Hydrodynamic Simulation of the Corpus Christi Bay Area Using QUODDY4

Part 1

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1 Introduction

A study of salinity transport and elevation variation in Corpus Christi Bay was conducted using the finite element simulator QUODDY4. QUODDY4 was developed at Dartmouth University by Lynch *et al* [1], and is publicly available at the web site www-nml.dartmouth.edu/Software/quoddy/quoddy4/. User documentation can also be downloaded from this site. Several modifications were made to the code to make it suitable for the Corpus Christi Bay data given to us by the TWDB. We will outline these modifications below.

Our preliminary experience with the QUODDY4 code is that it is not well-suited for simulation of Corpus Christi Bay. There could be several reasons for this. QUODDY4 uses a σ-coordinate system, thus it may have difficulty handling the widely varying bathymetry seen in the bay. Wetting and drying are not built into the code, thus the code quits executing if elevation goes negative. There are several very shallow regions in the bay where elevation could likely go negative, and in most cases, this was the primary reason for the code to halt execution. The code also stops if the computed temperature or salinity violate certain pre-set bounds. Temperature and salinity are computed in the code using a standard finite element approach, with no numerical stabilization added. Thus, the temperature and salinity profiles were seen to be very oscillatory and often violated the given bounds.

2 Mathematical Model

The mathematical model used in the QUODDY4 code is a three-dimensional barotropic shallow water model, with salinity and temperature transport, and a turbulence closure model. Defining

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + v \cdot \nabla,$$

the model consists of momentum equations:

$$\frac{dv}{dt} + f \times v + g \nabla_{xy} \zeta - \frac{\partial}{\partial t}(N_m \frac{\partial v}{\partial z}) = -\frac{g}{\rho_0} \int_z^{\zeta} \nabla_{xy} \rho dz + F_m + \frac{\sigma}{\rho}(v_\sigma - v).$$

Temperature and salinity conservation:

$$\frac{dT}{dt} - \frac{\partial}{\partial z}(N_h \frac{\partial T}{\partial z}) = F_T + \frac{\sigma}{\rho}(T_\sigma - T),$$

$$\frac{dS}{dt} - \frac{\partial}{\partial z}(N_h \frac{\partial S}{\partial z}) = F_S + \frac{\sigma}{\rho}(S_\sigma - S).$$

Equations for turbulent kinetic energy and mixing length, as described in Mellor and Yamada [2] and Galperin *et al* [3]:

$$\frac{dq^2}{dt} - \frac{\partial}{\partial z}(N_q \frac{dq^2}{dz} = 2[N_m((\frac{\partial u}{\partial z})^2 + (\frac{\partial v}{\partial z})^2) + \frac{g}{\rho_0} N_h \frac{\partial \rho}{\partial z}] - 2[\frac{q^3}{B_1 l}] + \frac{\sigma}{\rho}(q_\sigma^2 - q^2),$$

$$\frac{dq^2 l}{dt} - \frac{\partial}{\partial z}(N_q \frac{dq^2 l}{dz} = lE_1[N_m((\frac{\partial u}{\partial z})^2 + (\frac{\partial v}{\partial z})^2) + \frac{g}{\rho_0} N_h \frac{\partial \rho}{\partial z}] - lW[\frac{q^3}{B_1 l}] + \frac{\sigma}{\rho}(q^2 l_\sigma - q^2 l).$$

Vertically integrated continuity equation:

$$\frac{\partial \zeta}{\partial t} + \nabla_{xy} \cdot \int_{-h}^{\zeta} v dz = \int_{-h}^{\zeta} \frac{\sigma}{\rho} dz + (P - E).$$

The 3-D continuity equation:

$$\frac{\partial w}{\partial z} = -\nabla_{xy} \cdot v + \frac{\partial}{\partial z}(\frac{\sigma}{\rho}).$$

Equation of state:

$$\rho = \rho(T, S).$$

Instead of solving for elevation using the vertically integrated continuity equation above, QUODDY4 uses a wave equation formulation similar to what is used in TxBLEND. The mathematical equations above are discretized numerically using continuous, piecewise linear finite elements on prismatic elements.

3 Modifications to the code

Several modifications to the code were needed to allow it to run the Corpus Christ Bay model. These include

- Ability to read and interpolate ramped-up time-varying elevation data for the open sea boundary.
- Ability to handle spatially varying initial salinity profile.
- Ability to read and interpolate wind forcing data.

- Incorporation of Nueces River inflow and intake/discharge from the power plant located on the bay.

The data used in the simulations was extracted from data provided by the TWDB. Time-varying elevation, wind forcing and inflow data were read and the data values were interpolated using linear interpolation within the code. The first modification to the code resulted in few problems. However, incorporating a spatially varying salinity profile caused the code to crash after only a few iterations. By cutting the time step to three seconds and modifying a few parameters, such as the horizontal diffusion coefficient, we were able to complete a five day simulation. Adding wind data to the code caused tremendous problems, thus we were forced to modify the data and cut down on the magnitude of the wind forcing in order to keep the code running. The additional modifications to the code also required a great deal of testing before successful simulations could be obtained. With all of the modifications incorporated, we were finally able to run an 18 day simulation before the code halted execution with a negative elevation. Based on discussions with the TWDB personnel in October, we also attempted additional runs with new data sets provided by TWDB, and using more levels in the vertical direction.

4 Results

A finite element mesh provided by the TWDB consisting of 6836 nodes and 12058 elements in the horizontal was used in our simulations, with 15 layers in the vertical direction. A time step of 3 seconds was chosen. The finite element mesh is shown in Figure 1. The starting date was April 1, 1987. The code simulated roughly 18 days before crashing with a negative elevation at a node. Below we show elevation, salinity and velocity profiles for this simulation.

In Figures 2-4, contours of salinity in the top layer are shown at days 6, 11 and 16. Similar profiles for layers 5, 10 and 15 are shown in Figures 5-13. The units of salinity are parts per thousand (ppt).

Next, we show vertical profiles of velocity at 5 locations within the domain: (1) near the entrance to the ship channel, (2) midway through the ship channel, (3) near the harbor bridge, (4) the northern part of Corpus Christi Bay, and the (5) western part of Nueces Bay. These locations are shown on the finite element mesh in Figure 14. Profiles at 15.125 days through 16 days were plotted at 3-hour intervals. Each plot consists of the magnitude of the velocity, multiplied by 1 or -1 depending on the direction. Velocities are in m/sec. Figure 15 is for the location near the entrance to the ship channel, Figure 16 for the midway point of the ship channel, Figure 17 for the harbor bridge, Figure 18 for the northern part of Corpus Christi Bay, and Figure 19 for the western part of Nueces Bay.

Vertical profiles of salinity at each of the 5 locations above are given in Figures 20-24. Salinity ranged between 0 and about 30 ppt throughout the domain.

Finally, in Figures 25-32, elevation contours are given, starting at 15 days at intervals of 3 hours. The unit of elevation is meters.

5 Conclusions

We have presented preliminary results obtained from the QUODDY4 simulator applied to three-dimensional circulation and temperature and salinity transport in Corpus Christi Bay. The simulator had a great deal of difficulty modeling this problem, usually halting execution due to elevation going negative or salinity or temperature going out of range after only a few days of simulation. Possible causes of these difficulties include the inability of the simulator to handle wetting and drying, and the use of a σ-coordinate system.

References

[1] D.R. Lynch, J.T.C. Ip, C.E. Naimie and F.E. Werner, *Comprehensive coastal circulation model with application to the Gulf of Maine*, Continental Shelf Research, 1995.

[2] G.L. Mellor and T. Yamada, *Development of a turbulence clsoure model for geophysical flow problems*, Reviews of Geophys. Space Phys., 20, 851-875, 1982.

[3] B. Galperin, L.H. Kantha, S. Hassid and A. Rosati, *A quasi-equilibrium turbulent energy model for geophysical flows*, J. Atmos. Sci., 45, 55-62, 1988.

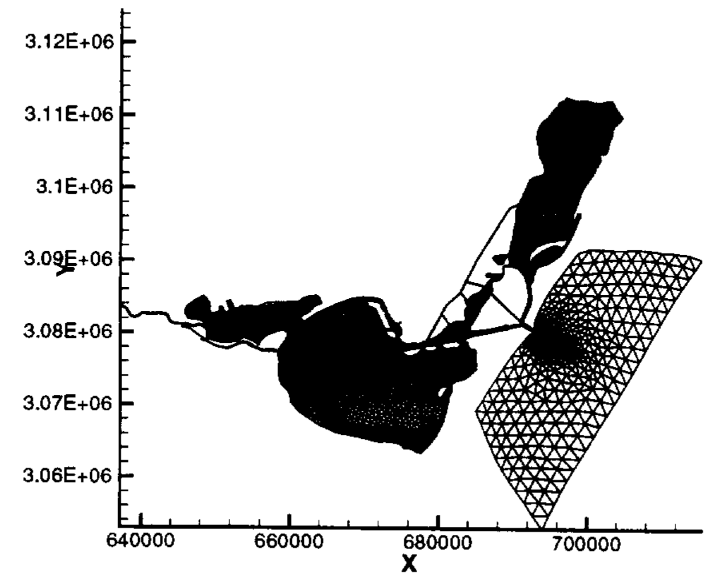

Figure 1: Finite element mesh used in simulations

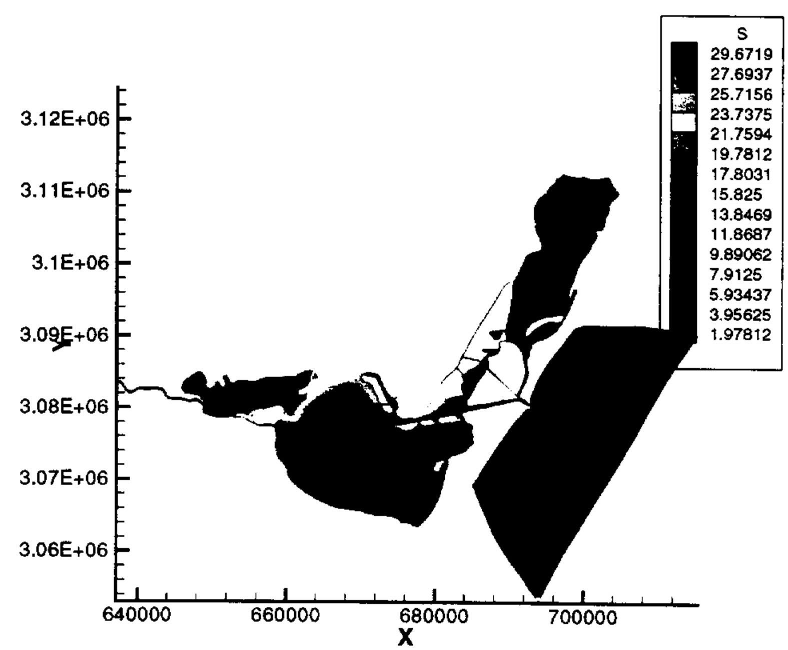

Figure 2: Salinity profile, day 6, top layer

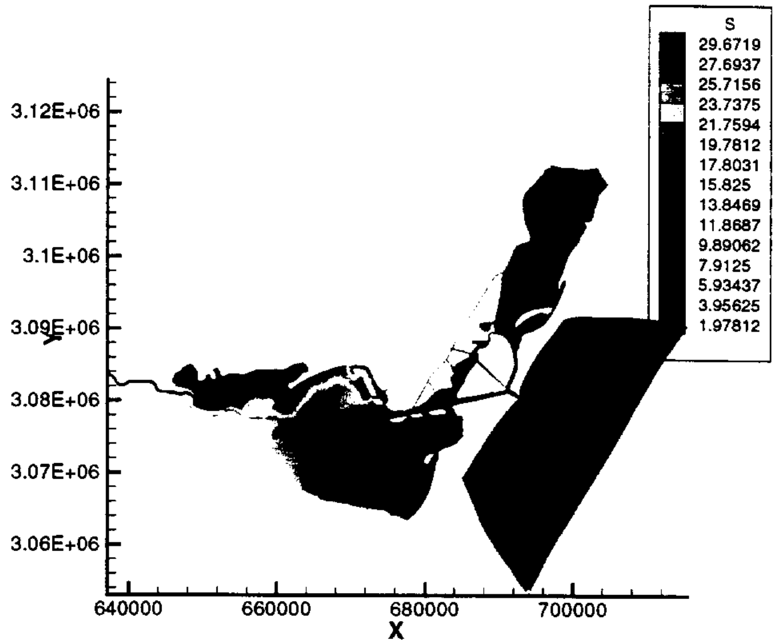

Figure 3: Salinity profile, day 11, top layer

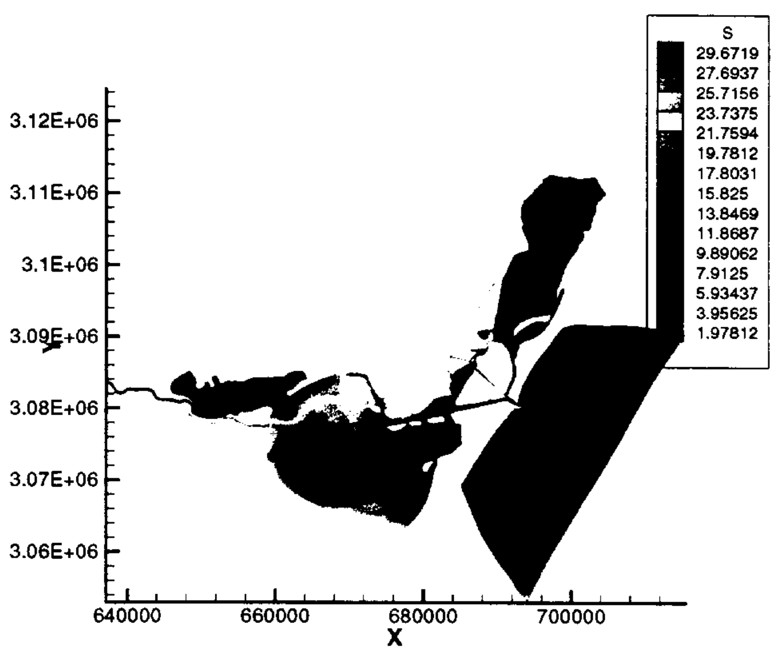

Figure 4: Salinity profile, day 16, top layer

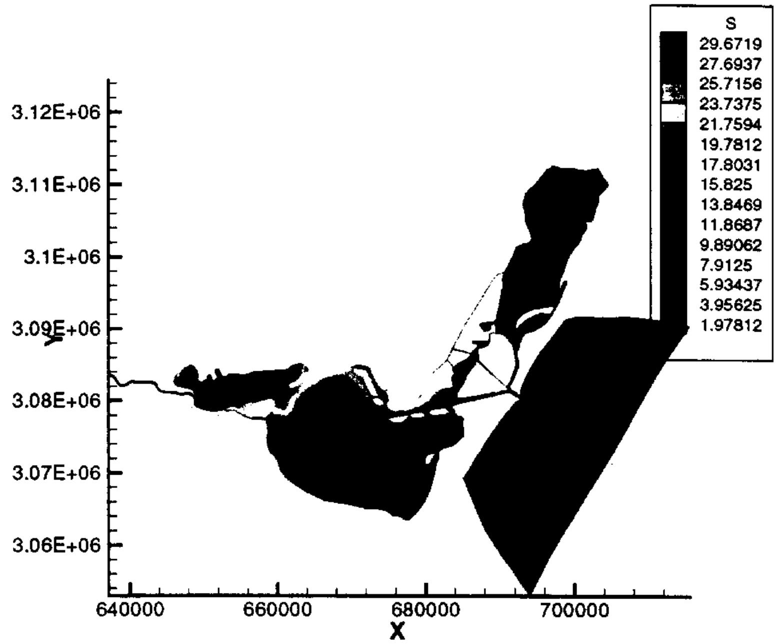

Figure 5: Salinity profile, day 6, layer 5

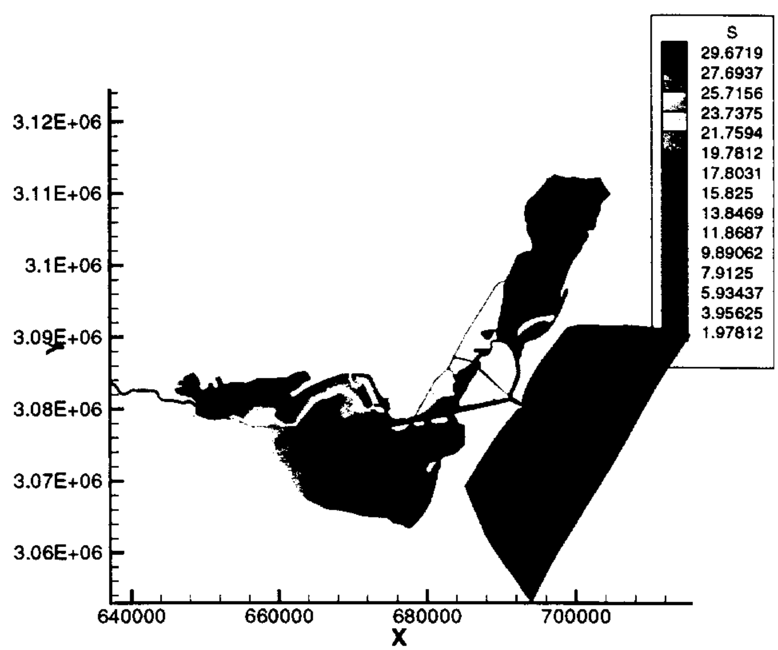

Figure 6: Salinity profile, day 11, layer 5

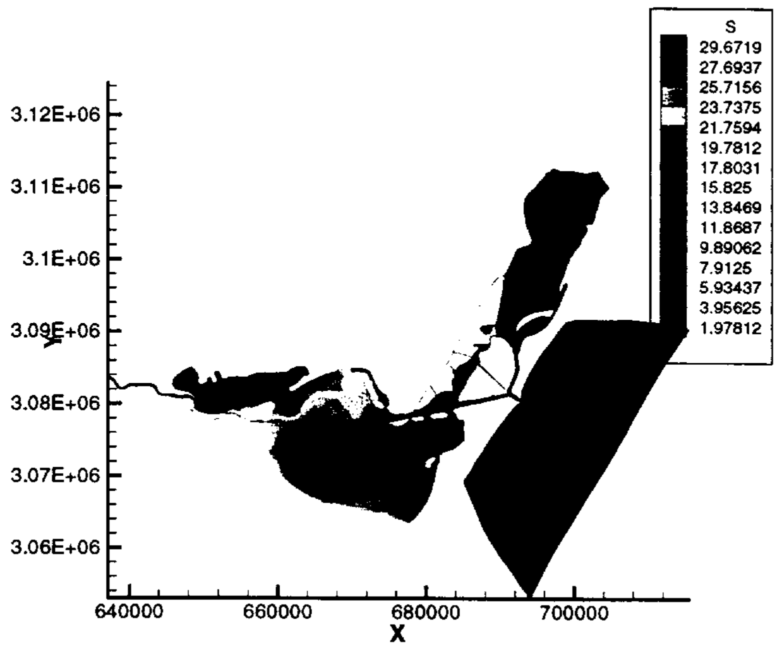

Figure 7: Salinity profile, day 16, layer 5

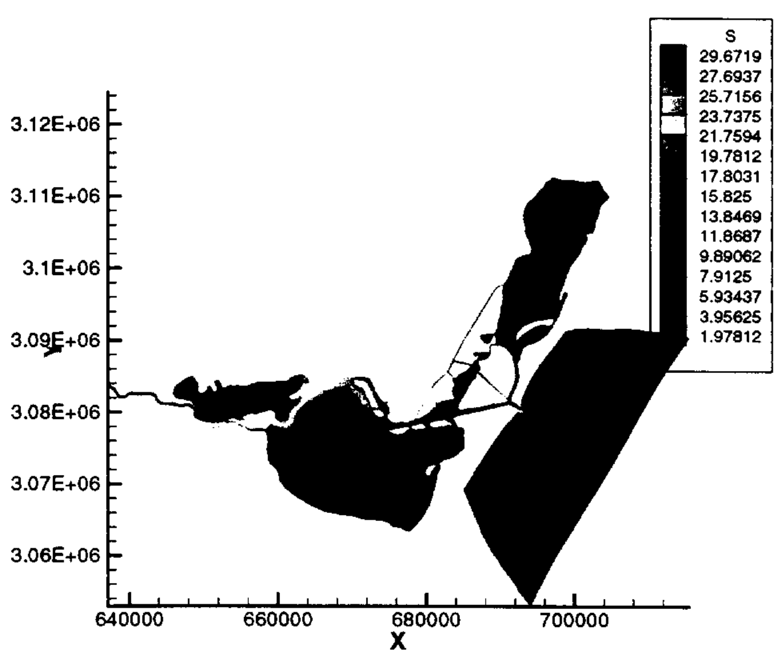

Figure 8: Salinity profile, day 6, layer 10

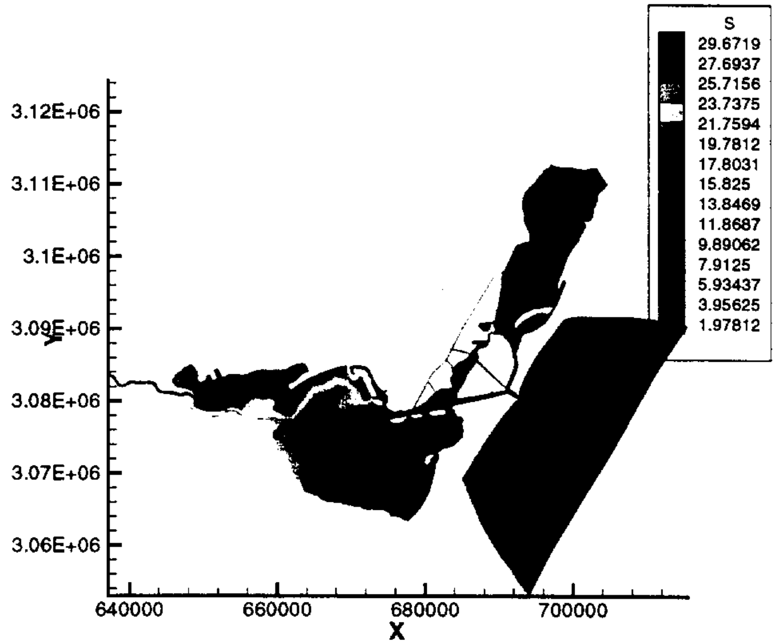

Figure 9: Salinity profile, day 11, layer 10

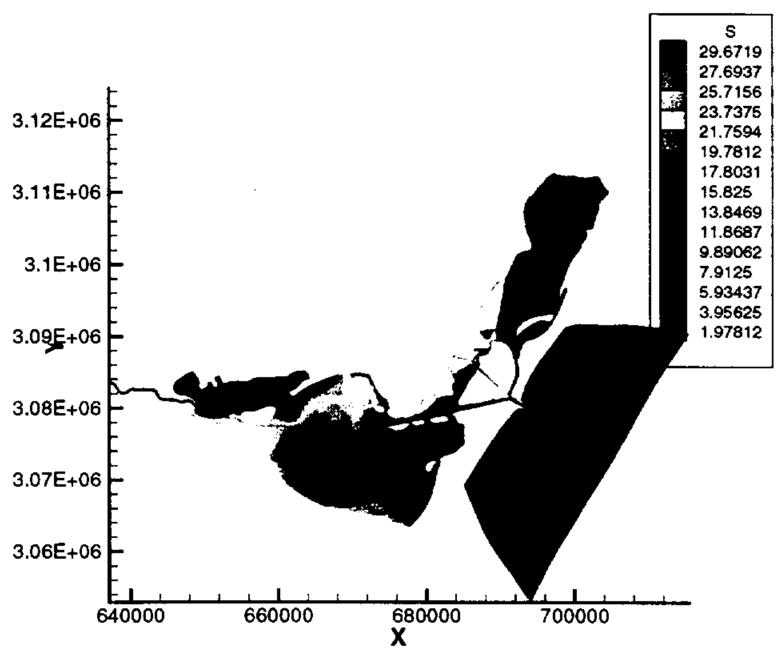

Figure 10: Salinity profile, day 16, layer 10

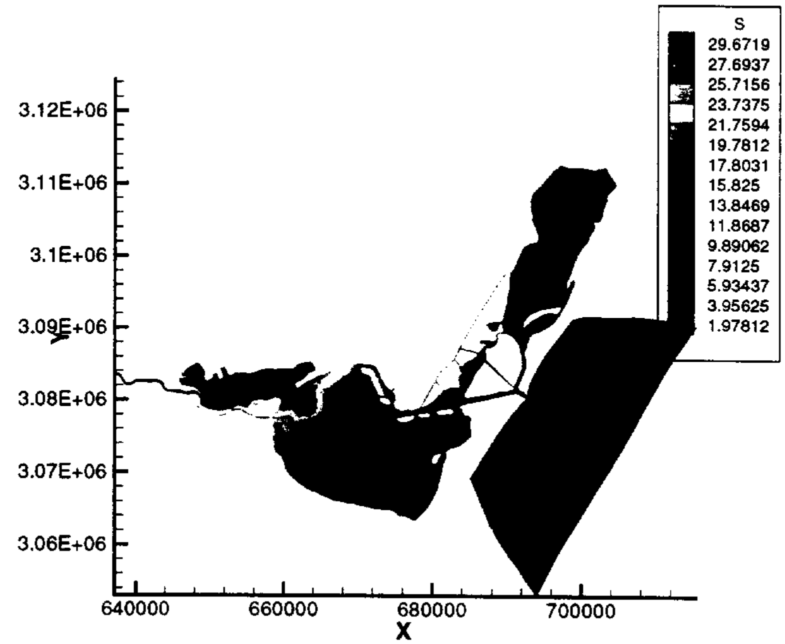

Figure 11: Salinity profile, day 6, layer 15

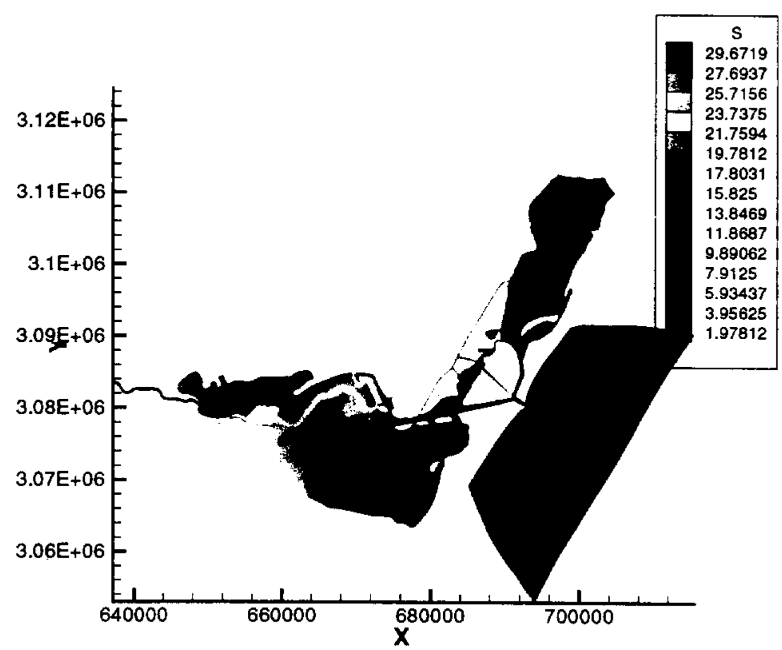

Figure 12: Salinity profile, day 11, layer 15

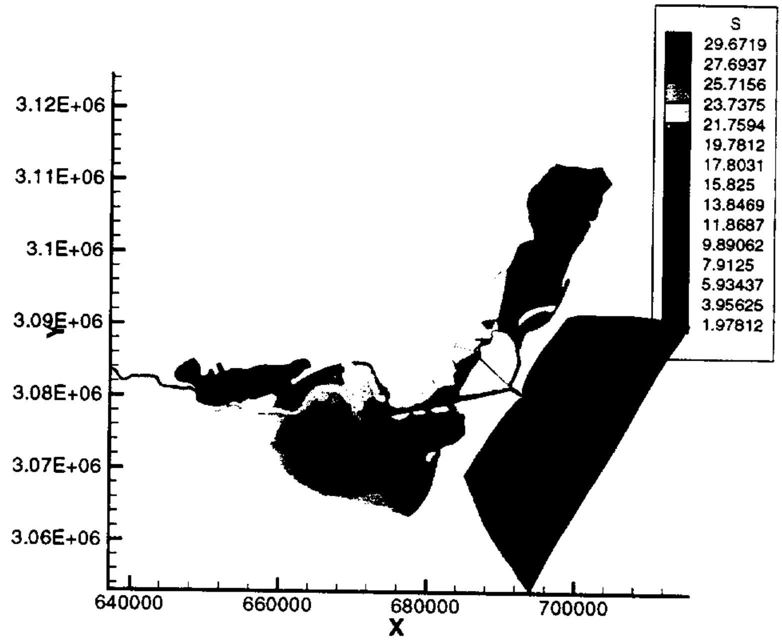

Figure 13: Salinity profile, day 16, layer 15

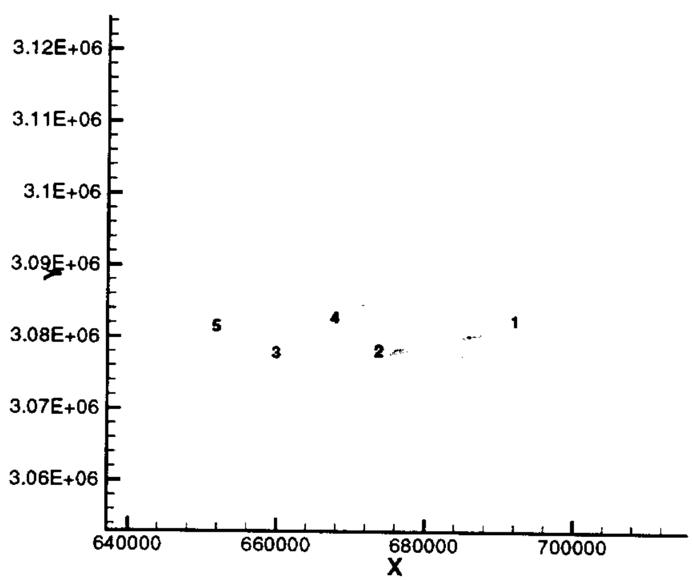

Figure 14: Locations 1-5 indicate where velocities and salinity are plotted below.

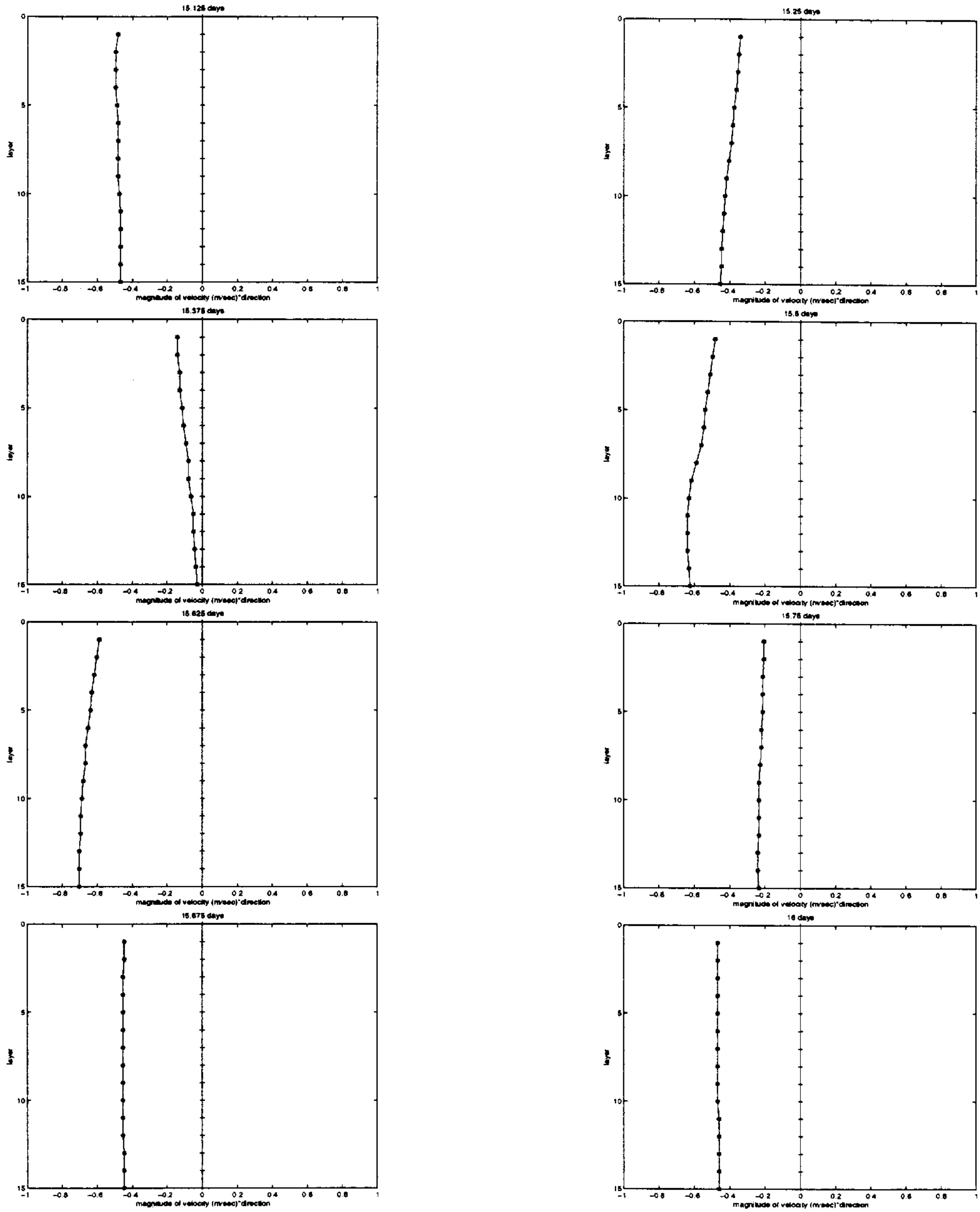

Figure 15: Vertical profiles of velocities at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at entrance to ship channel (location 1)

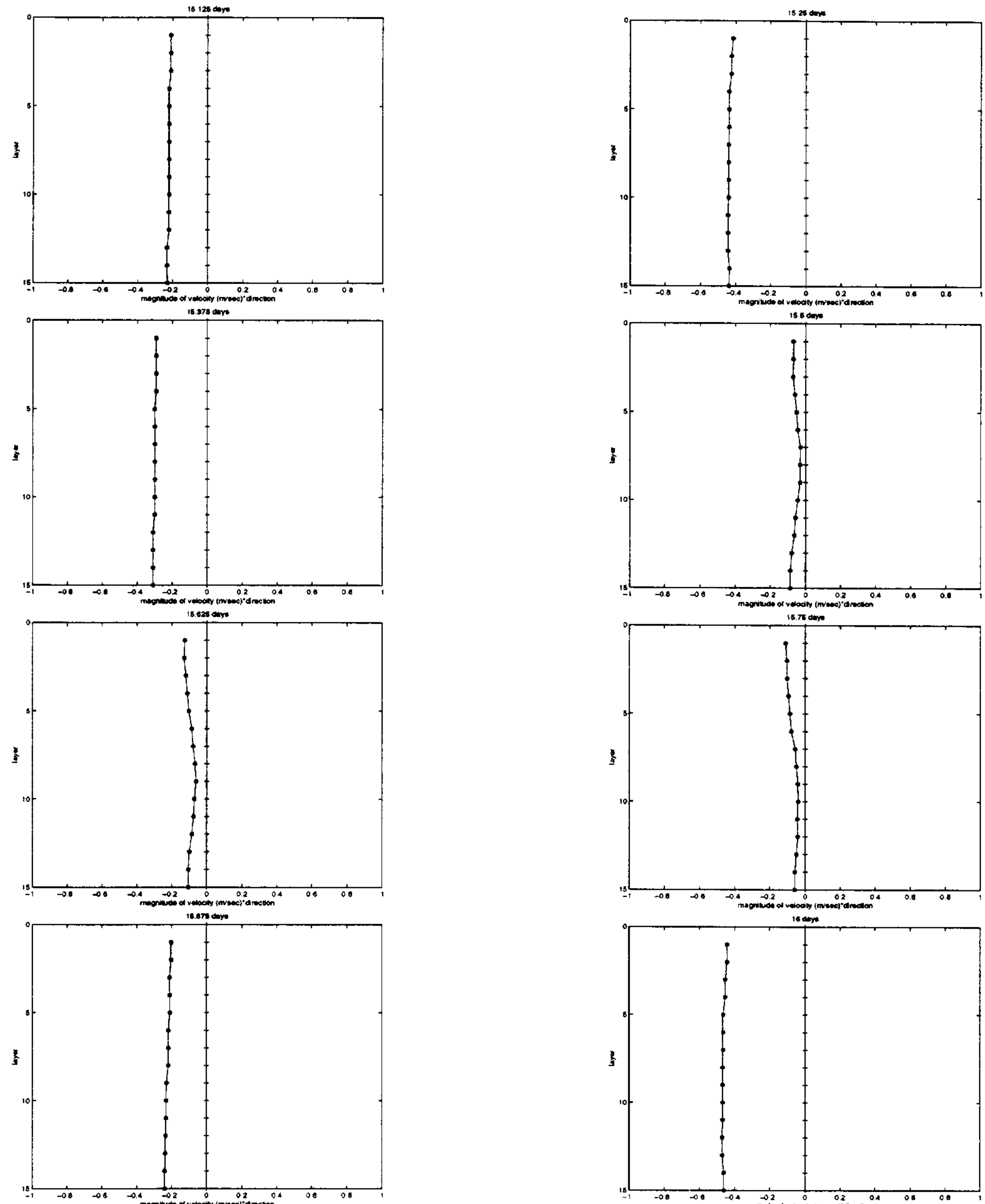

Figure 16: Vertical profiles of velocity at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at midway of ship channel (location 2)

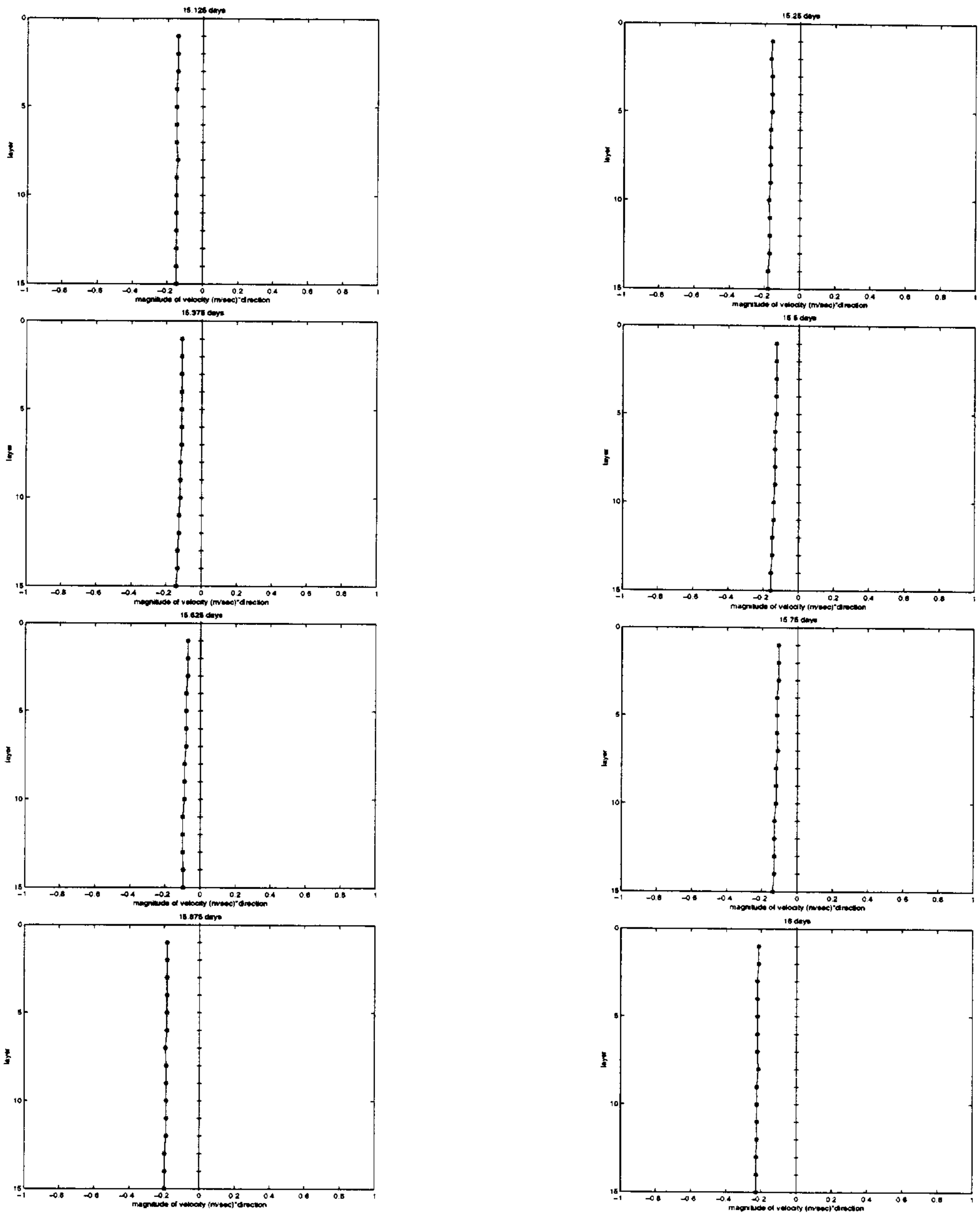

Figure 17: Vertical profiles of velocity at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at harbor bridge (location 3)

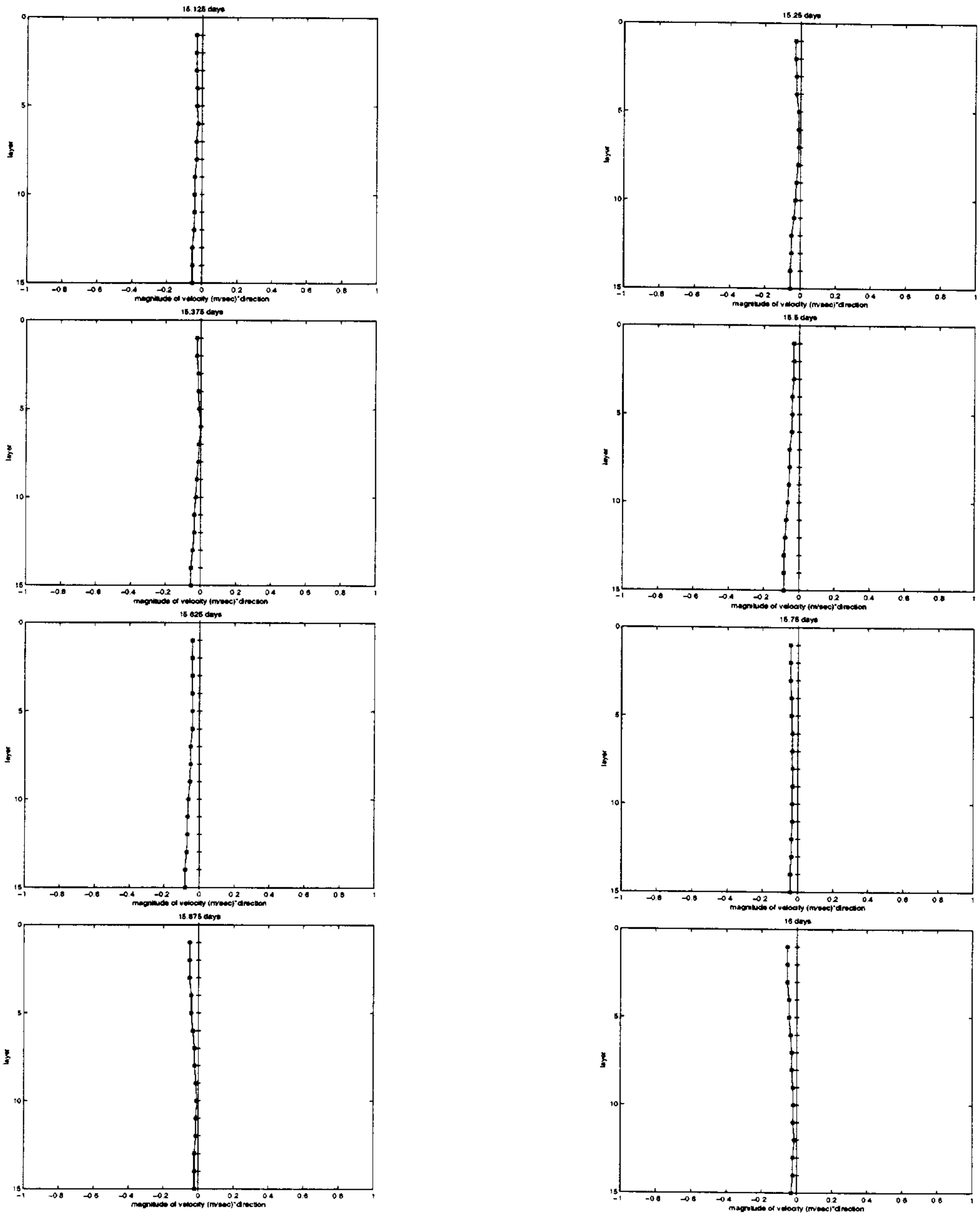

Figure 18: Vertical profiles of velocity at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at northern part of Corpus Christi Bay (location 4)

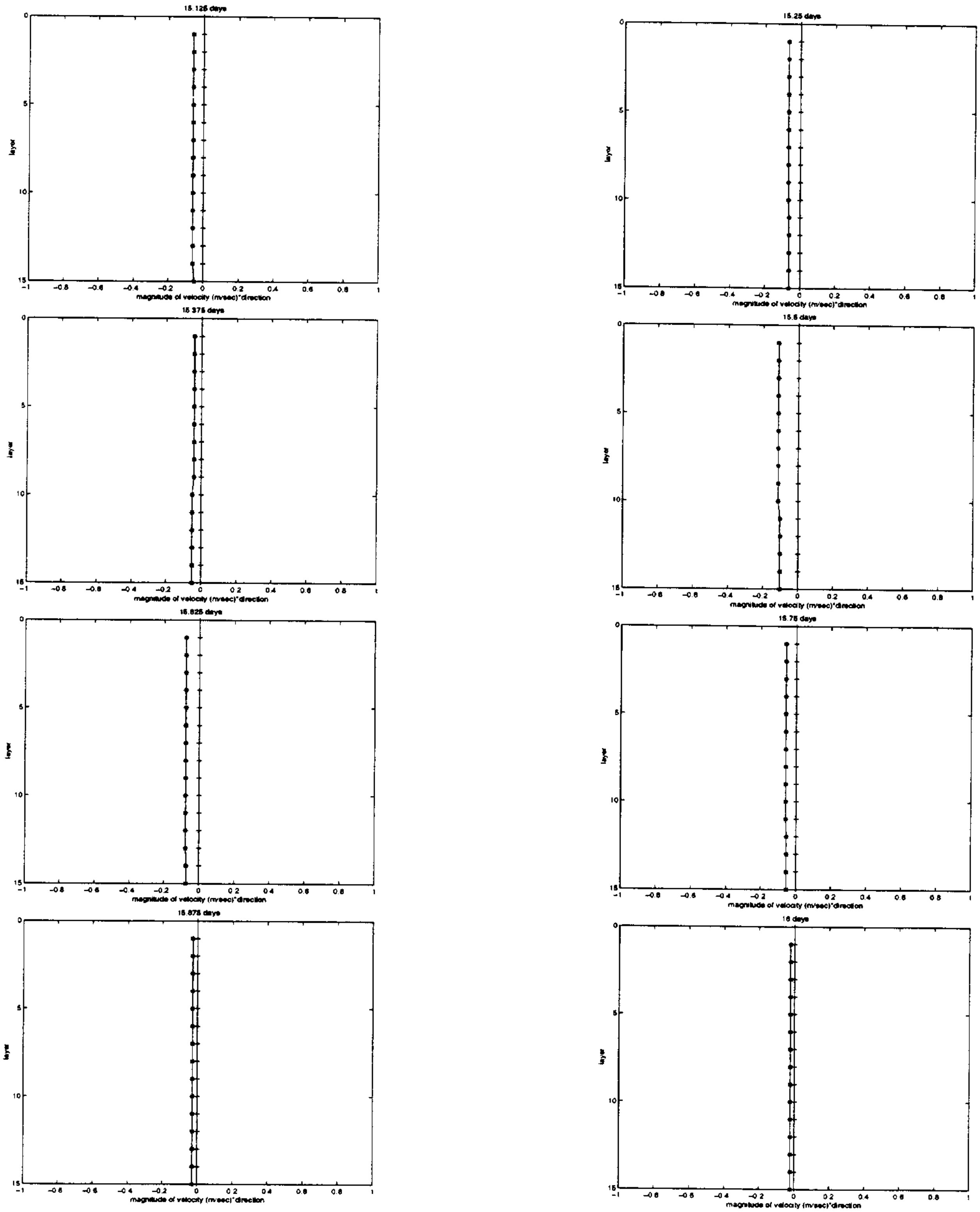

Figure 19: Vertical profiles of velocity at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at western part of Nueces Bay (location 5)

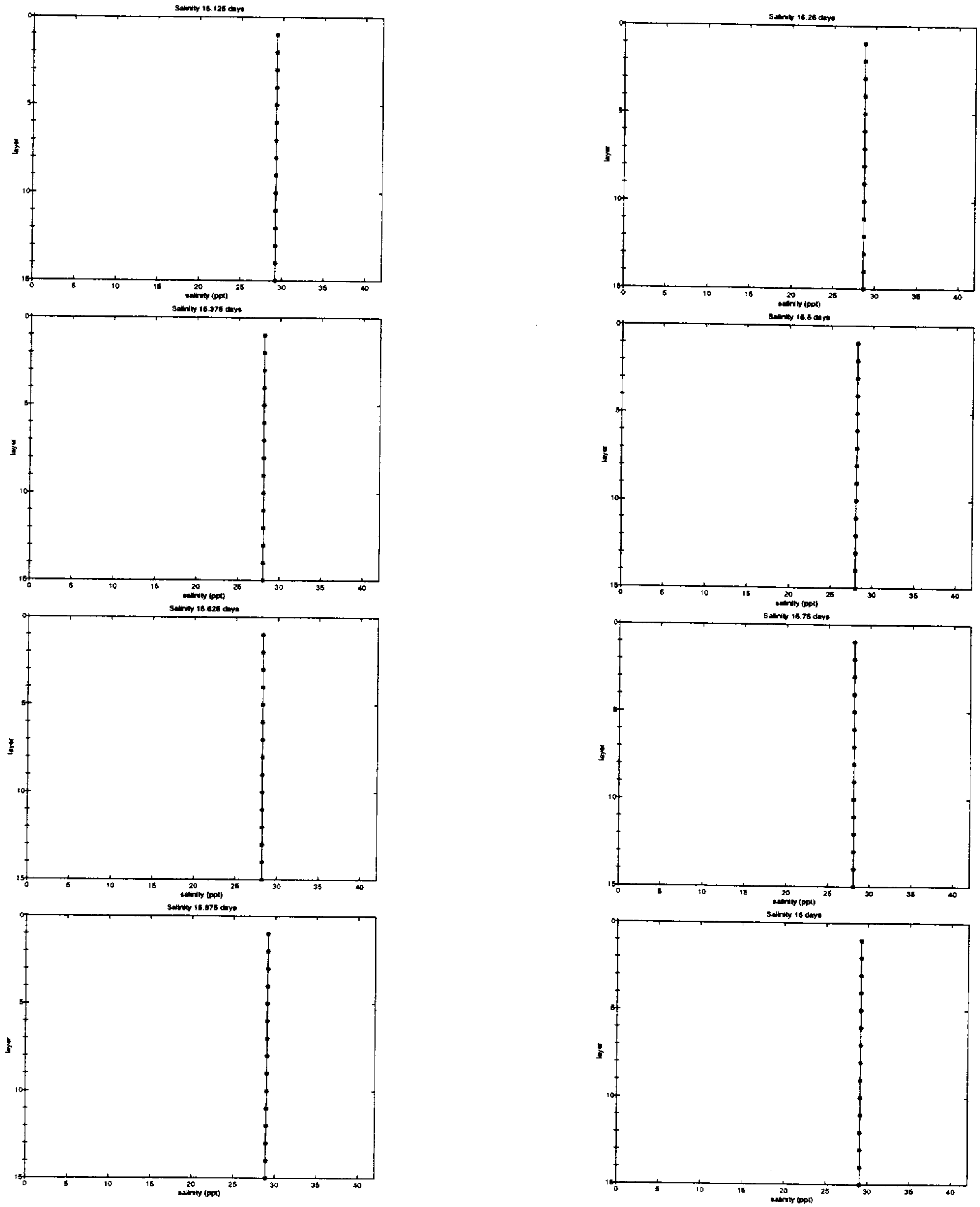

Figure 20: Vertical profiles of salinity at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at entrance to ship channel

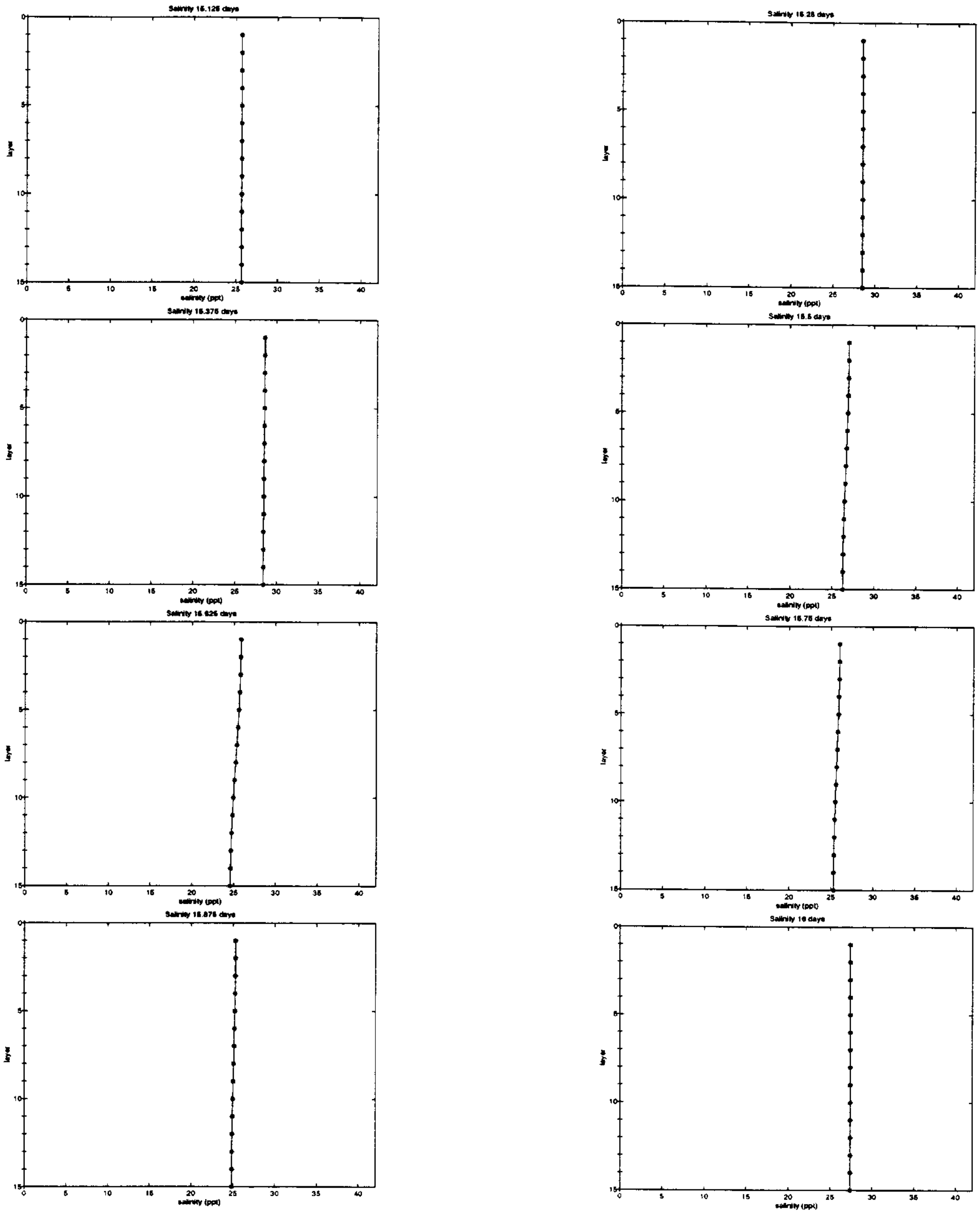

Figure 21: Vertical profiles of salinity at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at midway of ship channel

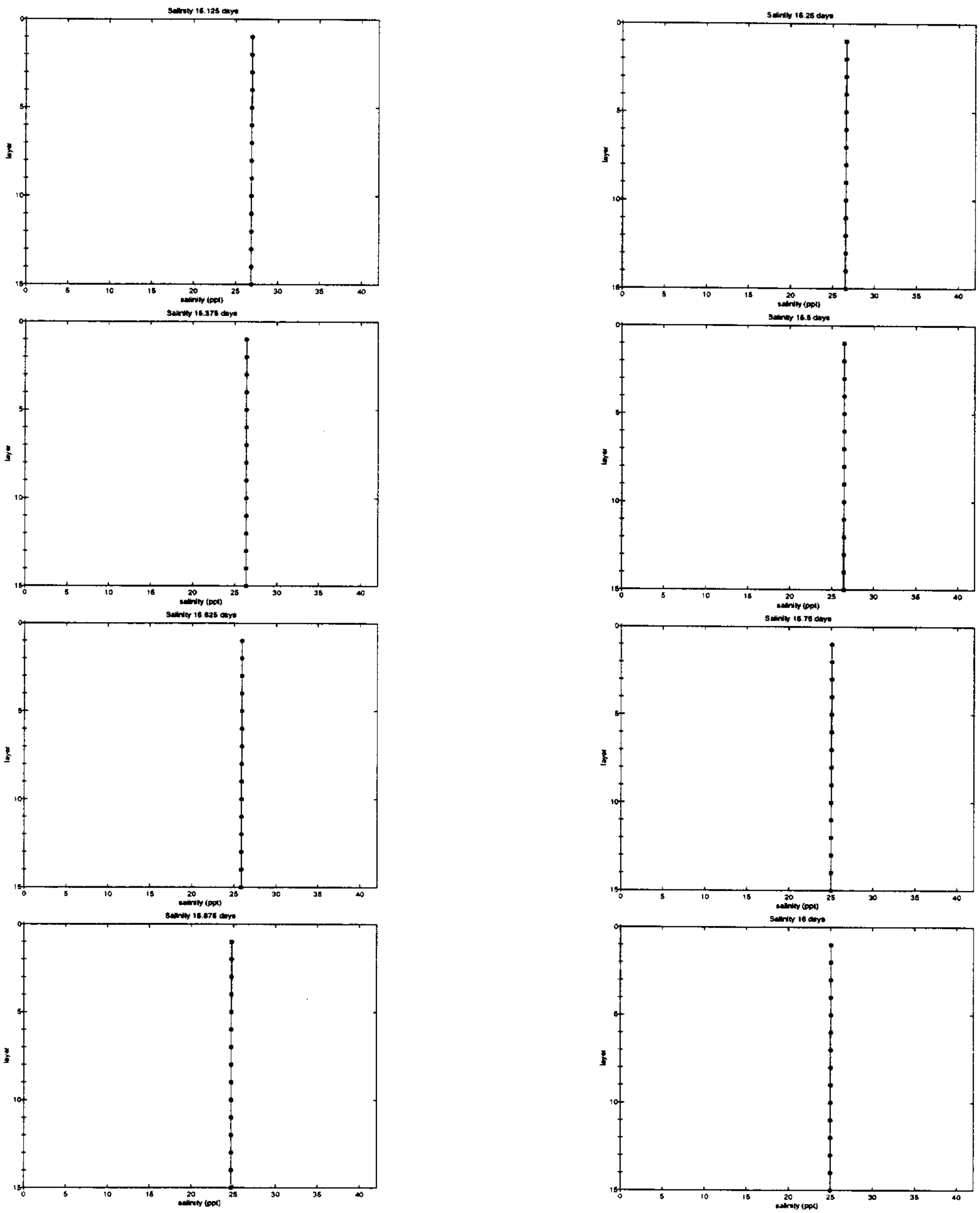

Figure 22: Vertical profiles of salinity at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at harbor bridge

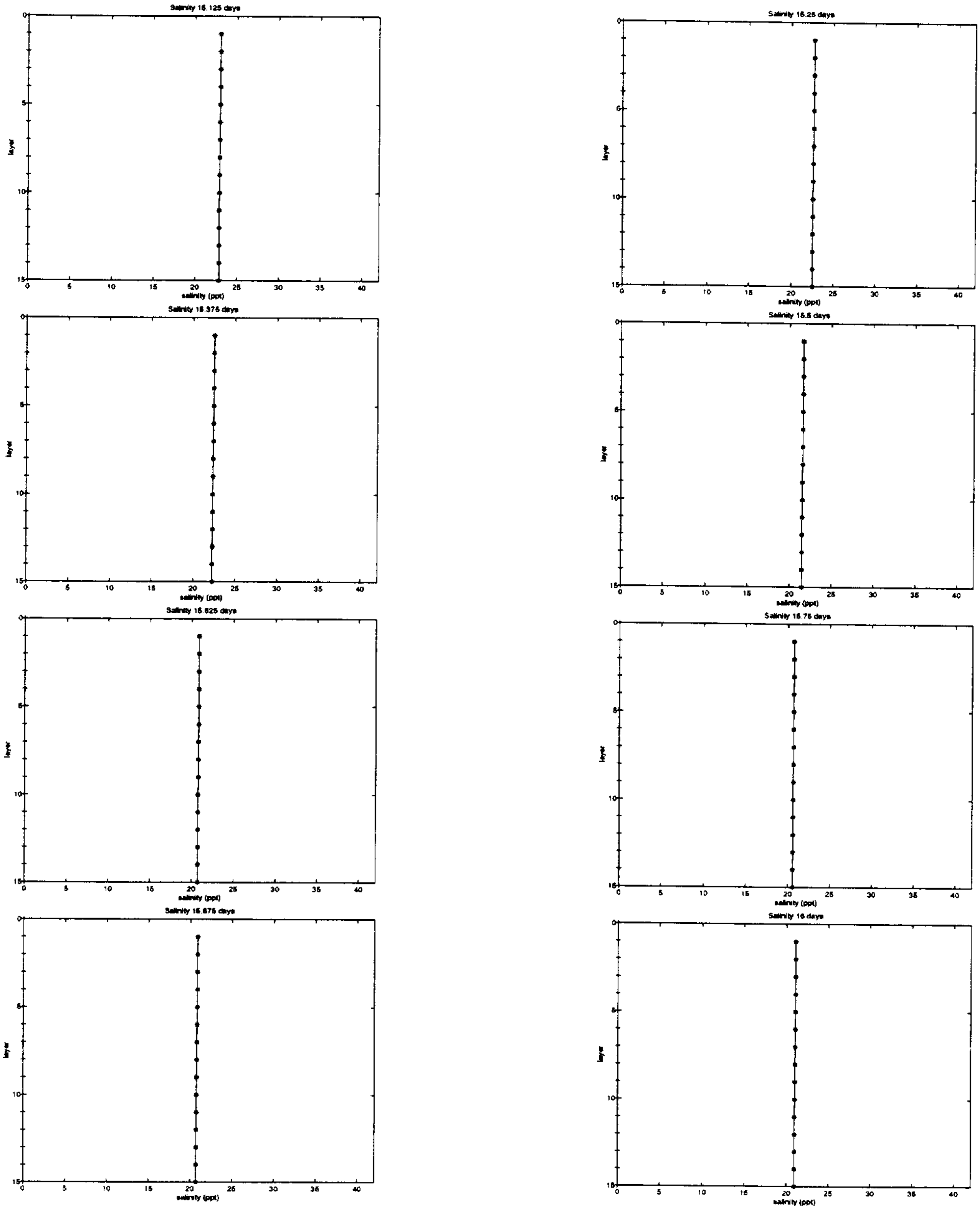

Figure 23: Vertical profiles of salinity at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at northern part of Corpus Christi Bay

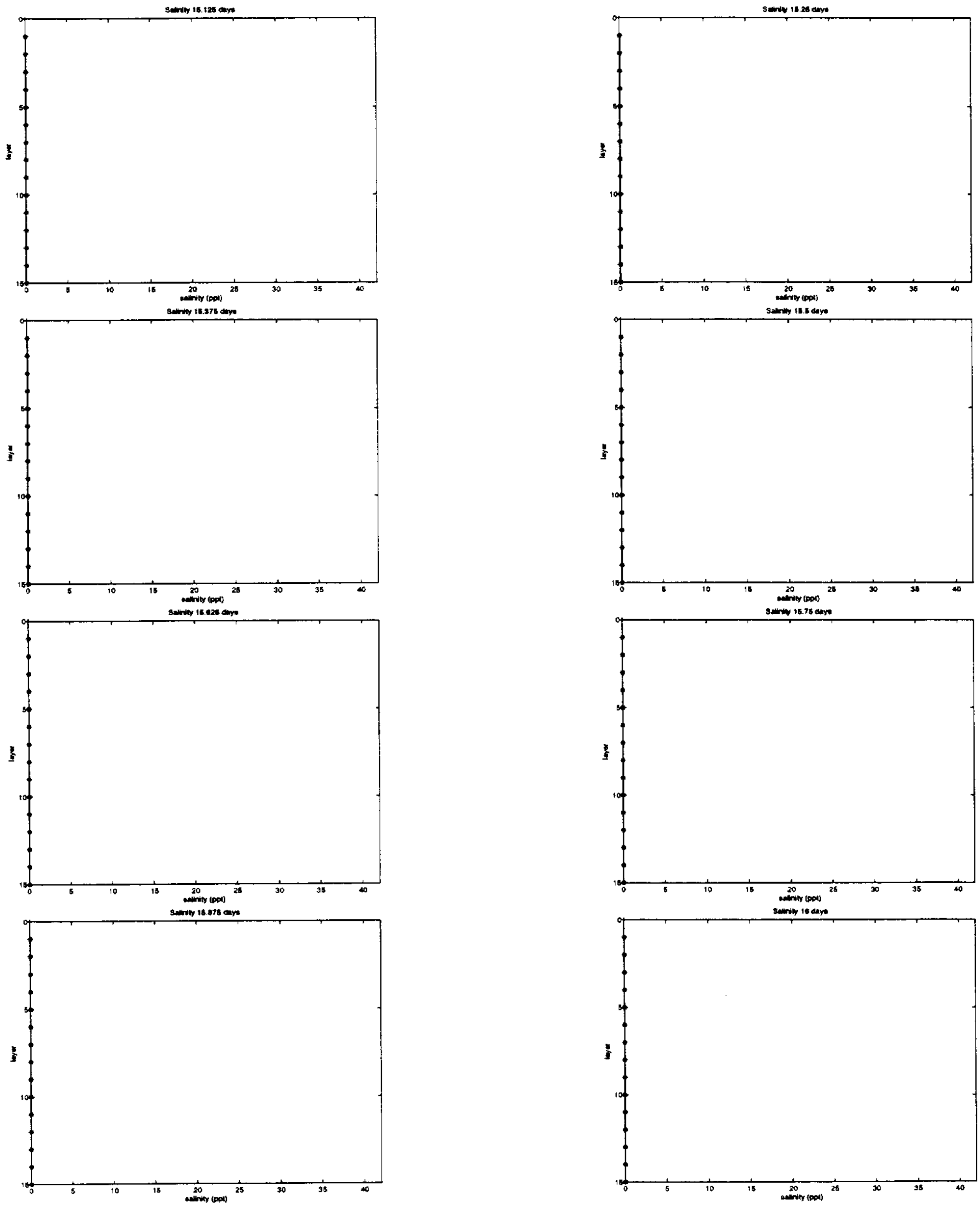

Figure 24: Vertical profiles of salinity at days 15.125, 15.25, 15.375, 15.5, 15.625, 15.75, 15.875 and 16, at western part of Nueces Bay

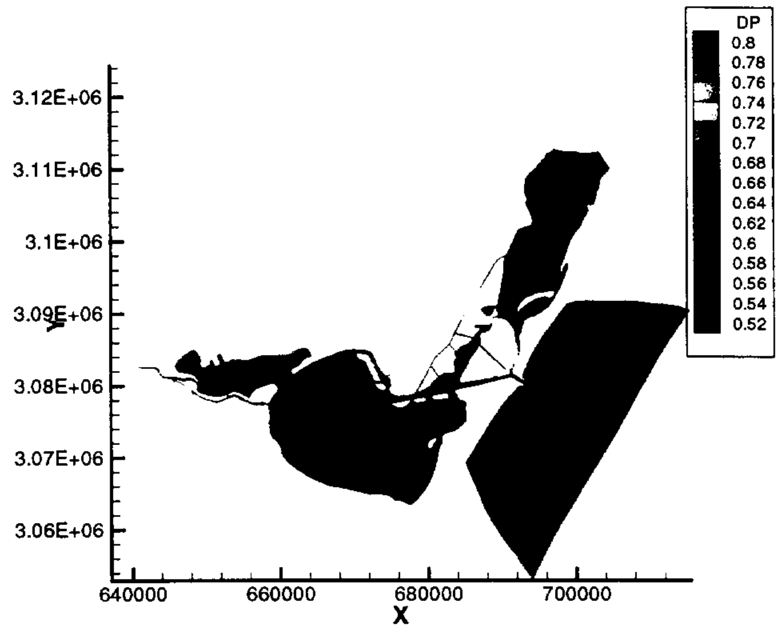

Figure 25: Elevation profile at 15.125 days

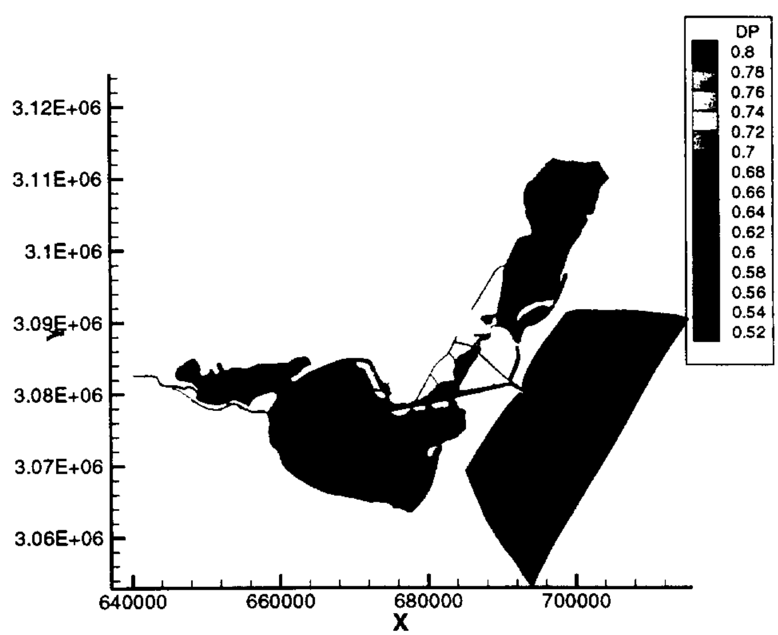

Figure 26: Elevation profile at 15.25 days

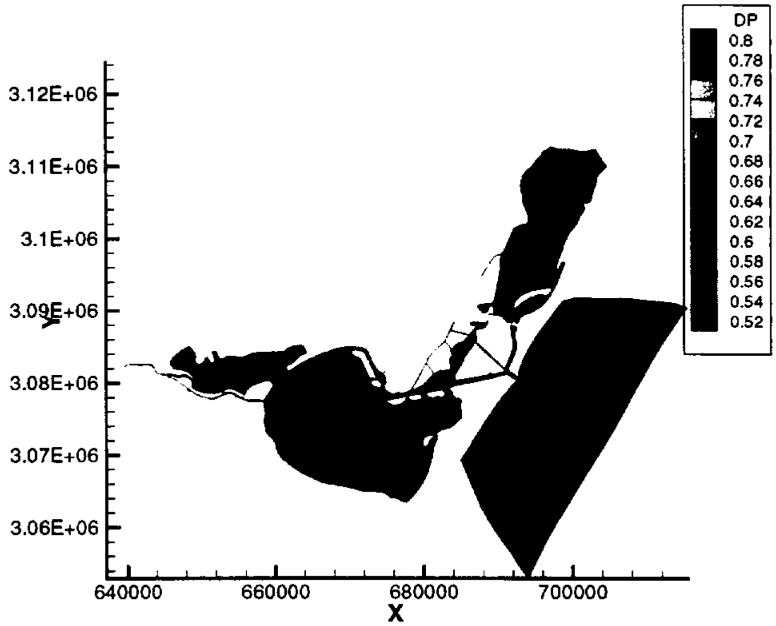

Figure 27: Elevation profile at 15.375 days

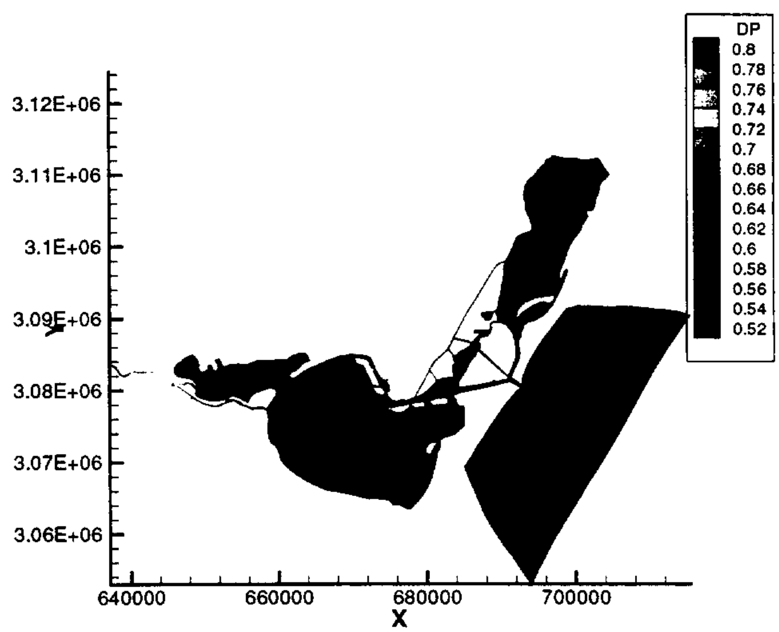

Figure 28: Elevation profile at 15.5 days

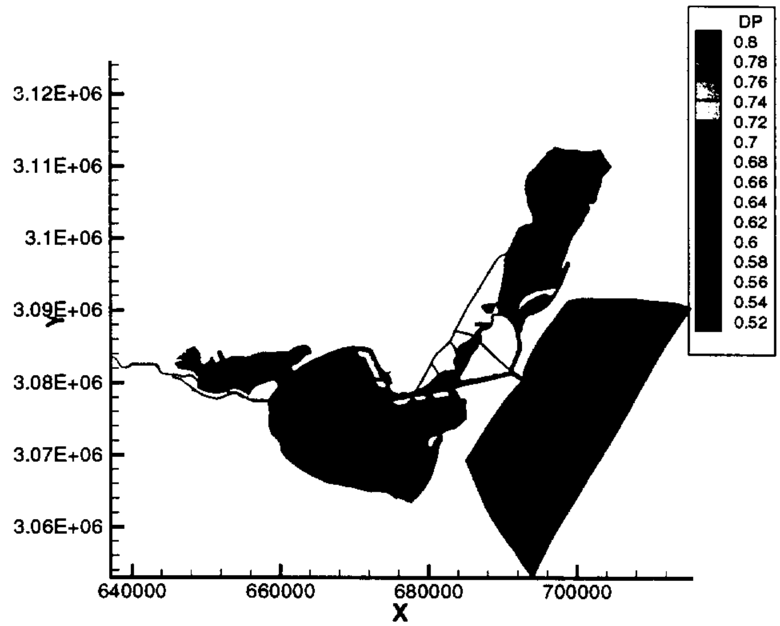

Figure 29: Elevation profile at 15.625 days

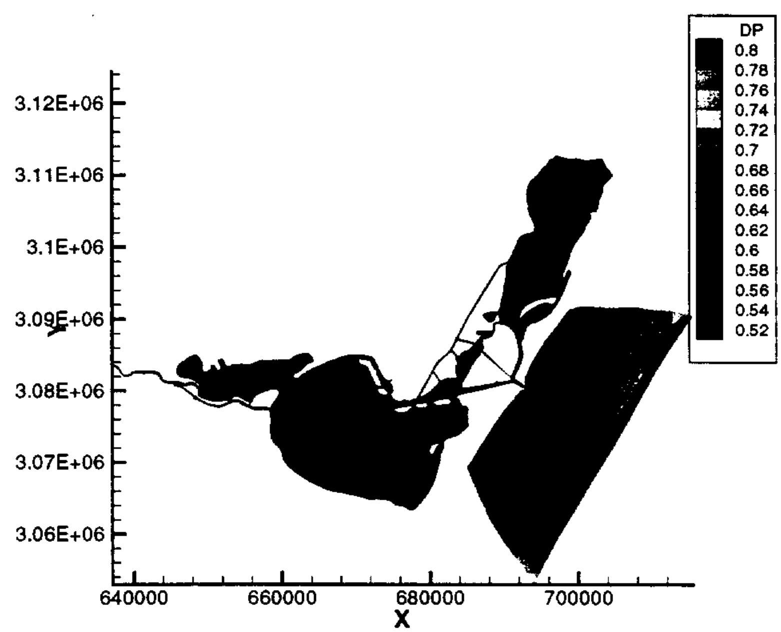

Figure 30: Elevation profile at 15.75 days

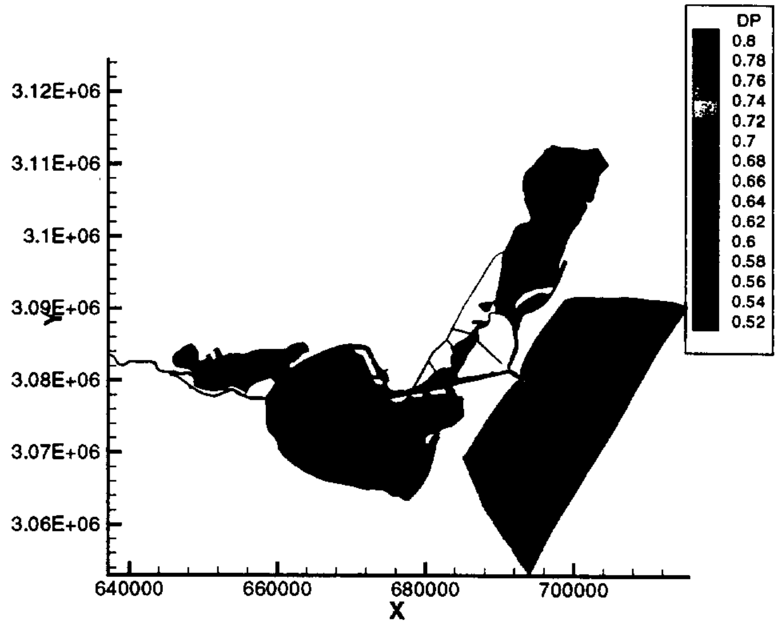

Figure 31: Elevation profile at 15.875 days

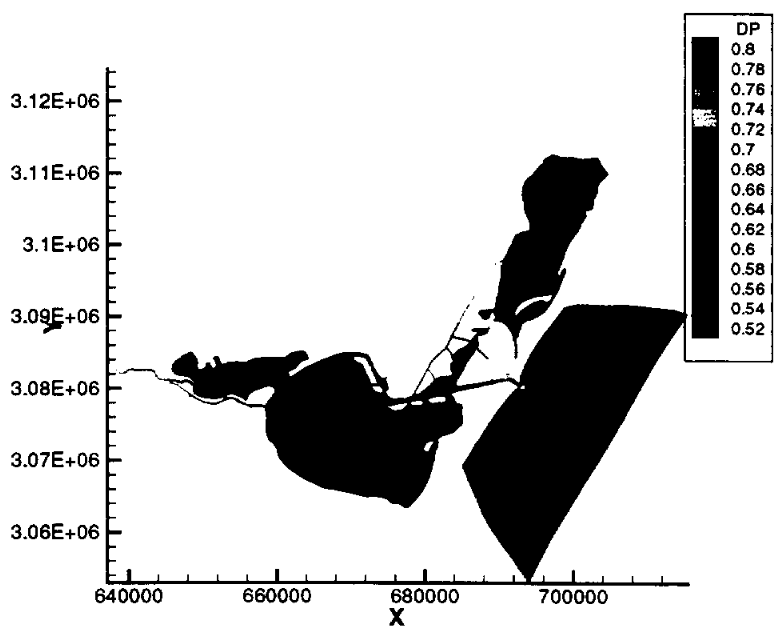

Figure 32: Elevation profile at 16 days