WATER QUALITY MODELING OF THE CHESTER RIVER BASIN

Sung-Chan Kim and Carl F. Cerco
US Army Corps of Engineers Engineer Research and Development Center
Vicksburg, Mississippi 39180

INTRODUCTION

The Chester River and the Eastern Bay (Chester River basin from now on) are tidal water bodies located on the Maryland eastern shore of Chesapeake Bay (Fig 1). The longest tributary, the Chester River, has about 70 km long tidal reach whereas the Eastern Bay is about 40 km long. Both the Chester River and the Eastern Bay have wide mouths (about 10 km wide) and they are connected through a narrow passage. The watershed is about 1900 km^2 and is composed of mostly agricultural land and forest.

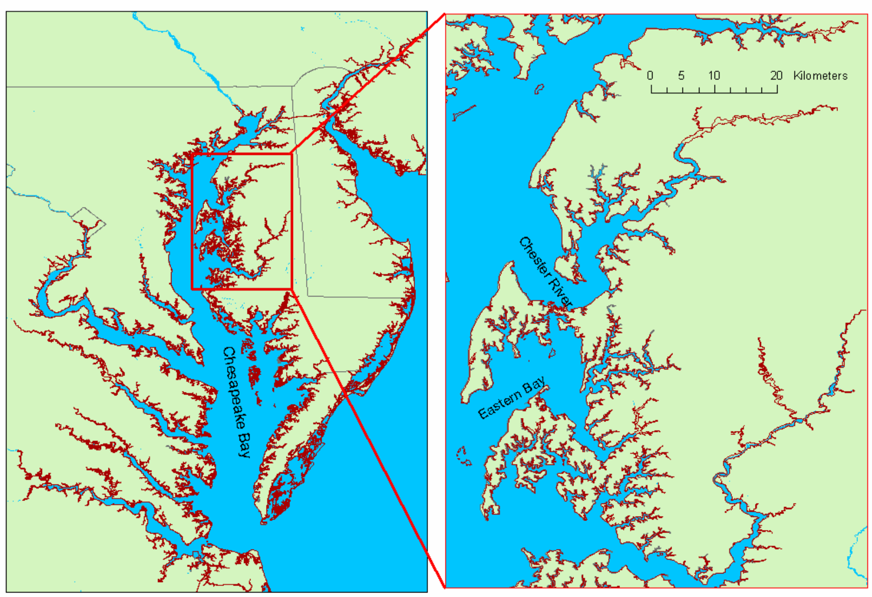

Fig 1. Location Map

It was listed as being impaired by nutrients due to signs of eutrophication which is the over-enrichment of aquatic systems by excessive inputs of nutrients especially nitrogen and phosphorus. The nutrients act as a fertilizer leading to the excessive growth of aquatic plants, which eventually die and decompose, leading to bacterial consumption of dissolved oxygen. A TMDL (Total Maximum Daily Loads) establishes the allowable loadings or other quantifiable parameters for a water body and thereby provides the basis for States to establish water quality-based controls. The objective of a TMDL is to allocate allowable loads among different pollutant sources including point and non-point sources so that the appropriate control actions can be taken and water quality standards achieved. The calculation must include a margin of safety and account for seasonal variation in water quality. Utilizing a sequence of models, including a watershed model for loading distribution, a hydrodynamic model for transport mechanism, and a eutrophication model for kinetics, is ideal for a TMDL development especially for a large and complex system in which temporal and spatial variations are large.

The Chester River basin has been represented in subsets to multiple eutrophication modeling studies of the Chesapeake Bay using CE-QUAL-ICM model (Cerco and Cole 1994, Cerco et al. 2002, Cerco and Noel 2003). The representation of the basin has been coarse, however, in keeping with a grid that represents the entire Bay. A new TMDL strategy for the basin was developed by refining computational grid. The TMDL development by model implementations is described in this paper.

MODELS

The US Environmental Protection Agency Chesapeake Bay Program (EPA-CBP) watershed model (EPA-WSM) is a modified version of the HSPF (Hydrologic Simulation Program FORTRAN) model (Bicknell et al. 1996). This is provides hydrological loadings to the hydrodynamic model CH3D-WES (Computational Hydrodynamics in Three Dimensions-Waterways Experiment Station) and nutrient loadings to the eutrophication model CE-QUAL-ICM.

The CH3D model makes computations on a generalized curvilinear or boundary-fitted horizontal grid. However, to ensure that long-term stratification in the deep channels is maintained, the vertical grid is Cartesian. Boundary-fitted grids in the horizontal directions allow for a better representation of the bay's boundary as well as internal features such as channels and islands. All physics impacting circulation and mixing in water bodies such as Chesapeake Bay are included. These include the impact of freshwater inflows, tides, wind forcing, the impact of the earth's rotation, surface heat exchange, and the effect of turbulence on the mean circulation. The vertical turbulence closure model computes the eddy viscosity and diffusivity from the kinetic energy and dissipation of the turbulence. This type of closure model is known as a k-ε turbulence model. The production of turbulence occurs due to wind stress at the surface, velocity shear in the water column, and bottom friction. Density effects due to salinity and temperature are fully coupled with the developing flow field. Thus, advection/diffusion equations for the salinity and temperature are solved along with the conservation of mass and momentum equations for the flow field. An equation of state relates the water density to the salinity and temperature fields. Surface heat exchange is modeled through the Edinger et al.'s (1974) concept of an equilibrium temperature. Model details can be found in Sheng (1986) and Johnson et al. (1991, 1993).

The CE-QUAL-ICM was designed to be a flexible, widely-applicable eutrophication model. Initial application was to Chesapeake Bay (Cerco and Cole 1994). Subsequent additional applications included the Delaware Inland Bays (Cerco et al. 1994), Newark Bay (Cerco and Bunch 1997), and the San Juan Estuary (Bunch et al. 2000). Each model application employed a different combination of model features and required addition of system-specific capabilities. 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 kinetic sources and sinks. The solution of mass conservation equation on a digital computer requires discretization of the continuous derivatives and specification of parameter values. The equation is solved using the QUICKEST algorithm (Leonard 1979) in the horizontal plane and a Crank-Nicolson scheme in the vertical direction. In this application, 24 state variables were modeled—Temperature, Salinity, Fixed Solids, Freshwater Group, Spring Diatoms, Other (Green)Algae, Microzooplankton, Mesozooplankton, Dissolved Organic Carbon, Labile Particulate Organic Carbon, Refractory Particulate Organic Carbon, Ammonium+Urea, Nitrate+Nitrite, Dissolved Organic Nitrogen, Labile Particulate Organic Nitrogen, Refractory Particulate Organic Nitrogen, Total Phosphate, Dissolved Organic Phosphorus, Labile Particulate Organic Phosphorus, Refractory Particulate Organic Phosphorus, Chemical Oxygen Demand, Dissolved Oxygen, Dissolved Silica, and Particulate Biogenic Silica.

MODEL SETUP AND DATABASE

The numerical grid for the Chester system is shown in Figure 2. As can be seen, the modeled domain extends from the Susquehanna River southward to a location just above the Patuxent River entrance. All major tributaries and embayments along eastern and western shores are included. There are 1,734 computational cells in the horizontal plane of the numerical grid with the number of maximum vertical layers of 20. Of these, 427 cells are in the Chester River basin, including the Chester River and the Eastern Bay. Average cell length along the Chester River axis is about 1 km. Maximum number of vertical layers in the Chester estuaries is 9. Each layer is 1.52 m thick, except for the top layer, which varies with the tide and averages 2.14 m thick. The total number of computational cells is 7,917. There are 9 river inflows. Open boundary consists of 12 surface cells and total number of active cells of 107. In computation domain, there are 76 by 98 horizontal grids with 20 vertical layers. The geometry and the bathymetry of the grid were formed based on NOAA navigational chart data. Time step for the CH3D model was 5 minutes.

Fig 2 also shows the computational grid overlaid upon the EPA-WSM segments (Linker et al. 2000) as well as Maryland Department of Environment (MDE) WSM which has more detailed resolution for the Chester River basin. Analysis of hydrological inputs (Fig 3) shows the loading from the Chester River basin is small. The major source of freshwater to upper Chesapeake Bay, the Susquehanna River, is taken from the USGS gage 01578310. The year

1997 may be viewed as a dry year. The year 1998 and 1999 exhibited a typical spring peak in March followed by a typical dry summer. The years 1997 and 1998 had normal spring high flows followed by low summer flows, while the year 1999 exhibited relatively low spring flow followed by summer dry period then exhibited a storm peak in September

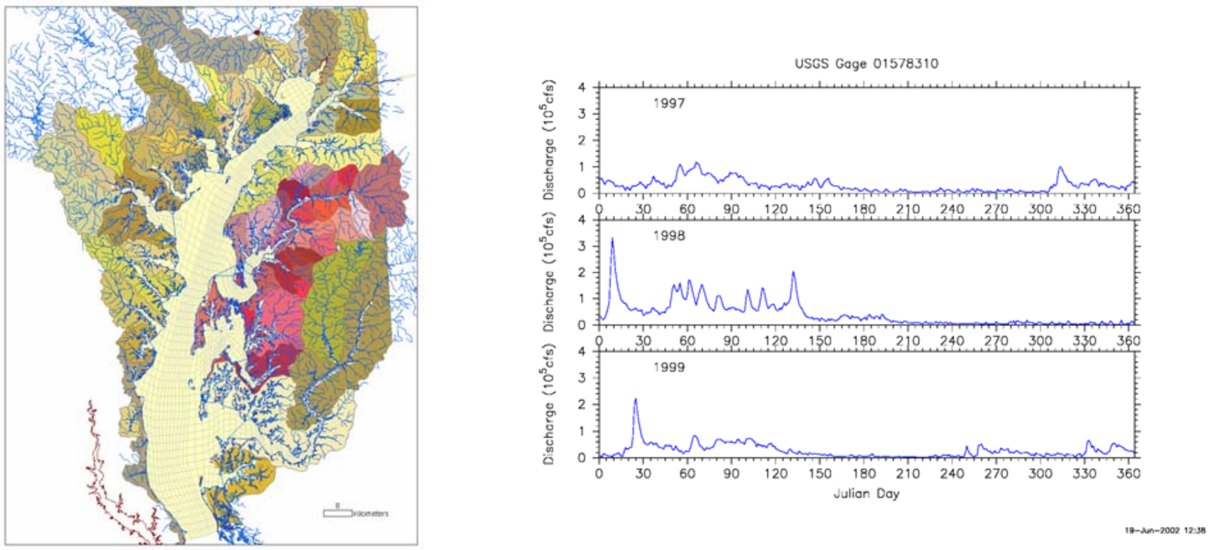

Fig 2. Computational grid overlay with both CBP-HSPF model segments for the Chesapeake Bay basin and MDE-HSPF model segments for the Chester River basin. Also shown is the USGS stream gage 01578310 at Conowingo Dam in Susquehana River (filled circle). Right panel shows discharge at the gage 01578310 over three year period between 1997 and 1999.

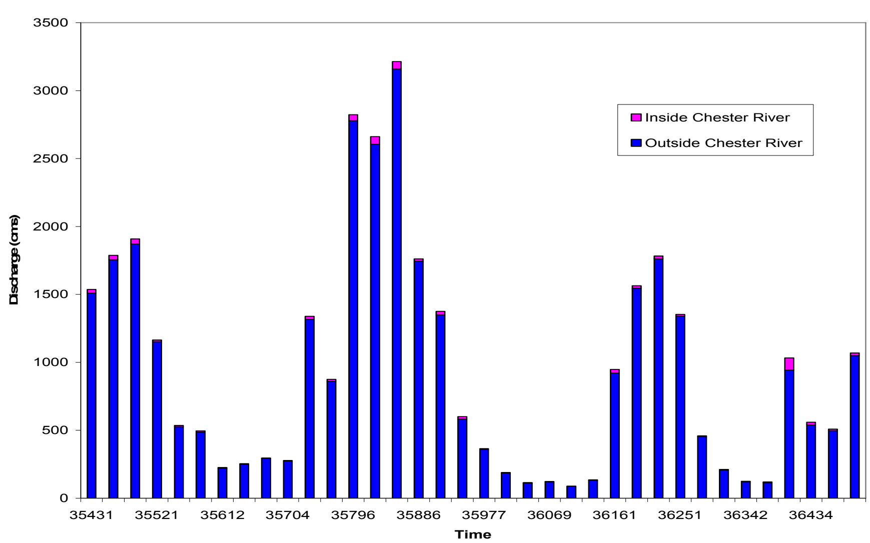

Fig 3. Hydrological input

All loads were provided and input to the model on a daily basis. An annual summary of distributed loads to the Chester watershed is provided in Table 1. The watershed model does not include organic carbon as a state variable. Organic carbon loads at the fall lines in the Chester system watershed were computed as 17.5 times the organic nitrogen load, based on observations at Greensboro at the Choptank River fall line. The ratio 12 was used elsewhere, based on observations at Conowingo. Twelve municipal and sixteen industrial point-source dischargers are located in the Chester watershed. Loads from these were treated as inputs to the eutrophication model. Monthly flows and concentrations for each discharger were provided by MDE. These were converted into loads and routed to appropriate model locations. No organic carbon concentrations were provided. We computed organic carbon loads as twice the total nitrogen load. This ratio was adapted from the present Chesapeake Bay model (Cerco and Noel 2003). A summary of point-source loads to the estuarine portion of the Chester system is presented in Table 2.

Table 1. Annual Distributed Loads to the Chester Estuary

Year	Flow $m^3\ s^{-1}$	NH4 kg N d^{-1}	NO3, kg N d^{-1}	Total N kg N d^{-1}	PO4 kg P d^{-1}	Total P kg P d^{-1}	TSS kg d^{-1}
1997	15.45	466	3,948	5,021	231	294	75,591
1998	19.48	533	4,090	5,971	442	574	344,639
*1999	12.07	478	3,041	4,000	270	319	46,458

*1999 includes only the period between January and August.

Table 2. Annual Point-Source Loads to the Chester Estuary

Year	NH4, kg N d^{-1}	NO3, kg N d^{-1}	Total N, kg N d^{-1}	PO4, kg P d^{-1}	Total P, kg P d^{-1}
1997	92	89	228	20	30
1998	66	84	197	18	25
1999	90	43	174	17	24

Loads from shoreline erosion were adapted from the present Chesapeake Bay model (Cerco and Noel 2003). This load was 3.9 kg d^{-1} silt and fine clay per meter of shoreline. Associated nutrient and carbon concentrations were 0.68 mg g^{-1} phosphorus, 0.33 mg g^{-1} nitrogen, and 4.1 mg g^{-1} organic carbon. Shoreline length of the Chester system is about 455 km, giving total Loads 1.77 x 10^6 kg d^{-1} solids, 1,207 kg d^{-1} phosphorus, 586 kg d^{-1} nitrogen, and 7,275 kg d^{-1} organic carbon. An inventory provided by the EPA Chesapeake Bay Program indicates the Chester River basin adjoins 31.5 x 10^6 m^2 of emergent wetlands. Based on relationships developed for the present Chesapeake Bay model (Cerco and Noel 2003) wetlands were assigned dissolved oxygen uptake of 2 g m^{-2} d^{-1} and organic carbon export of 0.3 gm^{-2} d^{-1}. We converted EPA CBP calculated daily atmospheric nutrient loads into equivalent monthly-average areal loads for the Chester estuary.

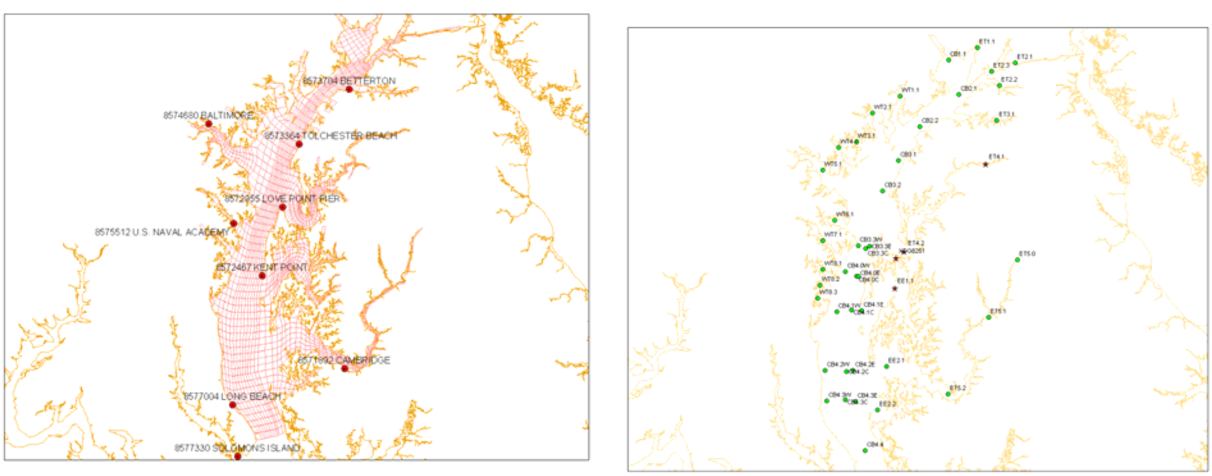

Fig 3. NOAA tide gage stations (left) and the CBP long-term monitoring stations (right).

Surface wind and Surface heat flux were taken from Baltimore-Washington International (BWI) airport meteorology data. Water level at open boundary was from tide gage data at the Solomons Island—NOAA Gage 8577330 (Fig 3). River discharge and temperature were taken from USGS gages and HSPF model output. For lateral flows, both HSPF model output and point source dischargers were used. The US Environmental Protection Agency Chesapeake Bay Program (EPA-CBP) conducts regular monitoring of approximately 90 stations in Chesapeake Bay and tributaries. For salinity and temperature at open boundary, the data from a CBP long-term monitoring station CB5.1 was used. Initial salinity and temperature were prepared using the 1996 winter data from CBP monitoring stations. At the EPA-CBP stations, observations have been collected 10 to 20 times per year since mid-1984. Observations collected in upper Chesapeake Bay formed the basis for temporal calibration and verification of the model over the three-year interval 1996-1998. Stations of particular interest in the Chester estuary were ET4.1, ET4.2, and EE1.1. Maryland Department of Environment conducted six surveys on the Chester system in 1999 three in spring and three in summer. Spatial coverage was extensive. A total of sixty-one stations in the estuarine portion were sampled. These surveys provided the basis for spatial calibration and verification of the model.

Model Results

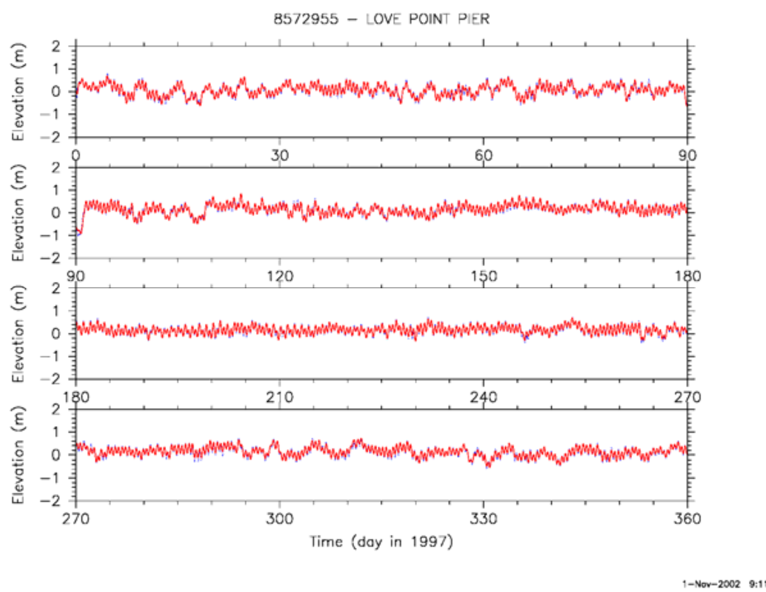

Fig 4. Surface elevation at Love Point pier tide gage location during 1997: simulation (red) compared with tide gage observation (blue)

Model computations were compared to observed tide at multiple stations in the upper Bay. One of these stations was Love Point Pier (NOAA gage 8572955), located near the mouth of the Chester River. Computed intra-tidal and inter-tidal elevations behave consistently with observation. Fig 4 shows simulated water elevation (red) compared with observation (blue) for 1997. Low frequency fluctuation, closely related to surface wind, captured all the meteorological events. Tidal frequency fluctuation is in good agreement in both amplitude and phase. The remaining 2 years, 1998 and 1999, showed similar patterns. The results were consistent throughout the other NOAA tide gage stations.

Salinity was the primary determinant of the calibration of the hydrodynamic model. This conservative substance integrates short-term and long-term effects of tides, currents, and run-off. At selected Chesapeake Bay Program long-term monitoring stations in and near the Chester system, comparisons were made in a variety of formats. Time series plots of surface and bottom salinity show seasonal variations—freshening during spring and then increasing salinity until autumn (Fig 5). It also showed inter annual variation—wet in 1998 and dry in 1999. Also shown is more stratified water in the channel than shoals. The freshwater from the Susquehanna moves south hugging western shoal, resulting fresher water in the western shoal than eastern shoal. Eastern Bay is closely related to the main Bay.

Downstream of the Chester River is also influenced by the main Bay whereas the upstream is controlled by the discharge from the fall line. The pass connecting Eastern Bay and the Chester River is also well represented.

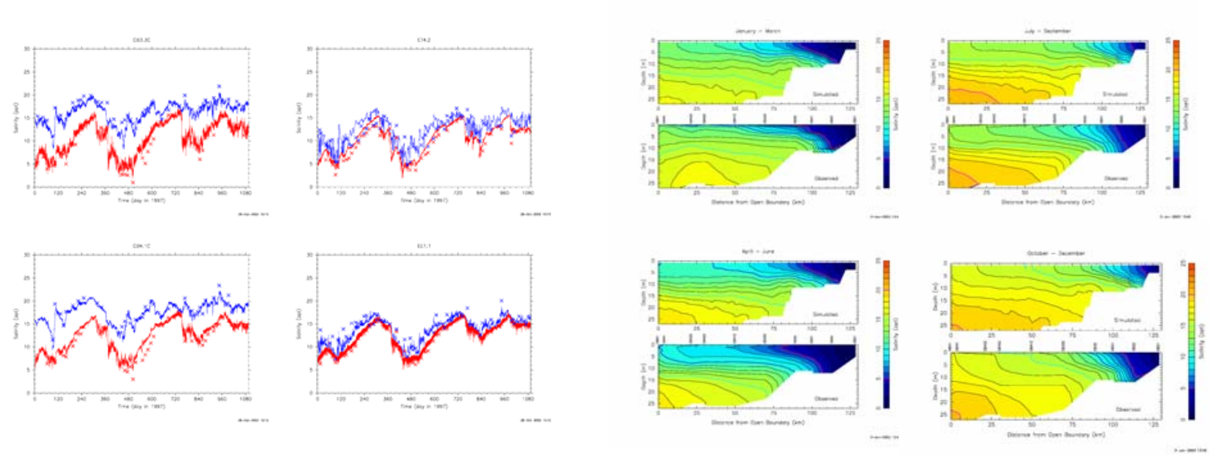

Fig 5. Left panel shows time series of salinity at the main Bay and connected stations in the Chester estuary. Right panel shows the variations of salinity structures along the main Bay.

Vertical profiles show that the structures vary in time and space. The location of pycnocline is reasonably simulated. The mixing in upper layer is also well represented in terms of the thickness. The surface mixing is mostly controlled by the surface wind and the overall structure is dependent on turbulent mixing especially as a function of stratification. We are using an empirical approach of Bloss et al. (1988). In the channel of the main Bay (CB4.1C and CB3.3C), the stratification during spring and de-stratification during autumn is well simulated. Lower reach of the Chester River (ET4.2) shows reasonable structures.

In order to investigate the exchange between the system and the main Bay, salinity distributions along CB4.1W to EE1.1 transect was compared (Fig 6). First, it shows fresher water in the western shoal of the main Bay. It also shows that the Eastern Bay (EE1.1) is closely related to the condition in the main Bay. In general, the seasonal variation is reasonably simulated.

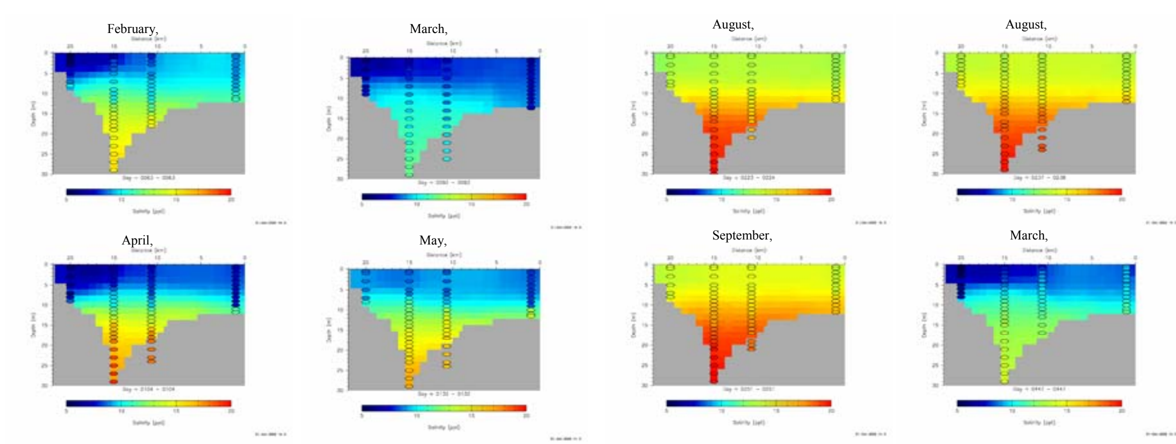

Fig 6. Time variations of vertical structures across the main Bay off the Eastern Bay.

Time series plots at the CBP long-term station in the system showed reasonable behavior of water quality variables (Fig 7). The model was not able to capture high concentration of bottom chlorophyll during spring at the entrance of the Eastern Bay (EE1.1) and the Chester River (ET4.2). This is also shown for the main Bay. At the upstream station of the Chester River (ET4.1) Dissolved Oxygen was higher in the model during summer, especially in 1998. The influence of the main Bay appears only substantial near the mouths (EE1.1 and ET4.2). The cumulative distribution plots show reasonable bottom Dissolved Oxygen prediction at EE1.1 and ET4.2 and surface Chlorophyll prediction at ET4.1.

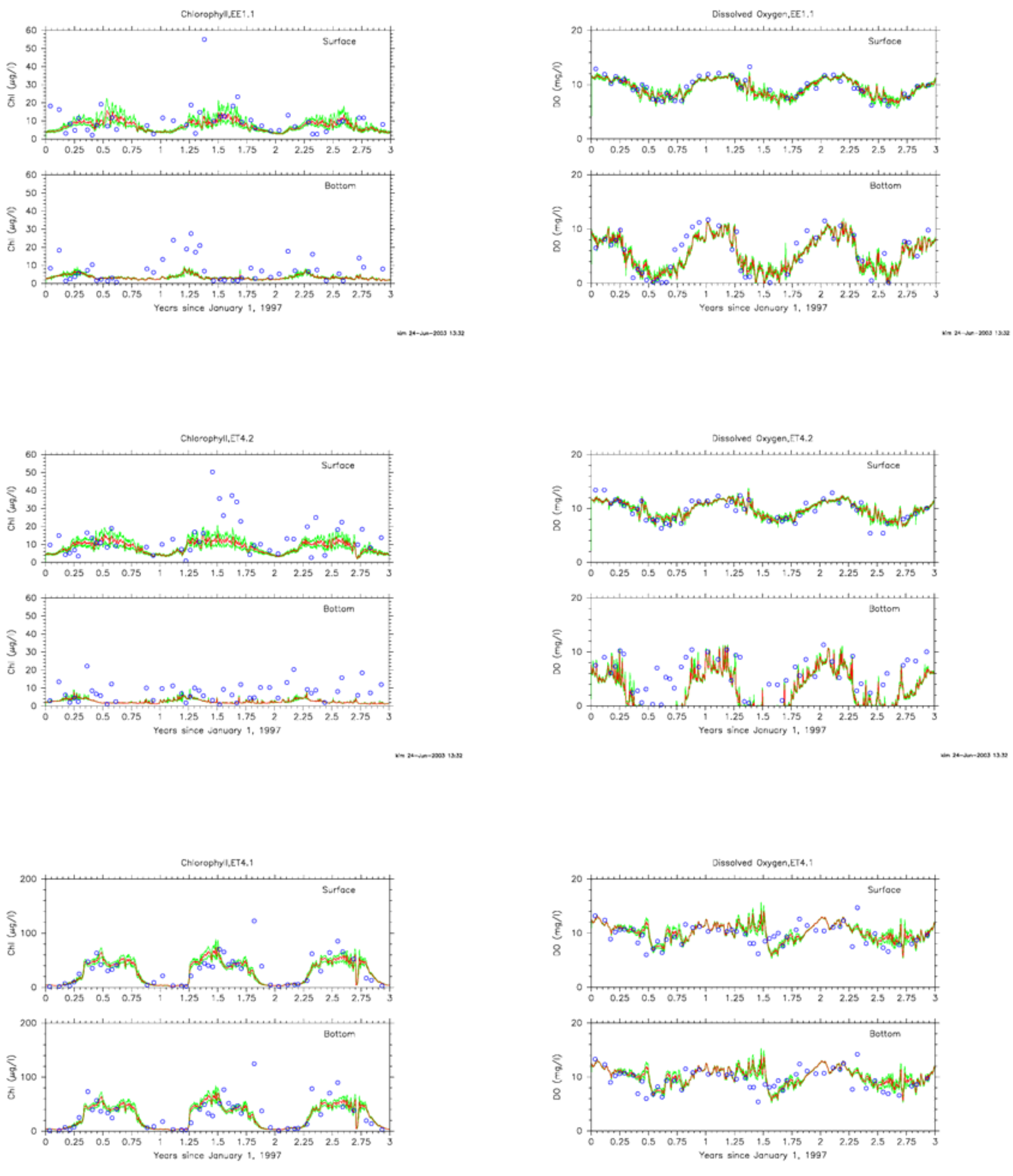

Fig 7. Time series of chlorophyll and dissolved oxygen from 3 CBP monitoring stations in the Chester estuary—EE1.1, ET4.1, and ET4.2.

The cumulative distribution plots for the 1999 MDE intensive survey stations in the Chester River (Fig 8) show reasonable bottom Dissolved Oxygen prediction. In the Eastern Bay and its tributaries, including Miles, Wye, and Wye East Rivers, show reasonable Dissolved Oxygen prediction but Chlorohpyll prediction was off. This suggests that the Dissolved Oxygen, influenced by the conditions of the main Bay that is considered well simulated. This was also shown by the salinity simulation of hydrodynamic model. The predicted sediment flux also was close to that of observation .

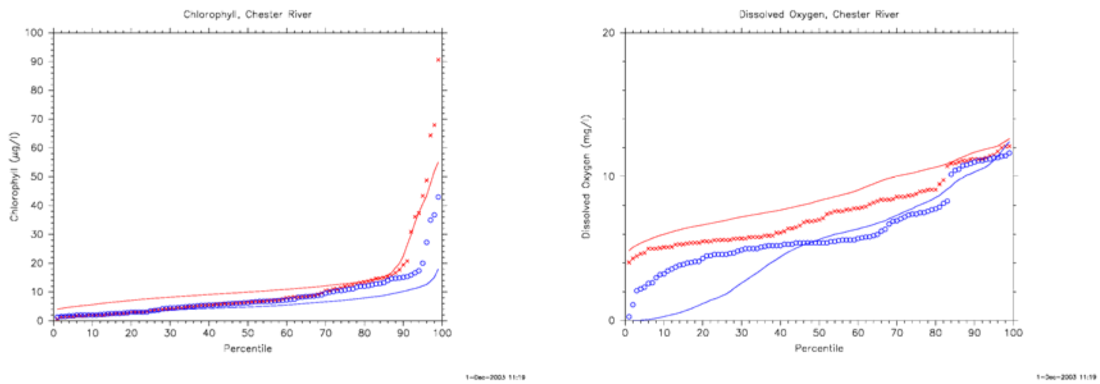

Fig 8. Cumulative distribution of Chlorophyll and dissolved oxygen from 1999 MDE intensive survey stations.

Conculuding remarks

This study shows tightly linked hydrology-hydrodynamic-eutrophication models can be utilized in a TMDL development. This approach is especially powerful to investigate the results from loading reductions. The present approach has been successfully applied not only to estuarine systems but also to large reservoir and lake environments.

References

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

Cerco, C., and Cole, T. (1994). "Three-dimensional eutrophication model of Chesapeake Bay," EL-94-4, US Army Corps of Engineers Waterways Experiment Station, Vicksburg MS.

Cerco, C., Johnson, B., and Wang, H. (2002). "Tributary refinements to the Chesapeake Bay model," ERDC TR-02-4, US Army Engineer Research and Development Center, Vicksburg, MS.

Cerco, C., and Noel, M. (2003). "The 2002 Chesapeake Bay eutrophication model," ERDC TR-03-XX, US Army Engineer Research and Development Center, Vicksburg, MS.

Edinger, J., D. Brady, and J. Geyer. (1974). "Heat exchange and transport in the environment," Report 14, Department of Geography and Environmental Engineering, John Hopkins University, Baltimore, MD
Johnson, B.H., Kim, K.W., Heath, R.E., Hsieh, B.B., and Butler, H.L. (1991). "Development and verification of a three-dimensional numerical hydrodynamic, salinity, and temperature model of Chesapeake," Technical Report HL-91-7, US Army Engineer Waterways Experiment Station, Vicksburg, MS

Johnson, B. H., K. W. Kim, R. Heath, B. Hsieh and L. Butler. (1993). "Validation of a three-dimensional hydrodynamic model of Chesapeake Bay". *Journal of Hydraulic Engineering*, 119, 2-20.

Linker, L., Shenk, G., Dennis, R., and Sweeney, J. (2000). "Cross-media models of the Chesapeake Bay watershed and airshed," *Water Quality and Ecosystem Modeling*, 1(1-4), 91-122.

Sheng, Y. P. (1986). "A three-dimensional mathematical model of coastal, estuarine, and lake currents using boundary-fitted grid," Report No. 585, A.R.A.P. Group of Titan Systems, Princeton, NJ.