A PC-based tidal prism water quality model for small coastal basins

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ABSTRACT

A tidal prism water quality model has been developed for small coastal basins. The model simulates the physical transport using the concept of tidal flushing. The model includes up to the secondary branches (those branch from the primary branches) by treating them as storage areas, which exchange the water masses with the adjoining primary branches (those branch from the main channel) as the tide rises and falls. The model has twenty-four state variables in the water column and twenty-seven state variables in the sediment. An innovative solution scheme, which involves decoupling of the kinetic processes from the physical transport and analytical solutions of the linearized kinetic equations, results in a simple, efficient and yet accurate computational procedure. A graphic interface is built into the model to facilitate its use. The model is being applied to the Lynnhaven Bay, Virginia, U.S.A.

INTRODUCTION

The coastal basins, connecting the land masses to the larger water body or coastal sea, constitute the pathway of nutrients and sediments. The application of a sophisticated model, such as a three-dimensional model, to small coastal basins is often unfeasible or impractical due to their limited size and relatively shallow depths. Because of its simple and straightforward nature, a tidal prism model that simulates the physical transport using the concept of tidal flushing is ideal for small coastal basins including those with a high degree of branching.

To provide a tool for water quality management of small coastal basins, the Virginia Institute of Marine Science has developed a tidal prism model in
the late 1970s (Kuo & Neilson). The model was applied to several small coastal basins in Virginia (e.g., Ho et al.), and has been employed by the Virginia Water Control Board for point source wasteload allocations and by local planning district commissions to address impacts of nonpoint source management. The US Army Corps of Engineers also has used the model to assess the water quality impact of canal construction (Kuo & Hyer).

The model (Kuo & Neilson) is improved in terms of the model representation of the branched geometry and of the biogeochemical kinetic processes. The original model simulates the conditions only in the main channel and its primary branches (those branch from the main channel). The model is improved to include the secondary branches (those branch from the primary branches) by treating them as storage areas, which exchange the water masses with the primary branches as the tide rises and falls. The kinetic portion of the original model is expanded to describe more completely eutrophication processes. First, the kinetic formulations used in the Chesapeake Bay three-dimensional water quality model (Cerco & Cole) are modified and used in the present model. Second, the sediment process model that was used for modeling of the Chesapeake Bay mainstem and major tributaries (DiToro & Fitzpatrick) is slightly modified and incorporated into the present model to enhance the predictive capability of the model. An innovative solution scheme, which involves decoupling of the kinetic processes from the physical transport and analytical solutions of the linearized kinetic equations, results in a simple, efficient and yet accurate computational procedure. A graphic interface is built into the present model to facilitate its use. The model is being applied to the Lynnhaven Bay, Virginia, U.S.A. This paper presents the improvements made to the original tidal prism model (Kuo & Neilson). A complete documentation, both the physical transport and the kinetic processes, of the improved tidal prism water quality model can be found in Kuo & Park.

MODEL DESCRIPTION

The change of mass in the $i$th model segment over one tidal cycle, $\Delta m_i$, may be expressed as:

$$\Delta m_i = [\text{mass in}] - [\text{mass out}] + [\text{sources}] + [\text{kinetics}]$$

(1)

where [sources] includes point and nonpoint source inputs over one tidal cycle, and [kinetics] represents the biogeochemical kinetic processes, which may cause an increase or a decrease of a particular substance within a segment. The first two terms in the right-hand side of eqn (1) involve water movement and are combined to be referred to as "physical transport", and the last term [kinetics] is referred to as "kinetic processes" in this paper.
1. Physical Transport
The tidal prism model simulates the longitudinal distribution of dissolved and particulate constituents at slack-before-ebb (SBE). The rise and fall of the tide at the mouth of a tidal basin cause an exchange of water masses through the entrance. This results in temporary storage of seawater and freshwater in the basin during flood tide, and drainage of these waters during ebb tide. Since water brought into the basin on flood tides mixes with the water inside, a portion of the pollutant mass in the basin is flushed out on ebb tides. This flushing mechanism due to the rise and fall of the tide is called tidal flushing. The tidal prism model in Kuo & Neilson\(^1\) simulates the physical transport using the concept of tidal flushing for the main channel and its primary branches. The same concept was extended to the secondary branches by treating them as storage areas. Water masses are transported from the storage areas to the adjoining primary branch as the water surface falls on ebb tides. Water masses are transported in the opposite direction as the water surface rises on flood tides. As in the main channel and the primary branches, a returning ratio is used to represent the fraction of water volume that leaves a storage area at falling tide and returns from the adjoining primary branch at the following rising tide. Detailed description of the concept of treating the secondary branches as storage areas can be found in Kuo & Park.\(^7\)

2. Kinetic Processes in Water Column and Sediment
The tidal prism model in Kuo & Neilson\(^1\) has ten water column state variables. The present model has been expanded to have twenty-four state variables in the water column (Table 1). The kinetic formulations used in the Chesapeake Bay three-dimensional water quality model (Cerco & Cole\(^4\)) are modified and used in the present model. Figure 1 illustrates the kinetic processes included in the water column of the model.

The sediment process model developed by DiToro & Fitzpatrick\(^5\) was used for modeling of the Chesapeake Bay mainstem and major tributaries. This sediment process model was slightly modified and incorporated into the present model. The model has twenty-seven state variables in the sediment (Table 1). Figure 2 illustrates the processes included in the sediment of the model. The sediment process model, upon receiving the particulate organic matter deposited from overlying water column, simulates their diagenesis and the resulting fluxes of inorganic substances and sediment oxygen demand back to the water column. The coupling of the sediment process model with the water quality model not only enhances the model's predictive capability of water quality parameters but also enables it to simulate the long-term changes in water quality conditions in response to changes in nutrient loadings.

3. Solution Scheme
The solution of eqn (1) is performed in multi-step computations after the kinetic processes are decoupled from the physical transport (Fig. 3). First,
### Table 1. Model state variables.

#### WATER COLUMN:

1) salinity  
3) cyanobacteria (blue-green algae)  
5) green algae  
6) refractory particulate organic C  
8) dissolved organic C  
9) refractory particulate organic P  
11) dissolved organic P  
13) refractory particulate organic N  
15) dissolved organic N  
17) nitrite+nitrate N  
18) particulate biogenic silica  
20) dissolved oxygen  
22) total suspended solid  
24) fecal coliform bacteria  

2) temperature  
4) diatoms  
7) labile particulate organic C  
10) labile particulate organic P  
12) total phosphate P  
14) labile particulate organic N  
16) ammonium N  
19) available silica  
21) chemical oxygen demand  
23) total active metal\(^a\)

#### SEDIMENT:

1-3) particulate organic carbon, \(G_1, G_2\) and \(G_3\) classes in Layer 2  
4-6) particulate organic nitrogen, \(G_1, G_2\) and \(G_3\) classes in Layer 2  
7-9) particulate organic phosphorus, \(G_1, G_2\) and \(G_3\) classes in Layer 2  
10) particulate biogenic silica in Layer 2  
11-12) sulfide/methane\(^b\), Layer 1 and 2  
13-14) ammonium nitrogen, Layer 1 and 2  
15-16) nitrate nitrogen, Layer 1 and 2  
17-18) phosphate phosphorus, Layer 1 and 2  
19-20) available silica, Layer 1 and 2  
21) ammonium nitrogen flux  
22) nitrate nitrogen flux  
23) phosphate phosphorus flux  
24) silica flux  
25) sediment oxygen demand  
26) release of chemical oxygen demand  
27) sediment temperature

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\(^a\) Total active metal may not be modeled by using total suspended solid as sorption site for phosphate and dissolved silica.

\(^b\) Sulfide is modeled for salt water while methane is modeled for fresh water.
the concentration fields \( (C_i) \) are updated in "n" steps for the kinetic processes over a half tidal cycle. Then, the calculated concentration fields \( (C_i^{*\text{a}}) \) are modified by the physical transport and external sources for an entire tidal cycle. Finally, the calculated concentration fields \( (C_i^{*\text{a}}) \) are updated for the kinetic processes for the remaining half tidal cycle, to give the concentration fields at the next tidal cycle \( (C_2) \). To prevent negative concentration due to excessive kinetic consumption, the solution of the kinetic equation is divided into as many steps as needed over a half tidal cycle. To avoid a truncation
Figure 2. A schematic diagram for sediment process model.

Figure 3. Solution scheme with "n" times of kinetic (BGC: biogeochemical) update over a half tidal cycle, C2 = concentration after one tidal cycle.
error, which is inherent to the finite difference solution of a differential equation, the kinetic equations are linearized, mostly for Monod type expressions, and then solved analytically. This new solution scheme, which involves decoupling of the kinetic processes from the physical transport and analytical solutions of the linearized kinetic equations, is described in detail in Park & Kuo.8

4. Graphic Interface
A graphic interface is built into the present model to facilitate its use. The graphic interface consists of three parts, pre-processor, model-graphic and post-processor. The pre-processor allows limited edition of input data files. The model-graphic allows the examination of the model results as the model computations progress. The post-processor allows the examination of the model results, which are saved from the previous model runs.

MODEL APPLICATION

The present model is being applied to the Lynnhaven Bay, Virginia, U.S.A. Since 1975, the Virginia Department of Environmental Quality has been monitoring bimonthly the water quality conditions in the Lynnhaven Bay. A supplementary field program was conducted in 1994, and the data are being combined with the monitoring data to be used for model calibration and verification (Park et al.5).

CONCLUSIONS

A tidal prism water quality model, which has twenty-four water column state variables and twenty-seven sediment state variables, has been developed for small coastal basins. The model simulates the conditions up to the secondary branches. The coupling of sediment process model with water quality model not only enhances the model’s predictive capability of water quality parameters but also enables it to simulate the long-term changes in water quality conditions in response to changes in nutrient loadings. An innovative solution scheme, which involves decoupling of the kinetic processes from the physical transport, and analytical solutions of the linearized kinetic equations, results in a simple, efficient and yet accurate computational procedure. A graphic interface is built into the present model to facilitate its use. The model is being applied to the Lynnhaven Bay, Virginia, U.S.A. The model, being a generic model applicable to any small coastal basins and tidal creeks, and operational on a personal computer, should provide a tool for water quality management of small coastal basins.

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REFERENCES


