Reprinted from Estuarine and Coastal Modeling III
Proceedings of the 3rd International Conference
Sponsored by the Waterway, Port, Coastal and Ocean Div./ASCE
September 8-10, 1993, Oak Brook, Illinois

DREDGING IMPACTS ON DELAWARE ESTUARY TIDES

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Abstract

This study summarizes historic dredging activities and historic tidal trends in the Delaware Estuary. Since 1910, large-scale dredging and maintenance projects in the Delaware Estuary have increased navigation channel depths from approximately 20 ft (6.1 m) to 40 ft (12.2 m). Upper Delaware Estuary tidal ranges also increased approximately two-fold during this period. The potential influence of dredging activities on Delaware Estuary tides is examined through application of variable depth hydrodynamic models. The models suggest that historic increases in upper Estuary tidal ranges are associated with the deepening of middle/upper Estuary navigation channels. The models also suggest that competing effects of bottom friction and upstream "funneling" regulate tidal amplification in the Delaware Estuary and other similar systems.

Introduction

During the last few centuries, major U.S. estuaries were dredged, diked, or otherwise altered to accomodate historic navigational demands. For example, prior to World War II, the Delaware Estuary was dredged to facilitate the passage of deep-draft vessels (e.g., DiLorenzo et al., 1993). Subsequently, tidal ranges in the upper Delaware Estuary increased from approximately 4 feet to 8 feet (DiLorenzo et al., 1992), and freshwater tidal marshes colonized newly submerged areas (Orson et al., 1992). Similarly, two-fold tidal range increases

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followed historic dredging activities in another east-coast system, the upper Hudson River Estuary (Geise and Barr, 1967). Prudent management of these systems requires an understanding of the relation between estuarine morphology and tidal amplification. Accordingly, this study examines historic dredging influences on the Delaware Estuary tidal regime.

Study Area

The Delaware Estuary extends approximately 134 miles (215.6 km) from the Cape May - Cape Henlopen transect to the head-of-tide at Trenton, New Jersey (Figure 1). The upper Delaware Estuary serves as the world's largest freshwater port (Philadelphia Planning Commission, 1982). Navigation over the lower 128 miles of the Estuary is facilitated by an existing shipping channel dredged to a project depth of 40 feet. Delaware Estuary widths decrease (i.e., "funnel") nearly monotonically with upstream distance above the Lower Delaware Bay. Delaware Estuary tides are predominantly semi-diurnal (Parker, 1984). Mean tidal ranges vary from approximately 4.25 ft (1.29 m) near the mouth to 8.25 feet (2.51 m) at Trenton – an approximate two-fold amplification of the tide over the length of the Estuary. The tidal "bulge" arrives at the head-of-tide approximately 6.5 hours after it traverses the entrance. The ratio of the mean tidal volume flux (at the entrance) to the mean freshwater inflow is approximately 300-to-1 (Galperin and Mellor, 1990). Thus, under mean-inflow conditions, the Delaware Estuary has been classified as a vertically homogeneous estuary (Biggs, 1978).

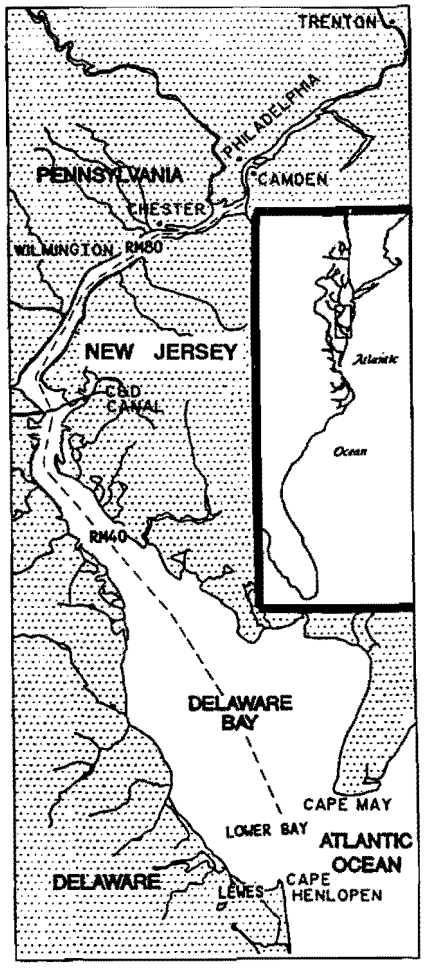


Figure 1. The Delaware Estuary

Conceptual Models

The influence of an important study area feature, upstream width contractions, on estuarine tides is conceptualized by Dyer (1973): "...As an estuary narrows towards the head, the tidal range tends to increase upstream because of the convergence but decreases because of friction." This statement suggests a dynamic balance whereby frictional damping effects compete with geometrical funneling effects. Depending upon the relative magnitude of these effects, upstream tides may be damped (i.e., frictionally dominated) or amplified. Such balances are graphically illustrated in Parker's linearized model of the existing Delaware Estuary (Parker, 1984) – a model based on assumptions of exponential width decreases (upstream), vertical banks and constant depth. Parker states: "...The major effect of linear friction on a tidal wave is to reduce its amplitude, shorten its wavelength, and slow it down. ...The width-decrease has just the opposite effect, not only increasing amplitude, but increasing wave propagation speed and wavelength. Without the width decrease, friction would have been even more dominant in the Delaware Estuary and the tidal amplitude at Trenton would have been smaller than at Lewes, instead of larger. Because of the counteracting effects of friction and the width decrease, the actual M_2 tidal wavelength in the upper Delaware Estuary was almost the same as the frictionless, constant-width wavelength...".

Parker's statement for the existing Estuary may also apply to the former (i.e., pre-dredged) Estuary, although former shoaling effects are not included in Parker's constant-depth model. Upstream shoaling may enhance funneling effects, since upstream reductions in conveyance area arise not only from width contractions but also from depth reductions. However, upstream shoaling also enhances bottom friction effects and may preclude tidal amplifications. To incorporate such effects, the numerical tidal model adapted for this study is based on actual historic depth profiles for the Delaware Estuary. Also, a variable-depth analytical model is used to provide further physical insight into these competing effects.

Historic Depth Changes

Since 1910, the U.S. Army Corps of Engineers (COE) has dredged and maintained Delaware Estuary shipping channels, altering former 20 ft (6.1 m) controlling depths to present 40 ft (12.2m) depths. Figure 2 displays a former navigation channel profile, based on U.S. Coast and Geodetic Survey Charts published in 1890. Figure 2 also shows various COE project depths and years of project *completion*. Overall, channel depths of the middle (River Miles 40-80) and upper (River Miles 80-134) Estuary increased significantly between 1910 and 1944. Below the Philadelphia Navy Yard, greatest depth increases

occurred just before World War II. Presently, navigation channel widths range from 400 ft (121.9m) in the middle Estuary to 1,000 ft (304.8m) in the lower Estuary. Figure 3 shows the effects of historic dredging projects on mean cross-sectional areas of the Delaware Estuary. Since 1890, dredging activities have significantly increased the conveyance areas of the middle/upper Estuary. Tides have increased concomitantly within these areas, as outlined below.

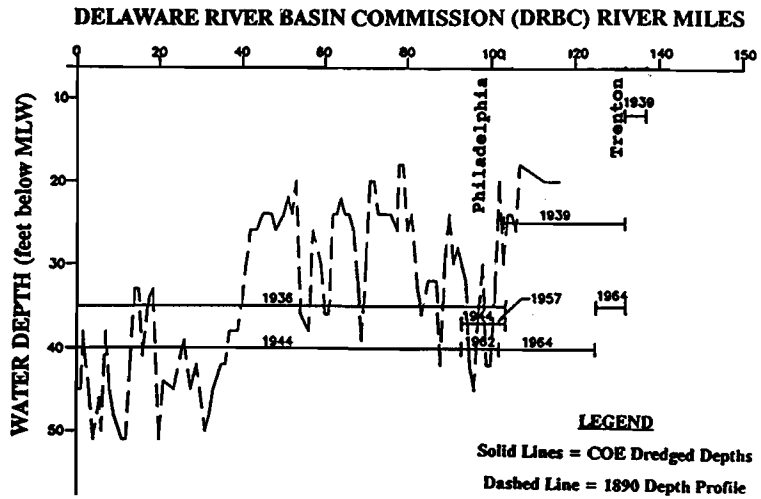


Figure 2. *Historic Navigation Channel Depths in the Delaware Estuary*

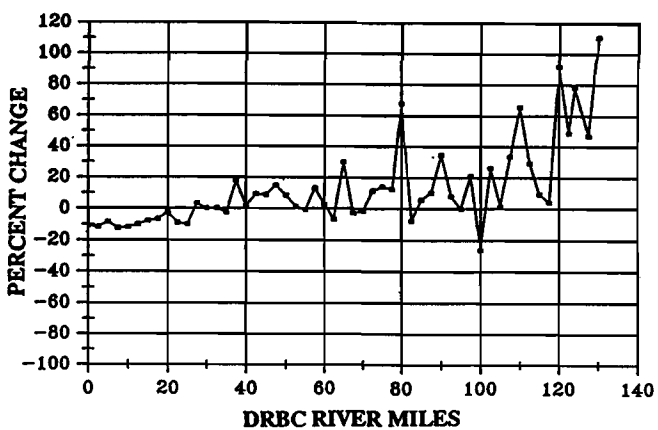


Figure 3. *Percent Changes in Delaware Estuary Conveyance Areas: 1890-Present*

Tidal Trends

Figure 4 displays yearly mean tidal ranges at three long-term gaging stations in the Delaware Estuary, based on data supplied by the National Ocean Survey (NOS) and its predecessor organizations. The Delaware Bay entrance station at Lewes, Delaware (lower curve) shows no apparent long-term trend in yearly mean ranges. The nearly periodic variations at this station are consistent with a 19-year, tidal-epoch periodicity. Tidal range data reported for the Philadelphia station (middle curve) shows a net increase of approximately one foot over the 66-year record. A marked increase is apparent between 1930 and 1943, coincident with the period of intense dredging activities. The Trenton station (upper curve), located near the head of tide, shows a mean range varying from 8.0 ft - 8.3 ft (2.4 m - 2.5 m) during the observational period 1978-1990. This amplified tidal range far exceeds the former 4.2 ft (1.3 m) range reported in the 1910 Tide Tables. It also exceeds the 6.63 ft (2.0 m) Trenton range recorded by the NOS organizations for the 1941-1959 tidal epoch. Thus, the data suggests that Trenton tidal ranges have doubled over the last century. These increasing trends at both the Philadelphia (River Mile 97) and Trenton (River Mile 133) stations are associated with historic increases in estuarine conveyance areas (Figure 3). Also, the data suggests that these historic increases in tidal amplification may be due to reductions in the hydraulic resistance of the navigation channel of this "funnel-shaped" estuary.

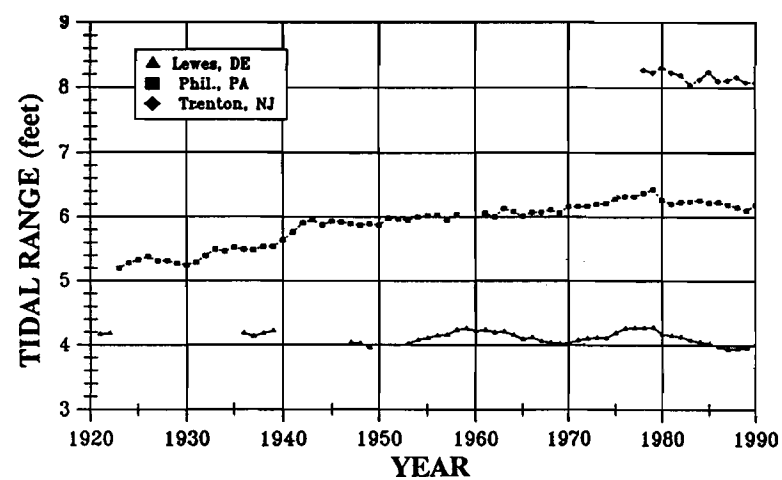


Figure 4. NOS Yearly Mean Tidal Ranges in the Delaware Estuary

Numerical Simulations

To quantify potential dredging impacts, an established hydrodynamic model, RMA-10 (e.g., King, 1985), was applied to this system. RMA-10 is a three-dimensional, finite-element, hydrodynamic and salinity model. RMA-10's finite-element formulation and quadratic interpolation scheme allow for schematizatizations of irregular shorelines and navigation channels, as illustrated in Figure 5. This schematization of study area geometry consists of a network of some 3,061 nodes and some 1,387 triangular, quadrilateral or linear elements. Generally, the spacing of these nodes decreases in regions of sharp bathymetric gradients and lateral constrictions. The grid also extends offshore from the Delaware Estuary entrance to a region of smaller hydraulic gradients. It terminates along a current-meter mooring arc employed in a recent observational study conducted by Garvine (1991). This "telescoped" outer boundary provided valuable data on boundary currents and salinity (at nodal points A-F in Figure 5), the latter also being modeled by the authors (DiLorenzo et al., 1993).

RMA-10's vertical coordinate system is flexible in that it allows the user to specify the number of vertical grid layers at corner nodal point. In this analysis of barotropic tides in a vertically homogeneous estuary, only two layers are specified in the lower and middle Estuary; one layer in the upper Estuary. Note that two layers in RMA-10 corresponds to five points in the vertical (including element mid-points). RMA-10's vertical coordinate system is a "modified transformation" (King, 1988) that: (a) preserves the bottom profile; (b) transforms the water surface to a constant elevation; and (c) adjusts the vertical velocity component to maintain overall continuity (King, 1988). King developed this scheme to avoid errors associated with sharp breaks in the bottom profile.

Due to budgetary constraints, this project utilized historic time-series data for both model input and model-data comparisons. Primary data sources included 1985-1987 surveys conducted by the University of Delaware, NOAA and the COE. The tidal model was forced with tidal elevations observed near two ocean boundary nodes (i.e., mooring arc corner nodes O and V in Figure 5) and near the Chesapeake Bay entrance to the C&D Canal. Where gaps occurred, the boundary data were interpolated spatially, as described by DiLorenzo et al. (1993).

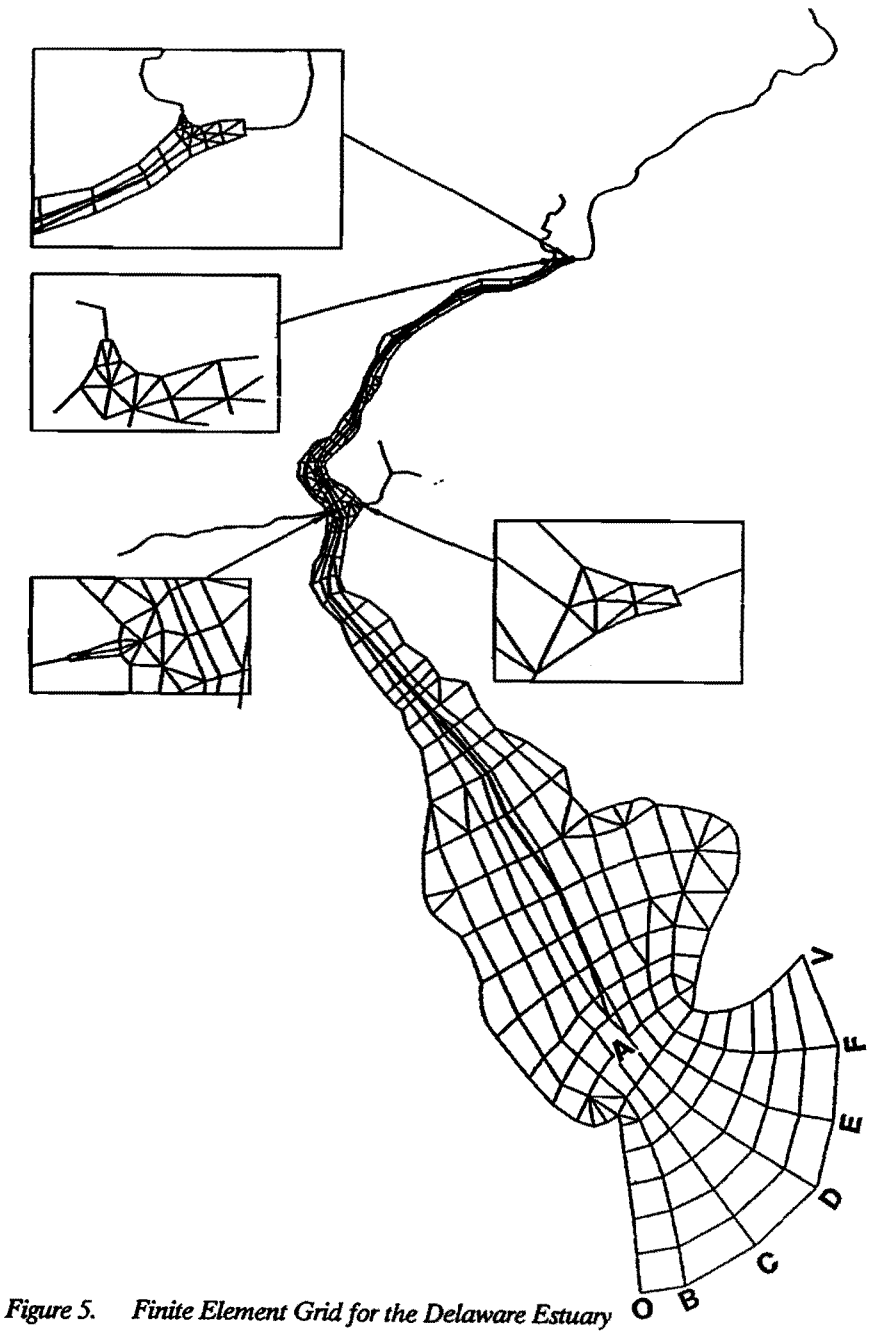


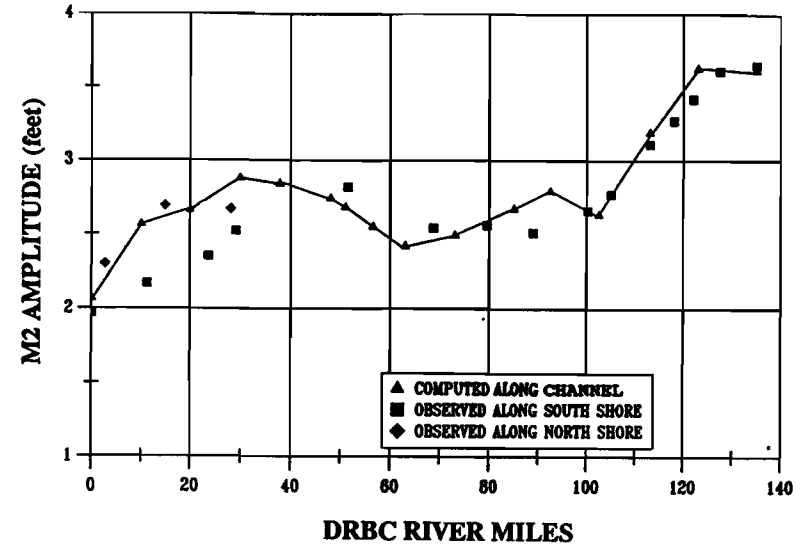
Figure 5. Finite Element Grid for the Delaware Estuary

RMA-10 was calibrated by varying the adjustable model coefficients (e.g., bottom friction coefficients for a given reach) so as to reproduce observed amplitudes and phases of tidal elevations and currents. To avoid excessive model "tuning" these coefficients were varied within a limited range based on hydraulic characteristics of the study area. The basic calibration strategy used in this study was similar to that employed by Walters (1992) – a strategy designed to minimize the number of estuarine regions having a different, selected value for the bottom friction coefficient. Accordingly, the model domain was divided into three separate zones for calibration purposes, and within each zone a single value of the manning's coefficient, n, was specified. These include: (1) a Delaware Bay zone (RM0-RM55, n=0.018); (2) a mid-estuary zone (RM55-RM100, n=0.010); and (3) a tidal river zone (RM100-RM135, n=0.028). In addition, a fourth value (n=0.035) was used for Salem River tidal embayment areas located opposite the C&D Canal (near RM59). Like Walters, a relatively high frictional coefficient was specified for the tidal river zone, consistent with its relatively rough bottom, lateral constrictions, and sinuous channel geometry; a relatively low value was needed to match the observed data for the mid-estuary reach.

The present calibration also included uniform multiplier values for the eddy diffusivities within each estuarine zone. The RMA-10 model was designed to evaluate the eddy viscosities for each element within a particular zone by multiplying a given element's length by the specified multiplier value. This scheme automatically increases the diffusivity values for large elements. Reasonable literature values should be selected for this parameter, since excessive eddy viscosities artificially smooth spatial variations. Here, average scaled horizontal eddy viscosities range from approximately 5,000 ft^2/sec to 10,000 ft^2/sec (500 m^2/sec to 1,000 m^2/sec). The selected vertical viscosity is 0.01 ft^2/sec (0.001 m^2/sec).

Results of the M2 tidal calibration are illustrated in Figures 6-7. Figure 6a compares "observed" and simulated M2 tidal amplitudes along the length of the Delaware Estuary. These observed amplitudes are gleaned from harmonic analyses of the NOAA Circulation Survey data, as reported by Parker (1984). The simulated amplitudes in Figure 6a result from the calibration strategy outlined above. As illustrated, results from the tuned model generally track the observed longitudinal profile of M2 tidal amplitudes, including the marked amplification of upstream tides. Likewise, Figure 6b displays both observed and computed phase lags for the M2 tide. Again, the Walter's calibration approach allows for a general tracking of the observed data.

(a)



(b)

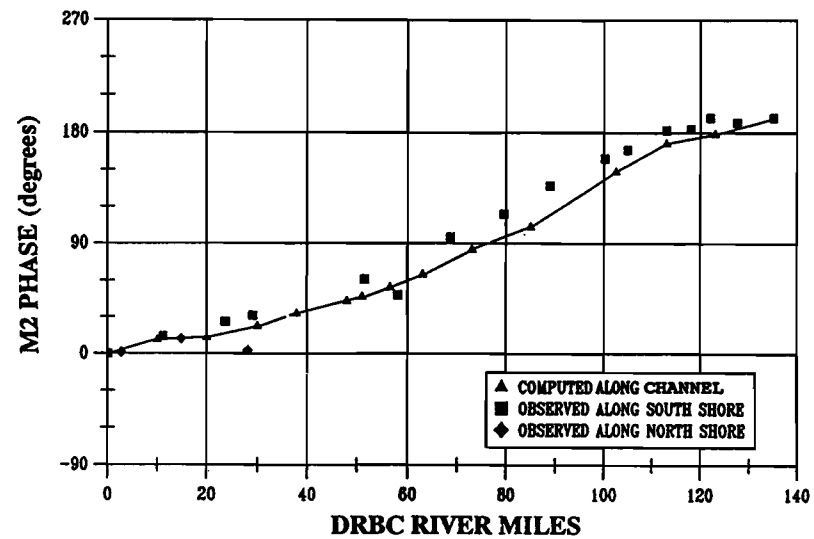


Figure 6. M2 Tidal Elevation Calibration: (a) Amplitude Calibration; (b) Phase Calibration

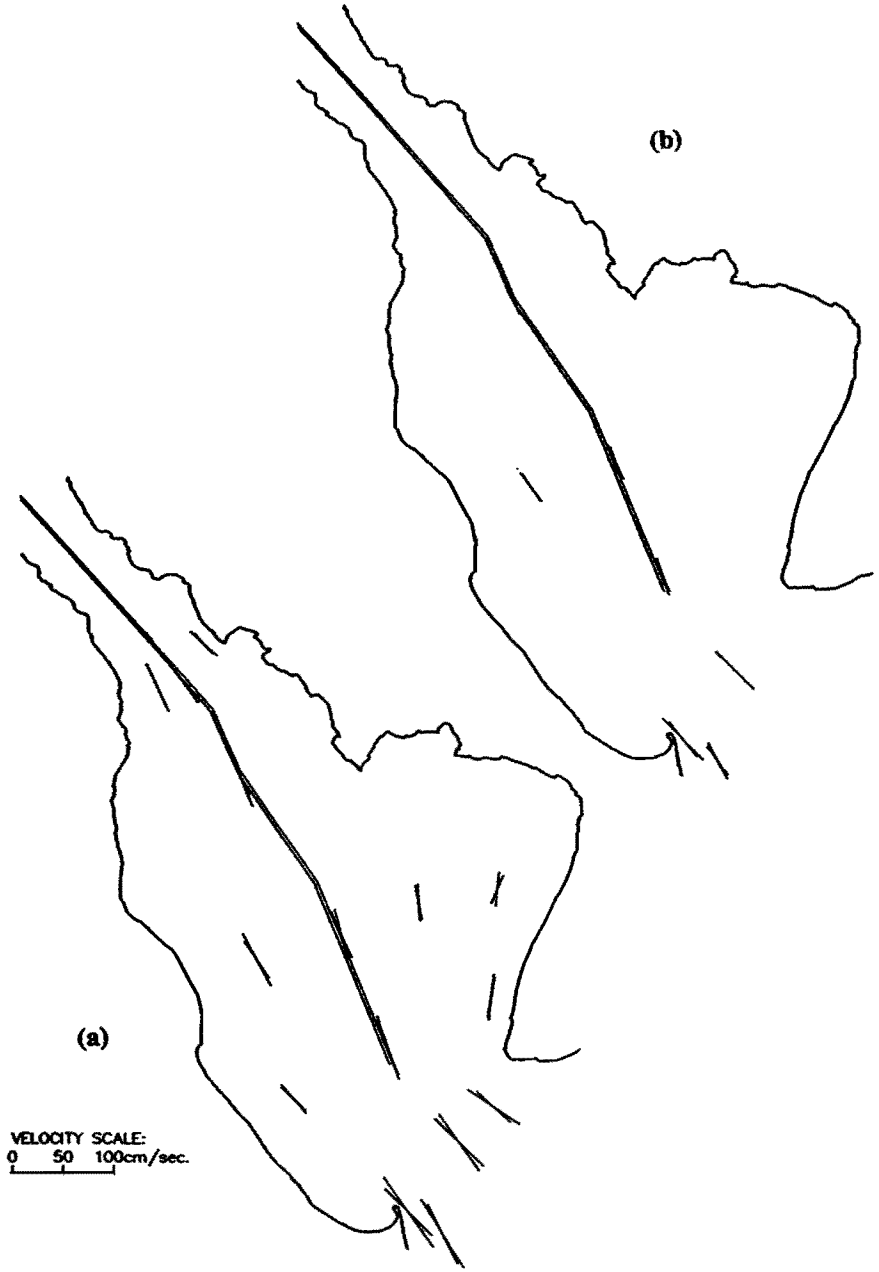


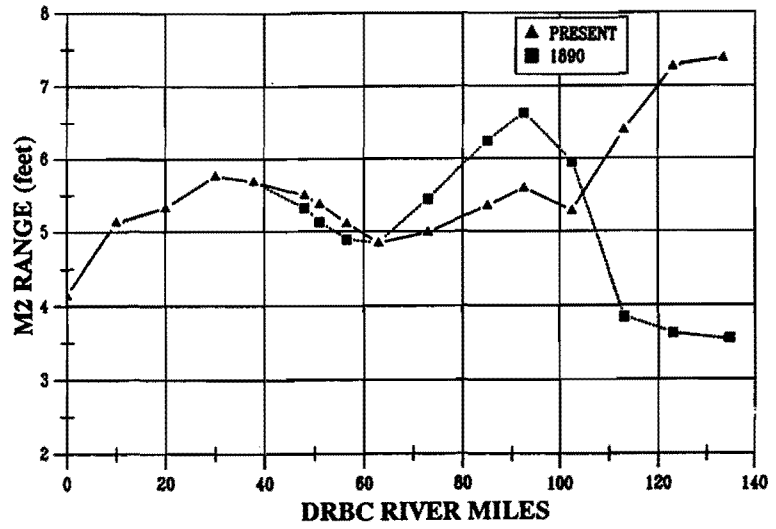
Figure 7. Principal-Axis Components of Observed (solid) and Computed (dashed) M2 Tidal Currents: (a) 4-meters depth; (b) near-bottom

Figure 7 displays principal-axis components of observed and computed M2 tidal currents. Here, the "observed" currents are based on harmonic analyses of NOAA Circulation Survey data reported by Moses-Hall (1992) at multiple depths. Overall, Figure 7 shows satisfactory agreement between observed and simulated currents at all 21 current meter locations. Generally, a good agreement is attained along the main navigation channel (delineated in Figure 7); slight deviations are apparent along the shallower nearshore areas. Larger deviations near the open boundary may be reduced through future grid refinements.

With the calibration parameters held constant, the adapted model is applied in scenario simulations of past and projected depth changes. Figure 8 illustrates results of hindcast simulations of M2 tides. In this scenario, model depths were input in accordance with the published U.S. Coast and Geodetic Survey Chart for 1890. Figure 8a shows the simulated M2 tidal range profile for both present and 1890 bathymetries; Figure 8b shows corresponding M2 phase lags. The model sucessfully reproduces the basic feature of the former M2-component tides – the lack of amplification of upper Estuary tides. As previously noted, the full (multi-constituent) tidal range at Trenton was reported as approximately 4 feet in 1890. Also, the model sucessfully reproduces the 1890 tidal phase lag of approximately 9 hours at Trenton for the pre-dredged geometry.

Besides historic depth changes outlined above, an additional 5 foot (1.52 m) depth increase is planned for the main navigation channel of the Delaware Estuary (from Philadelphia to the mouth). At most, this modification would increase conveyances areas by about 4% – a relatively small change in comparison to historical upper-estuary changes (Figure 3). Results from model simulations of the planned 5-foot depth increase are shown in Figure 9. Preliminary model results suggest no significant impact on Delaware Estuary tidal ranges.

(a)



(b)

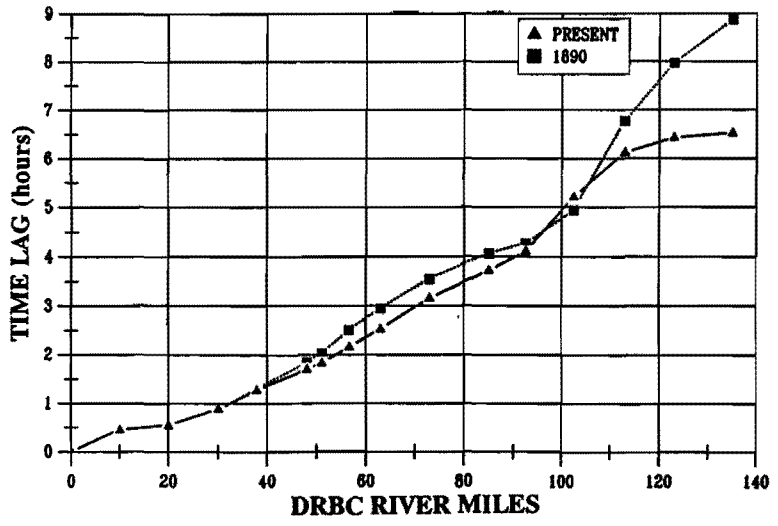


Figure 8. Hindcast Comparison Simulations of M2 Tidal Elevations: (a) Computed M2 Ranges Along Main Channel; (b) Computed High Water Lags Along Main Channel

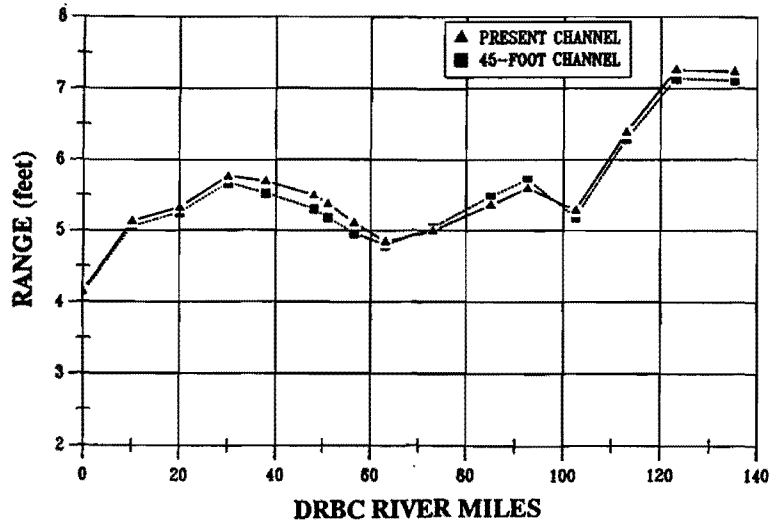


Figure 9. Comparison of Observed M2 Tidal Ranges and Simulated Ranges for Projected 45-foot Channel Depths

Analytical Model

The adapted RMA-10 model provides a useful "tool" for evaluating effects of specific depth-change scenarios such as those described above. However, a physical understanding of such effects is aided further by means of simplified analytical models. Accordingly, the analytical estuarine tidal model of Prandle (1980; 1991) is adopted for this study. This model assumes that tidal propagation is governed by the one-dimensional, shallow-water wave equations in linearized form, as expressed below:

$$\frac{\partial U}{\partial T} + g\frac{\partial \eta}{\partial X} + SU = 0$$

$$\frac{\partial \eta}{\partial T} + \frac{1}{B}\frac{\partial}{\partial X}(BHU) = 0$$

where: U is the sectionally averaged velocity along the X-axis; T represents time; η is the vertical elevation; g is the gravitational constant; S is a linearized friction coefficient; and both the depth-averaged width, B, and depth, H, vary with X according to assumed power laws:

$$B = \left[\frac{X}{\lambda}\right]^n \cdot B_1$$

$$H = \left[\frac{X}{\lambda}\right]^m \cdot H_1$$

where: λ is the "constant-depth" wavelength and B_1, H_1 are constants. Thus, a flat-bottom estuary corresponds to m=0; a straight-sided estuary to n=0. Likewise, estuaries having relatively steep bottom and side slopes correspond to relatively large m and n values, respectively. The assumed boundary conditions at both the head of tide (X=0) and open boundary ($X=X_o$) are:

$$\eta(X_o,T) = A_o \exp[i(\omega T+\phi)]$$

$$\eta(0,T) \quad \text{finite}$$

where A_o, ω, ϕ and P are the boundary tidal amplitude, frequency, phase and period, respectively. Prandle's solution to this simplified formulation is as follows:

$$\eta(x,t) = \left[\frac{k\psi(x)}{k\psi(x_o)}\right]^{1-\nu} \frac{J_{\nu-1}[k\psi(x)]}{J_{\nu-1}[k\psi(x_o)]} A_o \exp[i(\omega t+\phi)]$$

where:

$$J_{\nu-1} = \text{Bessel function of order } \nu\text{-1}$$

$$\psi(x) = \frac{4\pi x^{(2-m)/2}}{2-m}$$

$$k = \left[1 - i\frac{SP}{2\pi}\right]^{1/2}$$

$$\nu = (n+1)/(2-m)$$

$$x = \frac{X}{\lambda}; \quad t = \frac{T}{P}; \quad \lambda = \sqrt{gH_1} \cdot P; \quad s = SP$$

The above solution may be applied to the Delaware Estuary (Prandle, 1980) for prescribed values n=2.1; m=0.3; X_o=95.1 miles (153 km); $\lambda(M_2)$= 193.3 miles (311 km), and period P=12.42 hours. Given these values, Prandle's model is adapted to the upper 70% of the Delaware Estuary (DRBC River Miles 40-135) – an area where width variations closely approximate an exponential function (Parker, 1984). Model calibration for various prescribed frictional coefficient values is illustrated in Figure 10. Based on this figure (and an analogous phase calibration) a value of $s=1.2(2\pi)=2.4\pi$ is selected.

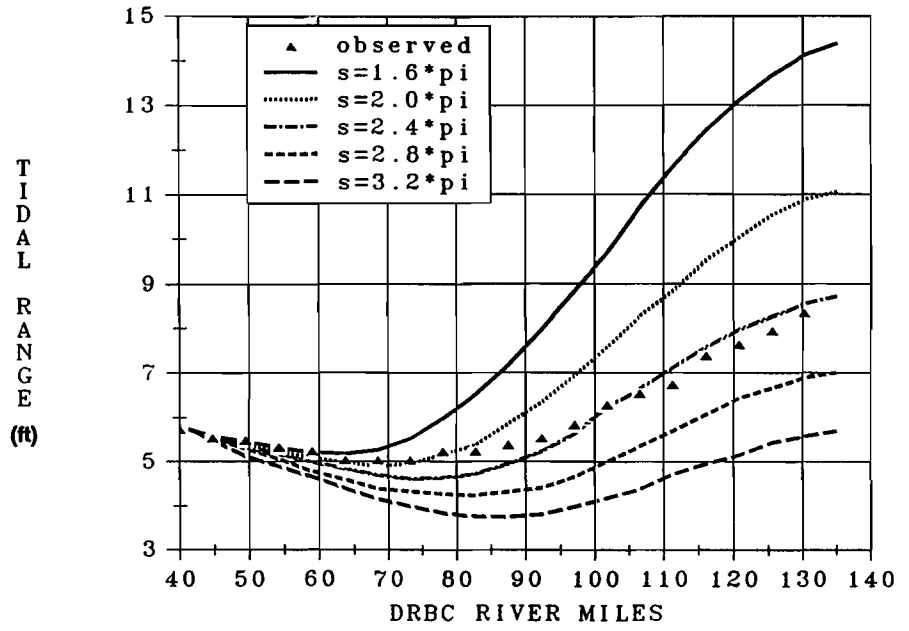


Figure 10. Adaptation of Prandle's Analytical Model to the Delaware Estuary: Friction Parameter Calibration

For the fixed, prescribed value of the depth exponent (m=0.3), Figure 11a displays the sensitivity of the calibrated elevation amplitude response to variations in the width exponent parameter, n. Alternatively, for the fixed, prescribed width exponent (n=2.1), Figure 11b displays model sensitivity to variations in the depth exponent. Note that the abcissa in Figure 11 represents scaled distance from the head-of-tide ($X/\lambda=0$) to the open boundary (i.e., $X/\lambda=0.49$ or RM40). The contours in Figure 11 represent lines of equal non-dimensional tidal amplitude (i.e., η/A_o) for various scaled longitudinal distances (X/λ) and width/depth exponents (n or m).

One can summarize the tidal amplitude response of Figure 11a by reading contour values along horizontal lines (axes) corresponding to fixed "n" values. For example, along a line of relatively small n (e.g., n=0.9), the amplitude contours decreases landward. Thus, the model suggests that relatively small upstream width convergences (i.e., small n) are insufficient to overcome frictional damping effects on tidal amplitudes. Alternatively, along lines of

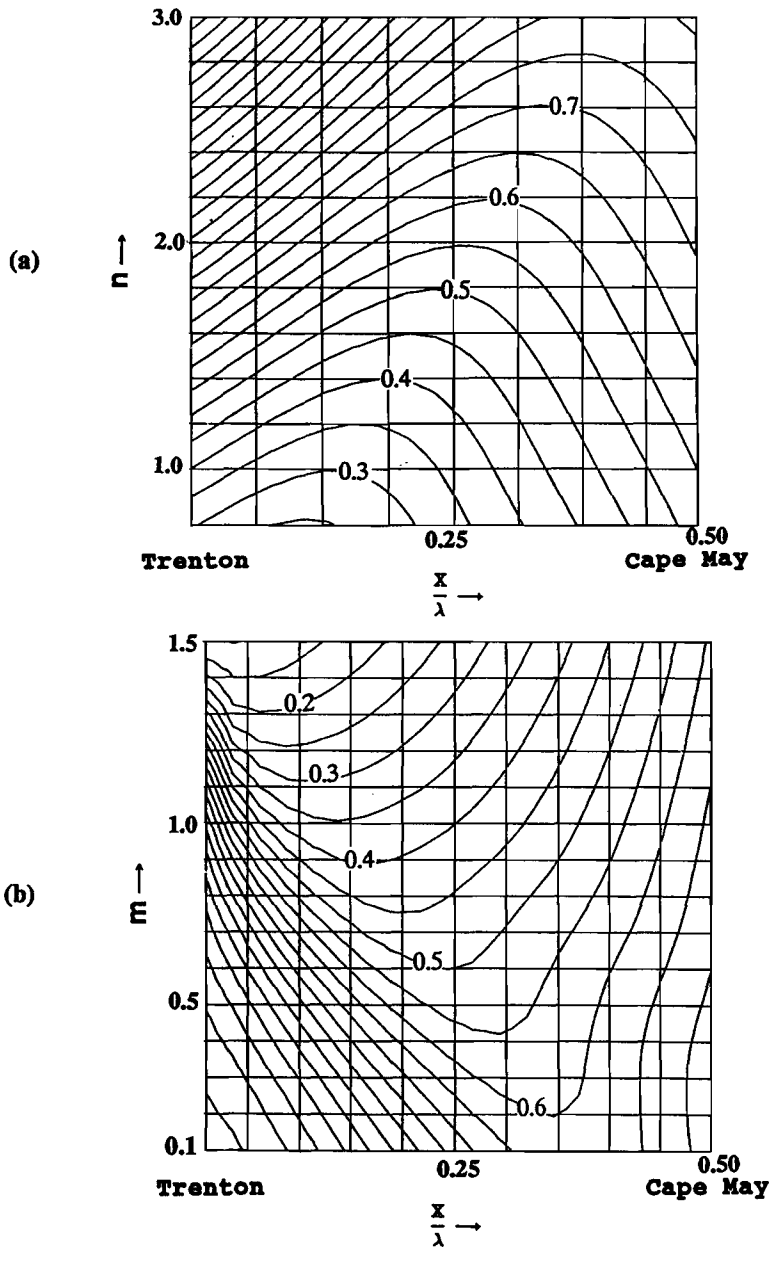


Figure 11. Simulated Elevation Amplitude Response of Prandle's Analytical Model: (a) Sensitivity to Variations in the Width Exponent; (b) Sensitivity to Variations in the Depth Exponent

relatively large n (e.g., n=2.5), the amplitude response first decreases in the lower estuary and subsequently increases markedly upstream. Thus, the model suggests that funneling effects resulting from relatively large width (and large conveyance area) decreases (i.e., large n) may overcome damping effects of friction and permit tidal amplification.

Along a horizontal line of relatively small "m" (e.g., m=0.1) in Figure 11b, the amplitude response first decreases and then increases landward. Thus, for this near "flat-bottom" case, the effects of width convergence may counteract frictional damping effects in the middle/upper estuary. This result is consistent with Parker's result. Note that the m=0.3 line in this figure corresponds to the existing Delaware Estuary. Alternatively, along horizontal lines corresponding to large m (e.g., m=1.5), a damped response is predicted over most of the estuary. Thus, the model suggests that upstream shoaling and corresponding steep bottom slopes in the Delaware Estuary may result in damped tides. This result is consistent with historic (i.e., pre-1900) observations of damped upper Delaware Estuary tides.

It should be noted that because of its simplifying assumptions, this analytical model has several limitations. For example, the model can not describe effects of width/depth variations on non-linear mechanisms such a quadratic friction, advection and continuity effects, as well as freshwater inflow effects. The authors intend to examine such effects in a future study which utilizes both scale analysis techniques and RMA-10 simulations of the dynamic balance. In any case, the analytical model serves as a useful conceptual tool for assessing gross effects of estuarine geometry on Delaware Estuary tides.

Conclusions

Over the past century, the mean tidal range near the head of the Delaware Estuary has increased two-fold in association with historic dredging activities in the middle/upper estuary. Furthermore, the tidal phase-lag between the head-of-tide and the entrance has decreased from its historic value of about 9 hours to approximately 6.4 hours. Numerical model simulations also suggest that an additional 5-foot (1.5-meter) dredging of the navigational channel (below Philadelphia) will have a comparatively small or negligible impact on the tidal regime. Independent analytical model studies suggest that funneling effects resulting from relatively large upstream width (and conveyance area) decreases may overcome frictional damping effects and amplify tides in the Delaware and other similar estuaries. The analytical model suggests that such effects are more likely to occur with the current Delaware Estuary bathymetry rather than it's former (pre-dredged) state.

Acknowledgements
The authors would like to thank Dr. Richard Garvine, Dr. K.-C. Wong and Dr. Jonathan Sharp of the University of Delaware for their helpful suggestions. The assistance of RMA-10's author, Dr. Ian King, is also appreciated. We are also grateful to the reviewers for their helpful comments.

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