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TWO-DIMENSIONAL MODELING OF CURRENT CIRCULATION AND CONTAMINANT TRANSPORT IN SURFACE WATERS

Mohamed A. Abdelrhman and Edward H. Dettmann, U.S. Environmental Protection Agency, National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division, 27 Tarzwell Drive, Narragansett, RI 02882.

The main objectives of this paper are to briefly describe and evaluate three different applications of two-dimensional, depth-averaged, finite-element models for hydrodynamics (RMA2) and transport (RMA4) ([1] and [2], respectively), which were run using the FastTABS user interface [3]. Model evaluations are based on the ease and success of performing simulations, calibration, reproduction of prediction runs, and CPU time. A 190-MHz DEC Alpha 2100 Server was used to run these applications. The models are used to simulate dynamic flow circulation and transport in the New Bedford Harbor and Slocum River estuaries, side embayments of Buzzards Bay, MA, as well as steady-state circulation in Lake Havasu, an in-line impoundment on the Colorado River in Arizona (Figure 1). The applications included different physical conditions and were used to address environmental issues in surface waters such as flushing behavior, residence time, salinity distribution, and origins of different water masses, which may be responsible for observed contamination. The three applications are briefly presented in the order of their complexity.

Lake Havasu showed signs of contamination by coliform bacteria in the London Bridge Channel and Thompson Bay (Figure 1a). The modeling effort focused on defining current circulation patterns and the origins of water masses entering the channel for selected meteorological conditions, as a guide to future field sampling. The results will serve to guide future studies to identify possible areas of coliform loading and transport pathways for these bacteria. Steady-state conditions were assumed in the Colorado River and Lake Havasu. The finite-element grid consisted of 1515 quadratic triangular elements with a total of 3300 nodes. Hydrodynamic simulations identified circulation patterns in the lake for a wet summer season with 15,000 cfs flow and a dry winter season with flow of 6,000 cfs during calm winds. Wind effects on circulation were simulated for prevailing southerly summer winds of 10 mph and northwesterly winter winds of 17.3 mph. Figure 1a shows summer circulation during prevailing southerly winds. Water masses along the northern shore of The Island and from the middle region of the lake entered the London Bridge Channel during windy periods, while during calm periods only water flowing along the eastern boundary entered the channel. These steady-state simulations of the hydrodynamic model were easy to perform and converged to the solutions in 27 seconds of CPU time [4].

The New Bedford Harbor (NBH) estuary displays stressed ecological conditions due to a heavily populated and industrialized watershed. The region north of Rt. I-195 (Figure 1b) has elevated levels of PCBs and has been designated as a Superfund site. Tidal flushing, salinity distribution and velocity field were simulated [5] as part of an in-progress multidisciplinary study of the effect of multiple stressors on estuarine ecosystems. A finite-element grid was constructed with a total number of 1076 quadratic triangular and quadrilateral elements including 3194 nodes. Tidal flushing was calculated for 9 tidal cycles during extreme spring and neap tidal conditions.

The NBH was treated as a vertically well-mixed estuary during the simulation period. Hydrodynamic results were calibrated using field observations of water surface elevation and flow velocity. The model grid was refined a few times to avoid model instabilities and obtain successful calibration results. Transport simulations were calibrated using observations from a dye study. For the median freshwater inflow rate of 0.54 m^3/s, freshwater residence time varied from 2.5 days for spring tide to 3.5 days for neap tide during calm wind conditions. Figure 1b shows the simulated dye distribution 9 spring tidal cycles (112 hr.) after tagging the estuary north of the hurricane barrier with 100 ppb of a conservative tracer. The area north of Rt. I-195 had the poorest flushing behavior, as indicated by maintainance of the highest concentrations during the flushing simulation. These results are being used with observed ecological data to evaluate effects of anthropogenic stressors. The CPU times for the hydrodynamic and transport simulations for 9 tidal cycles were 58.4 and 5.3 minutes, respectively, with a time step of 30 minutes.

The Slocum River estuary was selected as a less-stressed reference system for NBH during the ecological study mentioned above. Tidal flushing, salinity distribution and current velocities were simulated [6] to aid evaluation of ecosystem health under natural stresses (e.g., salinity, flushing behavior, etc.). This estuary has extended tidal flats, and model boundaries change location as a result of wetting and drying during tidal flooding and ebbing. Moreover, a complex sand bar system is exposed at the mouth of the estuary during low tidal stages. This restricts flow out of the estuary, causing a delay of approximately two hours in the time of low tide inside the system. A finite-element grid of 1632 quadratic triangular and quadrilateral elements with a total of 4775 nodes was used for model simulations. The models treated the moving boundary problem by excluding or adding elements to the solution domain according to water surface elevation. This process triggered instabilities in the hydrodynamic model and mass loss in the transport model which were hard to control. The time step was reduced from 30 minutes to 15 minutes and extensive grid refinements were tried, but did not always control model instabilities. This problem was addressed by allowing gradual wetting and drying of elements by assuming a linear relationship between water surface elevation and water coverage of an element at low water levels (referred to as "element porosity"). This technique reduced abrupt changes in the solution domain, and improved mass conservation. The model became stable for many run conditions, and calibration of the hydrodynamic model was performed using field measurements of water surface elevation for a full tidal cycle. Calibration of the transport model was performed using field measurements of salinity along the length of the estuary at slack high tide. The hydrodynamic and transport models simulated a period of 9 tidal cycles prior to the field survey of salinity, using field measurements of freshwater inflow and predicted tide elevations from NOAA tide tables. Freshwater residence time was 4.07 days and 5.31 days for spring and neap tidal conditions, respectively, with a median freshwater inflow of 0.7 m^3/s. Figure 1c presents the distribution of salinity during slack ebb of a spring tide. CPU times for 112 hr. of simulation (time step = 15 min.) were 262 and 16 minutes for the hydrodynamic and transport simulations, respectively.

The RMA2 and RMA4 models are suitable for use by scientists and engineers with some modeling background. Application of the depth-averaged finite element models for steady-state conditions in Lake Havasu was direct, easy, and satisfactory. After a few trials and minor grid refinements, the application to the dynamic conditions in NBH, which had fixed boundaries, was successful and calibration was satisfactory with a model time step of 30 minutes. The application to the Slocum River estuary was much more difficult because of model instability triggered by and mass loss arising during wetting and drying of elements. This proved to be a particularly difficult problem in regions with a steep water surface slope. Grid refinement and reduction of simulation time step did not always eliminate model instability, which was generally alleviated by use of an algorithm simulating gradual wetting and drying of individual elements. Such stability problems are commonly encountered with moving boundary problems, and indicate the need for further development of algorithms for smooth handling of such applications.

The user interface available for RMA2 [3] permits screen-based grid generation and specification of input data, screen-based editing of the grid and input data, as well as graphical viewing of simulation results, and is quite convenient. The user interface for RMA4 does not allow for screen-based input or editing of input data, but does permit graphical viewing of model output. For applications with the number of grid nodes used in these applications, run times on 486-based personal computers were quite slow, making early phases of the work described here tedious, but run times on the DEC Alpha 2100 and comparable work stations are fast enough for convenient model use. Brief theoretical basis with general mass and momentum conservation equations are included in model documentation [3], users must refer to other documents (e.g., [1] and [2]) to ascertain that physical processes relevant to their application are included in the models. The limitations of two-dimensional models in describing vertical variations due to wind forcing and buoyancy (density variation) effects should not be underestimated. Three-dimensional models are better suited to such cases. The transport model implements the advection-diffusion equation with sink-source and first-order decay terms. More sophisticated water quality and contaminant processes are not treated by the model. Robustness of these models will be tested in future applications, which may include coupling to water quality and ecological models for use on advanced computers.

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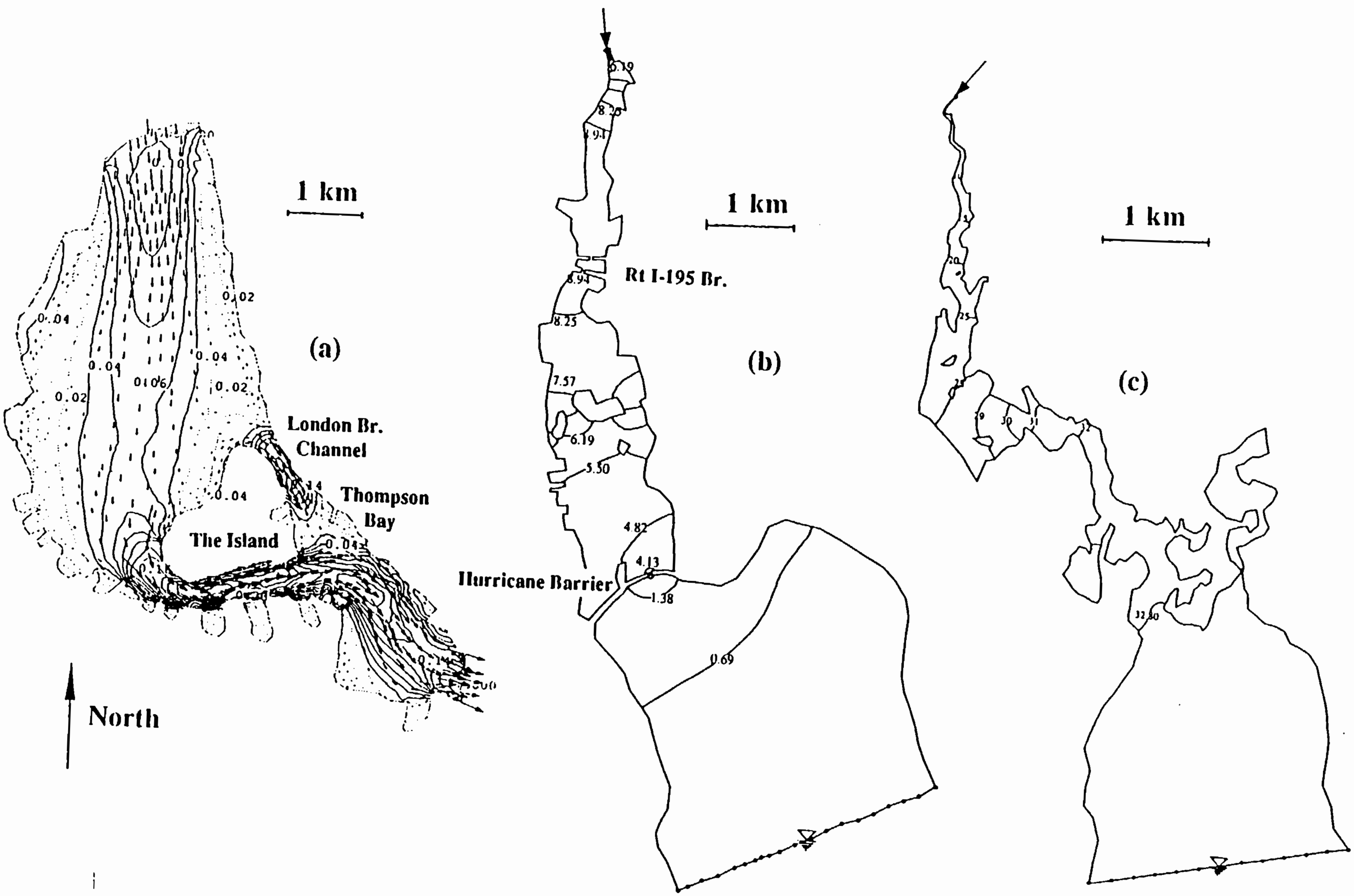
1 km
(a)
0.04
0.02
0.04
0.06
0.02
0.04
0.02
0.04
London Br.
Channel
Thompson
Bay
The Island
0.04
North
1 km
(b)
6.19
8.25
8.91
8.94
Rt I-195 Br.
8.25
7.57
6.19
5.50
4.82
4.13
Hurricane Barrier
1.38
0.69
1 km
(c)
20
25
29
30
31
32.80

Figure 1: Sample simulation results: (a) current vectors and velocity contours (fps) in Lake Havasu during prevailing summertime winds, (b) dye distribution (ppb) in New Bedford Harbor at high tide 9 tidal cycles after tagging with a uniform concentration of 100 ppb, and (c) salinity distribution (parts per thousand) in the Slocum River at low tide.

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16. ABSTRACT

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