

## RAPID METHODS FOR ESTIMATING NAVIGATION CHANNEL SHOALING

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### ABSTRACT

The US Army Corps of Engineers' navigation mission is to provide safe, reliable, and efficient waterborne transportation systems (channels, harbors, and waterways) for the movement of commerce, national security needs, and recreation. Federally maintained channels through as many as 600 coastal inlets and through bays, estuaries, and rivers are therefore dredged. Many of these navigation channels have been deepened, widened, and lengthened to accommodate larger vessels and greater transit speed, and to increase maneuverability. These channel expansions have led to increasing and, at many sites, unanticipated maintenance dredging requirements, because in part the relationship between an increase in channel cross-sectional area and the subsequent shoaling rate is nonlinear. As waterborne commerce and the need for national security continue to grow, vessels are expected to become larger, wider, or both due to economies of scale and increased cargo capacity. It is anticipated that coastal inlet entrance channels will continue to be enlarged in the future. This paper discusses empirical and analytical relationships for predicting channel shoaling based upon historical maintenance dredging data for Corps channels that have been deepened, widened, and lengthened. A new analytical relationship based on an equilibrium channel depth and width is presented to calculate channel infilling and bank encroachment, and tested with the available data.

**Keywords:** inlets, dredging, infilling, migration, siltation, analytical techniques.

### INTRODUCTION

Channel depth at many deep-draft ports is constraining the new and larger classes of container ships. In the United States, in year 2000 approximately 30%, or 30,000 vessels had a maximum design draft greater than the channel depth of the port at which they called (Hackett 2003). If all channel and port modifications planned through 2020 are completed, constrained calls are expected to remain relatively constant; without navigation improvements, constrained calls are forecast to increase to 54,000. Investment decisions require analysis to determine the benefit of deepening, widening, and lengthening of a channel. Such analysis primarily concerns estimation of future long-term annual dredging maintenance volume for the proposed improvements.

To support cost-benefit analyses for navigation channel deepening and widening, predictive methods are typically needed at two study phases: a time-limited planning or decision-support phase during which a potential project is examined and further study justified based on information readily available, and a longer term feasibility phase in which the design is developed and optimized. The problem is to estimate the increased dredging maintenance volume and dredging cycle for a deepened and/or widened channel. A channel may be deepened without widening, and occasionally a portion of a channel may be widened for improved navigation throughput or as part of advance dredging maintenance. If a channel is deepened, dredging maintenance volume is expected to increase because navigation channels are typically dredged to the depth contour equal to the project depth, and greater depth or width makes the channel a more efficient sediment trap. A deeper channel is longer relative to a shallow channel and would be expected to capture a greater volume of sediment.

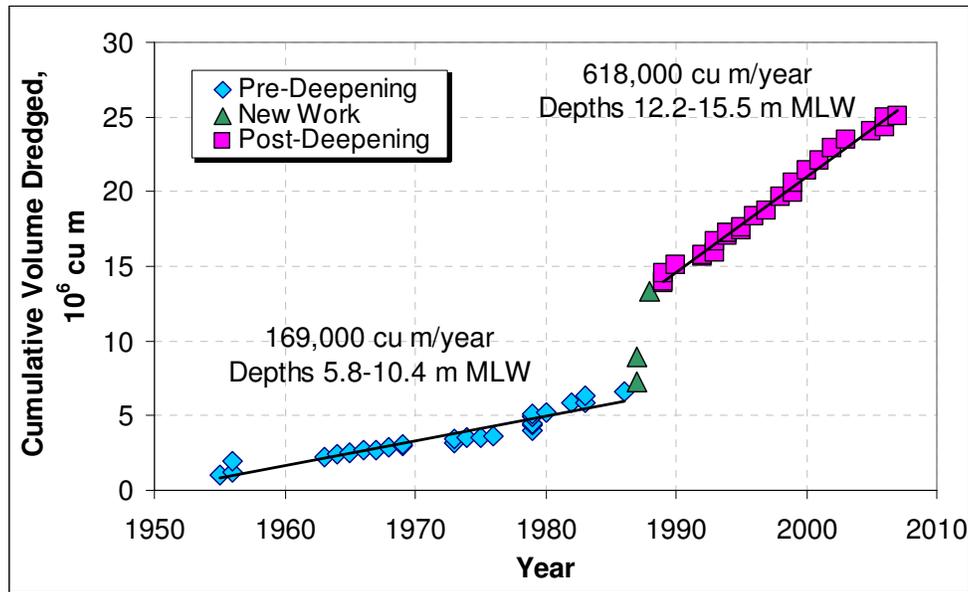
To illustrate this increase in dredging maintenance with increased dredged depth, Figure 1 shows historical maintenance dredging rates for St. Marys Entrance, located on the FL/GA border. In 1881, St. Marys Entrance had a natural channel inlet throat depth of 5.8 m mean low water (MLW). Beginning in 1924, the channel was deepened to 8.5 m, and continued to be deepened to 10.4 m in 1954 and to 12.2 m in 1974. From 1987 to 1988, the seaward end of the channel was deepened from 12.2 to 15.5 m MLW and widened from 122 to 152 m. Cumulative dredged volume plotted in Figure 1a indicates a 265% increase in average volume after deepening and widening in 1987-1988. At St. Marys Entrance, the record shows that the dredging rate depends more on channel depth than length. Figure 1b shows that the dredging rate normalized by channel length is correlated with the channel depth, with squared correlation coefficient  $R^2 = 0.75$ . High correlation indicates that depth is a dominant factor in capturing

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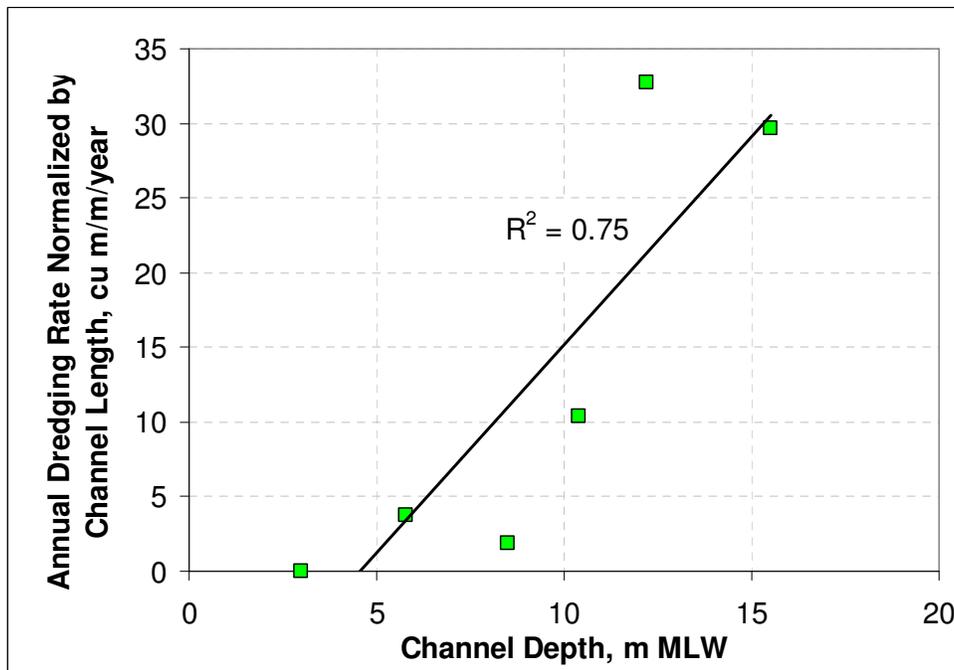
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sediment in the channel at St. Marys Entrance, regardless of channel length. This result is interpreted as stating the dominant cross-channel shoaling takes place in the nearshore and around the ebb shoal, where breaking waves, wave-induced transport, and transport under flood tide are strong, as compared to shoaling seaward of the ebb shoal where the waves and currents are less energetic. Figure 2 shows how channel shoaling (as inferred from maintenance dredging data) varies along the length of the channel depending on the forcing processes and sediment grain size. Predictive technology is needed to estimate such increases.



a. Cumulative dredging volume prior to and after navigation channel deepening and widening.



b. Correlation between normalized dredging rate and channel depth.

Figure 1. Shoaling rates for St. Marys Entrance Channel, FL/GA.

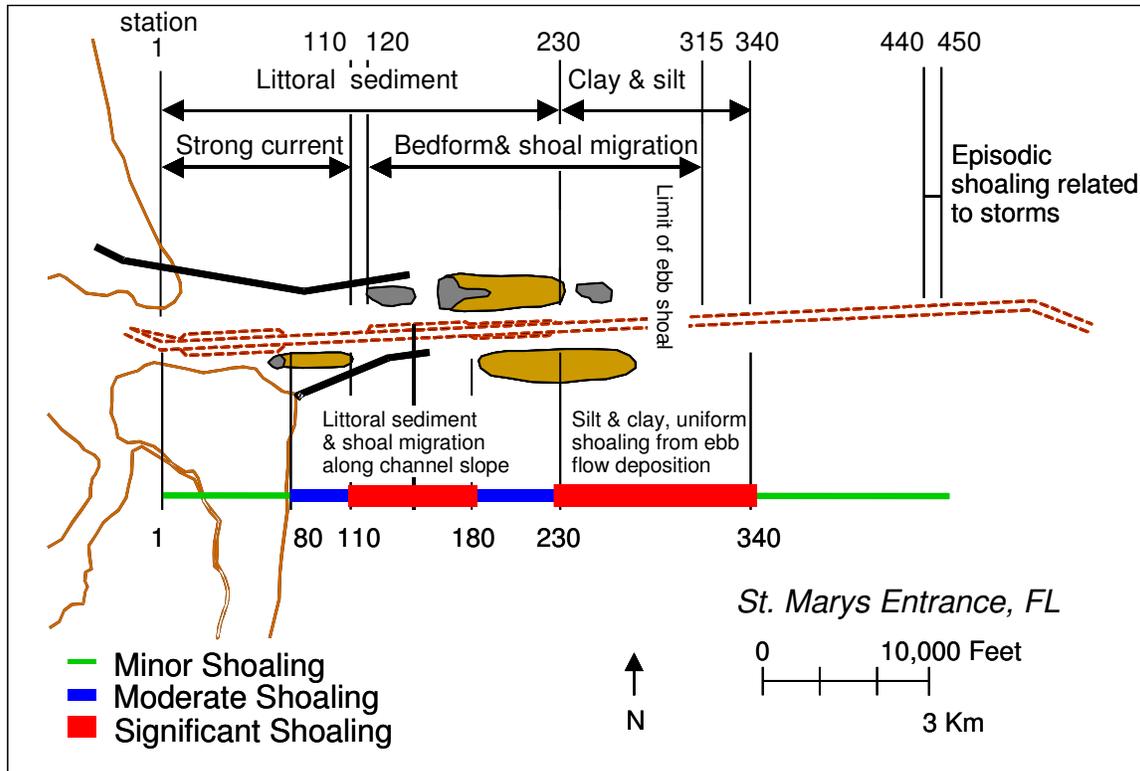


Figure 2. Channel shoaling along St. Marys Entrance, FL/GA (after Johnston et al. 2002)

Numerically intensive or meso-physics based models are available for use in a feasibility phase of channel maintenance evaluation (e.g., Kadib 1976, Bijker 1980, Van Rijn 1991, Walstra et al. 1999, Reed et al. 2005). As Trawle (1981) has noted, however, dredging data sets that would serve for model validation typically exhibit large variability. Such models require substantial data input and computational resources to determine the wave and current forcing at the site, from which sediment transport rates and channel shoaling can be calculated (Manzenrieder 1994). It appears that development of empirically based approaches for estimating channel maintenance dredging requirements can benefit decision-support planning, as well as provide guidance for establishing and interpreting computation-intensive engineering models. Because an inlet and its navigation channel are part of a sediment-sharing system with the adjacent beaches, the rate of natural sediment bypassing must be considered in addition to the channel infilling rate.

Navigation channel performance can be limited by bank encroachment, typically as intrusion by a spit, shoal, or sand wave into a channel; through deposition or infilling of sediment along the channel bottom; and by bank erosion (Figure 3). Bank encroachment together with bank erosion result in migration or meandering of the channel. If the channel fills above project depth, or if some minimum width is reached, maintenance dredging is necessary. Project depth is the minimum allowable depth for supporting the design vessel. For discussions herein, the term shoaling includes is the sum of infilling from the bed (deposition) and bank encroachment.

Dredging requirements must be estimated in design and modification of channels based on hydrographic survey data and estimated shoaling rates available from the existing channel. Deepening and widening may be considered as part of advance maintenance to reduce dredging frequency and cost, and to promote favorable environmental consequences. Savings can be accrued by reducing the number of dredge mobilizations and demobilizations, and channel-condition surveys, and by scheduling dredges when equipment can be shared among regional projects. Advance maintenance may also be scheduled to accommodate favorable weather and endangered species windows to reduce the cost of dredging, avoid disturbance to the environment, and to maintain the channel through storm seasons when dredging is more expensive or risky.

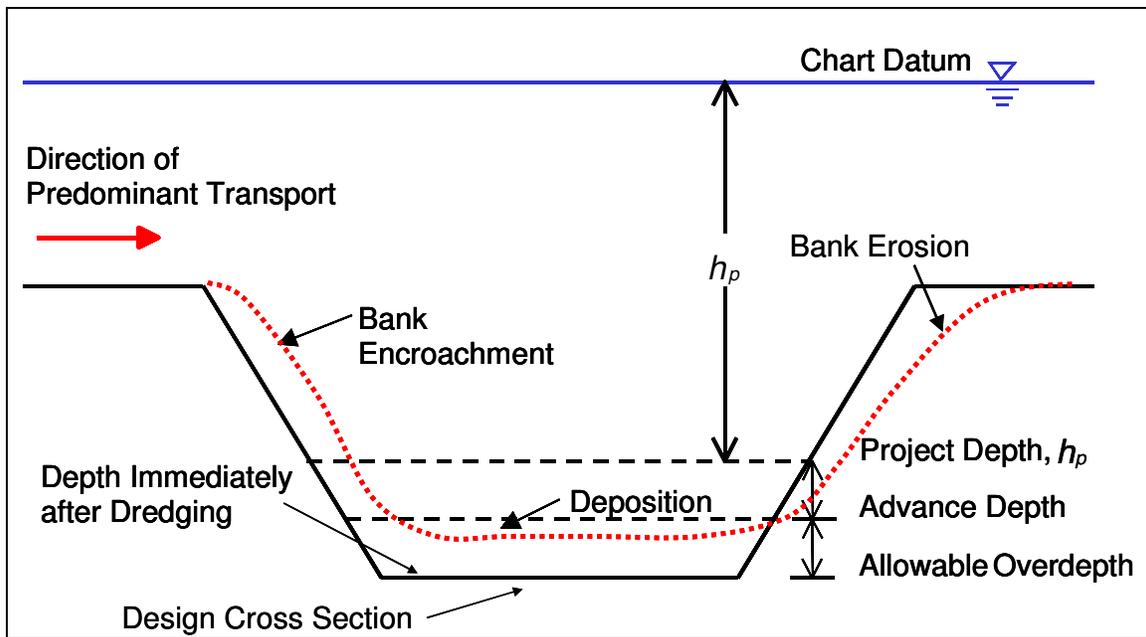


Figure 3. Schematic of channel evolution by bank encroachment, deposition, and bank erosion.

This paper reviews available analytical and empirical methods and introduces a morphology-based mathematical model of channel shoaling by cross-channel sediment transport. The morphologic model calculates channel shoaling either by infilling from the bed or by bank encroachment, and includes time-dependent bypassing as a function of the magnitude of shoaling. The model takes advantage of information typically available in engineering projects: the depth and width of the channel in its natural state prior to dredging, and an estimate of longshore (cross-channel) sediment transport that contributes to shoaling of the channel. Gradients in transport along the channel are not represented directly, but do enter indirectly through incorporation of the natural channel depth. The model has a closed-form solution for the simple case of constant input transport rate and yields quantitative predictions of the decrease in depth by shoaling, channel narrowing by bank encroachment, and sand bypassing. Comparisons are made to an existing analytical method and channel survey data to demonstrate the applicability of the model and demonstrate content of data sets typically available in practical situations.

### REVIEW OF ANALYTICAL AND EMPIRICAL METHODS

This section reviews analytical and empirical methods for calculating channel infilling by cross-channel transport that do not depend on intensive hydrodynamic and wave modeling to assess existing predictive capability. Common notation is adopted to aid comparison. Various authors have considered different sections of an inlet entrance channel, such as the offshore, outside the area of breaking waves; on the ebb-tidal shoal; and in the surf zone. Although most quantitative methods appear to focus on one such section of the channel such as illustrated in Figure 2, they appear to be applicable to any section if the inputs are specified appropriately. The main requirement is that the channel fills by cross-channel transport of sediment, whatever the origin of the transport-forcing mechanism.

Sediment intercepted by a navigation channel can reduce channel width by accumulating on the sides (bank encroachment) and reduce channel depth through deposition on the bottom (infilling) (Figure 3). Figure 4a shows an example of bank encroachment at Shinnecock Inlet, NY, and Figure 4b shows bed deposition at St. Marys Entrance, FL/GA. The calculation methods reviewed in this section have not accounted for channel bank encroachment. Sediment can also pass over a channel by moving in suspension, and material deposited in the channel can be re-suspended and transported out; both processes contribute to channel bypassing. At inlets, the net bypassing rate in the predominant direction of transport to the down-drift beach enters in sediment budgets, and the gross rate of longshore transport relates to channel dredging requirements.



Gole and Tarapore (1971) presented an empirical method for estimating channel infilling by cross-channel transport seaward of the wave-breaking zone, for fine-grained sediments. However, the method appears equally applicable to sand in the wave-breaking zone, if a decrease in channel width by bank encroachment is not of concern. For the region seaward of the wave-breaking zone, tidal or other regional currents carry the cross-channel transport into the channel. Bypassing was represented by calculating the amount of suspended load of certain sediment fall speed that would be transported over the channel for a specified width, unaltered cross-channel current upstream of the channel, and sediment fall speed. A depth-averaged current upstream of the channel was assumed, giving the current in the channel by assumption of constant discharge. These two assumptions are common to all methods described below and will not be repeated in this review. Assuming further that the sediment-carrying capacity is proportional to the square of the velocity, the rate of infilling was derived to be proportional to  $(h_d^2 - h_a^2)/h_a^2$ , in which  $h_d$  = depth of initially dredged channel, and  $h_a$  = ambient depth upstream of the channel. The method is calibrated by an empirical multiplicative coefficient that was determined by comparison to dredging data. Data for four ports in India gave a coefficient value ranging from 0.245 to 0.30, indicating relative robustness of the method. This method is not readily adaptable for predictions of infilling if the channel dimensions are to be changed, because of the data dependence and lack of accounting for channel width.

Mayor-Mora et al. (1976) developed an analytical method for infilling in a dredged channel by settling of suspended sediment. Mikkelsen et al. (1980) subsequently verified the method with data from a test pit dug near the location of the channel under consideration. The test pit was 200 m wide (channel width), 400 m long, and 2 m deeper than the ambient depth of 7 m. Current velocity, waves, suspended sediment concentration inside and up drift of the test pit, and sediment grain size were measured, and echo soundings were made about every 3 weeks over a 5-month period. The centerline of the pit filled at a rate of 1.7 cm/day shortly after dredging, decreasing to 1.2 cm/day near the end of the monitoring. The predictive expression of Mayor-Mora et al. (1976) is:

$$q_R = \left[ q_{in}(1 - e^{-Fh_a/h_d}) - q_{hd}(1 - e^{-F}) \right] \cos \alpha \quad (1)$$

where  $q_R$  = infilling rate per meter length of channel,  $q_{in}$  = input transport rate of suspended sediments at equilibrium updrift of the channel at ambient depth  $h_a$ ,  $q_{hd}$  = transport rate of suspended sediment in the equilibrium condition in the channel at depth  $h_d$ ,  $\alpha$  = angle between the direction of the current and a normal to the channel, and the coefficient  $F$  given by:

$$F = \frac{w^2 W_0}{\epsilon_s V \cos \alpha} \quad (2)$$

where  $w$  = sediment fall speed,  $W_0$  = initial width of channel (assumed not to change),  $\epsilon_s$  = sediment eddy diffusion coefficient, and  $V$  = current velocity upstream of the channel, determined by another model or specified directly.

Derivation of Equation (1) depends on an assumed steady current and wave field (waves enter in determination of the equilibrium suspended transport both up drift and in the channel, and in the diffusivity coefficient), equilibrium forms for the velocity profiles, and modification of the concentration profile with depth, among other factors. Elapsed time does not enter, which gives a constant infilling rate unless Equation (1) is re-evaluated with updated forcing conditions. For large grain sizes, the value of  $F$  is large, meaning that Equation (1) reduces to  $q_R \approx q_{in} - q_{hd}$ . Although not described in the original papers, the bypassing rate can be considered to be equivalent to  $q_{hd}$ . Mikkelsen et al. (1980) calculate  $q_a$ ,  $q_{dh}$ , and  $\epsilon_s$  from micro-scale physics relations, making this procedure difficult for decision-support or initial planning studies that must be done quickly.

Vicente and Uva (1984) present a method based on the assumption that a channel will infill exponentially toward equilibrium as governed by the equation:

$$\frac{dh}{dt} = -K(h - h_e) \quad (3)$$

where  $h$  = depth in the channel (they used elevation in the channel, here converted to depth),  $K$  = empirical relaxation coefficient, and  $h_e$  = equilibrium depth of the channel in the zone of interest, also determined empirically. If the forcing is assumed constant over the time interval of interest, Equation (3) has the solution:

$$h = h_d - (h_d - h_e)(1 - e^{-Kt}) \quad (4)$$

Vincente and Uva (1984) determined  $K$  and  $h_e$  by fitting to channel survey data, noting that only two surveys are necessary. The method is rational in assuming exponential behavior and an equilibrium depth, but by determining the equilibrium depth and relaxation time through data fitting, it is highly empirical and holds few advantages over simply estimating channel infilling based on experience. Also, channel width and bypassing rate are not considered explicitly, making the method difficult to apply to new channel designs for which data are not available. Manzenrieder (1994) gave a similar procedure in which the volume of material dredged beyond a natural depth (called the “artificial” volume) was assumed to decrease exponentially. Fitting to data for a section of channel at Wilhelmshafen, Germany, where the channel is oriented perpendicular to the tidal current, gave the half-life of the artificial volume.

Galvin (1982) refined an empirical method presented in Galvin (1979) to calculate the rate of infilling of channels together with the bypassing rate at the crest of an ebb-tidal shoal, assumed to be the constraining depth for navigation. The method appears applicable to any location along an inlet channel subjected to sedimentation by waves and tidal current. The method is expressed in terms of a bypassing transport ratio, here called  $T$ , defined as the ratio of the bypassing rate after dredging to the bypassing rate before dredging. By taking a ratio, an unknown multiplicative empirical coefficient entering both transport rates cancels. Based on assumptions of shallow-water wave theory and on the sediment transport being proportional to the product of a bottom shear and current velocity, Galvin (1982) finds the transport ratio as:

$$T = \left( \frac{h_a}{h} \right)^m \quad (5)$$

in which the exponent  $m$  ranges between  $3/2 < m < 5/2$ , the limits depending on whether one assumes the tidal discharge through the inlet section remains the same ( $m = 3/2$ ) or increases ( $m = 5/2$ ) after dredging. Therefore, the Galvin (1982) method can account for some along-channel transport processes. The deposition ratio is  $1 - T$  and, for an input longshore sediment transport rate per unit length of channel  $q$ , the infilling rate becomes:

$$\frac{dh}{dt} = -\frac{q}{W}(1-T) = -\frac{q}{W} \left( \frac{h^m - h_a^m}{h^m} \right) \quad (6)$$

Galvin (1982) notes several physically reasonable properties of this channel infilling and bypassing method: (1) the maximum rate of infilling occurs immediately after dredging, (2) the channel fills faster if the post-dredging velocity is reduced by increasing channel dimensions, and (3) infilling depth approaches the ambient depth  $h_a$  more slowly if the depth of the dredged cut,  $h_d - h_a$ , is smaller, for  $h_d$  held constant. Forman and Vallianos (1984) applied the Galvin method to a project study, calculating statistical estimates of daily infilling rates.

Galvin (1982) also gives an estimate of the time  $t_p$  to reach project depth  $h_p$  after dredging:

$$t_p \approx \frac{W}{q} \left[ (h_d - h_p) + \frac{h_a}{m} (\ln A - \ln B) \right] \quad (7)$$

where

$$A = \frac{h_d - h_a}{h_d - h_p}, \quad B = \frac{1 + \left(\frac{m-1}{2}\right) \frac{h_d - h_a}{h_a}}{1 + \left(\frac{m-1}{2}\right) \frac{h_p - h_a}{h_a}} \quad (8)$$

Equation (7) is an approximate solution of an integral that cannot be solved in closed form.

Van de Kreeke et al. (2002) presented an analytical solution of channel infilling and migration under a tidal current, with waves as a stirring mechanism. The model is applicable to deeper water and computes widening and infilling of a Gaussian-shaped channel through sediment diffusion processes for both bed load and suspended load, driven by tidally averaged moments of the current. Van de Kreeke et al. applied the analytical solution to the access channel to the Port of Amsterdam, for which the ambient depth  $h_a = 17$  m, channel width = 600 m, median sand size = 0.2 mm, and maximum channel depth = 20 m. For the analytical solution to be applicable, seven dimensionless quantities must be of order  $\varepsilon$ , where  $\varepsilon = (h_d - h_a)/h_a$ . The van de Kreeke et al. analytical solution is applicable for long time periods, with channel "...time scales measured in hundreds of years." The required time period related to nearshore forcing makes direct adaptation of this solution infeasible, where the majority of channel infilling occurs by wave-induced longshore currents, requiring maintenance dredging on order of a few years.

Of the methods available for empirical estimation of channel infilling and bypassing, only the Galvin (1982) method can be applied to (1) estimate changes in the channel infilling rate due to channel modifications, (2) the nearshore, where wave-driven cross-channel currents are the dominant forcing mechanism for channel infilling, and (3) estimate channel bypassing. None of the methods reviewed allow calculation of bank encroachment, although the van de Kreeke et al. (2002) solution gives channel migration as a requirement at second order.

### MORPHOLOGIC CHANNEL SHOALING MODEL

The paradigm for development of this model is that a channel that may infill from the bed, decreasing the navigable depth (termed channel infilling), and from the up-drift bank, decreasing the navigable width (termed bank encroachment). Dredging is assumed to occur at intervals such that channel meandering and migration are prevented before significant lateral deformation can occur. Bypassing is represented by suspended load transported over the channel and by re-suspension and transport of material that has been deposited in the channel. Such processes are depicted schematically in Figure 5. Model assumptions and development follow those of Kraus and Larson (2003). Assumptions for the present version of the model are:

1. Shoaling (both channel infilling and bank encroachment) occurs by cross-channel transport, whatever the type (primarily due to wave-generated current, but also potentially due to tide, wind, and regional currents).
2. The gradient in along-channel transport is negligible for each segment of the channel analyzed.
3. A natural channel depth,  $h_n$  and width,  $W_n$  exist and can be identified, which represent the long-term time-averaged or equilibrium depth and width, respectively, of the navigation channel if it were not maintained. If a natural channel was not present prior to dredging, then  $h_n$  is the local ambient depth  $h_a$ , and  $W_n = 0$ .
4. The rate of sediment leaving the channel is the product of the rate of sediment entering the channel and a ratio relating the natural, dredged, and actual conditions at that time. For channel infilling, the ratio relates natural, dredged, and actual channel depths; for bank encroachment, it represents the natural, dredged, and actual channel widths.

The conceptual framework of the model for the situation of transport directed to the right, assumed to be the dominant direction of transport, is shown in Figure 5. The down-drift bank of the channel is assumed to be stable. The causes and circumstances of channel migration are not well understood, and some channels remain in position, whereas others migrate, a topic beyond the scope of this paper. Immediately after dredging, the channel has width  $W_d$  and depth  $h_d$ .

A dredged channel, if not maintained, is assumed to fill until the natural depth is re-established. In applications, this depth can be determined by examination of the channel at a coastal inlet prior to dredging, through survey data during times when dredging may have been delayed, or as the depth at adjacent channel sections where dredging is minimal or not required.

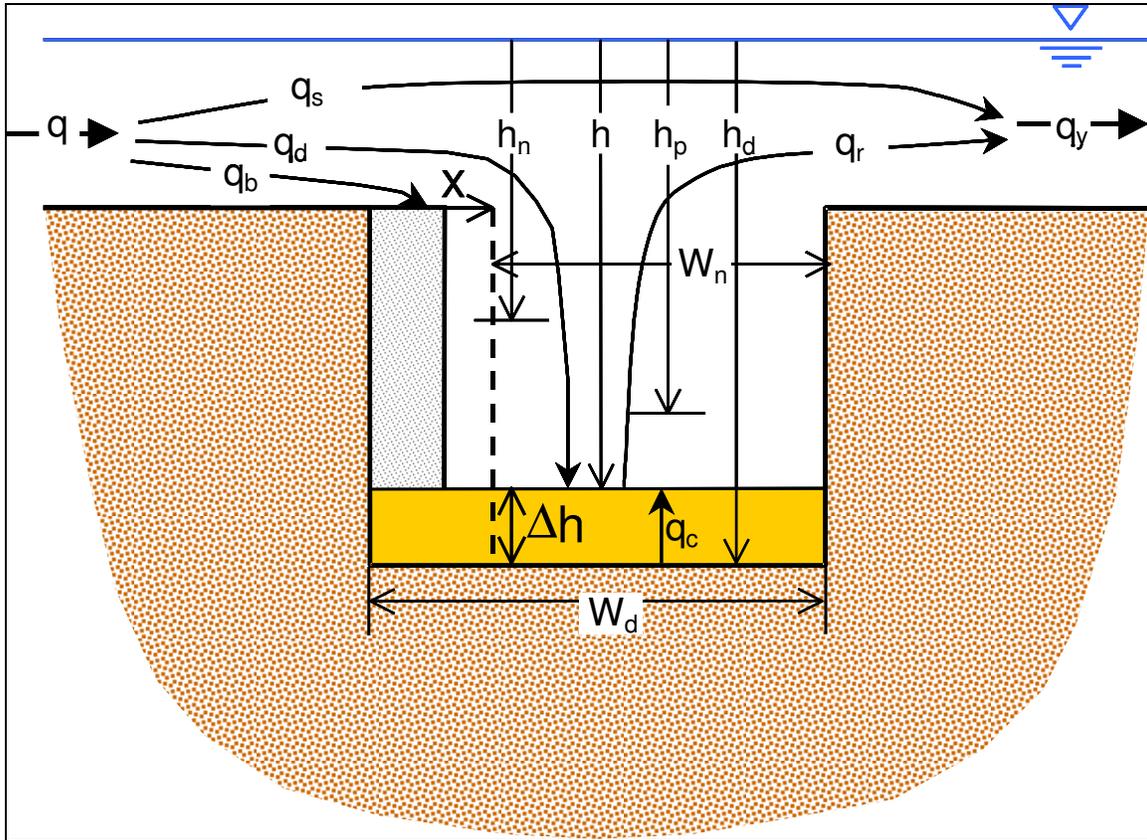


Figure 5. Definition sketch for channel shoaling model.

The model is derived by considering the sediment pathways as shown in Figure 5:

$$q = q_b + q_d + q_s \quad (9)$$

in which  $q$  = total rate of sediment approaching channel per unit channel length,  $q_b$  = transport contributing to bank encroachment per unit channel length,  $q_d$  = deposition rate per unit channel length, and  $q_s$  = suspended transport that bypasses the channel per unit channel length. The rate of channel infilling is given by,

$$q_c = q_b + q_d - q_r \quad (10)$$

in which  $q_c$  = rate of channel infilling per unit channel length and  $q_r$  = rate of resuspension from the channel bed per unit channel length. The rate of sediment bypassing per channel length,  $q_y$ , is:

$$q_y = q_r + q_s \quad (11)$$

Assigning proportionality factors to simplify as  $a_b = q_b/q$ ,  $a_d = q_d/q$ , and  $a_s = q_s/q$ , there results  $a_b + a_d + a_s = 1$ . Thus, once two of the proportionality factors have been estimated, the third may be calculated.

The rate of sediment  $q_r$  that is resuspended and leaves the channel is assumed to be proportional to the deviation of the existing depth from the natural depth (Model Assumption 4, above):

$$q_r = \frac{h_d - h}{h_d - h_n} q_d = a_d \frac{h_d - h}{h_d - h_n} q \quad (12)$$

which follows an assumption introduced in the Inlet Reservoir Model for coastal inlet morphology change and bypassing (Kraus 2000) and applied to channel infilling by Kraus and Larson (2003). Equation (12) expresses the physical picture that the sediment resuspension rate, determined by  $q_r$ , is smallest shortly after dredging and then increases (linearly) as the channel approaches the natural depth. If there is no input rate of transport (no cross-channel current), then no sediment is expected to leave the channel. For the situation of a portion of channel crossing the surf zone, the transport rate per unit channel length can be estimated as the total longshore transport rate  $Q$  multiplied by the ratio of effective length of channel being considered,  $L_c$ , to the total width of the surf zone.

Sand volume increases if the channel shoals, and the continuity equation becomes, for small time interval  $\Delta t$  and applying Equation (12) for  $q_r$ :

$$(W_d - x)\Delta h = (q_r - q_d)\Delta t = -a_d q \left[ \frac{h - h_n}{h_d - h_n} \right] \Delta t \quad (13)$$

in which  $\Delta h$  = depth change, and  $x$ =distance of bank encroachment over  $\Delta t$ . The governing equation for channel infilling is then:

$$\frac{dh}{dt} = \frac{-a_d q}{W_d - x} \left( \frac{h - h_n}{h_d - h_n} \right) \quad (14)$$

For constant input rate and  $a_b = 0$  (no bank encroachment, so  $x = 0$ ), the solution of Equation (14) is:

$$h = h_n + (h_d - h_n) e^{-t/\tau_d} \quad (15)$$

in which:

$$\tau_d = \frac{W_d (h_d - h_n)}{a_d q} \quad (16)$$

is a characteristic time describing the duration of channel infilling for constant input rate of sediment approaching the channel. The form of Equation (15) is identical to the solution of Vicente and Uva (1984), Equation (4), except their values of  $K$  in the exponential and the equilibrium depth  $h_e$ , are to be determined through fitting to dredging data, whereas the two quantities  $\tau_d$  and  $h_n$  in the present formulation can be estimated from site evaluation.

From Equation (15), the shoaling rate is given as, for the situation of negligible bank encroachment:

$$\frac{dh}{dt} = -\frac{a_d}{W_d} q e^{-t/\tau_d} \quad (17)$$

for which the negative sign means that channel depth decreases as the channel fills. For short elapsed time, to second order, the solution is:

$$\frac{dh}{dt} \approx -\frac{a_d q}{W_d} + \frac{a_d^2 q^2}{W_d^2 (h_d - h_n)} t \quad (18)$$

At first order, the initial infilling rate is independent of the dredged depth and natural depth, depending directly on the input rate and inversely with channel width. A larger sediment volume deficit,  $h_d - h_n$ , decreases the infilling rate at second order.

The time  $t_p$  for the channel to fill to project depth  $h_p$  is given from Equation (15):

$$t_p = \tau_d \ln \left( \frac{h_d - h_n}{h_p - h_n} \right) \quad (19)$$

For calculating bank encroachment, the rate of sediment input to the bank is  $q_b = a_b q$ , and the output rate is:

$$(q_b)_{out} = \frac{x}{(W_d - W_n)} q_b \quad (20)$$

where  $W_n$  is the natural channel width prior to dredging. From Figure 5, the rate of bank encroachment  $dx/dt$  is:

$$\frac{dx}{dt} = \frac{a_b q}{h - h_a} \left( 1 - \frac{x}{W_d - W_n} \right) \quad (21)$$

If  $h = \text{constant}$ , meaning no infilling takes place, such as for an inlet where the adjacent beaches are primarily gravelly ( $a_d = a_s = 0$ ), Equation (21) has the solution

$$x = (W_d - W_n) (1 - e^{-t/\tau_b}) \quad (22)$$

in which:

$$\tau_b = \frac{(W_d - W_n)(h_d - h_a)}{q} \quad (23)$$

is a characteristic time describing the duration of bank development for constant input rate of sediment deposited on the side of the channel.

In the general case of both channel shoaling and bank encroachment, Equations (14) and (21) form a set of coupled, first-order, nonlinear differential equations. Kraus and Larson (2003) describe an analytical solution for similar equations not involving the natural depth and width obtained by linearization under the assumption of small change in depth or bank growth. In the present study, Equations (14) and (21) are solved numerically by a trapezoidal or mid-point solution method.

## EXAMPLE APPLICATIONS

This section describes tests of the model and a methodology for its application. First, sensitivity testing of the numerical method was conducted by separately varying dredged channel depth and width for a range of dredging intervals. These tests indicated that model performance is in accord with general physical expectations that (1) the rate of channel shoaling (infilling and bank encroachment) is greatest immediately after dredging and decreases with time, and (2) the channel shoaling rate increases as dimensions of the dredged channel increase relative to the natural channel dimensions. The following examples demonstrate comparison with the Galvin (1982) model and example data set, and with field data at three sites.

### Galvin's (1982) Example

The shoaling model was applied to a realistic example presented by Galvin (1982) to compare with his relationship and to test trends in performance. Galvin's example has two parts, in which a channel with the following characteristics must be deepened to a depth,  $h_d$ , such that it will remain at or below the project depth,  $h_p$ , for 8 months:  $h_n = 2.5$  m,  $h_p = 4$  m,  $W_0 = 30$  m, effective channel length  $L_c = 150$  m,  $Q = 10,000$  cu m/year (during the 8-month period considered), and required  $t_p = 8$  months = 0.67 year. The ambient depth,  $h_a$ , is not given and is not required if bank encroachment is neglected ( $a_b = 0$ ). The Galvin method gave the solution as  $h_d = 5.35$  m. With  $a_d = 1.0$  and  $a_b = 0$ , the present shoaling model predicted the required dredged depth to maintain at least a 4-m project depth as  $h_d = 6.0$  m, or 12% greater than the Galvin method value.

The second part of the example asks for the maximum reduction in the bypassing rate, which Galvin determines from the maximum channel trapping rate right after dredging. Galvin set  $h_d = 5.1$  m and obtained the first month's channel trapping rate = 1,040 cu m/month. With the shoaling model,  $h_d$  was set to 5.1 m, and this same quantity was calculated as 960 cu m/month, 92% of the Galvin method value. Thus, for this hypothetical example, the shoaling model agrees favorably with the Galvin (1982) model.

### Field Applications

Shinnecock Inlet is a meso-tidal inlet located on the south shore of Long Island, NY, with a median grain size of 0.35 mm. Net longshore sand transport is from the east, with a nominal rate of 200,000 cu m/year (Research Planning Institute 1983; Kana 1995). At Shinnecock Inlet, four channel transects were evaluated, as shown in Figure 6 and Table 1. Here, the longshore transport was assumed to have a triangular distribution across shore, with a peak at the transect with the greatest shoaling rate and decreasing both seaward and shoreward of that transect. The increase in channel elevation,  $\Delta h$ , and the bank encroachment distance,  $\Delta x$ , were evaluated and modeled for these four transects. The east jetty transect was the only one that exhibited bank encroachment (a jetty tip shoal shown in Figure 8a), and this process was modeled with  $a_b = 0.15$ . Calibration of all transects resulted in  $a_d$  values ranging from 0.18 to 0.5, and  $a_s$  values ranging from 0.35 to 0.82 (Table 1). These calibrations illustrate the capability of the coupled differential equations to simulate variations in channel bank encroachment, infilling, and suspended transport bypassing the channel.

**Table 1. Channel Transects Evaluated with Morphologic Shoaling Model**

Shinnecock Inlet: Sep 1998 to Apr 2001							
Transect	Measured (m)		Model Parameters			Predicted (m)	
	Average $\Delta h$	$x$	$a_d$	$a_b$	$a_s$	$\Delta h$	$x$
East Jetty	0.42	7.3	0.5	0.15	0.35	0.44	7.1
T1	0.78	0	0.18	0	0.82	0.77	0
T2	0.96	0	0.31	0	0.7	0.95	0
T3	0.93	0	0.4	0	0.6	0.94	0
Freeport Entrance Jetty Channel: 1983 to 1988 (pre-deepening and widening) <sup>1</sup>							
0+00 to 30+00	$2.1 \times 0.15 = 0.32$	0	0.08	0	0.92	0.32	0
Freeport Entrance Jetty Channel: 1992 to 2002 (deepened and widened) <sup>2</sup>							
0+00 to 30+00	$1.4 \times 0.15 = 0.21$	0	0.08	0	0.92	0.17	0
Keystone Harbor: Oct 1987 to May 1990 <sup>1</sup>							
T2	0	8.5	0	0.7	0.3	0	8.5
Keystone Harbor: May 1990 to May 1991 <sup>2</sup>							
T2	0	3.5	0	0.7	0.3	0	3.7

<sup>1</sup> Calibration of model.

<sup>2</sup> Verification of model, using calibrated parameters.

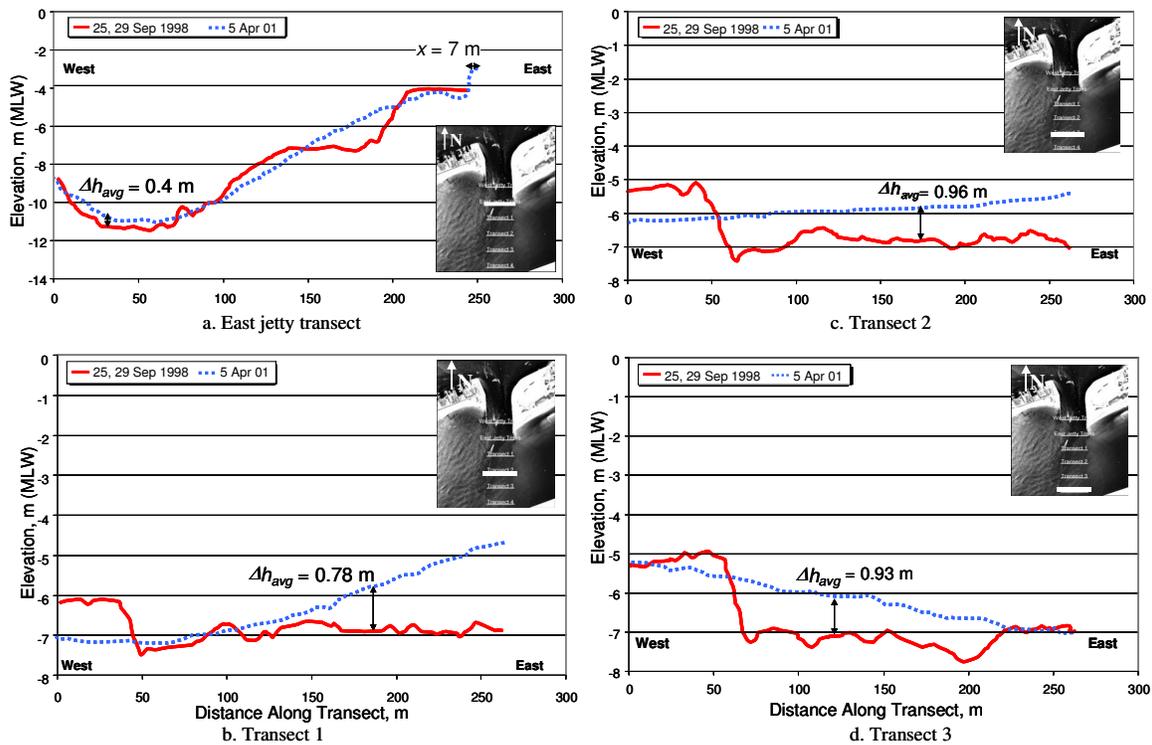


Figure 6. Shinnecock Inlet, NY, channel cross-sections.

To further test the model, two time periods of channel shoaling data for different channel configurations at one location were desired. Data for Freeport Entrance, TX, located in the Gulf of Mexico in a micro-tidal environment were available to calibrate the model based on dredging from 1983 to 1988, when the channel was maintained at 11-m depth and 61-m width. The model was then tested by holding the parameter values constant for a post-deepening and widening condition from 1992 to 2002, when the channel was maintained at 13.7-m depth and 122-m width. Samples of dredged sediment in the jetty entrance channel indicated approximately 15% sand, 35% silt and 50% clay. Channel shoaling occurs entirely by infilling (no bank encroachment). It is likely that the silts and clays move from the river and bay into the jetty channel via along-channel transport, rather than by cross-channel processes. Thus, 15% of the observed infilling was attributed to longshore (cross-channel) transport and served for comparison with model simulations. Net longshore sand transport was estimated to be 250,000 cu m/year to the south (U.S. Army Engineer District, Galveston 1992). Because of the observed uniform infilling on the channel transects and those at the tips of the jetties (Figure 7), longshore sand transport was assumed uniformly distributed.

Starting with the pre-deepening and widening channel configuration, the model was calibrated to reproduce the observed infilling rate of  $2.1 \text{ m} \times 0.15 = 0.32 \text{ m}$  for a 915-m long by 61-m wide section of the jetty channel. The calibrated model parameters were  $a_d = 0.08$  and  $a_b = 0$ . Keeping these parameters fixed, the deepened and widened channel configuration was modeled, resulting in a predicted infilling elevation of 0.17 m for the 915-m long by 122-m wide section, versus  $1.4 \text{ m} \times 0.15 = 0.21 \text{ m}$  of infilling that occurred. Thus, the model predicted approximately 80% of the infilling that occurred in the channel, after a 150% increase in channel cross-sectional area.

The Galvin (1982) model was also applied to the Freeport data set with a value of 15% for the percentage of cross-channel transport by sand infilling. The Galvin model over-predicted the infilling rate by 43% and 20% for the first and second time periods, respectively, with the parameter  $m=3/2$  (no change in tidal flow). With  $m=5/2$  (tidal flow increased), the Galvin model over-predicted the infilling rate by 84% and 42% for the same time periods. To obtain best results with the Galvin model, the percentage sand infilling by cross-channel transport was calibrated to 8% (for  $m=5/2$ ) to 10% (for  $m=3/2$ ) of the full value; however, there are no data to support this calibration. The benefits of the present model over the Galvin method are: (1) the present model gives linear equations to lowest

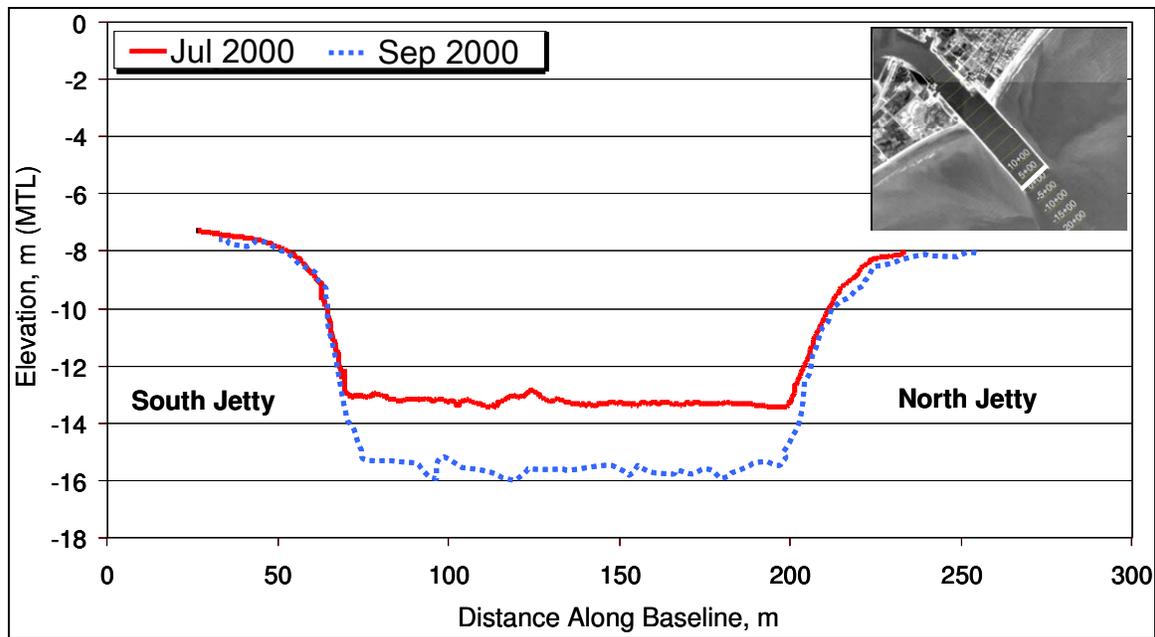


Figure 7. Freeport Entrance Channel, TX, channel cross-section at jetty tips.

order; (2) readily available morphological quantities of equilibrium depth and width are incorporated and determine the solution structure; (3) for long time periods, Galvin's model predicts channel infilling to the ambient depth, whereas the present model returns the channel to the natural width and depth; and (4) bank encroachment can be described. For example, the Galvin method could not treat the Shinnecock Inlet east jetty transect example described above or the following application.

As a final example with a different (extreme) sediment size, channel shoaling at Keystone Harbor, WA, is considered (Larson and Kraus 2003). The channel of this small harbor, located on a gravelly coast facing Puget Sound, becomes limited due to bank encroachment from the north (Figure 8). Gravel moves along the coast and enters the channel, gradually restricting its width. The north bank grows southward without decrease in depth. There is negligible tidal prism in this channel, with the main current supplied by ferries that enter and leave the harbor at relatively great speed. With  $a_b = 0.7$  to represent gravel, and the remainder of material assumed to be silt that washes away ( $a_d = 0$ ), calibration of the model with data from October 1997 to May 1990 period gives channel bank encroachment equal to 8.5 m for  $q = 5,000$  cu m/year,  $h_d = 7$  m, and  $h_n = 0$  (no natural channel because there is no tidal forcing in this artificially created harbor). Keeping the same values of  $a_b$  and  $a_d$  for a second time period from May 1990 to May 1991 gives bank encroachment equal to 3.7 m, as compared to a measured value of 3.5 m.

## CONCLUSIONS

A morphology change model for channel shoaling was developed based on partitioning of sediment-transport processes occurring at a dredged channel as infilling, bank encroachment, and sediment bypassing the channel. The model and methodology are applicable to channels on the open coast and in estuaries, bays, and lakes. Data required are those typically available: ambient depth adjacent to the channel, natural channel depth and width (prior to dredging), dredged channel depth, channel dimensions, and estimate of the cross-channel sediment transport rate (the longshore transport rate in nearshore applications). Successful model performance indicates that study should be made of depth and width of natural channels to develop empirical predictive relations based on the tidal and other forcing.

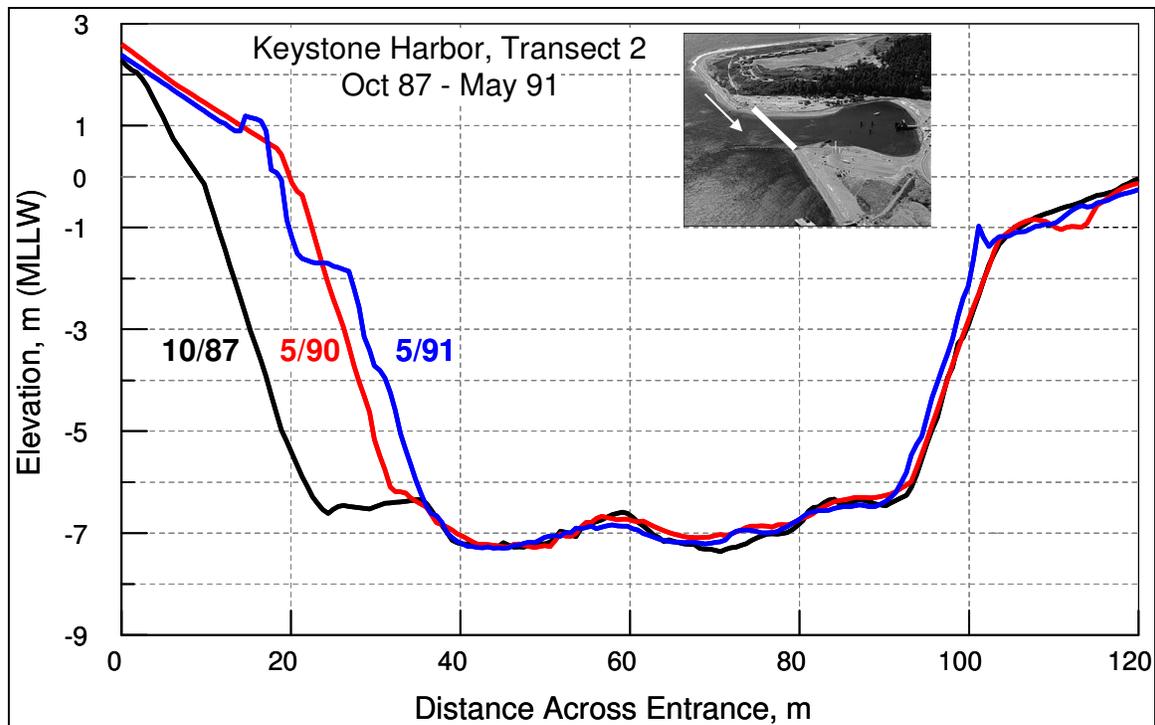


Figure 8. Keystone Harbor, WA, channel cross-sections.

Parameters relating to the percentage of channel shoaling by bank encroachment and by infilling (or, alternatively, the percentage of sediment transport bypassing the channel) must be specified by the user, or can serve as calibration coefficients. Sensitivity tests indicated rational performance of the model. Predictions of the model compared favorably with an independently published example, and the model reproduced channel performance at three sites, Shinnecock Inlet, NY, Freeport Entrance, TX, and Keystone Harbor, WA. The model was calibrated and validated for the jetty channel at Freeport, TX, and reproduced 80% of the infilling that occurred after channel deepening and widening. Keystone Harbor provided an example of bank encroachment, for which the simple morphologic model predicted a decrease in channel width only 6% greater than the measured value.

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