Available online at www.sciencedirect.com
ScienceDirect
Estuarine, Coastal and Shelf Science 74 (2007) 742–755
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ecss

Embayment characteristic time and biology via tidal prism model

Mohamed A. Abdelrhman

United States Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division, 27 Tarzwell Drive, Narragansett, RI 02882, USA

Received 1 July 2006; accepted 9 May 2007
Available online 25 June 2007

Abstract

Transport time scales are often offered by scientists, and accepted by ecologists, as qualitative indicators of the susceptibility of ecological components within an embayment. However, rigorous quantitative methods were never presented to confirm this intuition. Transport time scales in water bodies are classically based on their physical and chemical aspects rather than their ecological and biological character. The direct connection between a physical time scale and an ecological effect has to be investigated in order to quantitatively relate a transport time scale to ecology. This concept is presented here with some general guidelines and clarifying examples. To be able to relate physical time scales to biological processes, a simple tidal prism model is developed that calculates temporal changes in concentration and the related exposure. This approach provides a quick method to calculate the characteristic time for transport in a large number of embayments, which can also help in classification endeavors.

Keywords: embayment; tidal prism model; characteristic time; concentration; threshold; biology; exposure

1. Introduction

This paper deals with the relationship between transport time scale of an embayment and biological processes. This context was discussed before by Abdelrhman (2005, 2006). The reader is encouraged to refer to these publications and the references therein for detailed explanations; however, a general and brief review is presented below. This paper is non-traditional as it pertains to developing a new understanding of the concept of physical transport time scale and its relevancy to biology. This understanding was obtained by simplifying (or bypassing) many details in both physics and biology, without compromising the scientific integrity of the paper. Idealized examples are offered to clarify the general definitions and relationships. Applications to real situations are also presented to demonstrate the practical uses and benefits of this approach.

The general concept of a ‘‘transport time scale’’ has been used in aquatic studies for decades. Most recently, three related measures of this time have been emphasized in the aquatic literature, i.e., ‘‘flushing time,’’ ‘‘age,’’ and ‘‘residence time’’ (Monsen et al., 2002). According to Monsen et al., flushing time is the ratio of the total mass of a constituent (or water) in a water body to its overall rate of renewal, age is the time a water parcel at a specified location has spent in the water body since entering it, and residence time is the time until a water parcel at a specified location leaves the water body. In addition, the ‘‘transit time’’ is another time scale that considers the total time spent by a molecule from entering until leaving the embayment (Bolin and Rodhe, 1973; Zimmerman, 1976; Takeoka, 1984), and the ‘‘turnover time’’ is the time needed to exchange all the material in the embayment with new material. All these time scales originate from physical properties of the water body (e.g., volume, tidal forcing, freshwater inflow, mixing, exchange) and chemical properties of constituents (e.g., concentration or mass, decay, partitioning). They focus on the movement, exchange, and mixing of

E-mail address: abdelrhman.mohamed@epa.gov

0272-7714/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2007.05.008

water and its constituents, and not on how these relate to the ecology of a system and its biological components.

When dealing with biological components (endpoint beneficiary of the above-mentioned time scales), one may raise the following essential questions: Is there a direct quantitative relationship between these transport time scales and biology? What is this relationship? How can we obtain this relationship? To answer these questions the analysis should include biological components of interest then proceed to define the relevant and appropriate transport time scale(s). The main objective of this paper is to present simple model to address the above questions. The specific objective is to identify the effect of constituent loading patterns and the relevant transport times on the exposure of a biological component in an embayment (or suite of embayments).

2. Model

In a numerical model, it is customary to start with fine scale temporal variations in loading and spatial delineations of an embayment, and then proceed through a simulation to calculate concentration variations. This approach is very meticulous in defining spatial and temporal changes in concentration and it is highly recommended when expertise and resources are available. However, it may not match the biological responses of interest, which may function on coarser spatial scales and longer time periods. Meanwhile, management decisions sometimes favor simpler and less sophisticated approaches that can be applied rapidly to suites of embayments (i.e., classes). The approach presented here falls in this category. It is based on tidal prism analysis (e.g., Sanford et al., 1992; Luketina, 1998) with modifications to accommodate temporal variability in tidal forcing and loading and to produce time-varying concentration. It should be emphasized, however, that this tidal prism model is not designed to resolve details on time scales less than a tidal phase (flood or ebb) or spatial scales less than the size of the embayment.

The following simplifying assumptions are made to illustrate the method in an idealized embayment (Fig. 1): volume of freshwater inflow is assumed negligible relative to the volume of water in the embayment; the embayment is well mixed with negligible estuarine circulation; semidiurnal tides (as in the northeastern continental USA) exist throughout the year. The constituent can be any conservative nutrient, chemical, contaminant, etc. To simplify the analysis, details about the constituent's kinetics, sources, sinks, and partitioning are not included. The model preserves not only diurnal variations in tidal ranges and phase duration, but also changes due to spring–neap cycles throughout the year.

During the two phases of any tidal cycle (flooding and ebbing, Fig. 1a) the constituent will be loaded to and/or flushed out from the embayment. The conservation of a tracer mass requires that:

$$\frac{dM}{dt} = m_{in} - m_{out} \quad (1)$$

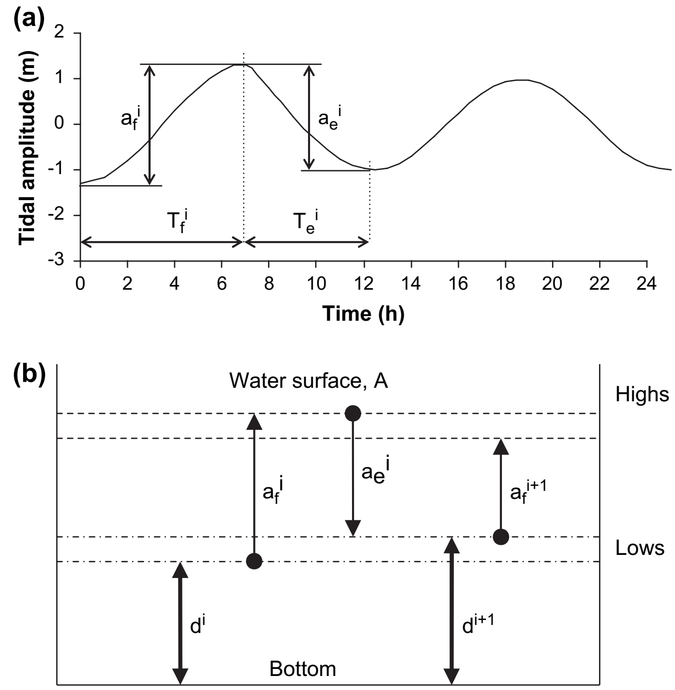

Fig. 1. Sketches of the idealized setting: (a) typical semi-diurnal tide (e.g., as in northeastern USA) with varying flood–ebb periods ($T_f^i \neq T_e^i$) and ranges ($a_f^i \neq a_e^i$), (b) embayment with variable tidal prism ($a_f^i \neq a_e^i$). Double headed arrows indicate the time-varying water depth and single headed arrows illustrate the time-varying range of the water surface, which starts from the level marked by the dot and ends at the level of the arrow head.

where M is the total mass (kg) of the tracer inside the embayment, m_{in} is the rate of mass (kg h^{-1}) entering the embayment, m_{out} is the rate of mass (kg h^{-1}) leaving the embayment, and t denotes time. The change in mass for each tidal phase (flood or ebb) can be calculated by numerically integrating Eq. (1) through the time period for each tidal phase (e.g., Luketina, 1998). To preserve the effect of tidal changes, the method used here tracks the conservation of mass for each tidal phase as well as the concentration at the end of that phase (i.e., at peak flood and at dip ebb). The total change in mass throughout a full tidal cycle is the sum of changes during these two phases which can be expressed by:

$$\Delta M = M^{i+1} - M^i = M^i_{in\text{-}flood} + M^i_{in\text{-}ebb} - M^i_{out\text{-}ebb} \quad (2)$$

where M^i is the mass at the beginning of flooding phase for the ith tidal cycle. The superscript represents the tidal cycle and the subscripts identify masses entering or exiting during flooding and ebbing periods.

During the flooding period, T_f (Fig. 1a), loading from the watershed and seaward open boundary of the embayment causes mass of the constituent to increase inside the embayment by:

$$M^i_{in\text{-}flood} = nT^i_f + M^i_{entering} \quad (3)$$

where n (kg h^{-1}) is the mass of the constituent loaded to the embayment from the watershed per hour, T_f (h) is the flooding period of a general cycle, and $M_{entering}$ is the mass entering