Supplementary Information

Simple relationships between residence time and annual nutrient retention, export, and loading for estuaries

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S1. Derivations

Averaged mass balance equations

We assume the estuary or coastal embayment of interest is a partially enclosed waterbody with tidal inflow and outflow through one principal opening. The instantaneous (unaveraged) mass balance of water volume can be written as follows:

$$\frac{dv(t)}{dt} = q_{in}(t) - q_e(t) + q_f\ (t) \tag{S1}$$

where q_{in} (m^3s^{-1}) is volume flux of total (mixed new ocean and ebb) water into the estuary through the ocean boundary; q_e (m^3s^{-1}) is the volume flux of total mixed water that leaves the estuary through the ocean boundary; q_f (m^3s^{-1}) is freshwater input to the estuary; and v (m^3) is the volume of the waterbody.

The instantaneous mass balance for a transported, reactive substance can be written as follows:

$$\frac{dm(t)}{dt} = \dot{m}_{in}(t) - \dot{m}_e(t) - \dot{m}_k(t) + l(t) \tag{S2}$$

where $\dot{m}_{in}(t)$ and $\dot{m}_e(t)$ are mass fluxes into and out of the estuary through the ocean boundary (gs^{-1}), respectively; $\dot{m}_k$ is net mass removal (or generation if < 0) within the estuary (gs^{-1}); $l(t)$ is loading (gs^{-1}); and $m(t)$ is the total mass in the estuary (g).

We next assume that (1) the waterbody is well mixed, (2) the net removal of the substance from the water column due to biochemical processes or settling is proportional to the spatial mean concentration (i.e., a first order reaction), and (3) diffusive export and import are negligible. The instantaneous mass balance (Eq. S2) for a transported, reactive substance can then be written as follows:

$$\frac{dc(t)v(t)}{dt} = q_{in}(t)c_{in}(t) - q_e(t)c(t) - k(t)c(t)v(t) + l(t) \tag{S3}$$

where $c_{in}(t)$ is the concentration at the ocean boundary (gm^{-3}); $c(t)$ is the spatial mean concentration over the waterbody (gm^{-3}); and $k(t)$ is the reaction coefficient representing net removal within the estuary (s^{-1}).

Since we are more interested in long-term average water and mass balances over a period T (T = subtide, month, year, etc.), we next average each instantaneous mass balance equation above (Eqs. S1 and S3) over the period T. A variable of interest "f"can be decomposed into its temporal average (denoted here by an overbar) and fluctuating (primed) part (Monismith 2010), i.e.:

$$\bar{f} = \frac{1}{T}\int_{t}^{t+T} f(t)dt \quad and\ f(t) = \bar{f} + f' \tag{S4}$$

If we substitute the decomposed form (Eq. S4) for each dependent variable in Eq. S1 and then average that equation over the period T (noting that $\overline{f'}$ = 0), the time-averaged water mass balance can be written as:

$$\frac{d\bar{v}}{dt} = \overline{q_{in}}(t) - \overline{q_e}(t) + \overline{q_f}(t) \tag{S5}$$

where all variables are time-averaged over the period T. $\overline{q_{in}}$ (m^{3}s^{-1}) is the time-averaged (mixed new ocean and ebb) water flux entering the estuary through the ocean boundary; $\overline{q_e}$ (m^3 s^{-1}) is the time-averaged flux of mixed water that leaves the estuary through the ocean boundary; $\overline{q_f}$ (m^3 s^{-1}) is the time-averaged freshwater input; and $\bar{v}$ is the average volume of the waterbody (m^3).

To derive the time-averaged substance mass balance equation, let us substitute the decomposed form (Eq. S4) for each time-dependent variable in Eq. S3 and then average the equation over period T. This produces:

$$\begin{aligned}\frac{d(\bar{c}\bar{v} + \overline{c'v'})}{dt} &= \overline{q_{in}}\,\overline{c_{in}} + \overline{q'_{in}c'_{in}} - \overline{q_e}\,\bar{c} - \overline{q'_e c'} \\ &\quad -\bar{k}\bar{c}\bar{v} - \bar{k}\,\overline{c'v'} - \bar{c}\,\overline{k'v'} - \bar{v}\,\overline{k'c'} - \overline{k'c'v'} + \bar{l} \qquad \text{(S6)}\end{aligned}$$

where products of primed variables represent high-frequency correlations; whereas products of variables with individual overbars represent the products of temporal means. To arrive at a tractable form of the averaged substance mass balance, we assume that terms involving high-frequency correlations are much smaller in magnitude than their counterparts based on products of temporal means. In other words, we assume that $|d(\overline{c'v'})/dt| \ll |d(\bar{c}\bar{v})/dt|$, $|\overline{q'_{in}c'_{in}}| \ll |\overline{q_{in}}\,\overline{c_{in}}|$, $|\overline{q'_e c'}| \ll |\overline{q_e}\,\bar{c}|$, and the same with the internal loss terms (those involving net removal rate "k"). It is important to note that our assumption of the relative unimportance of terms containing high-frequency fluctuations may not always be justified, such as when tidal dispersive flux $\overline{q'c'}$ is of a magnitude similar to or greater than advective flux $\bar{q}\bar{c}$ (Lucas et al. 2006; Fram et al. 2007; Martin et al. 2007). However, if we accept that these assumptions are satisfactory, Eq. S6 can be written much more simply as:

$$\frac{d(\bar{c}\bar{v})}{dt} = \overline{q_{in}}\ \overline{c_{in}} - \overline{q_e}\,\bar{c} - \bar{k}\bar{c}\bar{v} + \bar{l} \qquad (S7)$$

where $\bar{c}$ and $\overline{c_{in}}$, respectively, are time-averaged concentrations of the substance (gm^{-3}) inside and entering the estuary from the ocean, respectively. It can be seen that Eq. S7 is the first-order approximation of Eq. S6 as it neglects all high-frequency (primed) terms. For our study, the averaging period T = one year, so Eqs. S5 and S7 are the annually averaged mass-balance equations. For convenience moving forward, we use daily units for the time dimension in the averaged equations.

Relation between residence time and outflow

The average water flux to and from the sea, $\overline{q_e}$ and $\overline{q_{in}}$ (replaced, respectively, by Q_e and Q_{in} hereafter and in the main manuscript), are needed to solve some of our simple model equations but are often unknown. Here we derive a relationship that enables their estimation if the mean residence time is known. The "spatial mean residence time" is used in the derivations that follow and can be computed based on the "residence time distribution function" of material within a waterbody. Consider a quantity of scalar material present in a waterbody at time t=0. Following Bolin and Rodhe (1973), Takeoka (1984) showed that if (1) R_0 is the total amount of material within the waterbody at t = 0, and (2) $R(t)$ is the amount of material remaining inside the waterbody at some later time t (and whose residence time is accordingly larger than t), then the residence time distribution function can be written as:

$$\varphi(t) = -\frac{1}{R_0}\frac{d\,R(t)}{dt} \tag{S8}$$

The residence time distribution function $\varphi(t)$ represents the frequency distribution of material elements in the waterbody associated with different residence times, across the full range of residence times; that distribution function is scaled such that the integral of $\varphi(t)$ over all residence times is 1. The mean residence time of the material is given by (Takeoka 1984):

$$\widehat{\tau_r} = \int_0^{\infty} t\varphi(t)\,dt \tag{S9}$$

After integrating Eq. S9 by parts and considering only cases for which mean residence time has a definite value, $\widehat{\tau_r}$ can be expressed as (Takeoka 1984):

$$\widehat{\tau_r} = \int_0^{\infty} r(t)\,dt \tag{S10}$$

where $r(t) = \frac{R(t)}{R_0}$ is the "remnant function," i.e., the ratio of the mass of material remaining inside the waterbody at time *t* to its initial total mass. Takeoka's (1984) approach was derived under the assumption that "the transport mechanism works steadily"; therefore, the residence time here ($\widehat{\tau_r}$) is strictly assumed to apply through all time (caret denotes time-invariance). This relationship has been applied in numerical models to compute residence time based on simulations with tracer releases (e.g., Shen and Haas 2004).

To derive a relationship between outflow Q_e and mean residence time for use in our models, we consider a very simple well-mixed system with: (1) an initial tracer concentration of 1 inside the estuary, (2) no internal source or loss processes occurring within the estuary, (3) a total mean estuary volume $\hat{V}$ that does not change with time, and (4) a constant outflow $\widehat{Q_e}$. Applying these assumptions to the instantaneous constituent mass balance equation (Eq. S3), the transport problem of water mass initially present in the system (marked with tracer concentration *c*) can be written as:

$$\frac{d\hat{V}c(t)}{dt} = -\widehat{Q_e}c(t) \tag{S11}$$

(Note that lower case "*c*" represents instantaneous [i.e., non-time averaged] concentration. See "Averaged mass balance equations" subsection above in Supplementary Information S1). The remnant function can then be expressed as:

$$r(t) = \frac{\hat{V}c(t)}{\hat{V} \cdot 1} = e^{-\frac{\widehat{Q_e}}{\hat{V}}t} \tag{S12}$$

Integrating this from 0 to ∞ (as in Eq. S10) produces a simple expression for the average residence time:

$$\widehat{\tau_r} = \frac{\hat{V}}{\widehat{Q_e}} \tag{S13a}$$

It can be seen that average residence time $\widehat{\tau_r}$ is the scale that reflects flushing of the waterbody by constant outflow rate $\widehat{Q_e}$. The form of Eq. S13a suggests that our time-averaged outflow Q_e (which is constant within the averaging period T) may be approximated by an analogous expression for the mean residence time for the corresponding period. The same result can be obtained if water mass itself is treated as a tracer, as shown by Deleersnijder (Working Note 2019, http://hdl.handle.net/2078.1/219115). In order to transform Eq. S13a (which is based on component parameters assumed constant for all time) into an analogous expression with component parameters assumed constant only over the averaging period T, we must assume that T is long enough to approximate infinity relative to the timescale for flushing of the estuary. Under such an assumption:

$$\tau_r \approx \frac{V}{Q_e} \tag{S13b}$$

where mean residence time τ_r, estuary volume V, and mean outflow Q_e are assumed constant over the averaging period T and, in practice herein, are represented as averages over that period. The exceedance of the mean residence time by the averaging period appears to represent a minimum requirement for applicability of Eq. S13b. Eq. S13b here is the same as Eq. 5 in the main manuscript.

S2. Procedural Summary for Calculations

Here we summarize the procedures followed for calculating results presented in the 'Results and Discussion' section. In the following, these definitions apply: τ_r (mean residence time), *NE:L* (*net export*:*loading*), K (adjusted net removal rate), k (net removal rate), β (ocean exchange factor), TN (total nitrogen), TP (total phosphorus), R (correlation coefficient), Q_e (mean outflow to ocean), Q_{in} (mean inflow from ocean to estuary), Q_f (freshwater inflow), C (mean concentration in estuary), C_{in} (mean concentration just downstream of estuary), V (estuary volume), τ_k (net removal timescale), τ_f (time for renewal of estuary volume by freshwater inflow), TSS (total suspended solids concentration).

(1) Computation of residence time in Chesapeake Bay:

  a. The 3D hydrodynamic model implementing the adjoint scheme of Delhez et al. (2004) was previously run to compute annually- and estuary-averaged residence time τ_r for the Chesapeake Bay from 1980-2012 (Du and Shen 2016).

(2) Verification of *NE:L* model (Eq. 7):

  a. Equation 7 describing *NE:L* as a function of τ_r was fit to the Nixon et al. (1996) dataset, using $K=\beta k$ as a fitting parameter. Our cross-system K (K_{TN}^{X-sys}) for total nitrogen (TN) was compared to Dettmann's (2001) loss rate derived by that author's own similar fitting exercise.

  b. The goodness of fit (R) for our mechanistically derived Equation 7 was compared to that of Nixon et al.'s (1996) empirical linear-log fit for the same estuary-lake dataset.

(3) Estimation of inter-annually varying *NE:L* for TN in the Chesapeake Bay:

  a. Using *NE:L* and τ_r from Nixon et al. (1996) for the Chesapeake during 1985-1986, a Chesapeake-specific value of K ("K_{TN}^{Ches}") was backed out from Eq. 7 and assumed to be time-invariant.

  b. Q_e and Q_{in} (annual means) were estimated for years 1985-2012 using Eqs. 5 and 3, respectively, in combination with model-computed τ_r (step 1a) and U.S. Geological Survey measured annual mean Q_f (https://waterdata.usgs.gov/nwis/sw).

c. A β value (see Eq. 7) for TN in the Chesapeake Bay was estimated for each year using estimated annually varying mean water fluxes at the ocean boundary (Q_e and Q_{in}, step 3b), and mean annual measured TN inside the Bay (C) and near the Bay mouth (C_{in}). An averaged β was computed across years.

d. From K_{TN}^{Ches} and averaged β, a time-invariant estimate of k ("k_{TN}^{Ches}") was calculated for the Chesapeake.

e. Using Eq. 7, interannually varying τ_r (step 1a), constant k (step 3d), and annually varying β (step 3c), a time series of $NE:L$ was estimated for the Chesapeake.

(4) Computation of TN loading:

a. To demonstrate the sensitivity of the simple loading model (Eq. 8) to the value of k, we derived a modest though realistic range of k based on Nixon et al.'s (1996) dataset. Specifically, the Chesapeake-specific estimate of k (step 3d) was converted to a *range* of possible values using ±20% of the standard deviation of individual estuarine K values derived from Nixon et al.'s (1996) 11 estuaries and the same method as in step 3a above. The objective of this range for k was not to quantify error or uncertainty, but simply to demonstrate the importance of k (a parameter that may not be readily available for many estuaries) to estimation of loading.

b. A time series of annual TN loading was estimated for years 1985-2012 using Eq. 8, estuary volume V, annual mean nutrient concentration inside (C) and near the mouth (C_{in}) of the Bay from Chesapeake Bay Program observations, model-computed τ_r (step 1a), estimated τ_k ($1/\ k_{TN}^{Ches}$) (based on step 3d and the range based on step 4a), and τ_f (V/Q_f). This time series was compared to loading estimated by the Chesapeake Bay Program.

(5) Computation of total phosphorus loading:

  a. A Chesapeake-specific value for k ("k_{TP}^{Ches}") was backed out of Eq. 10 using 1985-1986 mass input and output data from Boynton et al. (1995), mean observed 1985 C and C_{in} based on Chesapeake Bay Program data, model-computed τ_r for 1985, U.S. Geological Survey 1985 measured freshwater flow, and volume. We used Eq. 10 instead of Eq. 7 because total phosphorus (TP) input from the ocean between 1985-1986 was larger than export and, although Eq. 7 should theoretically work for cases with negative net export, herein we only tested Eq. 7 for cases of positive net export.

  b. A time series of annual TP loading was estimated for years 1985-2012 using Eq. 8, annual volume-weighted mean nutrient concentration inside (C) and near the mouth (C_{in}) of the Bay from Chesapeake Bay Program observations, model-computed τ_r (step 1a), estimated τ_k ($1/ k_{TP}^{Ches}$) based on step 5a, and τ_f (V/Q_f). This time series was compared to loading estimated by the CBP.

  c. To improve TP loading estimates relative to Chesapeake Bay Program estimates, a variable k was computed as a power function of total suspended solids concentration, TSS (details in "Results and Discussion" section).

S3. Supporting data

Here we provide the data used to compute TN and TP loading in the "Results and Discussion" section. Data include residence time (τ_r), water fluxes in and out of the estuary at the ocean boundary (Q_{in} and Q_e, respectively), volume-weighted annual mean concentrations (C), average concentrations at the ocean boundary (C_{in}), freshwater flow rates (Q_f), and average TSS concentrations in the upper and middle bay (Table S1). Freshwater discharge is based on data collected by the U.S. Geological Survey for the major rivers of the Chesapeake Bay (http://waterdata.usgs.gov/nwis/). The Chesapeake Bay Program's estimated TN and TP loadings from watershed, point source, and atmospheric deposition are listed in Tables S2 and S3, respectively. The mean volume used for the Chesapeake Bay is 7.5×10^{10} m^3 (Du and Shen 2016). The observational dataset that was used for estimating volume-weighted mean concentrations and inflow concentrations of TN and TP is that collected by the Chesapeake Bay Program (https://www.chesapeakebay.net/data). τ_r was computed by Du and Shen (2016) using a three-dimensional hydrodynamic model.

Table S1. Data used for computing annual loadings of total nitrogen and total phosphorus

Year	Mean TN C	TN C_{in}	Mean TP C	TP C_{in}	Q_{in}	Q_e	τ_r	Q_f	TSS[1]
unit	kg/m3	kg/m3	kg/m3	kg/m3	m3/s	m3/s	s	m^3/s	mg/L
1985	5.9821E-04	4.5442E-04	4.2300E-05	6.9300E-05	3.3354E+03	4.7092E+03	1.5926E+07	1.3738E+03	20.53
1986	6.2689E-04	4.7685E-04	3.6332E-05	4.8350E-05	2.9663E+03	4.8392E+03	1.5498E+07	1.8729E+03	18.14
1987	6.2409E-04	4.6359E-04	3.7769E-05	4.1347E-05	2.7187E+03	4.1773E+03	1.7954E+07	1.4587E+03	14.88
1988	6.0819E-04	2.3306E-04	2.7811E-05	3.4096E-05	2.9082E+03	4.1379E+03	1.8125E+07	1.2296E+03	13.43
1989	6.5053E-04	2.8220E-04	3.2116E-05	4.4542E-05	3.1084E+03	4.9138E+03	1.5263E+07	1.8054E+03	16.36
1990	6.2190E-04	2.5461E-04	3.1938E-05	3.2727E-05	2.9712E+03	5.1735E+03	1.4497E+07	2.2024E+03	20.05
1991	6.3179E-04	2.9055E-04	3.3623E-05	4.4160E-05	2.9090E+03	4.2384E+03	1.7695E+07	1.3294E+03	13.55
1992	5.7617E-04	2.9737E-04	3.0657E-05	4.3273E-05	3.5084E+03	5.1225E+03	1.4641E+07	1.6142E+03	15.84
1993	6.8823E-04	3.4115E-04	3.6290E-05	4.3746E-05	3.3338E+03	5.7066E+03	1.3143E+07	2.3728E+03	22.15
1994	7.0809E-04	3.1209E-04	3.5356E-05	3.8011E-05	2.8072E+03	5.1509E+03	1.4561E+07	2.3437E+03	18.70
1995	5.6036E-04	3.1312E-04	3.5877E-05	4.4190E-05	3.5879E+03	4.8534E+03	1.5453E+07	1.2654E+03	13.90
1996	7.5421E-04	3.3206E-04	4.3689E-05	4.6812E-05	3.1018E+03	5.9828E+03	1.2536E+07	2.8810E+03	24.12
1997	6.2099E-04	3.0296E-04	3.8328E-05	4.0772E-05	3.8788E+03	5.2223E+03	1.4361E+07	1.3436E+03	16.08
1998	6.1599E-04	3.5354E-04	3.5826E-05	5.0070E-05	2.2152E+03	4.0844E+03	1.8362E+07	1.8693E+03	15.18
1999	4.9636E-04	2.6957E-04	3.1751E-05	3.5324E-05	2.6718E+03	3.8890E+03	1.9285E+07	1.2172E+03	14.70
2000	5.8596E-04	3.0666E-04	3.6613E-05	4.2304E-05	2.7150E+03	4.2706E+03	1.7562E+07	1.5556E+03	15.32
2001	4.9531E-04	2.5022E-04	3.2241E-05	3.1950E-05	2.4797E+03	3.5460E+03	2.1150E+07	1.0663E+03	12.71
2002	4.8516E-04	2.9472E-04	3.3206E-05	3.3703E-05	3.4710E+03	4.9872E+03	1.5039E+07	1.5161E+03	10.65
2003	6.9604E-04	3.0129E-04	3.8206E-05	3.4363E-05	4.0588E+03	6.8129E+03	1.1008E+07	2.7542E+03	19.94
2004	7.0086E-04	2.9764E-04	3.4154E-05	3.0329E-05	3.6711E+03	6.6362E+03	1.1302E+07	2.9651E+03	22.33
2005	6.3416E-04	3.0869E-04	3.6077E-05	3.0989E-05	3.0461E+03	5.1247E+03	1.4635E+07	2.0786E+03	23.70
2006	5.7936E-04	2.6820E-04	3.4743E-05	2.5970E-05	3.1842E+03	5.3149E+03	1.4111E+07	2.1307E+03	17.64
2007	5.5493E-04	2.6441E-04	3.2293E-05	2.6869E-05	2.9859E+03	4.6019E+03	1.6298E+07	1.6160E+03	14.11
2008	5.3683E-04	2.8308E-04	3.4681E-05	3.0975E-05	2.7934E+03	4.5965E+03	1.6317E+07	1.8031E+03	16.83
2009	5.0461E-04	3.0213E-04	3.3457E-05	3.6487E-05	3.5155E+03	5.0540E+03	1.4840E+07	1.5384E+03	16.37
2010	5.5762E-04	2.5383E-04	3.1768E-05	2.4539E-05	3.3901E+03	4.9965E+03	1.5010E+07	1.6064E+03	15.80
2011	5.9494E-04	2.5261E-04	3.3503E-05	2.7296E-05	2.8398E+03	6.1123E+03	1.2270E+07	3.2725E+03	24.22
2012	5.2740E-04	2.5046E-04	3.3616E-05	3.2801E-05	3.2774E+03	4.7097E+03	1.5924E+07	1.4324E+03	15.97

[1] TSS values are upper and middle estuary values.

Table S2. Annual loading of total nitrogen estimated by Chesapeake Bay Program[1]

Year	River Input	Wastewater downstream of RIM sites	Nonpoint downstream of RIM Sites	Atmospheric Deposition to Tidal Waters	Rounded Total	Rounded Total
	(lbs/yr)	(lbs/yr)	(lbs/yr)	(lbs/yr)	(lbs/yr)	($x10^6$ lbs/yr)
1990	194,710,000	65,250,538	54,303,673	24,053,085	338,000,000	338
1991	232,127,000	61,492,800	66,503,388	22,376,997	383,000,000	383
1992	145,359,000	61,258,087	39,708,948	22,420,499	269,000,000	269
1993	285,883,000	60,860,354	83,475,516	23,759,374	454,000,000	454
1994	293,329,000	59,530,714	85,571,105	23,587,356	462,000,000	462
1995	144,851,000	56,935,341	39,387,323	21,926,797	263,000,000	263
1996	323,326,000	55,572,472	94,546,778	24,333,863	498,000,000	498
1997	228,491,000	49,656,366	66,094,985	21,667,985	366,000,000	366
1998	273,387,000	46,767,877	79,251,640	21,657,428	421,000,000	421
1999	96,486,000	47,592,957	24,514,417	21,995,494	191,000,000	191
2000	150,766,000	44,983,912	40,687,529	21,955,406	258,000,000	258
2001	110,303,000	42,257,661	28,262,071	20,997,341	202,000,000	202
2002	98,754,800	41,557,086	24,421,933	21,249,467	186,000,000	186
2003	305,150,000	41,908,124	86,863,101	23,598,420	458,000,000	458
2004	386,593,000	40,496,815	113,418,519	21,213,508	562,000,000	562
2005	246,642,000	38,414,945	71,909,264	22,412,413	379,000,000	379
2006	203,935,000	36,297,307	57,984,911	21,541,169	320,000,000	320
2007	192,309,000	36,254,288	54,388,691	21,428,713	304,000,000	304
2008	179,332,000	35,742,646	46,686,707	21,316,256	283,000,000	283
2009	136,162,000	35,281,386	37,179,727	19,368,128	228,000,000	228
2010	192,801,000	35,774,340	56,627,445	17,420,000	303,000,000	303
2011	351,520,000	28,704,423	107,259,653	17,246,460	505,000,000	505
2012	185,028,000	26,919,850	54,424,242	17,070,000	283,000,000	283

[1] https://www.chesapeakeprogress.com/clean-water/water-quality (*Worksheet Last Updated: 10/9/2018 by Qian Zhang qzhang@chesapeakebay.net*)

Table S3. Annual loading of total phosphorus estimated by Chesapeake Bay Program[1]

Water Year (WY)	**River Input**	**Tidal Wastewater**	**Tidal Nonpoint**	**Rounded Total**	**Rounded Total**
	(lbs/yr)	**(lbs/yr)**	**(lbs/yr)**	**(lbs/yr)**	**(x10^6 lbs/yr)**
1990	9,533,000	3,645,610	2,419,879	15,600,000	15.6
1991	12,227,900	3,422,597	3,375,455	19,000,000	19.0
1992	6,488,910	3,021,830	1,273,836	10,800,000	10.8
1993	17,827,300	2,779,195	5,299,041	25,900,000	25.9
1994	17,427,400	2,956,466	5,073,161	25,500,000	25.5
1995	7,155,280	2,728,646	1,559,240	11,400,000	11.4
1996	27,428,600	2,717,077	8,482,267	38,600,000	38.6
1997	13,312,000	2,445,210	3,607,271	19,400,000	19.4
1998	19,952,400	2,295,891	5,831,683	28,100,000	28.1
1999	4,075,000	2,335,701	505,215	6,920,000	6.9
2000	7,062,400	2,373,854	1,468,899	10,900,000	10.9
2001	5,060,400	2,256,226	829,952	8,150,000	8.2
2002	4,063,820	2,309,376	481,009	6,850,000	6.9
2003	26,355,700	2,366,060	7,914,226	36,600,000	36.6
2004	27,507,400	2,274,423	8,383,582	38,200,000	38.2
2005	15,193,800	2,359,635	4,375,303	21,900,000	21.9
2006	11,831,800	2,257,171	3,265,505	17,400,000	17.4
2007	11,241,800	2,205,275	3,066,870	16,500,000	16.5
2008	9,427,200	1,964,709	2,502,641	13,900,000	13.9
2009	6,207,400	1,941,706	1,371,204	9,520,000	9.5
2010	14,525,300	1,843,223	4,266,569	20,600,000	20.6
2011	45,013,600	1,447,660	14,404,809	60,900,000	60.9
2012	10,443,400	1,416,785	3,032,654	14,900,000	14.9

[1] https://www.chesapeakeprogress.com/clean-water/water-quality (*Worksheet Last Updated: 10/9/2018 by Qian Zhang* qzhang@chesapeakebay.net)

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