Application of the MSB coupled embayment pollution-flushing model to Queenstown Creek

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Abstract

The MSB coupled embayment model of pollution flushing from a tidal basin has been applied to the Queenstown Creek of the Chesapeake Bay system and the results compared to an unpublished Rhodamine dye study conducted in 1987. The MSB model is based on the analytical tidal prism formulation developed by Barber. Until this present work, an MSB model of cascading tidal segments has not been applied to a real embayment. Tidal prism analyses have been validated against physical hydraulic modeling tests and one segment Mecca-Severino-Barber (MSB) models have shown agreement with real world dye studies, prompting this study of the more complex coupled embayment model. Presented in this paper is a simulation of pollution flushing from Queenstown Creek into the Chester River following the release of Rhodamine dye. The results are found to be in general agreement with the field data, and the nature of the MSB coupled embayment model obviates the need for the pollution return-flow parameter, *b*.
Keywords: tidal prism, pollution flushing, tidal embayment, MSB model, Queenstown Creek, Chesapeake Bay.

1 Introduction

Pollution flushing from coupled well-mixed tidal embayments is represented graphically and numerically in the MSB Coupled Embayment Model (MSB-CEM) [1]. Written in Stella [7], realistic basin bathymetries are incorporated [2] as is the dynamic loading of pollutants [3]. The rate equations of Barber's tidal

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prism model [4] have been applied to the interaction of differentiated basin segments. The relationships are based on the following mass flow equation:

$$\frac{d(CV)}{dt} = V\frac{dC}{dt} + C\frac{dV}{dt} = k + CQ \tag{1}$$

where Q is the discharge through the entrance to the embayment, C is the instantaneous pollutant concentration, k is the pollution loading function, and V is the volume of the embayment at time, t.

A series of basins connected in a cascading system is analogous to a model of coupled chemical reactors with time varying conditions of volume and pollution concentration. Figure 1 illustrates a schematic representation of the i^{th} embayment of a system in such perspective.

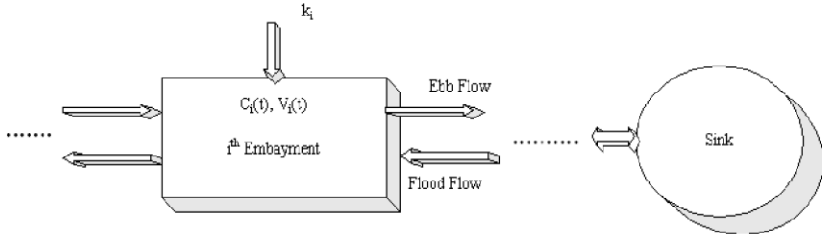

Figure 1: A general embayment, i, within a coupled series of basins.

With the exception of the terminal basins, all embayment segments have the same dynamic structure and are governed by the same rate equations. Each element in the system receives (and discharges) flood and ebb waters, with appropriate pollution concentrations from (and to) adjacent ones. The concentration rate equations for each interior i^{th} cascading element of the MSB-CEM are derived from the basic mass flow relationship, equation (1). During the ebb cycle,

$$\frac{d(C_iV_i)}{dt} = V_i\frac{dC_i}{dt} + C_i\frac{dV_i}{dt} = k_i + C_{i-1}Q_{i-1,i} - C_iQ_{i,i+1} \tag{2}$$

where$Q_{i-1,i}$and $Q_{i,i+1}$ are the flow rates into and out of the basin, respectively. That is, $Q_{i,j}$ is the flow rate from basin i to basin j. This equation can be rearranged to yield the concentration rate equation for the ebb cycle:

$$\frac{d(C_i)}{dt} = \frac{k_i + C_{i-1}Q_{i-1,i} - C_iQ_{i,i+1} - C_i\dfrac{dV_i}{dt}}{V_i} \tag{3}$$

A similar methodology can be applied to the flood cycle to obtain the following relationship:

$$\frac{d(C_i)}{dt} = \frac{k_i + C_{i+1}Q_{i+1,i} - C_iQ_{i,i-1} - C_i\dfrac{dV_i}{dt}}{V_i} \tag{4}$$

The rates for the basins at the terminal ends of the cascade can be similarly determined, the difference being that the head of the cascade is only connected to a single basin and the opposite end representing the receiving water is connected to a source/sink. Additionally, any number of basins can be connected to a single element, changing only the number of concentration inflows and outflows of the rate equations.

The discharge, *Q,* at each instant depends on the relative tidal heights in the basins. Tidal predictions from the National Oceanic and Atmospheric Administration (NOAA) were used to control the tidal heights of the model (with appropriate time delays for each element in the cascade), which were then applied to a numerical integration accounting for variable bathymetry [1] to characterize the volume of each embayment segment.

2 Queenstown Creek

Queenstown Creek is a tidal dependent of the lower Chester River, which constitutes a major tributary of Chesapeake Bay. The creek is located in Queen Anne's county of Maryland on the Delmarva Peninsula. The nearby community of Queenstown has a population of less than 1000. In 1987, a proposal for the expansion of Queenstown's wastewater treatment plant prompted the Department of the Environment, Division of Water Quality Monitoring to undertake a Rhodamine dye study to evaluate the possible effects on the ecosystem [5]. The study was carried out during the period between 23rdJune and 29th June 1987.

3 Synopsis of the dye study

According to the dye study report [5], an industry standard 20% Rhodamine WT (water tracing) solution was injected over a 24 hour period (two complete tidal cycles) between June 24th and 25th1987. The location of the dye injection point is shown in Figure 2. A calibrated field fluorometer capable of ppb sensitivity was used to measure the dye concentrations at numerous locations around the embayment every 24 hours after the beginning of the injection until 96 hours after the cessation of the injection. The study was conducted during the spring tidal cycle. Prior to the injection of the dye, the background concentrations were measured and subtracted from the final results to yield the true dye concentrations. Calibration temperature differences were also taken into account.

The bathymetry of the basin was also obtained using a recording fathometer, although this information has unfortunately been lost at some point over the past two decades.

The study concluded that the dye was discharged from the embayment "progressively, and consistently, to the receiving water of the Chester River via tidal currents" and that "the rate of dispersion is best characterized as moderate." The report also indicated that the dynamics of the basin were such that the dye released in the southern segment resulted in loading of the entire basin, as evidenced by “progressive tracer accumulation over time in Queenstown Creek”.

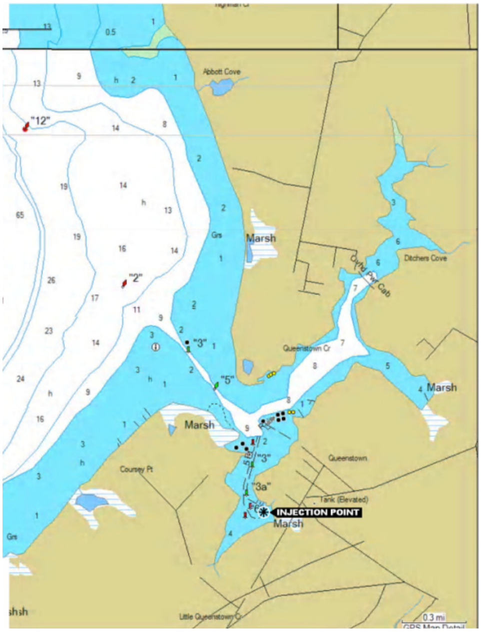

Figure 2: NOAA bathymetric chart of Queenstown Creek showing the location of the dye injection point.

4 Application of the MSB coupled embayment model

Given the previous conclusions of the dye study, it appears the embayment is fairly well mixed. However, one of the advantages of the MSB-CEM is that the entire system of basins need not be well mixed, only the individual segments [2].

The natural geography of the Queenstown basin lends itself to division into eight segments, as shown in Figure 3. The researchers of the dye study also recognized this and used approximately the same boundaries for their convenience [5]. Given the use of consistent calculations and rate equations, any number of divisions could have been applied to the system (as long as each individual segment remained well mixed, as previously discussed) [2].

The cascading segments of the basin were linked in the model as shown in Figure 4. The rate equations that govern the interactions between the coupled embayments were coded into the model using Stella’s biflow rates and a logical expression to effect a single equation governing both ebb and flow cycles.

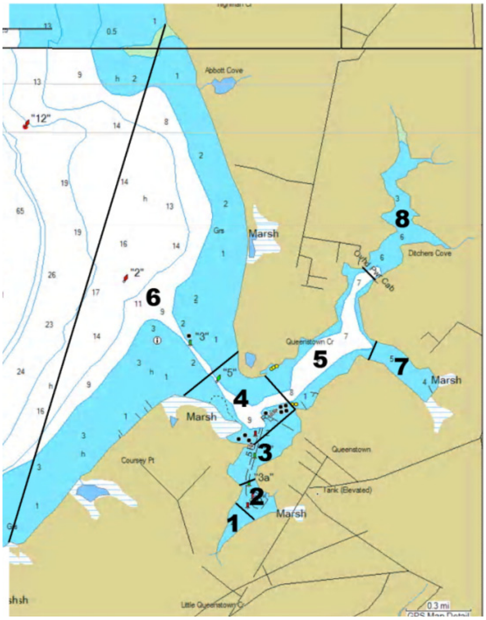

Figure 3: Queenstown Creek divided into eight coupled segments.

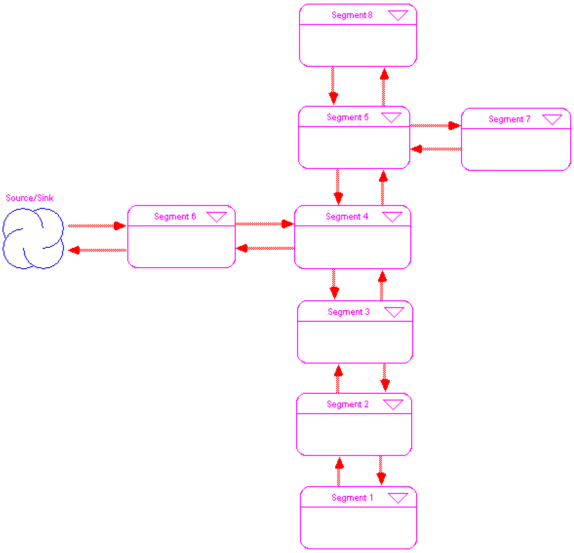

Figure 4: Schematic representation of the eight segment cascading basin model of Queenstown Creek.

The MSB model of a representative interior basin, segment 2, is shown in Figure 5 and has a similar structure to that used in a previous coupled embayment model study [2], the difference being the use of real tidal data, actual bathymetry, and the absence of the pollution-return parameter, *b*.

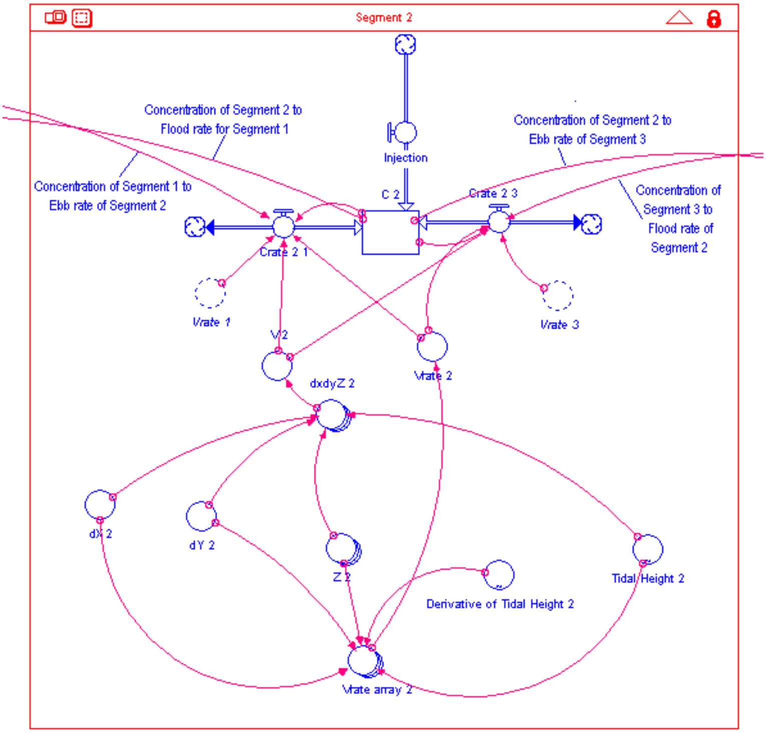

Figure 5: The second segment of the Queenstown MSB-CEM in Stella.

C 2 = Concentration of dye in Segment 2
Crate 2 1 = Rate of change in concentration of dye due to interaction between Segments 1 and 2
Crate 2 3 = Rate of change in concentration of dye due to interaction between Segments 2 and 3
Tidal Height 2 = Tidal Function of Segment 2 in meters over time
Derivative of Tidal Height 2 = Derivative of the tidal height function of Segment 2 to calculate flow
dX 2 = Length of a grid block from the bathymetry map of Segment 2
dY 2 = Width of a grid block from the bathymetry map of Segment 2
dxdyZ 2 = Array of the volumes of every bathymetry grid block of Segment 2 at time (t)
Z 2 = Bathymetric data array for Segment 2
V 2 = Volume of Segment 2 in meters cubed
Vrate 1 = Change in volume V over time of Segment 1 based on tidal flow
Vrate 2 = Change in volume V over time of Segment 2 based on tidal flow
Vrate 3 = Change in volume V over time of Segment 3 based on tidal flow
Vrate array 2 = Array of the change in volume of every bathymetry grid block over time of Segment 2
Injection = Loading function of the dye in Segment 2

Figure 6: Level, rate, and parameter definitions in the model.

The single segment MSB model has been applied to Great Salt Pond on Block Island, where a dye study yielded data consistent with the model predictions [6].

In the earlier theoretical study, a simple sinusoidal variation with time was used for the tidal height. For the Queenstown analysis, NOAA predicted tides were applied. Calculations of the tidal delays between the NOAA operated buoys of the Chester River were extrapolated to find the tidal delay between each embayment segment.

The bathymetry of each individual basin was calculated using the most recent NOAA charts. A grid was overlaid onto each segment in order to acquire depth data for the model.

By using the actual basin volume, the MSB-CEM avoids the imposition of a pollution return flow parameter, *b*, as concluded by previous work [2].When true volumes and tides are used, the exact pollution flow between adjacent segments is known. The outermost segment of the model (segment 6) is several orders of magnitudes smaller than the adjacent Chester River basin, which can be assumed to have a comparatively infinite volume, and hence, zero return flow, effectively acting as a sink (also described in [2]).

After normalizing the concentrations of each segment with the dye study data, the model was run for a simulation time of 110 hours with a time step of 0.05 hours. The time t = 0 coincides with the first dye measurement, taken at the cessation of injection, and also corresponds to low tide just before the flood cycle. As previously stated, the dye study recorded the concentrations of the embayment at 24 hour intervals following the cessation of injection; this provided the opportunity for four concentration values of each embayment segment to be compared with the model predictions.

5 Results

The agreement between the model predictions and the field data appears to be very good for segments 1 through 5, as is evidenced in Figures 7-11.

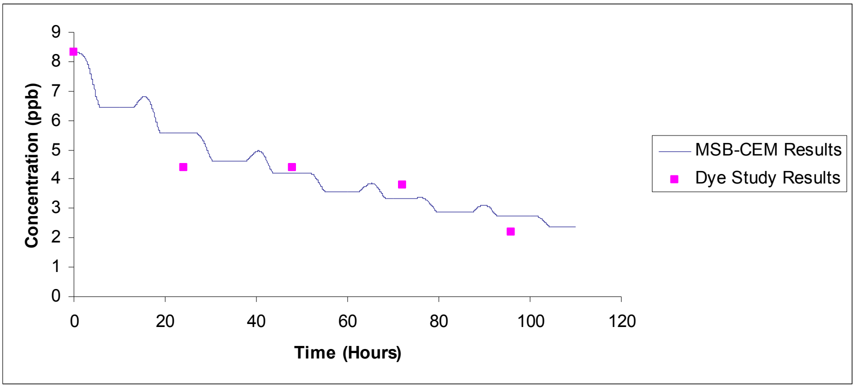

Figure 7: Concentration in segment 1 over time; comparison between predictions and observed dye study results.

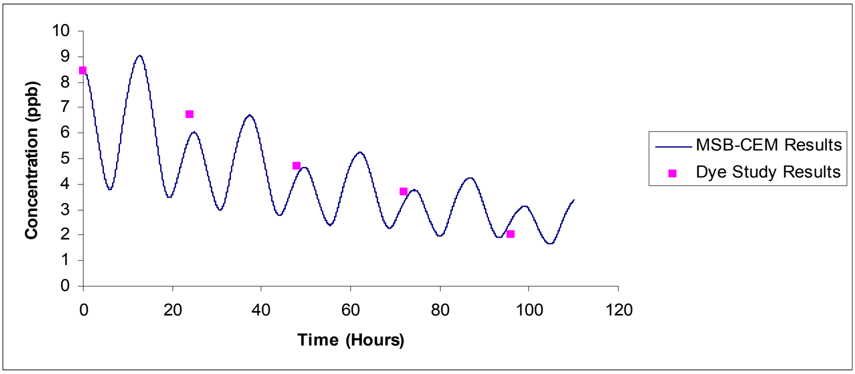

Figure 8: Concentration in segment 2 over time; comparison between predictions and observed dye study results.

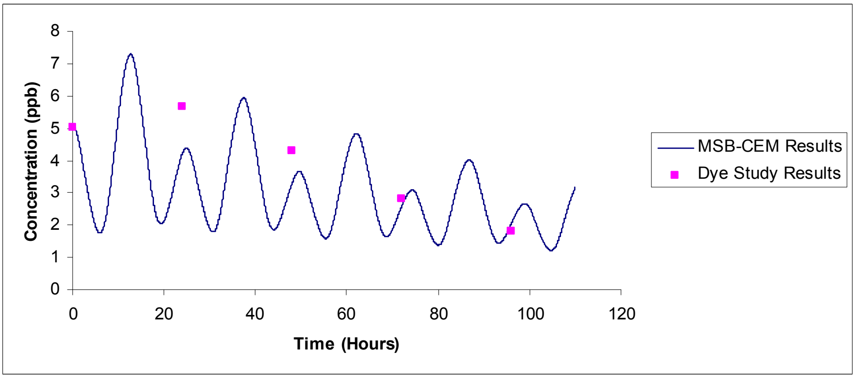

Figure 9: Concentration in segment 3 over time; comparison between predictions and observed dye study results.

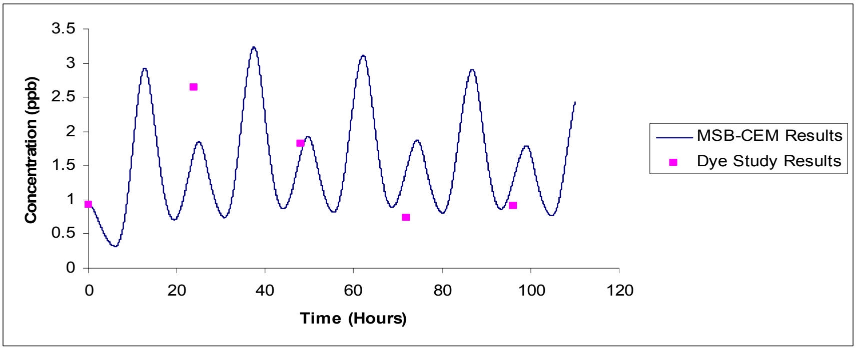

Figure 10: Concentration in segment 4 over time; comparison between predictions and observed dye study results.

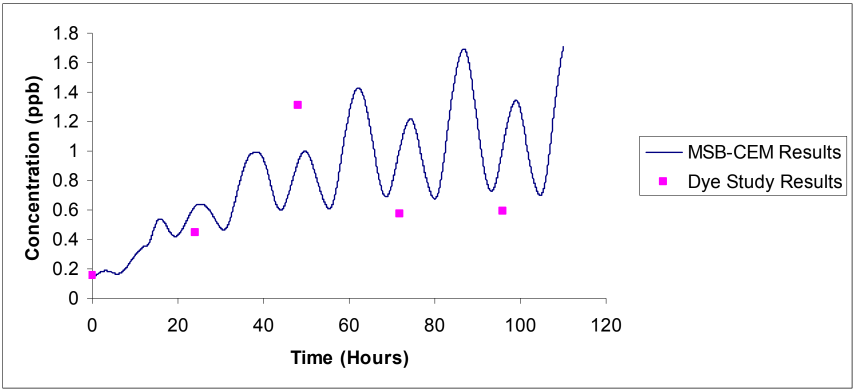

Figure 11: Concentration in segment 5 over time; comparison between predictions and observed dye study results.

The concentration profile of segment 1 (Figure 7) can be elucidated conceptually. As stated earlier, the simulation begins at the onset of the flood cycle. During the flood cycle, water flows from segment 2 into segment 1; if the concentration of segment 2 is greater than segment 1, then the concentration of segment 1 increases. Conversely, if the concentration of segment 2 is less than that of segment 1, then the flow from segment 2 causes the concentration of segment 1 to decrease. During the ebb tide, there is no change in concentration, as there is no water or dye entering the basin.

As one would expect, the arbitrary demarcation of segment 6 (the segment outside Queenstown Creek) results in model predictions well in excess of the measured data (see Figure 12).However, if the demarcation line of segment 6 is moved outwards away from the mouth of the creek, then the predicted concentrations could be expected to approach the measured data. Finally, the

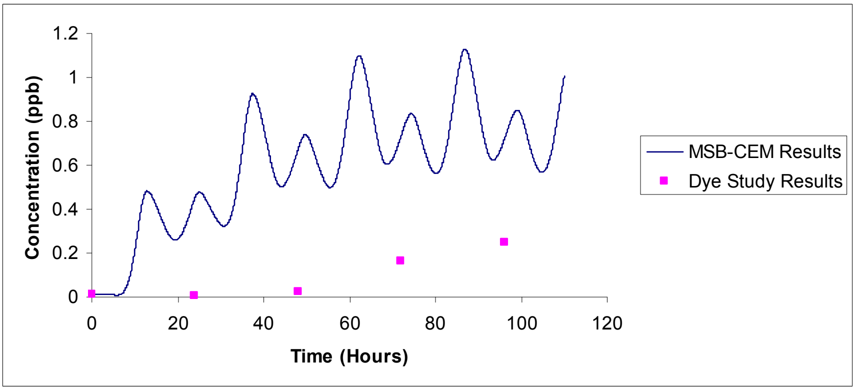

Figure 12: Concentration in segment 6 over time; comparison between predictions and observed dye study results.

innermost segments, 7 and 8, show the largest differences between the model predictions and the data. Sensitivity trials have shown that the predicted concentrations are very responsive to changes in bathymetry. As previously mentioned, the data of the actual 1987 bathymetry of Queenstown Creek has been lost over time; instead, the most recent NOAA bathymetry has been used. Undoubtedly, the shape of the embayment has changed over the years from silting and dredging, causing uncertainties that are especially pronounced in the two segments that are furthest from the discharge point and in the shallow flat areas of the creek. The large discrepancies in segments 7 and 8 are not unexpected given these circumstances.

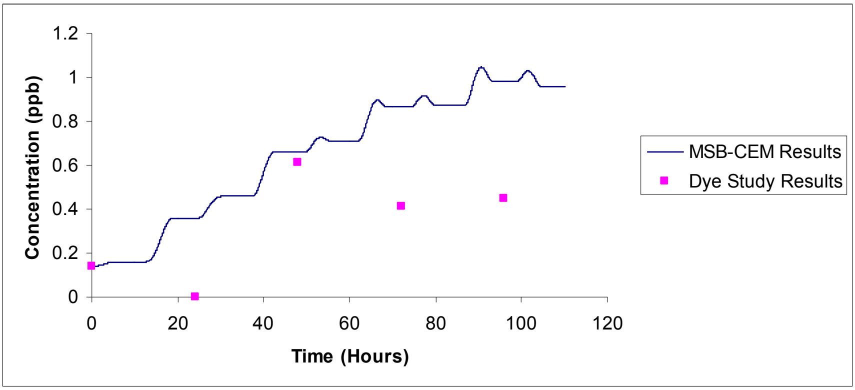

Figure 13: Concentration in segment 7 over time; comparison between predictions and observed dye study results.

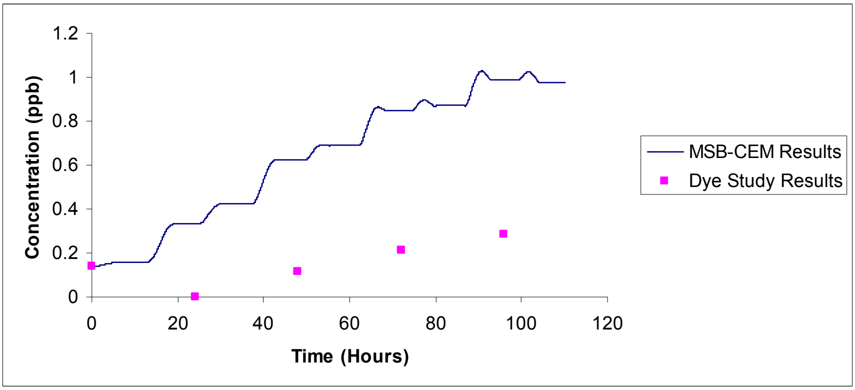

Figure 14: Concentration in segment 8 over time; comparison between predictions and observed dye study results.

Another factor to be noted is that some of the segments, in particular the shallow, innermost ones (namely 7 and 8) may not be well mixed, as is evidenced by the significant presence of marshland. The entire embayment itself need not be well mixed, but each individual segment must meet this criterion [2]. Because of the small size of the embayment, the lack of resolution of the NOAA bathymetric data precludes testing of this hypothesis.

6 Conclusions

Until this present study, the MSB coupled embayment model had not been validated against real data. The opportunity to do so was provided by a recently discovered unpublished Rhodamine dye study conducted on Queenstown Creek in 1987. Predictions from the present model have shown excellent agreement with the actual dye measurements and the conclusions of the dye study report were corroborated. The confirmation of the soundness of the model substantiates previous work that shows the pollution return flow parameter, *b*, is unnecessary when modeling complex embayments.

Acknowledgements

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[7] Stella is a product of ISEE Systems, Inc., formerly High Performance Systems of Hanover, New Hampshire, USA.