Journal of Coastal Research	7	3	745–757	Fort Lauderdale, Florida	Summer 1991

Evolution of an Urban Estuarine Harbor: Norfolk, Virginia

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ABSTRACT

NICHOLS, M. N., and HOWARD-STROBEL, M. M., 1991. Evolution of an Urban Estuarine Harbor: Norfolk, Virginia. *Journal of Coastal Research*, 7 (3), 745–757. Fort Lauderdale (Florida). ISSN 0749-0208.

The history of dredging and disposal has been compiled from historical charts and records to determine the course of harbor evolution at Norfolk, Virginia. Dredging activities between 1872 and 1982 have produced large geometric changes with important hydrographic and sedimentological consequences. The harbor once had a shallow irregular channel floor bordered by broad shoals, marshland and tributary creeks. Today after 100 years, dredging has deepened the channel 1.8 fold, smoothed the natural profile and increased sedimentation rates more than 90 times expected rates. Disposal as land fill has buried many creeks and marshes, moved the shore channelward and reduced the estuary area 26%. As a consequence these changes have reduced the tidal prism and entrance exchange. The dredge-fill-sedimentation cycle follows three stages of harbor evolution: (1) dredging entrance bars and the estuary head, (2) channel enlargement seaward with bordering landfill and open water disposal, and (3) contained disposal seaward of the early port, or ocean disposal. This case study shows that a series of small dredge and disposal projects in a small estuarine harbor can produce large cumulative effects that are the same order as natural geologic processes. Several other harbors follow similar stages of harbor evolution.

ADDITIONAL INDEX WORDS: *Estuarine sediments, harbor, dredging and disposal, estuary hydrodynamics.*

INTRODUCTION

In most estuarine harbors of the U.S. Atlantic coast, drastic changes have taken place in the shore configuration, bathymetry, hydraulic regime and sedimentation rates. Not all changes are of recent origin. They began on a large scale with the advent of steam power, enlargement of iron ship hulls and increased ship drafts in the late-1800s. Concurrently, steam power also made it possible to accelerate channel dredging, and thus provide greater water depth for larger ships. This set off a sequence of dredging, dumping and landfill activity. At first the changes were relatively small, producing only local variations in the immediate harbor environs. Later, however, the changes were large-scale and proceeded over many decades. The regularly dredged channels today therefore, are a cumulative effect of numerous small changes, mainly in the last 100 years.

This paper addresses the historical changes produced by dredging and filling in the Elizabeth River estuary, Norfolk Harbor, Virginia. It focuses on large-scale and long-term effects of dredging and disposal, which are expressed by changes in bathymetry and shore configuration. These changes are analyzed to extract temporal trends showing the course of harbor evolution.

DATA SOURCES AND METHODS

The amount and location of material dredged comes from extensive files, charts and annual reports of the U.S. Army Engineer District, Norfolk (U.S. ARMY ENGINEER DISTRICT, NORFOLK, 1872–1982). These data consist of: (1) project records of federally controlled, U.S. Army Corps of Engineers projects, including the main shipping channel and adjacent anchorages; and (2) permit records of non-Corps projects, mainly

90122 received 3 September 1990; accepted in revision 30 January 1991.

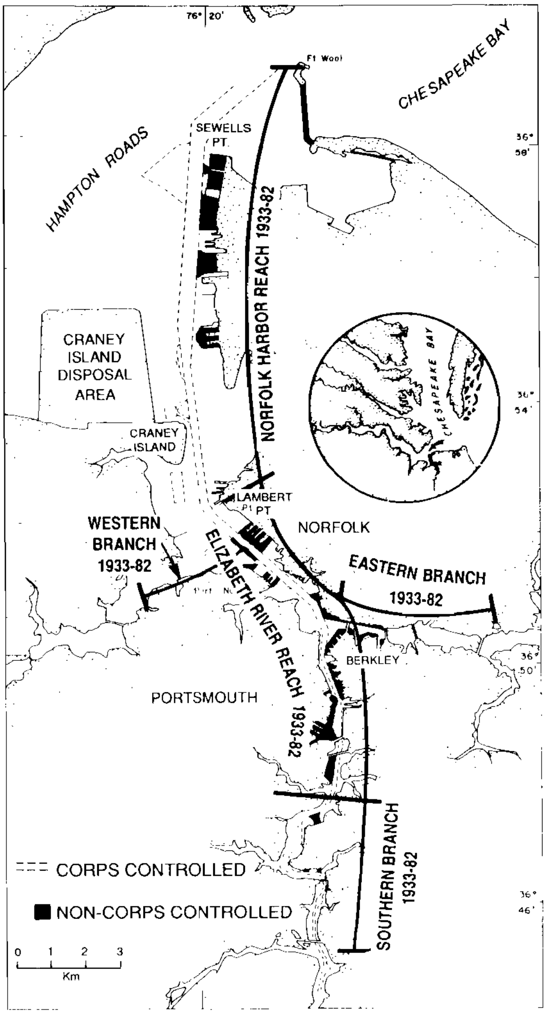

Figure 1. Location of Elizabeth River estuary, Norfolk Harbor (inset), designation of dredged channels with Corps non-Corps (private) zones of maintenance dredging responsibility.

private projects, including channels off the main shipping channel, anchorages and berths (Figure 1). The amount and location of dredged material removed from the channels is defined by comparing Corps bathymetric survey charts prepared before and after dredging.

The locations of historic disposal areas, shoreline changes and landfill history are taken from both Corps charts and records as well as charts of the U.S. Coast and Geodetic Survey (National Ocean Survey) dated 1853, 1872–73, 1911 and 1982. Changes are revealed by comparing shorelines and bathymetry, after adjustment to a common vertical datum, coordinate system and common scale by reduction or enlargement in a Map-O-Graph unit.

SITE DESCRIPTION

The Elizabeth River system which includes Norfolk Harbor, is a drowned tributary estuary of Chesapeake Bay incised in coastal plain deposits (Figure 1). Prior to the advent of large-scale dredging and disposal the shoreline was indented with small creeks bordered by marshes, which formed a dendritic pattern of waterways (Figure 2A). The longitudinal channel profile was interrupted by deep holes and shoals of muddy sediment (Figure 3).

Present-day channel sediments are predominantly soft mud with water content ranging 35 to 70% and total organic carbon 0.8 to 3.5%. A sediment budget (Nichols and Howard-Strobel, 1987) revealed that the estuary receives 55,000 tons of fine sediment on the average each year, of which 93% is introduced from seaward zones in Hampton Roads, 3% from upland runoff and 4% from combined industrial and waste water discharge in addition to plankton production.

Although the estuary was initially shaped by geologic processes, man's concentrated urban activities, which accelerated about 1880, have greatly modified the bathymetry and reshaped the shoreline. Shores and beaches have been bulkheaded to prevent erosion and provide transportation facilities like piers, docks, boat slips and shipping terminals. Creeks and marshlands have been buried for airfields, industry and residential areas. Channels have been dredged for a length of 36 km to accomodate shipping. Today, after 100 years of accelerated development little is left of the natural system along the main estuary.

HISTORICAL BACKGROUND

The trends of dredging and filling have proceeded with growth of the cities of Norfolk and Portsmouth, their environs, and the changing patterns of maritime trade, industry and military activities. Port development and related dredging activities evolved in three stages:

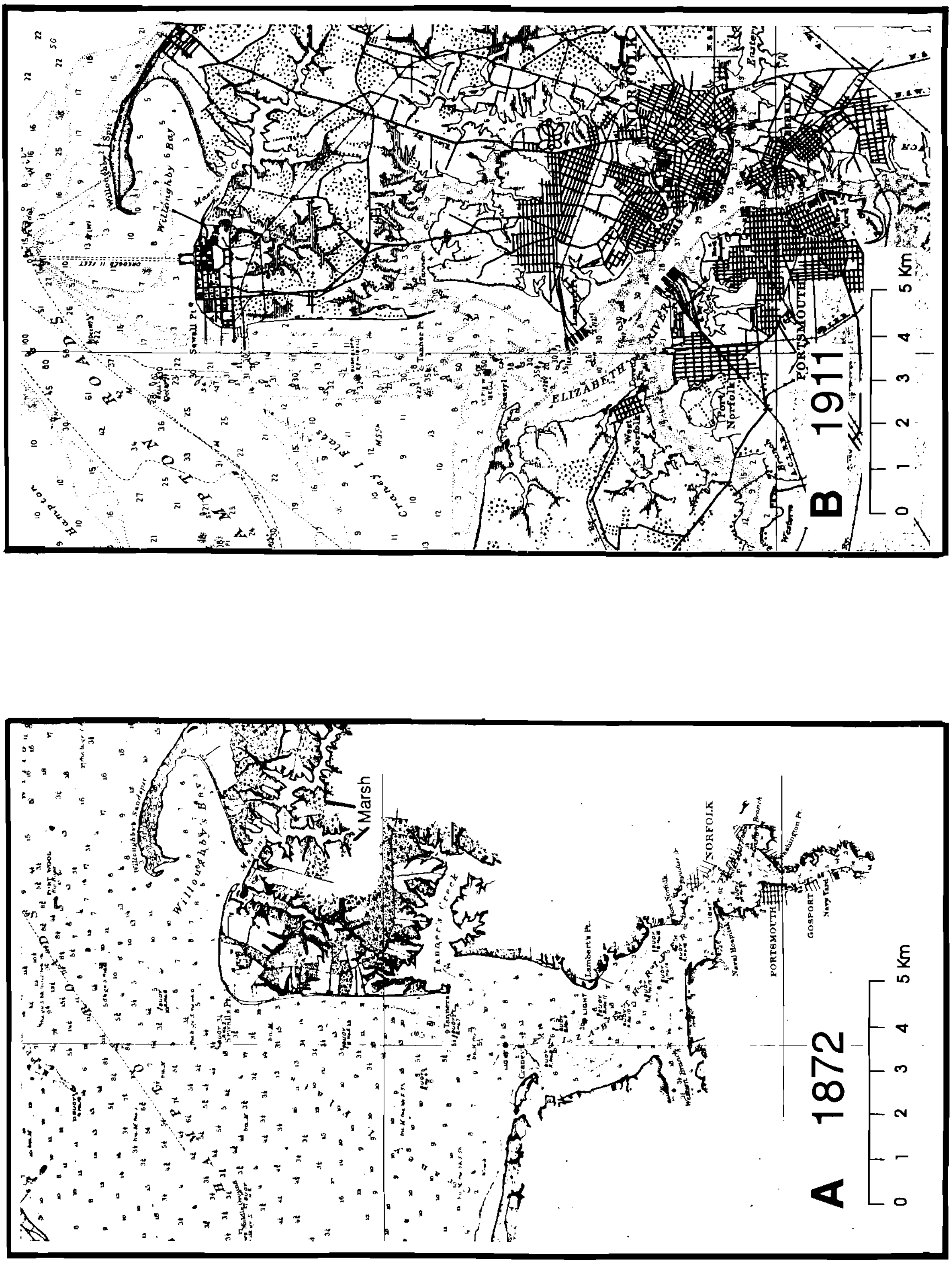

Figure 2. Historic charts of the U.S. Coast and Geodetic Survey showing shore morphology and bathymetry of the Elizabeth River; (A) 1872, prior to extensive dredging activity, (B) 1911, after early development and construction of coal piers.

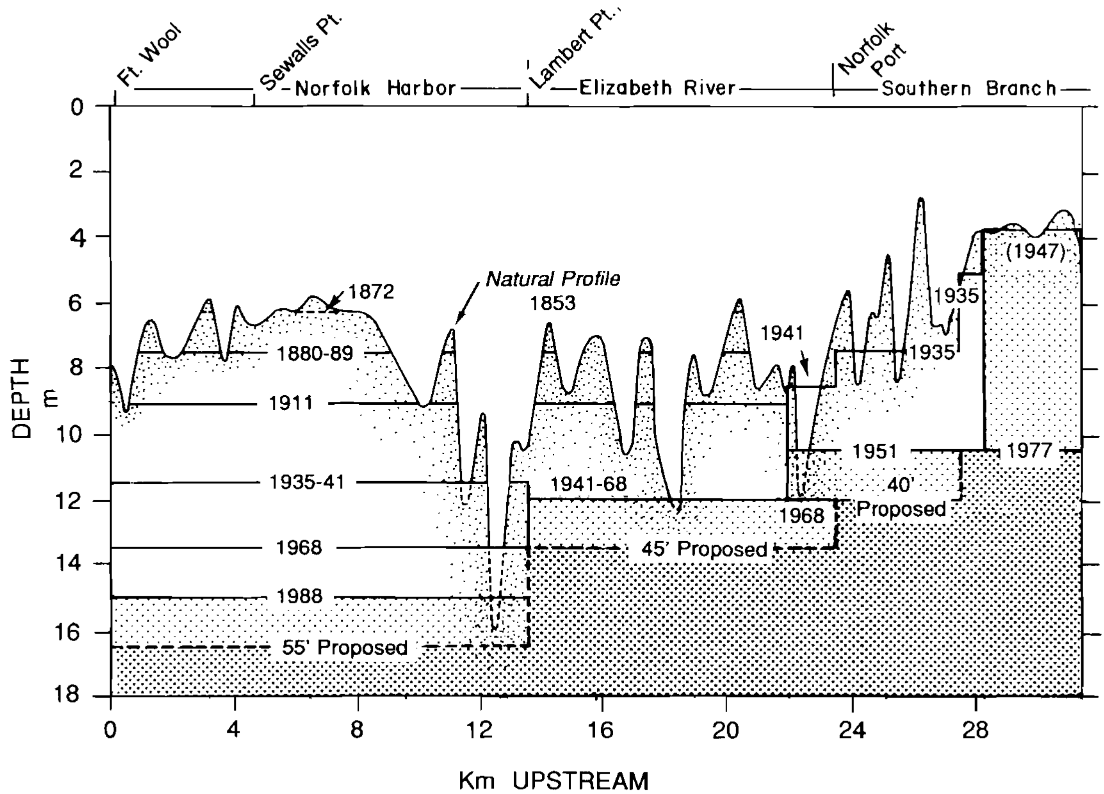

Figure 3. Longitudinal profile of the Elizabeth River channel showing its natural profile in 1853 in relation to profiles after successive dredging between 1872 and 1988. Proposed channel depths, 40 ft (12.2 m), 45 ft (13.7 m) and 55 ft (16.8m), are those tested in the hydraulic model for current and salinity changes (Richards and Morton, 1983).

1) Colonial agriculture and early port development, 1625–1880; limited dredging and disposal;
(2) Large-scale development, 1880–1955; intensive channel enlargement and widespread disposal;
(3) Modern development, 1955–1982; continued dredging and centralized disposal.

Settlement of estuary shores began in the early 1600s as part of the plantation tobacco economy in the region. In 1682 a few wharves handled local shipping needs at Norfolk but by 1725 trade with Europe and the West Indies, besides the interchange of goods in the North Carolina-Chesapeake Bay region, fostered port growth together with shipbuilding and repair facilities. Natural channel depths were adequate to accommodate most sailing ships of the time. By 1802, however, 12 wharves extended about 500 m into the estuary (Wertenbaker, 1962). The shore between wharves was bulkheaded and backfilled to construct docks, thus prograding the shore channelward. Construction of a naval shipyard at Portsmouth about 1812, extended waterfront development along the Southern Branch of the Elizabeth River. As Norfolk and Portsmouth grew in the mid-1800s inner shores of tributary creeks and bordering marshlands were filled by refuse, ship ballast, construction debris and oyster shells. Small streams were converted into sewers and small creeks into canals (Wertenbaker, 1962).

Large-scale development began in 1880 when railroads reached the harbor from inland coal

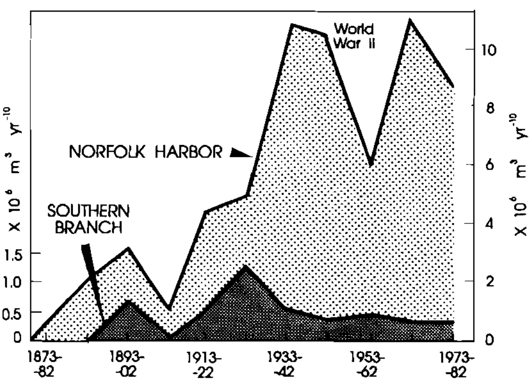

Figure 4. Temporal trends of maintenance dredging rates averaged by decade for Norfolk Harbor reach (right scale) and Southern Branch (left scale) with time over 100 years, 1873-1982.

fields. About the same time, steamboats were improved to transport relatively large amounts of coal. By 1889 six coal transhipment facilities were completed. Numerous wharves were constructed, pier slips dug and access channels dredged from the main channel to the slips (Figure 2B). These facilities brought more ships and larger, deeper draft ships than in earlier decades. As the ship size and draft increased, the natural channel depth was no longer adequate for shipping. This situation set off a chain of long-term dredging and disposal activities that is still in progress today. Modern development is described in subsequent sections.

DREDGING TRENDS

Dredging of the main shipping channel began in 1872 to lower entrance bars to the 6.4 m depth off Sewells Point and off Town Point, Norfolk (Figure 3). To support larger ships and harbor expansion for coal exports in the 1880s, the channel was deepened to 7.6 m and lengthened both seaward and landward. Subsequent deepening removed shoals, filled holes and lengthened the channel which gradually smoothed the natural profile and produced a "stair step" configuration (Figure 3). Lateral channel extension into tributaries transformed the axial channel into a branching network. Although each increment of dredging was relatively small, the cumulative change over 100 years has been great. For example, channel depth increased 1.8 to 2.4 fold, length 2.6 fold and volume 3.7 fold (Table 1).

Table 1. *Summary of physical changes in the Elizabeth River estuary, Virginia between 1872 and 1982.*

Feature	1872 Condition[1]	1982 Condition[2]	Percent Change	Proposed or Expected Future Condition[3]
Mean channel Depth[4]				
m	5.8	10.7-13.7	+ 84 to 136	12.2-16.8
Channel Length[4]				
km	16	43	+ 170	43
Channel Width[4]				
m	61-122	76-457	+ 25 to 275	76-457
Channel Volume [4]				
x 10^6 m^3	26	96	+ 269	109
Estuary Surface Area				
x 10^6 m^2	58	46	− 26	—
Maintenance Material Removed [5]				
x 10^6 m^3 yr^{-1}	0	2.8	—	3.3
Sedimentation Rate,				
mm yr [1]	1.7-5.0[6]	150-1500	+ 87 + 880	190-2400

[1]Original or near-natural condition.
[2]Condition after 100 years of dredging.
[3]U.S. Army Engineer District, Norfolk (1979).
[4]Main axial shipping channel.
[5]Average, 1962-1982.
[6]Typical lower Chesapeake tributary (Brush *et al.*, 1980).

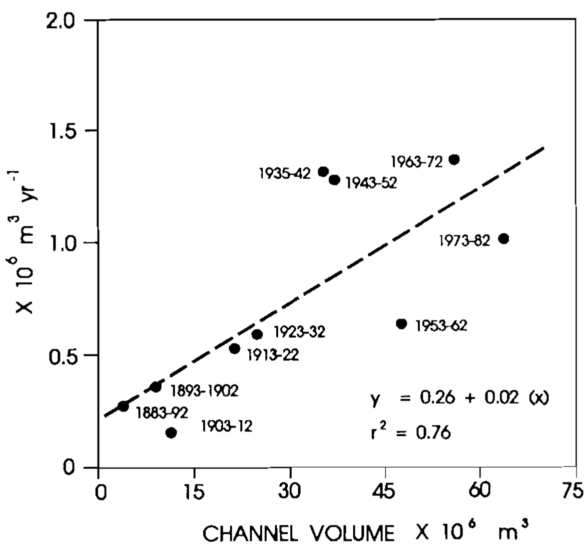

Figure 5. Annual maintenance dredge-rates averaged by decade as a function of channel size (volume) for 100 years of record, 1873 and 1982. Linear regression line, dashed, excludes anomalous data of World War II emergency dredging, 1935-1952.

Maintenance Dredging

In the early dredged channel, 1872-1889, when depths were 6.4 to 7.6 m, repetitive maintenance dredging was infrequent, averaging less than 2.4 x 10^6 m^3 yr^{-10} (Figure 4). However, when the channel was deepened to 9.1 m in 1911-1922, the rate of maintenance dredging reached 5.0 x 10^6 m^3 yr^{-10}, more than double the amount dredged in the early channel. In the 1930s and 1940s, as the size of the channel increased, maintenance dredging rates also increased (Figure 5). They reached a peak in 1940 when 5.0 x 10^6 m^3 were removed in one year from Norfolk Harbor Reach (Figure 1) as a World War II emergency effort. Interestingly, maintenance dredging rates in the seaward zone, Norfolk Harbor Reach, fluctuated 10 to 12 x 10^6 m^3 yr^{-10} in the 1960's and 1970's whereas rates in the landward zone, Southern Branch, continued at a relatively low level, about 0.5 x 1.0 m^3 yr^{-10} (Figure 4). The overall linear trend (Figure 5) implies that as channels are enlarged, the amount of maintenance material increases. This is because greater sedimentation is induced by the increased area of sediment accumulation and by deepening below natural depths. Therefore, with an unlimited sediment supply, the more channels are enlarged and dredged deeper, the more sediment must be removed to maintain a specified depth. Thus, dredging in such an estuarine harbor system is self-perpetuating.

Distribution of Dredged Material

Sediment deposited in the main shipping channel is not distributed uniformly but mainly accumulates in shoals along lower margins of the channel sides (Figure 6A) and in pier slips and berths. Accumulation in these zones is encouraged by lower energy dissipation in margins than in the central channel, which is influenced by ship prop-wash and tidal currents. The average maintenance dredging rate, 1.8 x 10^6 m^3 annually, is greatest in the deep seaward sector, the Norfolk Harbor Reach (Figure 6B), where sedimentation rates are fast (Figure 6C). Landward the rate drops abruptly to less than 0.4 x 10^6 m^3 yr^{-1} in the Elizabeth River Reach, and then declines to less than 0.1 x 10^6 m^3 yr^{-1} in the Southern Branch. Before about 1907, however, the distribution differed since dredging rates were greatest in the inner Elizabeth River Reach near the early port. After 1907 the location of maximum dredging rates shifted seaward to the Norfolk Harbor Reach and subsequently it remained in this reach for 70 years. The Norfolk Harbor Reach is the deepest reach and it is closest to the major supply of sediment entering the estuary from Hampton Roads via landward flow through the lower salt layer. The source of sediment supply is evidenced by a sediment budget (NICHOLS and HOWARD-STROBEL, 1987). The transport route is documented by current measurements in hydraulic model tests based on present-day geometry (RICHARDS and MORTON, 1983).

DISPOSAL TRENDS

When dredged quantities were relatively small in the 1870s and 1880s, material was dumped near the dredge sites. Initially this was in deep holes and adjacent open water shoals inside the harbor. Material dumped on nearby shoals however, was subject to transport back into the dredged channel. Consequently, dredged material was then dumped outside the estuary in the open waters of lower Chesapeake

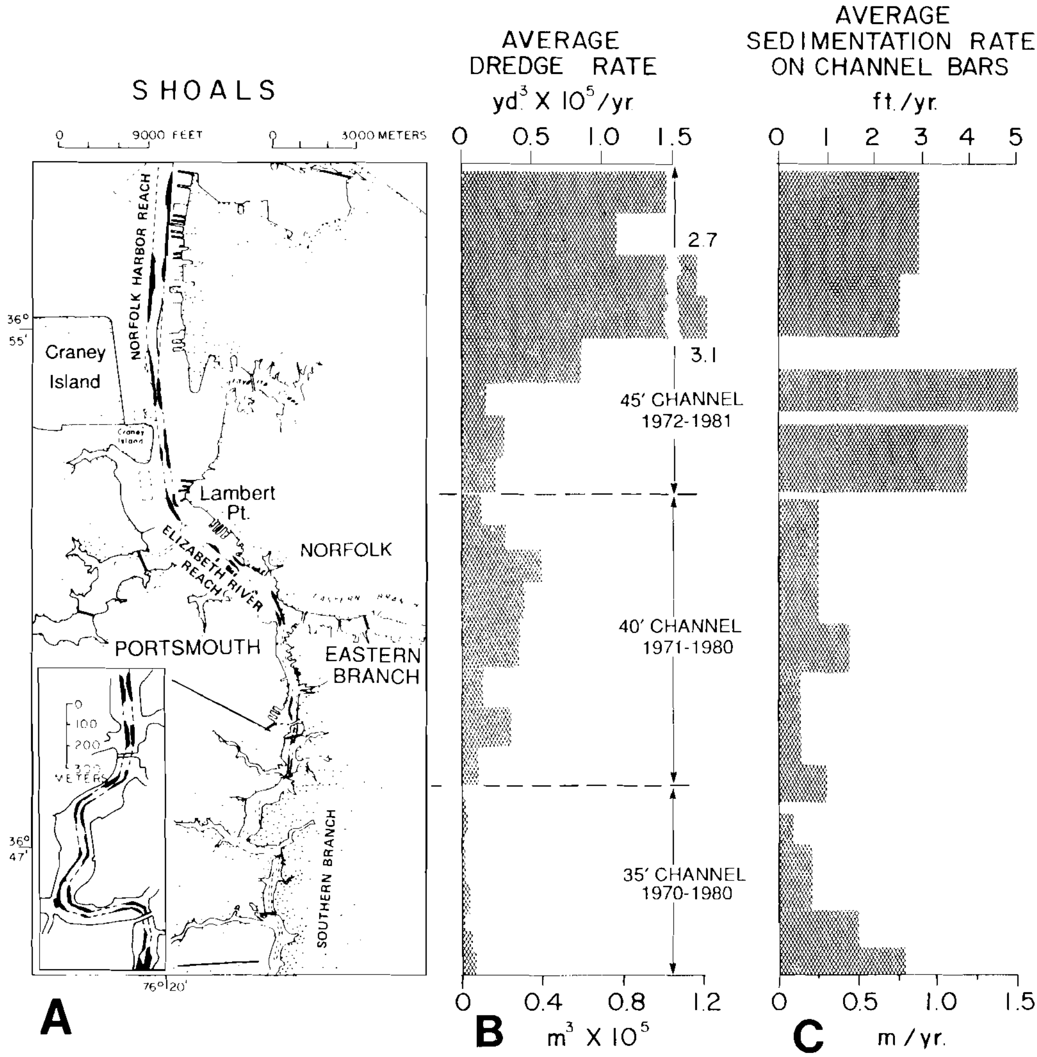

Figure 6. Distribution of maintenance dredged material in the Elizabeth River. (A) approximate location of shoals, (B) average annual dredge-rate, and (C) average sedimentation rate on shoals in the channel. The sedimentation rates are derived from the dredging rates over a 5- to 19-year period between 1962-1981. Data based on bathymetric changes of the Corps of Engineers (Berger *et al.*, 1985).

Bay (Figure 7). Additionally, some material from the main channel and from pier slips, was placed behind bulkheads, and in small creeks and marshlands to fill low land near downtown Norfolk and Portsmouth. By 1911 after several decades of channel deepening and maintenance dredging, large shore areas and lowlands were filled to construct coal transhipment facilities and the Jamestown Exposition Park at Sewells Point (Figure 8).

Accelerated dredging during World Wars I and II resulted in large-scale land reclamation along seaward areas of the estuary. Between Sewells Point and Tanner Point, construction of piers, docks and bulkheads prograded the shoreline channelward 100 to 850 m (Figures 9A, 9B). South of Willoughby Bay two large creeks were buried to construct a naval airfield. Between 1918 and 1951, open water disposal, totaling 21 x 10^6 m^3, continued in lower Ches-

Table 2. *Comparison of the total amount of dredged and dumped material from the Elizabeth River between 1880 and 1982. Dredged material categorized by (1) main shipping channel and anchorages (Corps-controlled) and (2) channels off the main channel (by permit, non-Corps-controlled).*

	Dredged Material Volume, x 10^6 m^3, %			Disposal Material Volume, x 10^6 m^3, %	
(1) Corps-Controlled (Main Channel)					
Maintenance	74	44	Open Water	31	24
New Work	40	24	Land Fill[1] (< 1956)	18	14
(2) Non-Corps-Controlled (Off Main channel)			Disposal Basin[2] (1956-1982)	67	53
Maintenance	34	20	Other[3]	11	9
New Work	20	12			
Total	168			127	

Imbalance: Dredged Material Minus Disposal Material: 41 x 10^6 m^3 or 24%

[1]Land fill in creeks, marshes and along shores.
[2]Craney Island Disposal Area, material from Elizabeth River only, Corps and non-Corps (U.S. Army Engineer District, Norfolk, 1979).
[3]Undifferentiated land fill, non-Corps by permit.

apeake bay. To avoid shoaling of the dump sites and to minimize adverse impacts on fishing, beach recreation and naval amphibious training, the dump sites were relocated from time to time (Figure 7).

Recognizing the problems of open water disposal and need for long-term disposal capacity, in 1954-1957 the Corps of Engineers constructed a large disposal basin located north of Craney Island (Figure 8). This structure encloses 10.4 km^2 and consists of stone-faced dikes elevated 5.2 m above mean low water, extending the estuary mouth 3.2 km seaward (Figure 8). Between 1956 and 1981 the basin received 67 x 10^6 m^3 of dredged material, which constituted most of the material dredged from the Elizabeth River system. Additionally, it received 39 x 10^6 m^3 from outside the harbor. Ultimate filling to an elevation of 9.1 m by about 2010 will add another increment of landfill to the harbor. The basin alleviates dispersion of contaminated dredged material associated with open-water disposal. It centralizes disposal in the harbor thus reducing transport distance and resultant costs of disposal.

DREDGING AND DISPOSAL BUDGET

Although dredging and disposal produce changes in relatively small increments, the changes are permanent and cumulative. It is useful therefore, to determine the total amount of material dredged and compare the amounts dredged and dumped. Table 2 summarizes the cumulative volume of dredged and disposal material over 100 years. Of note, maintenance material makes up 64% of the total dredged material, 108 x 10^6 m^3; the rest (36%) is "new" material resulting from channel deepening. The bulk of the material, 68%, comes from the main channel (Corps-controlled). Of the total dredged material, an estimated 168 x 10^6 m^3, 127 x 10^6 m^3 is accounted for in the dump sites. The apparent deficit, an estimated 41 x 10^6 m^3, or about 24% of the total amount dredged, may be caused by incomplete disposal records, including lack of post-disposal bathymetric surveys on open water sites, and the lack of measurements of the volume of disposal material placed in land fill sites. Additionally, there are apparent post-disposal "losses" such as dumped material removed by bottom currents, or a decrease in volume in land fill by settlement and sediment consolidation.

Despite these shortcomings, the budget reveals the enormous amount of sediment moved by dredging and disposal activity in a relatively small system. For example, the cumulative amount of dredged material, 168 x 10^6 m^3, constitutes about 80% of the total present-day estuary volume. For comparison, the amount is equal to a 100-year average annual

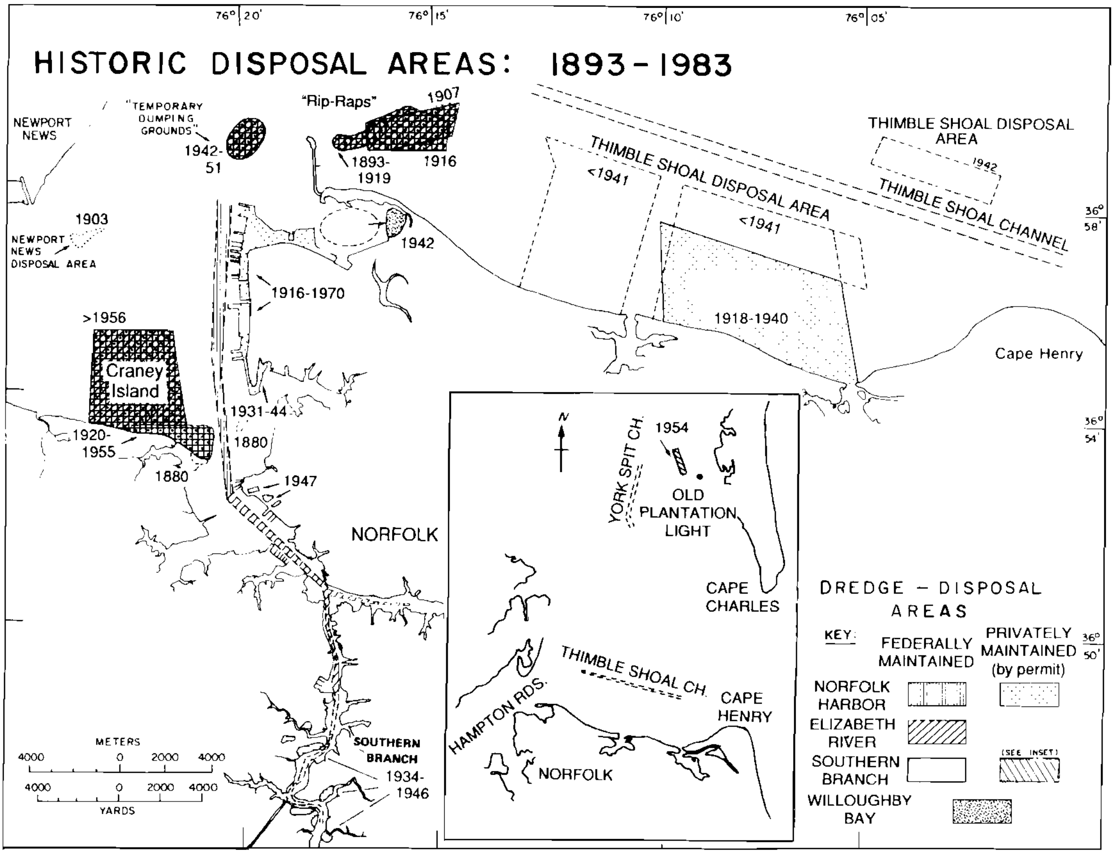

Figure 7. Historic disposal areas in open water of lower Chesapeake Bay and the Craney Island disposal basins. Patterns of hachures and dots relate the disposal areas to the dredged area from which the material reportedly was derived. Cross hatch pattern on disposal sites indicates material derived from several channel segments in the Elizabeth. Blank areas in Thimble Shoal disposal areas received material mainly from Thimble Shoal Channel.

sediment flux of 0.64×10^6 tons yr^{-1} or about 50% of the annual average sediment discharge of the James River at Richmond. This rate is about 280 times the current yearly sediment input to the Elizabeth River estuary from proximate upland sources indicated by a sediment budget (NICHOLS and HOWARD-STROBEL, 1987). Dredging activities therefore, are the same order as geologic processes and thus can be an important term in estuary sediment budgets.

DISCUSSION

The history of dredging and disposal activities at Norfolk Harbor is instructive because it reveals how a series of small changes in a relatively small system can produce relatively large cumulative effects. Since most dredging studies are conducted project-by-project, they reveal relatively small changes or short-term effects (MCDOWELL and O'CONNOR, 1977) and the long-term cumulative effects of combined dredging and disposal often escape attention. This study shows that long-term continued channel enlargement over 100 years, can lead to drastic changes in sedimentation rates, a 90- to 900-fold increase relative to the expected natural rates in similar tributaries (BRUSH *et al.*, 1980). Additionally, it demonstrates that the cumulative effect of land-filling has narrowed the estuary and thus reduced the tidal prism an estimated 24% compared to the orig-

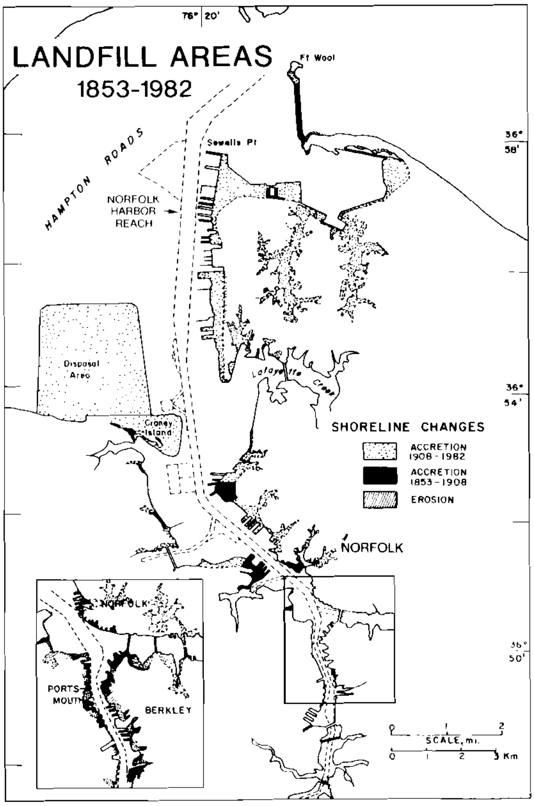

Figure 8. Historic land fill areas and corresponding shoreline changes between 1853 and 1908 (opaque) and between 1908 and 1982 (dotted). Main shipping channel dashed.

inal prism. Such a change likely weakened maximum tidal currents through the mouth and reduced entrance exchange.

The effects of deepening on the hydraulic regime of the estuary are demonstrated by hydraulic model tests of a proposed 1.5 to 3.0 m deepening (RICHARDS and MORTON, 1983). Although the depth changes are relatively small (Figure 3), they reveal that maximum tidal currents near the bottom would diminish 3.2 to 12.5 cm s^{-1}. Additionally, near-bottom salinity would increase 0.5 to 4.0 0/00 and haline stratification would intensify. Thus, even small geometric changes can produce substantial hydraulic effects.

The history of dredging and disposal at Norfolk reveals a general pattern of harbor evolution (Figure 10). Initial activity, stage 1, begins by dredging entrance shoals and deepening at the early port site near the estuary head. Disposal is mainly within the harbor, either in open water or as land fill on bordering lowlands and shores (Figure 10). The second stage consists of channel lengthening and enlargement, particularly in the seaward sector. Dredged material is dumped outside the harbor in open water, and on bordering lowlands and shores in seaward reaches. In the third stage, open water disposal and land fill is replaced by contained disposal close to the site of major dredging, *i.e.*, seaward of the early port site (Figure 10). When the containment basin is full, contained disposal is expected to expand seaward. Alternately, material will be dumped in the ocean. The overall seaward trend of land fill with time was likely caused by urban growth of the port which limits disposal sites and by a parallel expansion of waterfront facilities which utilized the land fill. Additionally, disposal has been close to the main dredging site in seaward reaches, a feature that reduces transport and resultant costs.

Although the harbor was initially shaped by geologic processes, its recent revolution has been determined by man's activity on a scale of decades. Channel deepening has reversed the natural geologic evolution of estuarine filling by sedimentation, while land disposal has reversed the natural shore retreat and transgression. Consequently, shores are prograding channelward thus narrowing the harbor and producing homogenic sediment facies (produced by man), a term introduced by HARD and PALMER (1976) (Figure 10). It is anticipated that the cycle of dredge-fill-sedimentation at Norfolk will continue but at a slower pace. Dredging is the means to maintain commerce and accommodate the ever-increasing size of ships needed to keep the port competitive. With continued disposal in containment basins, which keeps sediment out of the dredged channel, it is possible maintenance dredging rates will level off. This is the case for the Delaware, Savannah and Hudson estuaries (NICHOLS, 1979).

The pattern of harbor evolution at Norfolk (Figure 10) is partly reflected by similar trends elsewhere. For example, Baltimore, Maryland, also an estuarine harbor, shows initial activity at the estuary head (stage 1) and later, channel deepening and enlargement seaward with disposal on bordering shores or lowlands, or in

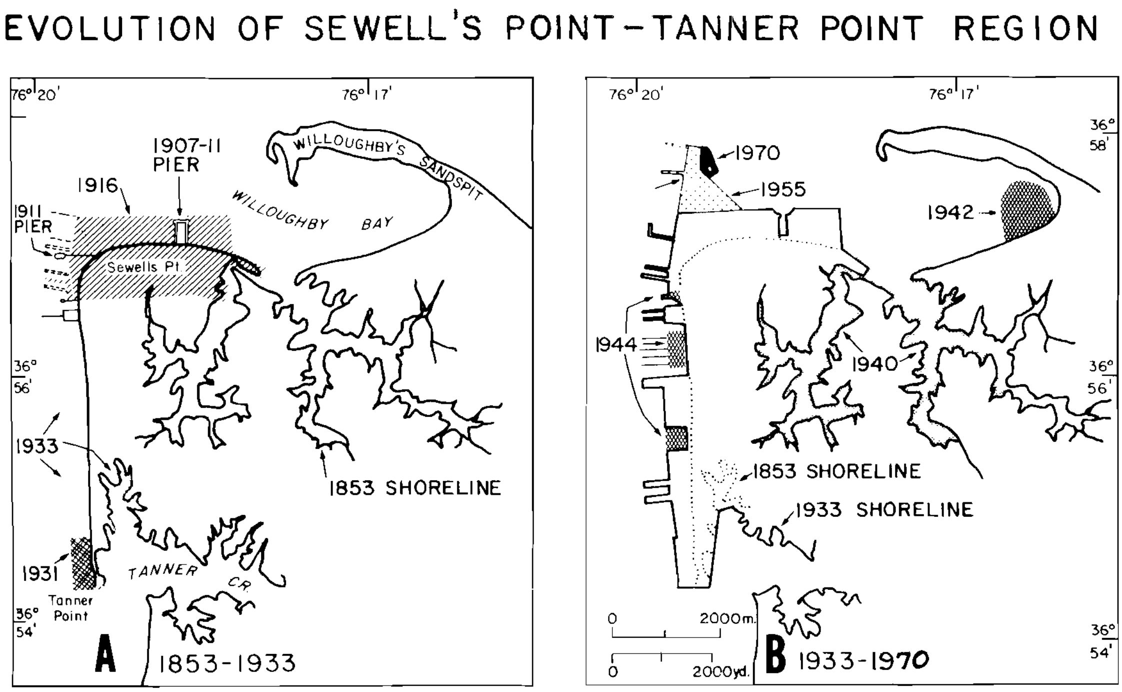

Figure 9. Evolution of land fill in the Sewell's Point—Tanner Point area; (A) 1853-1933; (B) 1933-1970.

open water of Chesapeake Bay (stage 2) (SCHUBEL and WILLIAMS, 1976). In contrast to Norfolk however, much material is dumped in open water along the channel. Recently, contained disposal has started (stage 3), but unlike Norfolk it is outside the harbor environs in Chesapeake Bay. A 100-year dredging history of Tampa Bay, Florida (LEWIS, 1976; FEHRING, 1985) also reflects the key stages of evolution with stage 2 including open water disposal along the channel and subsequently, contained disposal in central reaches (stage 3). Part of the dredged material, *i.e.* clean sand, is disposed at ocean dump sites. Dredging of Newark Bay, New Jersey, which began in 1880, led to a large increase of maintenance dredging in 1930 with resultant disposal on bordering lowlands and shores (stage 2) and in central contained disposal basins (SUSZKOWSKI, 1978). When most land fill sites and basins were filled to capacity in 1969, 75% of the dredged material was disposed by open water dumping in the Atlantic Ocean. Plans for containment area islands seaward of the ports of New York and New Jersey have been proposed (COCH *et al.*, 1983). This is a likely precursor to a future stage (4) at Norfolk. As estuarine harbors eventually lose their disposal capacity, seaward disposal sites are the chief alternative.

CONCLUSIONS

The specific conclusions and generalizations of this study are:

(1) A series of small dredge and disposal projects in a small estuarine system can produce large long-term cumulative effects.
(2) The main effect of channel deepening and enlargement is increased sedimentation rates, which in turn, necessitate greater maintenance dredging rates. By narrowing an estuary, lateral land fill reduces the estuary surface area and intertidal volume thus reducing the tidal prism and entrance exchange.
(3) Within a period of decades dredging

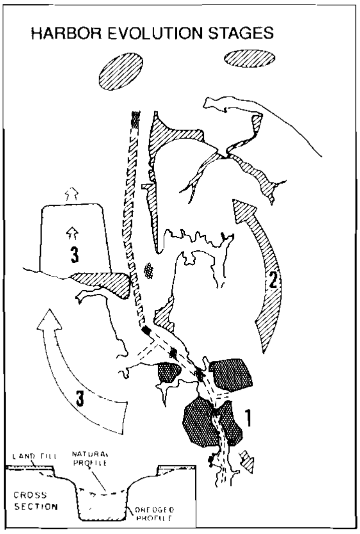

Figure 10. Schematic diagram showing stages in the evolution of dredging and disposal in Norfolk Harbor. For explanation of stages see text. Inset lower left in schematic cross section comparing typical natural and dredged profiles.

activity can reverse the natural geologic evolution of estuarine filling by sedimentation while associated land filling can reverse the natural marine transgression.

(4) An estuarine harbor like Norfolk may be expected to evolve through three stages: (1) dredging entrance bars and the estuary head, (2) channel lengthening and seaward enlargement with land fill on bordering shores or in open water outside the harbor, and (3) contained disposal within the harbor seaward of the initial port site, or alternately, ocean disposal.

ACKNOWLEDGEMENTS

This study was supported by grant R806002-02 of the U.S. Environmental Protection Agency, Chesapeake Bay Program. Thanks are due to Mr. Gene Whitehurst of the U.S. Army Engineer District, Norfolk, for assistance with Corps' historical dredging records. Kay Stubblefield of VIMS drafted the figures. This is Virginia Intitute of Marine Science contribution number 1639.

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□ RÉSUMÉ □

Pour déterminer l'évolution du port de Norfolk (Virginie), on a compilé des cartes marines et des enregistrements permettant de reconstituer l'histoire des dragages et des dépôts. Les dragages effectués entre 1872 et 1982 ont entraîné de grands changements de la géométrie dont les conséquences sont importantes pour l'hydrographie et la sédimentologie. Le port avait alors un chenal au fond irrégulier bordé de hauts fonds, un marais et des anses. A présent, soit 100 ans aprés, les dragages ont élargi de 1,8 fois le chenal, aplani le profil naturel et multiplié par plus de 90 la sédimentation. Les dépôts, ont recouvert de nombreux anses et marais, en colmatant le rivage qui s'est déplacé vers le chenal; la surface de l'estuaire a diminué de 24%. Ces modifications ont eu pour conséquence la réduction du prisme de marée et des échanges à l'entrée. Le cycle dragage — comblement — sédimentation correspond aux phases de l'évolution du port: (1) dragage des bancs de l'entrée et de la tête de l'estuaire; (2) élargissement du chenal vers la mer, colmatage des rives et dépôt au large; (3) retenue des dépôts au large de l'ancien port ou dépôt océanique. Ce cas montre qu'une série de petits dragages et des dépôt projetés peuvent avoir, pour un petit port estuarien, des effets cumulés semblables à des processus naturels géologiques. Plusieurs autres ports suivent la même évolution.—*Catherine Bousquet-Bressolier, Laboratoire de Géomorphologie EPHE, Montrouge, France.*

□ RESUMEN □

Se ha realizado una recopilación de los dragados y vertidos históricos, a partir de cantos antiguos y documentación complementaria con el fin de determinar la evolución de la bahía de Norfolk, Virginia. Los dragados entre 1872 y 1982 han producido grandes cambios geométricos de importantes consecuencias hidráulicas y sedimentológicas. La bahía comenzó disponiendo de un canal irregular, poco profundo, flanqueado por bancos de arena, marismas y canales tributarios. Hoy, después de 100 años, el dragado ha incrementado 1.8 veces el calado del canal, suavizando el perfil natural del mismo e incrementando las tasas de sedimentación por encima de 90 veces los esperados. Vertidos con el objeto de relleno y ocupación de tierras han desecado numerosos canales y marismas, trasladando la línea de tierra hacia el canal y reduciendo el área del estuario un 26%. Como consecuencia, se ha reducido el prisma de marea y la renovación de agua. El ciclo dragado-carga-sedimentación cuenta con tres etapas en la evolución de la bahía: (1) dragado de las barras en la entrada al estuario y de la cabeza del mismo, (2) crecimiento del canal hacia el mar, rellenando la zona laterial próxima al canal y vertiendo el producto del dragado en mar abierta, (3) vertido contenido en zonas externas al puerto inicial o vertido en mar abierta. En este caso, el estudio muestra que series de pequeños dragados y vertido en pequeños puertos en estuarios pueden producir grandes efectos acumulativos del mismo orden que los procesos geológicos naturales. Otros puertos han seguido similar proceso evolutivo.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ ZUSAMMENFASSUNG □

Historische Karten und Aufzeichnungen zeigen die Bagger- und Verklappmaßnahmen, die die Hafenentwicklung von Norfolk, Virginia (USA) bestimmt haben. Baggerunungen zwischen 1872 und 1982 verursachten große morphologische Veränderungen mit bedeutenden hydrologischen und sedimentologishchen Konsequenzen. Ursprünglich hatte der Hafen eine flache, unregelmäßige Gewässersohle mit Untiefen sowie Marschflächen mit kleinen Wasserläufen. In den letzten 100 Jahren wurde die Wassertiefe um das 1,8 fache vergrößert und die natürlichen Profile geglättet. Die Sedimentationsraten sind heute 90 mal größer als vorhergesagt. Durch Aufspülungen reduzierte sich die Wasserfläche des Ästuars um 26%. Deshalb verringerte sich auch das Tidevolumen und der Wasseraustausch mit benachbarten Meeresarmen. Aus dem Bagger- und Resedimentationskreislauf ergeben sich 3 Zustände der Hafenentwicklung: (1) Die Notwendigkeit Untiefen im Mündungsbereich des Ästuars zu beseitigen. (2) Die Vergrößerung der Hafenzufahrt bei gleichzeitiger seitlicher Baggergutablagerung oder Seeverklappung. (3) Die Verklappung des Baggergutes in umschlossenen Flächen seewärts des früheren Hafens bzw. die Seeverklappung. Diese Fallstudie zeigt, daß eine Abfolge kleinerer Bagger- und Verklappmaßnahmen in einem tidebeeinflußten Hafen eine große kumulierende Wirkung ähnlich wie geologische Prozesse erzeugen kann. In mehreren anderen Häfen ergibt sich ein ähnliches Bild der Hafenentwicklung.—*Reinhard Dieckmann, WSA Bremerhaven, FRG.*