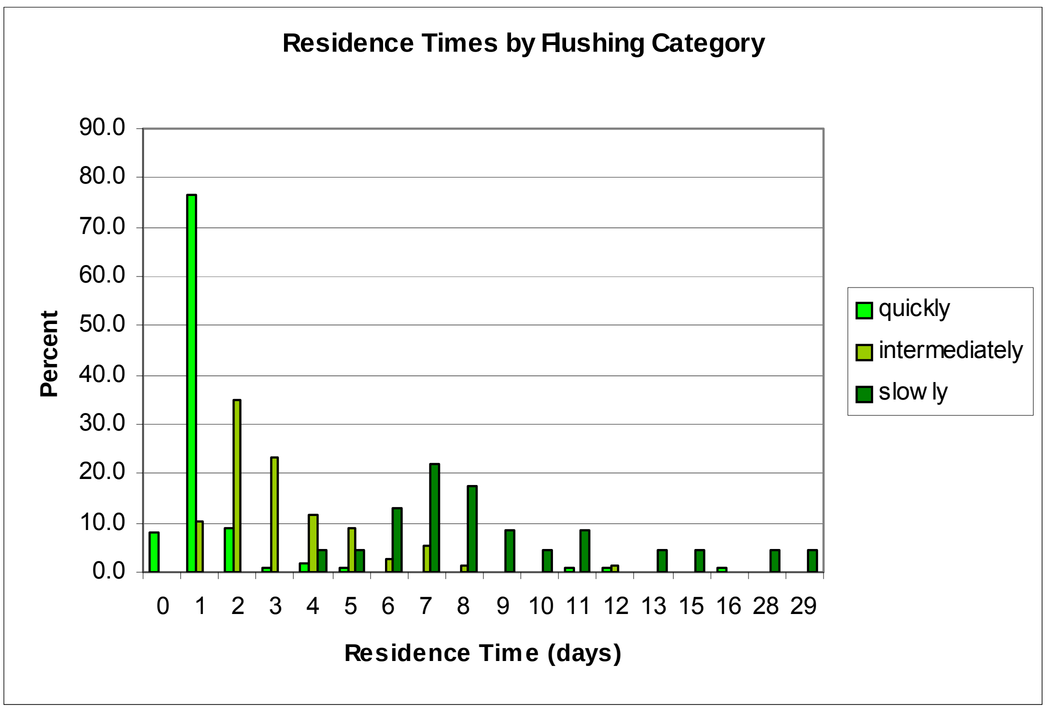

Figure 9. Residence times vs. tidal flushing category.

It is important to remember that residence times are the result of complex interactions of multiple hydrodynamic and hydrologic processes as well as water body geometry. The residence times calculated here are dependent upon the quality of the input data, and the tidal flushing categories are the result of dividing a continuum of values. The uncertainties should be considered when using these results in management applications.

CONCLUSIONS

Residence times for water bodies in the Virginia coastal zone were calculated using three water quality models, depending upon the complexity of the water body. Residence times range from 0.1 to 29 days. One outlier has a residence time of 72 days.

Descriptive statistics were used to group the residence times in tidal flushing categories (quickly, intermediately, and slowly flushed) that reflect a relative time frame in which a water body is flushed. The results suggest that mean depth may be used as an approximate estimation of the flushing characteristics.

Residence times and flushing categories were joined to a geographic information system layer in order to spatially display and analyze results.

LITERATURE CITED

Casulli, V. and R. A. Walters. 2000. An unstructured grid, three-dimensional model based on the shallow water equations. *International Journal for Numerical Methods in Fluids*, 32:331-348.

Casulli, V. and P. Zanolli. 1998. A Three-dimensional semi-implicit algorithm for environmental flows on unstructured grids. Proceedings of Conference on Numerical Methods for Fluid Dynamics, University of Oxford.

Cheng, R. T., V. Casulli, and J. W. Gartner. 1993. Tidal, residual, intertidal mudflat (TRIM) model and its applications to San Francisco Bay, California. *Estuarine, Coastal, and Shelf Science*, 36:235-280.

Cheng, R. T. and V. Casulli. 2002. Evaluation of the UnTRIM Model for 3-D Tidal Circulation. Proceedings of the 7th International Conference, ASCE, p. 628-642.

Virginia Division of Shellfish Sanitation (DSS), 2007. http://www.vdh.state.va.us/EnvironmentalHealth/Shellfish/closureSurvey/index.htm#Survey

Li, Y. 2006. Development of an unstructured grid, finite volume eutrophication model for the shallow water coastal bay: application in the Lynnhaven River Inlet System. PhD dissertation. School of Marine Science, College of William and Mary, Gloucester Point, Va. 305 p.

Maryland Department of the Environment (MDE). 2004. Total Maximum Daily Loads of Fecal Coliform for Restricted Shellfish Harvesting Areas in the St. Mary's River Basin in St. Mary's County, Maryland. Final report submitted to Watershed Protection Division U.S. Environmental Protection Agency, Region III. 51 p.

Monsen, N.E., J.E. Cloern, and L.V. Lucas. 2002. A comment on the use of flushing time, residence time, and age as transport time scales. Limnology and Oceanography 47(5): 1545–1553.

Mukai, A.Y., J. J. Westerink, and R .A. Luettich. 2002. Guidelines for using the east coast 2001 database of tidal constituents within western North Atlantic Ocean, Gulf of Mexico and Caribbean. US Army Corps of Engineers, ERDC/CHL CHETN-IV-40, 20p.

Shen, J. and L. Haas. 2004. Calculating age and residence time in the tidal York River using three-dimensional model experiments. Estuarine, Coastal and Shelf Science 61:449-461.

Takeoka, H. 1984. Fundamental concepts of exchange and transport time scales in a coastal sea. *Continental Shelf Research* 3(3):322-326.

Zimmerman, JTF. 1976. Mixing and flushing of tidal embayments in the western Dutch Wadden Sea, Part I: Distribution of salinity and calculation of mixing time scales. Netherlands J Sea Res 10(2):149-191.

APPENDIX A

Residence times and tidal flushing categories for water bodies. The descriptions of the columns are found in Appendix B and the metadata file (waterbodies.shp.xml) associated with the shapefile called waterbodies.shp.

Water Body ID	Water Area (m2)	Watershed Area (m2)	Water Volume (m3)	Water Perimeter (m)	River Length (m)	Residence Time (days)	Tidal Range (feet)	Mean Depth (m)	Method	Flushing Category
1	1758153	45681619	1476090	18056	3530	3.59	1.2	0.84	simple	intermediately
2	14294689	94538690	28555470	60768	8263	7.04	1.57	2	simple	slowly
3	1492896	67679488	434880	19803	4505	0.92	1.57	0.29	simple	quickly
4	21850195	160519573	45135990	116301	14410	7.62	1.5	2.07	simple	slowly
5	10127805	41644608	21692160	60465	9317	7.98	1.5	2.14	simple	slowly
6	531251	13625626	185580	31283	2950	1.32	1.38	0.35	simple	quickly
7	13546540	119186134	26912430	101633	11175	28	1.28	1.99	prism	slowly
8	10543746	74067827	17450460	91076	1614	7.65	1.2	1.66	simple	slowly
9	2070022	26812963	2255850	38007	2959	4.89	1.2	1.09	simple	intermediately
10	6923025	39211205	8527770	101011	7736	8.43	0.8	1.23	simple	intermediately
12	3094312	9063888	5724000	39874	5258	9.84	1.05	1.85	simple	slowly
13	17182924	153144163	44373060	139473	19596	29.4	1.05	2.58	prism	slowly
14	2406018	31297996	4140270	25409	5253	7.15	1.3	1.72	simple	slowly
15	4684402	22597850	8401680	54260	6321	9.04	1.1	1.79	simple	slowly
16	2648875	19923555	5494590	31631	5740	10.82	1.05	2.07	simple	slowly
17	1176083	8273371	1545300	18378	5478	6.87	1.05	1.31	simple	intermediately
18	1388524	4126885	1049310	17918	2507	3.25	1.3	0.76	simple	intermediately
20	3252508	18153671	5445630	39754	4304	7.85	1.18	1.67	simple	slowly
21	24246577	202368315	69100380	163548	17238	12.54	1.25	2.85	simple	slowly
23	4852562	75043855	3751200	45589	6647	2.88	1.44	0.77	simple	intermediately
24	1058763	55119095	355140	22324	4008	1.12	1.44	0.34	simple	quickly
25	2370445	174355937	1062000	53803	11191	1.37	1.51	0.45	simple	quickly
27	510585	20906225	181440	9386	2521	1.28	1.38	0.36	simple	quickly
28	2006635	38874950	903150	24649	5712	2.11	1.31	0.45	prism	quickly
29	1240204	22600340	660780	17102	4611	1.8	1.4	0.53	prism	intermediately
30	680622	3520417	438480	12825	2361	2.87	1.25	0.64	simple	intermediately
31	685406	7019424	533520	8912	2270	3.27	1.3	0.78	simple	intermediately
32	664439	4600031	652950	11582	2453	4.84	1.12	0.98	simple	intermediately
33	561955	1688553	345150	10104	1203	2.86	1.2	0.61	simple	intermediately
35	12854819	168300937	22148370	87183	20513	5.87	1.6	1.72	simple	slowly
37	3370559	18549716	3520260	41130	4068	5.85	0.98	1.04	simple	intermediately
38	3727775	10383968	1147500	53050	3665	1.75	0.98	0.31	simple	quickly
39	2817628	10857288	2192220	36232	4582	2.88	1.51	0.78	simple	intermediately
40	878188	3340895	559080	14589	1858	1.55	2.3	0.64	simple	intermediately
41	8632687	49006671	16966620	94047	11824	4.58	2.4	1.97	simple	slowly
42	17435896	84303779	45984960	98037	14057	7.03	2.1	2.64	simple	slowly
43	19283307	156872519	47156760	87229	11401	6.47	2.1	2.45	simple	slowly
44	13176420	57203302	22216410	124531	10631	10.96	0.85	1.69	simple	slowly
45	1818322	9000983	823680	29453	2687	1.06	2.4	0.45	simple	quickly
46	1429580	13139251	1365750	30041	2130	2.31	2.3	0.96	simple	intermediately

47	599009	8212863	202050	11127	3361	0.7	2.65	0.34	simple	quickly
48	2974497	104057811	2001240	85661	3358	1.78	1.97	0.67	simple	intermediately
49	120009	36157361	38160	10921	2782	0.4	3.1	0.32	simple	quickly
50	257627	59808954	77760	17739	3923	0.62	1.64	0.3	simple	quickly
51	995179	47064205	658530	29688	8914	1.43	2.4	0.66	simple	intermediately
52	725839	11106108	310410	16994	1961	1.07	2.2	0.43	simple	quickly
53	21933063	68447041	32800230	222195	6555	5.8	2.4	1.5	prism	slowly
54	24338221	140576991	22502610	185771	14775	3.73	2.3	0.92	prism	intermediately
56	3458927	5779527	3751830	23229	4404	2.45	2.5	1.08	simple	intermediately
58	10007871	77129732	7944030	101856	14719	1.7	2.6	0.79	simple	intermediately
59	862667	14942709	621900	36448	2952	1.64	2.4	0.72	simple	intermediately
60	359826	56133247	215460	19875	5670	1.19	2.1	0.6	simple	intermediately
61	8272209	134697233	6664230	144973	12295	1.58	2.8	0.81	simple	intermediately
62	3761592	68624174	1937520	64353	8611	1.01	2.8	0.52	simple	intermediately
63	28492579	83241003	34820640	237564	16002	3.91	3.1	1.22	prism	intermediately
64	149714	8037091	46440	12769	1714	0.59	2.7	0.31	simple	quickly
65	7237429	33785152	5005170	94468	12685	1.49	2.6	0.69	simple	intermediately
66	7330601	31285296	52278366	33461	10754	15.4	2.6	7.13	simple	slowly
68	2701056	15472595	9262148	36538	9653	7.39	2.6	3.43	simple	slowly
70	7496900	62941717	4107510	140639	7648	12	1.9	0.55	3-D	intermediately
71	7889023	36869824	12939210	122165	8655	72	1.05	1.64	3-D	slowly
76	6112546	52914884	5946480	61884	7559	2.51	2.17	0.97	simple	intermediately
77	5000813	45826141	3289950	53361	7849	1.75	2.1	0.66	simple	intermediately
79	6270811	20332284	5374620	65347	2182	2.41	2	0.86	simple	intermediately
80	7562823	39987335	8225100	70986	7811	7.27	1.8	1.09	prism	intermediately
81	5458237	60390212	4491090	55020	4608	3.69	1.7	0.82	prism	intermediately
82	9817932	35277793	9258930	69122	10951	5.15	1.57	0.94	prism	intermediately
83	4036936	16928182	2043810	39651	2040	1.8	1.57	0.51	simple	intermediately
84	8267886	65376115	7884630	67972	7803	3.12	1.7	0.95	simple	intermediately
85	9887303	76175487	6482160	96735	3686	4.03	1.8	0.66	prism	intermediately
86	8264563	49829464	4032540	72409	6131	2.75	0.98	0.49	simple	quickly
87	988616	15895322	265230	20580	2334	0.83	1.77	0.27	simple	quickly
88	8739142	42919985	7077510	61298	3987	2.31	1.97	0.81	simple	intermediately
90	2703291	20254712	862650	38381	5819	0.74	2.4	0.32	simple	quickly
11_1	298037	1921237	88560	7245	1417	1.56	1.05	0.3	simple	quickly
11_2	425433	2181693	127440	10694	2444	1.58	1.05	0.3	simple	quickly
11_3	153824	1440839	95490	3007	2439	3.21	1.05	0.62	simple	intermediately
11_4	113794	891173	62010	2975	905	2.84	1.05	0.54	simple	intermediately
14_1	363296	2548272	226710	5036	1541	2.65	1.3	0.62	simple	intermediately
14_2	415630	2615510	470430	8787	2092	4.82	1.3	1.13	simple	intermediately
14_3	653639	4418862	367380	10221	1977	2.39	1.3	0.56	simple	intermediately
16_1	4706569	18907900	8040150	57310	6272	9.05	1.05	1.71	simple	slowly
16_2	835207	4593625	1059930	15085	3686	6.68	1.05	1.27	simple	intermediately
17_1	48652	1156835	14850	1897	566	1.49	1.05	0.31	simple	quickly
17_2	64618	802286	14850	2500	558	1.17	1.05	0.23	simple	quickly
18_1	2901495	2644995	2348010	20901	3467	3.51	1.3	0.81	simple	intermediately
1A	6618607	124884025	9537120	54698	9603	4.83	1.6	1.44	simple	intermediately
1A_1	232212	23568794	69930	11630	5392	0.82	1.6	0.3	simple	quickly
22_1	96373	5046783	29970	4571	997	1.11	1.35	0.31	simple	quickly

22_2	351758	7178301	141480	9975	2101	1.58	1.35	0.4	simple	quickly
22_3	217423	5015933	65160	7314	1606	1.17	1.35	0.3	simple	quickly
22_4	78054	548124	19350	2164	785	1.02	1.35	0.25	simple	quickly
22_5	31168	335480	7020	1332	455	0.91	1.35	0.23	simple	quickly
22_6	121126	3229182	37530	6025	1564	1.19	1.35	0.31	simple	quickly
23_1	1016177	6048205	688320	13107	3399	2.6	1.44	0.68	simple	intermediately
23_2	652926	8070674	230850	12033	2001	1.33	1.44	0.35	simple	quickly
25_1	602232	24691414	250290	27008	5870	1.38	1.51	0.42	simple	quickly
25A	997964	46142357	714600	78359	7682	2.35	1.51	0.72	simple	intermediately
25B	7700859	221770122	14693490	16466	22476	6.56	1.51	1.91	simple	slowly
26A	410198	23073584	224820	21399	11208	1.75	1.51	0.55	simple	intermediately
26A_1	3194997	76611929	2952900	57979	14782	3.22	1.51	0.92	simple	intermediately
26B_1	230317	6198160	70650	13211	4811	1.06	1.51	0.31	simple	quickly
26B_2	443919	10321119	124470	10825	2372	0.98	1.51	0.28	simple	quickly
26B_3	514638	11030904	314280	20585	7738	2.15	1.51	0.61	simple	intermediately
27_1	542788	6943901	162990	8014	2613	1.18	1.38	0.3	simple	quickly
27_2	242547	3797141	59220	5265	1442	0.95	1.38	0.24	simple	quickly
27_3	690755	8478177	224280	13734	2832	1.28	1.38	0.32	simple	quickly
28_1	993902	6410051	532170	16564	2789	2.26	1.31	0.54	simple	intermediately
28_2	161691	924548	49770	4317	980	1.3	1.31	0.31	simple	quickly
30_1	104415	5207765	31590	3181	845	1.16	1.25	0.3	simple	quickly
30_2	503391	7935429	180990	14674	2681	1.54	1.25	0.36	simple	quickly
30_3	89761	4440672	57510	1652	451	2.45	1.25	0.64	simple	intermediately
31_1	513275	10836681	351360	7595	2673	2.77	1.3	0.68	simple	intermediately
32_1	257952	4724458	83880	7473	2267	1.53	1.12	0.33	simple	quickly
32_2	94986	3197682	28890	3079	1276	1.35	1.12	0.3	simple	quickly
32_3	90353	1871046	27450	3042	1010	1.42	1.12	0.3	simple	quickly
33_1	21219	464270	6750	951	349	1.38	1.2	0.32	simple	quickly
33_2	35926	992693	11340	1338	558	1.34	1.2	0.32	simple	quickly
33_3	807808	2780593	1011420	11752	1101	5.83	1.2	1.25	simple	intermediately
34_1	174586	2878136	142200	6296	1468	3.35	1.3	0.81	simple	intermediately
34_2	54828	1175564	35910	2144	504	2.65	1.3	0.65	simple	intermediately
34_3	194469	4469026	174240	6166	1746	3.6	1.3	0.9	simple	intermediately
34_4	290644	2748690	169650	5338	892	2.46	1.3	0.58	simple	intermediately
34_5	257337	5322682	228330	7048	1915	3.59	1.3	0.89	simple	intermediately
34_7	447724	12634092	504000	10573	3050	4.45	1.3	1.13	simple	intermediately
34_8	30844	1155326	7830	1469	418	0.97	1.3	0.25	simple	quickly
37_1	123751	3425384	36720	4617	1234	1.51	0.98	0.3	simple	quickly
37_2	779898	17082384	701640	15935	3932	4.68	0.98	0.9	simple	intermediately
37_3	359075	2813233	352530	6063	1768	5.44	0.98	0.98	simple	intermediately
37_5	874665	4731519	473940	11582	2267	3.04	0.98	0.54	simple	intermediately
39_1	693396	3375646	365670	9093	2116	1.95	1.51	0.53	simple	intermediately
39_2	140699	494181	58140	3147	986	1.53	1.51	0.41	simple	quickly
40_1	394110	1169205	137970	5696	1463	0.86	2.3	0.35	simple	quickly
40_2	99470	1938144	24300	4424	1771	0.58	2.3	0.24	simple	quickly
40_3	364939	1948819	114480	6391	1397	0.76	2.3	0.31	simple	quickly
40_4	115338	561469	33930	3922	490	0.72	2.3	0.29	simple	quickly
42_5	240037	2144628	86760	6269	1011	0.96	2.1	0.36	simple	quickly
42_6	152327	1007099	40320	3866	905	0.7	2.1	0.26	simple	quickly

45_1	1341388	5451014	896220	24638	2988	1.56	2.4	0.67	simple	intermediately
46_1	621602	6261899	371790	16143	2466	1.44	2.3	0.6	simple	intermediately
47_2	945632	11810374	407700	22663	3670	0.9	2.65	0.43	simple	quickly
47A	1040105	33211788	344070	8573	4865	0.67	2.65	0.33	simple	quickly
47A_1	289059	9339214	74160	2703	2397	0.52	2.65	0.26	simple	quickly
47A_2	29299	2845290	9450	5713	1474	0.59	2.65	0.32	simple	quickly
47A_3	57300	8050283	17820	17669	1751	0.53	2.65	0.31	simple	quickly
48_1	369663	14722265	100170	11766	4688	0.71	1.97	0.27	simple	quickly
48_2	667632	7243372	225630	22753	2877	0.95	1.97	0.34	simple	quickly
48_3	514771	8274010	147600	30480	5179	0.79	1.97	0.29	simple	quickly
48_4	28048	5684699	8640	2964	1380	0.6	1.97	0.31	simple	quickly
48_5	230971	1399102	79650	14581	836	0.98	1.97	0.34	simple	quickly
48_6	29058	287470	10260	3312	1001	0.99	1.97	0.35	simple	quickly
48_7	13933	161053	4590	1654	861	0.92	1.97	0.33	simple	quickly
48_8	5942	186570	1620	588	447	0.73	1.97	0.27	simple	quickly
49_1	80104	3428292	22950	5121	2510	0.49	3.1	0.29	simple	quickly
49_2	163920	16720633	49680	10110	4020	0.48	3.1	0.3	simple	quickly
49_3	63969	1930288	19440	5053	1701	0.53	3.1	0.3	simple	quickly
49_4	35616	13884323	11610	3422	1941	0.37	3.1	0.33	simple	quickly
49_5	42177	3929531	14040	4855	2605	0.53	3.1	0.33	simple	quickly
49_6	153059	19609189	54180	11579	4008	0.54	3.1	0.35	simple	quickly
49_7	55693	746045	17010	3357	1343	0.55	3.1	0.31	simple	quickly
50_1	56885	16770690	15930	5823	3149	0.52	1.64	0.28	simple	quickly
50_2	183027	35070931	57240	13887	6453	0.7	1.64	0.31	simple	quickly
50_3	78046	16853000	23760	7148	3282	0.65	1.64	0.3	simple	quickly
50_5	24984	1727560	6750	2493	1307	0.78	1.64	0.27	simple	quickly
51_1	303595	3723945	91080	7406	1365	0.69	2.4	0.3	simple	quickly
51_2	1535572	37975695	445860	30054	4417	0.65	2.4	0.29	simple	quickly
53_1	1816967	9024149	1479330	28242	4215	1.9	2.4	0.81	simple	intermediately
56_1	35147	5930625	20790	1270	591	1.02	2.5	0.59	simple	intermediately
56_2	64605	6875620	19710	3447	1138	0.58	2.5	0.31	simple	quickly
56_3	1573706	16217579	488880	32893	7063	0.69	2.5	0.31	simple	quickly
57_1	5417	3069018	1350	775	818	0.27	2.6	0.25	simple	quickly
57_2	8598	18627563	1890	1410	718	0.1	2.6	0.22	simple	quickly
58_1	1158138	7526803	534330	28153	2101	0.99	2.6	0.46	simple	quickly
58_2	69159	1447014	20880	5192	1679	0.63	2.6	0.3	simple	quickly
59_2	1099907	17969434	1058220	35863	8303	2.2	2.4	0.96	simple	intermediately
6_1	584431	9358117	255510	12718	2385	1.7	1.38	0.44	simple	quickly
6_2	331679	8529016	111330	10921	2129	1.27	1.38	0.34	simple	quickly
60_1	795511	50632402	832680	8097	10180	2.47	2.1	1.05	simple	intermediately
62_1	2118037	12296586	1083690	21887	6507	1.02	2.8	0.51	simple	intermediately
62_2	123607	2675642	35820	8298	3160	0.57	2.8	0.29	simple	quickly
62_3	221967	6009265	65610	14974	3462	0.57	2.8	0.3	simple	quickly
64_2	89530	4273952	27000	8379	2448	0.58	2.7	0.3	simple	quickly
65_1	33889616	387218535	64342530	543805	28285	4.05	2.6	1.9	simple	slowly
70_1	3927311	42428861	1851210	82200	10451	12	1.9	0.47	3-D	quickly
75_1	193152	38291539	72180	14306	6695	0.71	2.3	0.37	simple	quickly
75_2	451825	38931495	187290	29784	6584	0.9	2.3	0.41	simple	quickly
76_1	9150925	53759894	7090290	64772	12967	2.01	2.17	0.77	simple	intermediately

76_2	2544184	16634531	1613070	46641	4945	1.64	2.17	0.63	simple	intermediately
77_1	2469546	6469152	992160	56105	3610	1.08	2.1	0.4	simple	quickly
77_2	2730157	43609005	1959480	33257	5260	1.89	2.1	0.72	simple	intermediately
80_1	459212	6028014	188010	8771	2354	1.26	1.8	0.41	simple	quickly
80_2	486671	2661321	162630	12867	9599	1.04	1.8	0.33	simple	quickly
81_1	962531	4148951	424350	14557	12266	1.46	1.7	0.44	simple	quickly
85_1	511750	5880130	144720	12840	8257	0.87	1.8	0.28	simple	quickly
9_1	965263	7702090	584550	17364	3324	2.77	1.2	0.61	simple	intermediately
9_3	891225	14933761	265140	17356	1045	1.32	1.2	0.3	simple	quickly
9_4	590163	11064048	177120	15251	5656	1.32	1.2	0.3	simple	quickly
9_5	551995	8849590	167310	13556	2005	1.34	1.2	0.3	simple	quickly
9_6	73204	3049865	22410	3026	1045	1.24	1.2	0.31	simple	quickly
90_1	180099	7181455	55890	5913	1842	0.69	2.4	0.31	simple	quickly
E1	104588366	0	13645939	0	0	15.8	0	0.13	3-D	quickly
E10	13068636	30626142	5996430	0	0	0.72	3.6	0.46	simple	quickly
E11	2673404	15145003	691920	0	0	0.44	3.3	0.26	simple	quickly
E2	74029360	0	31238177	0	0	4	0	0.42	3-D	quickly
E3	51368374	0	31451616	0	0	7.3	0	0.61	3-D	intermediately
E4	27708398	0	2531386	0	0	4.3	0	0.09	3-D	quickly
E5	36715891	0	3233444	0	0	5.2	0	0.09	3-D	quickly
E6	39815284	0	2176368	0	0	10.5	0	0.05	3-D	quickly
E7	10454146	49343543	2935710	0	0	0.41	3.9	0.28	simple	quickly
E8	6821760	49343543	2272410	0	0	0.48	3.9	0.33	simple	quickly
E9	17753448	67503945	17818020	0	0	1.46	3.9	1	simple	intermediately

APPENDIX B

Shapefile and metadata file are in a separate zip file called waterbodies.shp. The projection of the shapefile is UTM, zone 18 and the horizontal datum is NAD83.

Below is a description of the columns in the attribute file (.dbf) of the shapefile, and is an excerpt from the metadata file.

AREA is the area of every polygon in the shapefile in m^2.

PERIMETER is the perimeter of every polygon in the shapefile in m.

WTRSHDID consists of letters and or numbers and is the identification code for the watershed that drains to a water body.

CODE is either land or water.

WATERID is the identification code for a water body. Only water bodies that have residence times calculated for them have a waterid. Each water body has a unique designation. Most of the waterids match the wtrshdid. Waterids are only found in polygons with code = water. If a water body consists of multiple polygons, all the polygons will have the same waterid. Waterid is equivalent to the column Water Body ID in Appendix A.

WATERAREA is the area of the water body in m^2. Only polygons with a waterid have a waterarea. Waterarea is equivalent to the column Water Area in Appendix A.

WTRSHDAREA is the area of the watershed that drains to a water body in m^2. Only polygons with a waterid have a wtrshdarea. Wtrshdarea is equivalent to the column Watershed Area in Appendix A.

WATERVOLUM is the volume of a water body in m^3. Only polygons with a waterid have a watervolum. Watervolum is equivalent to the column Water Volume in Appendix A.

WATERPERIM is the perimeter of a water body in m. Only polygons with a waterid have a waterperim. Waterperim is equivalent to the column Water Perimeter in Appendix A.

RIVERLENGT is the estimated longest length of a water body in m. Only polygons with a waterid have a riverlengt. Riverlengt is equivalent to the column River Length in Appendix A.

RESIDENCET is the residence time of a water body in days. Only polygons with a waterid have a residence time. Residencet is equivalent to the column Residence Time in Appendix A.

TIDALRANGE is the estimated tidal range of a water body in feet. Only polygons with a waterid have a tidalrange. Tidalrange is equivalent to the column Tidal Range in Appendix A.

MEANDEPTH is the average water depth of a water body in m. It is calculated by (water body volume) ÷ (water body depth). Only polygons with a waterid have a mean depth. Meandepth is equivalent to the column Mean Depth in Appendix A.

Method is the method used to calculate the residence time for each water body, described in the report. There are 3 codes:
Simple = simple equation method
Prism = tidal prism method
3-D = UnTRIM 3-D model
Only polygons with a waterid have a method listed. Method is equivalent to the column Method in Appendix A.

Flushing is the tidal flushing category assigned to each water body, described in the report. There are 3 codes:
quickly = quickly flushed water body
intermediately = intermediately flushed water body
slowly = slowly flushed water body.
Only polygons with a waterid have a flushing category listed. Flushing is equivalent to the column Flushing Category in Appendix A.