Simulating the effects of dredging on the pollutant particles originating from a wastewater treatment facility in a tidal river

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Abstract

A 2-D hydrodynamic finite element model with a Lagrangian particle module is used to investigate the effects of dredging on the horizontal dilution of pollutant particles originating from a Wastewater Treatment Facility (WWTF) in a tidal river. The model is driven by the semi-diurnal (M_2) tidal component and includes the effect of flooding and drying of mud flats. The particle tracking method consists of tidal advection plus a horizontal random walk model of sub-grid scale turbulent processes. Our approach is to perform continuous pollutant particle releases from the outfall, simulating three different scenarios: a base-case representing the present conditions and two different dredged channel / outfall location configurations. Lagrangian particle concentrations are simulated on finite elements and dilution improvement ratios are presented for both scenarios. Results show that although no particles leave the river in a single M_2 cycle, flushing takes place in longer time scales. Simulated dilution maps show that relocation of the WWTF outfall into the dredged main channel is required for increased dilution performance. The addition of a pool at the head of the river also improves dilution by adding to the tidal volume. Case oriented short-term investigations of coastal hydrodynamic problems suitable for Lagrangian particle methods should be encouraged to improve our knowledge of estuarine processes and how we model them while providing solutions to the management community in time and budget constrained decision making.
Keywords: numerical modeling, Lagrangian particle tracking, tides, pollutant, dredging, wastewater treatment facility, finite elements, dilution, random walk diffusion.

1 Introduction

In order to compensate for projected coastal population boost and resulting ecological pressure increase, the environmental regulations in the United States are becoming more and more stringent. This causes smaller towns with limited resources to struggle financially and technologically so as to meet these regulations in the very-near future. In the case of Waste Water Treatment Facilities (WWTF's) that discharge in ecologically sensitive waterways such as estuaries, this implies periodic upgrading or replacement of the treatment technology to make up for increased volume and/or changing pollutants. Since this technological operation is almost always financially unviable and in some cases even impossible, towns usually explore alternative methods to solve their WWTF discharge problems. These include measures such as dredging operations, consolidation and relocation of outfalls and diffuser reconfigurations or any combination of these. However, how these operations will effect the existing situation is usually hard to predict, considering the lack of resources and time to initiate and complete long-term investigations. In such cases, which demand relatively prompt and economical answers, proven numerical models can provide reliable predictions that engineers and managers can make use of, given the model limitations are well-known and this factor is incorporated into operational decision making.

In this paper, we study the effect of dredging on the hydrodynamics and domain-wide horizontal dilution improvement ratios of pollutants originating from the Town of Durham WWTF in Oyster River, New Hampshire. This secondary WWTF no longer meets present discharge dilution standards. Alternatives under consideration include upgrading treatment, moving the outfall several kilometers to a deeper location, and dredging. This last option would also keep the channel useable throughout the tidal cycle for recreational purposes and is the subject of the study described here. Our approach is to simulate a base-case, representing the present conditions, and two dredge / outfall location scenarios to study how these configurations will affect the distribution of pollutants in the river and the resulting lateral dilution improvement ratios. Lagrangian time-released particle methods, which are naturally suited for modeling of waterborne particles, are used to simulate pollutant distributions throughout the river in tidal time.

2 Oyster River

The Oyster River is a tributary of the Great Bay Estuarine System (GBES), located in the State of New Hampshire in the Northeastern United States (Figure 1). The river's tidal portion is 4.8 km long following its navigational channel and it extends from the GBES junction on the east to the Mill Pond Dam in Durham on the west. This relatively shallow river can be divided into two sections according to its bathymetry: a deeper lower section extending from the mouth at GBES to the Bunker Creek, and a shallower upper section extending between the Bunker Creek and the Mill Pond Dam at the head. The Mean Water Level (MWL) main channel depths average roughly 4 m in its lower section and 2.5 m in its upper section. The channel configuration is typical of New England estuaries and consists of a narrow and deeper main channel, surrounded by large areas of mud flats that dry at low tide on both sides. Several creeks entering the river also dry during low water periods.

The Oyster River's drainage area is approximately 78 km^2 and the mean freshwater discharge at the dam is 0.5 m^3/s [1]. Due to this freshwater input, there is stratification around the head when there is no current or wave agitation. This stratified water column quickly mixes under the influence of tidal currents and the river can be considered well-mixed under normal conditions. The river is subject to tidal action through the GBES junction. The M_2 tidal amplitude at the mouth is 0.83 m [2]. This causes maximum instantaneous tidal velocities on the order of 70 cm/s in the main channel in the lower half of the river [3]. The tidal currents are also strongly dependent on the topography.

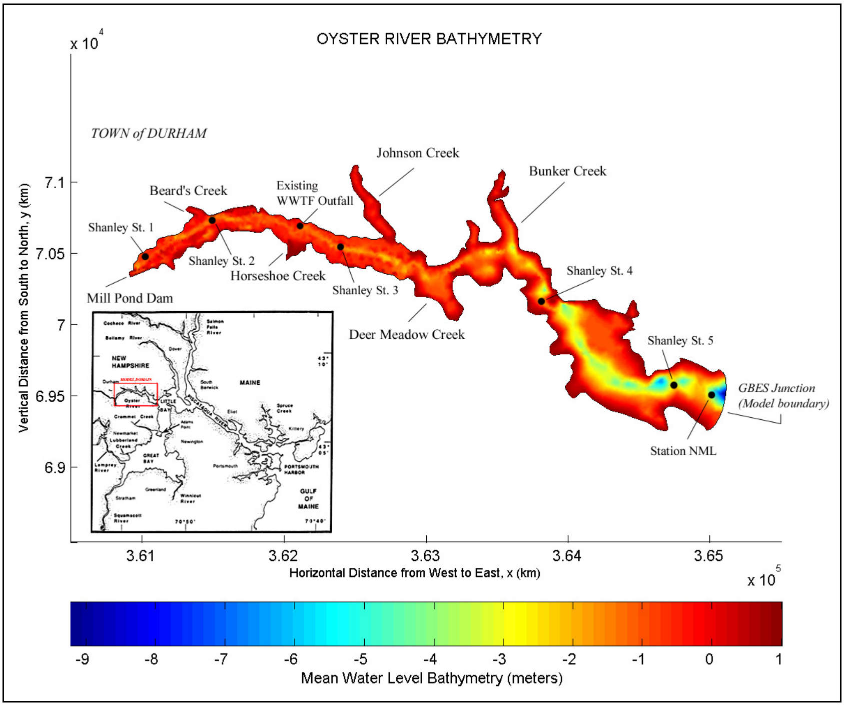

Figure 1: The Oyster River domain geometry and its MWL bathymetry. Important geographic features are also shown. Inset establishes the model domain (red rectangle) in relation to the Great Bay Estuarine System (GBES).

3 Numerical model

The vertically-averaged numerical circulation model (BELLAMY) accounts for flooding and drying of mud flats and solves for the state of the system based on tidal forcing and wind stress. The model includes riverine freshwater input, although salinity effects are ignored. The non-linear system of governing equations of the model is solved iteratively at each time step. The reader is referred to [4] for the standard governing equations and detailed solution schemes.

Lagrangian particle tracking is performed by advecting particles in the simulated Eulerian velocity field utilizing a 4^{th} order Runge-Kutta (RK) scheme at the end of each hydrodynamic model time step. Superimposed upon this is a random walk model of horizontal eddy diffusion [5], which enables a particle-based statistical treatment of turbulent mixing. For all results herein, the random walk model uses a uniform diffusivity.

4 Computational setup and dredge scenarios

A base-case representing the present conditions and two dredge scenarios are simulated in order to assess the effects of proposed dredging operations. The dynamic elements of the computational setup, such as the finite element mesh and the time step, vary between different simulations since they are dependent on the dredge scenario geometry, *i.e.* the width and length of the dredged channel and its bathymetry. These factors dictate what the grid resolution should be to resolve the flow, which, in turn, controls what the model time step should be to meet the Courant-Friedrichs-Lévy (CFL) condition. Several other elements of the computational setup, such as the boundary conditions and drag profile, are static, *i.e.*, invariable between different simulations.

All simulations are forced by the principal lunar (or M_2) tide, applied along the Eastern boundary that opens into the GBES. The amplitude and phase of this M_2 forcing function are 0.83 m and 166° respectively after Swift and Brown [2]. A constant bottom drag coefficient of 0.0025 is set throughout the domain. No riverine freshwater inflow at the head and no wind are specified in order to isolate and investigate the mixing resulting from tidal dynamics only. The water discharge from the WWTF outfall is also not specified due to its small contribution (0.057 m^3/s on average) to the tidal prism.

The Lagrangian particle setup consists of passive “pollutant” particles released from the existing or proposed outfalls at each model time step in tidal time. The number of particles released at each time step is arranged so that there is a total of 16,000 particles in the river at the end of the simulation. The initial particle launch coincides with maximum flood velocities at the outfall. This ensures that particles travel approximately the same distance in both directions with respect to the original release point in one M_2 cycle. A constant diffusion coefficient of 1.5 m^2/s is used to simulate the turbulent diffusion of particles launched in the flow field.

4.1 Base-case: the present situation

The base-case is discretized on a grid of 12,835 linear triangular elements, constructed using the public-domain grid generator BatTri [6]. The characteristic length of this grid, defined as $\sqrt{2A}$ where A is the element area, ranges between 2.6 m and 41.85 m with a mean of 18.8 m. The bathymetry of the grid (Figure 1) is interpolated from the National Oceanic and Atmospheric Administration (NOAA) digital charts complemented by a high resolution data set (down to 0.5 m between two points) acquired from the Center for Coastal and Ocean Mapping at the University of New Hampshire. A model time step of 27.945 seconds is used. Particles are released from the existing outfall location on the flats. Ten particles are released into the flow field at each model time step.

4.2 Dredge scenario #1: main channel dredging with existing outfall

The first dredge scenario (*DS1*), shown in Figure 2, consists of a dredged channel, which extends from the Mill Pond Dam down to where it intersects with the existing deep channel just south of Bunker Creek. The dredged depth is roughly 2.33 m with respect to Mean Water Level (MWL) and 1.5 m with respect to Mean Lower Low Water (MLLW). The bottom width of the channel is 6 m and the sides have a slope of 1:3, making the total dredged width 20 m at MWL. The base grid is modified to incorporate this dredge scenario. This required refining it to have approximately 7-10 computational nodes across the width of the dredged channel. The resulting computational grid, a section of which is shown in Figure 2 in the vicinity of the existing outfall, has 55,548 elements. The characteristic length ranges from 1.11 m to 41.72 m, with a mean of 7.10 m.

Due to the considerable increase in the mesh resolution in the upper half of the river resulting from the refinement process, the model time step is reduced to 11.178 seconds (this corresponds to a 4^{th} order RK particle tracking minimum time step of roughly 5.6 s) to satisfy the Lagrangian CFL condition in the dredged channel. It should be noted that this optimized time step does not satisfy the CFL criteria at every element of the grid for the observed maximum velocity of 70 cm/s given in [3]. This however does not affect the quality of the solution since the overall velocities in the domain are much smaller than this instantaneous maximum. The WWTF outfall is left at its present location on the flats. Four particles are released into the flow field at each model time step.

4.3 Dredge scenario #2: main channel plus the mooring pool dredging with relocated outfall

The second dredge scenario (*DS2*) consists of the addition of a mooring pool at the head of the river to the dredged channel defined in the first scenario (not shown). The MWL depth of the pool is set to 2.33 m with sides tapering at a slope of 1:3. Since the grid already has the necessary resolution in the pool area, no major changes are performed on the discretization used in the first dredge scenario, with the exception of the changing bathymetry in the pool region. The

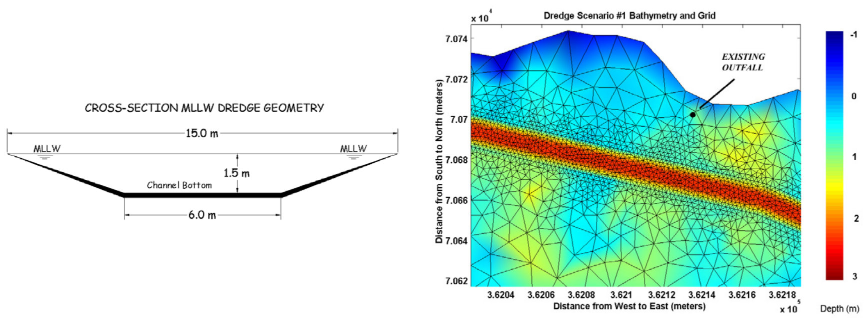

Figure 2: Dredge Scenario #1 definition sketch (left) at mean lower low water and its mean water level incorporation to the finite element domain (right) in the vicinity of the existing WWTF outfall.

model time step also remains the same as the first dredge scenario. At each model time step, four pollutant particles are released from the proposed WWTF outfall, which is moved into the dredged channel in this simulation.

5 Lagrangian study

In order to calculate dilution improvement ratios between the base-case and the dredge scenarios, depth-averaged particle concentrations at every grid element are calculated first for each of these three simulations according to:

$$C^e = \frac{NP^e}{A^e} \quad . \tag{1}$$

Here C^e is the depth-averaged concentration at the element (number of particles/m^2), NP^e is the number of particles in the element and A^e is the area of the element e (m^2). Then, once the concentration fields are known for all three cases, elemental dilution ratios are calculated for comparison couples (base-case, *DS1*) and the (*DS1*, *DS2*) according to:

$$D^e = \frac{C^e_{ref}}{C^e} \quad , \tag{2}$$

in which D^e is the elemental dilution improvement ratio, C^e_{ref} is the elemental reference particle concentration (base-case or *DS1*) and C^e is the particle concentration at element e for either the *DS1* or *DS2*. This calculation is performed on every grid element throughout the domain with approximately 4.6 minute time intervals in the tidal cycle. The discontinuity that occurs when C^e is equal to zero is eliminated by removing from the calculation the elements that do not contain particles at a specific time step of the *DS1* and *DS2* simulations. Note that the dilution calculation is independent of the water depth.

Due to the nature of the study and space limitations, we choose not to show the concentration fields here and instead concentrate on the dilution improvement ratio maps. Particle concentration and dilution improvement ratio maps at several stages of the tidal cycle and related animations, which are especially useful in showing the extent of flooding and drying in the river, can be accessed at http://www-nml.dartmouth.edu/Publications/internal_reports/NML-03-12/ for all three cases (base, *DS1* and *DS2*). Figure 3 shows the dilution improvement ratio, D^e, obtained as a consequence of the *DS1* at four different phases of the tide. At high-tide (Figure 3A), dilution ratios of roughly 0.5 to 1 are simulated around the outfall, meaning that the *DS1* particle concentrations are higher than or equal to the ones predicted by the base-case in the area. The increased dilution shown in red in the upper tip of the particle cloud is due the fact that this section is populated largely by base-case particles. Most of the *DS1* particles do not reach this area due to lower velocities. The effect of this is also seen at maximum ebb (Figure 3B), which shows mostly increased dilution due to the large amount of base-case particles that are being transported downriver from the upriver sections. The base-case particles are then swept away from the outfall area as a result of higher ebb velocities experienced in the base-case, and decreased dilution (shown in blue) is simulated at low tide (Figure 3C) around the outfall, which now contains mostly *DS1* particles. The large number of base-case particles that advect and diffuse farther in the seaward direction now result in increased dilution patches in this area. The following maximum flood (Figure 3D) contains one decreased dilution zone in the middle and two increased dilution zones in the seaward and landward extremities of the particle cloud. The seaward end increased dilution zone contains mostly the base-case particles from the previous ebb, while the landward end positive dilution zone contains base-case particles that are advected farther in the upriver direction because of higher velocities. The decreased dilution zone in the middle contains mostly *DS1* particles from the present flood and the ebb phase preceding it.

The particle concentrations simulated by the *DS2* are observed to be very similar to the ones simulated by the *DS1*. This is an expected result since the addition of the dredged mooring pool is somewhat a local disturbance and its effect on the system-wide currents is relatively small, decaying quickly as one moves seaward. Large differences (up to ±0.2 particles/m^3) exist but these are localized and occur in the close vicinity of the outfall region due to the fact that outfall locations are different between the two cases (the outfall is moved to its proposed dredged channel location in *DS2* from its present shallow location in *DS1*). Since the domain-wide differences between the *DS1* and *DS2* particle concentration fields are very small and visually hard to distinguish from each other, we are taking a different approach and present the results using more simplistic but succinct two-color contour maps in which the dilution is defined as either increased (red) or reduced (blue). Figure 4 shows snapshots of dilution ratios at four different phases of the M_2 tide as above. At high tide (Figure 4A), the overall dilution is increased with the addition of the mooring pool to *DS1* as shown by the large percentage of red regions. The decreased dilution around the proposed dredged channel outfall is a direct effect of the relocation of the outfall between the two dredge scenarios. Since particles are directly released into the dredged channel in *DS2*, the simulation shows increased concentration in this area. Maximum ebb picture (Figure 4B) shows increased dilution in general, with scattered decreased dilution zones. At low tide (Figure 4C), when the flow and particles are all confined in the dredged channel, increased dilution still dominates the domain, even around the proposed outfall. At maximum flood (Figure 4D), the same trend is repeated.

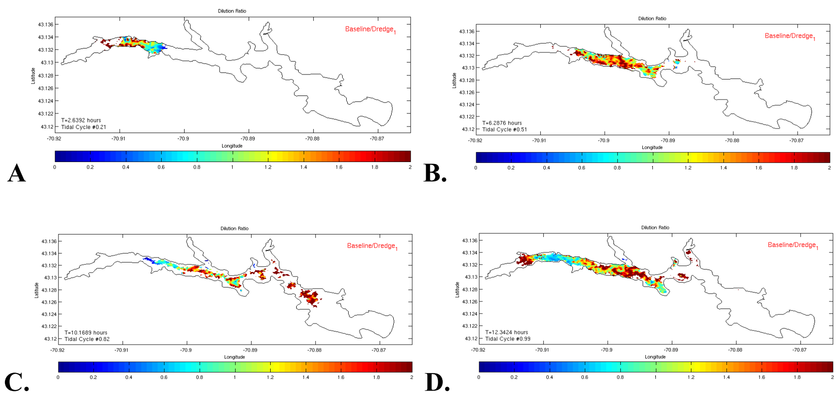

Figure 3: Dilution improvement ratios throughout the Oyster River caused by the *DS1*. Frames A through D show high tide, maximum ebb, low tide and maximum flood at the WWTF outfall respectively. Color bar gives the dilution ratio. Cooler colors (D^e<1) and warmer colors (D^e>1) show reduced and increased dilution respectively. A dilution ratio of 1 (green) means base-case and *DS1* concentrations are the same.

It is important to note that although this analysis draws a very informative picture of the overall horizontal dilution in the domain, it hides details. For example, the elements which do not contain reference particles (the numerator C^e_{ref} in eqn. (2)) but contain particles from either one of the *DS1* or *DS2* cases are excluded from Figures 3 and 4 since the definition of D^e, eqn. (2), requires the presence of both the numerator and the denominator. This is particularly important for the *DS1* versus *DS2* comparison since the reference case (*DS1*) particles are subjected to slower velocities than their counterparts in the *DS2* case and this causes *DS1* particles to be absent from a number of elements at the seaward end of the particle cloud which contain *DS2* particles. However, this only occurs on a very small percentage (4-5%) of elements and combined with a dominant seaward transport, which is a positive characteristic for flushing, justifies our method for comparative purposes.

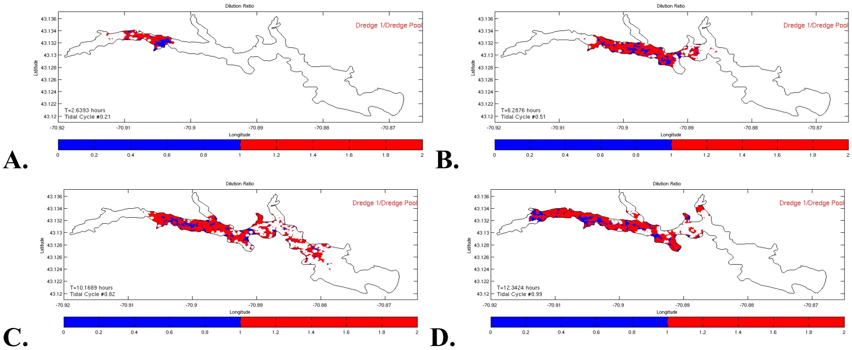

Figure 4: Regions of either increased (red) or reduced (blue) dilution throughout the Oyster River caused by the addition of the mooring pool to the *DS1*. Frames A through D show high tide, maximum ebb, low tide and maximum flood at the WWTF outfall respectively.

6 Conclusion

The effect of channel dredging as a way of improving the dilution and flushing characteristics of the Oyster River is investigated using a Lagrangian point of view using a vertically-averaged hydrodynamic model. A base-case representing the present conditions and two dredged scenarios are investigated. The Lagrangian particle release study performed using passive, non-decaying particles provides a clear and valuable view of the particle concentrations and dilution improvement ratio distribution in the river over tidal time. It is observed that in the absence of river inflow and Westerly winds, no particles originating from the WWTF outfall leave the Oyster River in one M_2 cycle. Widening and deepening of the main channel through dredging increases the far-field dilution away from the outfall; however an increase in the concentration of particles is observed around the present location of the outfall. This is due to the overall drop in current magnitudes in this shallow area which is outside the dredged channel. The relocation of the outfall into the main dredged channel in dredge scenario #2 improves this situation and increased dilution is simulated both around the proposed outfall and throughout the river during most phases of the tide. This emphasizes one more time the importance of relocating the WWTF outfall in the dredged channel.

The Lagrangian particle tracking methods have been improved extensively in the recent years [7, 8, 9, 10] due to the increase in computer power and advances in the modeling and visualization methodologies. Being able to launch a larger number of particles (O ≈ 1 million on parallel processors) than we were able to do a few years ago permits statistically significant experiments that complement the more traditional Eulerian methods and provide more insight by introducing Lagrangian residuals and particles with identities (*i.e.*, sediments, heavy metals, fish larvae, etc). Case-oriented short-term applications that bring these methods together such as the one presented here help improve our knowledge and understanding of natural processes and how we model them while providing solutions to the management community in time and budget constrained decision making. The encouragement of these types of applications by the scientific, engineering and managerial communities would generate a positive outcome which would ultimately lead to more effective tools to deal with recurring water quality and water resources problems in the long-term.

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