Chesapeake Bay Hypoxic Volume Forecasts

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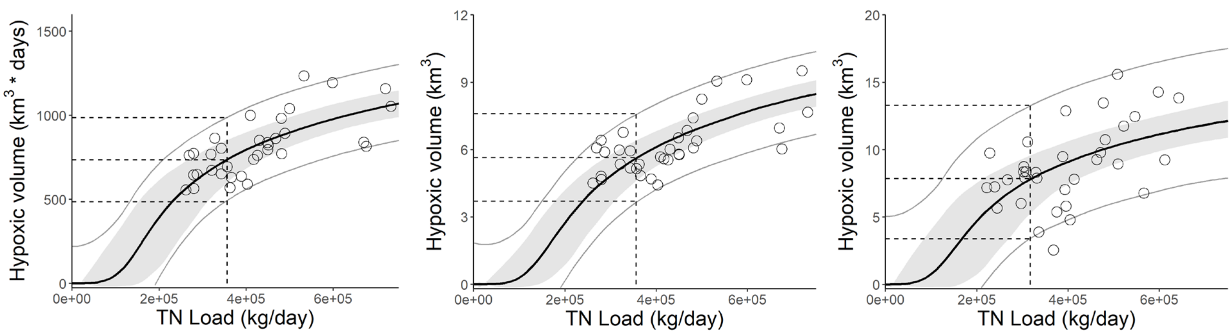
June 7, 2020

This year we transitioned research forecasts developed at the University of Michigan to operational forecasts by the Chesapeake Bay Program. We are pleased to move our research model into operations.

The 2020 Forecast - Given the average January-May 2020 total nitrogen load of 356,020 kg/day, the forecasts are 7.9 km^3 (95% prediction interval: 3.4-13.3) for the July average, 5.7 km^3 (3.7-7.6) for the summer average, and 734 km^3-days (485-985) for the total annual hypoxia. All three are close to their long-term averages.



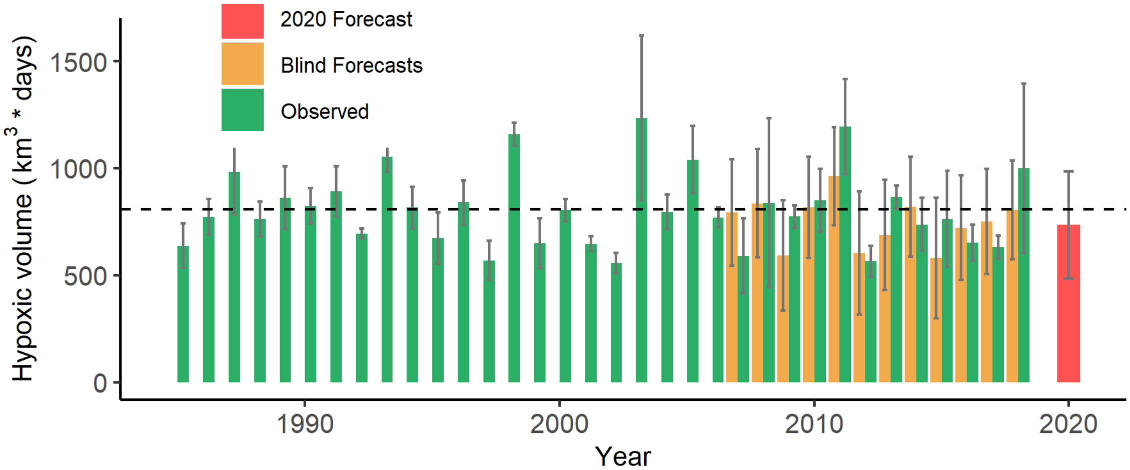
Forecasting relationship of total nitrogen vs. hypoxic volume (left: total annual HV, center: summer average HV, right: July average HV). Solid black curves are response curves calibrated to three sets of observations over 1985-2018 (means of the three sets of observations shown as circles). Shaded gray areas are 95% confidence intervals and solid gray curves are 95% prediction intervals. The vertical line represents the 2020 Jan-May TN load of 356,020 kg/day and the horizontal lines show the forecast hypoxic volume and prediction intervals associated with this load.

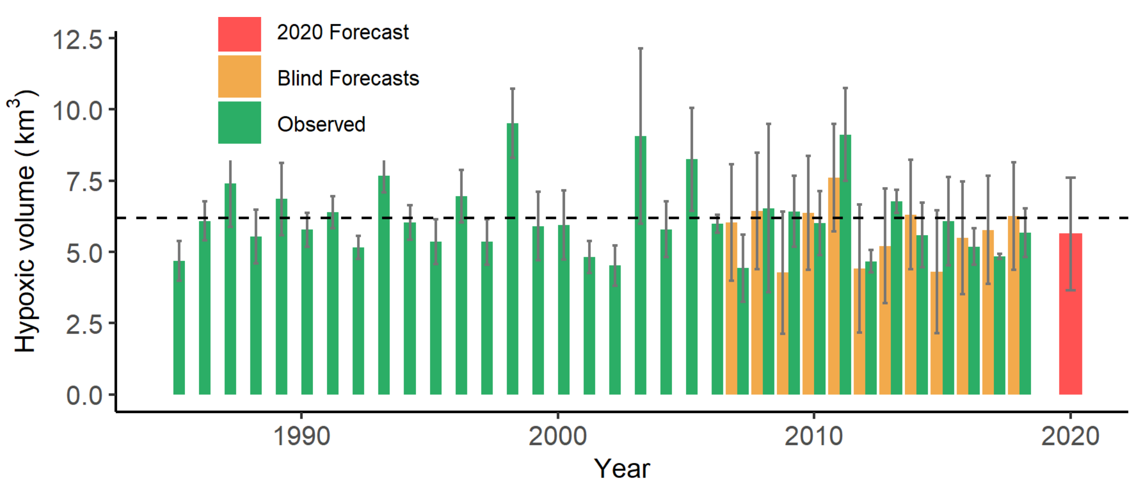
Model Update and Transition – Until this year, the model relied on Susquehanna River total nitrogen (TN) load as a proxy for the Bay's entire load to predict average July hypoxic volume (HV). Updates between 2007 and 2019 were based primarily on model recalibrations. The 2007 and 2008 model was calibrated to 1950-2003 data from Hagy (2002), and after that to HV from the Chesapeake Bay Program (CBP). The 2010-2014 model was calibrated to rolling 3-year windows (Evans and Scavia 2011), and the 2015–2019 models were calibrated to the full 1985-2017 data set and updated nitrogen loads from the USGS.

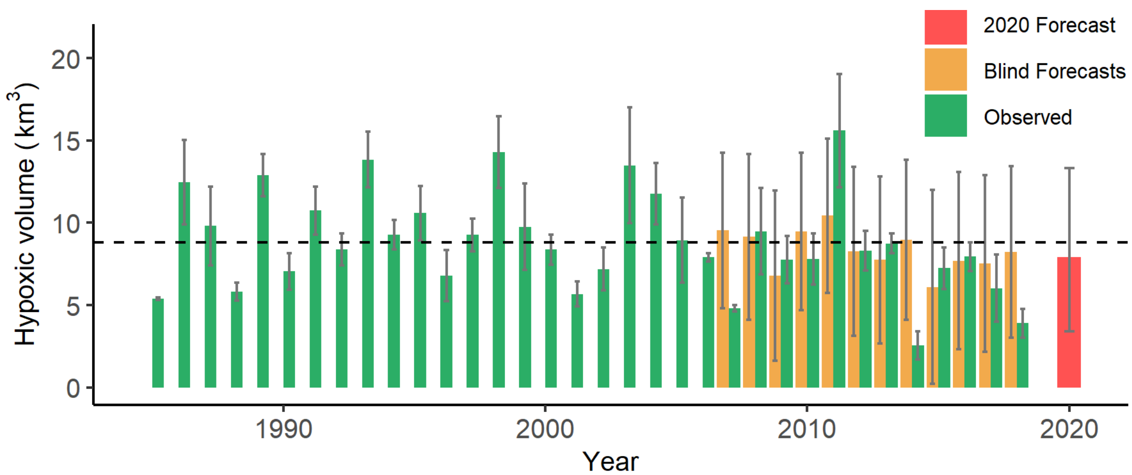
During the 2020 transition, the model was calibrated to a broader set of more relevant loads and HV estimates (Scavia et al. in review). Using loads from all of the primary tributaries, as well as point sources downstream from the tributary monitoring sites, the new forecasts include summer average and total annual HV, in addition to the July average. Summer average HV reduces the impact of individual storms that can disrupt individual cruise data, and total annual HV is a strong integrator of the full impact of the load.

Forecast Track Record – Annual forecasts provided each spring since 2007 have been shown to be rather robust (Testa et al. 2017). Between 2007 and 2018, observed HV fell within the forecast credible intervals in 8 of the 12 years with the under-prediction in 2011 and over-prediction in 2008 just outside the intervals. The substantial over-predictions in 2007 and 2014 were likely because storms like Hurricane Arthur disrupted stratification and temporarily reduced July HV. To circumvent this in the future, we have included summer average and total annual HV beginning with this year's forecast.

To establish a comparable track record for the new model, a series of blind forecasts were made for the same time period. For each year, the model was calibrated using data up to the preceding year and then used to forecast that year's HV.

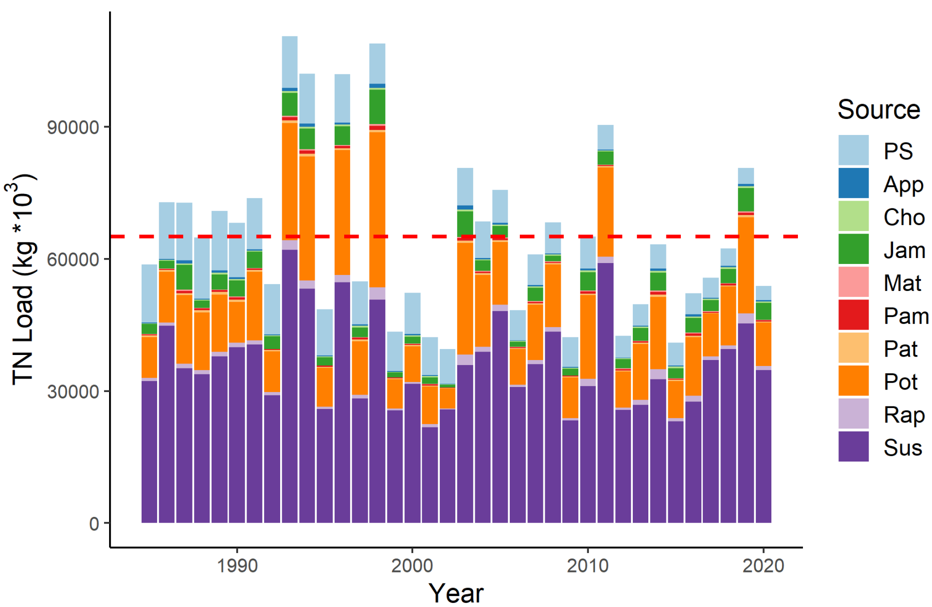






Observed total annual (top), summer average (center) and july average (bottom) hypoxic volume for the period of record. Green bars represent the observed HV (+/- 95% confidence interval), yellow represent blind forecasts (+/- 95% predition error). The horizontal line is the long-term average. The red bar is this year's forecast.

Nitrogen Loads – The nitrogen load, one of the key drivers of hypoxia in the Bay, increased significantly since the 1950s and remains relatively contant but highly variable from year to year. The plot below shows the Jan-May TN loads from primary tributaries and downstream point sources used to drive the model.



The Jan-May TN load (kg/day) including point sources downstream from the tributary monitoring stations (PS), the Susquehanna (Sus), Rappahannock (Rap), Potomac (Pot), Patuxent (Pat), Pamunkey (Pam), Mattaponi (Mat), Appomattox (App), James (Jam) and Choptank (Cho). The horizontal red dashed line indicates the long-term average Jan-May TN load.

The Model - The model is an adaptation of the Streeter-Phelps model that simulates dissolved oxygen (DO) depletion in rivers downstream from a point source of organic matter (Streeter and Phelps 1925). It has been applied extensively to rivers and estuaries (Chapra 1997), as well as to the northern Gulf of Mexico (Scavia et al. 2003, 2004, 2006, 2017, 2019) and the Chesapeake Bay (Scavia et al. 2006, Liu et al. 2011, Evans and Scavia 2010).

The model simulates subpycnocline DO concentration profiles along the main stem of the Chesapeake Bay via subpycnocline net advection, organic matter decomposition and oxygen consumption, and oxygen flux from the surface layer. Assuming a correspondence between the measured extent of summer hypoxia and that which would be achieved at steady state, the steady state solution to the model is:

$$\mathrm{DO} = \mathrm{DO_s} - \frac{k_\mathrm{d}\mathrm{BOD_u}F}{k_\mathrm{r} - k_\mathrm{d}}\left(\mathrm{e}^{-k_\mathrm{d}\frac{x}{v}} - \mathrm{e}^{-k_\mathrm{r}\frac{x}{v}}\right) - D_\mathrm{i}\mathrm{e}^{-k_\mathrm{r}\frac{x}{v}}$$

where DO = dissolved oxygen (mg/l), DO_s = oxygen saturation (mg/l), k_d = organic matter decay coefficient (1/day), k_r = reaeration coefficient (1/day), BOD_u = initial organic matter (mg/l), x = upstream distance (km), F = fraction of organic matter sinking below the pycnocline (unitless), D_i = initial oxygen deficit (mg l/), and v = net advection (km/day). While in the original Streeter-Phelps formulation v represents river advection, here it is a parameterization of the combined effects of horizontal transport and all ecological processes resulting in subsequent settling of organic matter from the surface. Therefore, it is a bulk parameter with no simple physical analog.

Nitrogen load is used as a surrogate for organic matter deposited below the pycnocline at the model origin (220 km down bay from the Susquehanna River mouth) with model distance following the up-estuary flow of bottom water. Simulated HV in year i (V_i) is calculated from the overall length (L_i) of the DO profile with concentrations less than 2 mg/l using the following empirical relationship derived from Chesapeake Bay measurements (Scavia et al. 2006):

$$V_i = 0.00391 * L_i^2$$

Other assumptions of the model include: transport results from advection rather than longitudinal dispersion, subpycnocline oxygen consumption can be modeled as a first-order process proportional to organic matter concentration, oxygen flux across the pycnocline can be modeled as a first-order process proportional to the difference between surface and bottom layer oxygen concentrations, and subpycnocline organic matter oxygen demand is proportional to TN load. Tests of these assumptions, as well as calibration to mid-July subpycnocline oxygen concentration profiles and HVs from 1950 to 2003, have been described elsewhere (Scavia et al. 2006).

Bayesian Inference – The original model (Scavia et al. 2006) was a Monte Carlo implementation used to accommodate potential variation in the bulk parameter, v. It was subsequently reformulated within a Bayesian framework (Liu et al. 2011, Evans and Scavia 2010) to account for uncertainty in additional parameters. In the present version, the model was calibrated using Bayesian fitting conducted with the software WinBUGS version 1.4.3 (Lunn et al. 2000, Gill 2002, Gelman and Hill 2007) interfaced with R version 3.5.2 (R Core Team 2018) through the package R2WinBUGS version 2.1-21 (Sturtz et al. 2005). All model parameters were kept constant across years and given the same priors used in the most recent model applications (Evans and Scavia 2010; Liu et al. 2011). We ran four Markov Chain Monte Carlo chains with 5,000 iterations each and checked convergence by ensuring that $\hat{R} < 1.1$ for all model parameters. We assessed model performance using the coefficient of determination (R^2), Nash-

Sutcliffe Efficiency (NSE), root mean square error (RMSE), mean absolute error (MAE), and residual standard deviation (RSTDE). Details are in Scavia et al. (in review).

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