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APPLICATION AND ASSESSMENT OF A SHALLOW-WATER TIDE MODEL TO PAMET RIVER, TRURO, MASSACHUSETTS

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SYNOPSIS

Modeling of a shallow-water tidal system in a Cape Cod Bay estuary has established that removal of a man-made barrier dike located approximately 2.5 kilometers from the inlet would probably not increase the size of the tidal prism by more than 5 percent. It remains to be seen, however, whether removal of other significant dikes located closer to the inlet would have a comparably small effect. Peculiar geologic aspects of the system under investigation may account for the relatively minimal effect that the initial dike studied apparently has upon the size of the tidal prism.

1. INTRODUCTION

a. Reasons for the Investigation

History records that Pamet Harbor on Cape Cod Bay was in the middle of the 19th Century a commercial port of some importance with a number of wharves, a daily packet boat to Boston and a considerable resident fleet of fishing vessels. Today the harbor has been altered by a stabilized inlet that receives little maintenance, and the tidal river that empties into the harbor has been altered with the multiple dikes required for a railroad and highways.

For all of this century the harbor has been plagued by severe shoaling that has severely limited its recreational use and made it almost useless for commercial purposes. The Truro Conservation Trust commissioned Graham S. Giese in 1983 to investigate the various effects of the man-made alterations on the natural tidal system. In particular, he was asked to determine whether removal of some or all of the man-made dikes or changes in their configuration would, in conjunction with well-conceived dredging, restore the harbor to a more viable state for recreational and (possibly) limited commercial use.

Initial projections using then-available mathematical estimating techniques predicted a roughly 16% increase in the size of the tidal prism if the existing dikes were eliminated. In the present investigation, that hypothesis was then tested by means of a computer-run shallow-water tide model. The model was used to estimate the effect on the tidal prism of eliminating the most prominent dikes in the system, Wilder's Dike and the land-fill for the state highway, Route 6, that lies just east of Wilder's Dike. Wilder's Dike incorporates a clapper valve that permits discharge of fresh water into the river but prevents tidal flow into the fresh-water wetlands east of the dike.

b. Background

Coastal ponds, lagoons and estuaries abound along the southern coast of New England. Unlike the mature coastal plains of the southern United States, this is a young terrain, characterized by small vertical scale (10-100 m) surface features formed or modified by the last (Wisconsian) stage of Pleistocene glaciation. The southern New England coast is also unlike the glaciated coast of northern New England, for while the ice removed sediments from the north, it deposited them in the south.

Submergence of the southern New England coast by rising sea level and fresh water table has produced a wide variety of complex and changing coastal ponds, estuaries and embayments. Where exposed to vigorous wave action, the loose, unconsolidated glacial deposits erode easily, providing ample sediment for littoral drifting. Tidal currents carry this material into the coastal ponds and estuaries where it is trapped, causing shoaling and circulation changes.

In addition to the natural changes resulting from sea-level rise and sedimentation, southern New England's coastal ponds and estuaries are frequently altered by society's intense development of the coastal zone. Dredging of navigation channels, and filling and diking for roads, railways and agriculture, have altered the physical processes controlling the circulation and sedimentation within these systems. As a result of these alterations, unanticipated shoals, pollution and eutrophication often offset the benefits expected from the original modifications.

Increased knowledge of the circulation and sediment transport characteristics of these coastal ponds and estuaries can be gained by application of general mathematical models derived from hydrodynamical principles. In this way, the controlling factors can be isolated and solutions adequate for the requirements of practical environmental management can be formulated. A versatile numerical model is required; one that can detail the complexities of flow in shallow, well-mixed estuaries, and can also be adapted to define the varying size of tidal flats and other exposed areas.

c. The Problem

We were given the opportunity to apply a general one-dimensional numerical model to a stressed estuary, Pamet River in Truro, Massachusetts, through the interest of a private conservation organization, the Truro Conservation Trust (TCT). Pamet River is a shallow estuary that crosses the glacial outwash plain of outer Cape Cod from east to west and joins Cape Cod Bay along its eastern boundary (Figure 1). An earlier study supported by TCT had concluded that a number of environmental problems related to the Pamet River could be attributed to the construction, in the 19th Century, of dikes for roads and railroads that reduced tidal circulation within the system (Giese and Mello, 1985). Important among those problems was a postulated decrease in the tidal prism of the estuary that resulted in increased sedimentation and channel shoaling.

The purpose of the present study was to employ numerical modeling to determine the hydrodynamical effects of removal of the major barriers to tidal flow in the Pamet estuary: Wilder's dike and the state highway (Route 6) and its approaches. To accomplish this, an existing finite difference model, developed by Speer *et al.* (in press), was applied to the Pamet River, both in its present configuration and altered by removal of the dike and highway complex.

Section 2 of this report describes the study area and summarizes the study methods. Sections 3, 4 and 5 describe the tide and current observations, the topographic surveying, and the numerical modeling work that was accomplished. Discussion and recommendations for future research are presented in Section 6.

2. STUDY AREA

The Pamet River (Figure 1) is an altered estuarine system composed of three branches, which occupy valleys cut into the Truro glacial outwash plains by melt water during retreat of the last Pleistocene ice advance (Oldale, 1968). The main stem, Great Pamet, extends completely across Cape Cod, from the ocean shore to Cape Cod Bay, and it is flanked by two smaller branches: Little Pamet to the north, and the south branch which has two forks, Mill Creek and Bang's Creek.

All three branches are shallow, and navigation for the most part is restricted to the dredged tidal inlet, boat basin and connecting channel - and these are not now navigable at low water. Also all three branches have been altered by construction of dikes with tidal gates that prevent or severely restrict upstream transport of salt water. The major barrier, Wilder Dike, was constructed in 1869 to replace a rotting bridge across the mid-section of Great Pamet, and in the mid-1950's fill for a new state highway (Route 6) was placed across the Pamet valley several hundred feet east of Wilder Dike. A culvert was placed under the highway to provide drainage from the freshwater marsh east of the highway. Dikes were also placed across Little Pamet, Mill Creek and Bang's Creek for a railway in the early 1870's. Because the system is very shallow, salinity of the water at low tide becomes extremely reduced on the "salt-water" (westerly) side of the dikes in response to fresh water inflow through the tide gates (Lewis, 1989).

The present study focuses on another possible effect of these dikes: their impact on channel size and sediment transport. In a study of shoaling and erosion problems at Pamet Inlet, Giese (1980) suggested that dike construction in the 19th Century, by decreasing the estuary's tidal prism, reduced inlet size by approximately 20 percent. In making this estimate, the tidal ranges presently observed at the dikes were taken to represent the ranges that would exist at those locations following dike removal. While that is a reasonable assumption for first-order approximation, a more accurate estimate can be achieved through numerical modeling. The development and testing of such a model was the objective of the present study. The first step was to implement an existing one-dimension numerical model for application to small, shallow estuaries similar to Pamet River. The second step was to verify the implemented model by comparison to field data. Finally, the verified model was applied to Pamet River both in its present configuration and with Wilder dike removed.

3. TIDE AND CURRENT OBSERVATIONS

Tide and current measurements were required both to apply the model to the Pamet River and to verify that the model satisfactorily reproduces the estuary's responses to tidal forcing. Locations of the instrument stations established for that purpose are shown in Figure 1.

a. Long-term Tide Station at the Boat Basin.

A long time-series of tidal elevation measurements was required to serve as a diagnostic indicator of the estuary's hydrodynamical characteristics and to provide a baseline for correlation of short-term measurements of tides and currents throughout the system. Thus a long-term base tide station was established at the Pamet Harbor boat basin because of the basin's central importance to harbor management and because the Harbor Master's office there provided security and easy access to the tide gauge.

Because the extreme shallowness of the estuary prohibited use of standard sea surface monitoring instruments, a special type of tide recorder - a "bubbler gauge" - was required. These devices provide a continuous measure of sea surface elevation by sensing the pressure of the overlying water column exerted on a gas (nitrogen) that is slowly bubbled out of a tube, the open end of which is anchored at the bottom of the harbor. We arranged for the two-year loan of such a bubbler gauge from the National Ocean Service, National Ocean and Atmospheric Administration.

The gauge's nitrogen tube was deployed from the shore to a deep section of the boat basin by SCUBA divers, and the recorder was installed in the Harbor Master's office. It was maintained and kept in good operating condition for 18 months. The recorder output analog records on strip charts, and calibration was provided by twice-weekly time checks and sea-surface elevation checks made in reference to a tide staff mounted on a piling. The contributions of the Harbor Master, Mr. Irving Wheeler, were invaluable in maintaining a regular calibration schedule.

Estuaries with a tidal distortion of the type found at Pamet are called "flood-dominant" estuaries, because the flood current runs for a shorter length of time, and therefore at a higher velocity, than the ebb current. Flood-dominant estuaries characteristically experience a net influx of sediment, resulting from the fact that shear stress exerted on a channel bed by flowing water is proportional to the square of the flow velocity. The resulting shoals in the lower Pamet channel so strongly limit low tide elevations that the usual fortnightly variation in the elevation of low tide is almost completely absent (Figure 2).

The analog tide records were digitized at the Institution's Information Processing Center, and the resulting digital data were subjected to harmonic analysis to extract the amplitudes and phases of the primary tidal harmonic constituents and their compound tides. (Tidal harmonic analysis is the representation of a tidal time series as the sum of several sine functions of known frequency). The results indicate a substantial amplitude reduction of the major semidiurnal constituents as compared to Cape Cod Bay tides, and a similarly substantial amplification of the higher frequency "overtides" which produce a highly distorted tidal curve (Figure 3a).

b. Short-term Tide and Current Observations.

Two auxiliary tide stations were established, one in Cape Cod Bay approximately 1,000 feet south of Pamet Inlet and the other at Wilder Dike, the easternmost extent of tidal flow. Both stations were kept in operation for more than one month in order to obtain the 29-day record length required for harmonic analysis. A comparison of 63 hours of tidal heights at these two stations and at the boat basin is presented in Figure 3a.

A current meter was deployed with its sensor initially 1 foot above the bed in the inlet channel, approximately 10 feet south of the north jetty. Unfortunately, the shifting channel bed forms buried the instrument and terminated the record after 6 days, but the data that were retrieved were sufficient to provide an approximate basis for comparison with currents predicted by the numerical model (Figure 3b).

4. TOPOGRAPHIC SURVEYING

Topographic surveying was required to establish the physical dimensions of the system for the purposes of numerical modeling. The objective of the topographic survey was to measure cross-sections of the waterway relative to the previous determined tidal reference levels. The cross-sections were located in relation to an approximately 1.7 km-long baseline that was established from the vicinity of Wilder Dike westward to the abandoned railroad dike at Pamet Harbor. Stations were established at intervals varying from 100 to 150 m along the baseline, and these stations were marked by galvanized pipes driven into the marsh. Elevations of the pipes were determined by spirit leveling with reference to established bench marks, and sections across the baseline were surveyed with reference to the pipes. (Locations of these sections and additional sections in the vicinity of the mouth of the system are shown together with the numerical model description in Figure 5.)

Figure 4 presents representative cross-sections across the inlet and the Great Pamet (locations are shown in Figure 1) along with the heights of mean high and low water on Cape Cod Bay. The cross-sections clearly demonstrate that throughout its entire length, with the exception of the dredged boat basin and the inlet throat, the channel elevation is above the level of offshore mean low tide. This fact explains the truncation of the tide records observed at low water (Figure 3a) as well as the consistency of the low water elevations (Figure 2). At low tide, tidal hydrodynamics alone do not define water flow within this system. Because the river's channel bed is higher in elevation than the level of mean low water in Cape Cod Bay, we will refer to the Pamet system as an "intertidal estuary".

5. NUMERICAL MODELING

a. Methodology

An existing finite-difference numerical model (Speer and Aubrey, 1985; Speer *et al.*, in press) was used to model Pamet River, both in its present configuration and as altered by the removal of Wilder Dike. The model is one-dimensional, meaning velocity is averaged over the cross-section of the channel. For results of one-dimensional modeling to be valid, the length of the tidal channel is assumed to much greater than its width, and its width, in turn, is assumed to be much greater than its depth. The numerical model is governed by two equations, conservation of mass and conservation of linear momentum. The two equations solve for two unknowns: S(x,t), the elevation of the water surface, and U(x,t), the cross-sectionally averaged velocity. The boundary conditions are: (1) a minimum allowable water depth in the channel at low tide (10 cm in this case) and (2) forcing of the surface elevation offshore (using data measured in Cape Cod Bay).

Figure 5 shows the one-dimensional numerical model grid for Pamet River along with the locations of topographic survey lines. The model system is made up of five branches: (1) Great Pamet, (2) Little Pamet, (3) Mill Creek-Bang's Creek, (4) the inlet channel, and (5) a central connecting branch. The inlet channel branch includes an additional five grid points not shown in Figure 6, which represent the tidal flow over the shallow ebb-tide delta. To model the removal of Wilder Dike an additional 23 grids were added to the end of the Great Pamet branch (doubling the total length of that branch). A cross-section of the model is shown in Figure 6. The numerical model is divided into two dynamically distinct portions: (1) a momentum carrying channel and (2) inter-tidal flats which act only to store inter-tidal water. The geometric parameters (h', h1-3, b1-4) describe the shape and elevation of the channel and flats at each grid point, spaced every 125 meters along the length of Pamet River.

The geometry of the numerical model is based upon a combination of topographic surveying at Pamet and the existing USGS topographic maps. Topographic surveying was essential to determine appropriate channel depths for the numerical model. The USGS maps were used primarily to estimate the total area of intertidal flats to be included in the model.

b. Results

The model of the Pamet River in its present configuration was calibrated by comparison of the numerical results to the tide and current observations taken in the field. The model successfully reproduced time series of tidal surface elevation. Table 1 and Figure 7 quantitatively compare the model results to field observations via harmonic analyses of the modeled and observed tides. (Tidal harmonic analysis is the representation of a tidal time series as the sum of a few sine functions of known frequency.) Not only does modeled tidal range match observed values well throughout the system, but set up, phase lag and tidal non-linearities are also comparable. Figure 7 compares mean twelve-hour tidal cycles as reconstructed from the harmonic analyses. In most cases, the characteristic features of the mean twelve-hour tide can be reproduced by summing M_2 (the largest amplitude component, with a period of 12.4 hours) and M_4 (which has a period of 6.2 hours). For more strongly distorted tides, the mean tide is better represented by summing M_2, M_4 and M_6 (which has a period of 3.1 hours).

At first glance, the numerical model does not appear to reproduce observed tidal velocity (Figure 7d) as well as it reproduces tidal elevations. The model predicts somewhat higher speed and more strongly non-linear currents through the inlet than those observed in the field. The model also predicts peak tidal currents at the inlet to occur roughly 30 minutes later than the typically observed peak velocities. Much of this discrepancy, however, is due to the fundamental difference in the nature of calculating model velocities versus observing field velocities. Field observations are point measurements whereas model velocities are averages over the entire cross-section of the channel. In real channels velocities tend to be lower than average along the bottom, where the current sensor was located. Furthermore, the real inlet cross-section is made up of laterally varying deeps and shallows with potentially different velocity characteristics (including local velocity distortion).

After the numerical model was calibrated by comparison to field measurements, the model was used to determine the response of Pamet River to the removal of Wilder Dike and the Route 6 fill. Column (3) in table 1 presents that response quantitatively, while a comparison of the tidal prism with and without the dike is given at the bottom of table 1. The response of the river to dike removal is illustrated using a series of profiles along the length of Pamet River to provide snapshots of sea surface elevation spaced evenly through a twelve-hour tidal cycle (Figures 8a and 8b). The profiles show tidal elevations produced by the numerical model, both for the present configuration of Pamet River and as altered by the removal of Wilder Dike and Route 6. The snapshots are spaced approximately every one and a half hours in time, from low tide, through flood to high tide (Figure 8a), and back through ebb tide to low tide (Figure 8b). The profile extends from the Cape Cod Bay end of the numerical model, through the inlet and central connecting branches of the model, and finally up the length of Great Pamet. To remove small amplitude numerical wiggles found inland of Wilder dike at low tide, the results in presented in Figure 8 have been processed by a spatial running mean filter. The results presented in table 1 and Figure 8 are discused in the following section.

6. Discussion and Recommendations

The tidal analyses performed as part of this study indicate that Pamet River is a flood dominant estuary, that is, an estuary in which the tides are distorted in such a manner that the flood current runs for a shorter length of time, and at a higher average velocity, than the ebb current. Because of this tidal distortion, there is a net influx of sediment into the estuary and, as a result, the valley originally cut by glacial melt water is now practically filled with sediment to the elevation of present-day sea level.

With the exception of the outermost part of the inlet channel and the dredged boat basin, the tidal channel beds are shallower than the tidal range in Cape Cod Bay. This fact places Pamet River in a special class of flood dominant estuaries which we will refer to as "intertidal estuaries". The tides within intertidal estuaries are truncated at low water because the tide outside the estuary falls below the level of the channel bed. Intertidal estuaries may be common along coasts with large tidal ranges. They have been reported from the coast of Maine by Lincoln and FitzGerald (1988), and the non-linear hydrodynamics characterizing them is discussed in Speer *et al.* (in press).

The results of numerical modeling of Pamet River with Wilder Dike and Route 6 removed indicates that while circulation within the estuary would be considerably altered by dike removal, the net effect on the tidal prism and sediment transport would be negligible. With the dike in place, both field observations and model results indicate that high tide occurs nearly simultaneously from Cape Cod Bay up to the dike. As the tide falls, the water surface drops more slowly at the east end of the system ("upper Pamet estuary") than at the west because of increased friction in the shallower channel.

Eventually the Cape Cod Bay tidal level drops below the level of the upper Pamet estuary channel bed, and the flow in that channel becomes decoupled from from the outside tide. When that occurs, the water in the channel changes from saltwater (salinity above 10 ppt) to fresh water (salinity below 1 ppt) that is introduced into the system through the tide gate at Wilder Dike. Field observations of water salinity changes throughout the tidal cycle (Lewis, 1989) confirm this pattern. The fresh water flow is controlled only by the channel slope and bottom friction; it is entirely independent of the tide. This condition continues in the upper Pamet estuary until well after the tide has turned at the inlet. Lewis (1989) has shown that the return of seawater to the upper Pamet west of Wilder Dike typically occurs in the form of a "salt wedge" underlying low salinity water and that the time lag in arrival of the salt wedge increases with distance from the inlet.

With the dike removed and flow under Route 6 unimpeded, the tide east of the present dike site will continue to rise at the time of high tide in Cape Cod Bay. When it does drop, it will eventually becomes decoupled from the outside tide as in the previous case, but because salt will have mixed throughout the system, the flow will not become fresh (although the salinity will drop due to increased upland drainage). At the present dike site, the height of high tide will be somewhat less and it will occur a little later in time than at present. More significantly, however, the truncation of low tides will be much reduced and tidal currents, particularly the flood, will be greatly increased.

The model results indicate however, that conditions at Pamet inlet will be altered little by the removal of Wilder Dike and the Route 6 fill. The present tidal prisms of 6.3×10^5 m^3 (mean tide) and 8.9×10^5 m^3 (spring tide) will not change by more than several percent. The pattern of tidal currents will similarly change little, although there will be a small increase in ebb velocities. The volume of the present spring tidal prism estimated by the model matches well the estimate of $8.5 \pm 1.4 \times 10^5$ m^3 given in Giese (1980), but the earlier report estimated a tidal prism increase of 1.8×10^5 m^3, or 16 percent above the model-estimated present prism, as a result of removing dikes within the Pamet system. While that estimate was based on the removal of several dikes and therefore cannot be compared directly to the results of the present study, its computation did not include the hydrodynamical principals that form the basis of our numerical model. We recommend application of the model to removal or alteration of other dikes within the system in order to acquire more accurate estimates of the potential impacts of such changes.

We close with brief discussion of observations that were peripheral to the major objectives of this study, but that may deserve consideration from the point-of-view of long term management of the Pamet system. Our limited topographic surveys across the fresh water marsh east of Route 6 suggest that that marsh surface is approximately 2 feet lower than the salt marsh surface west of Wilder Dike. Such a difference could be accounted for by the combination of two processes. First, having been cut off from access to the tides for a century and a quarter, the fresh water marsh has not received the supply of sediment that allows salt marsh levels to keep pace with rising sea level. The rate of relative sea level rise at Pamet River is approximately one foot per one hundred years. Second, drainage of interstitial water from salt marsh peat that is no longer flooded by spring tides results in compaction, and therefore lowering of the surface elevation, of the peat.

If the fresh marsh water table is controlled by the elevation of the culvert beneath Route 6, from whence the water flows at low tide through the tide gate at Wilder Dike into the upper Pamet estuary, and if the beach water table at Ballston Beach rises at a rate equal to, or greater than, the present rate of one foot per century, the gradient of the salt water table beneath Ballston Beach will become ever steeper, increasing the ground water flow of salt water into the fresh water Pamet system. Observations of water salinity as high as 20 ppt at the head of Pamet River have been reported by Lewis (1989). It is suggested that the implications of this increasing gradient between ocean and marsh on future flows of water (by either ground water flow or storm-induced overwash) between the two systems be investigated for the purpose of estimating changes in upper Pamet salinity and their timing.

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8. ACKNOWLEDGMENTS

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Table 1

(1)Field observations; (2) model results with dike; (3) model results without dike

------Sea surface------

	Offshore			Inlet			Harbor			Dike		
Dist.(km)	0.0			0.6			1.3			3.8		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Hours	1400	25	25	359	25	25	4000	25	25	2100	25	25
Range(m)	3.07	3.03	3.03	2.45	2.54	2.51	2.40	2.48	2.40	1.30	1.42	1.11
Set up(m)	0	0	0	0.18	0.15	0.16	0.22	0.17	0.20	0.55	0.55	0.58
M_2(m)	1.51	1.51	1.51	1.26	1.26	1.25	1.18	1.21	1.19	0.58	0.62	0.50
M_2 lag(°)	0	0	0	8.1	9.1	9.6	11.1	13.0	13.3	20.5	22.2	45.6
M_4/M_2	.016	.016	.016	.070	.099	0.103	.105	.120	.133	.441	.503	.437
$2M_2$-M_4(°)	232	232	232	7	40	45	38	44	43	9	8	58
M_6/M_2	.034	0	0	.017	.025	.026	.005	.021	.028	.080	.167	.164
$3M_2$-M_6(°)	38	0	0	109	229	241	96	189	183	65	58	126

------Velocity------

	(1)	(2)	(3)
Mean(m/s)	0.00	-0.10	-0.12
M_2(m/s)	0.42	0.48	0.49
M_4/M_2	.099	.330	.349
$2M_2$-M_4(°)	341	350	359
M_6/M_2	.069	.129	.160
$3M_2$-M_6(°)	77	55	79
M_2 surf-vel lag (°)	85	69	63

Tidal prism through inlet with dike at mean tide: 6.3 x 10^5 m^3; at spring tide: 8.9 x 10^5 m^3

" " " " without dike " " " 6.4 x 10^5 m^3; " " " 8.9 x 10^5 m^3

Figure Captions

Figure 1. Location of study area.

Figure 2. Tide record from Pamet River.

Figure 3. Field observation of Pamet River (a) tidal elevations at Cape Cod Bay, the harbor and Wilder Dike; and (b) tidal elevations and currents at the inlet.

Figure 4. Pamet River cross-sections at locations indicated on figure 1. Dashed horizontal lines represent offshore mean high and mean low water.

Figure 5. Plan of numerical model with locations of instrument stations and field-mapped cross-sections.

Figure 6. Cross-section of idealized channel used in numerical model. b1-b4 give horizontal dimensions; h1- h3 give vertical dimensions. S(x,t) is tidal elevation.

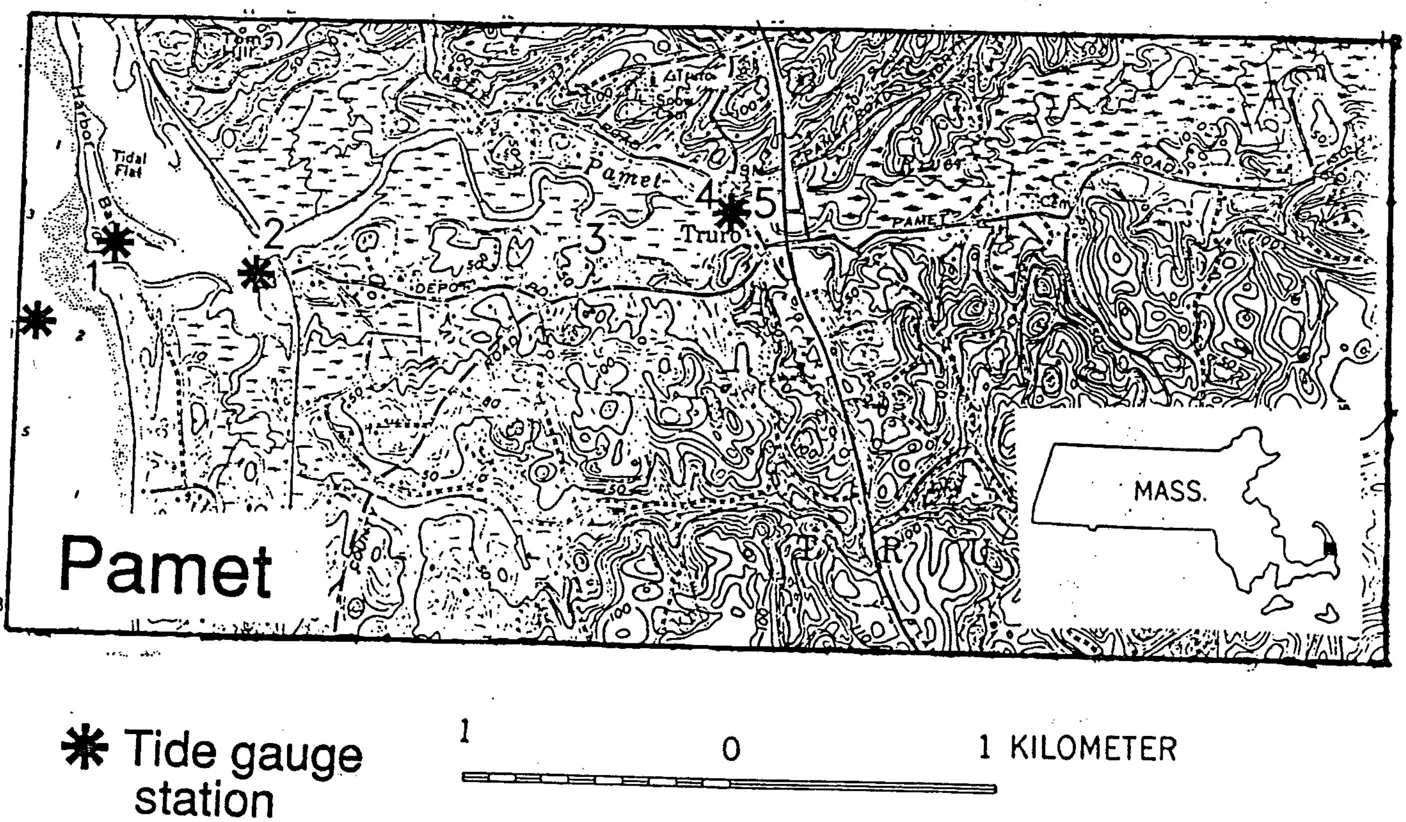
Figure 7. Reconstruction of tidal elevations and velocities from tidal harmonic constituents.

Figure 8a. Longitudinal sections showing modeled tidal changes in water surface during flood tide, with and without Wilder Dike.

Figure 8b. Same as 8a, during ebb tide.

Figure 9. Comparison of modeled tides at inlet, with and without Wilder Dike.

Figure 10. Comparison of modeled tides at location of Wilder Dike, with and without the dike.



1 - 5 Channel cross-sections (shown in figure 4)

Figure 1. Location of study area.

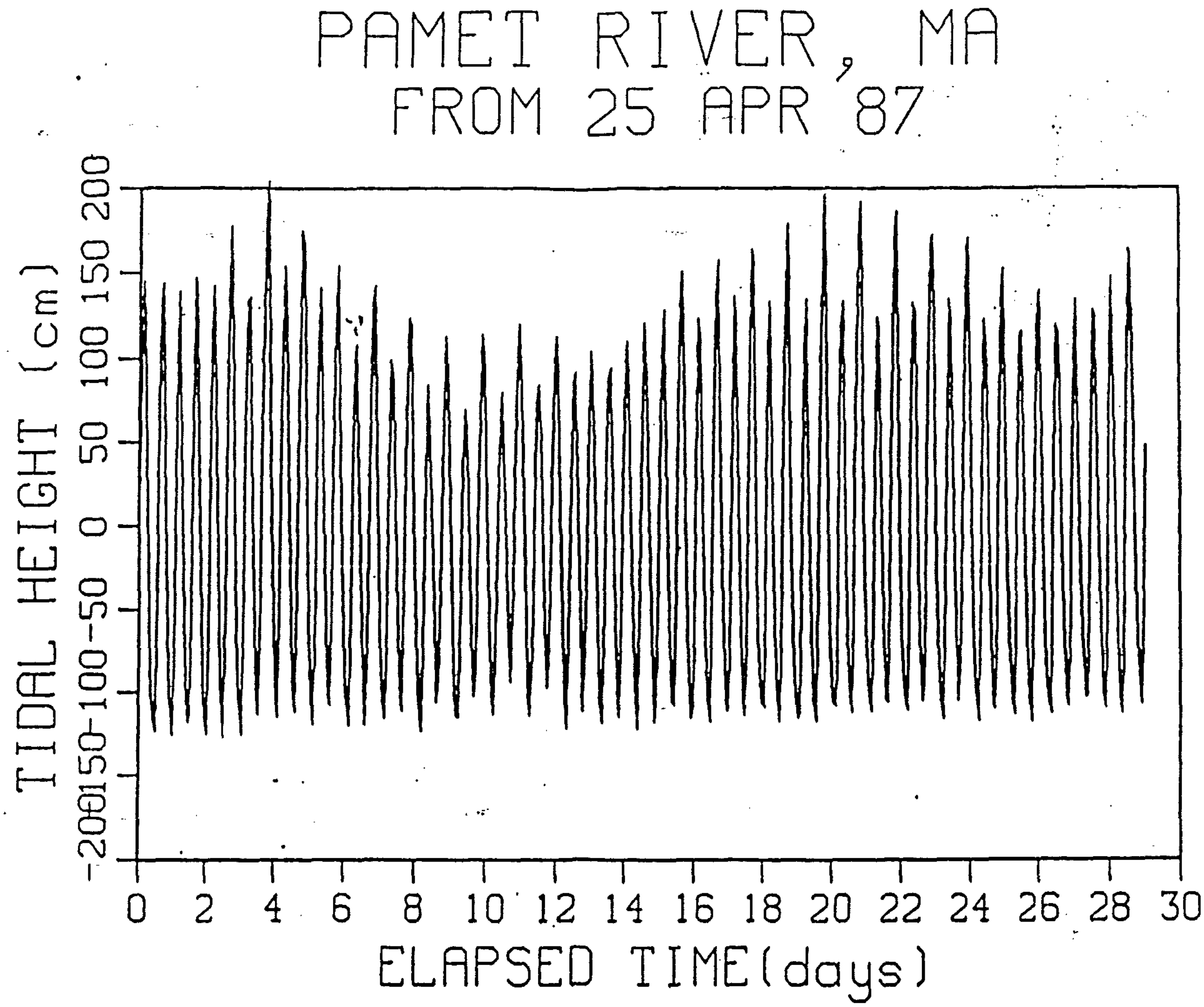
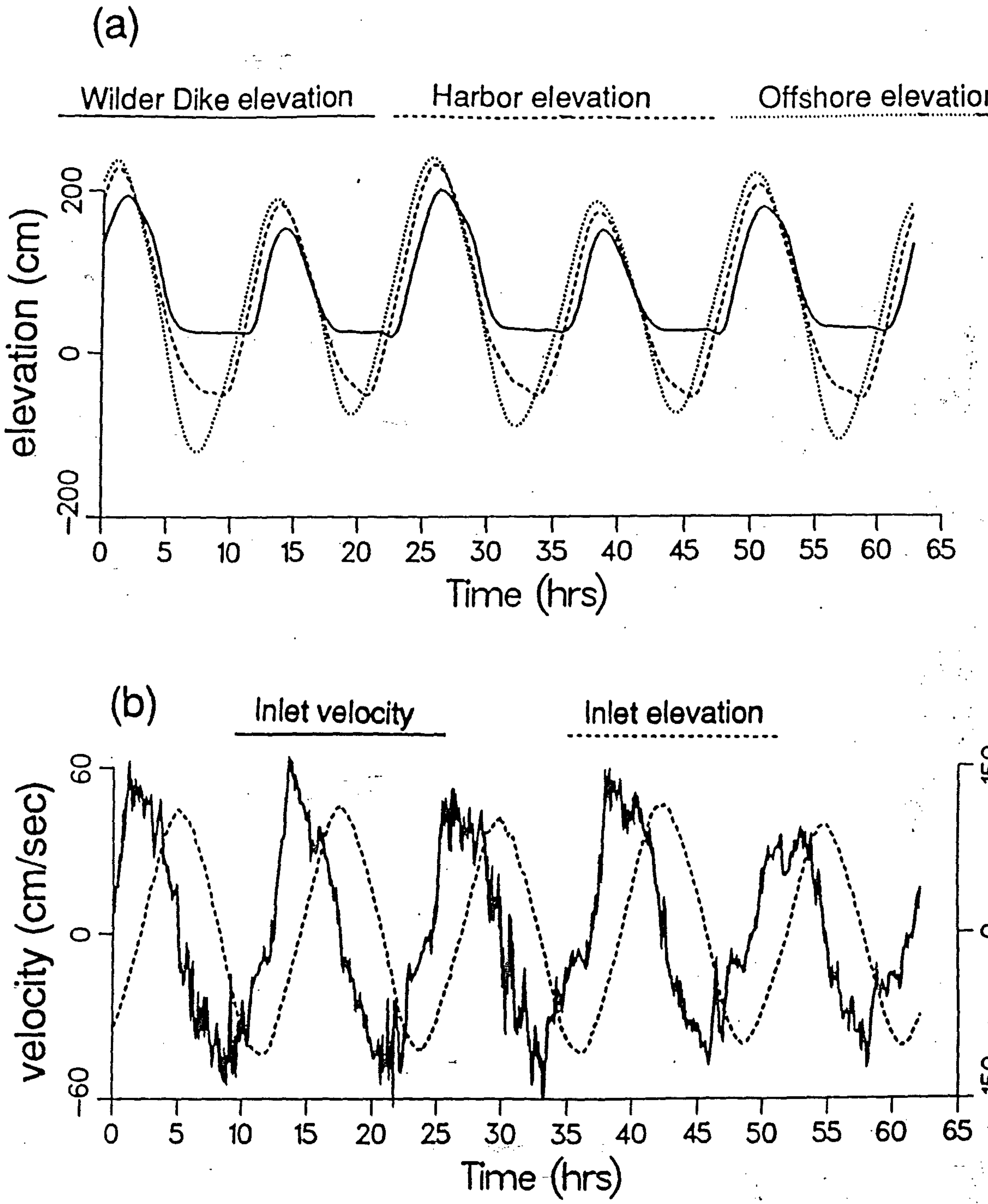


Figure 2. Tide record from Pamet River.



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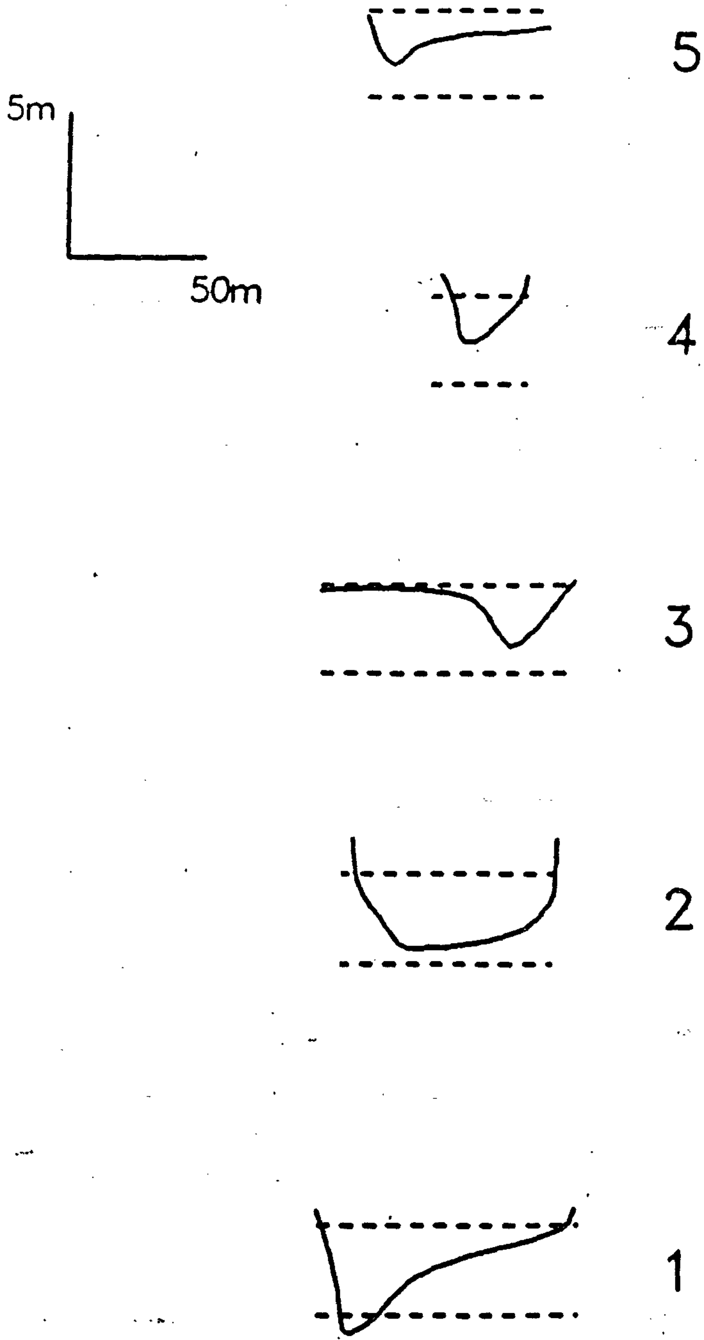

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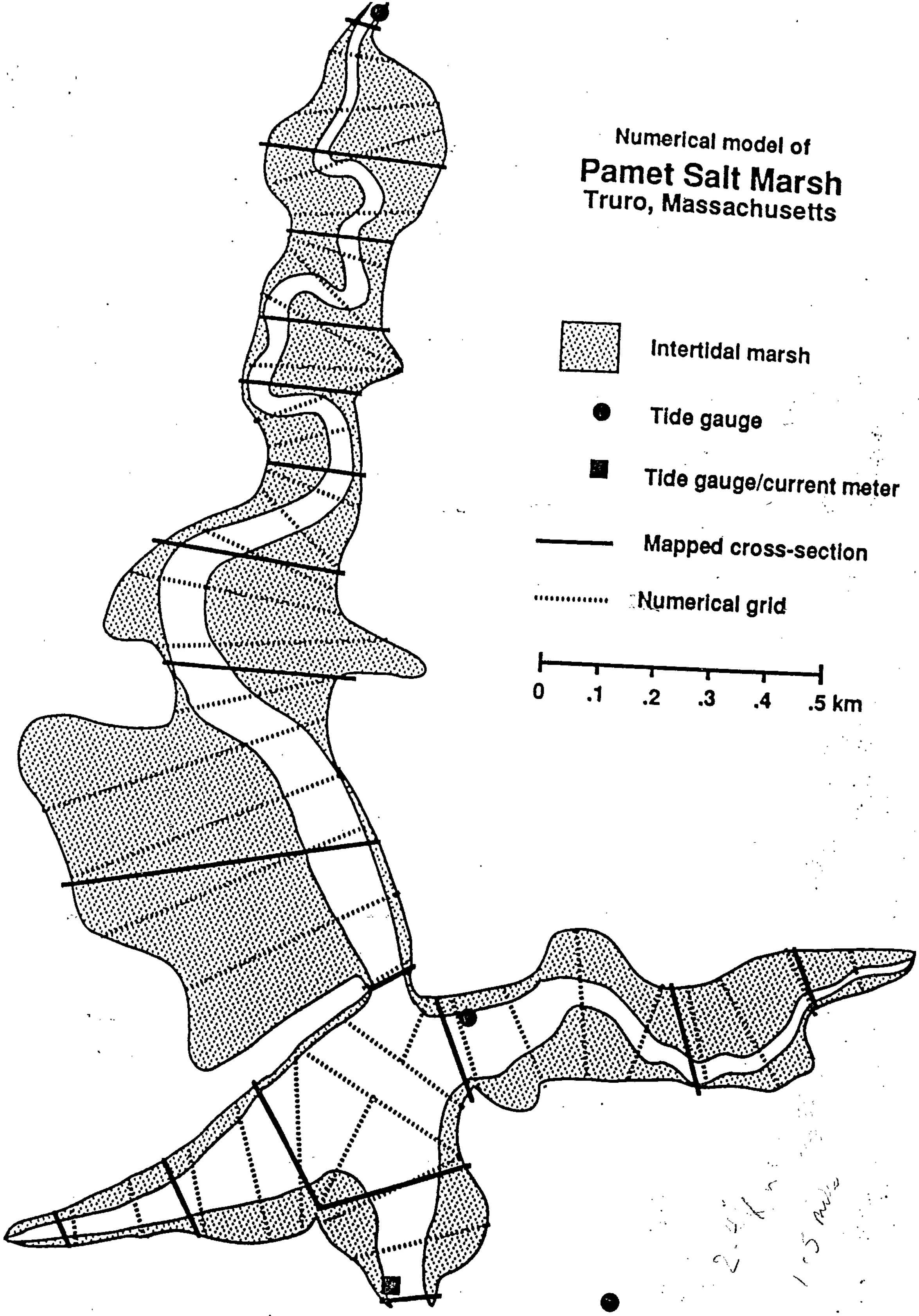

Figure 5. Plan of numerical model with locations of instrument stations and field-mapped cross-sections.

Cross-section of Model Channel

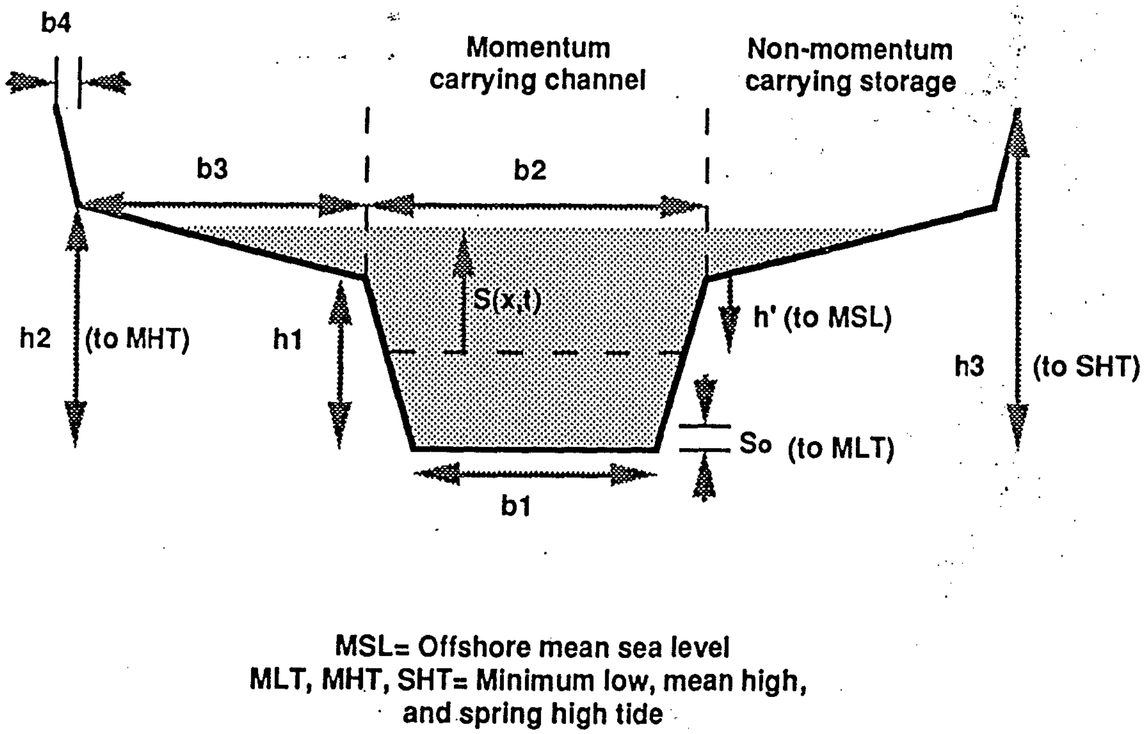

Figure 6. Cross-section of idealized channel used in numerical model. b1-b4 give horizontal dimensions; h1- h3 give vertical .imensions. S(x,t) is tidal elevation.

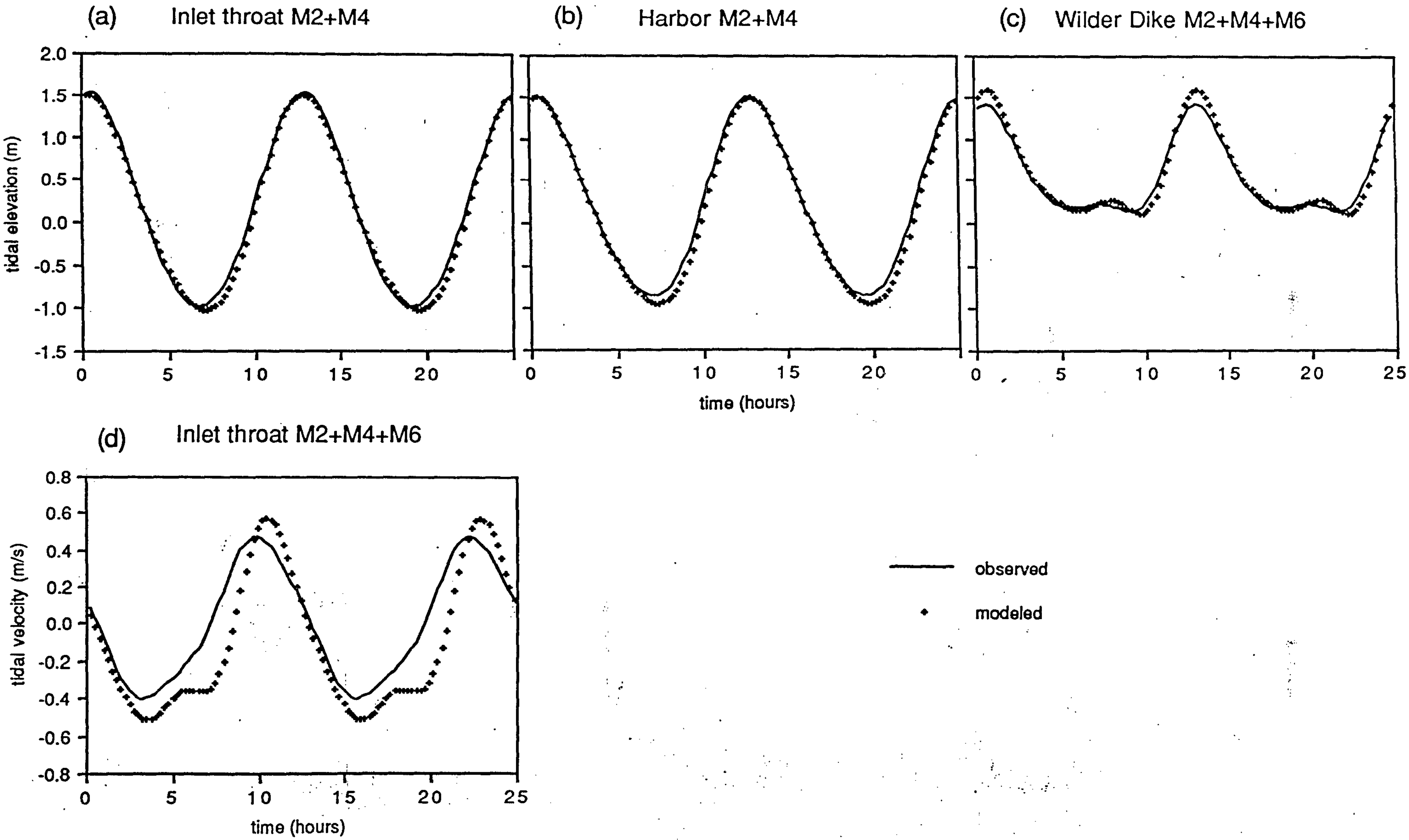

Figure 7. Reconstruction of tidal elevations and velocities from tidal harmonic constituents.

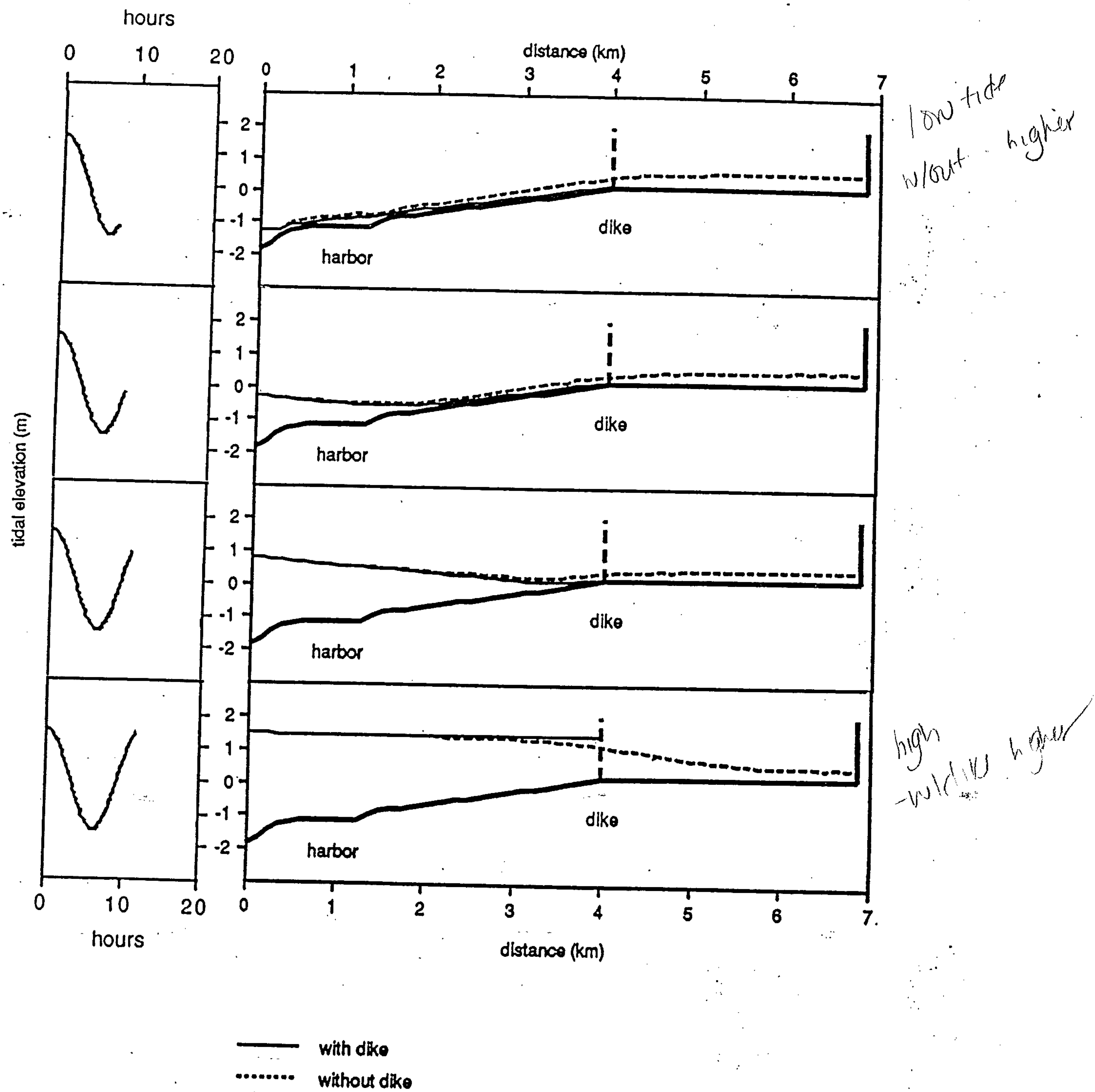

Figure 8a. Longitudinal sections showing modeled tidal changes in water surface during flood tide, with and without Wilder Dike.

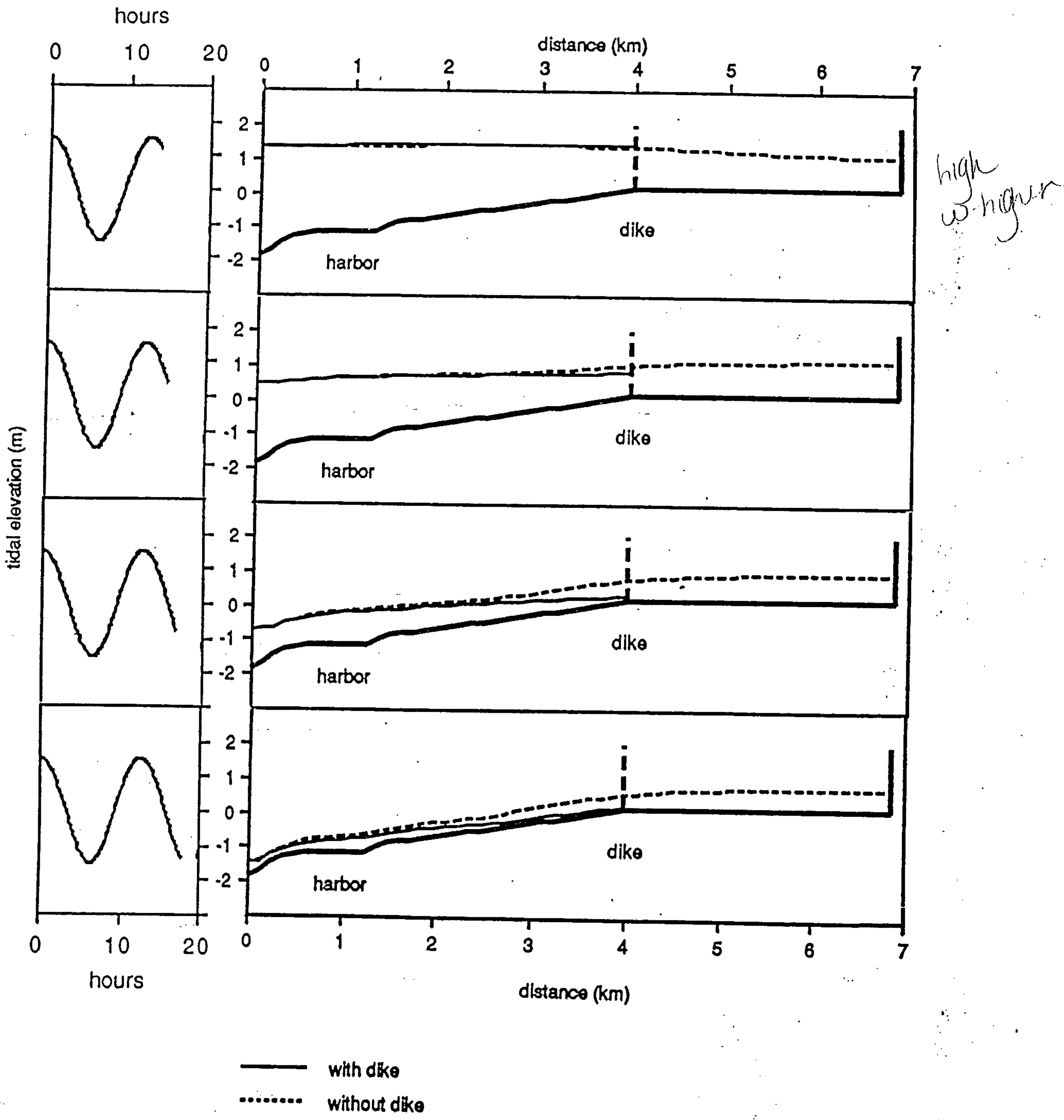

Figure 8b. Same as 8a, during ebb tide.

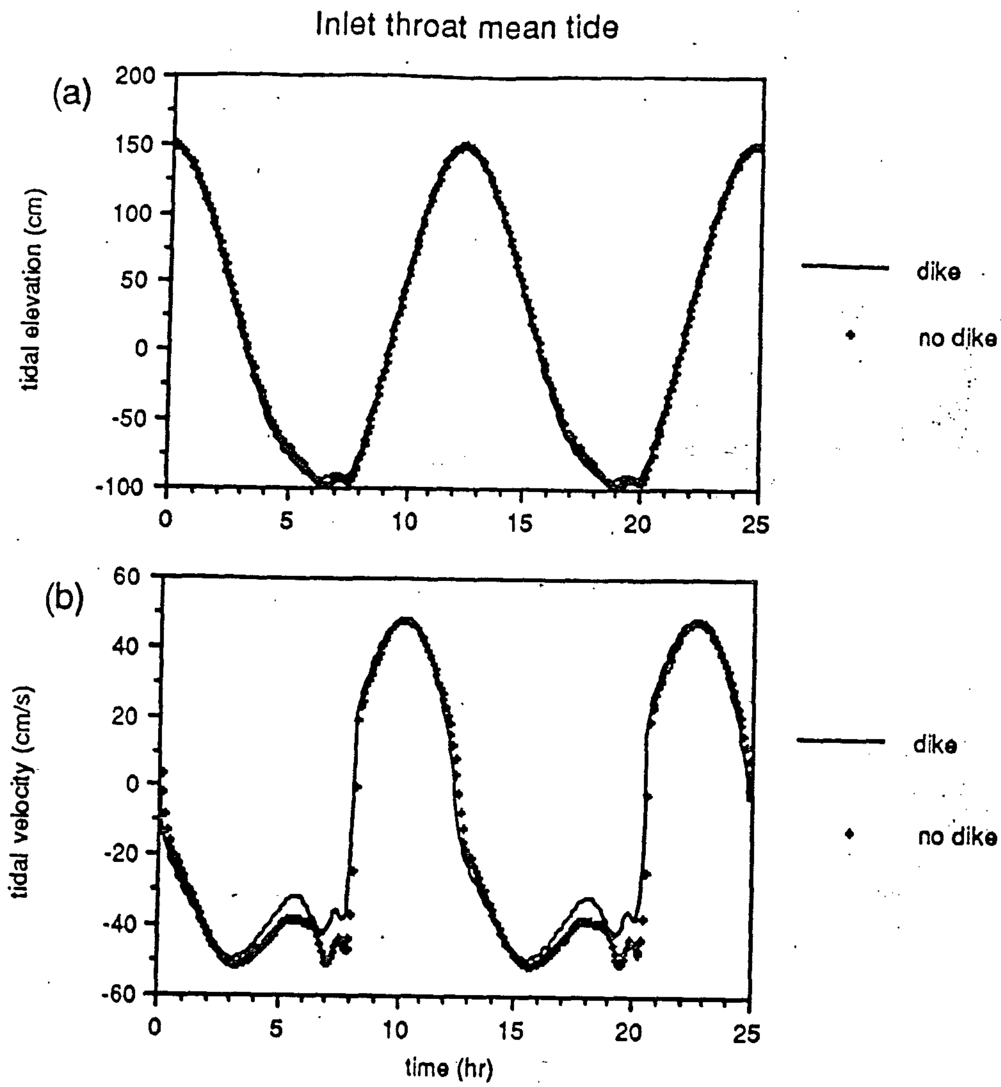

Figure 9. Comparison of modeled tides at inlet, with and without 'ilder Dike.