APPLICATION OF ADCIRC-2DDI TO MASONBORO INLET, NORTH CAROLINA: A BRIEF NUMERICAL MODELING STUDY

by

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APPLICATION OF ADCIRC-2DDI TO MASONBORO INLET, NORTH CAROLINA: A BRIEF NUMERICAL MODELING STUDY

PART 1: INTRODUCTION

1. The two-dimensional, depth-integrated version of the hydrodynamic model ADCIRC, [ADCIRC-2DDI], was used to simulate tidal flow through Masonboro Inlet, North Carolina. The primary objectives of this study were to demonstrate that ADCIRC-2DDI is able to simulate realistic flows through small coastal inlets and to identify any potential limitations that ADCIRC-2DDI might have for modeling inlet dynamics. The theory and implementation of ADCIRC-2DDI is described in detail by Luettich et al. (1991). ADCIRC-2DDI has been applied successfully to several large scale field sites including the Gulf of Mexico (Westerink et al., in review), the North Sea (Luettich et al. 1991) and the New York Bight. The present application is the first attempt to use this model on a purely small scale problem.

2. A model domain was established over approximately the same region as the "fine grid configuration" used by Masch et al. (1977) [hereafter M77]. Boundary geometry was digitized from the land formations shown in Figure 22 of M77. Bathymetries were taken from Figure 23 of M77 and are appropriate for September 1969 conditions. ADCIRC is presently not able to include tidal flats [i.e., parts of the model domain that are wet part of the time and dry part of the time]. Therefore, the two areas of tidal flats along the western side of M77's fine grid were not included in our grid because they have an elevation above mean sea level. Also there is presently no provision in ADCIRC for an "over flow " boundary. Therefore, the entire jetty [including the weir section] was assumed to be a solid boundary.

3. A triangular finite element grid was generated using the TRIGRID package (Henry and Walters 1991) and is shown in Figure 1. Also shown is a contour plot of bottom bathymetry from the nodal water depth information contained in the finite element grid. The grid contained 415 nodes and 704 triangles. For this grid ADCIRC-2DDI requires about 0.5 Mbytes of central memory and runs at about 0.5s per time step on an ALR 80486-33Mhz workstation.

4. ADCIRC presently requires the specification of elevation boundary conditions on all open boundaries. The boundary condition on each open model boundary was determined from water level measurements made on 12 September 1969 [as reported in Figures 16 – 20 of M77] at the gage closest to the model boundary. Water levels at each station were de-meaned and fit with an M_2 curve. The resulting boundary

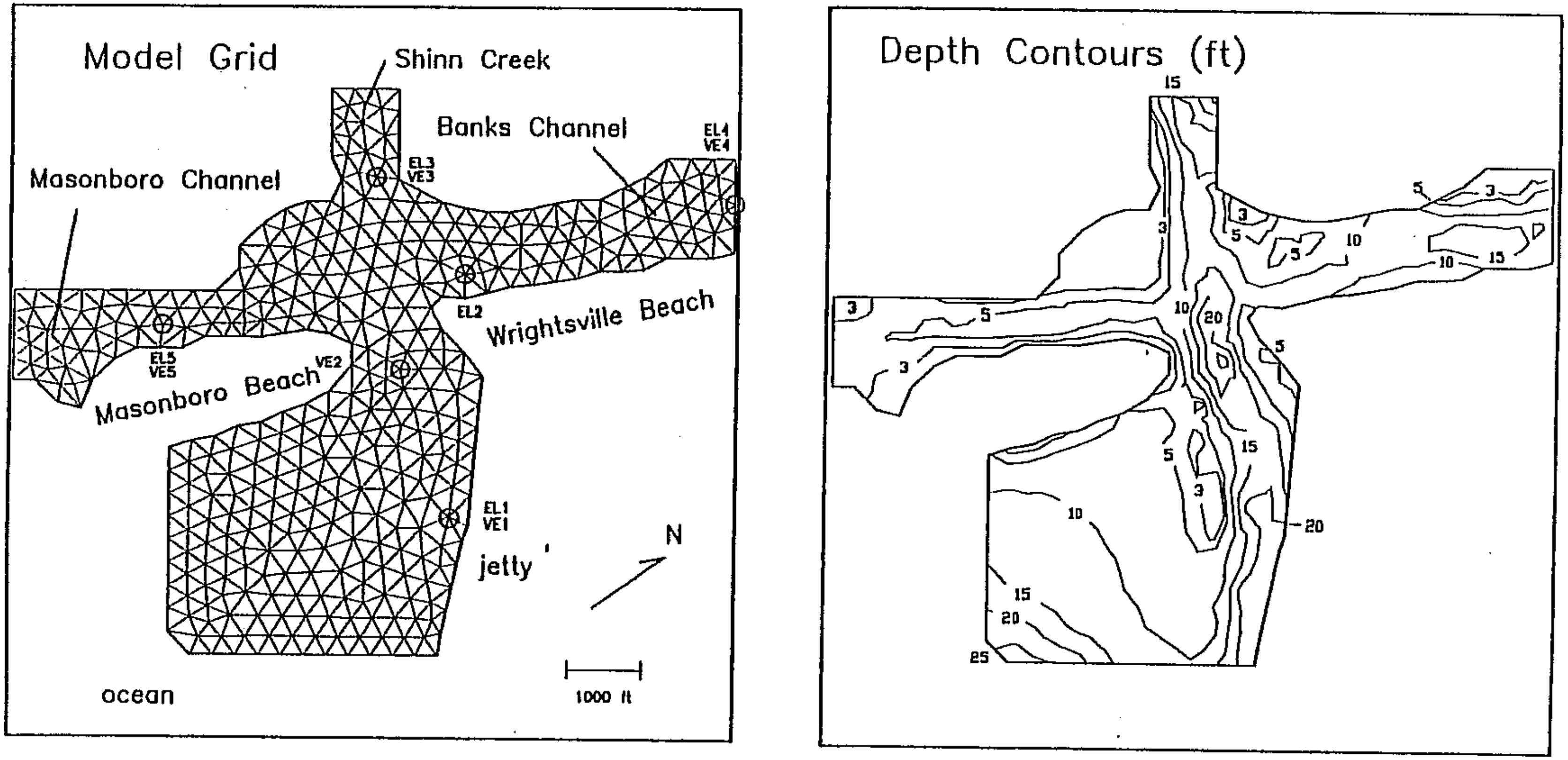

Figure 1. Finite element grid and bathymetry used in the ADCIRC-2DDI simulations of Masonboro Inlet. EL1 – EL5 mark the assumed locations of water level gages 1 – 5. VE1 – VE5 mark the assumed locations of velocity measurement stations 1 – 5.

conditions are given in Table 1. Figure 2 presents a comparison between the model boundary conditions and the measured elevations. It is noted that while measured water levels were nearly in phase at gages 2 – 5, there was approximately a 30 deg [or about 1 hr] phase lead at gage 1. The distance between gage 1 and gages 2 – 5 ranged from about 3500ft to 6500ft. Therefore only 5 to 10 percent of the phase difference can be accounted for by the inviscid propagation speed of the tidal wave.

Table 1
<u>Open Boundary Conditions Used in Model Runs</u>

Boundary	*Gage #	Amplitude (ft)	Phase (deg)
ocean	1	2.25	87
Banks Channel	4	1.90	116
Shinn Creek	3	1.85	116
Masonboro Channel	5	1.75	116

*gage locations are shown in Figure 1

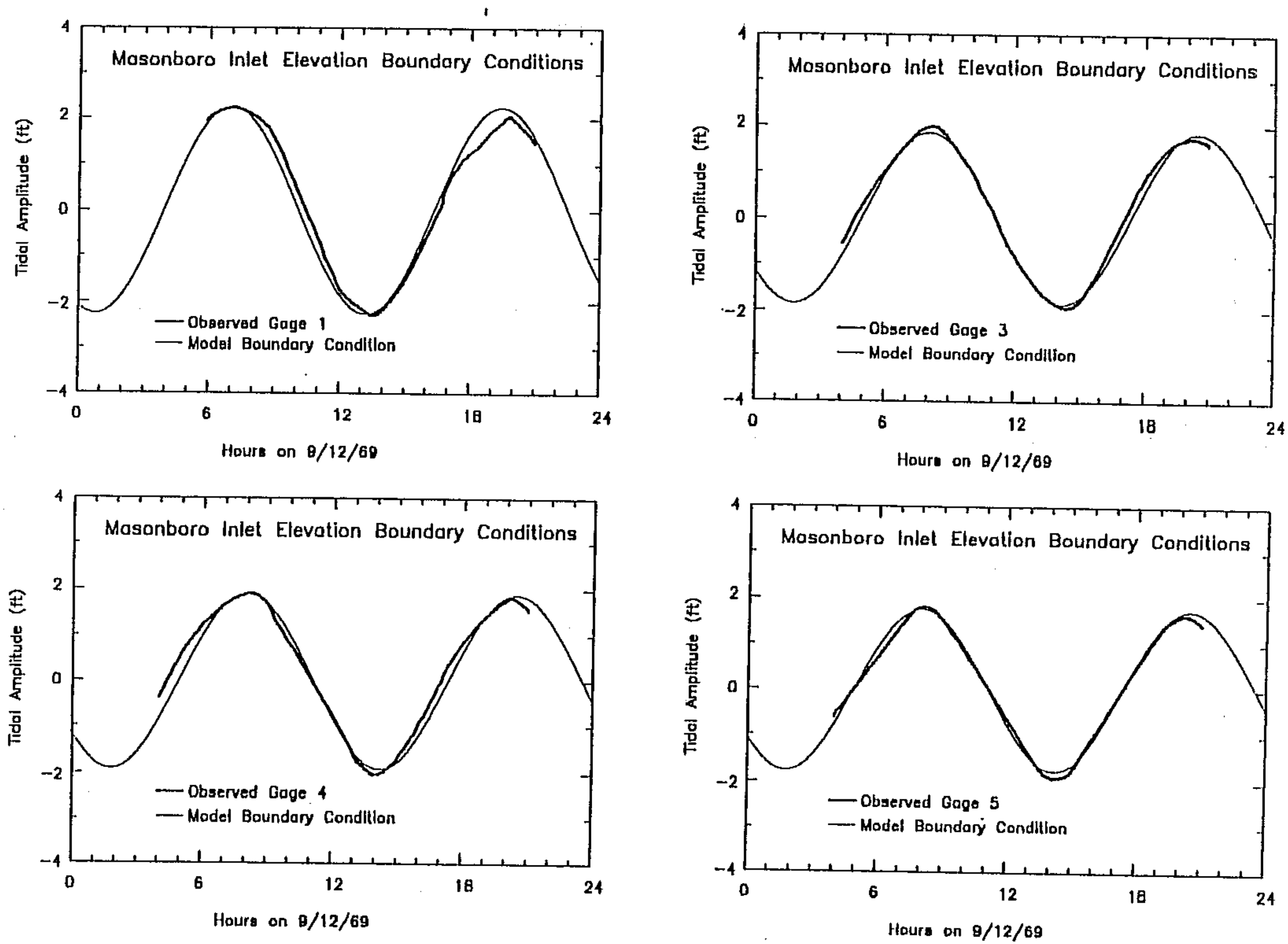

Figure 2. Comparison between measured elevations and boundary conditions used in the ADCIRC–2DDI simulations of Masonboro Inlet.

PART 2: SIMULATION RESULTS

5. ADCIRC–2DDI was cold started and run for five tidal cycles using the M_2 forcing shown in Table 1. The simulation was started at approximately mid–tide and a hyperbolic tangent ramp function was used to build up to the full forcing over approximately two tidal cycles to minimize transients introduced by the initial conditions. The first 45 hrs 40 min of the simulation were discarded to allow damping of initial transients. A 3 ft minimum bathymetric depth was imposed throughout the model domain to avoid problems with nodes becoming dry. The model was run using zero eddy viscosity and including all nonlinear terms except the advective terms. Regardless of the size of the time step that was used, the model became unstable within the first tidal cycle when advection was included. The simulation results presented below were obtained using a model time step of 5 s which matches that used in the fine grid simulations of M77.

6. The model was run for bottom friction coefficients, C_f, ranging from $0.001 s^{-1}$ to $0.01 s^{-1}$. Due to the small horizontal model domain, bottom friction is relatively ineffective in modifying the shape of the free surface wave as it passes through the inlet. Therefore the water level response was virtually identical over the range of friction coefficients. Figure 3 presents time series of water level for 12 September, 1969, at gage sites 1 – 5 using $C_f = 0.007 s^{-1}$. Due to the shortness of the measured time series and the use of elevations from gages 1, 3–5 as model boundary conditions, the comparisons in Figure 3 are not particularly enlightening. At low tide, (approximately 1400 hrs on 12 September) the model simulations appear to lead the observations at gages 1–3 and 5. This is due to errors in fitting the boundary conditions to the observations, the phase lead along the ocean boundary and the spatial displacement of the gage sites from the boundaries.

7. Figure 4 shows comparisons between simulated depth–averaged velocities and measured velocities at five velocity stations. [See Figure 1 for locations of velocity stations. Observed velocities were taken from Figures 28, 31, 34, 37 and 40 in M77]. Model results are presented for $C_f = 0.004 s^{-1}$, $0.007 s^{-1}$ and $0.01 s^{-1}$. Contrary to water level, depth–averaged velocity changes significantly over this range of bottom friction parameters. Depending on the choice of friction coefficient, the model does an adequate job of reproducing the observations. It accurately predicts lower flood and ebb velocities at gages 4 and 5 in comparison to those at gages 1 – 3. It also correctly predicts higher maximum flood velocities at gages 2 and 3 than at gage 1. However, the higher maximum ebb velocities that are predicted at gages 2 and 3, in

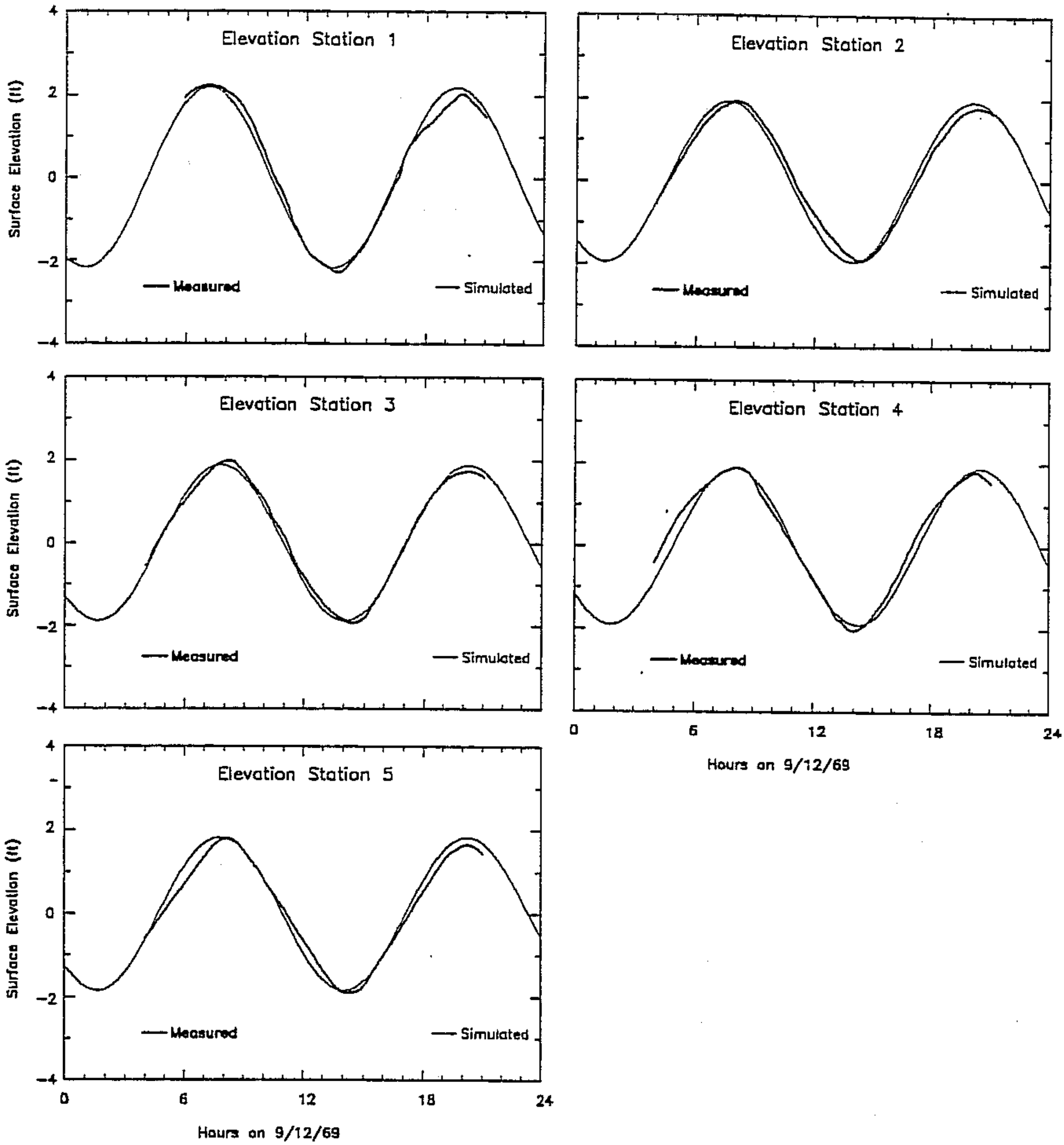

Figure 3. Comparison between measured and simulated water surface elevations at stations EL1 – EL5 for $C_f = 0.007\ s^{-1}$.

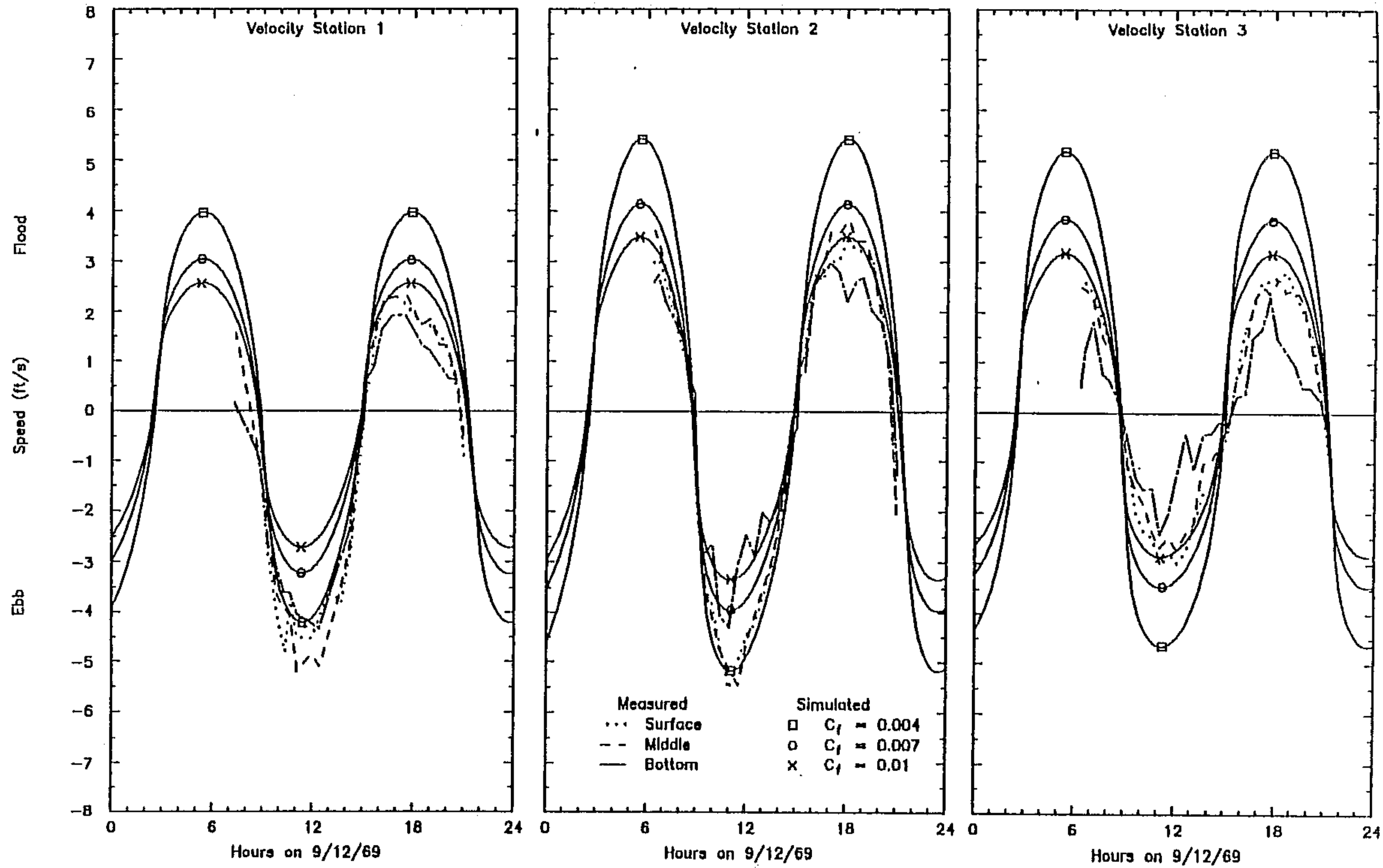

Figure 4a. Comparison between measured and simulated tidal velocities at stations VE1 – VE3 for three values of C_f.

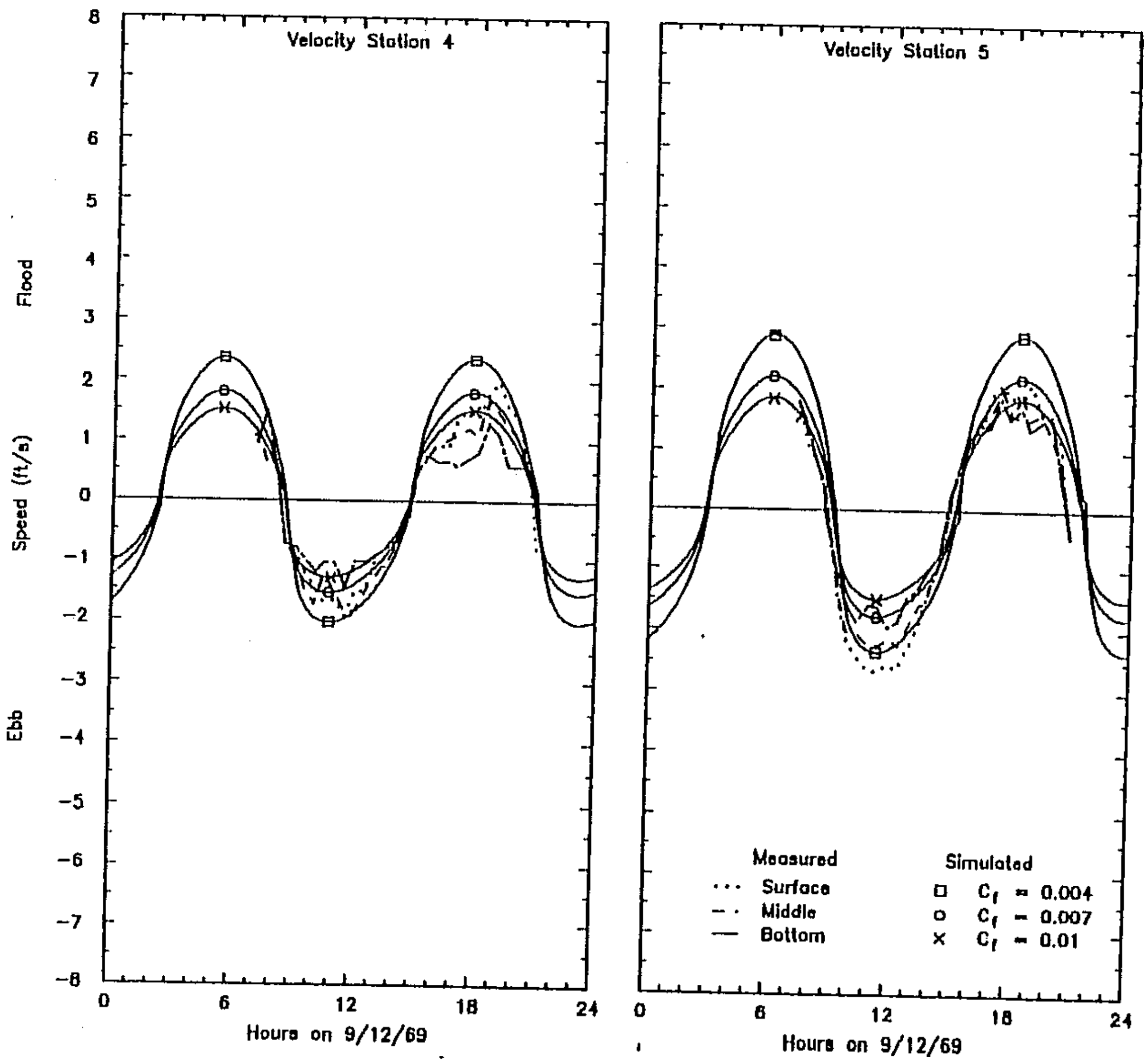

Figure 4b. Comparison between measured and simulated tidal velocities at stations VE4 – VE5 for three values of C_f.

comparison to gage 1, are in disagreement with the observations. In general the model tends to under predict ebb velocities and over predict flood velocities.

8. Figure 5 shows velocity vectors and water level contours every two hours during one tidal cycle on 12 September, 1969. A value of $C_f = 0.007$ was used for these runs. They indicate the primary flow follows the deep channel along the jetty into Masonboro Inlet and up into Shinn Creek. The water level phase lead at gage 1 causes a spatial change in surface elevation throughout the domain that can be larger than 0.75 ft at certain stages of the tide.

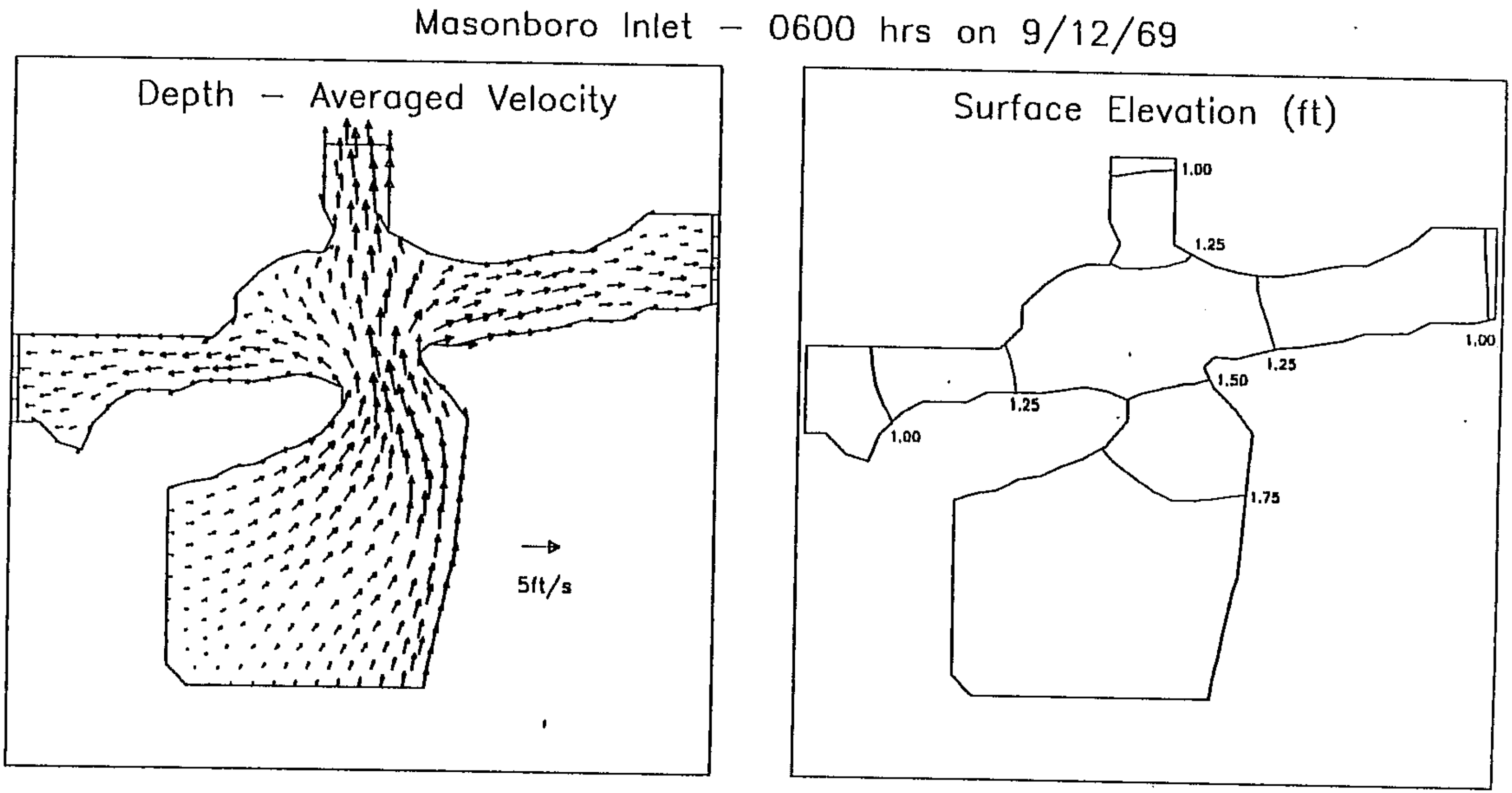

Figure 5a. Simulated depth–averaged velocity and water surface elevation using $C_f = 0.007\ s^{-1}$ for 0600 hrs on 9/12/69.

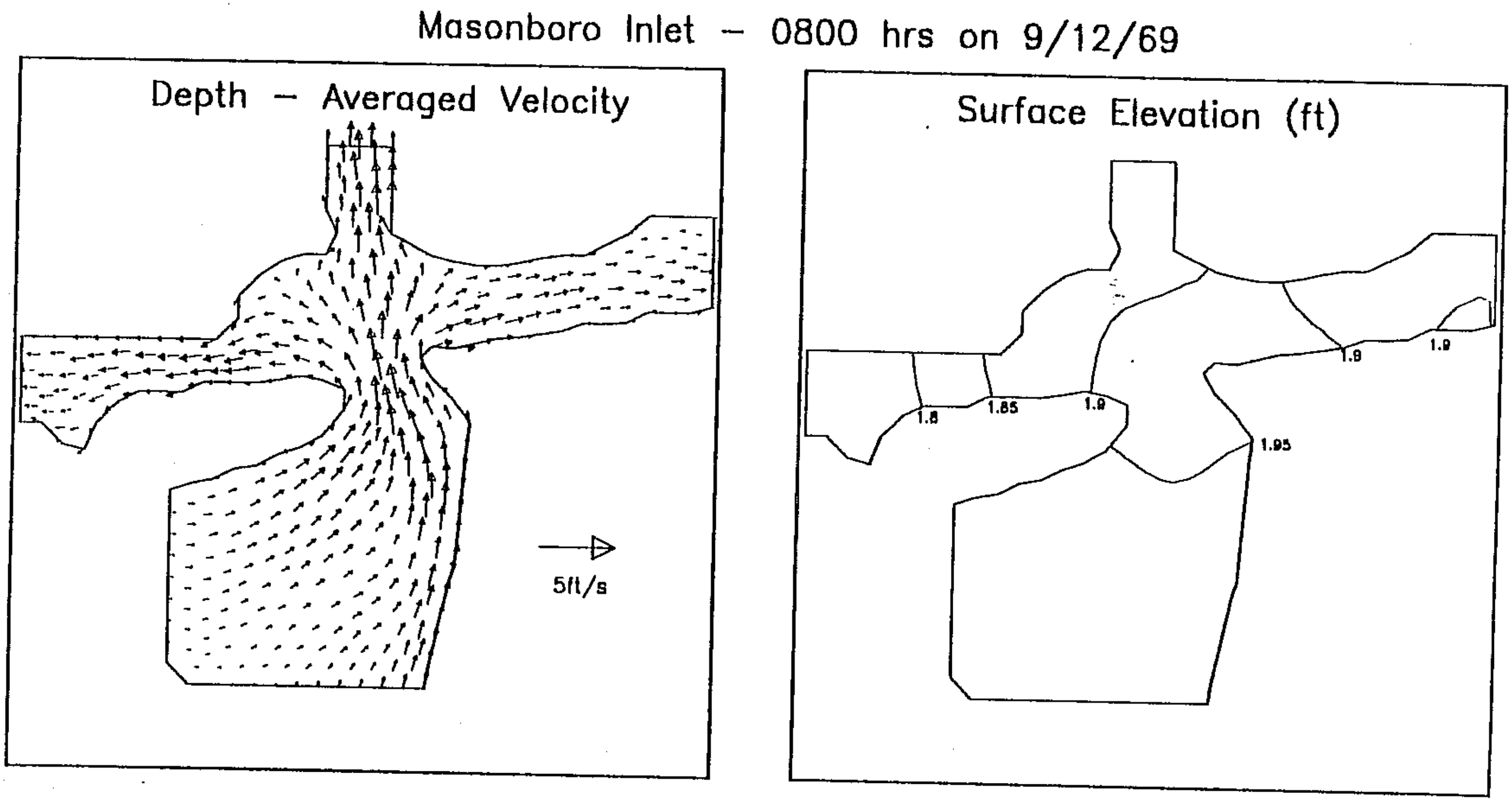

Figure 5b. Simulated depth–averaged velocity and water surface elevation using $C_f = 0.007\ s^{-1}$ for 0800 hrs on 9/12/69.

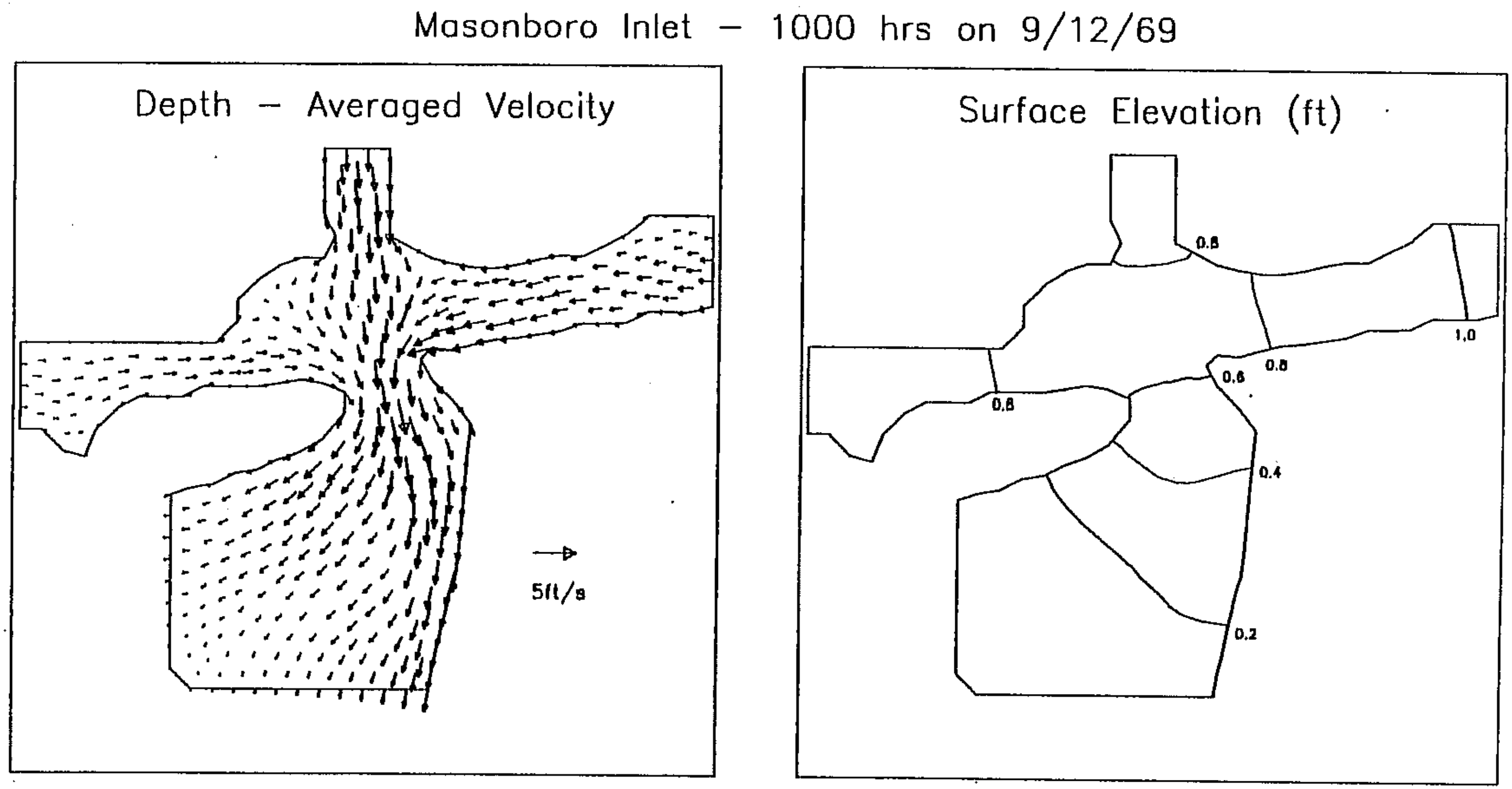

Figure 5c. Simulated depth–averaged velocity and water surface elevation using $C_f = 0.007\ s^{-1}$ for 1000 hrs on 9/12/69.

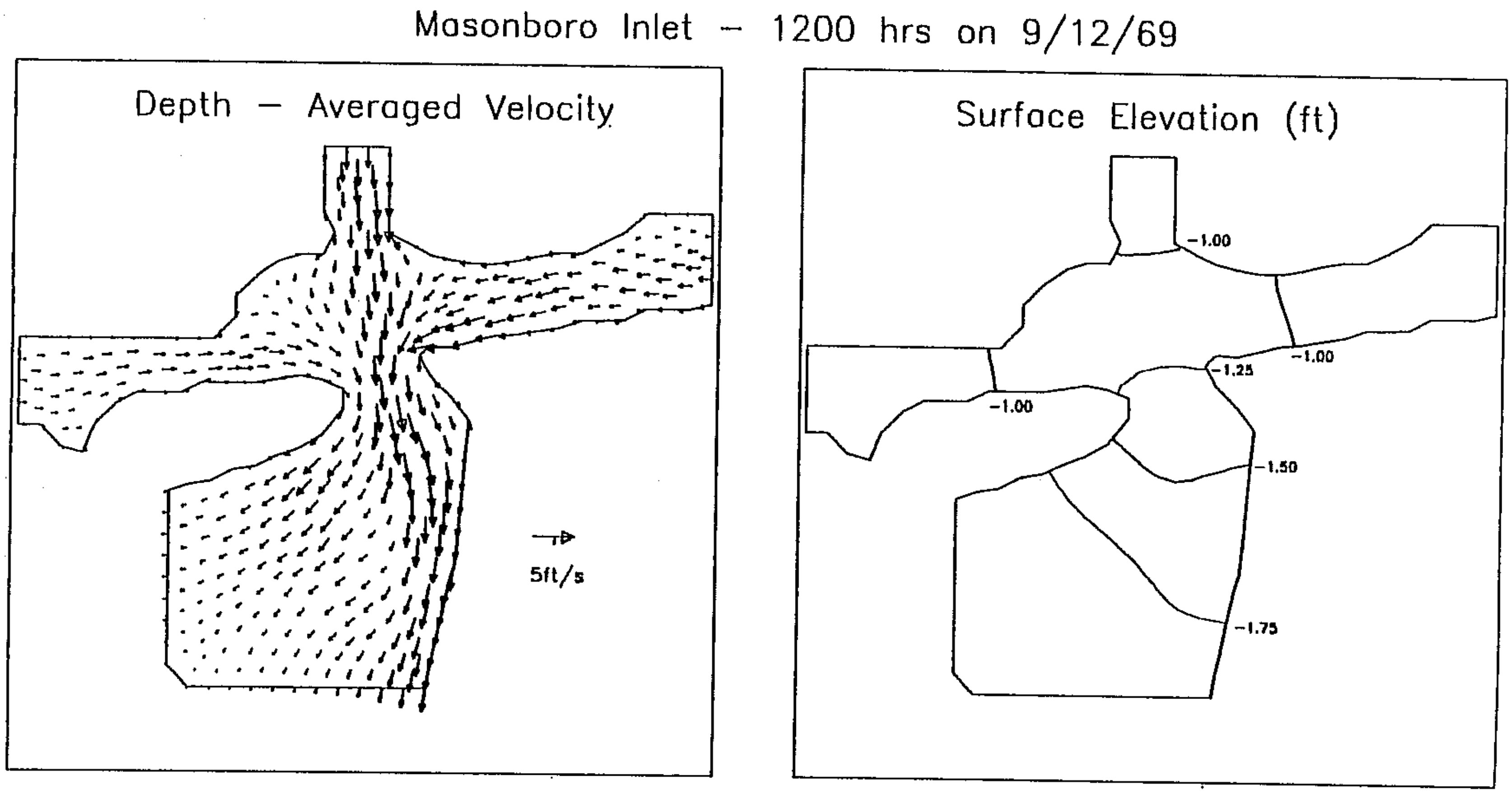

Figure 5d. Simulated depth-averaged velocity and water surface elevation using $C_f = 0.007\ s^{-1}$ for 1200 hrs on 9/12/69.

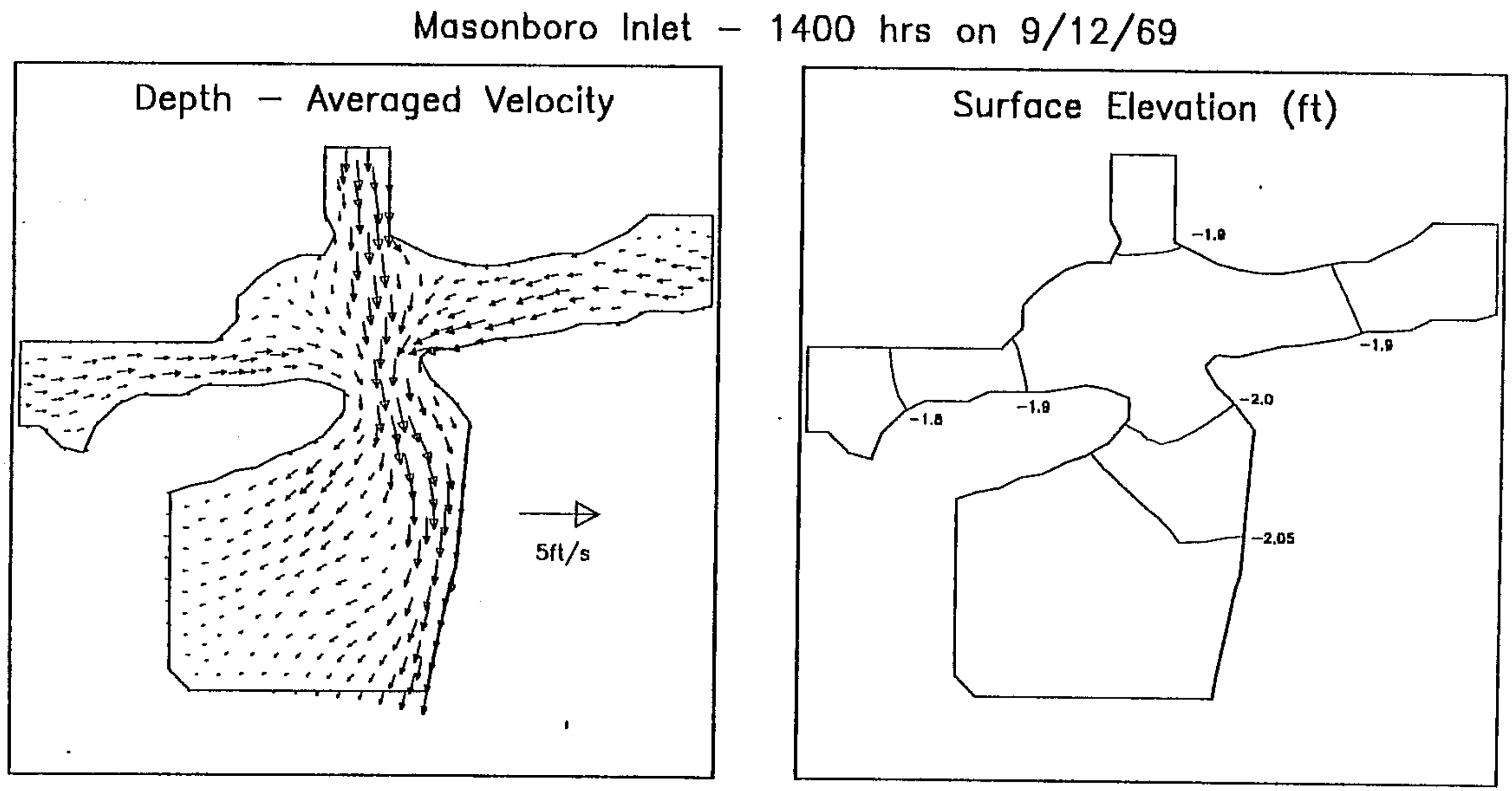

Figure 5e. Simulated depth–averaged velocity and water surface elevation using $C_f = 0.007\ s^{-1}$ for 1400 hrs on 9/12/69.

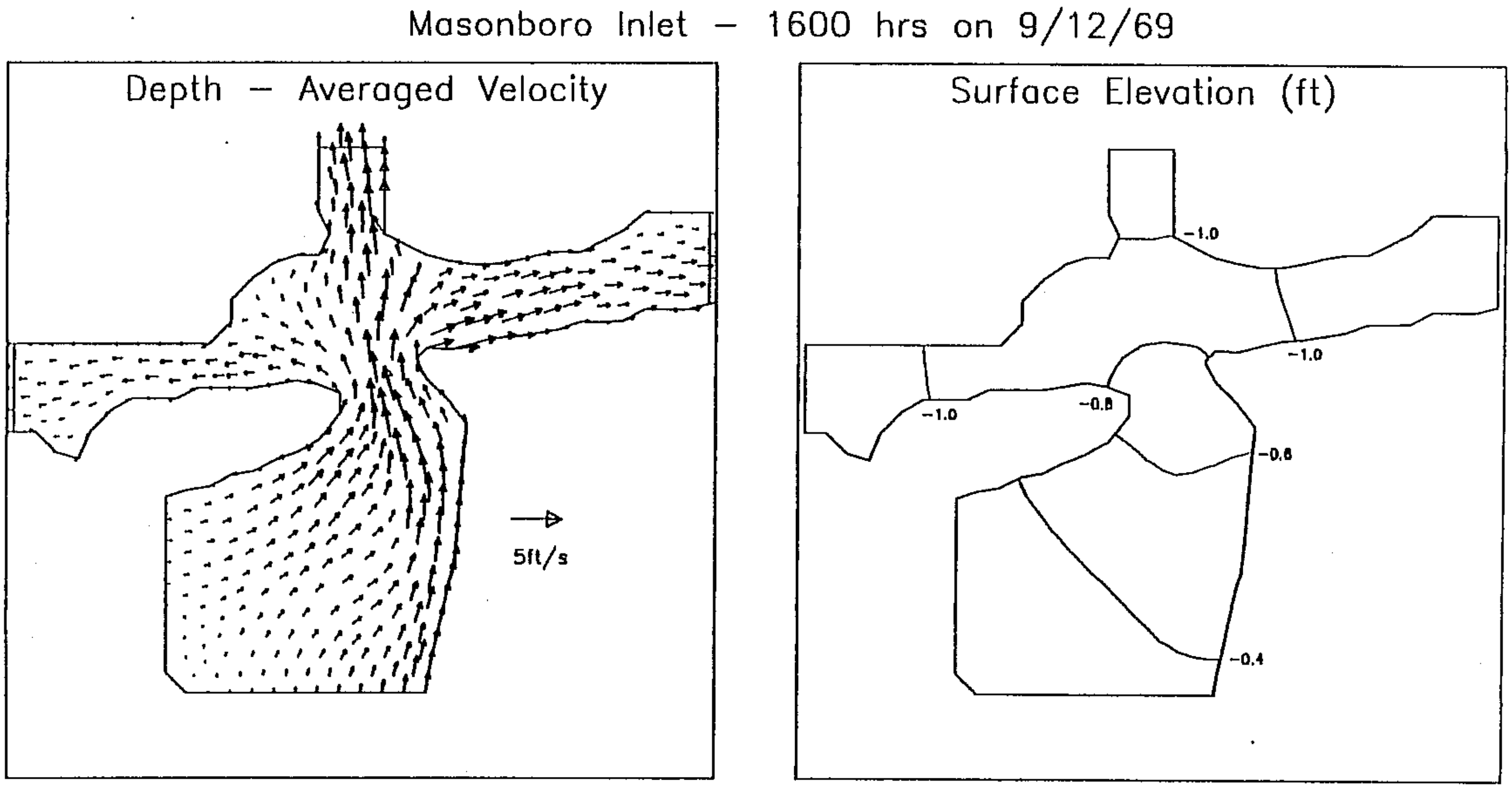

Figure 5f. Simulated depth-averaged velocity and water surface elevation using $C_f = 0.007\ s^{-1}$ for 1600 hrs on 9/12/69.

PART 3: INSTABILITY TESTS

9. The time stepping scheme used in ADCIRC–2DDI is unconditionally stable for the linear terms in the governing equations. However, to maximize the model's execution speed and minimize the required memory, ADCIRC–2DDI includes the nonlinear terms explicitly (Luettich et al. 1991). Therefore numerical instabilities are expected to be amplified when a time step is used that gives a Courant number based on wave celerity, $\mathfrak{C}_r$, [$\mathfrak{C}_r \equiv \Delta t\sqrt{gh}/\Delta x$] of order unity or larger.

10. To test this, the model was run using time steps of 10s, 20s and 30s. The results using a 20s time step are virtually indistinguishable from those presented in Figures 3 – 5. However, with a 30s time step the model became unstable. Figure 6 shows velocity vectors and water surface elevations a few time steps before the 30s time step run crashed. The numerical instability is located in two isolated areas, both of which have water depths of 3ft. Figure 7 presents time series plots of water surface elevation at two nodes, one within an area of instability and one outside of these areas, prior to the model failure. [See Figure 6 the for node locations.] Together, Figures 6 and 7 show that while the instability grows locally, the solution in the rest of the domain remains smooth. Only at the time step immediately prior to the crash are the instabilities large enough to affect the solution throughout the domain.

11. Figure 8 presents contour plots of $\mathfrak{C}_r$ for time steps of 5s, 20s and 30s. [Δx is based on the square root of the average element area surrounding each node.] For the 5s time step, $\mathfrak{C}_r < 0.45$ throughout the entire domain suggesting the model run should remain stable. For the 20s time step, $\mathfrak{C}_r$ reaches 2.0 in some areas of the domain, however, in the instability regions shown in Figure 7, it is below 0.75. For the 30s time step, $\mathfrak{C}_r$ reaches 3.0 in some areas of the domain; in the instability regions it is 1.0. These results indicate that it is not necessary to maintain $\mathfrak{C}_r < 1$ throughout the entire model domain for ADCIRC–2DDI to remain stable and provide accurate solutions. Rather, it is necessary to maintain $\mathfrak{C}_r < 1$ to inhibit the amplification of numerical instabilities only in regions where nonlinear processes are particularly important. In Masonboro Inlet nonlinear bottom friction and finite amplitude terms are expected to be significant in shallow water.

12. As noted in PART 2, all attempts to run ADCIRC–2DDI using the grid in Figure 1 became unstable when the advective terms were included. This does not appear to be related to the time integration since runs were tried using a time step as small as 0.5s. The Courant number based on advective velocity is similar in

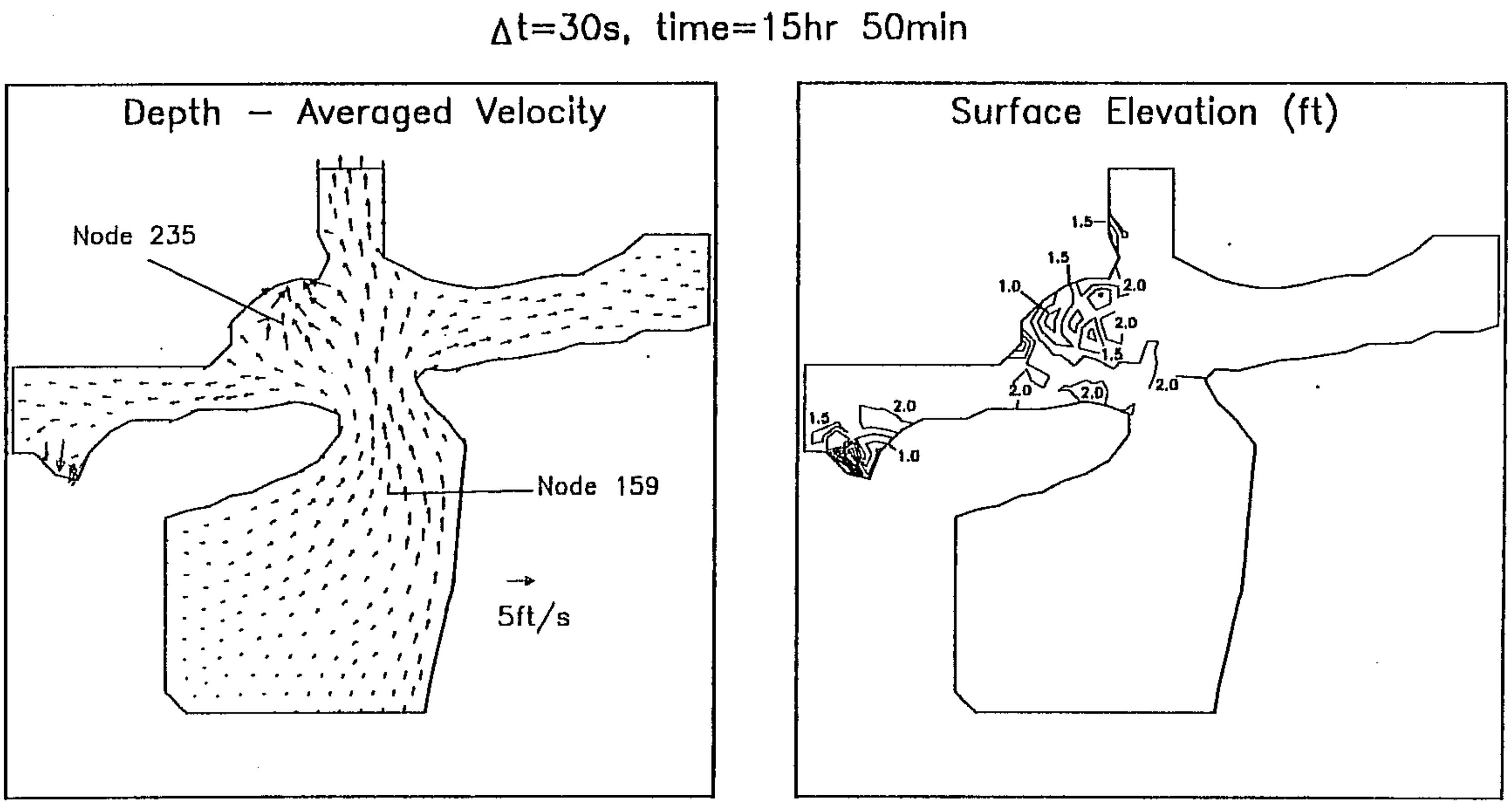

Figure 6. Simulated depth–averaged velocity and water surface elevation using $\Delta t = 30$ s shortly before model failure.

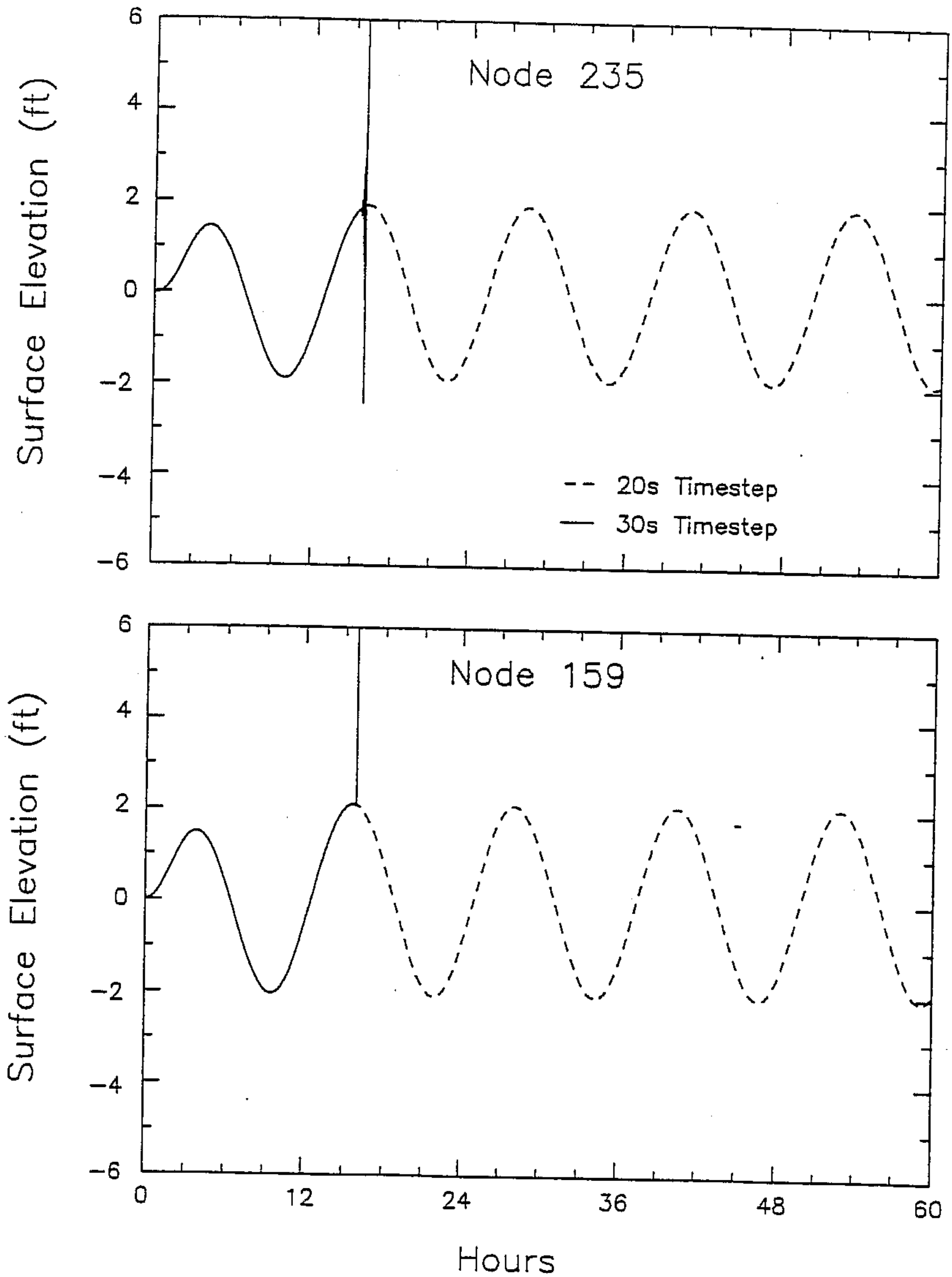

Figure 7. Time series of water surface elevation at nodes 235 and 159 for $\Delta t = 20$ s and $\Delta t = 30$ s.

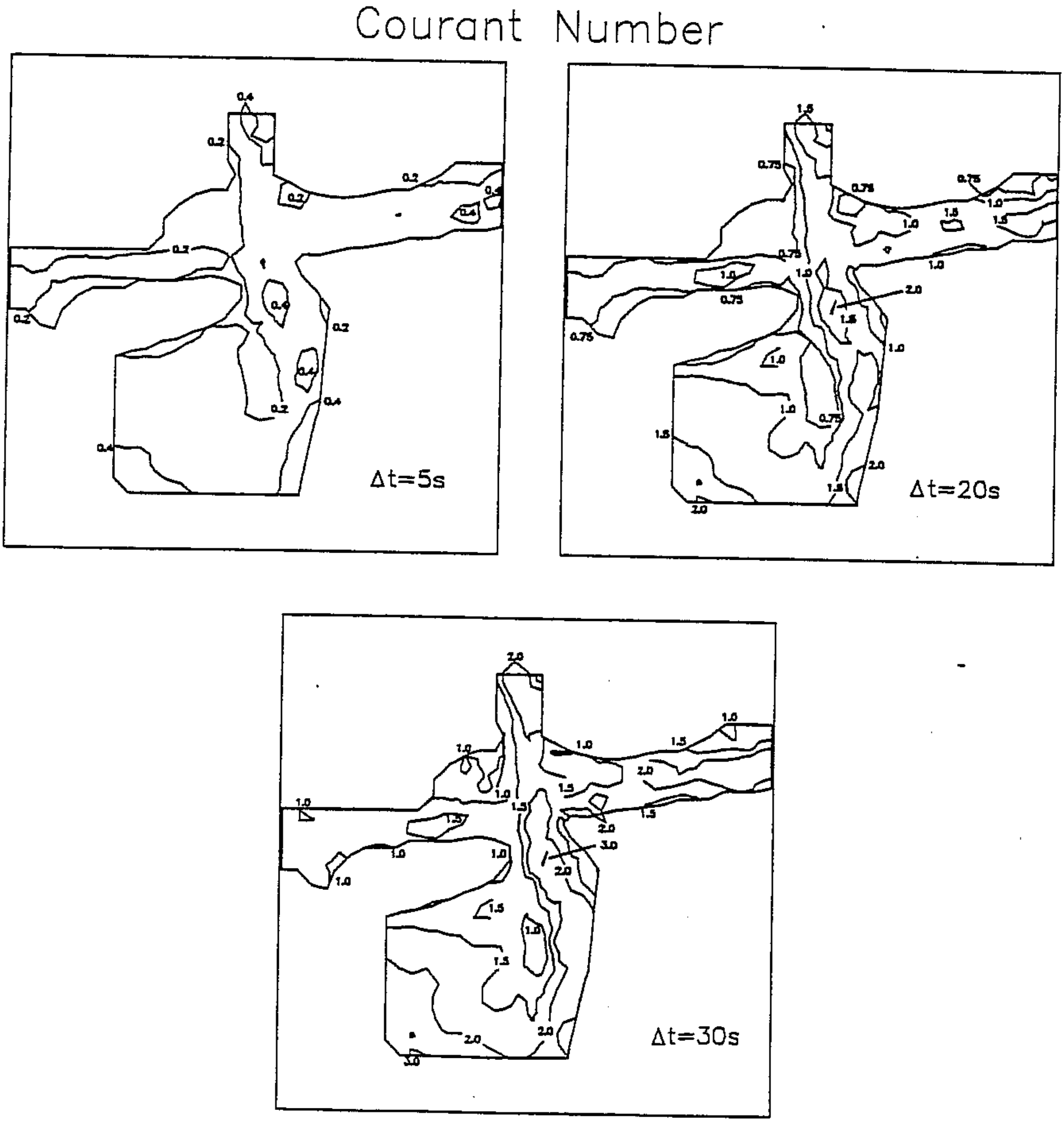

Figure 8. Contour plot of $\mathbb{C}_r$ for $\Delta t = 5$ s, $\Delta t = 20$ s and $\Delta t = 30$ s.

magnitude to the Courant number based on wave celerity and therefore it is well below unity in these runs. Figure 9 presents the typical failure mode encountered when the advective terms are included in the simulation. A large trough of water forms near the southwest corner of Wrightsville Beach on the first falling tide simulated by the model. This trough grows in time and eventually causes the model to crash. We believe this failure is due to the low order approximation used in ADCIRC-2DDI for the advective terms. For this approximation to provide stable and accurate results in flows where the velocity varies rapidly in space, considerably more grid resolution and/or a more accurate numerical treatment of the advective terms are probably required.

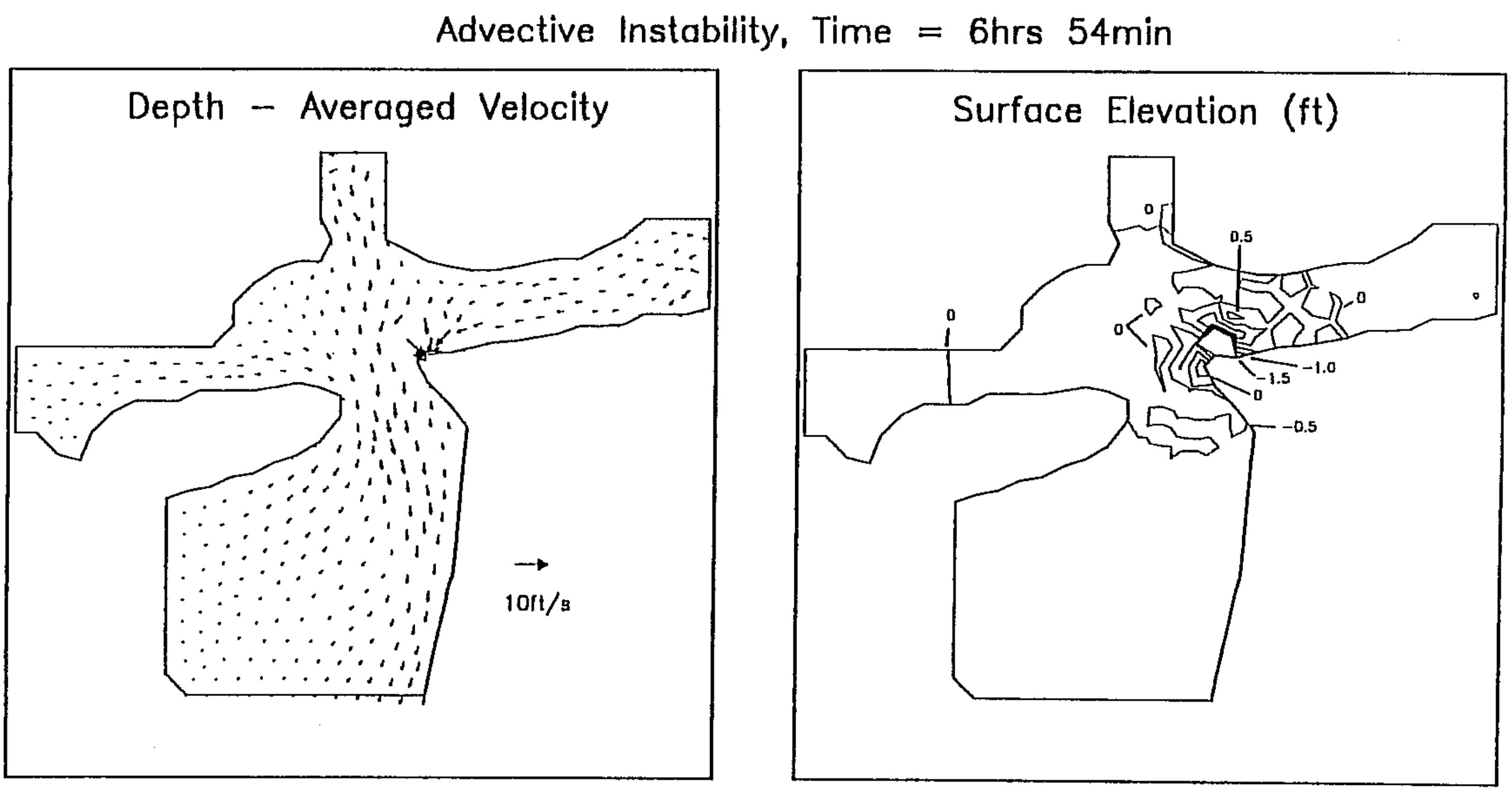

Figure 9. Simulated depth–averaged velocity and water surface elevation using $\Delta t = 5$ s and including the advective terms shortly before model failure.

PART 4: CONCLUSIONS

13. This brief numerical study of Masonboro Inlet, NC, is the first application of ADCIRC–2DDI to a small scale field problem. The grid flexibility of the finite element method using triangular elements makes ADCIRC–2DDI ideally suited for modeling flow through the irregularly shaped boundaries that are typical of coastal inlets. Using roughly estimated elevation boundary conditions, a reasonable representation of observed tidal velocities at 5 points within the domain was obtained for a bottom friction coefficient, C_f, in the range of $0.007s^{-1}$ to $0.01s^{-1}$. Due to the small scale of the problem, water surface elevation was quite insensitive to C_f.

14. The growth of instabilities due to the explicit treatment of nonlinear terms in ADCIRC–2DDI occurs when $\mathfrak{C}_r > 1$ in areas where nonlinear processes are significant. In Masonboro Inlet these areas were the shallowest regions of the domain. Since $\mathfrak{C}_r$ is directly proportional to the square root of water depth, if $\mathfrak{C}_r$ is kept below unity in shallow water, it can easily exceed unity in deeper areas. We saw no indication of instability in these deeper regions for $\mathfrak{C}_r \sim 3.0$. We were able obtain accurate, stable solutions for the flow through Masonboro Inlet using a time step 4 – 5 times larger than the one used in the M77 fine grid simulations.

15. Due to the large spatial gradients of velocity in Masonboro Inlet, ADCIRC–2DDI could not be run successfully when the advective terms were included.

16. The basic formulation of ADCIRC–2DDI makes its potential for use in modeling the dynamics of tidal inlets quite promising. However, several enhancements could be made to the model that would greatly improve its performance in these applications:

a. add discharge boundary conditions, as an alternative to elevation boundary conditions, along open boundaries, [this is currently planned for implementation in the fall of 1991],

b. add the ability to model areas that are periodically wet and dry so that tidal flats can be included in the model domain,

c. investigate the instability that occurs when the advective terms are included in the model. The solution to this problem may simply be to provide sufficient grid resolution in regions of rapidly varying flow. The use of a nonzero eddy viscosity may damp some of the instability and be physically correct in these small scale applications. Alternatively, it may be necessary to use a more accurate treatment of the advective terms in the model (e.g., a Petrov–Galerkin method or the method of characteristics).

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