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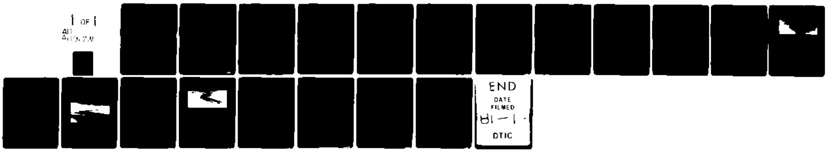

TP 80-6

A Method to Predict the Stable Geometry of a Channel Connecting an Enclosed Harbor and Navigable Waters

by

Craig H. Everts

TECHNICAL PAPER NO. 80-6

AUGUST 1980

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A desirable design criterion for an enclosed harbor is that the channel connecting it with navigable waters be self-maintaining. This condition will prevail where sediment movement is negligible, or in the case of moving sediment, where tidal or river discharge is sufficient to maintain acceptable channel dimensions. A method to predict the stable configuration of such a channel is presented in this paper. A relationship between stable channel cross-sectional area, cross-sectional shape, and bottom elevation of the channel and the water discharge through the channel is determined using the geometric characteristics of nearby natural channels and the hydraulic regimes that sustain those channels.

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PREFACE

This report presents a method for predicting the stable (self-maintaining) cross-sectional area and shape of a navigation channel between a landlocked harbor and open waters. Channel scour is assumed to result from the flow of water between the harbor basin and the adjacent, tidally controlled estuary or open ocean. Sedimentation in the channel is assumed to be controlled by the deposition of fine-grained material from suspension. Bedload sediment transport is considered to be minimal. Channel shape is a function of the sediment through which the channel is dredged, the tidal prism in the channel, and the depositional characteristics of the suspended sediment carried into the channel. An example of the method is given for a high tidal range (6 meters), sediment-laden (200 to 1,000 milligrams per liter) Alaskan harbor where the channel is cut through compacted silts and muds. This report is extracted from a paper by Everts (1977). The work was carried out under the coastal engineering research program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Craig H. Everts, Chief, Engineering Geology Branch, under the general supervision of N.E. Parker, Chief, Engineering Development Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

A cross-sectional area of an inlet gorge

C constant

d channel depth

L characteristic length of a channel cross section

n exponent

P tidal prism

Q total water volume moved through a channel during ebbtide

q characteristic unidirectional discharge

q_e ebbtide water discharge resulting from reversal of previous floodtide discharge

q_r normal water discharge of a river

r constant

s constant

t_l time of low water

t_h time of high water

w channel width

z sidewall slope

A METHOD TO PREDICT THE STABLE GEOMETRY OF A CHANNEL CONNECTING AN ENCLOSED HARBOR AND NAVIGABLE WATERS

by
Craig H. Everts

I. INTRODUCTION

A desirable criterion for the design of an enclosed harbor is that the channel connecting the harbor with navigable waters be self-maintaining. This condition may prevail where sediment movement is negligible, or in the case of moving sediment, where bottom shear stress caused by tidal or river discharge is sufficient to prevent deposition and thus maintain acceptable channel dimensions.

A method is presented to predict the stable configuration of a navigation channel connecting open tidal waters with an enclosed harbor. The stable cross-sectional area, cross-sectional shape, and bottom elevation of the channel are considered. A relationship between these variables and the water discharge through the channel is determined using the geometric characteristics of nearby natural channels and the hydraulic regimes that sustain the channels. Using appropriate field data, the method may be applied to the design of a navigation channel in any region where natural tidewater drainage or river channels exist.

An example is given using data obtained from a navigation channel at the harbor of Dillingham, Alaska, and from natural drainage channels on a tidal flat and in rivers near Anchorage, Alaska. The resulting relationship (tidal prism/channel cross section) may be used when sediments are like those on northern tidal flats, i.e., highly compacted glacial silt and mud-sized material generally lacking in clay materials and organic constituents.

II. METHOD

1. Background.

Theory does not exist to cover all circumstances of channel design because of the complex nature of the problem, which involves varying tidal ranges, varying quantities of sediment in transport, and varying compositions of channel bank and bed material from one location to another. However, two widely used procedures for estimating channel cross-section dimensions are the "tidal prism relationship," which is applied to sandy tidal inlets, and the "regime theory," which is mostly applied to river channels.

A *tidal prism* is defined as the total amount of water that flows into a harbor or estuary or out again with movement of the tide, excluding any freshwater flow (Allen, 1972). O'Brien (1931) first developed a power function form of the relationship

$$A = CP^n \qquad (1)$$

where

A = cross-sectional area of an inlet gorge below mean sea level (MSL)

C = constant

p = tidal prism corresponding to the diurnal or spring tide prism

n = exponent of P

Jarrett (1976) found that for the same tidal prism A values for Atlantic coast inlets are greater than those on the Pacific coast, citing a difference in wave climate among the contributing causes with the higher waves occurring along the Pacific coast. He hypothesized that the amount of littoral material entering an inlet would be greater there, and consequently the average flow velocity required to maintain Pacific coast inlets would probably be greater. In addition, Jarrett cited differences in the characteristics of the astronomical tides, and errors introduced by computational procedures in determining the tidal prism, as possible causes of the difference in Atlantic and Pacific coast A/P ratios. In all cases, the tidal prism/inlet channel area relationships were found for inlets where the predominant sediment was sand which was primarily moved as bedload. Tides were the major factor in controlling flow in the inlets, but longshore transport resulting from wave and wind action moved much of the sand to the inlet region.

The regime method, in which a channel in regime is defined as having no net erosion or deposition over a hydrological cycle, has been widely used since Lacey (1929) first proposed the method as a basis for the design of irrigation canals. Regime equations relating to channel cross-sectional geometry are essentially of the form

$$L = rq^{s} \tag{2}$$

in which L is some length characteristic of the cross section, q is some characteristic unidirectional discharge, and r and s are constants. A number of investigators have applied regime concepts to tidal flow conditions, and Chantler (1974) summarized and reanalyzed some of the data. The characteristic discharge used by the different investigators varied, but was usually some form of "dominant" or maximum discharge.

2. Approach.

Past studies indicate that development of a relationship between channel geometry and some measure of the flow through the channel will be a useful approach. However, two problems arise--the first in choosing a characteristic cross section, the other in choosing a flow parameter. In areas of high tidal range, the cross-sectional geometry will likely vary as the slope of the tidal flat and channel varies. The procedure used should, therefore, be adaptable to any cross section. Two flow characterizations have been used in the past. An instantaneous flow is considered in the regime theory. In calculating the tidal prism the total volume of water which passes through the cross section during a specified time period (usually one-half the tidal period) is used. For predictive purposes before harbor construction, the tidal prism approach is better because the prism can be calculated using data obtained from tide and river discharge records and topographic information such as may be available on natural channel dimensions. Data on maximum channel discharge rates, especially for tidal channels, are usually unavailable.

3. Formulation.

A navigation channel serving as access to an enclosed harbor is assumed to be sustained, and possibly created, by currents resulting from the rise and fall of the tide and by upland river discharge. Wave scour is not considered. It is further assumed that a relation of cross-sectional channel area to water discharge through a harbor channel, during ebbtide, will fall on a curve of the relationship of ebb discharge through natural channels cut in the same material at nearby locations. Ebbtide is used because at that time river and tidal discharges are additive, and tidal-flat flow is downslope into the channels.

The total water volume moved through a harbor channel or a natural channel during ebbtide, Q, produces the best relationship with the channel cross-sectional area where

$$Q = \int_{t_h}^{t_1} \left[q_e(t) + q_r(t)\right] dt \qquad (3)$$

where

q_e = ebbtide discharge of water through the channel cross section resulting from the previous flood discharge up the channel or on a tidal flat, or from the rise in channel stage caused by the backwater effect of river discharge;

q_r = normal river discharge, if any, that would occur if the tide was not present;

t_h = time of high water;

t_1 = time of low water.

Values q_e and q_r in channels may be determined using existing tide gage and river stage data and natural channel dimensions. The harbor basin discharge is equal to the water volume difference in the harbor between high and low tides. It is calculated using the proposed harbor dimensions and the tidal range at the harbor site.

In intertidal regions, it is assumed water moves into the channels from the adjacent planar parts of the tidal flat only during ebbtide and only when the vertical distance between the water surface and the tidal flat is small. It is further assumed that tidal-flat flow is downslope only, and thus conforms to the topography (usually a combination of seaward and channel-directed slopes). Flow on the tidal flats thereby adds to the channel discharge. Because of the variable topography of tidal flats and tidal-flat channels, the discharge must be obtained from cross sections and contour maps of the tidal flats. The volume discharged through a channel at any elevation on the tidal flat is, therefore, assumed equal to the volume under a horizontal plane at an elevation of the boundaries of the tidal-flat drainage at the channel location, bounded by downslope flow streamlines which intersect the channel above the cross section being studied. This is illustrated in the example provided in the next section.

The tidal discharge volume for river channels is computed using the water volume measured between high water elevation and low water elevation throughout the tidal reach of the river above the cross section. This is obtained using topographic data for the river from the site of observation to the head of tidewater plus river discharge and tide data.

III. EXAMPLE

Two streams, Eagle River and Ship Creek near Anchorage, Alaska, and a series of tidal-flat channels at Anchorage, illustrate the method used to obtain a channel cross-sectional area/ebbtide discharge relationship that can, in turn, be used to predict the stable cross-sectional area of a harbor navigation channel. The channel area of Dillingham Harbor, Alaska, is used to test the relationship. Sediments through which the channels flow are similar in each region and composed of well-compacted mud and silt-sized, glacial-fed material with less than 2 percent clay minerals. Channel and streambank elevations were in all cases less than 1 meter above mean higher high water (MHHW).

1. Anchorage Tidal-Flat Channels.

Channels were studied on a tidal flat in Knik Arm, the estuary serving the Port of Anchorage at the northeastern end of Cook Inlet (Fig. 1). Knik Arm carries an average suspended-sediment concentration of about 1,300 milligrams per liter (Everts and Moore, 1976), and has a median tidal range of 8.8 meters. Near Anchorage, the tidal flats are shore-connected, composed primarily of silt-sized material, and variable in width with a maximum extension of 600 meters into Knik Arm channel.

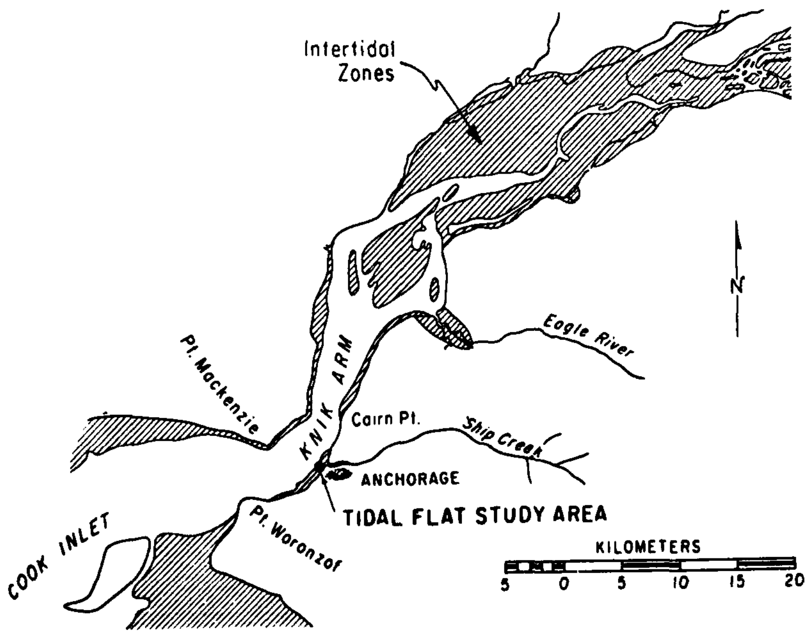

Figure 1. Location map of study area, Anchorage, Alaska.

Flow in the tidal-flat channels occurs primarily during ebbtide. During the flood part of the tide, water rises over the tidal flat as a sheet and is not carried preferentially in the channels. Figure 2 is an aerial view of the study

Figure 2. Aerial view to the southwest of the tidal-flat study area at Anchorage, Alaska. Arrow identifies channel shown in Figure 3.

area at Anchorage; the arrow identifies the tidal-flat drainage region shown in Figure 3. Figure 3 also shows cross sections at 2-foot contour intervals extending from one side to the other of the drainage region. Contours in Figure 3 are given in feet rather than meters because the original topographic computations from aerial photos and associated ground surveys were in feet.

For computational purposes, channel areas were calculated to be the area enclosed by the channel walls up to the obvious break in slope and extending upward to the contour elevation at the width of the drainage basin. On the cross section of the 22-foot contour (Fig. 3), the break occurs at 20.5-foot elevation, and the width is 35 feet. The cross-sectional area of the channel, defined by the diagonal line pattern, is 156 square feet (14.6 square meters). This is the area through which the discharge is assumed to pass.

Water discharge through the channel becomes important when the water surface elevation declines to the elevation of the cross section (Fig. 3). The ebbtide discharge through the channel is then calculated to be that volume of water which is upslope from the cross section. It includes the volume in the channel and above the channel break, and the volume on the tidal-flat surface that may be expected to move to the channel at or landward of the channel section. The volume is computed by drawing orthogonals to the tidal-flat contours at the cross section which intercepts the channel at its break. The easiest way to derive the volume is to sum the volumes of thin horizontal slices in the upslope volume. This volume for the channel at the 22-foot cross section is 8,800 cubic feet (250 cubic meters). The area-ebbtide discharge relationship is shown in Figure 4. The contour at 4 feet is omitted because of a bichannel condition.

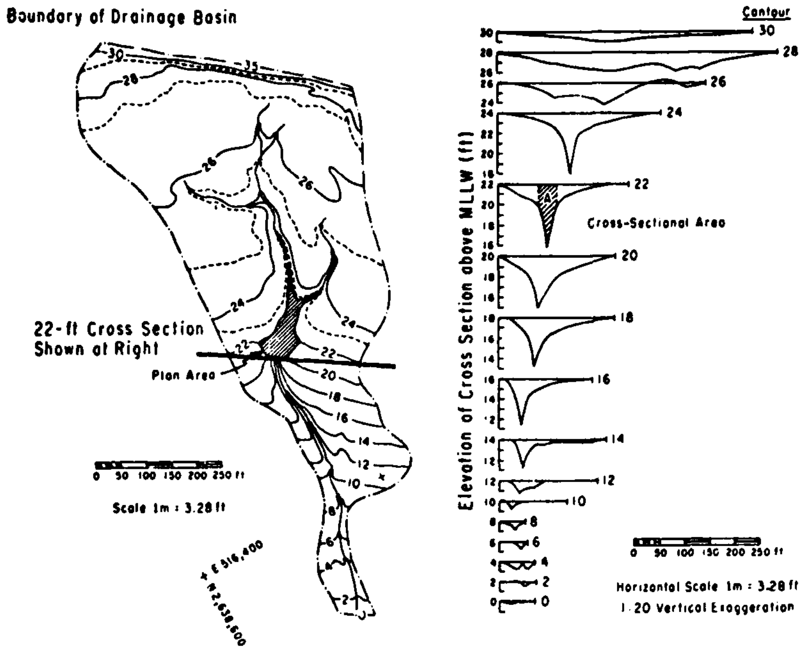

Figure 3. Plan view of tidal-flat drainage and cross section of the drainage region at the study area (Fig. 2). Crosshatched drainage region (plan view) enclosed all of the tidal flat below elevation of +22 feet (MLLW datum) that slopes toward and intersects the 22-foot cross-section channel (right). Only the channel flow area A is considered in the discharge-area computations.

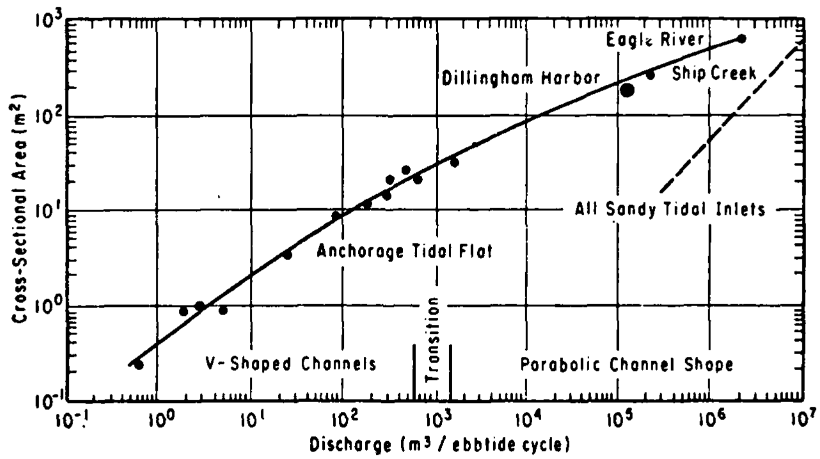

Figure 4. Channel area-ebbtide discharge relationship for certain Alaskan tidal channels cut in compacted mud and silt-sized sediments. Tidal inlet curve is from Jarrett (1976).

2. Eagle River and Ship Creek.

These rivers are tidal in their lower reaches. Eagle River (Fig. 5), which originates at Eagle Glacier, carries a large suspended load at a mean summer discharge of 30 cubic meters per second. Ship Creek carries much less sediment at an average summer discharge of about 3.2 cubic meters per second. In calculating the water discharge from these rivers during an ebb cycle, the average river discharge was added to the discharge resulting from the water volume of the cross section created as a result of the previous floodtide. This volume, calculated using survey data, hydrographic charts, and 1:80,000 topographic maps, is equal to the difference in river channel volume at high tide and at low tide. The total ebbtide discharge results are in Figure 4. In Eagle River, the total ebbtide discharge includes 70 percent from tidal flow and 30 percent from river discharge. The ratio for Ship Creek is 64 and 36 percent, respectively. Eagle River has a particularly extensive tidal reach near its mouth (Fig. 5).

Figure 5. An aerial view, east from Knik Arm, of mouth of Eagle River.

3. Dillingham Harbor.

Dillingham Harbor is a "half-tide" type harbor (Everts, 1976). Because of currents resulting from the high tides, as well as severe winter ice conditions, half-tide harbors are constructed as enclosed basins sited adjacent to, rather than within, navigable estuaries. Harbor depths are generally specified near mean lower low water (MLLW) to reduce initial excavation costs. The unique feature of these harbors is a sill at the harbor mouth designed to maintain adequate water levels during low tides. The sill provides flotation for vessels during low tidal stages, and it restricts navigation into or out of the harbor to times of higher tidal elevations.

Dillingham is located 500 kilometers southwest of Anchorage, Alaska, in the upper reaches of Nushagak Bay (Fig. 6). The local tidal range is 6 meters and suspended-sediment concentrations vary from 50 to 1,500 milligrams per liter of fine-grained material (1 to 100 micrometers). Local and transient fishing boats and commercial barges up to 15 meters long use the harbor. The harbor basin area is 21,500 square meters at the project elevation of +0.6 meter (MLLW). The sill elevation is +1.8 meters (MLLW), and sidewall slopes are 1:5. Moorage is provided for 140 boats. Sedimentation has averaged almost 2 meters per year since the harbor was constructed in 1961. Nearly continuous dredging during the ice-free season is now required to keep the harbor in use.

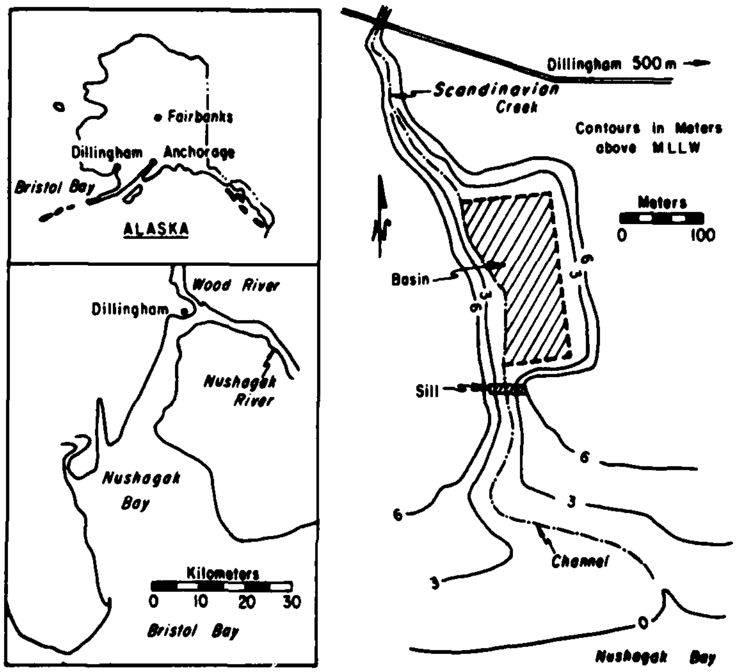

Figure 6. Location map of Dillingham Harbor, Alaska, showing the three elements which comprise a half-tide harbor: basin, sill, and navigation channel.

Flow into and out of the basin is almost entirely tide-dominated with negligible inflow from Scandinavian Creek. The channel is parabolic in shape (Fig. 7), with a top width near the basin of 45 meters. At low tide, the channel is nearly dry (Fig. 7); near the time of high tide, the channel is bank-filled near the entrance to the basin (Fig. 6). In this region an average 1.3 $\times 10^5$ cubic meters ebbtide prism passes through the channel cross section, which has a bank-filled area of about 160 square meters. Figure 4 shows the cross-sectional area to ebbtide discharge relationship for Dillingham Harbor.

4. Channel Geometry.

a. Cross-Sectional Area. The cross-sectional area/discharge relationship of the channel at Dillingham Harbor (Fig. 4) closely approximates that of natural channels in similar material in a region where the tidal hydrograph is similar in shape, if not amplitude. In the range of 300 to 1,500 milligrams

Figure 7. Navigation channel at Dillingham Harbor. View is toward Nushagak Bay from a location near the sill (Fig. 6).

per liter average suspended solids, the concentration of suspended sediment does not appear to be a critical factor. Note that in all cases discussed the amount of sand-sized material moving as bedload was negligible, except possibly near Knik Arm in Eagle River and Ship Creek. Cross-sectional area is calculated for the maximum water surface below which the ebb-tidal flow is capable of scouring fine-grained sediment. For rivers and for a harbor basin entrance, it is MHHW; for tidal-flat channels it is as shown in Figure 3.

b. Cross-Sectional Shape. Harbor and river channel cross-section shapes vary according to the hydraulic regime active within them. Channels, such as those on the tidal flat which carry less than 6×10^2 cubic meters per ebb cycle are V-shaped, and the channel area is

$$A = \frac{d^2}{z} \tag{4}$$

in which z is the sidewall slope, and d is the channel depth. Thus, the depth of the channel is

$$d = \sqrt{AZ} \tag{5}$$

When $Q > 1.4 \times 10^3$ cubic meters per ebb cycle, the channels are parabolic (concave-up sidewalls), and as the discharge increases the channel bottom becomes slightly broader and flatter. The cross-sectional area of a parabolic channel is

$$A = \frac{2}{3} wd \tag{6}$$

and the depth is

$$d = \frac{3}{2}\frac{A}{w} \quad (7)$$

in which w is the channel width.

c. Channel Bottom Elevation. Channel bottom elevations can be approximated using discharge-dependent width/depth ratios (w/d). The w/d ratio is < 10 (average = 6) for discharges of > 80 cubic meters per ebb cycle, and > 10 (average = 25) for discharges < 80 cubic meters per ebb cycle. Bottom elevation may be approximated using these values only for the region above MLLW. The depth to which a channel will be maintained by tidal flow, unless the river discharge and tidal flow is larger than about 10^6 cubic meters per ebb cycle, is at or just slightly below MLLW. Ship Creek and the Dillingham Harbor Channel bottom depths, at the MLLW shoreline of Knik Arm and Nushagak Bay, respectively, are about -1 meter (MLLW). The depth of Eagle River at its estuary mouth is unknown.

IV. DISCUSSION AND CONCLUSIONS

1. A cross-sectional area/ebb-tidal prism relationship exists between natural tidal-flat channels and stream channels, and artificial navigation channels which provide access to enclosed harbor basins. This relationship may be used to estimate the stable cross-sectional area, shape, and depth of a short navigation channel before harbor construction.

2. A controlling factor is the ebb-tidal prism. For a navigational channel, this prism is dependent on the proposed harbor basin volume between the low water and the high water mark. Thus, the size of the harbor controls the stable dimensions of the navigation channel.

3. An important assumption in the procedure outlined is that negligible bedload sediment is carried into the channel. In the example area, the average suspended-sediment concentration varies from 300 to 1,500 milligrams per liter. Scour versus deposition in the channels within this range is such that the relationship did not vary by an amount greater than the possible errors involved in estimating the cross-sectional area of the ebb-tidal prism.

4. In areas where sand-sized sediment dominates, the relationship shown in Figure 4 will vary, probably because of sand transported and deposited by longshore currents. The sediment-size difference is also probably a factor, as is the difference in channel depths relative to MLLW.

5. A critical factor in predicting the cross-sectional area of a navigation channel, when using natural channels as analogs, is a similarity of composition of the sediment comprising the boundaries of the channels, i.e., channel erodibility. The comparison between channels cannot be made unless this similarity exists.

6. The relationship shown in Figure 4 may be used for navigation channels which cross intertidal areas in Alaska where the sediments comprising those areas are predominantly highly compacted silts and muds which contain less than 2 percent clay materials.

7. Channel dimensions should be approximated for the location where the channel meets the basin. This is where the channel depth will probably be smallest with respect to MHHW if longshore transport is not a problem.

8. A stream through the harbor may increase the discharge and allow a larger navigation channel. Clear water inflow from a stream may also dilute the amount of suspended sediment in the harbor and decrease sedimentation within the basin.

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