CHAPTER 332

Storm-Derived Bar/Sill Dynamics in a Dredged Channel

Sean O'Neil, Student Member ASCE,[1] Keith W. Bedford, Member ASCE,[2] and David P. Podber, Student Member ASCE[3]

Abstract

The development of sediment bars and sills due to storm-induced flow events in a dredged Great Lakes tributary is studied. The hydrodynamics associated with long-waves from the lake, create flow reversals at the river mouth, and storm runoff produces large sediment loads delivered to the lake. A laterally-averaged numerical model, including a turbulence closure sub-model, is used to simulate the hydrodynamics. A simple sediment settling, resuspension and transport model is coupled to the hydrodynamic model. Model runs are made for flow and temperature conditions which would be typical of the region during the spring season. Runs are made with and without the sediment settling velocity term, which effectively represents the modeling of two grain sizes; clay particles which have extremely small settling velocities and tend to floc together producing neutrally buoyant particles, and silt sizes which have finite settling velocities.

Introduction

Harbor dredging is the necessary result of long term, persistent deposition of watershed-derived sediments. Periodic redredging is required to ameliorate the occurrence of sills and bars which form as a result of the interaction of wave climate, channel geometry, tributary flow and littoral drift. As opposed to the persistent and predictable tidal forcing on coastal harbors, the harbors on the Great Lakes are moderated by random, long-wave effects derived from storms. The storm surges and resulting seiches, coupled with a high sediment influx from watershed runoff, often

[1]Graduate Research Associate, [2]Professor and Chair, [3]Graduate Research Associate. Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, 470 Hitchcock Hall, 2070 Neil Avenue, Columbus, OH 43210-1275, USA. email: sean@superior.eng.ohio-state.edu

conspire to yield a two-sill bottom configuration which motivates maintenance dredging.

As part of a study designed to investigate the impacts of dredging operations, the physical processes responsible for the formation of sills and/or bars is explored by the use of detailed numerical models. The models developed as part of this study will also be used to enhance the tributaries portion of Great Lakes Forecasting System (e.g., Bedford and Schwab, 1994) which currently produces nowcasts four times daily and 24-hour daily forecasts of the state (water levels, wave heights, temperature, currents, etc.) of Lake Erie. This contribution details some of the results of the sill dynamics modeling and analysis for conditions marked by flow reversals and stratified flow.

Study Site

Toledo Harbor, on the Maumee River, is the third busiest port in the Great Lakes shipping arena. The site of the model investigation, shown in Figure 1, extends along

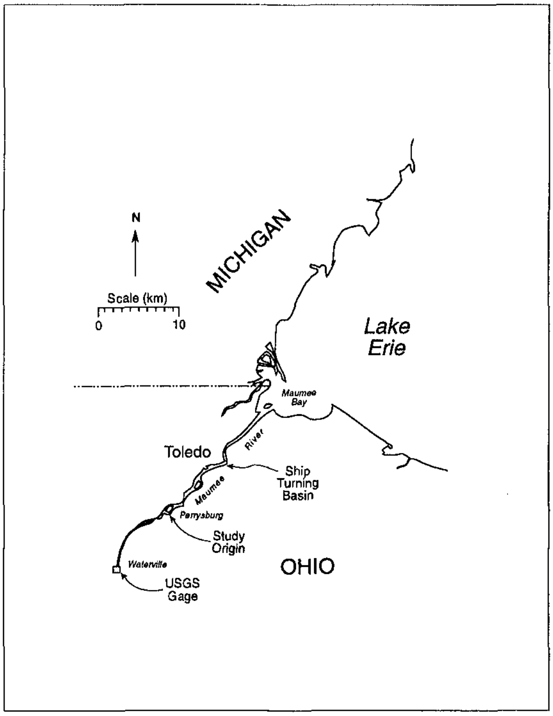

Figure 1: The Maumee River region.

the river, through the Maumee Bay, along a dredged navigation channel. The Maumee River delivers the single largest tributary-derived sediment load to Lake Erie, contributing 44% of the total annual load (Kemp *et al.*, 1976). This high load occurs because 85% of the watershed land use is for agriculture. The extreme shallowness of Maumee Bay, with an average depth 1.5 m (5 ft), and the Western Basin of Lake Erie, average depth 7.6 m (25 ft), necessitates the maintainance of the 152 m (500 ft) wide, 8.5 m (28 ft) deep navigation channel. The dredged portion of the model domain extends from a ship turning basin 9 km upstream in the river, to approximately 6 km into the bay. Figure 2 shows a profile of the modeled portion of the river and navigation channel including the double-silled bathymetric configuration near the mouth of the river.

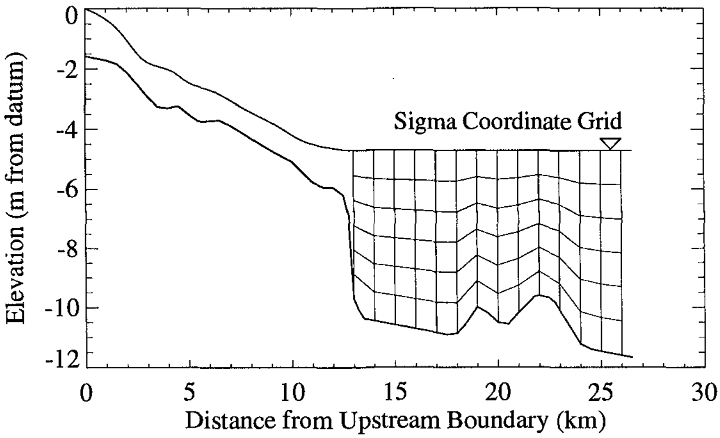

Figure 2: Schematic of model domain profile.

Physical Setting

The physical setting within the Maumee River, Bay and Western Basin of Lake Erie displays all of the features which might be found in a typical marine estuarine system, excluding of course tidal regularity. Storm events in the Lake Erie region occur with a frequency of 5-7 days during the spring and fall, with durations of 1-2 days. The corresponding increase of river flow rate and stage attain values that are significant fractions of the ambient levels.

A typical storm track during these seasons will follow the major axis, west to east, of Lake Erie, producing a significant storm surge at the eastern end of the lake. The storm surge will decay into a lakewide seiche with frequently observed 14.4, 9.1, 5.9 and 4.2 hour longitudinal modes. The seiche typically produces water elevation changes of more than 1 m, which is a significant fraction of the average water depth at Toledo Harbor. After the storm event, the decaying seiche may take 3-4 days to completely disappear. The narrow and deep dredged channel results in a "pipelining" of the excess flow due to runoff into the lake. The oscillations combined with the seasonal variations in water density gradients, here due to temperature differences between river and lake water, result in a system which behaves like a typical estuary during storms, and like a river during calm conditions. Flow reversals are frequently noted as are internal waves and oscillations.

Numerical Models

The numerical methods and schemes employed for this set of model runs have all been well documented and used by several researchers under a variety of conditions, therefore only a brief outline will be given as to how the model couplings occur. The one-dimensional, hyperbolic de St. Venant equations are solved to determine the river stage and discharge from Waterville, OH to the river mouth at Lake Erie, in this case using the upstream discharge at Waterville and the downstream stage at the lake, as boundary conditions. In turn, the values of discharge and stage are used as the boundary conditions for the two-dimensional hydrodynamic model, which is based on the laterally-averaged, hydrostatic, Navier-Stokes equations. The use of this type of model allows the vertical structure of the flow field to be captured without the expense of a fully three-dimensional model. The use of the model is justified by the fact of the narrow, deep dredged channel. The two-dimensional model is used only from the ship turning basin (see Figure 2) to the lake and uses specified temperature and velocity boundary conditions at the upstream, downstream and bottom. A turbulent closure submodel, the Mellor-Yamada level 2.5 scheme (e.g., Blumberg and Mellor, 1987), is employed to calculate the time-varying vertical eddy viscosities and diffusivities. At the water surface, the flux of velocity and heat are nil, and at the bottom a drag-law based on the square of the horizontal velocity just above the bottom, allows for a shear stress or no-slip condition.

The sediment transport component of the model solves the advection-diffusion equation for suspended sediment concentration using an upwind advection scheme, a size specific constant settling velocity term, and source/sink terms for the erosion and deposition of sediment. The erosion and deposition terms are parameterized using the model of Sheng and Lick (1979), where the deposition of sediment is proportional to the sediment concentration and erosion is proportional to an excess shear stress as compared to the shear stress for sediment resuspension. Boundary conditions are specified to be no sediment flux through the water surface, a well mixed upstream condition giving a constant input sediment concentration, and lake-like concentration and temperature profiles imposed downstream. Empirical parameters in the erosion and deposition terms are based on previous studies performed in the Western Basin of Lake Erie and reported in Sheng and Lick (1979).

Conditions and Assumptions

The specific imposed conditions and assumptions which are applied for the spring season case study are outlined. The boundary conditions at the two ends of the model would normally come from data, or possibly, the output from other models. For the spring storm conditions of interest, a typical steady river inflow was applied upstream, the magnitude of 141.6 m^3/s (5000 cfs) was determined from flow hydrographs obtained during the spring months (Pinsak and Meyer, 1976). To approximate the effect of the lake seiche after a storm, a downstream sinusoidal water elevation with an amplitude of 0.61 m (2 ft) and a period of 14 hours, was applied for four complete cycles. Given the short term nature of the simulation, the bottom was assumed to be fixed, so that the sills were not moving or changing shape. This is justified by the fact that (with the exception of the sping snow melt discharge) the bottom probably doesn't evolve much under the influence of a single storm event, but does over the course of a season or longer.

The river temperature was assumed to be a constant upstream value of 12°C and the lake was assumed to have a temperature of 7°C, typical for spring (Shindel *et al.*, 1993). The upstream sediment concentration was assumed to be 1 kg/m^3, and downstream a constant concentration profile, with maximum concentration near the bottom of 1 kg/m^3, imposed if the flow reversed and lake water traveled upstream. However, the form of the profile was found not to affect results in trials with different profile shapes. Model runs were performed for single sediment grain sizes, and two cases were examined. The Stokes' settling velocities were determined to be 1×10^{-5} m/s and 0 for the two cases of silt (median diameter 0.004 to 0.06 mm) and clay particles (median diameter < 0.004 mm).

Results

Analyses examine the impacts of flow reversals introduced by seiches versus regular downchannel river flow during inter-event periods. The following plots depict the water velocity field in the dredged channel as well as the suspended sediment concentration contours. These results were determined at several points within a single seiche cycle, where the cycle fractions are defined as in Figure 3. For brevity, not all of the cycle points designated in Figure 3 will be shown. Depicted in the figures is the third of four complete cycles run due to the fact that the fourth cycle of a run is generally not very different from the third.

The velocity fields shown in Figures 4-7 show that moderate seiche amplitudes are sufficiently strong enough to cause flow reversals in the river, even for riverine flow rates as high as 141 m^3/sec (see also Podber and Bedford, 1993). The upstream sill proximity is consistent with its origination from simple channel deposition of sediments introduced upstream, and the downstream sill is located at the furthest upchannel extent of the 14-hr seiche mode excursion distance. During spring conditions a stable gyre is present above the downstream sill and positioned such that horizontal velocities are zero directly above the peak of the downstream sill, as shown in Figures 5 through 7. As the cycle progresses, the gyre appears to move up and then back down in the water column, but maintaining its position above the downstream sill. This may be an extremely important agent in sill formation and migration. Note also that at all times in the cycle the stratification of the water is maintained, where

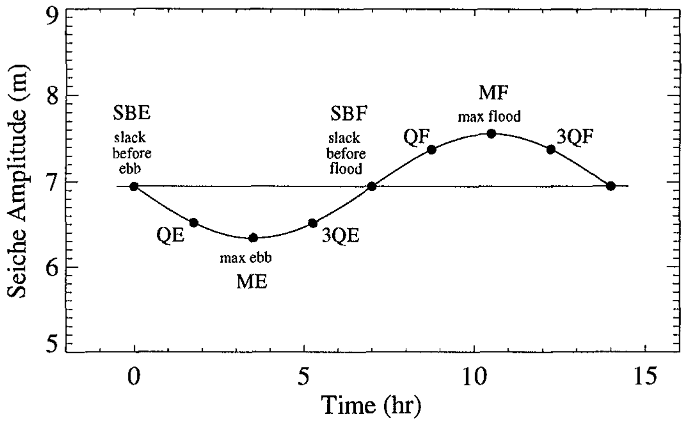

Figure 3: Definitions within a seiche cycle.

the warmer river water flows over the colder lake water. During the fall the inverse situation occurs.

In comparing the suspended sediment contours, it can be seen in all cases that there is a greater mass of the silt sized sediment within the water column than the neutrally buoyant particles. This is seen by fact that the larger valued contours are closer to the bottom and the lake side of the modeled domain. This is most likely due to the fact that neutrally buoyant particles enter the modeled region from the upstream direction, but they can only pass out through the downstream end of the model domain. For the case of the settling silt particles, some portion of the total mass of particles will be settling towards the bottom, and though the flow reversal will bring less sediment-dense water into the river, the settling sediment will tend to push the contours down and closer together. Also note that the extent of the upstream excursion of the intruding lake water has the effect of pushing the neutrally buoyant particles back to the upstream sill, whereas the maximum upstream extent of the silt particles is the downstream sill, which occurs at maximum flood.

Acknowledgements

This research was supported in part by the Coastal Ocean Program of NOAA. The Ohio Supercomputer Center provided computing resources under OSC Grant No. PAS891-1. The support is very much appreciated. This is a contribution from the Great Lakes Forecasting System.

References

Bedford, K. W. and Schwab, D. J. (1994). The Great Lakes Forecasting System: An Overview. In G. V. Cotroneo and R. R. Rumer, editors, *Hydraulic Engineering*

'94, Proceedings of the Conference, pages 197–201, Buffalo, NY. ASCE. See URL http://superior.eng.ohio-state.edu/.

Blumberg, A. F. and Mellor, G. L. (1987). A description of a three-dimensional coastal ocean circulation model. In N. S. Heaps, editor, *Three-dimensional Coastal Ocean Models*, Coastal and Estuarine Sciences 4, pages 1–16. American Geophysical Union.

Kemp, A. L. W., Thomas, R. L., Dell, C. I., and Jaquet, J.-M. (1976). Cultural impact on the geochemistry of sediments in Lake Erie. *J. Fish. Res. Board Can.*, **33**, 440–462.

Pinsak, A. P. and Meyer, T. L. (1976). Environmental baseline for Maumee Bay. Maumee River Basin, Level B Study, MRB Series No. 9, Great Lakes Environmental Research Laboratory.

Podber, D. P. and Bedford, K. W. (1993). Tributary loading with a terrain following coordinate system. In M. L. Spaulding, K. W. Bedford, A. F. Blumberg, R. T. Cheng, and J. C. Swanson, editors, *Estuarine and Coastal Modeling III, Proceedings of the 3rd International Conference*, pages 475–488. ASCE.

Sheng, Y. P. and Lick, W. (1979). The transport and resuspension of sediments in a shallow lake. *J. Geophys. Res.*, **84**(C4), 1809–1926.

Shindel, H., Klingler, J., Mangus, J., and Trimble, L. (1993). Water Resources Data – Ohio, 1992. Volume 2, St. Lawrence River Basin. Technical report, U.S. Geological Survey, Water Resources Division.

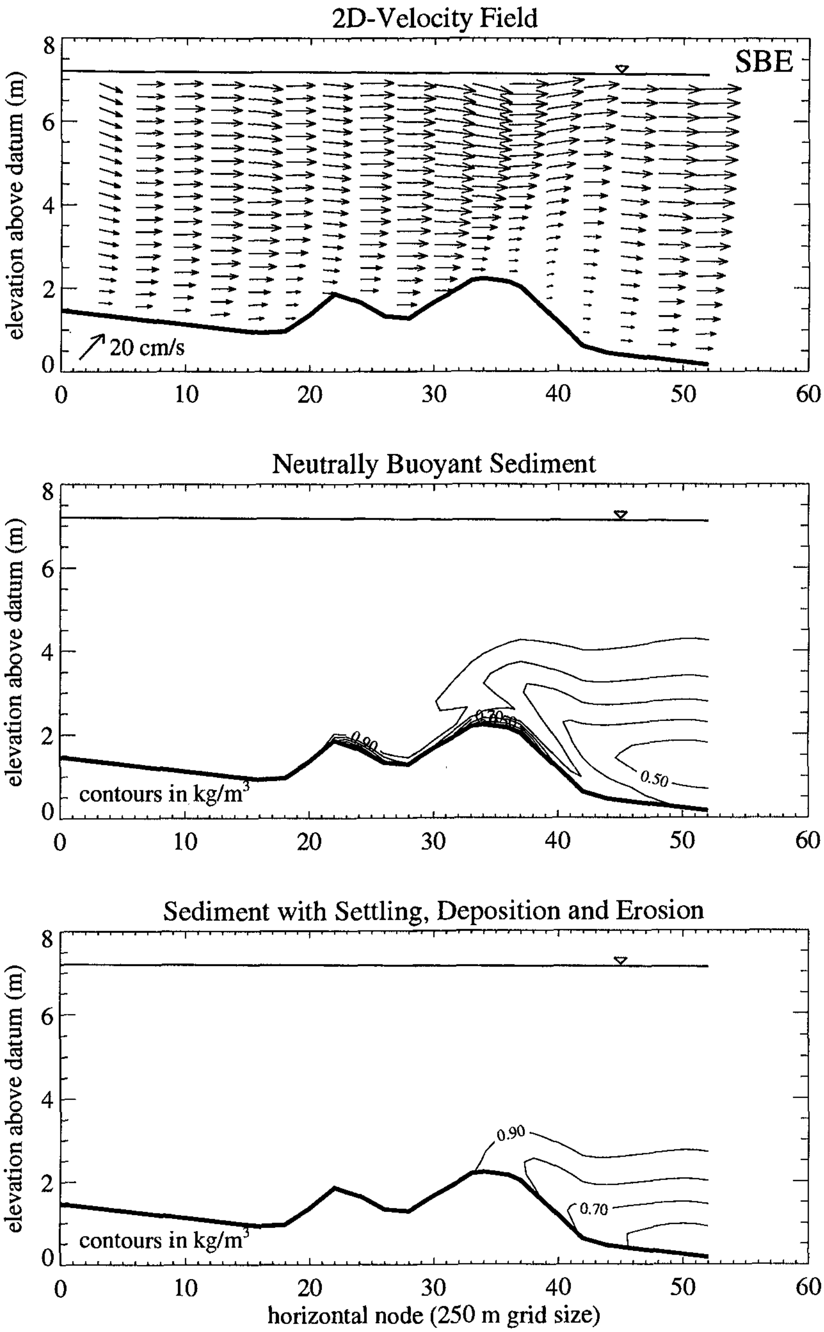

Figure 4: Velocity structure and suspended sediment contours for SBE.

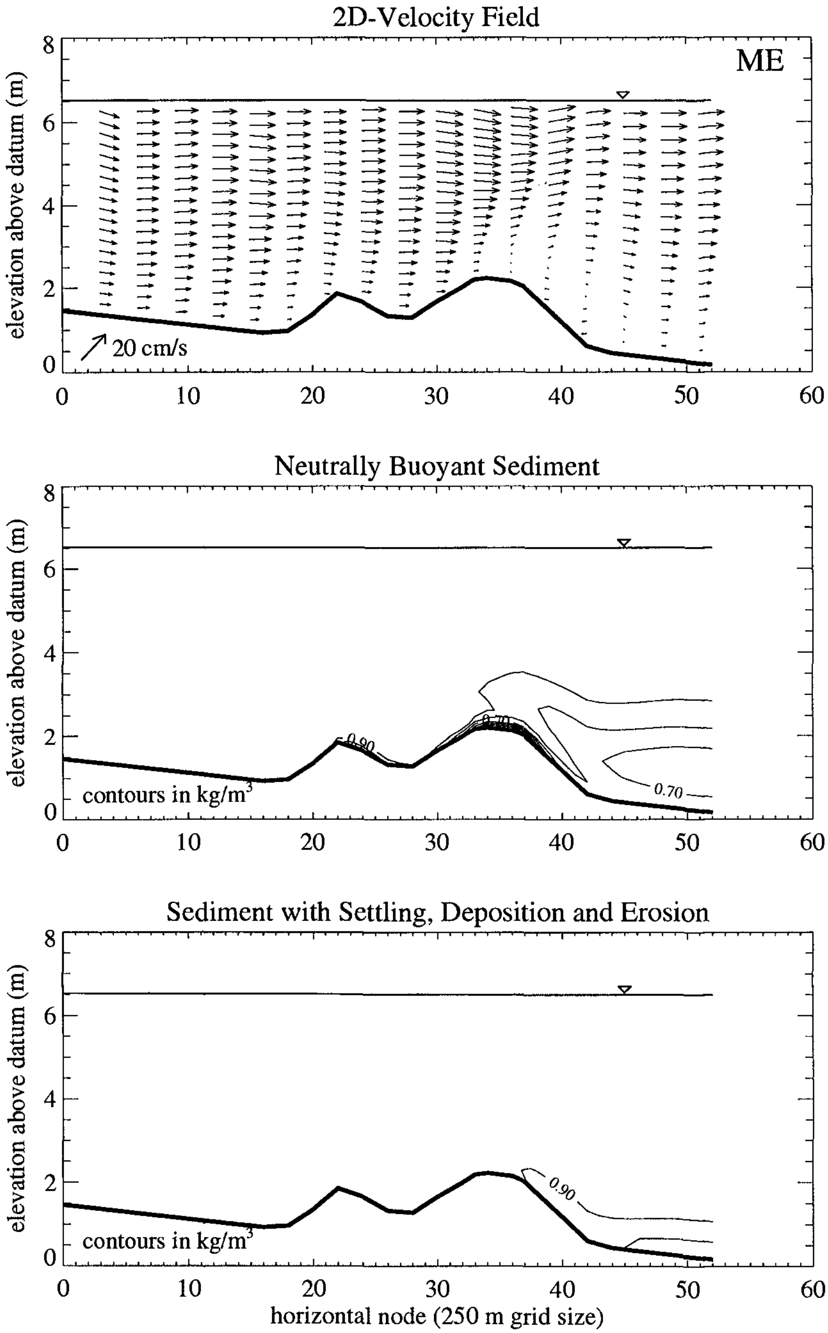

Figure 5: Velocity structure and suspended sediment contours for ME.

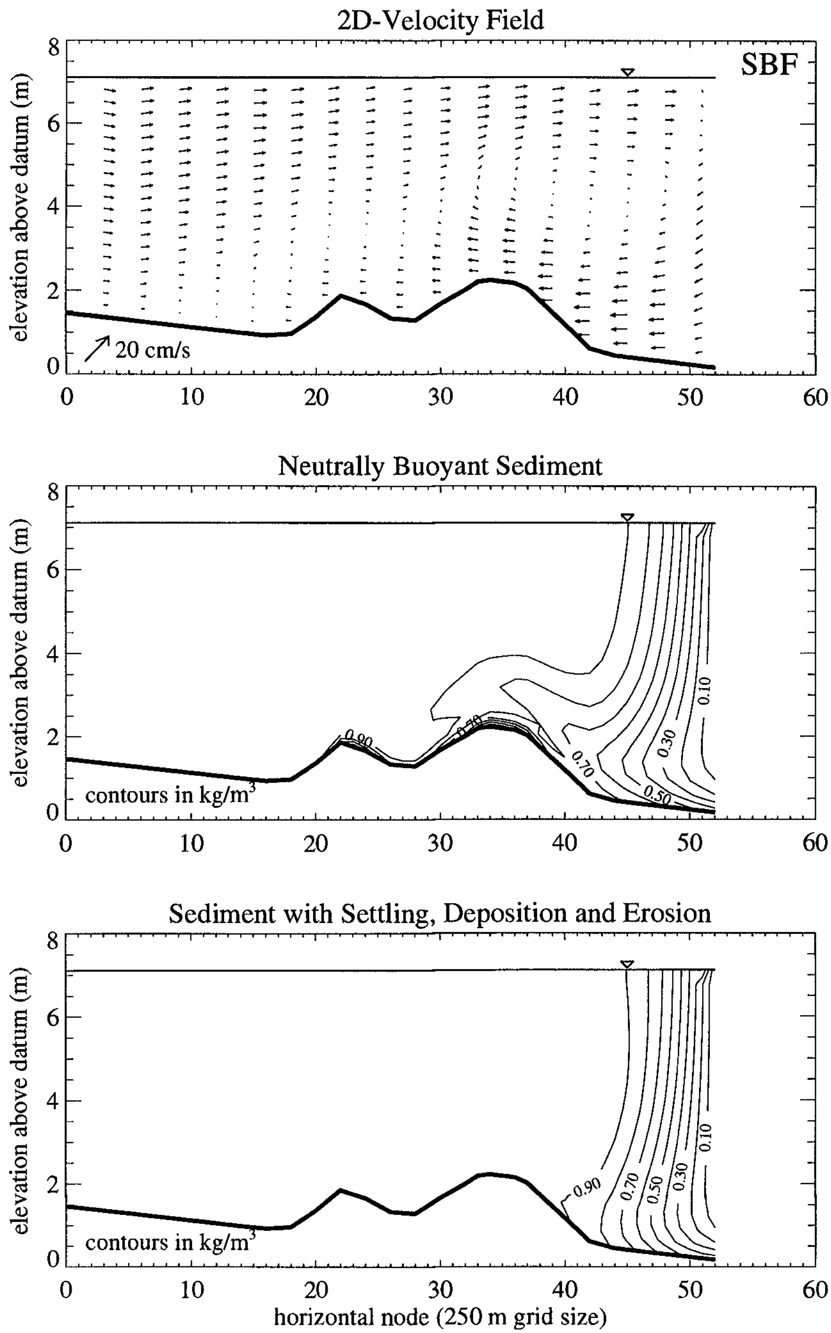

Figure 6: Velocity structure and suspended sediment contours for SBF.

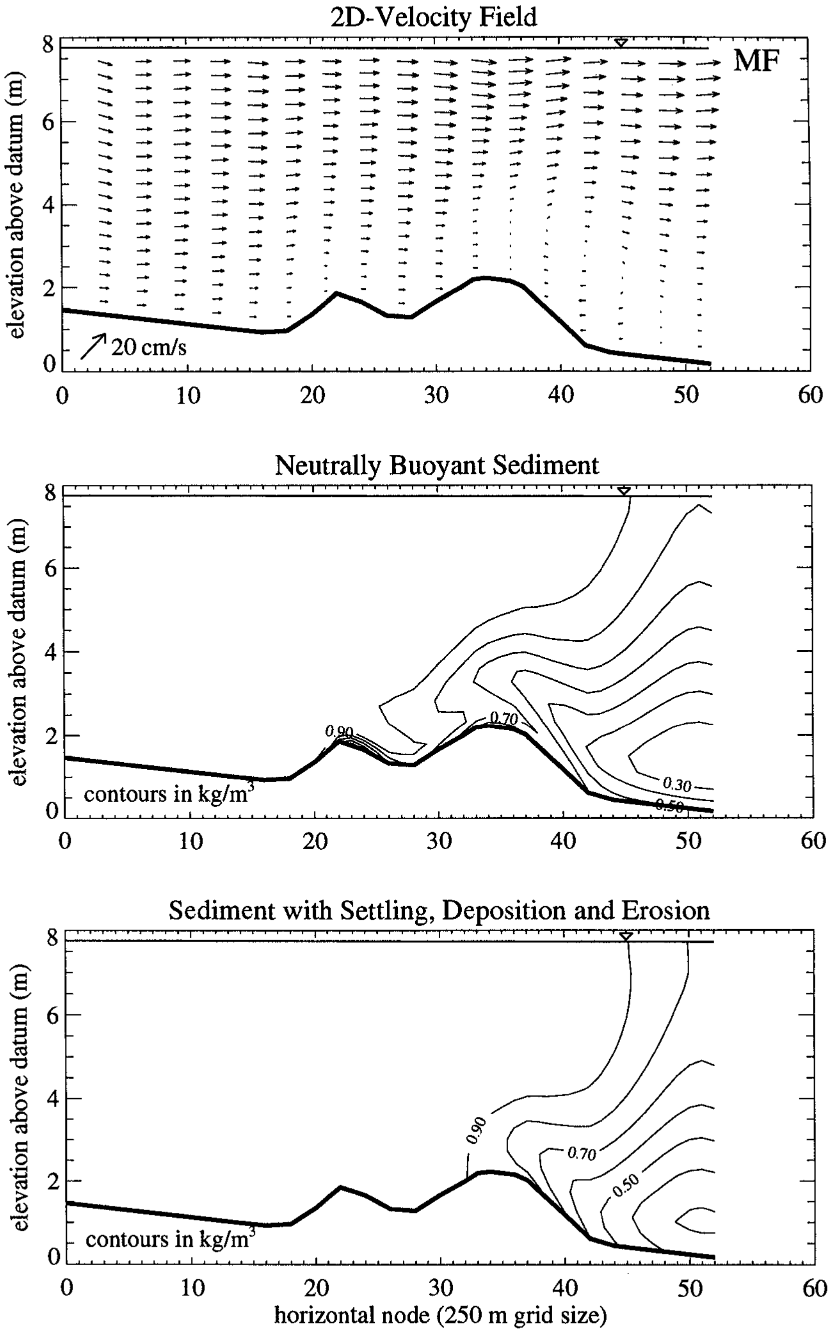

Figure 7: Velocity structure and suspended sediment contours for MF.