Application of the MSB model to ballast water exchange in tidal embayments

S. Mecca[1], S. Morris[2] & R. Barber[3]
[1]*Department of Engineering-Physics-Systems, Providence College, Providence, USA*
[2]*General Dynamics, USA*
[3]*Computational Engineering Group, STFC Daresbury Laboratory, Warrington, UK*

Abstract

For safety reasons, at a captain's discretion, older vessels are often forced to exchange ballast water while in port. This paper examines questions of the optimal strategy for such ballast water exchange. The MSB (Mecca-Severino-Barber) model for well-mixed tidal basins is applied to this marine operation, parameterising the start of the ballast water release at different times in the tidal cycle. This enables the identification of the optimal release time for a typical single pump, single chamber vessel exchanging water in a hypothetical tidal embayment. In practical applications, the optimisation procedure is somewhat more complicated due to the fact that the problem can have multiple objectives: minimising the maximum pollutant concentration as a result of the ballast water exchange and/or minimising the relaxation time *i.e.* the time taken for the pollutant concentration to reduce to an acceptable level. This necessitates the application of multi-objective optimisation.
Keywords: tidal prism, pollution flushing, tidal embayment, ballast water exchange, multi-objective optimisation.

1 Introduction

The MSB (Mecca-Severino-Barber) single embayment model [1] enables a graphical and numerical representation of the process of pollution flushing from a well-mixed tidal embayment temporally loaded with a known quantity of pollutant. The model, which is written in Stella (Stella is a product of ISEE

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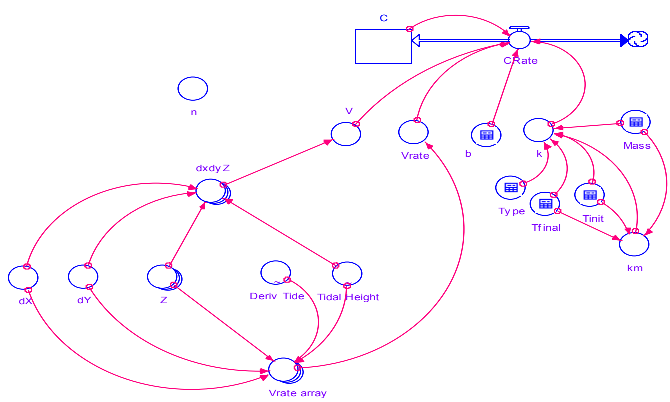
Systems, Inc. of Hanover, New Hampshire, USA), allows for dynamic loading of pollutants [2] and realistic basin bathymetries. The essential rate equations for the pollutant concentration in the embayment have been discussed by Barber [3] and can be derived from the following mass flow equation:

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

where Q is the volumetric discharge across the entrance of the embayment, k is the pollution loading rate (measured as a mass per unit time) and C and V are the instantaneous concentration and volume of the embayment at time, t, respectively. During the ebb flow period, $dV/dt = Q$, allowing the QC term on the right-hand side of eqn. (1) to be cancelled with the CdV/dt term on the left.



C(t) = Concentration of pollution
CrateFlood = Rate of change in pollution concentration during flood tide.
CrateEbb = Rate of change in pollution concentration during ebb tide.
b = Pollution return factor
k = Pollution loading rate (mass per unit time)
km = The highest value of k
n = Internal variable used to keep track of tidal cycles
Period = 12.42 hours in a tidal cycle
Tidal_Height = height above mean low tide (m)
V = Volume of the embayment (m3)
Vrate = Change in volume V over time based on tides
dX = Length of grid block
dxdyZ[i,j] = Volume of every block in the embayment grid at time (t)
dY = Width of grid block
max Tide = Max tidal swing (m)
Deriv Tide = Derivative of Tidal Height
Z[i,j] = Bathymetric data array for embayment
Mass=The total amount of pollutant to be dumped during a tidal cycle (kg)
Tinit=The time at which the polluting starts (hrs)
Tfinal=The time at which the polluting ends (hrs)
Type=This paramter decides the type of loading function to be used.
Type 1 is a constant loading
Type 2 is a user definable step function that is 0 until Tinit and is a constant value between Tinit and Tfinal and 0 again after Tfinal.
Type3 is an inclining ramp function with a definable start and end time.
Type 4 is an instaneous pulse.

Figure 1: Schematic representation of the single embayment MSB model.

During the flood flow period, the *QC* term on the right-hand side of the equation is zero provided there is no pollution return flow into the basin. This results in two rate equations for *dC/dt*, one for the ebb and another for the flood conditions. The MSB model employs the basic state variable approach used in *Systems Dynamics* to represent these rate equations, treating the time-varying pollutant concentration, *C*, in the embayment as a level. The single embayment model is shown graphically in Fig. 1 and described in references [1,2,4,5].

The return of polluted water during the flood tide is governed by an empirical factor, *b*, that is used to modify the volume of the tidal prism; this methodology has been discussed by Barber [3] and more theoretically by Sanford *et al.* [6]. The volume modifying factor is taken as (1-*b*), where *b* varies between 0, for no return flow, and 1, for total return flow. Recent studies using the MSB model have shown that the value of *b* can be mapped onto a physical interpretation of the ratio of the outer to inner basin volumes [2,4]. The MSB model has been validated against both physical tank tests [1] and rhodamine dye studies for single embayments [5] and more recently for concatenated basins [7].

The present study examines the scenario of a ship exchanging its ballast water in a tidal embayment using one, two, or three constant flow rate pumps operating for a sufficient length of time to exchange the ballast water, beginning at a particular time in the tidal cycle. Current regulations strongly recommend that ships exchange their ballast water outside of port. However, the regulations often leave the final decision to the discretion of the ship's captain who may decide for safety reasons to exchange ballast water in port to avoid the dangers associated with a change in the relative position of the centre of gravity and the centre of buoyancy of the ship [8]. Indeed, as ballast water is emptied from a single tank vessel, the centre of gravity and the centre of buoyancy move closer together increasing the potential for instability especially in rough sea conditions. Most modern vessels have multiple tanks/compartments and often multiple pumps. A brief summary of the ballast arrangements on a range of ships is shown in Table 1.

Table 1: Ballast arrangements on a range of ships – adapted from. Armstrong *et al.* [9].

Type Ship	Example	# of Pumps	Pumping Rates (m^3/hr)	# of Tanks	Total Capacity(m^3)
Bulk Carrier	Ormond (P&O)	2	2500	12	59568
Tanker	Similar to Bulk Carriers			3	
Containership	Jervis Bay (P&O)	1	500		16613
Cruise	Grand Princess (P&O)	1	250	29	4345

If a captain decides that it is best to exchange w*ater* whilst in port, the question arises as to when the pumping should be initiated. This decision will depend on many factors some of which relate to fees for having to wait in port longer than necessary, and other potentially more sensitive environmental issues such as consideration of both the maximum pollution concentration as well as the pollution relaxation time. It should be noted that often an overriding issue is that of invasive species taken on by ballast water at a source port and discharged at a destination port. Samples of ballast water reported in the work of Ivanov [10] show levels of eubacteria from 0.7 to 39.5%, enterobacteria from 0 to 2.5%, vibrio spp. from 0.2 to 35.8%, and E. coli. from 0 to 2.5%. In smaller embayments, the release of such ballast water can result in significant pollutant concentrations. The work of Drake *et al.* [11] concluded that ~10^{20} micro-organisms are discharged annually to the Port of Hampton Roads in the lower Chesapeake Bay.

2 Application of the MSB model

The model was applied to a typical tanker ballast exchange using constant rate pumping beginning at a particular time after high tide and continuing until the ballast water had been emptied. For the purposes of the study, the bathymetry of the embayment and the tidal variations were based on Great Salt Pond [5] which is situated on Block Island at the entrance to Long Island Sound. The release time was varied and the pollution concentration was tracked using the tidal variation shown in Fig. 2.

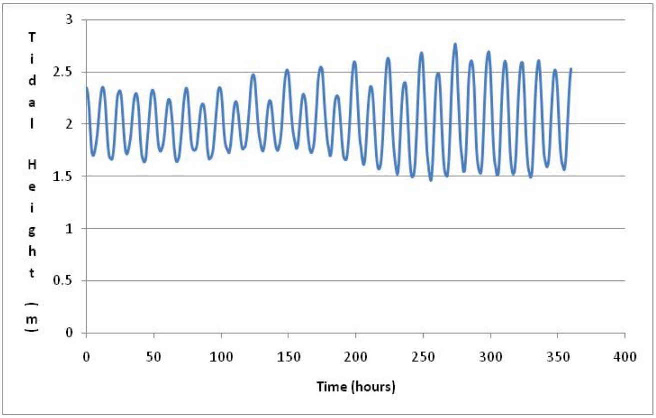


Figure 2: Tidal variation used in the simulations.

Both the maximum concentration and the time for the concentration to relax to 10% of its maximum value were tracked. The parametric simulations were carried out assuming one-, two-, and three-pump operations from a tanker. In addition, the pollution return parameter, *b*, was varied from 0 to 0.5 to determine the effects of the pollution return flow. In total, 192 simulations were performed to yield the results shown in Fig. 3.

The shape of the concentration profiles were found to be affected by the length of the release which is represented in the model as a pulse originating at the start of the release and terminating when the entire ballast contents have been emptied. Since the pumping rate is assumed constant, a square pulse is used for the pollution loading factor. While the conditions represented by these simulations are somewhat hypothetical (though we did use bathymetry and tidal

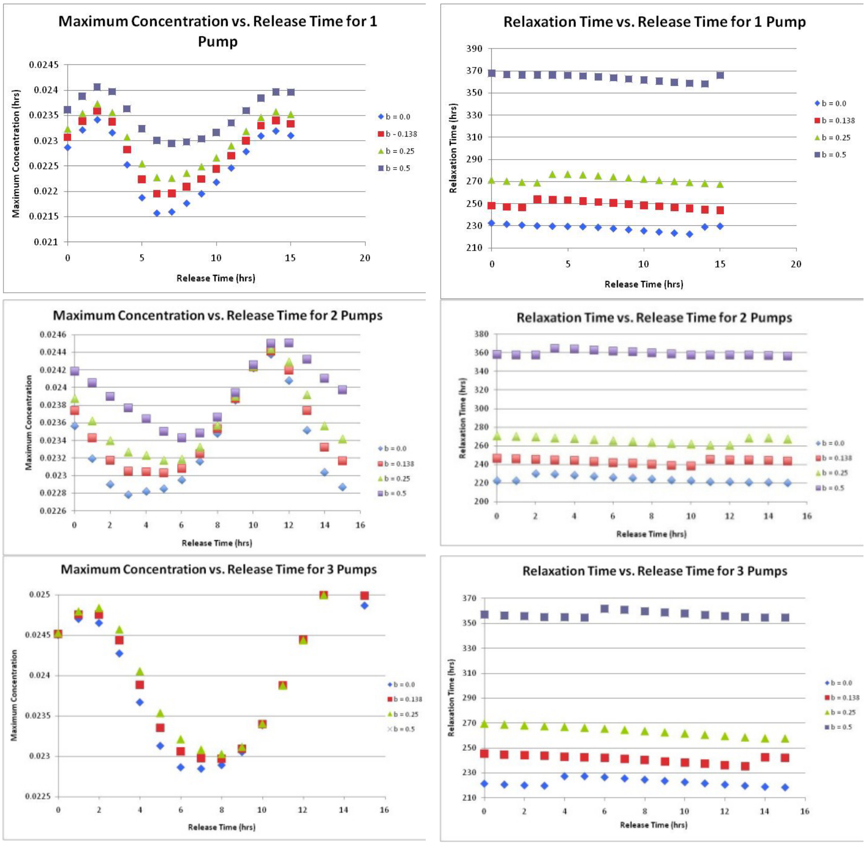


Figure 3: Maximum concentrations and relaxation times versus the release time for one-, two- and three-pump ballast exchange scenarios. See the text for details.

profiles consistent with an embayment used in a previous study [5]), there are nevertheless some interesting features in the results. The differences in maximum concentrations are rather small and the relaxation times span a week or more and are rather insensitive with respect to the release times. However, the concentration profiles have shapes similar to those observed in systematic studies of instantaneously released pollutants [2].

3 Optimisation considerations

It is informative to consider the results from the viewpoint of the optimal release times. Tables 2 and 3 give the release times corresponding to the smallest maximum concentrations and shortest relaxation times, respectively.

Referring to Table 2, if the objective is to minimise the pollution concentration in the embayment, then release times for a one-pump operation should be approximately 6-7 hours after high tide and this is relatively insensitive to the return flow parameter. For two-pump or three-pump operations, there is a similar insensitivity to b though the optimum release times vary with the number of pumps used. It should be noted that the table shows release times beyond 12.43 hours, the primary tidal period. If the tidal cycle was a pure sinusoidal function, the results for 12.43 hour release times would obviously be identical to those for 0 hour release times.

Referring to Table 3, if the objective is to minimise the relaxation time (here defined as the time for the pollutant concentration to return to 10% of its maximum value), then the release times vary quite markedly for different numbers of pumps with little sensitivity to b in the three-pump release times and modest sensitivity to b in the one- and two- pump scenarios.

Clearly, the results will depend on the bathymetry and the tidal variations in the embayment, and therefore a one-size fits all specification of optimal release time is not suggested.

Table 2: Optimal release times for smallest maximum concentration for four values of b and three different pumping scenarios.

No. of pumps	b			
	0.0	0.138	0.25	0.5
1	6	6	7	7
2	3	5	5	6
3	15	13	15	15

Table 3: Optimal release times for shortest relaxation times for four values of b and three different pumping scenarios.

No. of pumps	b			
	0.0	0.138	0.25	0.5
1	12	2	3	12
2	15	10	12	15
3	7	8	8	8

Finally, an obvious question is what is the optimum release time if both criteria, i.e. minimising the maximum concentration and shortening the relaxation time, are equally important? Indeed, when bacteria counts exceed a certain maximum, commercial and recreational activities may be curtailed. One also observes in many basins that shell-fishing and other activities may not be re-opened until pollution levels have relaxed to a certain value. So, both maximum levels of pollutant and times for return to pre-pollutant conditions may simultaneously be part of the objective function. This immediately suggests a multi-objective optimisation. If one can assign cost functions to each of these factors or otherwise assign weights to the multiple objectives, then usual optimisation schemes can be applied. Such assignments may not be too difficult as activities such as shell-fishing have measurable economic impact; recreational activities might be less tangible yet numerous studies of the impact of the BP Gulf of Mexico oil spill were able to assess these impacts. Lastly, the multi-objective optimisation problem can be simplified by a natural limiting of the domain of the problem by imposing constraints such as insisting that the maximum pollution concentration be less than some level related to a serious threat to health or to a threshold beyond which there would be an irreversible impact.

4 Conclusions

The MSB model for well-mixed basins has been applied to an important marine operation, namely, the discharge of ballast water from ships in port. The present study parameterises the optimum start time with respect to high tide. This has been carried out for one-, two- and three-pump operations for a hypothetical though not untypical ship in a somewhat hypothetical embayment to enable the question of when is the optimum time to commence the release of polluted ballast water. The answer(s) depend on whether the objective is to minimise the maximum pollutant concentration in the embayment or to minimise the time for the pollution to return to a particular fraction of the maximum value. More likely, the problem becomes a multi-objective optimisation question if one is trying to accomplish both. The results demonstrate the need to simulate basin-specific conditions including bathymetry, tidal variations at the time of the water ballast operations and, to a certain extent, the pollution return conditions of the tidal embayment. Finally, while the problem addressed in this paper is a real one for a number of vessels in existing shipping fleets, as retrofits and new ships come on line, there a number of ballast water management options, such as heat treatment using engine cooling water, filtration, uv irradiation, oxygen deprivation, shore-based discharge and treatment, and various electro-mechanical systems, that offer the promise that the problem will someday be eradicated. Such options have been in engineering and political discussions for some time [12].

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