7 Oysters

Introduction

Bivalve filter feeders were introduced to the Bay model as part of the Tributary Refinements phase (Cerco et al. 2002). The initial representation included two freshwater species, *Corbicula flumenea* and *Rangia cuneata*, and one saltwater species, *Macoma balthica*. Subsequently, native oysters, *Crassostrea virginica*, were substituted for *Macoma* in order to investigate the potential impact of a ten-fold increase in native oyster population (Cerco and Noel 2007). Oysters were included in the 2010 model version but received limited attention. Their activity was not explicitly incorporated in the 2010 TMDL. Oysters are the subject of renewed attention due to increases in the natural population in sanctuaries and tremendous growth of the aquaculture industry. Nutrient removal credits associated with aquaculture will be included in the Mid-Point Reassessment. Renewed management attention demands a corresponding renewal of the oyster module in the Chesapeake Bay model.

The revised oyster model considers three populations:

- Natural populations on reefs and subject to harvest.
- Natural populations in sanctuaries and not subject to harvest.
- Aquaculture operations.

Application of the model to each population requires resolution of the following issues:

- Location.
- Biomass.
- Model parameterization.

Representation of the freshwater bivalves is unchanged from the previous model version (Cerco and Noel 2010).

Model Basics

The fundamental mass-balance equation for the filter feeders is:

$$\frac{dO}{dt} = \propto \cdot Fr \cdot POC \cdot IF \cdot (1 - RF) \cdot O - BM \cdot O - \beta \cdot O - H \cdot O \qquad (1)$$

in which:

O = oyster density (g C m^{-2})

α = assimilation efficiency ($0 < \alpha < 1$)
Fr = filtration rate ($m^3\ g^{-1}\ C\ d^{-1}$)
POC = particulate organic carbon ($g\ m^{-3}$)
IF = ingestion fraction ($0 < IF < 1$)
RF = respiration fraction ($0 < RF < 1$)
BM = basal metabolism (d^{-1})
β = mortality (d^{-1})
H = harvest rate (d^{-1})

Parameters in the governing equation are largely as described by Cerco and Noel (2007).

Oyster reefs occupy small fractions of model computational cells which average 1 km x 1 km in extent. The foraging arena concept was introduced into the model (Cerco and Noel 2010) to represent the limited encounters between predators and prey induced by the small fraction of each computational cell occupied by reefs. We found, however, that the computed biomass of oysters, in g C, was excessive when the computed density, in $g\ C\ m^{-2}$, was multiplied by the cell area. We also found that the potential impact of oysters on prey was exaggerated despite the foraging arena. Consequently, the concept of "coverage" was introduced into this model version. Coverage is the fraction of cell area occupied by oyster reefs. Biomass is computed as the product of density, cell area, and fraction of cell covered by reefs. Corrections for coverage are also introduced into the mass balance equations for mass transfers between oysters and their surroundings.

Modifications for Aquaculture

Oyster density in each cell, computed by Equation 1, varies spatially and temporally depending on local conditions. Aquaculture operations, including year-round planting and harvesting, tend to reduce the intra-annual and inter-annual oscillations which occur in natural oyster beds. The spatial distribution of oyster biomass depends on the location of aquaculture operations. For water quality management purposes, managers wish to explore the impacts of varying levels of aquaculture activity. These effects and desires lead to a model representation in which oyster density in each cell is a specified constant value. Setting dO/dt = 0 in Equation 1 leads to the representation:

$$IF = \frac{BM+\beta+H}{\alpha \cdot Fr \cdot POC \cdot (1-RF)} \qquad (2)$$

The ingestion fraction becomes a variable rather than a parameter as in Equation 1. Employment of the variable ingestion fraction in the balance of the model formulations results in a constant oyster density which is specified at model initiation.

In the event the rate of biomass loss, represented in the numerator on the RHS of Equation 1, exceeds food intake, represented in the denominator, the computed ingestion fraction will exceed unity. This situation is physically impossible although the model will operate under these conditions. Consistent computation of an ingestion fraction greater than unity indicates that oysters cannot persist at the specified density under modelled conditions. Either sufficient food resources are unavailable or losses due to respiration, mortality and harvest exceed sustainable levels.

Location

Natural Population

Locations of more than 8000 oyster bars were determined as part of a 2008 study (MDNR 2008) of oyster restoration alternatives. Bar locations were mapped to the model grid (Figure 1) and consolidated by cell. The total bar area in each cell was employed to compute coverage (See Model Basics section). Oyster bars occurred in 2068 of the 11064 model surface cells. Coverage for the 2068 cells ranged from less than 0.01% to 100%. The median coverage was 5% and was less than 10% for the vast majority of cells with oyster bars.

Sanctuaries

Locations of oyster sanctuaries in Maryland were obtained by the project sponsor and mapped to the model grid. Considerable overlap occurred between the location of reefs determined in 2008 and the present location of sanctuaries. In the event a natural bar and a sanctuary were coincident, we assumed the bar is presently a sanctuary.

Aquaculture

Location of aquaculture operations presented considerable problems. Although this information is in the hands of various state agencies, they are not free to release what is considered proprietary information. For the state of Maryland, we were provided with the aquaculture harvest totals by county for the years 2014 – 2016 (Reichart-Nguyen 2016). We created a map of potential model aquaculture cells within these counties by assuming aquaculture is restricted to water less than 12 feet deep and salinity greater than 7 ppt (Figure 2). The depth constraint was based on assumptions regarding accessibility. The salinity constraint was determined by Cerco and Noel (2007) as the minimum required for a healthy natural population.

A GIS file was available which mapped private lease areas in Virginia. This map was superimposed on the model grid to indicate cells which contain leases (Figure 3). Potential aquaculture cells were then limited to lease areas less than 12 feet deep and greater than 7 ppt salinity.

As noted in the Model Basics section, it is possible to assign aquaculture to a cell which cannot support the specified level of activity. We minimized this possibility through a “self-locating” process. An exploratory model run was conducted in which oysters were assigned to all potential aquaculture cells. They were modelled as a natural population which was allowed to thrive or perish according to ambient conditions. We restricted aquaculture cells to those which supported a density of 10 mg C m^{-2} (Figure 4).

Biomass

Natural Population and Sanctuaries

The primary data source for the population on oyster bars is the Chesapeake Bay Oyster Population Estimate (CBOPE), a web site maintained by the Virginia Institute of Marine Science (VIMS 2017). The CBOPE was conducted to monitor progress towards a ten-fold increase in Chesapeake Bay oyster population called for in the Chesapeake 2000 Agreement. The site reports various categories of standing stock and harvest for Virginia (1994 – 2008) and Maryland (1994 – 2002). The state totals are reported for various basins within each state in various years. Major population categories include:

- Fishery-Independent Data – These data were collected during annual patent tong surveys in Virginia and annual dredge surveys in Maryland.
- Fishery-Dependent Data - Public/Commercial – Based on annual oyster landings reported to Virginia Marine Resources Commission (VMRC) and Maryland Department of Natural Resources (MDNR).
- Fishery-Dependent Data - Private Fishery – Based on reports by private leaseholders to VMRC and MDNR.

The total population in each state (Table 1) was considered to be the sum of the fishery-independent data plus the amount removed in public and private landings. For Virginia, the private landings were adjusted to remove aquaculture activities from 2005 onwards. The landings, adjusted for aquaculture, were tracked separately (Table 1) to assist in parameter assignment of the harvest rate in Equation 1.

Assignment to Basins

Reporting by basins was sporadic in the CBOPE and the state data could not be reliably split by basin over the reporting period. Based on alternative data sources, 12 basins were defined (Table 2). The Virginia basins were defined to coincide with harvest data provided by the VMRC (Wesson 2016). The Virginia population was split into basins in proportion to the total public harvest taken in each basin. The Maryland basins were defined to coincide with a 1994 - 2006 population estimate (Greenhawk and O'Connell 2007). The Maryland population was split into basins according to the proportions in the estimate.

Aquaculture

The aquaculture biomass was difficult to estimate due to the proprietary nature of the data on operations. In addition, necessary information was obtained through personal communication and sources were not always in agreement. The original source for Virginia aquaculture biomass was a summary of surveys conducted by Virginia Institute of Marine Science (Hudson and Murray 2016). The surveys reflect the number of oysters sold through Virginia aquaculture operations, 2005 - 2015. The surveys risk under-reporting the sales due to lack of response by some operators. Alternatively, the surveys risk over-estimating the sales since operations on the Atlantic side of the DelMarVa peninsula are included. Nevertheless, the report is the primary citable source for Virginia aquaculture data.

Number of oysters sold was converted to dry tissue weight using the factor for market-size oysters 2.1 g DW/oyster (Cerco and Noel 2007). Conversion of the harvest to standing stock required consideration of aquaculture practices and grow-out period from seed to harvest. Aquaculture practices can be broadly divided into “cage culture” and “bottom culture.” We were advised that roughly 80% of aquaculture in Virginia is conducted in cages and 20% is conducted on bottom. We were further advised (Parker 2017) that the grow-out period for cage culture is two years while the grow-out period for bottom culture is three years. Assuming linear growth and continuous planting and harvest, the standing stock of oysters in cages is 1.5 times the annual harvest. The standing stock of oysters on bottom is twice the annual harvest. Combining these factors indicates the biomass of aquaculture oysters in Virginia is 1.6 times the annual harvest (Table 3).

Data for Maryland aquaculture originated with the MDNR and was provided through the Oyster Recovery Partnership (Reichert-Nguyen 2016). The original data consisted of bushels harvested for the years 2014 – 2016. Statewide totals were provided as well as data for some counties. Bushels were converted to number of oysters using the factor 300 oysters/bushel provided along with the data. Number of oysters was subsequently converted to dry tissue weight using the factor for market-size oysters 2.1 g DW/oyster (Cerco and Noel 2007). We were advised that in Maryland roughly 80% of aquaculture is conducted on the bottom while 20% is conducted in cages. These proportions are the inverse of operations in Virginia. Utilizing the grow-out periods quoted previously, the Maryland aquaculture standing stock is 1.9 times the annual harvest (Table 3).

Assignment to Basins

Data on private landings for major basins in Virginia was provided by the VMRC (Wesson 2016). The Virginia aquaculture biomass was assigned to basins according to the fraction of the total private landings in each basin (Table 4).

Maryland aquaculture biomass was assigned to counties in proportion to the fraction of the total harvest represented by each county (Table 4). Data was not available for all individual counties, however. Fractions were assigned to these counties according to surface area.

Aquaculture Implementation – Calibration and Scenarios

The Virginia aquaculture biomass was negligible, compared to the reef biomass, through the Bay model calibration and verification years, 1991 - 2000 and 2002 - 2011 (Figure 5). Aquaculture in Maryland was non-existent during these periods. Consequently the aquaculture feature of the oyster model was not implemented in the calibration or verification. Aquaculture was implemented, however, in various Bay model scenarios for 2025 conditions since nutrient removal through aquaculture is under consideration as a Best Management Practice (Cornwell et al. 2016). We were provided with 2025 projections of aquaculture activity by state (Devereux 2017). The projections included number of oysters harvested and nitrogen and phosphorus content of individual oysters. Our model quantifies oysters as carbon so the total nitrogen removed was multiplied by our model carbon-to-nitrogen ratio, 6 g C g^{-1} N, to convert the projected harvest to model units. The aquaculture biomass was obtained from the harvest, as described previously, and distributed to cells capable of supporting aquaculture in each state. The projected harvest and biomass were subsequently converted to dry weight for comparison with previously computed values for the years 2005 – 2016 (Table 3). The 2025 projections are much greater than the most recent data but are consistent with extrapolations from present trends.

In Bay model scenarios, nutrient removal associated with aquaculture harvest is effected by reducing the watershed loads to appropriate regions of the bay. The harvest in the model is specified as zero (Equations 1 and 2) to prevent "double counting" of nutrient removal in both watershed loads and through algorithms in the oyster model. The oyster functions of particle filtration and nutrient recycling to the water and sediments remain in operation. Consequently, aquaculture in scenarios provides potential benefits in water clarity and enhanced nutrient burial and denitrification.

Model Calibration to Reef Population

The fundamental parameters for the oyster model are adapted from the 2005 study of the impact of a ten-fold increase in natural oyster population (Cerco and Noel 2007). The model is calibrated, based on current biomass data, through adjustment of the mortality and harvest parameters (Equation 1). First the harvest is assigned to calculate values representative of data, then the mortality is assigned to obtain representative biomasses. Harvest values range from 1.23×10^{-4} to 6.75×10^{-4} d^{-1} in the months from October through April. Harvest is zero otherwise. The seasonal assignment reflects that harvest from natural reefs is minimal during spawning season. Mortality ranges from 0.025 to 0.05 d^{-1} in the months from June to October. Mortality is zero otherwise. The seasonal assignment reflects the influence of temperature on predators and disease organisms.

The reef biomass data reflect annual surveys (fishery-independent data) combined with annual summaries of oyster landings (fishery-dependent data). These are compared to annual-average biomass computed by the model. Comparison of computations and observations (e.g. Figures 6, 7) indicates the model largely reflects the regional biomasses although intra-annual variations in the observations are not reproduced. The correlation (R^2) between computed annual average biomass in MD basins (Figure 8) and observed biomass is 0.62 and is highly significant ($p < 0.01$). The correlation between computed and observed biomass in VA (Figure 9) is lower, R2 = 0.47, but remains highly significant nonetheless.

Table 1
Reef Biomass and Harvest

Year	VA Biomass (kg DW)	VA Harvest (kg DW)	Harvested Fraction	MD Biomass (kg DW)	MD Harvest (kg DW)	Harvested Fraction
1994	512560	23548	0.046	411614	21614	0.053
1995	511522	7519	0.015	512930	51930	0.101
1996	681933	9923	0.015	561680	70680	0.126
1997	471609	8606	0.018	631470	68470	0.108
1998	581486	20475	0.035	721221	122221	0.169
1999	582623	9615	0.017	736000	147000	0.200
2000	657979	9753	0.015	720555	129555	0.180
2001	698260	13246	0.019	698568	138568	0.198
2002	561166	18215	0.032	184000	40000	0.217
2003	575272	9997	0.017			
2004	734962	33864	0.046			
2005	993351	71780	0.072			
2006	819680	37747	0.046			
2007	651726	29950	0.046			
2008	1039207	28039	0.027			

Table 2
Basin Fractions of Total Reef Biomass

VA Basin	Fraction	MD Basin	Fraction
Chesapeake	0.294	Chester	0.151
James	0.354	Eastern Bay	0.076
York	0.082	Choptank	0.118
Rappahannock	0.262	Little Choptank	0.026
Potomac	0.007	Tangier Sound	0.136
		Potomac	0.074
		Patuxent	0.037
		Chesapeake	0.371

Table 3
Aquaculture Biomass and Harvest

Year	VA Biomass (kg DW)	VA Harvest (kg DW)	MD Biomass (kg DW)	MD Harvest (kg DW)
2005	3398	2124		
2006	11892	7433		
2007	16989	10618		
2008	25483	15927		
2009	32279	20174		
2010	56063	35039		
2011	79847	49904		
2012	93438	58399		
2013	103631	64770		
2014	134211	83882	40905	21529
2015	118921	74326	60612	31901
2016			64550	33974
2025	508032	317520	241315	127008

Table 4
Basin Fractions of Aquaculture Biomass

VA Basin	Fraction	MD Basin	Fraction
Chesapeake	0.293	Anne Arundel	0.022
James	0.360	Calvert	0.030
York	0.128	Dorchester	0.475
Rappahannock	0.050	St. Marys	0.215
Potomac	0.170	Somerset	0.025
		Talbot	0.072
		Wicomico	0.162

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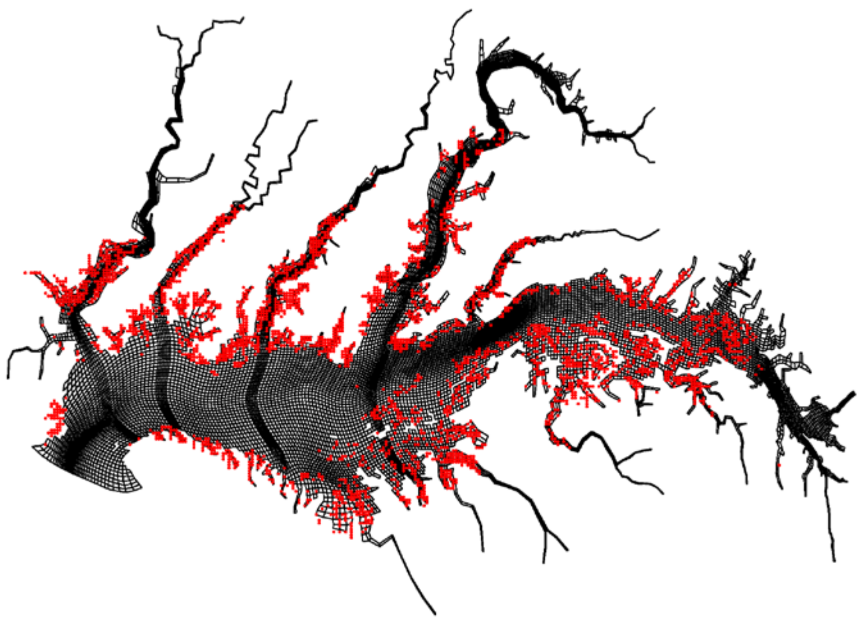

Figure 1. Location of natural oyster bars mapped to model grid.

Figure 2. Potential aquaculture cells in Maryland. Criteria are depth $\leq$ 12 feet and salinity > 7 ppt.

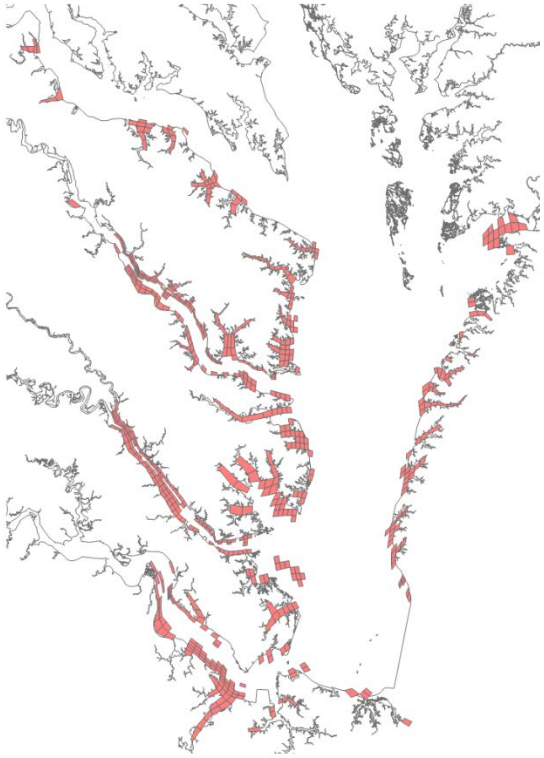

Figure 3. Potential aquaculture cells in Virginia. Cells shown include private lease areas and meet the criteria depth $\leq$ 12 feet and salinity > 7 ppt.

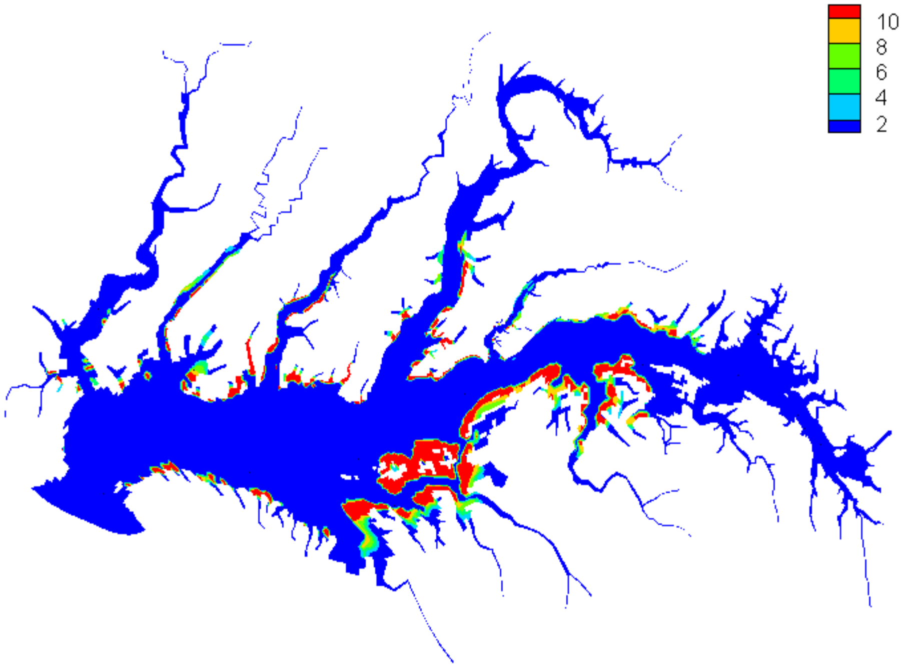

Figure 4. Self-location of aquaculture cells. Aquaculture is restricted to areas capable of supporting a density of 10 mg C m^{-2}.

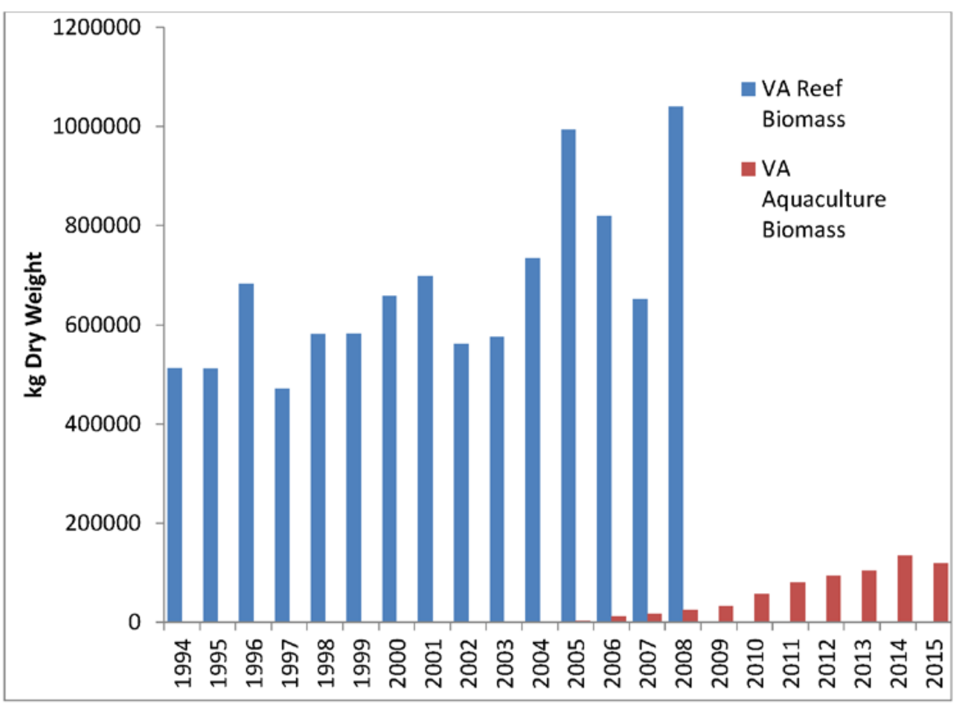

Figure 5. Virginia natural reef and aquaculture biomass 1994 – 2015.

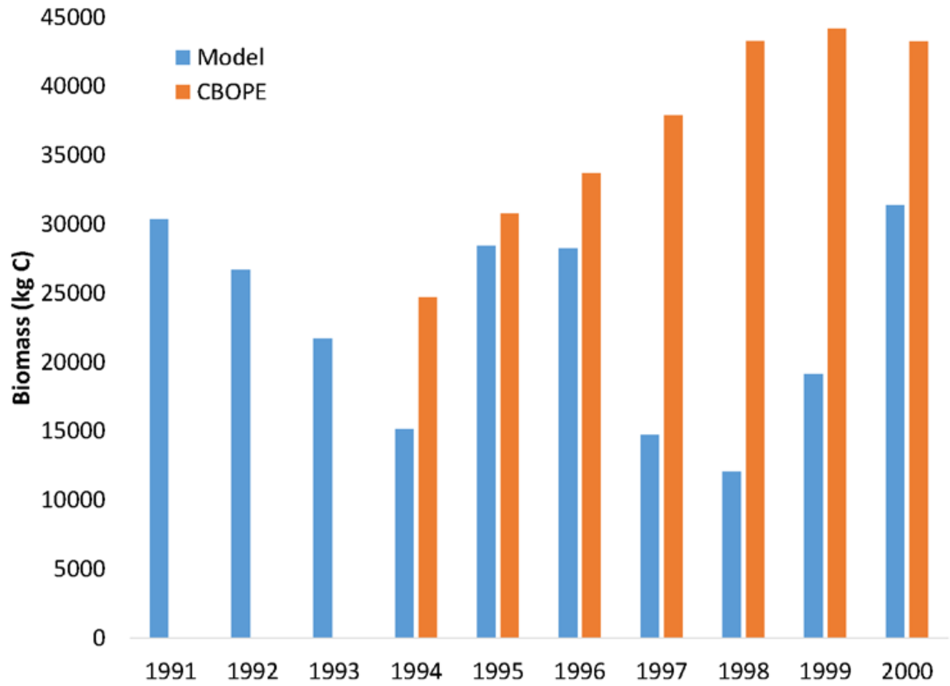

Figure 6. Computed (annual average) and observed oyster biomass in the Choptank River MD.

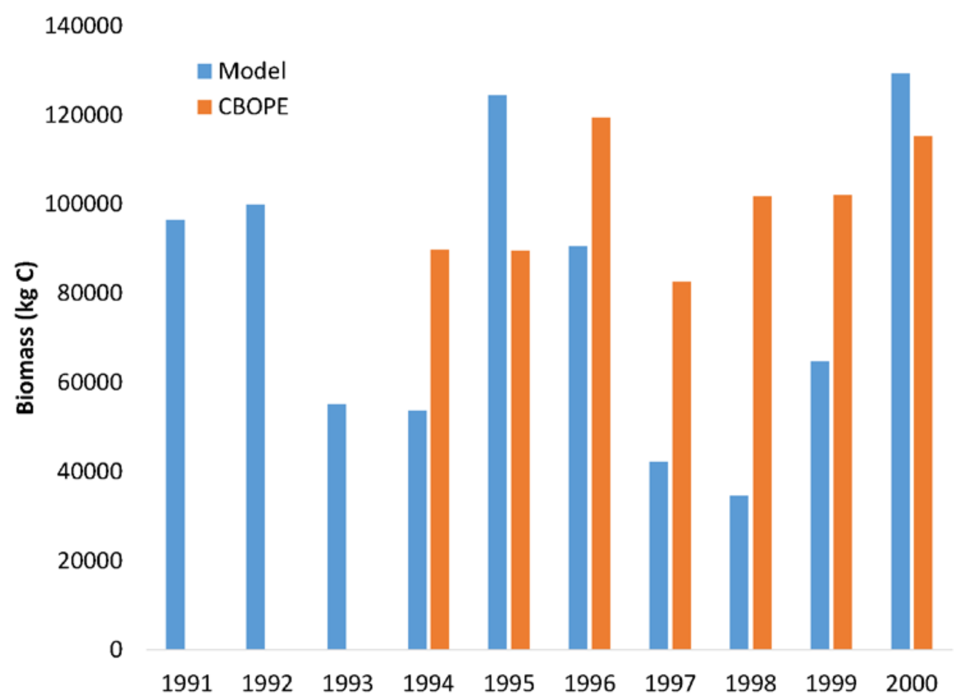

Figure 7. Computed (annual average) and observed oyster biomass in the James River VA.

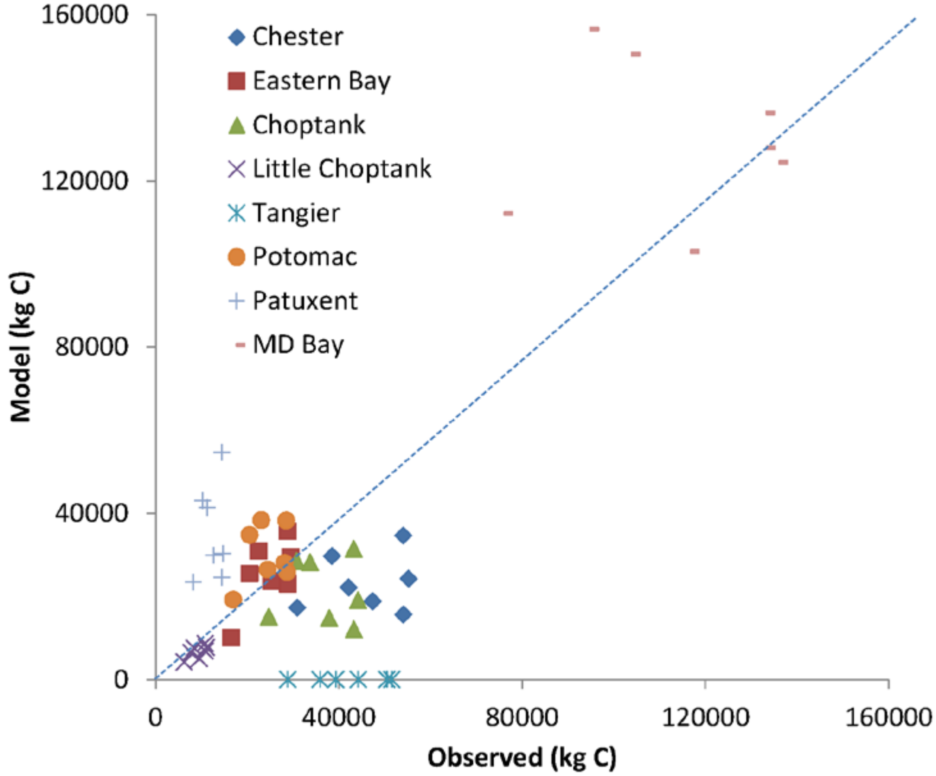

Figure 8. Computed vs. observed biomass for the MD basins designated in Table 2. Computed values are annual averages for the years 1994 – 2000. Observations are derived from the CBOPE.

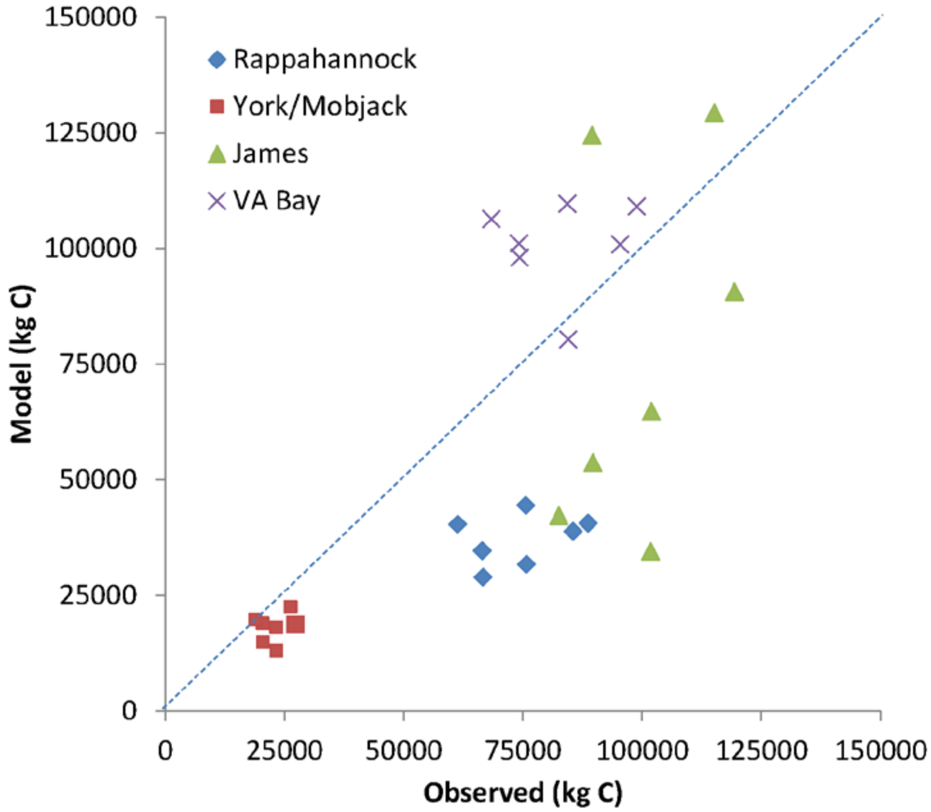

Figure 9. Computed vs. observed biomass for the VA basins designated in Table 2. Computed values are annual averages for the years 1994 – 2000. Observations are derived from the CBOPE.