

Conceptual Processes for Linking Eutrophication and Network Models

By *Dorothy H. Tillman, Carl F. Cerco and Mark R. Noel*

PURPOSE: This three-year study investigates the coupling of eutrophication and network models, applies the results to a specific problem, and recommends a general procedure for future endeavors in this area.

BACKGROUND: In recent years new ideas for nutrient management to control eutrophication in estuarine environments have been under consideration. One popular approach being considered in the Chesapeake Bay Program is called the “top down” approach based on the premise that restoring algal predators, such as oysters and menhaden, will limit excess phytoplankton production and possibly eliminate costly nutrient control programs. The approach is being considered to replace or use in conjunction with the “bottom up” approach of reducing nutrient loads. Guidance for nutrient control programs is frequently obtained from eutrophication models such as CE-QUAL-ICM (Cerco and Cole 1994). Eutrophication models provide temporal representations of carbon, nutrient, and oxygen cycling on a discrete spatial grid. These models usually represent the rate of primary production and/or phytoplankton biomass but extend no further to higher trophic levels. More complex eutrophication models that incorporate higher trophic level organisms (i.e., zooplankton and oysters) have limits and can run into numerical difficulties from multiple interacting partial differential equations needed to describe the food web. No models are presently available to provide guidance for “top down” management.

One approach to modeling the complex materials and/or energy transfers that describe interactions between higher trophic levels such as zooplankton, benthos, and fish is the network model. Network models provide complexity in representing the food web at the cost of simplicity in temporal and spatial resolution. At their basic level, they consider steady-state mass flows with little or no spatial resolution. They are equivalent to ledger sheets in which mass and/or energy flows must balance.

Eutrophication and network models (Figure 1) must be combined to address questions such as:

- How does watershed management affect fisheries harvest in adjacent water bodies?
- How does fisheries management affect water quality problems such as low dissolved oxygen?

No straightforward means of coupling the two modeling approaches is available or apparent.

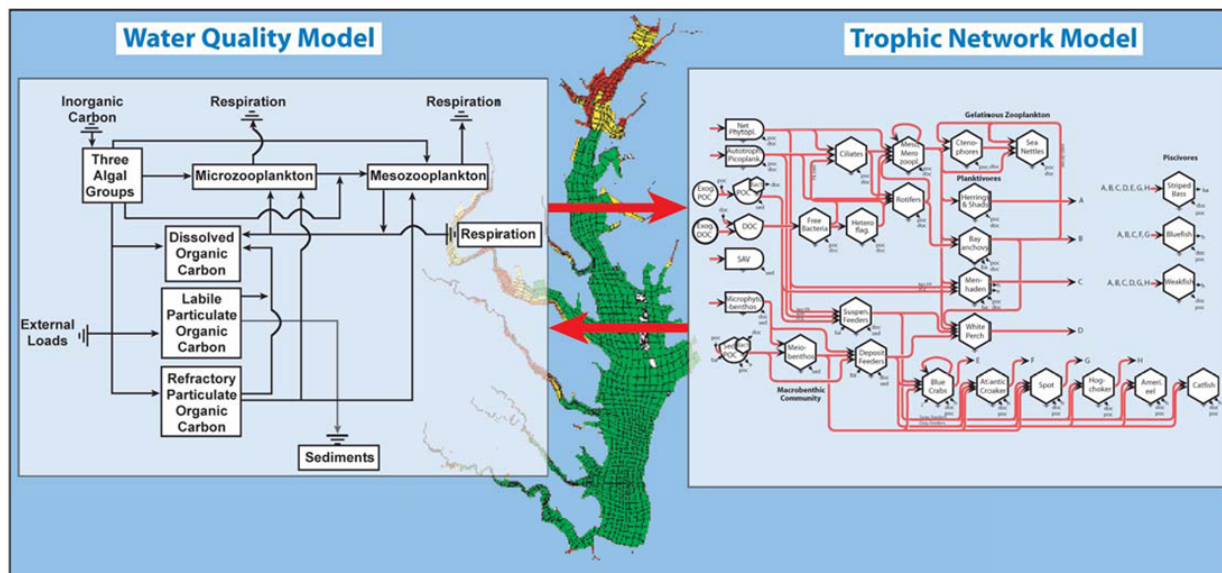


Figure 1. Coupling a eutrophication model with a network model.

MODEL APPROACH: Chesapeake Bay (Figure 2) was chosen as the study site since a fisheries network model (Ecopath with Ecosim, EWE) and a eutrophication model (CE-QUAL-ICM) are already in use and there is strong organizational backing within and outside the Corps. The Chesapeake Bay Environmental Model Package (CBEMP) is a combination of a highly modified HSPF watershed model (Bicknell et al. 1996, Linker et al. 2000), the CH3D-WES hydrodynamic model (Johnson et al. 1991) and the CE-QUAL-ICM eutrophication model (Cercio and Noel 2004). The hydrodynamic and eutrophication components of the CBEMP are Corps codes. The Chesapeake Bay model effort has been supported for 17 years by the EPA Chesapeake Bay Program and by the Baltimore District, USACE.



Figure 2. Chesapeake Bay study site.

EWE is a network model employed in fisheries management (Christensen et al. 2000). It is a freely distributed model supported by the Fisheries Centre, University of British Columbia. Recently, NOAA has funded an effort to apply EWE to fisheries management in the bay. Jim Hagy conducted the early EWE modeling effort on Chesapeake Bay (Hagy 2002). The model is in use at the NOAA Chesapeake Bay Office, at the Virginia Institute of Marine Science, and at the University of Maryland.

CE-QUAL-ICM MODEL DESCRIPTION: CE-QUAL-ICM (ICM) was designed to be a flexible, widely applicable, state-of-the-art eutrophication model. Initial application was to Chesapeake Bay (Cercio and Cole 1994). Since the initial Chesapeake Bay study, the ICM model code has been generalized with minor corrections and model improvements. Subsequent additional applications of ICM included the Delaware Inland Bays (Cercio et al. 1994), Newark Bay (Cercio and Bunch 1997), the San Juan Estuary (Bunch et al. 2000), Florida Bay (Cercio et al. 2000), St. Johns River (Tillman et al. 2004) and Mississippi Sound (Bunch et al. 2003). Each model application employed a different combination of model features and required addition of system-specific capabilities.

General features of the model include:

- Operational in one-, two-, or three-dimensional configurations
- Twenty-four state variables including physical properties
- Sediment-water oxygen and nutrient fluxes may be computed in a predictive sub-model or specified with observed sediment-oxygen demand rates (SOD)
- State variable may be individually activated or deactivated
- Internal averaging of model output over arbitrary intervals
- Computation and reporting of concentrations, mass transport, kinetics transformations, and mass balances
- Debugging aids include ability to activate and deactivate model features, diagnostic output, volumetric and mass balances
- Operates on a variety of computer platforms. Coded in ANSI Standard FORTRAN F77

ICM is limited by not computing the hydrodynamics of the modeled system. Hydrodynamic variables (i.e., flows, diffusion coefficients, and volumes) must be specified externally and read into the model. Hydrodynamics may be specified in binary or ASCII format and are usually obtained from a hydrodynamic model such as the CH3D_WES model (Johnson et al. 1991).

Conservation of Mass Equation. The foundation of CE-QUAL-ICM is the solution to the three-dimensional mass-conservation equation for a control volume. Control volumes correspond to cells on the model grid. CE-QUAL-ICM solves, for each volume and for each state variable, the equation:

$$\frac{\delta V_j C_j}{\delta t} = \sum_{k=1}^n Q_k C_k + \sum_{k=1}^n A_k D_k \frac{\delta C}{\delta x_k} + \sum S_j \quad (1)$$

in which:

- V_j = volume of j^{th} control volume (m^3)
- C_j = concentration in j^{th} control volume (g m^{-3})
- t, x = temporal and spatial coordinates
- n = number of flow faces attached to j^{th} control volume

- Q_k = volumetric flow across flow face k of j^{th} control volume ($\text{m}^3 \text{s}^{-1}$)
- C_k = concentration in flow across face k (g m^{-3})
- A_k = area of flow face k (m^2)
- D_k = diffusion coefficient at flow face k ($\text{m}^2 \text{s}^{-1}$)
- S_j = external loads and kinetic sources and sinks in j^{th} control volume (g s^{-1})

Solving Equation 1 on a digital computer requires discretizing the continuous derivatives and specification of parameter values. The equation is solved explicitly using upwind differencing or the QUICKEST algorithm (Leonard 1979) to represent C_k . The time step, determined by stability requirements, is automatically adjusted. For notational simplicity, the transport terms are dropped in the reporting of kinetics formulations.

STATE VARIABLES: CEQUAL-ICM incorporates 24 state variables in the water column including physical variables, multiple algal groups, and multiple forms of carbon, nitrogen, phosphorus, and silica (Table 1). Two zooplankton groups, microzooplankton and mesozooplankton, are available and can be activated when desired.

Table 1 Water Quality Model State Variables	
Temperature	Salinity
Fixed Solids	Cyanobacteria
Diatoms	Other Phytoplankton
Dissolved Organic Carbon (DOC)	Refractory Particulate Organic Carbon
Labile Particulate Organic Carbon	Nitrate + Nitrite Nitrogen (NO3)
Ammonium (NH4)	Dissolved Organic Nitrogen (DON)
Refractory Particulate Organic Nitrogen	Labile Particulate Organic Nitrogen
Total Phosphate (TP)	Dissolved Organic Phosphorus (DOP)
Refractory Particulate Organic Phosphorus	Labile Particulate Organic Phosphorus
Chemical Oxygen Demand (COD)	Dissolved Oxygen (DO)
Dissolved Silica	Particulate Biogenic Silica
Zooplankton 1	Zooplankton 2

ECOPATH MODEL DESCRIPTION: The governing equations of Ecopath originate from Christensen et al. (2004) but are no longer assumed to be steady state. Variable estimations are based on mass balance over an arbitrary period, usually a year, but can also be over growing seasons. The system is assumed to be a zero dimensioned, well-mixed system. Two main equations are implemented in Ecopath: 1) one to describe the production term, and 2) one to balance the energy input and output of the system.

The production term in Ecopath is written as:

$$P_i = Y_i + B_i \cdot M2_i + E_i + BA_i + P_i \cdot (1 - EE_i) \quad (2)$$

This equation can be rearranged as

$$EE_i = \frac{Y_i + E_i + BA_i + M2_i \cdot B_i}{P_i} \quad (3)$$

A set of linear equations representing the different groups in a system are set up and solved for one of the following four parameters of the groups: 1) biomass, 2) production/biomass ratio, 3) consumption/biomass ratio; or ecotrophic efficiency (EE_i). The unknown parameter is usually EE_i since there is no procedure available for field estimation (Christensen et al. 2004). The energy balance of the system is then calculated once the missing parameters have been estimated and mass balance is maintained with the following equation:

$$C_i = P_i - R_i - U_i \quad (4)$$

Terms for both equations are listed in Table 2.

Table 2 Parameters from Main Equations in Ecopath		
Parameter	Definition	Units
B_i	Average biomass	mgC m ⁻²
C_i	Consumption	mgC m ⁻² d ⁻¹
P_i	Production	mgC m ⁻² d ⁻¹
R_i	Respiration	mgC m ⁻² d ⁻¹
U_i	Unassimilation = egestion plus excretion	mgC m ⁻² d ⁻¹
E_i	Net emigration minus immigration or net export of biomass via advection or other process	mgC m ⁻² d ⁻¹
Y_i	Fisheries removals of biomass from ith	mgC m ⁻² d ⁻¹
BA_i	Accumulation or depletion of biomass	mgC m ⁻² d ⁻¹
$M2_i$	Biomass specific mortality rate due to predation	d ⁻¹
EE_i	Ecotrophic efficiency	Unit-less

HOOKS/LINKS BETWEEN ICM AND ECOPATH: Finding common hooks or links between ICM and Ecopath was relatively easy since both model systems are carbon based. Although Ecopath (as well as ICM) could have been investigated for other trophic exchanges, Hagy (2002) chose carbon as the currency for Ecopath on the Chesapeake Bay because more information was available describing carbon interactions than for other elements. Figure 3 presents the different pathways of carbon interactions in ICM and where common links were investigated. Some examples of common links that were identified between the two models included: 1) phytoplankton and benthic algal biomass and production, 2) zooplankton biomass

and production, 3) benthos biomass and production, 4) grazing rates on primary producers, and 5) predation rates on invertebrates.

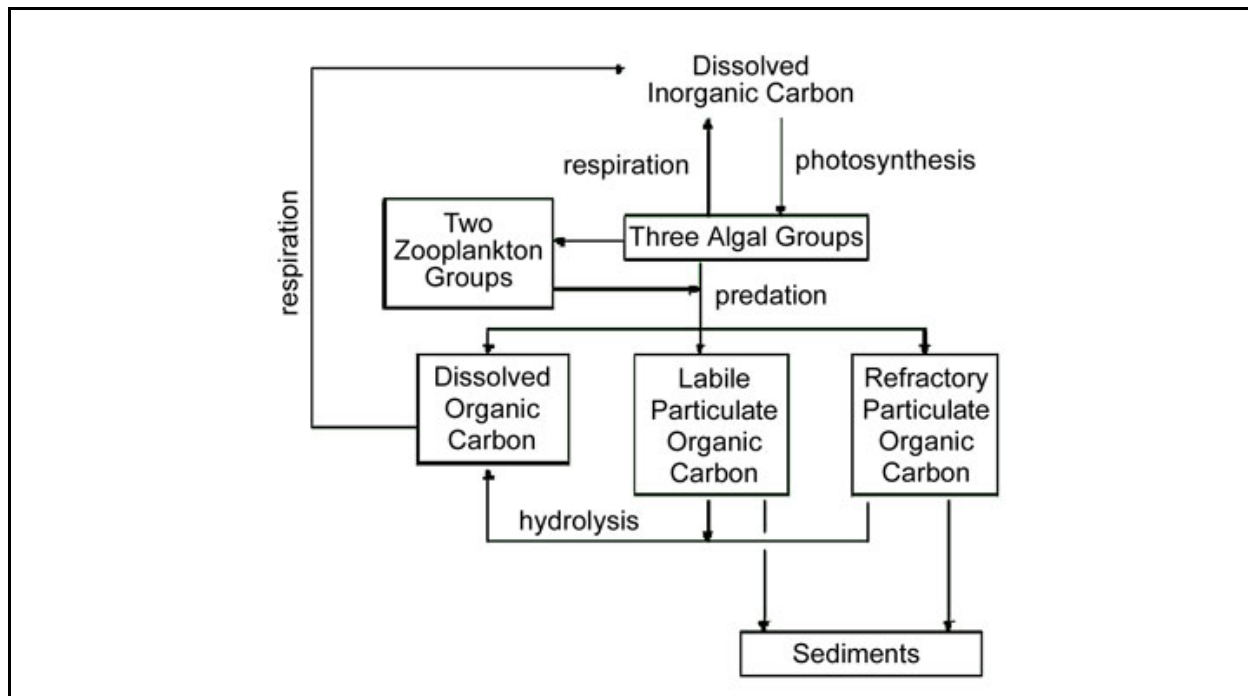


Figure 3. Carbon cycle in CE-QUAL-ICM.

To compare data between the two models, model differences had to be considered and modifications made. For instance, ICM results and process rates had to be spatially and temporally aggregated to the scales of the network model. Temporal results from the ICM were output as an annual average, then averaged over a 10-year study period. Spatially, Hagy had divided the main Chesapeake Bay up into three regions identified as the upper, mid, and lower Chesapeake Bay (Figure 4). Hagy did not include the tributaries in the Ecopath modeling effort, only the main channel of the Chesapeake Bay. Thus, output from ICM was spatially averaged over the cells that represented the three regions Hagy modeled and was also summed over the water column. All modifications made to ICM results were through post-processing procedures and not actual changes to the ICM code.

RESULTS AND DISCUSSION: A “loose” coupling of ICM and Ecopath was performed using manual interface for information exchange between

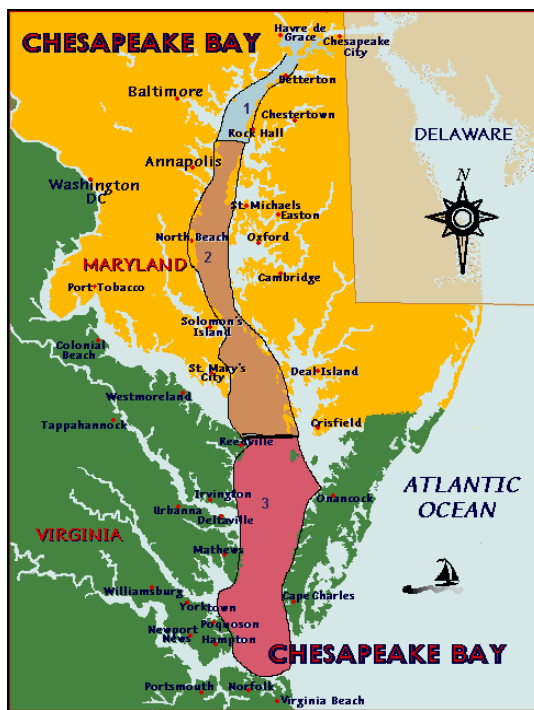


Figure 4. Chesapeake Bay Regions (note light blue = upper; light brown = mid; red = lower)

the models. Table 3 lists the constituents and process rates considered common links between the two models. For each constituent in the carbon cycle and their interactions, comparisons will be presented below for their common links.

Phytoplankton. Values for algal biomass (identified as algal carbon in Table 3) from ICM compare favorably in the upper and mid regions of the Chesapeake Bay and are almost twice as high in the lower region than values used in Ecopath. There are two possible reasons for the discrepancies between the models. Both are related to averaging procedures used in post processing ICM output to get comparable values to Ecopath. First, comparisons were made between values representing different time periods. For instance, ICM values represented a yearly average while Ecopath's values represented a summer period (June 1 to August 31). Initially it was assumed that Ecopath's values represented yearly values; thus, the comparison to yearly averaged ICM values. Second, ICM's areal average of grid cells to get regional values may not exactly match the areas representing Hagy's regions. If correcting the averaging procedures for temporal and spatial data does not improve discrepancies between models, model formulations need to be examined for improvements.

There are noted differences in net and gross primary production between models (Table 3). ICM values are approximately one-third to two-thirds less than the values used in Ecopath in all regions. Hagy (2002) estimated values for Ecopath from literature while values in ICM are calculated based on intensity of light, nutrient availability, and ambient temperature. These model parameters are influenced by the temporal and spatial averaging as discussed above. Differences may also indicate a need to revisit the components of primary productivity in ICM and examine for improvements.

Benthic Phytoplankton. Benthic algal biomass values from ICM (identified as Balgal in Table 3) are less than values from Ecopath in all regions. For benthic algae, again we must look at how comparing values from different time periods affects comparison results, and also consider whether taking an areal average of the ICM values over the entire region instead of just where benthic algae occur (i.e., in shallow water where light penetrates to the bottom) was the right averaging approach.

Other benthic algal common links showing differences were net benthic gross primary production, benthic algae specific respiration rate, benthic algae specific growth rate, and benthic algae specific predation rate (Table 3). For all parameters, ICM values are orders of magnitude less than Ecopath values. It is strongly suspected that differences come from taking an areal average over the entire region more so than comparing different time periods. If discrepancies are not the result of averaging procedures, then model formulation for components of primary productivity need to be examined.

Zooplankton Group 1. Zooplankton group 1 (microzooplankton) biomass from ICM, identified as Zoo 1 in Table 3, are less than half the values of Ecopath in the upper and mid regions of Chesapeake Bay and are comparable to Ecopath's value in the lower region. The reasons for the discrepancies are noted above under phytoplankton. Although there are differences, it is unrealistic to assume the values from each model will be exactly the same.

**Table 3
Common Links Between CE-QUAL-ICM and Ecopath**

Constituent/ Parameter Definition	Model Variable	Units	ICM Upper Chesapeake Bay (MD1) Values	Ecopath Upper Chesapeake Bay (MD1) Values	ICM Mid Chesapeake Bay (MD2) Values	Ecopath Mid Chesapeake Bay (MD2) Values	ICM Lower Chesapeake Bay (VA) Values	Ecopath Lower Chesapeake Bay (VA) Values
Algal carbon	C1(b,4)+C1(b,5)+ C1(b,6)	g C m ⁻²	1.879	1.595	3.999	3.913	4.3424	2.485
Algal net primary production	npp(b)	g C m ⁻² d ⁻¹	0.660	0.908	0.752	2.473	0.688	2.136
Algal gross primary production	gpp(b)	g C m ⁻² d ⁻¹	0.927	1.487	1.087	3.515	1.011	2.956
Balgal	bbm(b)	g C m ⁻²	0.033	0.293	0.219	0.265	0.131	0.293
Benthic net primary production	nppb(b)	g C m ⁻² d ⁻¹	0.0018	0.176	0.029	0.159	0.018	0.234
Zoo 1	C1(b,7)	g C m ⁻²	0.037	0.083	0.085	0.188	0.116	0.124
Zoo 2	C1(B,8)	g C m ⁻²	0.033	0.282	0.121	0.526	0.1543	1.073
DOC	C1(b,9)	g C m ⁻²	13.981	12.504	22.912	28.207	22.787	26.915
POC	C1(b,4)+C1(b,5)+ C1(b,6)+C1(b,7)+ C1(b,8)+C1(b,10) + C1(b,11)	g C m ⁻²	5.483	5.249	8.563	10.324	8.475	8.309
Detrital carbon	C1(b,10)+ C1(b,11)	g C m ⁻²	3.535	5.249	4.356	10.324	3.862	8.309
Deposit feeders	dfeed(b)/1000	g C m ⁻²	0.989	2.368	0.671	1.030	0.811	4.089
Filter feeders	sfeed(b,n)/1000	g C m ⁻²	0.378	27.232	0.823	0.421	0.240	6.962
SAV	patch(b)*sh(b)	g C m ⁻²	0.214	2.086	0.513	1.952	0.622	1.986
Carbon flux (particle)	Pcfws(b)	g C m ⁻² d ⁻¹	-0.719		-0.580		-0.495	
Rate of predation on all algal groups	APR+APR2+APR 3+AB1SZ+AB2SZ +AB3SZ+AB1LZ+ AB2LZ+AB3LZ	gm C m ⁻² d ⁻¹	0.521	0.471	0.611	0.210	0.617	0.485

(Sheet 1 of 4)

Table 3 (Continued)								
Constituent/ Parameter Definition	Model Variable	Units	ICM Upper Chesapeake Bay (MD1) Values	Ecopath Upper Chesapeake Bay (MD1) Values	ICM Mid Chesapeake Bay (MD2) Values	Ecopath Mid Chesapeake Bay (MD2) Values	ICM Lower Chesapeake Bay (VA) Values	Ecopath Lower Chesapeake Bay (VA) Values
Dissolved organic carbon production by all algae	AALGDOC	gm C m ⁻² d ⁻¹	0.0917	0.0606	0.101	0.786	0.091	0.749
Particulate organic carbon production by all algae	AALGPOC	gm C m ⁻² d ⁻¹	0.4086	0.01557	0.404	0.590	0.365	0.187
Respiration of dissolved organic carbon	AMNLDOC	gm C m ⁻² d ⁻¹	0.1267	0.8110	0.205	2.850	0.209	1.90
Microzooplankton specific respiration rate	ABMSZ	d ⁻¹	0.731	1.223	1.169	1.218	1.241	1.160
Mesozooplankton specific respiration rate	ABMLZ	d ⁻¹	0.535	0.121	0.856	0.165	0.894	0.736
Microzooplankton mortality due to low DO	AMSZ	d ⁻¹	0.2857		0.373		0.022	
Predation on microzooplankton by mesozooplankton	APRSZLZ	g C m ⁻² d ⁻¹	0.0000000804	0.09130	0.0000418	0.162	0.00004	0.151
Specific growth rate for microzooplankton	AGSZ	d ⁻¹	0.7013	2.053	1.152	2.031	1.217	1.896
Specific growth rate for mesozooplankton	AGLZ	d ⁻¹	0.5499	0.379	0.967	0.500	1.063	0.250
DOC production by microzooplankton	ADOC SZ	gm C m ⁻² d ⁻¹	-0.0125	0.0734	-0.0294	0.185	-0.040	0.126

(Sheet 2 of 4)

Table 3 (Continued)								
Constituent/ Parameter Definition	Model Variable	Units	ICM Upper Chesapeake Bay (MD1) Values	Ecopath Upper Chesapeake Bay (MD1) Values	ICM Mid Chesapeake Bay (MD2) Values	Ecopath Mid Chesapeake Bay (MD2) Values	ICM Lower Chesapeake Bay (VA) Values	Ecopath Lower Chesapeake Bay (VA) Values
POC production by microzooplankton	ALPOCSZ + ARPOCSZ	gm C m ⁻² d ⁻¹	0.0220	0.0734	0.053	0.185	0.076	0.043
DOC production by mesozooplankton	ADOCLZ	gm C m ⁻² d ⁻¹	0.0056	0.058	0.021	0.186	0.025	0.198
POC production by mesozooplankton	ALPOCLZ + ARPOCLZ	gm C m ⁻² d ⁻¹	0.0108	0.058	0.044	0.186	0.056	0.198
Predation on microzooplankton	APRSZ	gm C m ⁻² d ⁻¹	0.000	0.006	0.000	0.007	0.000	0.019
Predation on mesozooplankton	APRLZ	gm C m ⁻² d ⁻¹	0.001	0.093	0.007	0.107	0.008	0.099
Microzooplankton consumption of algal groups 1+2+3	AB1SZ + AB2SZ + AB3SZ	gm C m ⁻² d ⁻¹	0.026	0.214	0.061	0.477	0.089	0.303
Mesozooplankton consumption of algal groups 1+2+3	AB1LZ + AB2LZ + AB3LZ	gm C m ⁻² d ⁻¹	0.018	0.145	0.068	0.411	0.082	0.406
SAV shoot specific growth rate	APSH	d ⁻¹	0.000015	0.008	0.000018	0.009	0.000018	0.009
Benthic algae specific respiration rate	ABMB	d ⁻¹	0.0000035	0.201	0.000008	0.200	0.000008	0.201
Benthic algae specific growth rate	APB	d ⁻¹	0.00000637	0.601	0.000032	0.600	0.000032	0.799
Benthic algae specific predation rate	APRB	d ⁻¹	0.00000277	0.399	0.000024	0.287	0.000024	0.529

(Sheet 3 of 4)

Table 3 (Concluded)								
Constituent/ Parameter Definition	Model Variable	Units	ICM Upper Chesapeake Bay (MD1) Values	Ecopath Upper Chesapeake Bay (MD1) Values	ICM Mid Chesapeake Bay (MD2) Values	Ecopath Mid Chesapeake Bay (MD2) Values	ICM Lower Chesapeake Bay (VA) Values	Ecopath Lower Chesapeake Bay (VA) Values
Benthic algae specific predation rate	APRB	d ⁻¹	0.00000277	0.399	0.000024	0.287	0.000024	0.529
POC released to sediments by benthic algae	ABAPOC	gm C m ⁻² d ⁻¹	0.002	0.029	0.029	0.082	0.029	0.082

(Sheet 4 of 4)

Other zooplankton group 1 common links showing differences were microzooplankton specific respiration rate, microzooplankton specific growth rate, predation on microzooplankton by mesozooplankton, predation on microzooplankton by others, and microzooplankton consumption of algae groups (Table 3). For most parameters listed, ICM values are about half the value of Ecopath or slightly more than half. It was felt that this was a favorable comparison given the vastly different model frameworks. Parameters such as predation on microzooplankton by mesozooplankton and others and microzooplankton consumption of algae groups were on the order(s) of magnitude different. Like phytoplankton, different rates in ICM are calculated internally and considered factors such as prey availability, temperature, predation by organisms not modeled, low dissolved oxygen, etc. (Cerco and Noel 2004) while values for Ecopath came from literature. This may indicate a need to revisit the components of production for zooplankton as well as address discrepancies caused by the post-processing averaging procedures of the ICM output.

Zooplankton Group 2. Zooplankton group 2 (mesozooplankton) values from ICM, identified as Zoo 2 in Table 3, are almost half or an order of magnitude less than the values used in Ecopath in the mid and upper regions of Chesapeake Bay, respectively, while ICM values in the lower region are slightly greater than Ecopath values. Again, this was felt to be an acceptable comparison. As pointed out for algae and microzooplankton, discrepancies could be from post-processing errors or model formulation of mesozooplankton biomass changes.

Similar to zooplankton group 1, other zooplankton group 2 common links showing differences were mesozooplankton specific respiration rate, mesozooplankton specific growth rate, predation on mesozooplankton by others, and mesozooplankton consumption of algae groups (Table 3). ICM values for mesozooplankton specific respiration rate are about three to four times greater than Ecopath values for all regions. ICM calculates a mesozooplankton specific growth rate two times or more greater than the value used in Ecopath. ICM values of predation on and consumption of mesozooplankton are an order of magnitude less than Ecopath values. Like microzooplankton, averaging schemes or equations calculating mesozooplankton production in ICM may need to be examined and modified as needed.

Dissolved Organic Carbon (DOC). DOC biomass values from ICM (identified as DOC in Table 3) compare favorably with Ecopath values. By regions, ICM values are less than (by approximately 6.0 g C m^{-2}) Ecopath values in all regions except the upper region of the Chesapeake Bay. In this region ICM values are just slightly greater (approximately 1.3 g C m^{-2}). Reasons for the discrepancies have been pointed out above under phytoplankton.

Other DOC common links showing differences were DOC production by algal groups, production by microzooplankton, and production by mesozooplankton (Table 3). ICM values representing production of DOC by all algal groups were calculated to be about the same for all regions. These values were comparable to Ecopath values in the upper region but about seven times less in the mid and lower regions. ICM values for DOC production by microzooplankton are small negative numbers compared to small positive values used in Ecopath. ICM mesozooplankton production values of DOC were an order of magnitude less than values used in Ecopath. From the discussion of phytoplankton and zooplankton group 1, averaging schemes or equations calculating rate values in ICM need to be revisited and modified as needed.

Particulate Organic Carbon (POC). Like DOC, POC biomass values from ICM (identified as POC in Table 3) are comparable to values from Ecopath in all regions except the mid region of the Chesapeake Bay (approximately 1.7 g C m^{-2} difference). Possible causes for the discrepancies between the model results are discussed in the “Phytoplankton” section.

Other POC common links showing differences were POC production by all algal groups, production by microzooplankton, and production by mesozooplankton (Table 3). For POC production by all algal groups, ICM values compare favorably with Ecopath values (approximately +0.2 difference) except in the upper region. ICM values for production of POC by microzooplankton and mesozooplankton are two to three times less than values used in Ecopath. Discrepancies may again be related to the averaging procedures for temporal and spatial ICM results. If the discrepancies are not a result of the averaging scheme, then equations calculating components of production rate in ICM may need to be examined for improvements.

Submerged Aquatic Vegetation (SAV). SAV biomass values from ICM (identified as SAV in Table 3) are two to three times lower than values from Ecopath in all regions. Like benthic algae, the main reason considered for not producing ICM SAV biomass comparable to values used in Ecopath was the way an areal average of the ICM values was calculated over the entire region instead of just where SAVs actually occur (i.e., along shallow shorelines).

Another SAV common link showing differences between model results was SAV specific growth rate (Table 3). The ICM value for each region is orders of magnitude less than Ecopath values. Like benthic algae, this may be the result of taking an areal average over the entire region as discussed above.

Deposit and Filter Feeders. In ICM, deposit and filter feeders are sediment-dwelling organisms. Deposit feeders are benthos organisms that live within the bottom sediments and feed on deposited materials while filter feeders live at the sediment-water interface and filter the overlying water. Their biomass values from ICM (identified as Deposit and Filter Feeders in Table 3) are two to four times less than values used in Ecopath for all regions. As with all other constituents discussed above, discrepancies between the two models are most likely produced by post-processing averaging procedures of ICM output. However, if this proves not to be the case, then model formulations need to be examined for improvements.

SUMMARY AND FUTURE DEVELOPMENTS: This research explores the possibility of coupling a eutrophication model and a fisheries network model. Coupling these two models will provide managers a new perspective on how to improve management strategies and help answer questions such as: 1) how will management of watershed impact fisheries, or 2) can management of fisheries replace/supplement nutrient control? The models being considered are CE-QUAL-ICM and Ecopath with Ecosim (EWE), respectively. CE-QUAL-ICM is a time- and spatially varying multi-dimensional water quality model, and Ecopath is a fisheries network model with no temporal or spatial resolution. Both models have previously been applied to the Chesapeake Bay.

Common links between the two models were identified. However, because the ICM and Ecopath model frameworks were so vastly different, results from ICM were aggregated

temporally and spatially so that they could be compared to values used in Ecopath. Results from comparisons indicate that generally ICM and Ecopath values were similar to each other (e.g., within an order of magnitude or less). It is unreasonable to expect values from both models to be exactly the same since model frameworks are so greatly different. Many of the constituents and rates in ICM are calculated based on environmental conditions while Ecopath values are estimated from literature. Although most values compared reasonably well, some of the rates for SAV and benthic algae were orders of magnitude different. The temporal and spatial averaging of ICM output during post processing possibly caused this. To verify this, post-processing averaging procedures will be revisited to:

1. Check consistency in the temporal averaging interval.
2. Check consistency in spatial averaging of ICM cells to represent Hagy's three regions.
3. Check consistency of spatial averaging of SAV and benthic algae over only part of regions where they occur instead of the entire region.

If differences are not rectified by modifications to the averaging schemes, ICM model formulations for rates will be examined for improvements.

During the next phase of the study, a fundamental process in both models will undergo a major modification (e.g., phytoplankton primary production) once discrepancies between the models have been resolved. This will determine if both models behave similarly. ICM and Ecopath will also be "loosely coupled" to examine effects of different levels of menhaden on the Chesapeake Bay water quality. Information will flow two ways and possibly require many iterative model runs. From this process, management will gain some insight to the "top down" approach to control of eutrophication, and experience will be gained interfacing the two models.

ACKNOWLEDGMENTS: The authors gratefully acknowledge Dr. Jim D. Hagy of the US EPA, NHEERL/Gulf Ecology Division Gulf Breeze, FL, for providing the Ecopath with Ecosim modeling package for the Chesapeake Bay.

POINTS OF CONTACT: This technical note was written by Ms. Dorothy H. Tillman, Dr. Carl F. Cerco, and Mr. Mark R. Noel of the Water Quality and Contaminant Modeling Branch, Environmental Laboratory (EL), Engineer Research and Development Center (ERDC). Additional information can be obtained from the Manager of the System-Wide Water Resources Program (SWWRP), Dr. Steve L. Ashby (601-634-2387, Steven.L.Ashby@erdc.usace.army.mil). This technical note should be cited as:

Tillman, D. H., C. F. Cerco, and M. R. Noel. 2006. *Conceptual processes for linking eutrophication and network models*. ERDC/TN SWWRP-06-9. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

REFERENCES

Bicknell, B., J. Imhoff, J. Kittle, A. Donigian, R. Johanson, and T. Barnwell. 1996. *Hydrologic simulation program - FORTRAN user's manual for release 11*. Athens, GA: United States Environmental Protection Agency Environmental Research Laboratory.

- Bunch, B., C. Cerco, M. Dortch, B. Johnson, and K. Kim. 2000. *Hydrodynamic and water quality model study of San Juan Bay and Estuary*. ERDC TR-00-1, Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Bunch, B. W., M. Channell, W. D. Corson, B. A. Ebersole, L. Lin, D. J. Mark, J. P. McKinney, S. A. Pranger, P. R. Schroeder, S. J. Smith, D. H. Tillman, B. A. Tracy, M. W. Tubman, and T. L. Welp. 2003. *Evaluation of Island and Nearshore Confined Disposal Facility Alternatives, Pascagoula River Harbor Dredged Material Management Plan*. ERDC TR-03-3. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Cerco, C., and B. Bunch. 1997. *Passaic River tunnel diversion model study, Report 5, water quality modeling*. Technical Report HL-96-2. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Cerco, C., B. Bunch, M. Cialone, and H. Wang. 1994. *Hydrodynamic and eutrophication model study of Indian River and Rehoboth Bay, Delaware*. Technical Report EL-94-5. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Cerco, C., B. Bunch, A. Teeter, and M. Dortch. 2000. *Water quality model of Florida Bay*. ERDC/EL TR-00-10. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Cerco, C., and T. Cole. 1994. *Three-dimensional eutrophication model of Chesapeake Bay*. Technical Report EL-94-4. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Cerco, C., and M. Noel. 2004. *The 2002 Chesapeake Bay eutrophication model*. EPA 903-R-04-004. Annapolis, MD: Chesapeake Bay Program Office, U.S. Environmental Protection Agency.
- Christensen, V., C. Walters, and D. Pauly. 2004. *Ecopath with Ecosim: A user's guide*. Fisheries Centre, University of British Columbia.
- Hagy, J. D., III. 2002. *Eutrophication, Hypoxia and Trophic Transfer Efficiency in Chesapeake Bay*. Ph.D. diss., University of Maryland, College Park.
- Johnson, B., R. Heath, B. Hsieh, K. Kim, and L. Butler. 1991. *Development and verification of a three-dimensional numerical hydrodynamic, salinity, and temperature model of Chesapeake Bay*. Technical Report HL-91-7. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Leonard, B. 1979. A stable and accurate convection modelling procedure based on quadratic upstream interpolation. *Computer Methods in Applied Mechanics and Engineering* 19: 59-98.
- Linker, L., G. Shenk, R. Dennis, and J. Sweeney. 2000. Cross-media models of the Chesapeake Bay watershed and airshed. *Water Quality and Ecosystem Modeling* 1(1-4): 91-122.
- Tillman, D. H., C. F. Cerco, M. R. Noel, J. L. Martin, and J. Hamrick. 2004. *Three-dimensional eutrophication model of the Lower St. Johns River, Florida*. ERDC/EL TR-04-13. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

NOTE: The contents of this technical note are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such products.