Modeling Estuary Flushing Time in Three Dimensions

Bert Rubash Elizabeth Kilanowski

February 7, 2007

Abstract

Knowledge of the time scale of aquatic processes is a precondition for most estuarine studies: studies that involve biologic populations, nutrients, dissolved gases, contaminants, suspended particles, temperature, or salinity are dependent on knowledge of water transport in the study domain.

In this work a procedure was established to make accurate and consistent estimates of flushing time and residual tidal flow of an estuary in Northern Puget Sound using a three-dimensional numerical circulation model. Model boundary conditions were configured for typical tidal cycles, wind stress, and freshwater stream inflow.

This work illustrates how a three-dimensional model can be used for detailed analysis of the flushing of stratified waters characteristic of estuaries. The method expands and elaborates the continuously stirred tank reactor assumption with advective diffusion that varies in both space and time, enabling mapping of the variability of flushing over the model domain.

Introduction

Studies of most aquatic processes are dependent on knowledge of the time scale of water transport within the study domain. Residence time, age, and flushing time are three measures of the time scale of water renewal.[3] A fourth measure, residual tidal flow, is volumetric. The measure chosen for this study, flushing time, is the ratio of total volume (or mass) of water to its rate of renewal due to flow across boundaries.

This study expands the abstraction of a single-valued flushing time for an entire water body into a concrete and multidimensional measure of water renewal corresponding to actual configurations of tides, currents, winds, inflowing streams, stratification, and other physical characteristics and dynamics of an estuary.

Method

A mathematical definition of flushing time for a constant volume water body, τ, is the ratio of the volume, V, of a substance to its rate of change, Q,

$$\tau = \frac{V}{Q} \tag{1}$$

The substance may be the water itself, in a lake or bay, or a substance in the water such as a contaminant or dissolved oxygen.[1]

The concept of flushing time embodied in the above equation was applied to each computational cell of a numerical hydrodynamic model. The substance in equation 1 which serves as a proxy for water is a conservative dissolved tracer introduced at a concentration of 1 gram per cubic meter uniformly across the model domain as an initial condition. An expression for this proxy relationship—the flushing time of water as a function of the time-dependent concentration of a trace amount of a substance in the water—is

$$\tau(t) = \frac{t}{\ln\left(\frac{C_0}{C(t)}\right)} \tag{2}$$

A related result that can be derived from the flushing time results by reapplying equation 2 at the scale of the model domain instead of the individual computational cell, is a measure of the effective residual flow, Q, due to flows from tides, wind, and streams combined with advective diffusion. Rearranging equation 1 yields a time-dependent value for effective residual flow,

$$Q(t) = \frac{V}{\tau(t)} \tag{3}$$

Application

An ocean circulation model was configured with the physical characteristics of an estuary in Northern Puget Sound, Bellingham Bay, Washington. The bay is kidney-shaped, roughly ten kilometers east-west by 25 kilometers north-south with extensive river delta mud flats at the north and south ends. Typical middle bay depths are about 30 meters. The computer model was an adaptation of COHERENS, an ocean circulation model developed within the European Union [2]. The model was modified to accommodate wetting and drying of the extensive tide flats at the north and south ends of the bay.

A grid was prepared from raw bathymetry data, transformed to a 170 X 254 cell horizontal Cartesian grid by Delauney triangulation and interpolation. Horizontal cell dimensions are 100 meters X 100 meters. A tides routine was written for the model which uses 29 tide elements from the XTide program database for Bellingham Bay. Constant surface wind stress aligned with prevailing wind direction was applied, and flow data for a typical year from the USGS for the Nooksack river was synchronized with tide cycles for that year. Corresponding flow for three smaller streams was included at appropriate boundary points.

Results

Applying equation 2 to the entire estuary with t defined as elapsed time from model startup produces a time-series index of the rate of replacement of the water in the model as stream flow and tides vary. Initially the rate of replacement is due mainly to advection across the model boundary and elapsed time spans few tide cycles thus flushing time derived using equation 2 is unrealistically variable. As boundary effects spread across the model domain by means of advective diffusion, however, flushing time values derived using equation 2 converge toward a constant value.

The upper graph in Figure 1 includes a plot of the overall flushing time derived from the rate of decrease in tracer concentration starting with neap tides on June 15, 2005. A horizontal blue line in the upper plot indicates the point in time in the model run where the overall mass of tracer dropped to 1/e of the initial concentration at which point flushing time and model time in equation 2 are equal. For comparison with the upper graph, the lower graph is a plot of mean surface elevation for the bay showing mainly the influence of tidal flows. Mapping equation 2 over the estuary produces a graphic representation of the geographic distribution of flushing time magnitudes.

Figure 2 was produced at the modeling moment mentioned above when a 1/e fraction of the initial tracer mass remained in the bay, that is, when one flushing time of model time has elapsed since model initialization. Flushing time for surface waters is greatest in the center of the bay, far from incoming tides

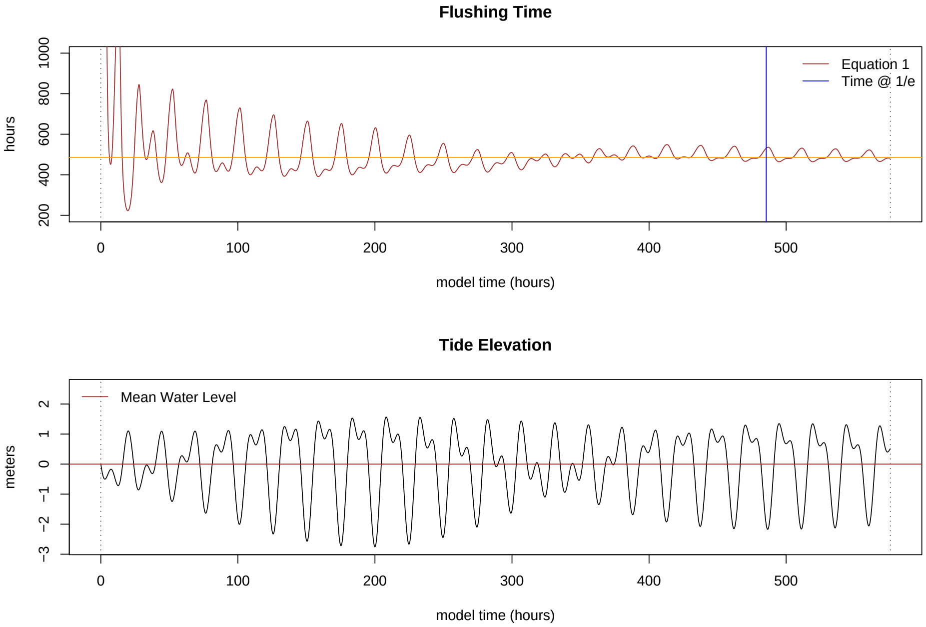
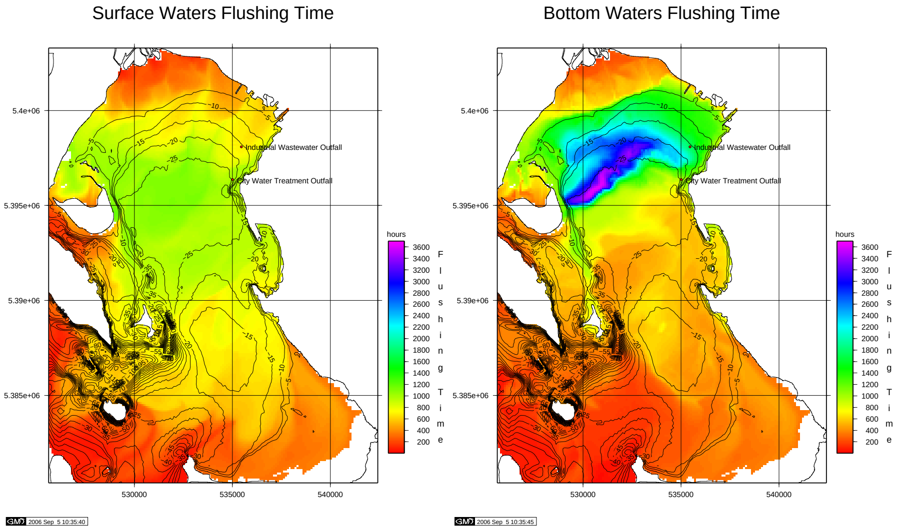


Figure 1: Whole-bay flushing time.


Surface Waters Flushing Time

Bottom Waters Flushing Time

(a) surface

(b) bottom

Figure 2: Local flushing times at model time = 485.5 hours

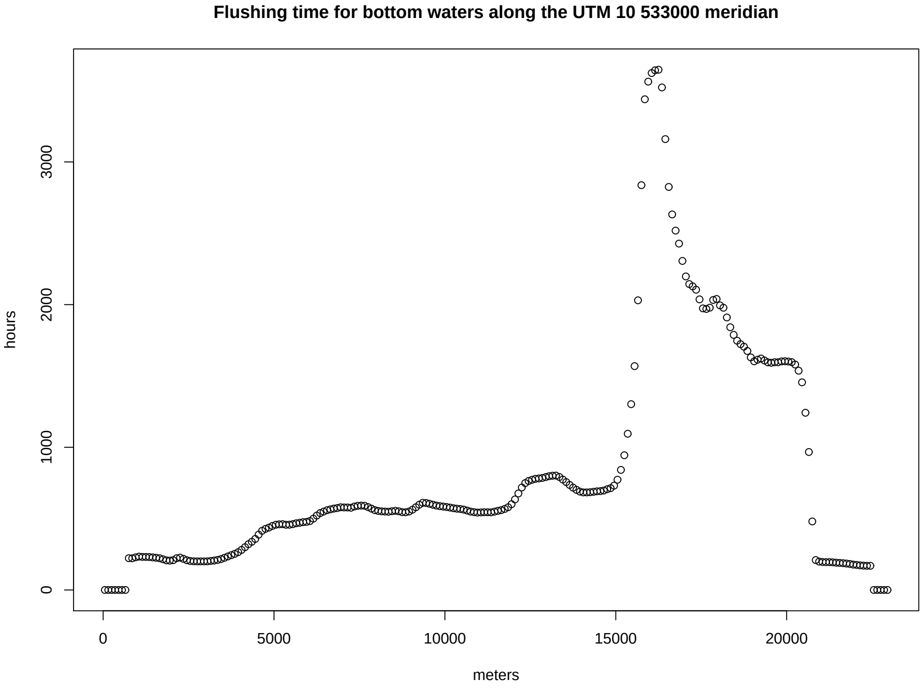

Flushing time for bottom waters along the UTM 10 533000 meridian

Figure 3: Flushing time along a meridian.

and fresh water flowing across the surface from the river on the northern shore, but shifted northward due to wind stress from prevailing southerlies which drag surface waters northward.

The pattern of flushing times for bottom waters is much more varied and interesting. A large region of bottom waters in the northern quarter of the bay has a much longer flushing times than elsewhere.

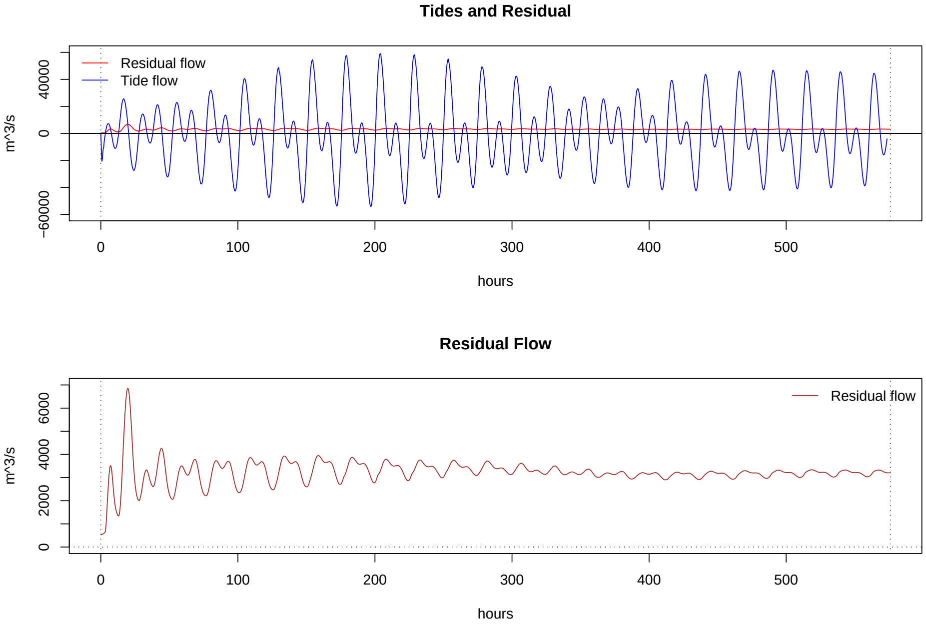


Figure 4: Comparison of tide and residual flow rates

Two discharge pipes are identified on the map. One is for industrial waste water from a paper mill and the other is for the City of Bellingham's municipal water treatment plant. Figure 3 is the bottom water flushing time along a meridian through the region of greatest flushing time in Figure 2. The bottom modeling layer is 0.81 meters thick at the industrial outfall and 1.19 meters thick at the municipal water outfall.

For this model configuration the time dependence of τ is stream flow and tide cycle dependency. The upper graph in Figure 4 is a superposition of residual flow volume and total tide flow volume exhibiting relative magnitudes. The lower graph is a plot of residual flow less stream flow for the bay.

Summary

With increasingly fast computers and the development of widely available ocean circulation modeling software an old method of estimating a single value for water body renewal from external sources, flushing time, can be expanded into detailed graphs and maps of the kinetics of renewal of complex and changing water bodies. This work illustrates the value one such expansion.

References

[1] S. E. Chapra. *Surface Water Quality Modeling.* WCB/McGraw-Hill, Boston, MA, 1997. pages 55-56.

[2] P. J. Luyten. Coherns - dissemination and exploitation of a coupled hydrodynamical-ecological model for regional and shelf seas, mas3-ct97-0088. Technical report, Management Unit of the Mathematical Models, 1999. MUMM Internal Report, 76 pp.

[3] N. E. Monsen, J. E. Cloern, L. V. Lucas, and Stephen G. Monismith. A comment on the use of flushing time, residence time, and age as transport time scales. *Limnology and Oceanography*, 47:1545–1553, 2002.