The Center for Marine Coastal Studies – North Carolina State University

SEDIMENT MOVEMENT IN TUBBS INLET, NORTH CAROLINA

By

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North Carolina State University
Raleigh, North Carolina

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ABSTRACT

A pattern of sediment movement and sediment transport rate into the estuary through Tubbs Inlet was established by mapping bedform and sedimentary structure orientation, analysis of tidal-current direction and velocity throughout a complete tidal cycle, and analysis of fluorescent tracer sand movement.

Bedform and sedimentary structure orientation and current flow data were used to formulate a general hypothesis of sediment movement. Confirmation and refinement of the movement pattern were made by using two thousand pounds of fluorescent tracer sand, equally divided between five colors. The tracers were introduced into the two estuarine channel systems, the inlet gorge (main channel), and the intertidal zone of the adjacent beaches.

The generalized sediment transport pattern indicated movement into the estuary across the intertidal sand flats of the inlet by flood-tidal currents. During flood tide waves are refracted around the ebb-tidal delta and focused toward the inlet. Breaking waves place sediment into suspension which is then transported by tidal currents. Sediment is moved landward through the main channel; however, net movement through the gorge is seaward. Current velocities in the main channel are maximum during ebb flow (90 to 100 cm/sec). Flood currents in the gorge range from 50 cm/sec to 75 cm/sec. Sediment is moved seaward, primarily through the main channel, and reintroduced into the littoral transport system bypassing the inlet.

Concentrated zones of tracer sand were detected as the "sand mass" moved along the recurved spit on the eastern side of the inlet. The rate of net transport of these zones was approximately 0.6 cm/sec (72 ft/hr). The movement rate of the concentrated zones was much less than the rates calculated for individual tracer grains. By using elapsed time between introduction and first detection and estimated path of travel of tracer grains, individual grain movement velocities were found to range from 10 cm/sec (20 ft/min) (flood direction) to 13 cm/sec (26 ft/min) (ebb direction).

Fluorescent tracer sand when used in conjunction with analysis of bedform and flow data is a valid method of monitoring sediment movement in the high-energy inlet environment.

PREFACE

Research described in this report was conducted as part of the Coastal Research Program at North Carolina State University.

The report is primarily written by the Senior Author in partial fulfillment of the requirement for the M.S. Degree.

The review of this report by Dr. C. J. Leith, Dr. C. W. Welby and Dr. J. L. Machemehl was very much appreciated.

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INTRODUCTION

Description of Study Area

General

Tubbs Inlet is located in the Southern Coastal Zone of the North Carolina Coastal Plain. The general location is shown in Figure 1. The study site (approximately 3.5 miles from the North Carolina-South Carolina line) forms a tidal pass in the barrier island system and lies between Sunset Beach to the west and Ocean Isle Beach to the east. The orientation of the coastline in the vicinity of the inlet is approximately east-west.

Sunset Beach on the west side of the inlet is approximately 1.6 miles (2.56 km) in length and 1400 feet (425 meters) in width with broken dunes of medium height. Substantial development of the beach began in 1958. The town was incorporated in 1963 (US Army, 1966).

Ocean Isle Beach on the east side of the inlet is approximately 6.4 miles (10.2 km) long and 1000 feet (300 meters) in width with a low and broken dune line. The town of Ocean Isle Beach was incorporated in 1959 (US Army, 1966).

The barrier island west of the inlet is approximately 600 feet (182 meters) wide and composed of dredge spoil. The major topographic feature is a 10 to 12 foot (3-4 meters) ridge which formed the southern edge (dune scarp) of the island. The northern edge of the island slopes gradually to the water's edge. There was essentially an absence of vegative cover on the dredge spoil thus allowing sand movement by the wind.

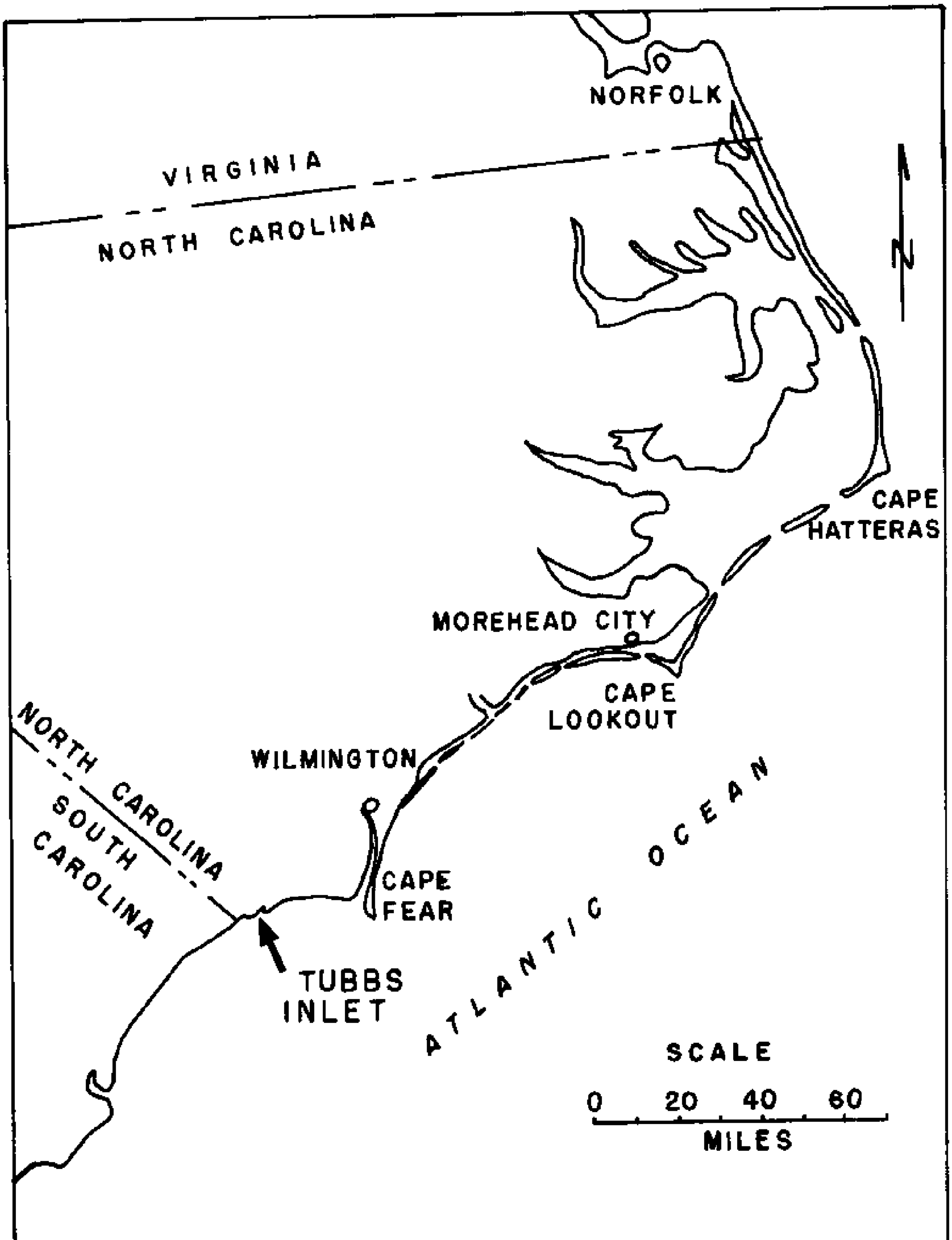


FIG. I. MAP OF THE NORTH CAROLINA COAST-LINE SHOWING LOCATION OF THE STUDY AREA.

East of the inlet, the barrier island narrowed to a point which was easily eroded by spring tide and storm waves. The dunes of this island ranged from 3 feet to 12 feet (1-4 meters) in height and were covered by American Beach grass.

The barrier islands are separated from the mainland by tidal marsh, estuarine channels, and the Atlantic Intracoastal Waterway. The intertidal marsh has a vegative cover of Spartina alterniflora. Tubbs Inlet drains approximately 2.5 square miles (6.4 square kms) of the marshland and the Atlantic Intracoastal Waterway via three estuarine channels which converge near the inlet. There are no streams or rivers introducing fresh water into the system. Fresh water is derived from rainfall and runoff from the immediate area which is considered negligible. Therefore, flood- and ebb-flow through the inlet were considered equal.

Geology

The surficial sediments of the coastal zone are undifferentiated Pleistocene and Holocene deposits of fine to coarse grained, sheet and lenticular sands and interbedded clays (N. C. State Geologic Map, 1958). These deposits cover the seaward dipping Cretaceous and Tertiary strata exposed to the west. The Cretaceous and Tertiary sediments continue seaward to form part of the adjacent continental shelf.

Early Pleistocene seas inundated much of the Coastal Plain area of North Carolina. During the Pleistocene terraces were formed, each marking an ancient shoreline along the emergent coast. The surficial sediments nearest the sea, composed almost entirely of sand, were deposited during the last interglacial stage (Wisconsin).

The evidence concerning the source for the beach sand is inconclusive; however, it is generally accepted that the net littoral movement is westward from Cape Fear (Frying Pan Shoals) and the Cape Fear River. However, Langfelder and others (1968) reported eastward littoral drift based upon wave refraction data. It is concluded that a seasonal reversal of drift does occur.

Lewis (1968) reported the following description of the sediment column in the vicinity of the inlet: (1) 0 to 24 feet (0 to 7.3 meters) below mean sea level--"sand," (2) 24 to 36 feet (7.3 to 11 meters)--"mud mixed with shell," and (3) below 36 feet (11 meters)--"rock."

Oceanographic and Meteorological Data

The mean tidal range at Tubbs Inlet is 4.5 feet (1.35 meters) and the spring tide was 5.1 feet (1.54 meters). Tidal currents of 100 to 125 cm/sec (2.0 to 2.5 knots) are generated by semidiurnal tides.

During the period of the tracer tests, 23 to 26 June and 1 to 4 July, 1972, the wind was from the south and southwest. Local land and sea breezes were experienced. Wind speeds varied from calm to 20 mph with wind speeds of 10 to 15 mph most common. These wind conditions are typical for this region during the summer months. Saucier (1972) reported a seasonal shift of the wind direction from southerly and southwesterly winds during the spring and summer to northerly and northeasterly winds during October and the winter.

Waves were also from the south and southwest. Wave heights from two to three feet were experienced during the study period. Wave gauge data near the inlet were not available; however, visual observations made from the piers at Sunset Beach and Ocean Isle Beach recorded a dominant wave period of five seconds. These observations correspond with wave gauge data and observations from Holden Beach pier (approximately 14 miles to the east) furnished by the Coastal Engineering Research Center.

A five second period wave from 205 degrees true was considered to be typical of those during the study period and was used for a wave refraction diagram (see page 68, Figure 27).

Unusually high tides and lowland flooding was experienced in mid-June due to Hurricane Agnes. By late June conditions had normalized. No other unusual conditions occurred during the study period.

Objectives of Study

The primary objectives of this study were:

1. to gain insight into the processes at work in an inlet environment by combining and correlating more classical geological parameters (bedform and sedimentary structure orientation) and oceanographic parameters (tidal flow characteristics, and waves) and to form a hypothesis of sediment transport and distribution patterns,
2. to test the hypothesis of sediment movement by using fluorescent tracer sand and test the validity of the tracer technique in an inlet environment, and
3. to gain data on Tubbs Inlet useful in curbing migration and increasing navigability.

Method of Study

In order to establish a data base from which to work, past trends and recent changes were noted from aerial photography, field observations and preliminary surveys. Bedform and sedimentary structure orientation were analyzed and mapped while current velocity and direction measurements were obtained from selected stations in the inlet system. From these data a generalized hypothesis of sediment movement was formed.

Separate ebb- and flood-flow movement tests were conducted using fluorescent tracer sand to monitor sediment transport under various environmental conditions. Transport rates for individual grains and net movement of concentrated zones were calculated based upon the movement of tracer material.

HISTORY OF TUBBS INLET

History (Prior to 1969-1970)

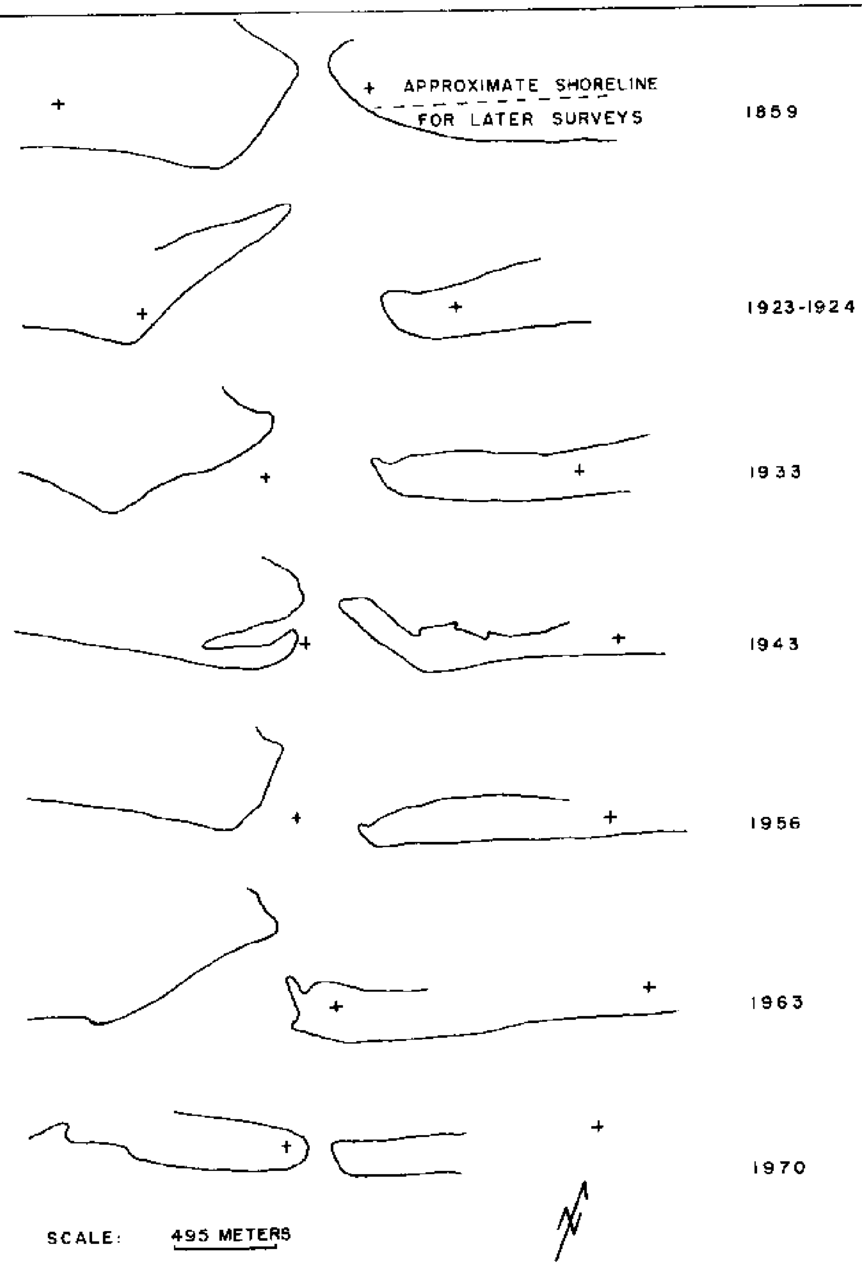
The history of Tubbs Inlet prior to relocation in 1969-1970 was characterized by westward migration. Figure 2 shows the surveyed shoreline from 1859 to 1970. With the development of Sunset Beach in the 1950's and 1960's the migration of the inlet posed a serious problem. Damage to roads and houses forced artificial relocation of the inlet in 1969. This was accomplished by dredge and fill operations.

Aerial photography of the inlet from 1938 to 1972 and ground surveys were extensively used in this study. Figure 2 shows the shoreline as obtained from ground surveys, while Figure 3 shows aerial photography for a 34 year period.

The 1859 survey indicated the shoreline approximately 200 feet (60 meters) seaward of the present position; however, the inlet gorge position is consistent with the western migration trend.

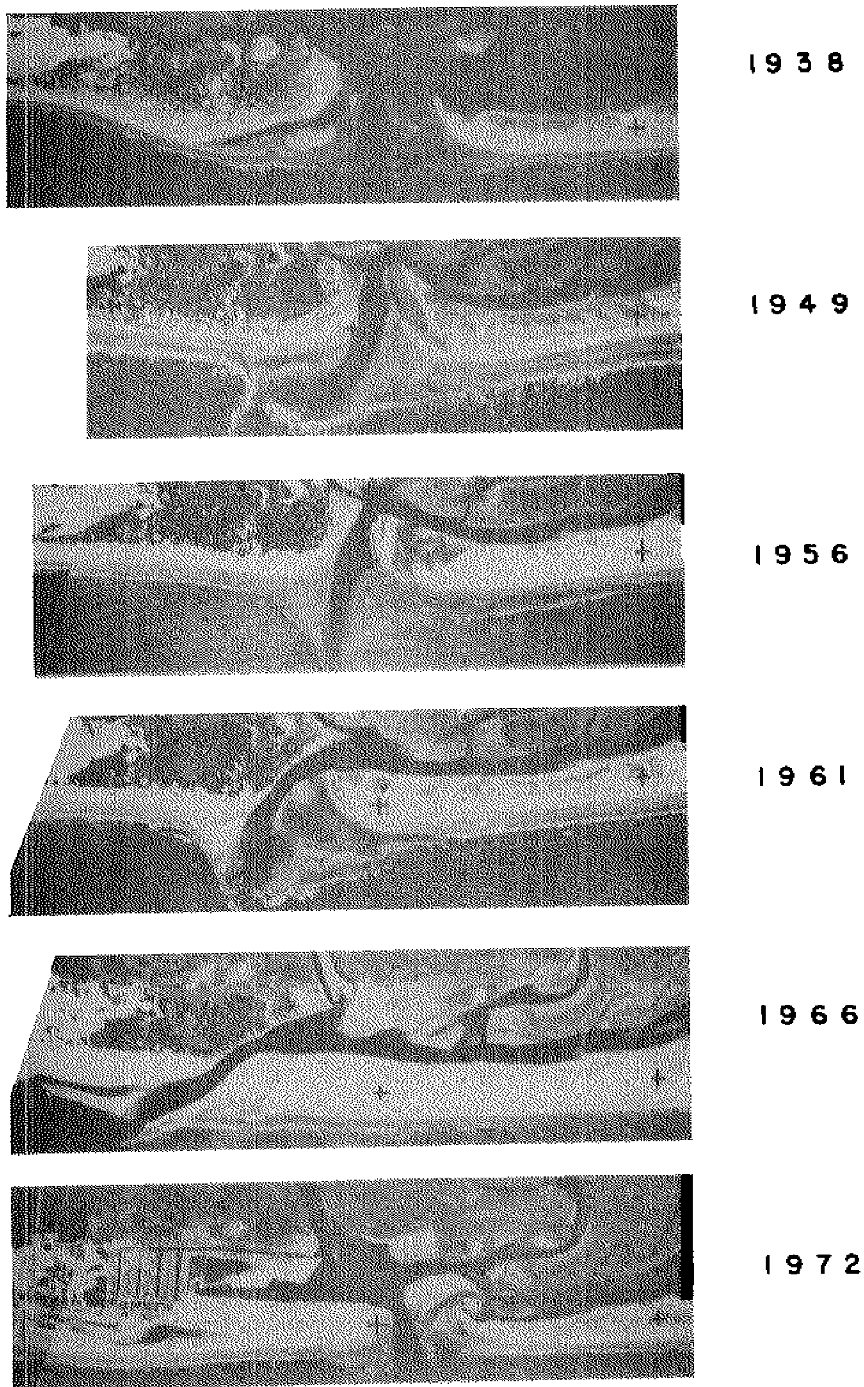
The 1924 survey indicated that Still Creek flowed directly into the inlet gorge. The mouth of the inlet was reported to consist of two entrances and was "subject to frequent and complete changes of position" (USC and GS, 1924).

Photography of 1938 revealed that the inlet gorge had moved westward so that Still Creek no longer flowed directly into the inlet. The inlet channel was approximately perpendicular to the beach. A westward movement of 36 feet (11 meters) was observed between 1938 and 1949. Table 1 shows inlet width, gorge orientation, and distance from the 1938 position obtained from aerial photography. Using the 1938 position



NOTE: SHORELINE IN 1859 SURVEY WAS INCONSISTENT WITH RECENT SURVEYS. THE X MARKS ARE IN THE SAME POSITIONS ON ALL DRAWINGS. (ADAPTED FROM DATA COMPILED BY US ARMY CORPS OF ENGINEERS)

FIG. 2 SURVEYED SHORELINE OF TUBBS INLET, N.C.



NOTE: THE X MARKS ARE IN THE SAME POSITIONS ON ALL PHOTOGRAPHS.

SCALE: 1030 METERS

FIG. 3. SHORELINE IN VICINITY OF TUBBS INLET, N.C.

Table 1. Tubbs Inlet dimensions and location from 1924 to 1972

Date	Distance*	Inlet Width**	Inlet Gorge Width	Gorge Orientation***
1924	-571 (173)	1838 (557)	578	230 degrees
4 Apr 1938	0	1683 (496)	409 (124)	160 degrees
20 Nov 1949	+36 (11)	1980 (600)	340 (103)	160 degrees (Bay end) 205 degrees (Ocean
25 Mar 1956	+445 (135)	1429 (433)	281 (85)	170 degrees
29 Mar 1961	+1736 (526)	1122 (340)	330 (100)	215 degrees (Bay end) 170 degrees (Ocean)
18 Mar 1966	+3128 (948)	1122 (340)	307 (93)	210 degrees (Bay end) 218 degrees (Ocean)
? 1969	+3432 (1040)	?	?	230 degrees
? Mar 1970	-495 (150)	376 (114)	241 (73)	155 degrees
5 Feb 1972	-495 (150)	1492 (452)	294 (89)	140 degrees
29 Jul 1972	-495 (150)	1600 (485)	281 (85)	135 degrees

* Distances in feet (meters). Distance in Column 2 is relative to 1938 position. Minus sign if east of 1938 position and plus sign if west.
** Width at maximum high-water limits.
*** True North.

of the gorge center as a reference, the intervening positions are shown by minus or plus signs indicating position east or west of the reference, respectively. The inlet gorge migrated 409 feet (124 meters) between 1949 and 1956. As shown in Table 1, the most active migration was between 1956 and 1966 when the gorge moved 2683 feet (810 meters).

The main channel became elongated as it was aligned with Eastern Channel. As shown in the 1966 photograph (Figure 3), a part of the channel actually flowed along the beach. No evidence indicated any increase in flow in Eastern Channel which could have resulted in a westward migration. Therefore, it is probable that strong westward littoral drift forced the inlet to move in that direction. It appeared as if the estuarine mouth of the channel was trying to "catch up" to the ocean mouth.

The inlet continued to erode the western bank until 1969, at which time dredging operations to close or relocate the inlet were initiated. Lewis (1968) noted that the "inlet moved 80 feet (24 meters) westward" in approximately two months between 23 November 1967 and 7 February 1968. The relocation was accomplished by filling the eastern end of Sunset Beach with dredge spoil. Fill material was obtained from the old channel and the bay.

History (Subsequent to Relocation)

Since the relocation of the tidal pass in 1969 and 1970, the inlet gorge has remained relatively stationary. The original channel depth was not known; therefore, it is not possible to know if the gorge has deepened or shoaled. The width of the gorge has increased slightly since April, 1970. The cross sectional profile of the gorge has become very asymmetrical (see p.44, Figure 20), which demonstrates the erosive action on the western side. The asymmetry is most pronounced on the bay end of the gorge. The orientation of the gorge at the time of the study was southeast (135 degrees); however, there seems to be a slight trend toward elongation and reorientation to the east. Other inlets in Brunswick County (Shallotte and Lockwood Folly) have been observed during 1972 to reorient more eastward.

The most prominent change occurring since relocation has been the increase of the inlet width. The width increased 1100 feet (333 meters) during the 22 months from April, 1970 to February, 1972, with most of the width change due to enlargement of the eastern intertidal flat.

It is interesting to note the morphological similarity of the inlet in 1938 and the summer of 1972. The gorge orientation is approximately perpendicular to the beach. The large intertidal flat (large inlet width) is common to both time periods. The configuration of shortest channel length and wide intertidal area appear to be stable (nonmigratory) conditions.

LITERATURE REVIEW

Use of Tracer Material

Tracer material has been successfully used in recent years to trace sediment movement in rivers, estuaries, submarine canyons, and on beaches (Kidson and Carr, 1962; Wright, 1962; Yasso, 1966; Ingle, 1966; Crickmore, 1967; Stuiver and Purpura, 1968; Boon, 1969; Komar, 1969; McArthur, 1969; Duane, 1970; and Ward and Sorensen, 1970). With the exception of Stuiver and Purpura (1968), these studies have not involved tidal inlets with different physiographic sub-divisions and variable tidal currents. These inlet features necessitated a large volume of tracer material, simultaneous use of several identifiable tracers, and introduction and sampling techniques adaptable to the water depth. Reference is made to Ingle (1966) and Ward and Sorensen (1970) for a summary of the history and development of the use of tracer material. Ingle (1966) performed definitive work using fluorescent tracer sand on beaches in southern California; however, this work was qualitative or at best semiquantitative. His assumption that a small percentage of tracer is lost to burial is questionable.

Techniques and procedures used in this study are based upon the works of several authors (see Appendices A, B, and C for descriptions of techniques).

The review of the literature concerning sediment movement revealed the significant problems involving quantitatively monitoring movement and detecting the direction of movement. The determination of sediment movement rate remains an elusive quantity as well as the thickness of the mobile layer. Unfortunately, these problems remain unsolved. Using tracer material in rivers and on beaches Crickmore (1967) and Komar (1969) experienced limited success in obtaining quantitative results. Boon (1969) conducted a tracer study along a Virginia beach for which he obtained quantity of sand transported. His tracer study compared favorably with that quantity obtained by using beach profile data.

Stuiver and Purpura (1968) used fluorescent tracer sand in South Lake Worth Inlet, Florida, in conjunction with littoral drift studies. Both ebb and flood movement through the inlet and sediment bypassing the inlet were monitored.

Oertel (1972) used fluorescent tagged sediment to study the processes by which shoal areas of the ebb-tidal delta of a Georgia tidal inlet were formed. Tidal current transport and wave-induced transport were monitored; however, no quantitative data were obtained.

Bedform Morphology

Bedforms resulting from water flowing over sandy material have been studied by hydraulic engineers and geologists for many years. Much theoretical and experimental work has been conducted and many descriptive nomenclatures developed, resulting in a vast literature on the subject. Therefore, only the criteria pertinent to this study are discussed. Allen (1968) presented the main features of the alternative approaches to the study of bedforms.

Allen (1968) delineated between bedforms using chord lengths of less than 60 cm and height of less than 4 cm to represent smallscale ripples and chord lengths greater than 60 cm and heights greater than 4 cm to represent largescale ripples.

Simons and others (1961) recognized the following sequence in the development of bedforms with increasing flow intensity: (1) plane bed without movement; (2) ripples (smallscale ripples); (3) dunes (largescale ripples); (4) transitional forms to supercritical flow forms; (5) plane bed with movement; (6) standing sand waves, and (7) antidunes. The first four bedforms occurred in subcritical flow while the last three bedforms normally occur in supercritical flow.

Boothroyd and Hubbard (1972) classified bedforms on the basis of spacing alone. The terms "spacing," "chord," and "wavelength" are synonymous, meaning the distance, parallel to direction of flow, between crests or troughs of adjacent bedforms. This system further subdivided the largescale ripples into megaripples and sand waves. Discussion of this classification system is continued in the next section in context with the description of the bedforms observed in Tubbs Inlet.

GENERAL HYPOTHESIS OF SEDIMENT MOVEMENT

Inlet Morphology

The major morphological features affecting sediment transport within the inlet were established as early as February, 1972. A comparison of survey maps shown in Figures 4 and 5 indicates that all the major depositional features present in February were enlarged by June, thus indicating a net sediment transport into the inlet environment (i.e., the eastern intertidal flat, the recurved spit, the flood-tidal delta, and the Jinks Creek ebb spit were enlarged).

The recurved spit shown in Figure 5 (also, see p. 34, Figure 14) extending from the eastern barrier island was well developed by the commencement of the tracer study in June. The flood-tidal delta (see Figure 14) was also well developed in February. The enlargement of these features decreased the flushing ability of the ebb flow from Eastern Channel by diverting the flow. An intertidal channel (see Figure 14) across the intertidal flat and flood-tidal delta was also evident in February. It was determined, from observation in March 1972, that the intertidal channel had become more north-south oriented as the spit increased in size. By June, the water of Eastern Channel was forced to enter and exit through a small channel located between the Eastern Channal Island and the marsh as shown in Figure 5. This resulted in subsequent erosion of the marsh and island.

The ebb spit in Figures 4 and 5 near the mouth of Jinks Creek was formed in February, thus reducing the flushing of sediment from Jinks

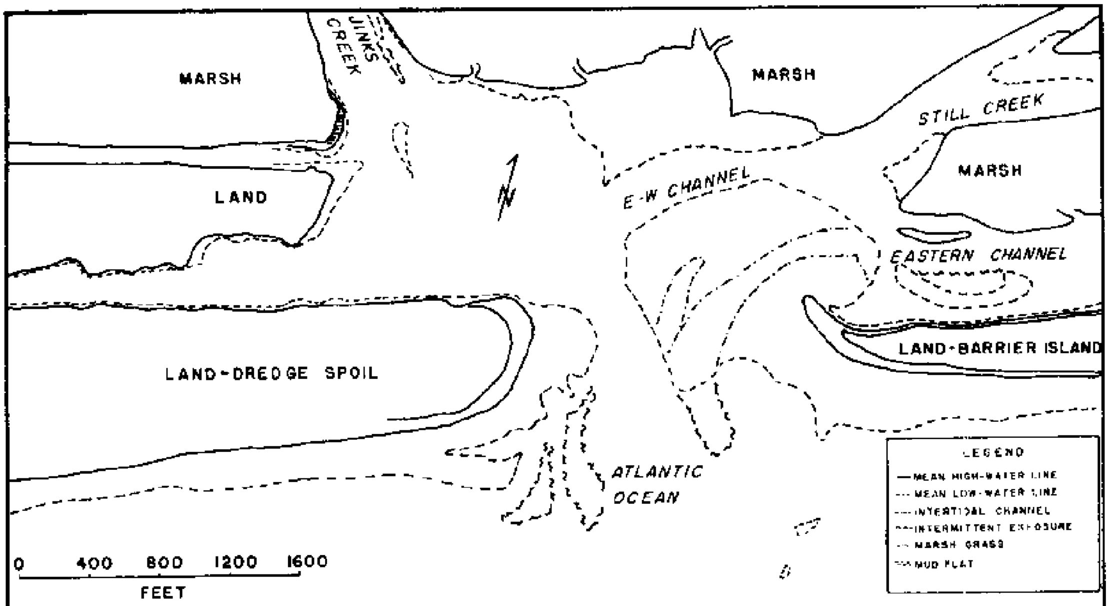


FIG. 4. GENERALIZED SHORELINE OF TUBBS INLET ON 5 FEBRUARY 1972.

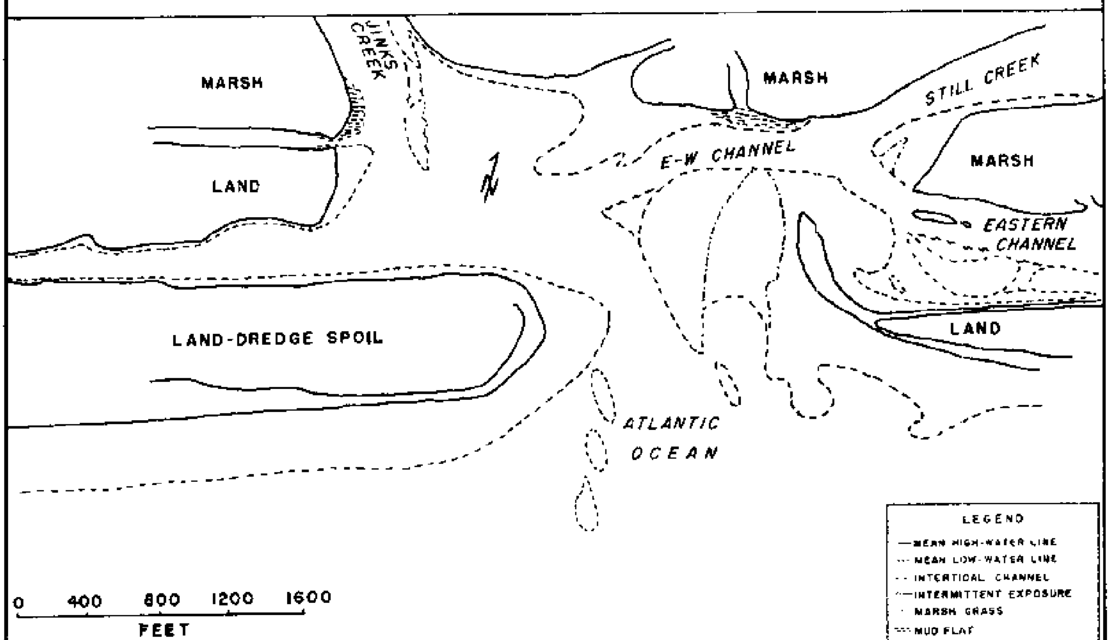


FIG. 5. GENERALIZED SHORELINE OF TUBBS INLET ON 23 JUNE 1972.

Creek. The spit also prevented flood currents from introducing sediment into Jinks Creek.

A rapid sediment accumulation was observed in the vicinity of the junction of east-west (E-W) channel with the basin as shown in Figures 4 and 5.

Classification System for Bedforms

From an analysis of the bedforms and structures observed in the inlet system a generalized hypothesis of sediment transport and distribution has been formulated. The hypothesis qualitatively indicates the direction and suggests the intensity of the water current causing the sediment movement. The bedforms have been analyzed using a combination of classification systems from Allen (1968), Harms (1969), and Boothroyd and Hubbard (1972).

Megaripples are defined as bedforms with spacings of 0.6 meters to 6 meters while sand waves have spacings of greater than 6 meters. Megaripples are morphologically distinct from sand waves. Megaripples are sinuous to highly cuspate, with well-developed scour pits down-current of the crest. Since the lateral dimension is not linear they are considered three-dimensional bedforms. Sand waves are straight to sinuous two-dimensional bedforms with no or poorly developed scour pits. Transitional bedforms exist at about the 6 meter spacing and generally take the form of poorly-developed sand waves.

The sequence of development of bedforms observed by Boothroyd and Hubbard (1972) is compared to that of Simons and others (1965) in

Figure 6. The first forms of the sequence are ripples [termed low-energy and high-energy ripples by Harms (1969)]. Linear megaripples are next in sequence. As flow intensity increases, cuspate megaripples occur. With more intense flow megaripples are planed-off into two types: ones with short spacings analogous to washed-out dunes of Simons (1965, and ones with spacings of 6 meters.

The maximum velocity controls the bedform type. Tidal-current velocity asymmetry (difference of maximum flood and ebb velocity) and velocity duration (time span above a given velocity) are important in determining bedform morphology.

Boothroyd and Hubbard (1972) delineate in Figure 7 the velocity versus water-depth fields in which each member of the sequence occurred in Parker and Essex Estuaries, Massachusetts. The observations and measurements made during this study agreed with those of Boothroyd and Hubbard (1972).

The most common bedforms found in Tubbs Inlet were smallscale ripples, linear and cuspate megaripples, and small (transitional) sand waves. Cuspate megaripples are considered to be indicative of relatively high flow strength (0.80 m/sec) and small tidal-current asymmetry (maximum ebb and flood velocities nearly equal). Sand waves indicate large tidal-current velocity asymmetry and a velocity of less than 0.80 m/sec. Velocities of greater than 0.80 m/sec result in megaripples superimposed on the sand-wave form (Boothroyd and Hubbard, 1972).

Harms (1969) described ripples produced by currents, waves, and combined currents and wave energy. Ripples formed by currents are indicative of relatively low flow strength (0.15 to 0.60 m/sec) and are delineated as low-energy ripples (0.15 to 0.28 m/sec) and high-energy ripples (0.21 to 0.60 m/sec). Current-formed ripples are asymmetric, while wave-formed ripples are symmetrical and have rounded profiles with continuous crests. The symmetry is due to the oscillatory motion of the waves. The forms produced by the combined actions of currents and waves have characteristics of the two sources of energy. Asymmetric but straight ripples indicate the current dominates the wave energy.

In the following sections, areas of the inlet system are discussed based on either their location and environment, morphology and type of bedforms present, and/or orientation of the bedforms. The areas and bedforms are shown in Figure 8, as well as zones of deposition and non-deposition along the channel edges, flats, and bars.

Intertidal Bedforms

Intertidal Channel (Area 1)

The small channel across the eastern intertidal flat shown in Figure 8 was formed by flood and ebb currents. The cuspate megaripples on the channel bottom indicated current velocities in excess of 0.80 m/sec during the latter portion of flood tide and first part of ebb flow. The bedforms were both ebb- and flood-oriented. The channel floor was characterized by coarse sand and shell fragments. In the north-central portion, the intertidal channel narrowed as shown in Figure 8. North of the restricted intertidal channel the preserved bedforms were ebb-oriented sinuous to cuspate megaripples as shown in Figure 9. Ebb-oriented

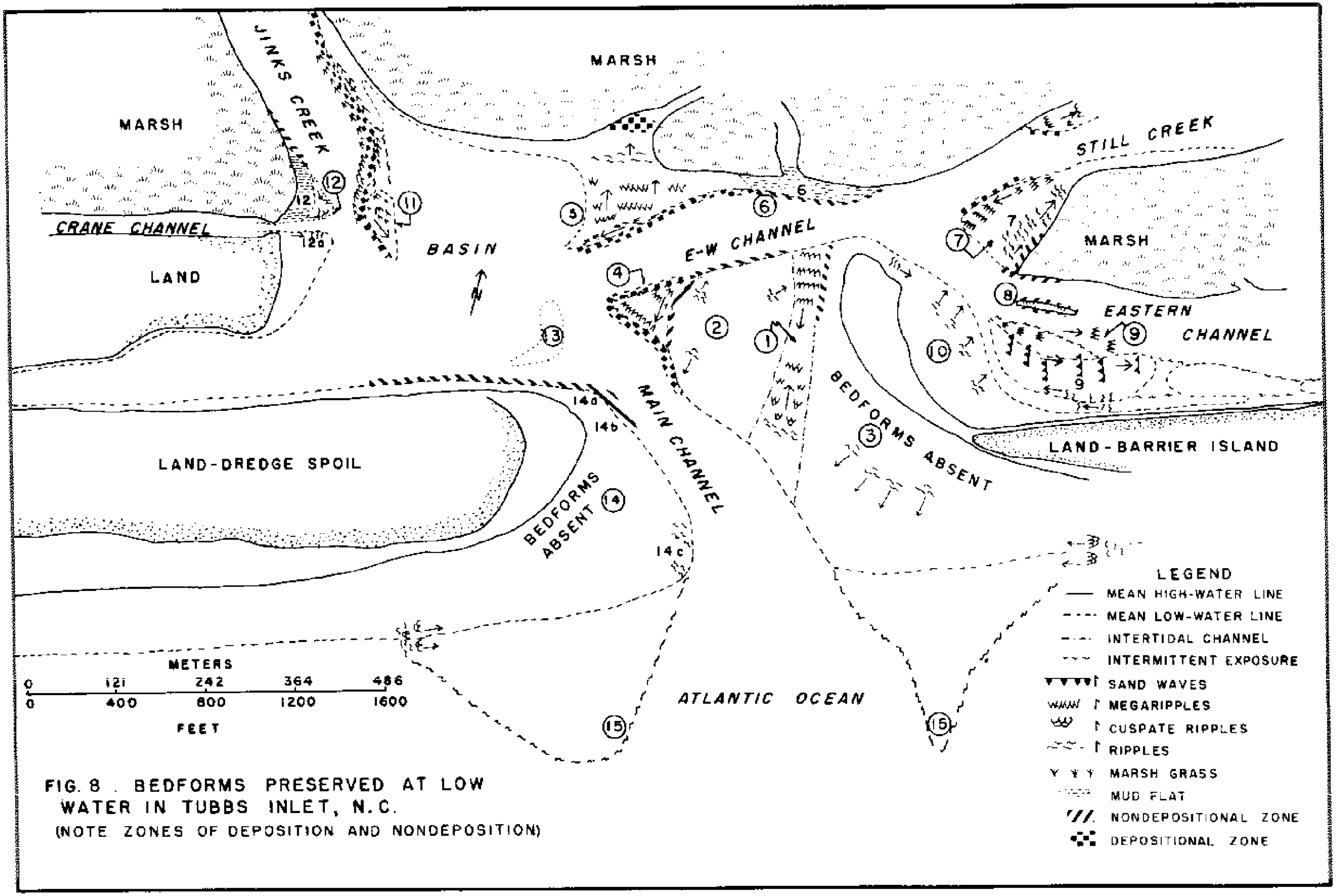


FIG. 8 . BEDFORMS PRESERVED AT LOW WATER IN TUBBS INLET, N.C.
(NOTE ZONES OF DEPOSITION AND NONDEPOSITION)

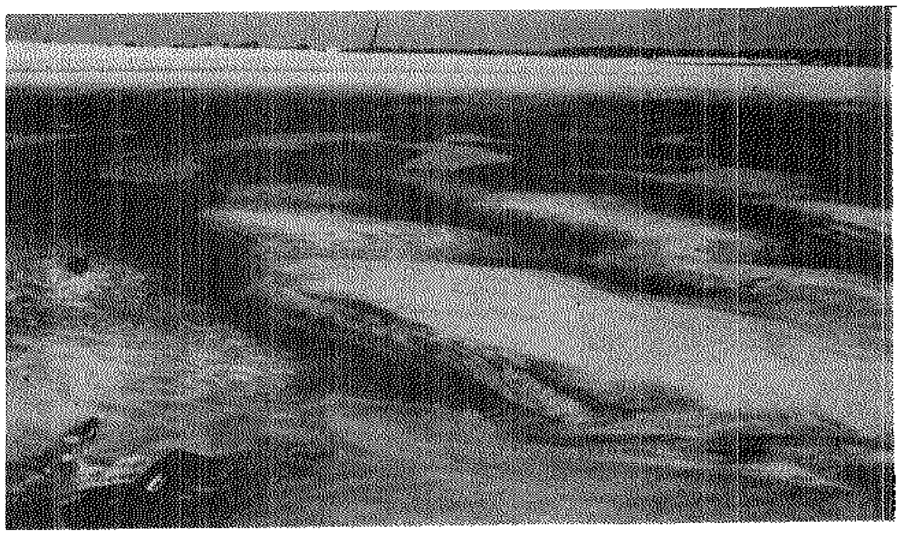


FIG. 9. SINUOUS EBB MEGARIPPLES IN INTERTIDAL CHANNEL. (EBB FLOW FROM RIGHT TO LEFT)

smallscale ripples were found superimposed on larger megaripples. The ebb-oriented bedforms were transformed into flood-oriented megaripples with the incoming tidal current. Flood-oriented megaripples and altered linear ripples were preserved on the exposed surface at low tide in the intertidal channel south of the narrow portion. Ripples were superimposed on sinuous, flood-oriented megaripples which were thought to represent the less unidirectional and weaker ebb current. The ebb currents in the southern portion of the channel were not of sufficient energy to alter completely the bedforms.

Both ebb and flood megaripples in the channel were observed to migrate during periods of peak flow during the late stages of flood tide and early ebb flow. Reversal of flow direction within the channel was very rapid, often reversing direction and reaching near maximum velocity within one-half hour. Current velocity of 1.02 m/sec was measured during flood flow in the northern end of the intertidal channel.

Farther to the south of the narrow portion near the main channel, the intertidal channel was less defined. The bedforms, as shown in Figure 10, were small asymmetrical flood ripples which were modified by the ebbing current and small shoaling waves.

Flood-Tidal Delta (Area 2)

During maximum high tide the flood-tidal delta was subjected to small shoaling waves and gentle tidal currents, forming straight and nearly symmetrical ripples. The crests were rounded due to the waves; however, there was slight asymmetry, thus indicating a recent tidal current. At low water the sediment surface reflected water runoff from

FIG. 10. FLOOD RIPPLES NEAR SOUTHERN END OF INTERTIDAL CHANNEL. (FLOOD FLOW FROM RIGHT TO LEFT)

a low north-south oriented topographic high trending across the delta. The orientation of the ripples is shown in Figure 8.

Eastern Tidal Flat (Area 3)

The surface of the intertidal sand flat and beach east of the intertidal channel was without bedforms. Smallscale ripples from weak runoff currents and symmetrical ripples from shoaling waves during ebb tide were common. However, a general pattern of westward migration was substantiated by cross-bedding observed in the subsurface.

Sediment in the surf and swash zone during the latter portion of flood tide (high water) moved as a continuous sheet resulting in planar surfaces. Loose, porous sand accumulated high on the beach face near the spit. There was a net movement of sand toward the estuary within this zone. The distance between the high-water limits across the inlet increased as a result of the eastern beach retrieval. Retrieval of the barrier beach was in part due to wave attack during spring tides and storms. Sand was transported alongshore into the inlet during flood tide to form the spit which in turn furnished sand for the formation of the flood-tidal delta in the inlet.

Western Point of Flood-Tidal Delta (Area 4)

The surface gradient of the western point sloped very gently to the west so that the shallow subtidal as well as intertidal bedforms could be observed. Bedforms preserved at low water were ebb-oriented megaripples as shown in Figure 11, and reflected ebb flow toward the inlet gorge from E-W channel. With the tide reversal, the bedforms were com-

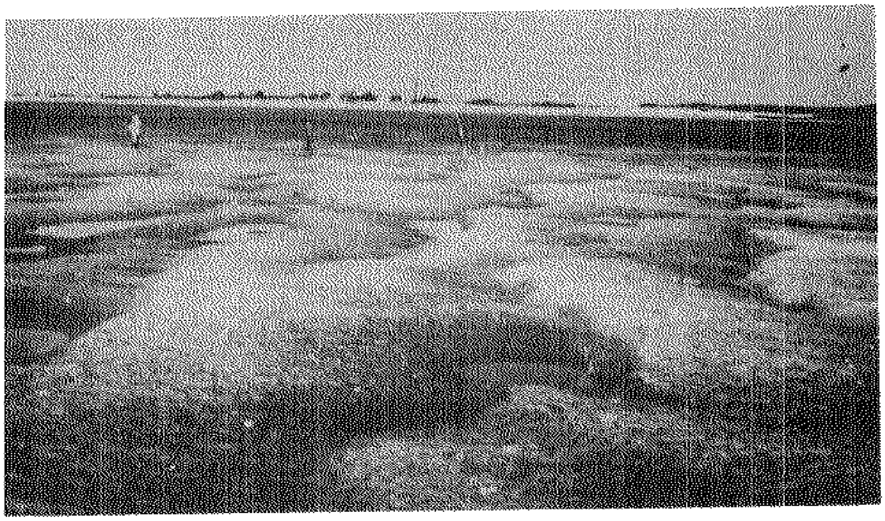


FIG.11. SINUOUS EBB MEGARIPPLES ON WESTERN POINT OF FLOOD-TIDAL DELTA. (EBB FLOW FROM RIGHT TO LEFT)

pletely altered to reflect the incoming tidal current. A nondepositional bank separated the megaripple zone from the flood-tidal delta to the east (Area 2). Megaripple modification and migration was observed during incoming flow. This fact suggests a current velocity of greater than 0.6 m/sec. The point prograded westward due to the ebb flow of E-W channel and accretion on the southern side due to the flood current from the main channel.

Point Bar North of Intersection of E-W Channel and Basin (Area 5)

The bedforms in this depositional zone reflected the influence of flood and ebb currents. Sand was transported to the north by flood-tidal energy into the marsh and was deposited as loose, porous sand with few bedforms. The flat surface was probably due to rapid deposition of sediment as the flood current decreased rapidly upon entering the marsh grass.

Flood-oriented straight to slightly sinuous megaripples were formed on the southern portion of this bar. The bedforms on the southwestern tip of the bar were completely changed to ebb-oriented megaripples having deep (30 to 40 cm) scour pits, reflecting the influence of the ebb flow from E-W channel. The modification of the point bar to the ebb spit was reflected by the ebb-oriented bedforms. The source of the sediment was probably seaward as well as eastward from E-W channel. The orientation of bedforms is shown in Figure 8.

Mud Flat on E-W Channel (Area 6)

The oyster covered mud flat was a nondepositional area for sand.

Point Bar at Intersection of Still Creek and Eastern Channel (Marsh Point) (Area 7)

Marsh Point was a westward prograding depositional zone. Incoming tidal flow swept over Marsh Point and was then deflected into Still Creek by the mud cliff on the western boundary of the marsh. The flow passing to the south of this point and entering Eastern Channel was observed to undercut and erode the marsh. The northern side of the bar sloped gradually into Still Creek and received sediment faster than it was flushed. This resulted in the gradual filling of Still Creek and caused ebb flow to be diverted toward the northern bank of the channel.

Flood currents passing over the sand-covered point formed small, straight megaripples with smallscale ripples superimposed on the stoss-side. These bedforms near the marsh remained flood-oriented. The straight megaripples near the western end and on the northern side of the point bar which extended subtidally into Still Creek were changed with the outgoing tidal flow to straight, ebb-oriented megaripples. The orientation of these bedforms is shown in Figure 8.

Eastern Channel Island (Area 8)

This grass covered island was eroded by the undercutting flow from Eastern Channel. Deposition occurred on the southern side of the island as a result of flood-tidal flow. Figure 12 shows the beginning of accretion on the southern side of the island.

Eastern Channel Shoal (Area 9)

The shoal was dominated by small flood-oriented sand waves as shown in Figure 13, which indicated velocity asymmetry. Ebb flow across the

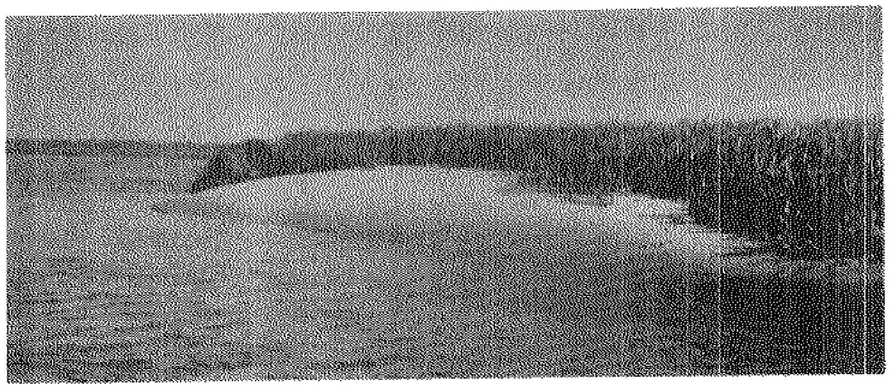


FIG. 12. ACCRETION OF SEDIMENT NEAR EASTERN CHANNEL ISLAND. (FLOW FROM LEFT TO RIGHT. ACCRETION AREA APPROXIMATELY 10 METERS LONG)

FIG. 13. FLOOD SAND WAVES ON EASTERN CHANNEL SHOAL. (FLOOD FLOW FROM LOWER LEFT TO UPPER RIGHT)

shoal was weak. The sand waves extended into the shallow subtidal zone of Eastern Channel and were altered to small slightly sinuous megaripples with shallow scour pits. Very rarely would these megaripples be more than slightly altered by the ebb current.

A small ebb channel drained the southern portion of the shoal. Small-scale ebb ripples were preserved on the channel bottom and edge of the shoal.

Back Barrier Sand Flat (Area 10)

The sand surface in this area was usually dominated by smallscale ebb ripples. Such bedforms were occasionally altered to indicate flood currents that swept around the spit.

Ebb Spit in Jinks Creek (Crane Bar) (Area 11)

This shoal was formed by the ebb flow exiting from Jinks Creek. The bedforms preserved at low water were ebb-oriented linear megaripples and smallscale ripples. The megaripples extended westerly into the subtidal portion of the channel. Ebb-oriented linear to cuspate megaripples were always observed on the eastern bank of Jinks Creek.

Flow data indicated velocity symmetry with ebb flow velocity only slightly higher. The flood flow was restricted to the channel west of the spit. The channel bedforms were partially altered to flood megaripples but were not well defined in the flood direction. By the time the spit was inundated, the flood flow strength was not sufficient to significantly alter the ebb bedforms on the spit.

The eastern edge (lee side) of the spit was rather steep and remained free of loose sand due to the gently bifurcated flood current which swept the spit. The spit and basin were shielded from intense flood-tidal flow by a subtidal shoal (Area 13) located near the bay mouth of the inlet gorge.

Mud Flat on Jinks Creek (Area 12)

Sand was present only on the eastern point of the flat. A mud flat and oyster bed was near the shore. Very small ebb ripples were found here, indicating currents originating from Jinks Creek and Crane Channel. The sand on the point south of Crane Channel entrance (Area 12a) was loose with small ripples indicating current originating from Crane Channel. The point bar was prograding eastward.

Subtidal Shoal (Area 13)

The shallow subtidal shoal appeared to be a flood-tidal delta. It effectively shielded the basin from receiving strong tidal currents and sand-sized sediment.

Bottom samples from the basin revealed mud with virtually no sand. Clay and silt sediment covered the bottom of this relatively low energy environment.

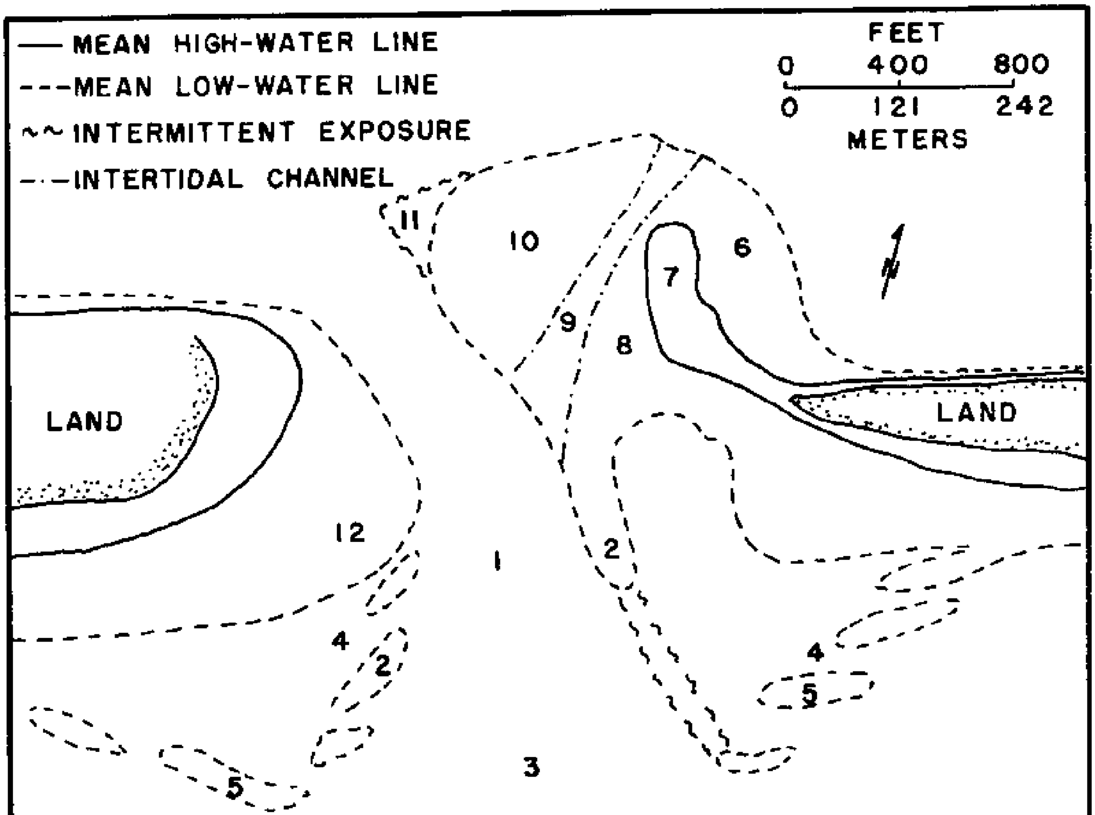
Flood water was deflected to either side of the shoal to flow either in the channel which paralleled the southern shore of the basin or toward the northern shore (Area 5) and E-W channel. Ebb flow influenced the basin less than flood flow. Weak flood currents were measured in the basin, while multidirectional weak currents were measured during ebb flow. Ebb water coming from the west and northwest flowed along the southern boundary of the basin. Ebb water from the east flowed toward the gorge from E-W channel as indicated by bedforms in Area 4.

Western Tidal Flat (Area 14)

The northern bank of the western tidal flat was without bedforms. Ebb-oriented megaripples were rarely observed near the northeastern point (Area 14a). The four foot high intertidal bank was steep and was typical of the entire depth of the channel wall. The sand of the northern portion near the high-water line (Area 14b) was loose, porous, and free of bedforms. The gradient of the bank decreased to nearly horizontal in a southerly direction along the main channel. The sand on the southern portion (Area 14c) was firm with smallscale ripples indicative of the most recent tidal currents and waves. Asymmetrical ripples with rounded crests indicated waves and gentle currents from the last runoff.

Ebb-Tidal Delta (Area 15)

Sediment accumulation seaward of an inlet mouth has been modeled by Hayes and others (1972). The five components of the model were recognized at Tubbs Inlet. These features are illustrated in Figure 14. They are: (1) major ebb channel, (2) channel-margin linear bars, (3) terminal lobe, (4) marginal flood channels, and (5) swash bars. Since the sand surface of the channel-margin linear bars was not observed during tidal flow, the bedforms cannot be described. Hayes and others (1972) account for the formation of these channel-margin linear bars by the interaction of ebb currents and waves.



COMPONENTS OF EBB-TIDAL DELTA.

1. MAJOR EBB CHANNEL
2. CHANNEL-MARGIN LINEAR BARS
3. TERMINAL LOBE
4. MARGINAL FLOOD CHANNELS
5. SWASH BARS

COMPONENTS OF EASTERN INTERTIDAL FLAT.

6. BACK BARRIER SAND FLAT
7. RECURVED SPIT
8. EASTERN TIDAL FLAT
9. INTERTIDAL CHANNEL
10. FLOOD-TIDAL DELTA
11. WESTERN POINT

12. WESTERN TIDAL FLAT

FIG. 14. COMPONENTS OF EBB-TIDAL DELTA AND EASTERN INTERTIDAL FLAT.

Oertel (1972) describes channel-margin linear bars as swash platforms. During flood-tidal flow, when wave approach and current are landward, the higher parts of the shoals are planar resulting from turbulent wave activity. Tidal currents transport sediment shoreward around the shoal margin and through the marginal tidal channels. The dispersion pattern of fluorescent tracer test run by Oertel (1972) during ebb flow indicated seaward movement induced by ebb currents and then landward movement by refracted and interferring waves.

Swash bars result from wave action whereas the marginal flood channels result from flood currents. Flood-oriented linear and cuspate ripples which indicated movement approximately parallel to the beach were preserved in runnels (flood channels) near the beach and on the bottom of the marginal channels. The preservation of flood-oriented bedforms at low water indicates negligible ebb flow in regions of the swash bars and marginal channels. Ebb flow was primarily restricted to the major ebb channel and furnished sediment to the terminal lobe.

Flow Data and Discussion of Channels

Tidal-current velocity and direction measurements were taken at the locations shown in Figure 15. Currents were measured with a Hydro Products Model 650-S current meter. Measurements at Stations 1 through 6 and Station 9 were taken hourly through two tidal cycles during 48 hours. The flow through the main channel was measured at Stations 6, 7, and 8 for one tidal cycle (12 hours) with a time interval for measurement of 12 to 20 minutes. Measurements at all stations were taken one and one-half

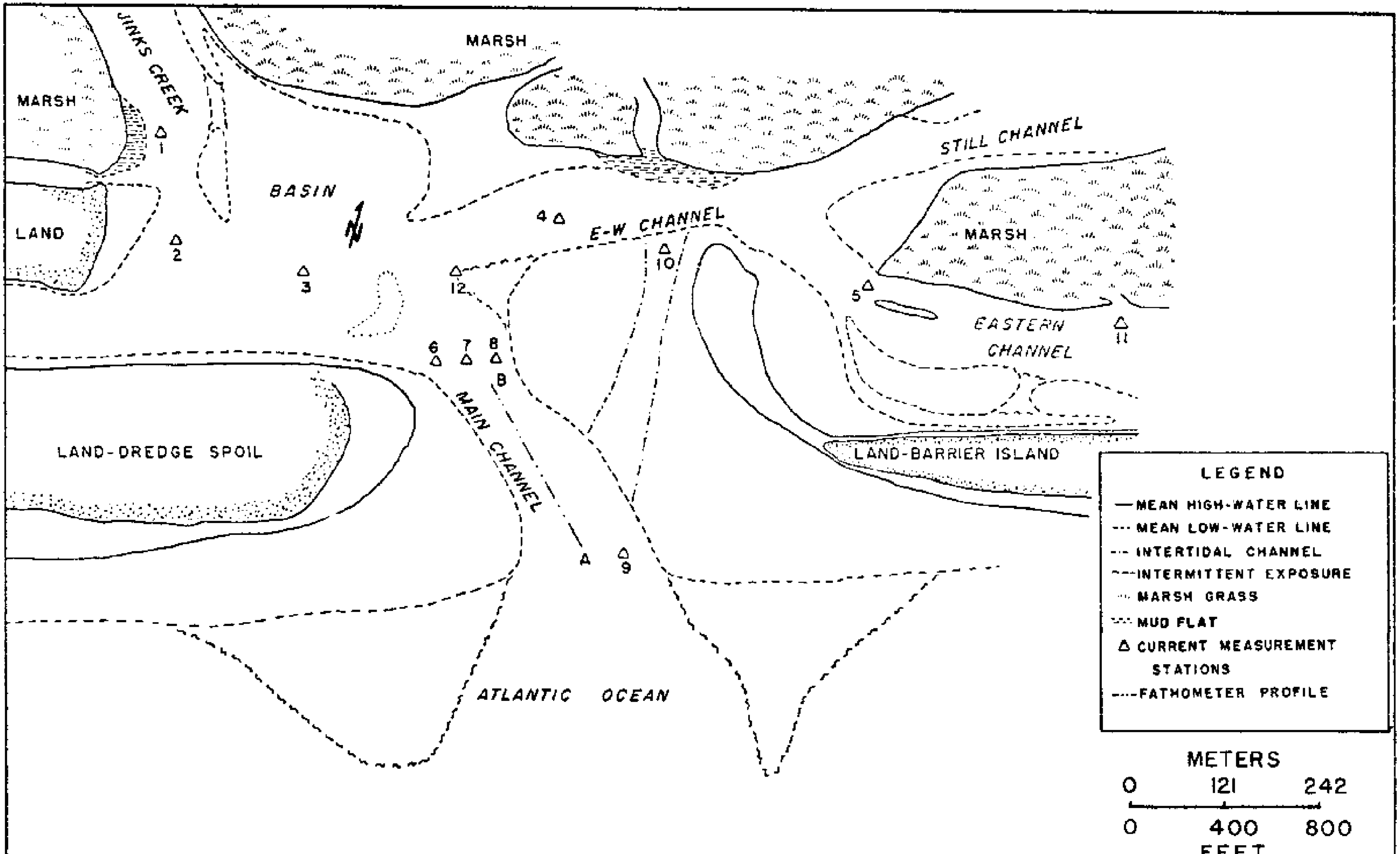


FIG. 15. CURRENT MEASUREMENT STATIONS.

feet (0.45 meters) above the inlet bottom and one and one-half feet (0.45 meters) below the water surface. Bathymetry data were obtained using a model DE 719 Raytheon precision survey fathometer depth recorder. Generalized bathymetry of the inlet is shown in Figure 16.

Directions and velocities at each station were statistically reduced to a resultant direction and velocity and are presented in Table 2. Tidal velocity curves shown in Figures 17, 18, and 19 indicate time-velocity symmetry or asymmetry of flood and ebb flow. Bottom current velocity was plotted on all curves.

The ebb-dominated megaripples in the vicinity of Jinks Creek mouth and Crane Bar previously discussed were influenced by the slightly asymmetric ebb velocity measured at Stations 1 and 2 (Figure 17).

The tidal velocity curve for E-W channel (Station 4, Figure 17) was slightly asymmetrically ebb dominated. Maximum ebb velocities of 0.80-.85 m/sec and maximum flood velocities of 0.70-.75 m/sec were sufficient to cause bedform migration in each direction.

Eastern Channel (Station 5, Figure 18) was slightly flood dominated. The duration of flood velocity above 0.60 m/sec was approximately twice that of the ebb direction.

Flow through the inlet gorge is shown in Figure 18. Ebb flow was more prominent on the west side of the main channel while flood flow on the east was of longer duration. This imbalance was due to horizontal segregation of ebb and flood flow. During flow reversal from ebb to flood tide, it was observed that the sediment-free ocean water of flood tide entered the gorge as a surface-wedge. The front of the flood wedge

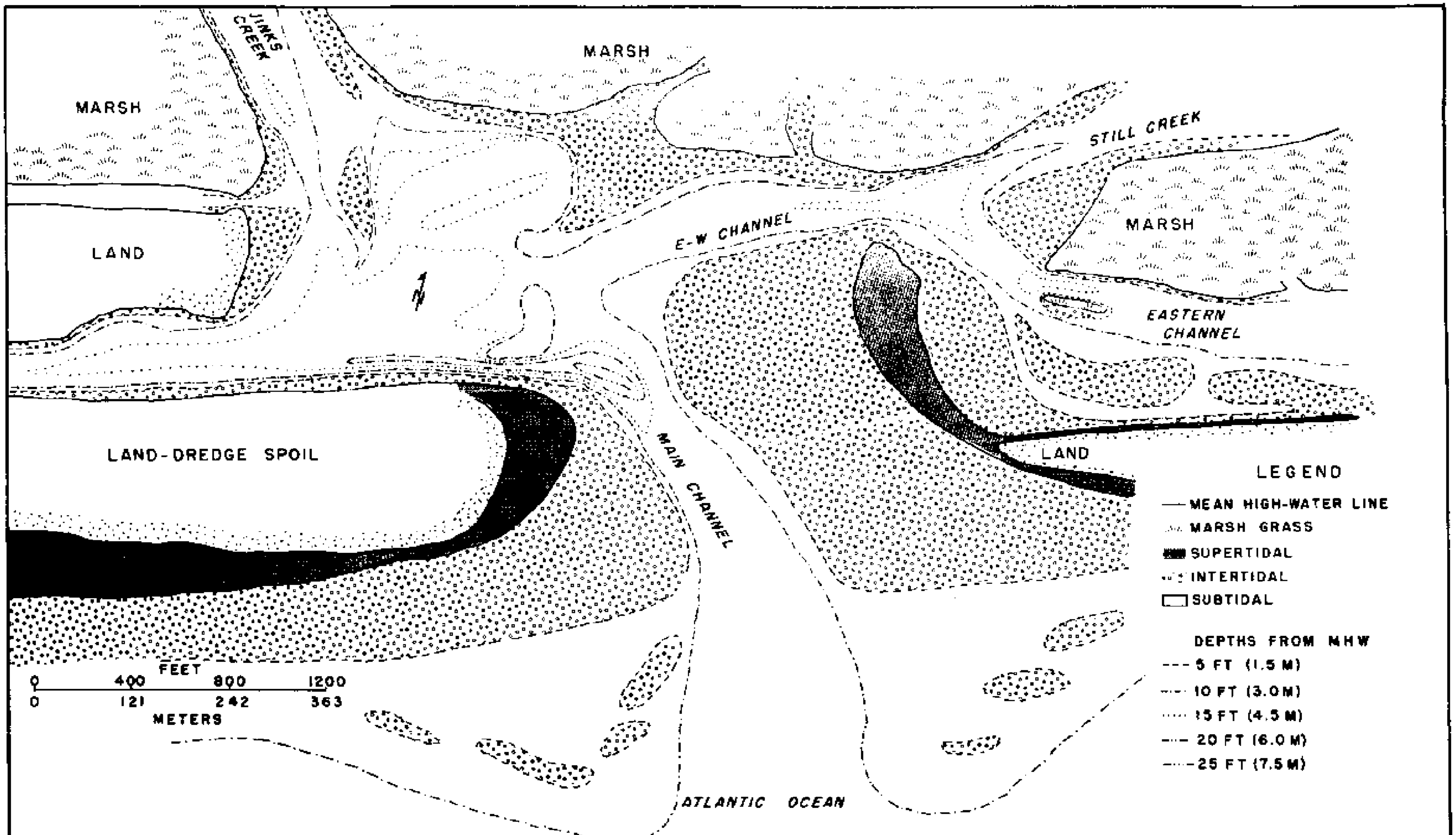


FIG.16. GENERALIZED BATHYMETRY OF TUBBS INLET, N.C.

Table 2. Resultant current directions and velocities

Station*	Date	Meter Depth**	Flood Flow Direction/Velocity (Degrees True/cm/sec)	Ebb Flow Direction/Velocity (Degrees True/cm/sec)
1	2 Aug	S	338/40.3	122/47.4
		B	327/34.2	122/43.4
2	1 Aug	S	245/9.2	093/28.6
		B	193/5.1	119/23.5
2	2 Aug	S	024/3.1	137/37.2
		B	271/11.2	099/19.4
3	1 Aug	S	325/7.7	097/17.9
		B	322/14.8	100/5.1
3	2 Aug	S	320/9.2	120/48.5
		B	322/32.1	100/12.6
4	1 Aug	S	052/51.5	274/81.6
		B	063/48.5	271/71.4
4	2 Aug	S	055/54.1	256/82.6
		B	058/50.0	258/73.4
5	1 Aug	S	073/86.2	297/71.4
		B	067/91.8	303/51.0
5	2 Aug	S	065/88.2	242/70.9
		B	067/76.0	229/94.4
6	3 Aug	S	333/20.0	104/61.2
		B	360/30.6	111/57.1
7	3 Aug	S	326/42.3	103/70.9
		B	314/48.5	107/59.7
8	3 Aug	S	324/88.2	139/66.3
		B	322/57.1	126/49.5
9	1 Aug	S	337/37.7	112/86.7
		B	336/37.2	112/82.6
9	2 Aug	S	315/49.5	110/86.7
		B	328/46.4	119/74.0
Miscellaneous Readings (Single Measurements)				
10	2 Aug	B	015/102.0	None Taken
11	2 Aug	S	040/35.7	None Taken
		B	040/30.6	None Taken
12	2 Aug	B	None Taken	235/61.2

* Station locations shown in Figure 15.

** S - denotes surface current measurement.
B - denotes bottom current measurement.

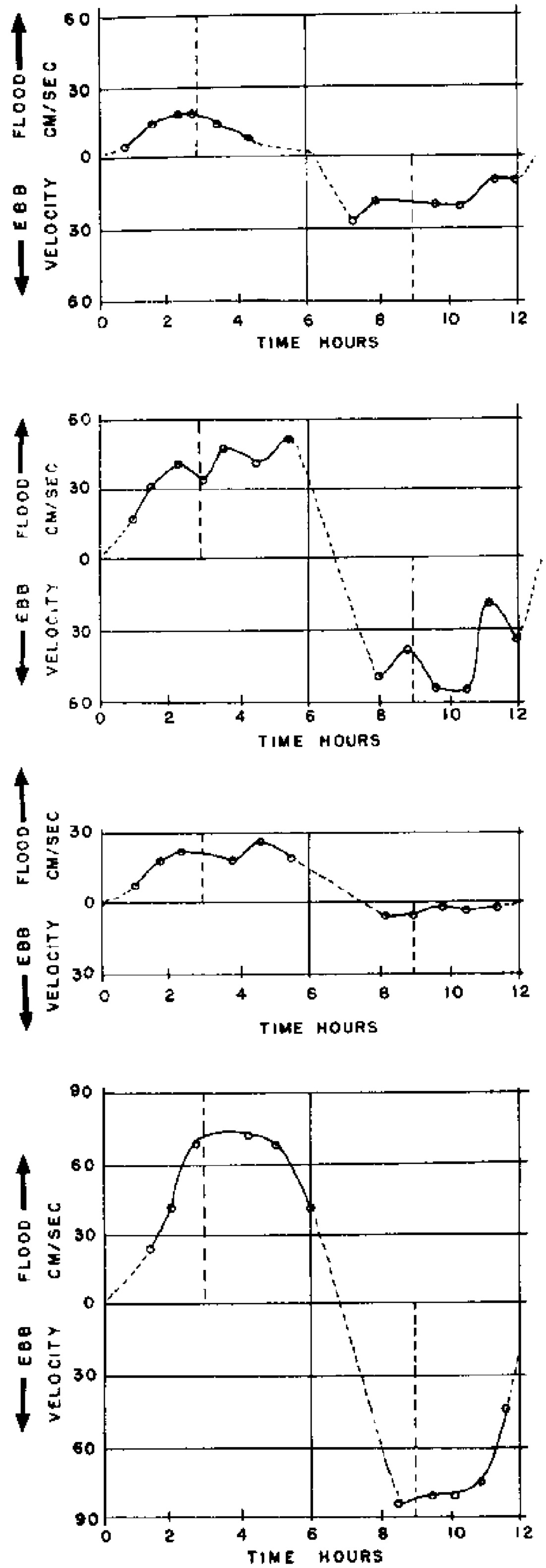


FIG. 17 STATION 2 2 AUG 1972

FIG. 17 STATION 1 2 AUG 1972

FIG. 17 STATION 3 2 AUG 1972

FIG. 17 STATION 4 2 AUG 1972

NOTE: STATION LOCATIONS SHOWN IN FIGURE 15.

FIG. 17. TIDAL-CURRENT VELOCITY-TIME CURVES, STATIONS 1-4.

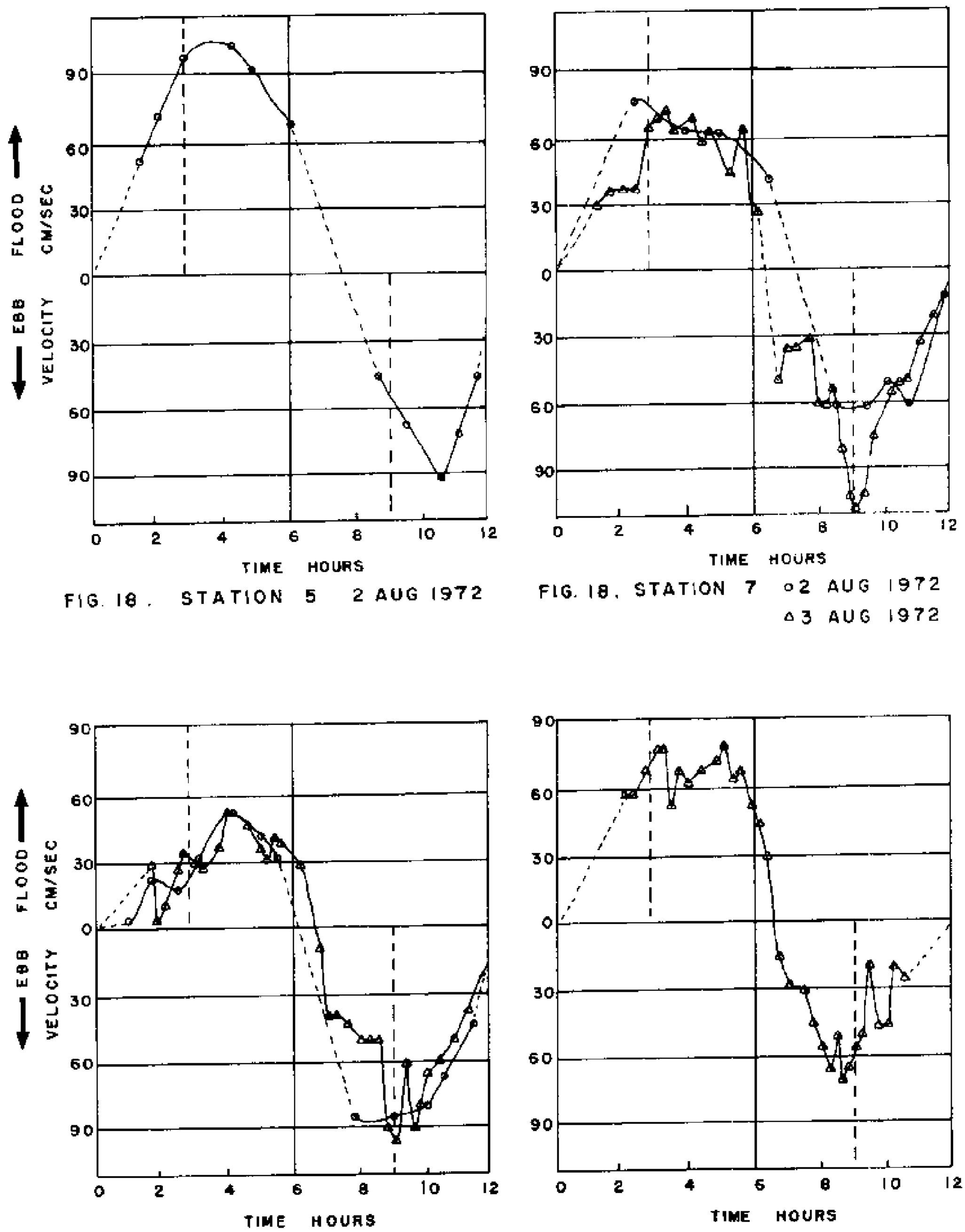


FIG. 18. STATION 5 2 AUG 1972

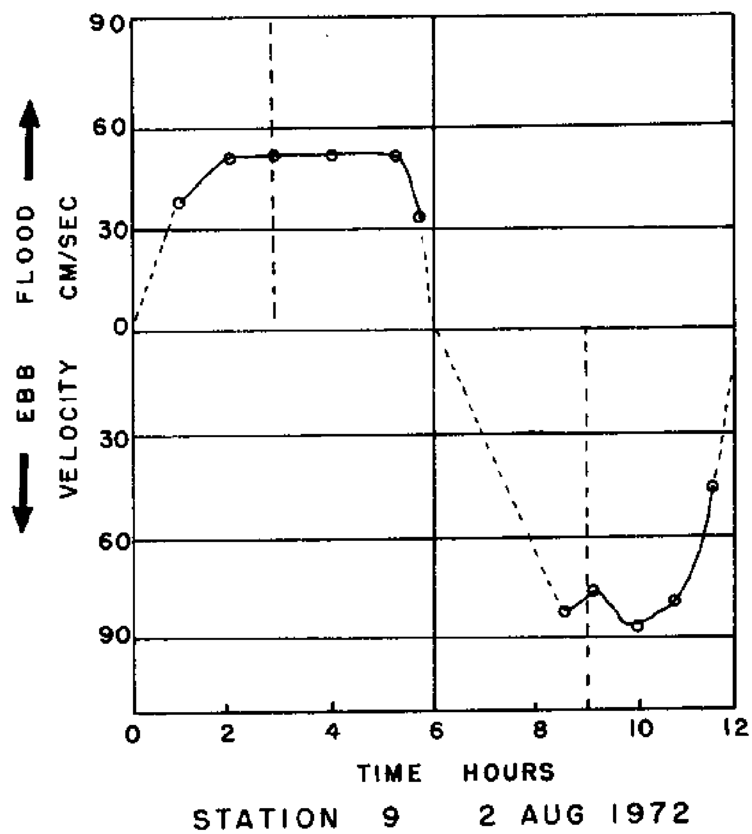
FIG. 18. STATION 7 ○2 AUG 1972
△3 AUG 1972

FIG. 18. STATION 6 ○2 AUG 1972
△3 AUG 1972

FIG. 18. STATION 8 3 AUG 1972

NOTE: STATION LOCATIONS SHOWN IN FIGURE 15.

FIG. 18. TIDAL-CURRENT VELOCITY-TIME CURVES, STATIONS 5 - 8.



NOTE: STATION LOCATION SHOWN IN FIGURE 15.

FIG. 19. TIDAL-CURRENT VELOCITY-TIME CURVE, STATION 9.

reached the eastern side of the basin mouth (Station 8, Figure 15) while ebb flow (very low velocity) continued emptying sediment-laden water into the western portion of the main channel (Station 6, Figure 15). As flood flow continued, the flow through the channel became evenly distributed. During ebb tide, water closely paralleled the southern boundary of the basin as it flowed toward the gorge. The resultant directions of the currents at Stations 6 and 7 (Table 2) indicate easterly flow, while Station 8 indicates southerly direction (Table 2). The inlet gorge was cut by the exiting current as it flowed toward the ocean. Maximum ebb velocity (1.08 m/sec) was reached near the deepest portion (27 feet-8.2 meters) of the channel (vicinity Station 6, Figure 15). See Figure 20 for cross-sectional profiles of the channels.

The main channel widened and decreased in depth toward the ocean to form the major ebb channel of the ebb-tidal delta. The velocity curve at Station 9 (Figure 19) shows that the maximum ebb velocities were greater than flood velocities. These maximum ebb velocities were reached late in the ebb cycle corresponding to the period of more channelized flow. Ebb velocity (0.8 to 0.9 m/sec) was sufficient to form megaripples and to cause them to migrate seaward thus forming the terminal lobe. The maximum flood velocity (0.51 m/sec) was maintained approximately one-half of the flood cycle. The long duration of 0.51 m/sec flood flow was sufficient to transport sediment over the crest of the megaripples, thus modifying the orientation.

The bedforms on the channel bottom are illustrated on the fathometer profile (Figure 21). The profile extends northerly from A to B in Figure

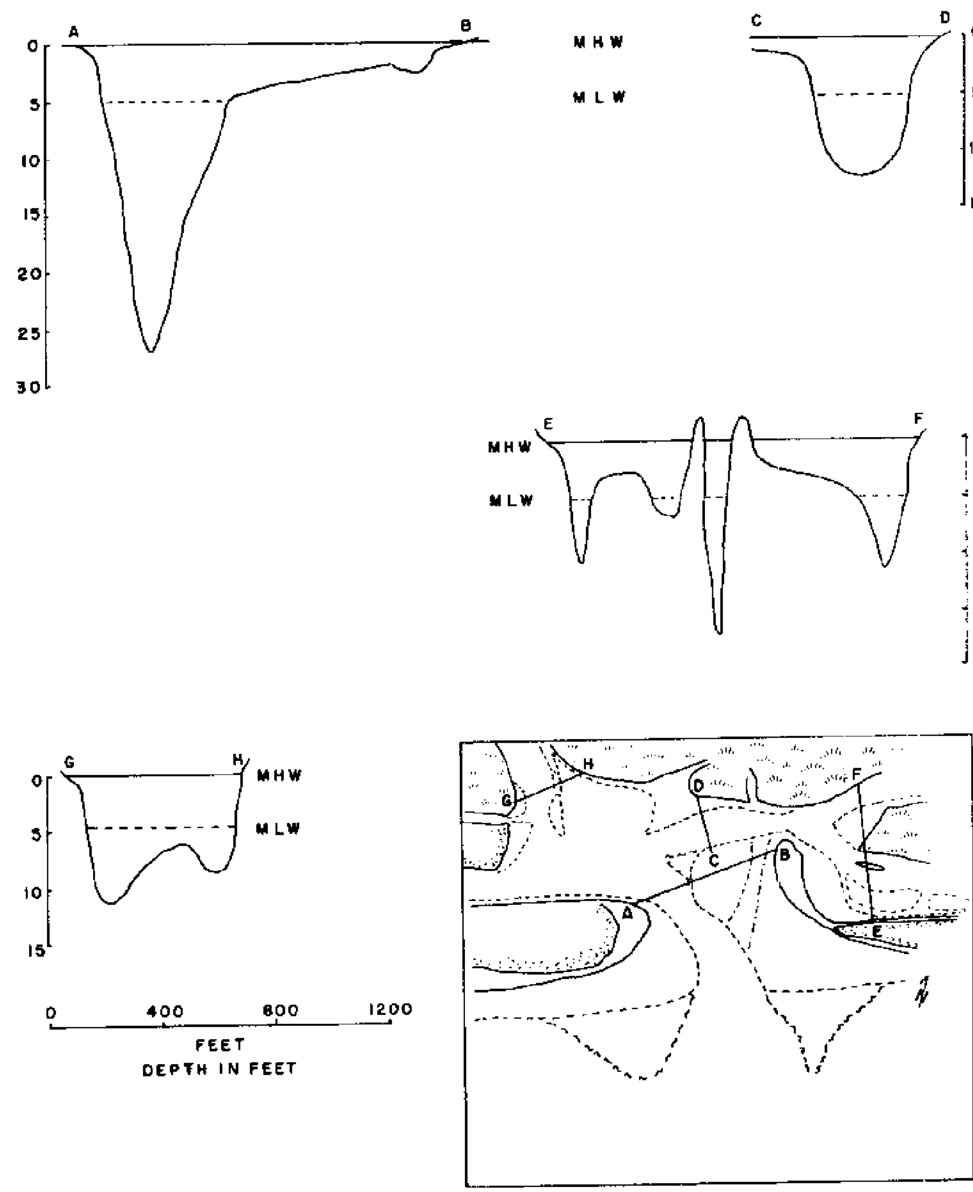
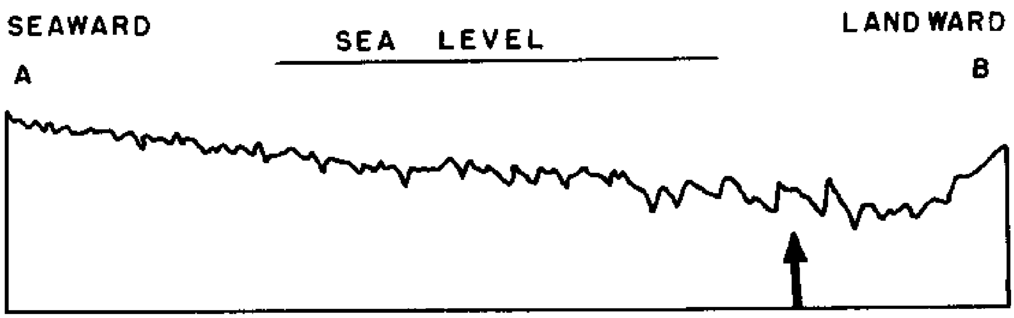


FIG. 20. CHANNEL CROSS SECTIONS IN TUBBS INLET, N.C.



SCALE: 1.1 METERS
46 METERS

NOTE: LOCATION OF PROFILE SHOWN IN FIGURE 15. PROFILE MADE DURING LATTER HALF OF EBB FLOW.

FIG. 21. FATHOMETER PROFILE MADE IN MAIN CHANNEL.

15. The profile was made during the latter half of ebb flow; therefore, the bedforms are well defined ebb-oriented sand waves (shown by arrow, Figure 21). The longest sand waves on the profile have spacings of approximately 35-40 feet (11-12 meters) and heights of approximately 4 feet (1.1 meters). The average water depth at the sand waves was 10 feet (3 meters). Observations indicated that the sand waves maintained ebb flow orientation throughout a tidal cycle. In the shallow seaward portions of the channel, the megaripples were not directionally distinguishable and probably were altered with each passing tidal flow. The ebb-oriented sand waves and flow data indicated a net seaward transport of bedload sediment within the channel.

Preliminary Work on the Eastern Intertidal Flat

To determine areas of erosion and accretion and depth to which sediment moved during a tidal cycle, preliminary experiments were conducted on the eastern intertidal flat in May, 1972. This was accomplished by inserting 2 foot (0.6 meter) vertical plugs of nonfluorescent painted sand into the intertidal flat. The plugs were inserted in lines parallel to and perpendicular to the beach as shown in Figure 22A. After 24 hours (two tidal cycles) the plugs were located and both the depth of overburden and amount of tagged sand remaining were measured. The results shown in Figure 22B revealed that the most active erosion and redeposition area was the high-water swash and surf zones. The total remaining amount of tagged sand of plugs 1 and 6 was undetermined.

Vertical profiles at each of the plug locations were examined and plugs 1, 2, 3, 7, 8, and 9 revealed graded bedding from coarse sand and

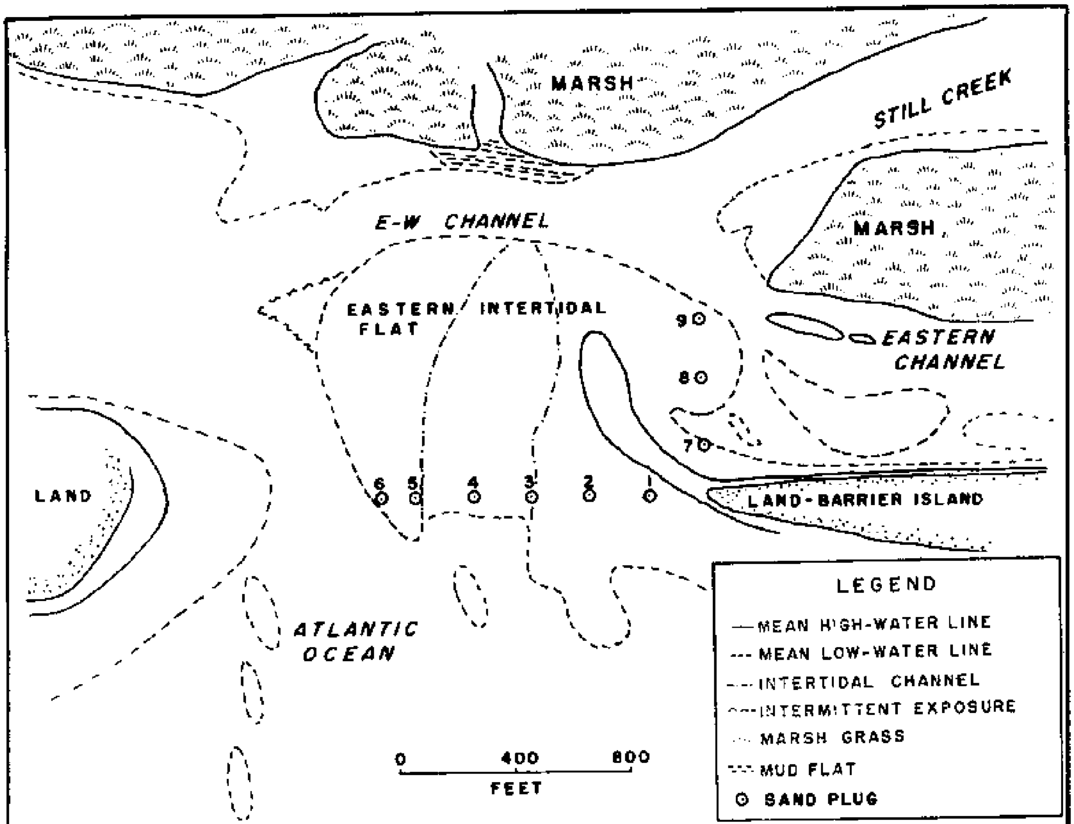


FIG.22 A. LOCATION MAP OF NONFLUORESCENT SAND PLUGS.

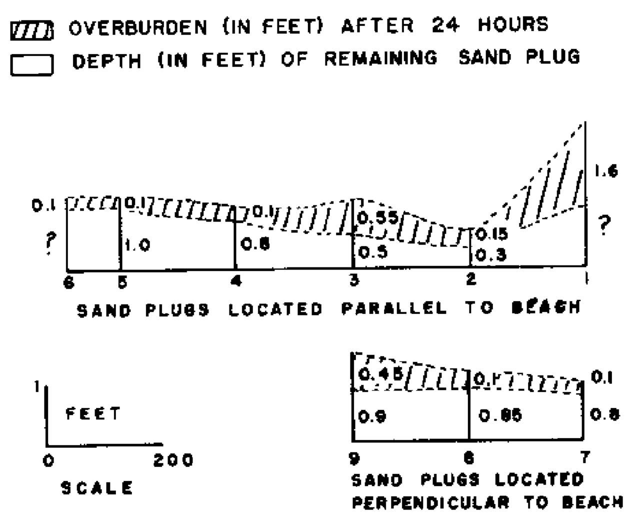


FIG.22B. PROFILES SHOWING AREAS OF EROSION AND ACCRETION AND DEPTH OF SAND MOVEMENT.
NOTE: ALL DEPTHS IN FEET.

shell hash to medium or fine sand (Wentworth scale) and revealed also smallscale planar to festoon cross-bedded laminae. The cross-bedded laminae indicated current directions approximately equal to those of the surface bedforms. At plugs 4, 5, and 6 no graded bedding was found and the sand ranged from medium to fine. Cross-bedding was noted but current direction could not be ascertained. The surface was covered with straight and cuspate smallscale ripples.

Preliminary Hypothesis of Sediment Transport

There was a net landward movement of sediment into Tubbs Inlet evidenced by the large intertidal flat and flood-tidal delta. The source of the material seemed to be primarily from the barrier island and beach east of the inlet, as suggested by intense sediment movement along the front of the spit. The absence of bedforms in the breaker zone suggested "sheet flow" of sediment.

Sediment moved across the eastern intertidal flat via the small intertidal channel. This became increasingly important during high water when sediment was exchanged between the main channel and E-W channel resulting in a net landward transport of sediment across the intertidal flat.

The estuarine channels served as depositories and sources for inlet sediment. Jinks Creek was a source for sediment for the ebb spit (*i.e.*, Crane Bar). The southern portion of Eastern Channel and Still Creek received sediment due to incoming flow. Eastern Channel was capable of flushing much of the flood introduced sediment; however, there was a net flood dominance resulting in gradual flow restriction. The E-W channel and main channel were capable of flushing the sediment from their boundaries which kept the channel and gorge open.

The western tidal flat was narrower than the eastern flat, and was the result of the scouring effect of the tidal currents (especially ebb current) on the western side of the gorge. This scouring action in the past had resulted in westward migration of the inlet channel. The gorge was asymmetrical (Figure 20) with the western boundary steeper. The steepness of the channel wall and the intertidal bank, particularly along the northern and northeastern portions of the flat, prevented inundation of the entire flat until near maximum high water when flood currents were low. The southern and southeastern portions of the flat and beach had a more gradual slope. Most sediment that moved into the inlet from the western side did so by moving alongshore into the main channel and not by moving directly across the intertidal flat. Seaward bound sediment was also contained in the gorge.

This hypothesis of sediment distribution was tested by a tracer study. Based on the above preliminary study conclusions and the configuration of the inlet, five tracer introduction stations were chosen and each station received a different color tracer sand. To prevent bias, samples were taken over the entire inlet.

FLUORESCENT TRACER MOVEMENT DATA

Tracer Technique

The two popular methods of tagging sediment are fluorescent and radioisotopic. The fluorescent method was chosen because of reduced environmentally related problems, relative convenience, and economy of the technique.

The objectives of using tracer material in Tubbs Inlet were satisfied: the first objective was to prove qualitatively the hypothesis of sediment distribution formulated in the previous section; the second objective was to test the validity of using tracer material in the highly complex and high energy environment of a tidal inlet.

The procedure for dyeing used in this study was that of McArthur (1969) with a few modifications. Yasso (1966) first suggested the tracer components of lacquer paint, vinyl plastic and two organic solvents. The proportions of the components and the mechanics of dyeing are discussed in Appendix A, and are the results of the experimentation of McArthur and later by the author. A total of 2000 pounds (445 kilograms) of tracer was produced using the method described which was equally divided among five different colors.

Examination of the tracer sand with a binocular microscope revealed that from 10 to 20 percent of the grains were not fully coated by the fluorescent paint. This, however, presented no problems in detection of the tagged grains, although it may have affected the true volume of dyed sand introduced at any specific site.

Sediment movement in the estuarine channels of the inlet and the intertidal flats and beaches was monitored. Tracer material was introduced onto the channel beds without placing it into suspension by using commercially available water soluble bags. Tracer was introduced onto the intertidal sand flats and beaches by raking it into the sand surface. (See Appendix B for details concerning introduction techniques).

Sampling fulfilled two objectives: (1) to trace the initial movement of tracer sand, and (2) to determine net sand movement over several days. The former was accomplished by using vaseline coated cards (for shallow water poles were used, and for deeper water [estuarine channels and inlet gorge] lead blocks were used). Card preparation, handling, and sample retrieval were similar to that used by Ingle (1966). This method of sampling was satisfactory through the first two tidal cycles. Beyond this time the tracer was not consistently detectable on the sand surface and hence core samples were relied upon.

The experiments using painted plugs conducted on the eastern intertidal flat indicated that 30 cm (12 inch) cores would be necessary to assure a representative sample of material moved during a 24 hour period. Many core samples were taken at the same time as surface samples to test the reliability of each method of sample retrieval. It was concluded that core samples provided the necessary quantity and quality for analytical work. Komar (1969) abandoned taking card samples and then relied on volumetric subsurface samples in his study on California beaches. Card and core sample devices and techniques for handling samples are discussed in Appendix B.

Analysis of the samples was performed by counting fluorescent grains in the core samples and on the cards under a long wave ultraviolet light. (See Appencix C for analytical methods). In the core samples, which averaged 574 grams (1.26 lbs) (dry), fluorescent grains ranged from one to approximately 500 grains (only two cores had more than 160 tracer grains). The median number of grains detected in each core sample was approximately 3.5 grains and the mean was 15 grains. Eighty-two percent of the total number of cores (284) contained dyed sand. Seventy-three percent of the total card samples (169) revealed dyed grains. Seventy percent of the card samples which contained tracer sand had 3 or less tracer grains. Sixty-eight persent of the core samples which contained tracer sand had 6 or less tracer grains. The median number of coated grains on the cards was two grains while the mean was four.

The variation of tracer concentration on the cards was not great enough to allow meaningful analysis of tracer dispersion. Tracer presence on card samples did however enable determination of the geographical extent of the tracer movement and calculation of velocities of individual tracer grains. Variation of tracer concentration between core samples was sufficient to trace zones of concentration of tracer sand or a "sand mass" into the inlet.

Samples with less than four fluorescent grains were used to indicate presence of tracer while those with four grains indicated low concentration, five to 20 grains indicated medium concentration and those with greater than 20 grains were considered highly concentrated.

Core samples taken four weeks after introduction of tracer material revealed the presence of tracer in the inlet system. Most of these residual tracers were found near introduction points (Marsh Point). However, some tracer was found buried in the intertidal channel bedforms. Therefore, use of different colors of tracer material is mandatory when working in the same area within a period of several weeks.

Tracer Tests

Separate movement tests were conducted for ebb and flood flow. The ebb test was initiated on the morning of 23 June, 1972 when fire orange tracer was introduced into Eastern Channel and Still Creek, and horizon blue tracer was introduced into Jinks Creek. Introduction was during slack high water.

Timing of the tides delayed execution of the flood test until 1 July, 1972. At slack low water that morning, signal green and lightning yellow tracers were raked into the eastern and western beaches respectively. Blaze orange tracer (distinctly different from the fire orange of the ebb test) was introduced into the seaward mouth of the main channel. (See Figures 23 and 24 for the tracer introduction locations and sampling stations for the ebb and flood movement tests respectively).

Card and core sampling began immediately after introduction. Many card samples taken the first day of the ebb test were possibly contaminated (see Appendix B); therefore, initial movement of the tracer is inconclusive. Core samples were taken during the ebb tide following introduction and at low tide for three days after introduction.

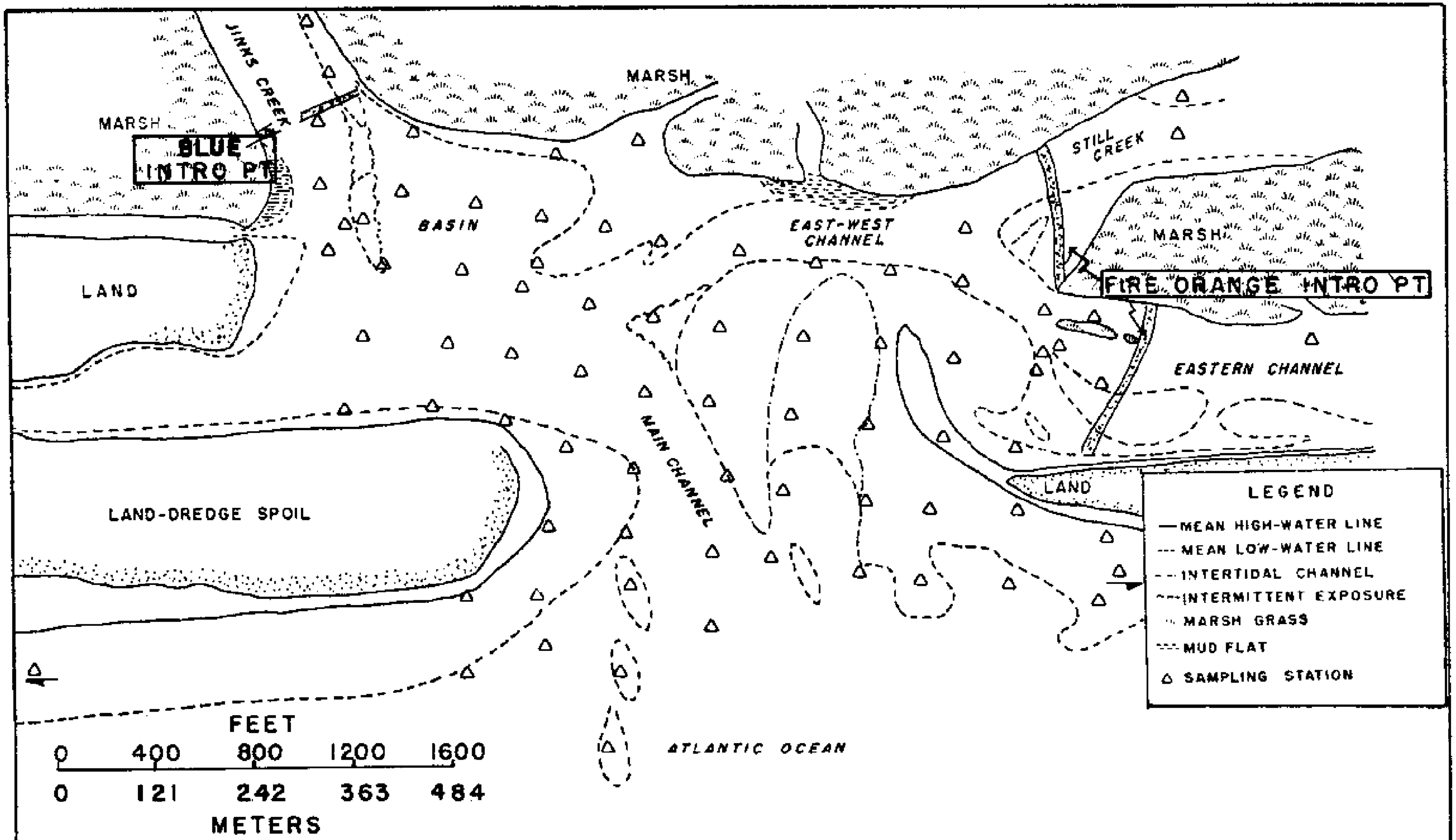


FIG. 23. TRACER INTRODUCTION AND SAMPLING STATIONS FOR THE EBB MOVEMENT TEST, 23 JUNE 1972.

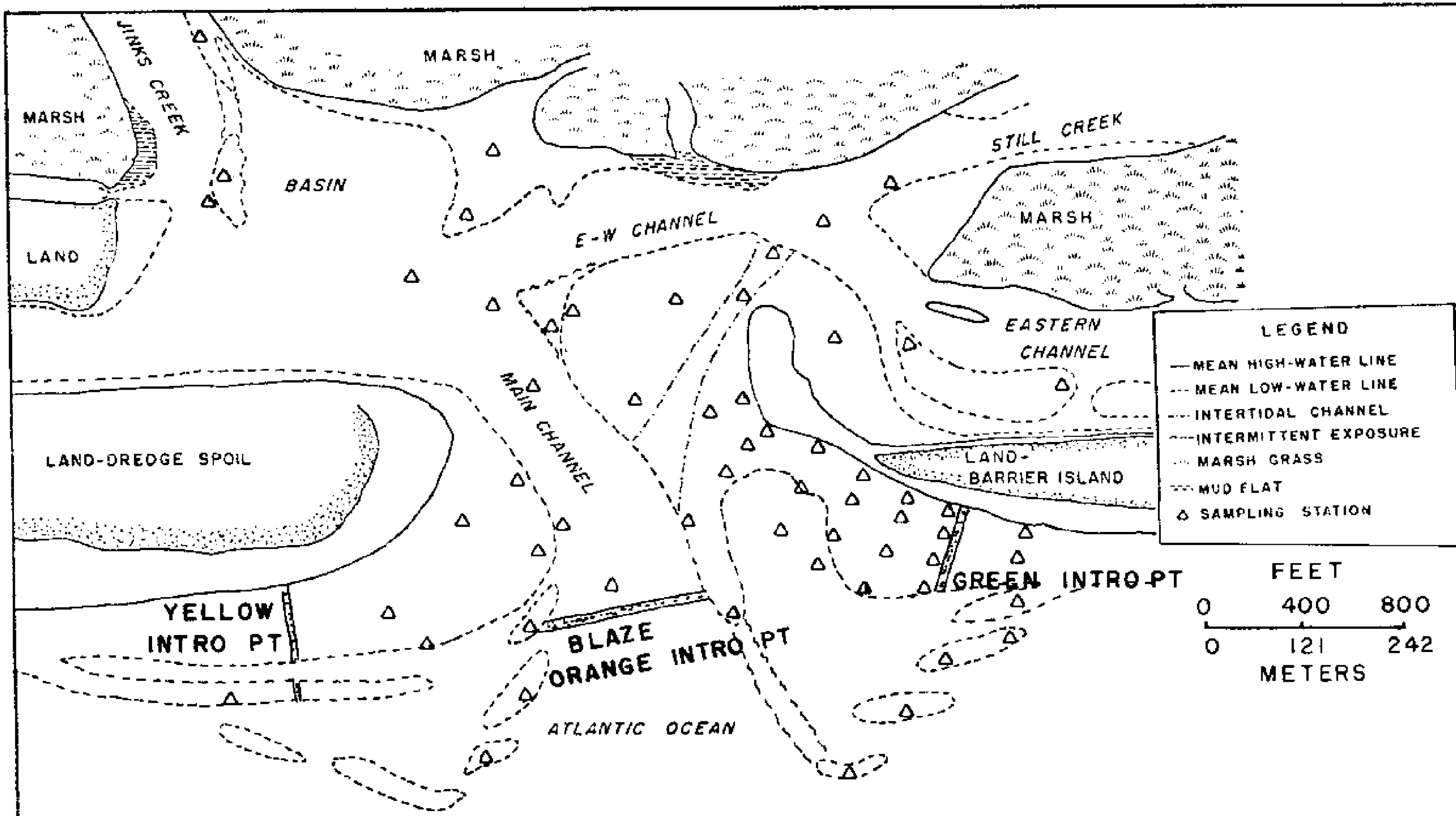


FIG. 24. TRACER INTRODUCTION AND SAMPLING STATIONS FOR THE FLOOD MOVEMENT TEST, 1 JULY 1972.

Card samples (and limited core samples) were taken continuously during the flood tide following introduction of the flood test tracers. Core samples from the intertidal sand and card samples from the subtidal channels were taken at low tide for four days after introduction.

Movement Patterns

Ebb Test Results

No definite pattern of tracer distribution was detected. This is due to two possible reasons: (1) tracer was restricted primarily to the major channels and was not distributed in concentrated amounts in the intertidal zone, and/or (2) the sampling technique (card method) did not sufficiently detect the tracer movement in the channel.

The tracer sand detected early in the test probably represented that tracer introduced into the subtidal channels (particularly Eastern Channel, with its high velocity - 0.80-0.90 m/sec).

Fire orange tracer was not detected in concentrated amounts in the intertidal channel within 72 hours of introduction. This indicates that Eastern Channel and Still Creek do not supply significant amounts of sand to the intertidal flat.

Tracers detected during each sampling period of the ebb test are discussed in Appendix E.

Flood Test Results

Initial tracer detection occurred as isolated grains and no distribution pattern was discernible. However, with the passage of time, concentration zones of tracer sand were detected and enabled determination of movement patterns.

Green tracer moved along the recurved spit into the inlet from the eastern beach (Refer to Figure 25 for location of station numbers). Green tracer was also detected in concentrated amounts on the western tidal flat (Station 6). Yellow tracer moved from the western beach alongshore to become concentrated on the eastern end of the western tidal flat (Station 6). Yellow tracer was also detected near the recurved spit on the eastern tidal flat (Station 7). Early detection of blaze orange tracer on the northern shore (Station 8) indicated sediment transport from the main channel. No early detection of yellow or green tracer on the channel-margin linear bars suggests that the adjacent beaches are not sources for these bars.

Inlet Bypassing and Littoral Drift

Blaze orange tracer from the main channel was detected 0.3 nautical mile (NM) (0.53 km) west of the inlet prior to detection of yellow tracer. Green tracer from the eastern beach was detected at the same time as yellow tracer. This suggests that a "null point" exists on the western beach, west of which sediment moves down the beach and each of which sediment moves into the inlet. This point may be approximately where the swash bars (ridge and runnel system) "weld" to the beach.

The westward movement indicated by the tracer suggests that local offshore topography may alter the expected direction of transport. It is difficult to explain the prominent westward movement in light of the southerly and southwesterly waves. Indefinite results were due to: (1) the study was not designed to test bypassing and, therefore, sampling

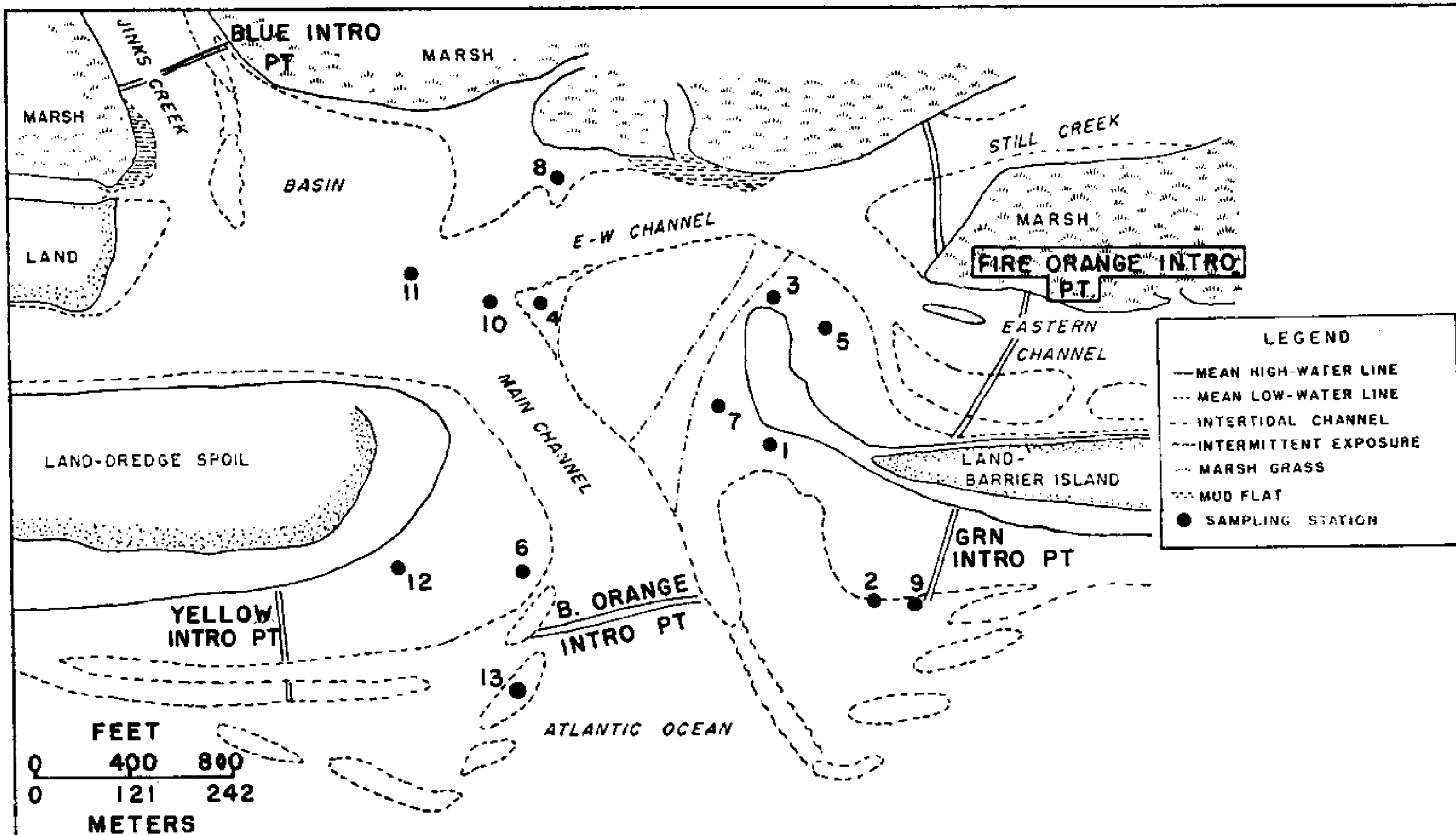


FIG. 25. STATIONS USED FOR CALCULATION OF TRACER MOVEMENT RATES.

NOTE: STATIONS REFERENCED IN TABLES 3 AND 4 AND TEXT.

was not sufficient, and (2) the placement of tracers in close proximity to the inlet prohibited tracers from being subjected to forces other than strong tidal currents and refracted waves.

See Appendix E for location of detected tracer sand during each sampling period.

Transport Rates

Individual Grain Transport Rates

Calculation of individual grain movement rates was possible based on the estimated path and distance of travel and elasped time to first detection. Table 3 shows grain velocities and estimated area of transport. The rates calculated for ebb flow compare very well, as do those for the flood test. The movement rates for tracers which originated from either beach were nearly equal (10 cm/sec). It is probable that the tracer grains were present at the sampling stations prior to detection; therefore, the movement rate was probably greater.

The transport rates for green, yellow, and blaze orange tracers were based on movement detected during the first two hours of flood tide. The path estimated (since the intertidal flat was not inundated) for the green and yellow tracer moved the grain alongshore to the vicinity of the main channel and then landward. By subtracting the distance traveled in the main channel and computing a velocity for the remaining distance over the remaining time, a velocity of 2.0 to 2.1 cm/sec (41 ft/min) was approximated for movement alongshore in the inlet.

Table 3. Approximate movement rates of individual tracer grains

Color Tracer	Source Location	Sample Location*	Elapsed Time-Hours	Primary Area of Transport	Velocity		
					cm/sec	ft/min	ft/hr
Ebb Tidal Flow							
Fire Orange	Intro Point	12 and 13	2.5	E-W channel to main channel then seaward	13.3	26.7	1600
Blue	Intro Point	12 and 13	2.5	Jinks Creek to main channel then seaward	11.1	22.2	1335
Flood Tidal Flow							
Green	Intro Point	11	2.0	Alongshore to main channel then inland	10.0**	20.0	1200
Yellow	Intro Point	11	2.0	Alongshore to main channel then inland	10.2**	20.5	1225
Blaze Orange	Intro Point	11	2.0	Through main channel	6.6	13.3	800

*See Figure 32 for location of the card sample locations used in calculation of movement rates.
**Velocities greater than for blaze orange tracer because of longer estimated travel path.

Concentration Zones Transport Rates

The movement of zones of medium concentration (5-20 grains/sample) and high concentration (20 grains) of tracer was best recognized along the recurved spit on the eastern tidal flat. The movement rate calculated for this tracer was approximately 0.5 cm/sec (62.5 ft/hr) to 0.66 cm/sec (79 ft/hr). These and other tracer movements rates are shown in Table 4.

Considering travel paths through the inlet, the average net landward transport velocity was 0.67 cm/sec (80.5 ft/hr).

The movement of the "sand mass" or zone of concentrated tracer occurred at a much slower rate than the individual tracer grains.

Alongshore Movement Rates

Detection of tracer sand 0.3 NM (0.53 km) east and west of the tidal inlet enabled calculation of approximate movement rates for tracer which moved out of and around the inlet and that which moved directly down the beach. Table 5 shows these rates.

Table 4. Approximate movement rates of concentration zones

Color Tracer*	Source Location	Sample Location**	Elapsed Time-Hours	Primary Area of Transport	Velocity cm/sec	Velocity ft/min	Velocity ft/hr
Green*	Intro Point	1	12	Med. to high water surf and swash zone-tidal current	0.66	1.32	79
Green	Intro Point	2	12	Low water surf and swash-tidal current	0.14	0.28	16.7
Green*	Intro Point	3	24	High water surf and swash-tidal current	0.5	1.04	62.5
Green*	Intro Point	4	24	Tidal current across intertidal flat	0.69	1.38	83.0
Green	3-end of spit	5-back barrier	12	High water tidal current around end of spit	0.21	0.42	25.0
Green	Intro Point	6	36	Across flat and main channel	0.42	0.84	50.0
Green	4	6	12	Ebb current through main channel	0.84	1.67	100.0
Yellow*	Intro Point	7	12	Flood tidal current	1.39	2.78	167.0
Blaze Orange*	Intro Point	8	24	Flood tidal current	0.63	1.25	75.0
Blaze Orange	Intro Point	9	24	?	0.32	0.63	37.5

Average net movement velocity of tracer through the inlet: 0.67 cm/sec (1.34 ft/sec - 80.5 ft/hr)

*Indicates movement rates used in calculating average velocity which resulted in sediment movement through the inlet.

**See Figure 32 for location of the sample locations used in calculation of movement rates.

Table 5. Approximate alongshore movement rates

Color Transport	Source Location	Sample Location*	Elapsed Time-Hours	Primary Area of Transport	Velocity		
					cm/sec	ft/min	ft/hr
Blaze Orange	Intro Point	0.3 NM West	36	Probably seaward from inlet gorge then alongshore	0.74	1.48	88.8
Green	Intro Point	0.3 NM West	48	Bypassed inlet or carried to main channel then seaward and alongshore	0.76	1.52	91.6
Yellow	Intro Point	0.3 NM West	48	Probably directly down the beach or into main channel then seaward and alongshore	0.30	0.63	37.5
Green	Intro Point	0.3 NM East	60	Probably directly down the beach	0.25	0.5	30.0

*Samples collected 0.3 nautical miles east and west of inlet at low water.

SEDIMENT TRANSPORT IN TUBBS INLET

Generalized Sediment Movement Pattern

Based on the analysis of bedform and sedimentary structure orientation, tidal current flow data, and movement of tracer sand, a generalized sediment movement pattern for the inlet system was established. Figure 26 shows this generalized pattern.

Sediment moves into the estuary through the inlet primarily over the eastern tidal flat along the recurved spit. This movement occurs during the latter portion of the flood tide cycle. Three reasons lead to this conclusion: (1) the detection of green tracer sand close to the high-water line, (2) the results of the nonfluorescent sand experiment which indicated more transport and deposition on the intertidal flat near the spit, and (3) measured flood currents within the channels reached maximum velocity near the middle to late portion of the flood cycle.

Net sediment movement through the intertidal channel across the eastern flat was landward based on detection of flood test tracer and the absence of ebb test tracer sand.

The pattern of transport from the western beach suggested by bedform orientation and flow data was confirmed by tracer movement (i.e., movement alongshore toward the inlet gorge and not directly across the tidal flat). This was primarily a function of beach and intertidal flat profile gradient. The western beach and southeastern portion of the flat were wide and gently sloping. However, the slope increased steeply

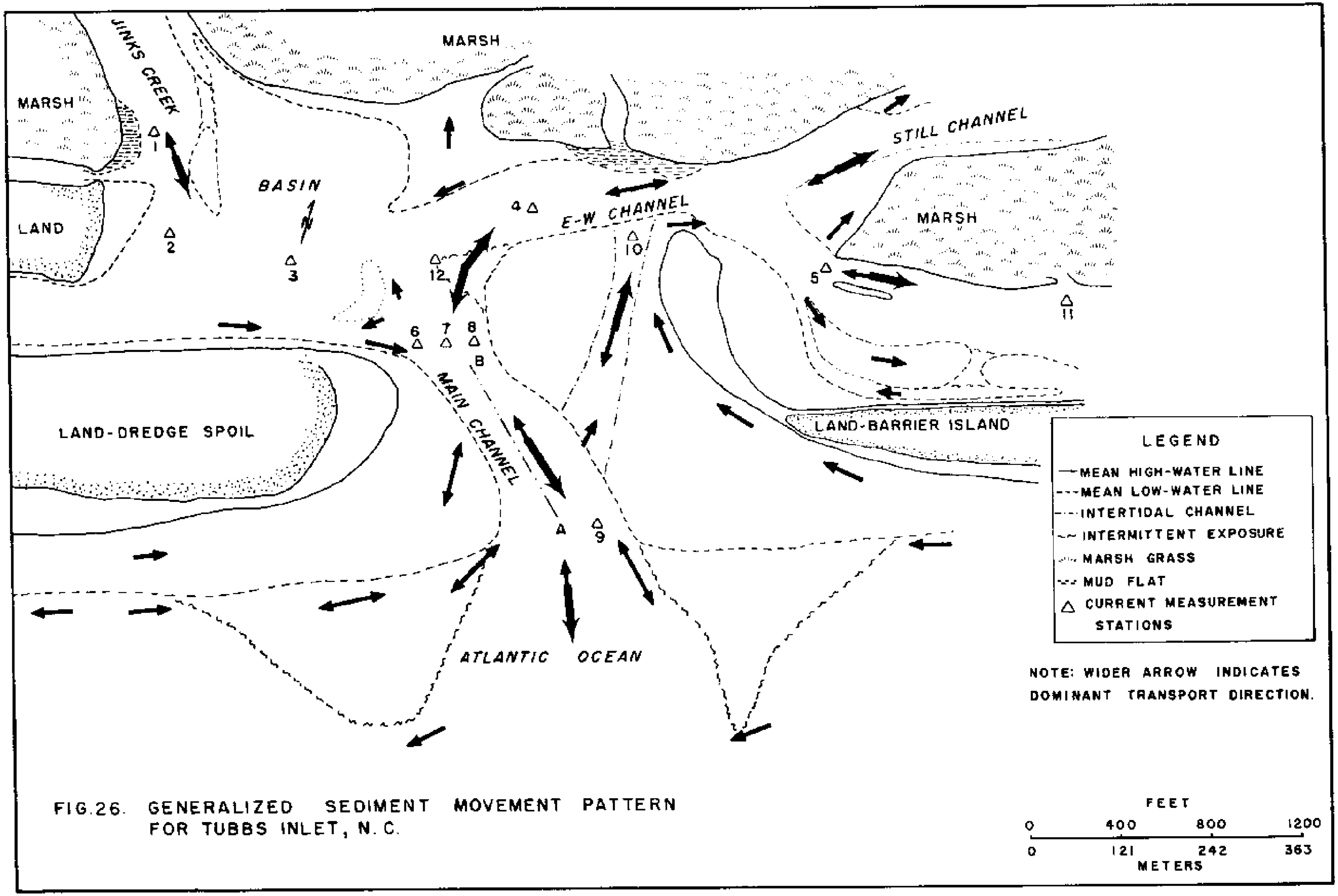


FIG. 26. GENERALIZED SEDIMENT MOVEMENT PATTERN FOR TUBBS INLET, N. C.

toward the northern portion of the flat; therefore, the western flat was completely inundated only at maximum high water when flood current velocity was low. This resulted in negligible transport high on the beach and flat profile, especially near the northeastern portion of the flat where the elevation was highest. The steepness of the main channel intertidal bank and the high intertidal flat concentrated the incoming flow along the seaward portion of the flat. This flow pattern resulted in deposition and progradation of the southeastern portion of the flat.

Flood currents through the inlet gorge distributed sediment over the entire inlet system; however, the bar on the northern shore (Station 8, Figure 25) was the major depositional site for this sediment. The quantity of sand entering the inlet through the channel from the ocean was considered small in comparison to that originating from the intertidal flats and beaches. Net sediment through the main channel was seaward.

Ebb flow predominated in Jinks Creek; however, tracer from Eastern Channel was detected in Jinks Creek indicating flood flow transport of sand into that channel.

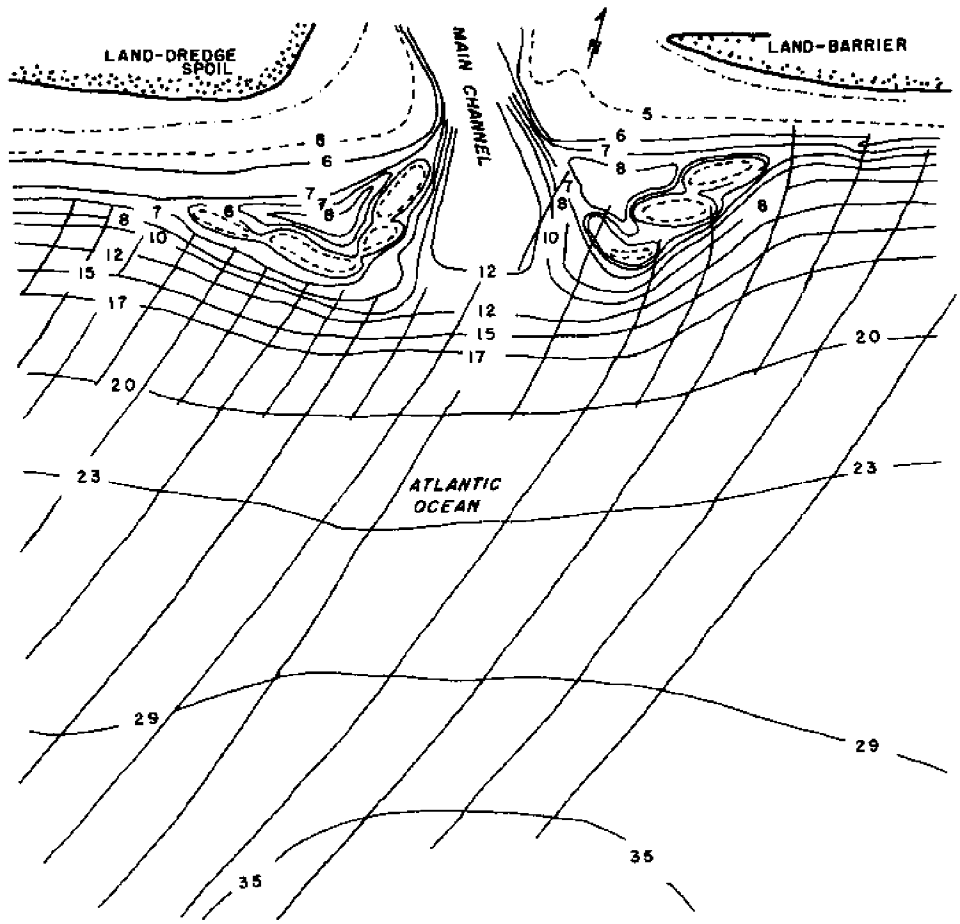
Eastern Channel and Still Creek received sediment introduced by flood currents, thus restricting the ebb flow and reducing the flushing ability of those streams.

Inlet Dynamics

The primary factors controlling sediment transport in an inlet environment are tidal currents and waves. During low water waves shoal or break on the swash bars of the ebb-tidal delta (see Figure 14) and affect sediment distribution in the inlet very little. The sediment bypassing the inlet as part of the bar network and the sediment from the major ebb channel are, however, influenced by the incoming waves.

Increased water depth over the inlet system during flood tide allows waves to become an active transport agent within the inlet. Incoming waves are refracted by the ebb-tidal delta and are focused toward the inlet. See Figure 27 for a wave refraction diagram for Tubbs Inlet. Waves appear to be concentrated toward the eastern side of the inlet due to wave approach and bottom topography.

Turbulence from breaking waves places sediment into suspension which is then transported by the flood current flowing as a sheet over much of intertidal sand flats.



0 400 800 1200 1600
FEET

DEPTH CONTOURS IN FEET FROM MEAN HIGH-WATER LINE.

LEGEND

—·— MEAN HIGH-WATER LINE
---- MEAN LOW-WATER LINE
—X— BOTTOM CONTOUR LINE
—— INCOMING WAVE ORTHOGONAL

NOTE: WAVE APPROACH IS FROM SOUTHWEST (205 DEGREES) WITH A PERIOD OF 5 SECONDS. THE WAVES REFRACT AROUND THE EBB-TIDAL DELTA AND BREAK INTO THE INLET.
NEARSHORE BATHYMETRY SURVEYED DURING STUDY PERIOD. OFFSHORE BATHYMETRY GENERALIZED FROM NAUTICAL CHARTS 835-SC AND 1236.

FIG. 27. WAVE-REFRACTION DIAGRAM AT THE MOUTH OF TUBBS INLET AT MAXIMUM HIGH WATER.

CONCLUSION

General

The movement pattern indicated by the tracer study was in good agreement with the pattern suggested by mapping of bedform arientation and analysis of flow data. However, the tracer did allow refinement of local transport patterns not reflected in the preserved bedforms.

The significance of flood-tidal flow was confirmed by use of tracers, especially the movement of sediment from the western tidal flat to the eastern intertidal flat. This movement was not suggested by analysis of the preserved bedforms and current measurements may not explain this movement.

This movement of tracers from western to eastern (and vice versa) and movement landward through the gorge possibly indicated that significant sediment was moved in suspension.

Modification of flood-oriented megaripples to ebb-oriented megaripples in the northern portion of the intertidal channel indicated current of greater than 80 cm/sec and suggested significant seaward sediment transport. After evaluating the tracer movement, seaward transport through the intertidal channel was not deemed significant.

The generalized sediment movement pattern recognized as a result of this study complements the model suggested by Hayes and others (1972) for a typical inlet with a comparable tidal range.

Evaluation of Tracer Technique

The technique of using tagged sand in the inlet environment to monitor qualitative sediment movement was proved to be valid.

Detection of sediment movement patterns and calculation of movement rates were possibly based on tracer dispersal. Movement rates of individual grains and concentration zones revealed that isolated grains can travel many times faster than the migration of a "sand body."

The tracer technique revealed that there were areas where sand was consistently deposited and served as sources for redistribution and redeposition. The tracer technique demonstrated that there was a net estuarine transport of sand into the inlet system and that it was possible to trace this transport.

To evaluate the usefulness of the tracer technique in this environment without any supporting evidence would be difficult; however, when used concurrently with other methods of study, it provides valuable information.

Recommendations for Additional Research

The results of this study (i.e., the history of the inlet, the sediment distribution pattern, the current data, sediment movement data, description of bedforms, and mapping of the inlet) has provided a data base with which further research can be conducted.

The presence of inlets in a barrier island affects beach and dune stability by providing a means by which beach sand is lost to the estuary. The reintroduction of the sediment from the estuary back into the alongshore transport system through the inlet is dependent upon the flushing ability and stability of the inlet. This study has provided data which should be applied to further study of natural bypassing and down-drift beach nourishment. It is recommended that such a study be conducted so that a quantitative estimate of material entering the inlet compared to that bypassing the inlet be established. A corollary objective of such a study would be to determine an accurate relationship between littoral drift and inlet stability.

Data from this study could be used as a basis for a quantitative estimate of material moving into the inlet if a reliable sand movement depth could be calculated.

Inlets along the North Carolina coast provide excellent locations for research. Many are small, unimproved, and easily accessible and are actively changing.

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APPENDICES

Appendix A

Tracer Sand Production Procedure

The method of marking sand with fluorescent paint used in this study was first discussed by Yasso (1966) and later by McArthur (1969). The components are "Day-Glo Acrylic Lacquer Safety Paint," Union Carbide "VMCH Vinyl Plastic," and two organic solvents: toluene, $C_4H_5CH_2$, and methyl ethyl ketone, $CH_3COC_2H_5$. The proportions found to give the best results are given in Table 6.

Table 6. Paint and solvent mixture[a]

Acrylic lacquer paint	500 gms (1.1 bls)	1980 gms (3.36 lbs)	Tracer Sand
Toluene	500 gms (1.1 lbs)		
Vinyl plastic	100 gms (0.22 lbs)		
Toluene	700 gms (1.54 lbs)		
Ketone	180 gms (0.4 lbs)		
Sand (dry)	2500 gms (55 lbs)		

[a]Adapted from McArthur (1969)

The mixture of paint and toluene and the mixture of plastic, toluene, and ketone can be mixed several weeks prior to use; however, the two mixtures should be combined only shortly before mixing with the sand.

To dry the wet sand for dyeing, the sand was placed in a portable concrete mixer (6 cu ft capacity) into which heated air was blown from a space heater (120,000 BTU capacity). The dry sand was removed and mixed with the paint and plastic mixture while still hot. The tagged sand was placed into the mixer and tumbled to allow the solvents to vaporize and leave a thin fluorescent coating on the grains. The configuration of equipment is illustrated in Figure A1.

Several modifications to McArthur's method (1969) were found to be important in preparing large quantities of tracer sand:

1. It was important to mix the toluene with the plastic prior to adding the ketone. This prevented clumps of plastic. The proportions given in Table 6 involved slightly less plastic than recommended by McArthur and further decreased the tendency of the plastic to clump.

2. The concrete mixer and space heater mentioned previously are larger than discussed by McArthur. It was found that this equipment allowed tracer to be produced in convenient 55 lb (25 kg) batches. Drying and heating time for this amount of sand was approximately 35 to 45 minutes. Total preparation time for the 55 lb (25 kg) batch was about one hour.

3. Aggregation problems were minimized by screening the dyed sand while putting it back into the mixer for drying.

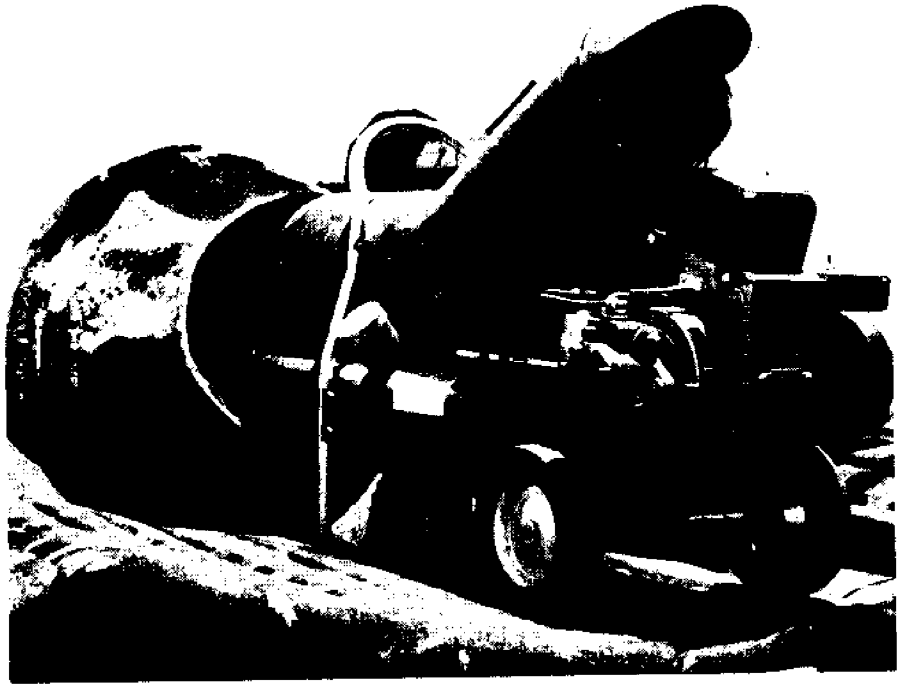

FIG. A1. EQUIPMENT USED IN PREPARATION OF TRACER SAND.

Tracer Introduction

Water soluble bags were used to place tracer on the channel beds without placing it into suspension. Observed release time for water soluble bag sediment was approximately 45 seconds from entry into the water. For ease of handling and more even distribution across the channels, only 25 lbs of dyed sand was placed in each bag. Lack of pre-wetting of the dyed grains to overcome surface tension presented no significant problem when the tracer was introduced into a relative high energy environment such as the estuarine channels (0.49 to 1.2 m/sec current).

To test the movement of the tracer from all environments (subtidal and intertidal), it was necessary to place the soluble bags of tracer into the shallow water of the intertidal zone. Due to the low velocity conditions in this zone, (accentuated by a neap tide of approximately four ft) the tracer remained in place. Some tracer had to be physically crushed and distributed into the natural sand. Tracer was observed in the immediate vicinity of the introduction points four days after introduction. The colored sand was observed to have been incorporated into the bedforms after two tidal cycles. This problem was restricted to Marsh Point (Area 7), and to a limited degree on Eastern Channel shoal (Area 9), and near the eastern bank of Jinks Creek.

Tracer introduction on the beach between low and high water was accomplished by spreading the dyed sand on the surface and mixing to a 50 percent concentration with the beach sand by raking. The depth of mixing was approximately 1.3 cm, and patches of dyed sand 1.8 to 3 meters square were placed every 7 to 8 meters perpendicular to the waterline. It was necessary to wet the dyed sand prior to introduction. Figure B1 illustrates this method.

Sampling Techniques

The technique of using vaseline or grease coated cards attached to a pole or lead weight for retrieval of sand grains from the surface was described by Ingle (1966) and served as a basis for the card sampling technique used in this study.

Heavy black cards, 3 x 3 in (8.5 cm), were coated with vaseline prior to entry into the surf zone or boat departure from shore. Coated cards were placed on clipboards (Figure B2) which were easily carried into the water, or in the boat. Wooden poles and 5.45 kg lead blocks (Figure B2) were used as means of placing the card firmly and squarely on the sand surface. Rubber bands were used to attach the card to the poles and lead blocks. The sand coated cards were removed and placed in small plastic bags on which was marked the sampling grid location, date, and time. The bag was then returned to the clipboard. Two persons working as a team were required to use this technique satisfactorily. Three teams were used to cover the inlet--one team on either side of the main channel on the intertidal flats, and the third team sampling the channels and deeper subtidal portions from the boat. Due to the relative high energy conditions of the inlet resulting in burial of tracer material and large distances of sample locations from the introduction points, the card samples proved reliable only through the first two tidal cycles after introduction.

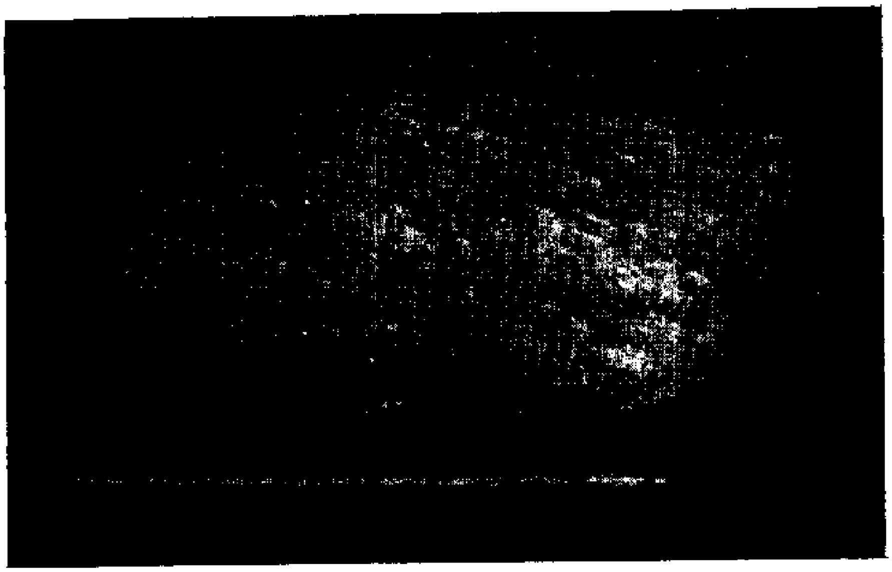

FIG. B 1. INTRODUCTION OF TRACER SAND BY RAKING INTO BEACH.

FIG. B 2. SAMPLING EQUIPMENT.

A. CORE BARREL AND DRIVING BOARD
B. POLE WITH 8.5 X 8.5 CM SAMPLING CARD
C. CLIPBOARD FOR HOLDING SAMPLING CARDS
D. 5.45 KG LEAD BLOCK WITH CARD

Card sampling during the first day of the ebb test was hampered by contamination problems. Some tracer was spilled into the boat and, as a result, card samples taken from the boat during the first few hours were possibly contaminated. Therefore, most of the card samples of the first day of the ebb test, which reflect the initial ebb movement, are not incorporated in the results of this study. The contamination problem was solved by thoroughly washing the boat and by using plastic gloves while applying vaseline to the cards.

The card method was useful for sampling sand transported on the surface at the instant of sampling which was the resultant of the energy conditions at that time. In an inlet, energy conditions are constantly in a state of flux as a result of the tidal phase. Therefore, it is necessary to obtain material representative of the complete energy spectrum, *i.e.*, the complete tidal cycle.

This was accomplished by taking 30 cm (12 inch) core samples from the tidal flat, bars, and beaches while exposed at low tide. Shallow subtidal areas were also sampled with cores.

Seventy-five core barrels were made from plexiglass tubing so that the entire inlet could be sampled expeditiously without having to clean out the core barrels between samples.

Detected concentrations were compared relatively so that zones of concentrations could be mapped and their migration monitored. McArthur (1969) in working on a beach in the vicinity of Panama City, Florida, concluded one point sample satisfactorily characterized tracer concentration in the general vicinity of a sample station.

The core tube was pushed or hammered into the sand with a 2 x 4 inch (5 x 10 cm) board. A cork was placed in the top creating a vacuum when the tube was pulled upward. Sample recovery was virtually 100 percent. Sample location, date, and time were marked on the tube with a waterproof felt-tip pen at the time of sampling. The sand cores were later placed in plastic bags and labeled. No attempt was made to retain the original vertical distribution of sand within the core.

The sand samples were placed on paper plates in the laboratory and allowed to dry at room temperature. Card samples were retained in the original plastic bags in case any grains may have been removed from the card during handling; however, this presented no problem.

Appendix C

Analytical Methods

The analysis of the core samples was performed in the laboratory by counting the number of coated grains. The sand was spread on a black surface and examined in darkness under a long wave ultra-violet light. Card and core samples were analyzed in the manner illustrated in Figure 31. Area of the card covered by sand was estimated using a grid over the card (Figure C1). The brilliance of the fluorescent paint and recognizable colors facilitated rapid recognition of the coated grains from non-coated grains. The accuracy of the counting procedure was tested by duplicating the analysis of three samples several times over four days. The resulting count each time was nearly identical. Objectivity during analysis was retained by keeping the sample location unknown until after analysis was complete. All analytical work was performed by the author to reduce operator variables.

Analytical time for each core sample was 15 to 20 minutes. Card samples took only 8 to 10 minutes to analyze.

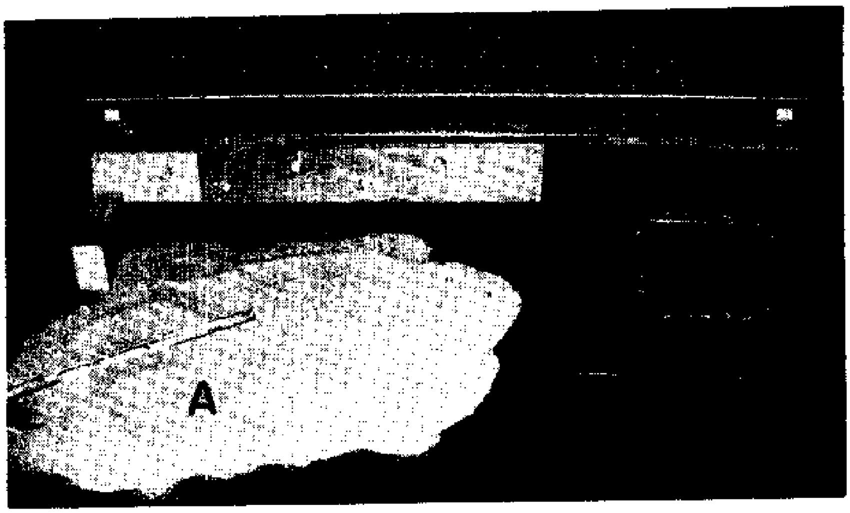

FIG. C1. ANALYTICAL METHODS.

A. SAND FROM CORE BARRELS
B. CARD SAMPLE WITH GRID FOR ESTIMATING AREA OF CARD COVERED BY SAND
C. LONG WAVE ULTRA-VIOLET LIGHT

Appendix D

Surveying Technique

The sample grids on the intertidal flats were surveyed using a transit and stadia board. A range pole held vertically in the boat allowed very good range and bearing approximations for placing buoys in the subtidal environment. Two-way communications (walkie-talkies) between the surveying instrument and rodman and boat facilitated placement.

Sampling positions were marked by anchors and buoys. Anchors were made by filling one-gallon plastic milk cartons with concrete. Floats were one-half gallon milk cartons with grid locations painted on the side. The anchors were buried about one foot deep initially in the intertidal and shallow subtidal environments, but many were uncovered with each tidal flow. The anchors remained stationary in all locations except the shallow high velocity environments, such as the intertidal channel and breaker zone. These had to be relcoated on several occasions and their positions rechecked regularly. Buoy markers were placed at alternate sampling positions and the intervening positions were estimated by sighting down the row of buoys.

Appendix E

Detailed Description of Tracer Sand Movement

General

Card samples and core samples were collected continuously during the first tidal flow after introduction and at subsequent low tides until completion of the test. Detailed results of the sample analysis and location maps of the detected tracer sand are discussed for the ebb movement and flood movement tests. It is necessary to use the maps to follow the discussion. See Figures 23 and 24 for location of introduction and sampling stations.

Ebb Movement Test

Initial Movement - 23 June AM. Due to inconclusive results of the first day samples (see Appendix B), it was not possible to delineate source or depositional areas. However, the samples collected during the morning of 23 June near Eastern Channel and on the western tidal flat and ebb-tidal delta were valid. Blue and fire orange tracers were present in samples from the western swash bars (channel-margin linear bars) taken during mid-ebb flow. The locations of the detected tracers are shown in Figure E1 (Station 13).

Subsequent Movement - 23 June, Midnight Low Tide. Core samples from the eastern tidal flat and flood-tidal delta collected at the midnight low tide, 23 June, 18 hours after introduction, contained tracer as shown in Figure E2. The tracers in these samples were probably due to redistribution instead of a direct supply to the intertidal areas. However, it does indicate that the estuarine channels do supply sand

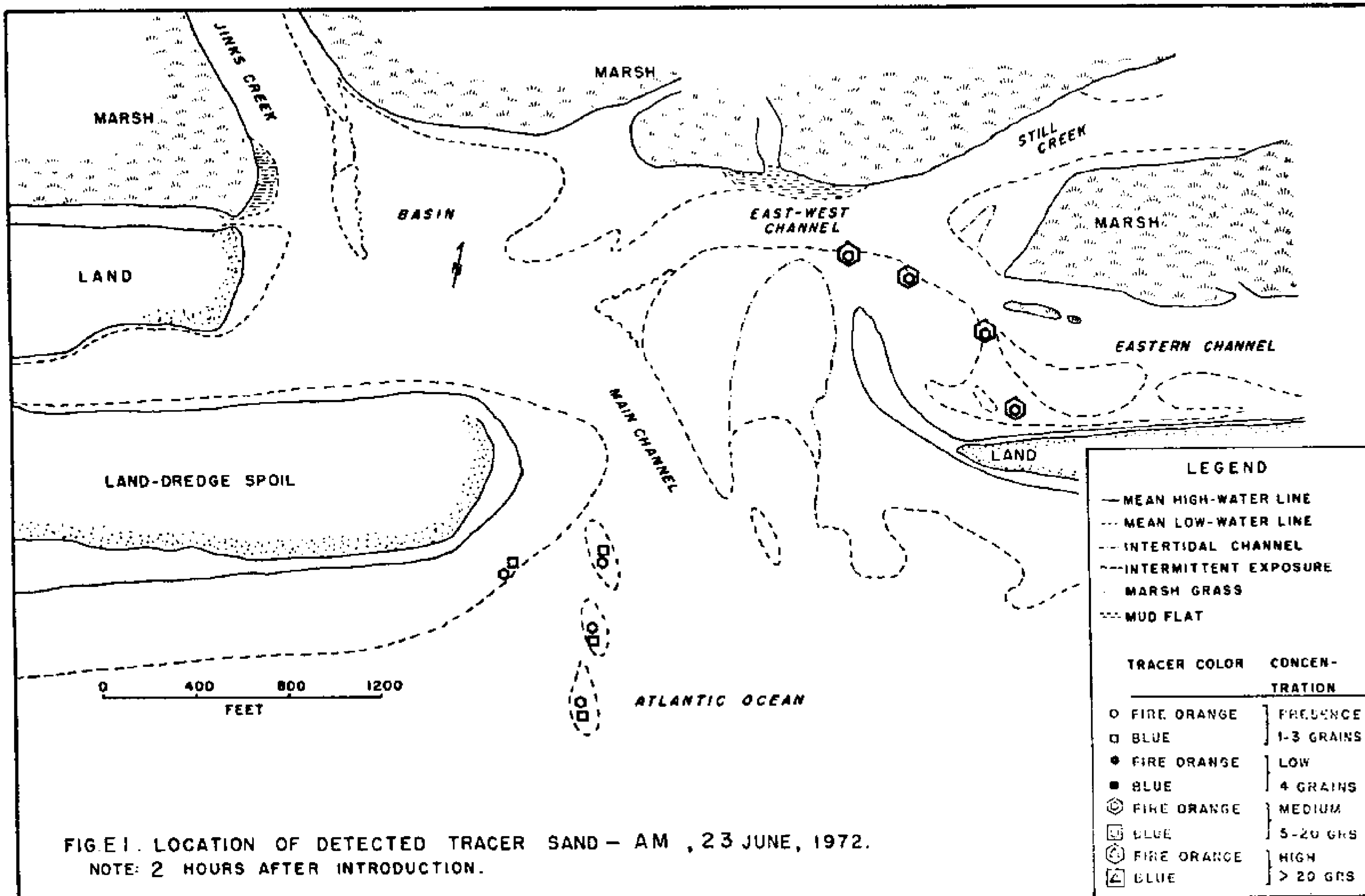

FIG.E1. LOCATION OF DETECTED TRACER SAND – AM , 23 JUNE, 1972.
NOTE: 2 HOURS AFTER INTRODUCTION.

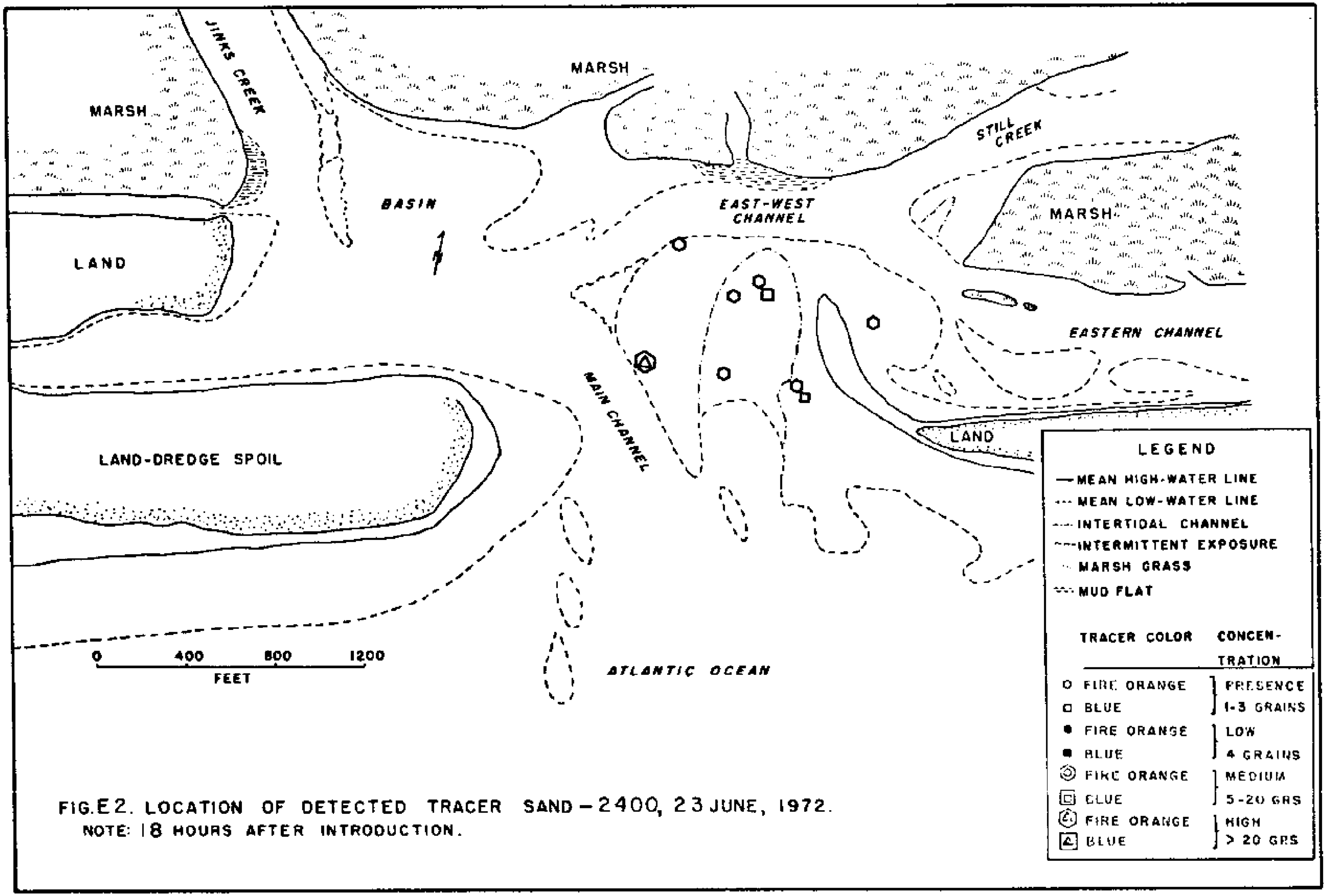

FIG. E2. LOCATION OF DETECTED TRACER SAND - 2400, 23 JUNE, 1972.
NOTE: 18 HOURS AFTER INTRODUCTION.

for the entire inlet system. Tracer had moved seaward around the end of the spit on the eastern flat. Tracer detected at noon 24 June did not contribute meaningful data to the dispersal pattern; however, the sample locations are shown in Figure E3.

25 June, Noon Low Tide. It was not until low tide at noon on 25 June, 54 hours after introduction, that a pattern of sediment movement was detected. See Figure E4 for locations of detected tracers. Tracer was found concentrated along the western side of the main channel and the western tidal flat. A detectable amount of tracer was not found on the eastern intertidal sand flat. Some Eastern Channel and Still Creek tracer was detected near the western tip of the flood-tidal delta (Figure E4, Station 4). A detectable amount of fire orange tracer was found in Jinks Creek. Fire orange tracer was consistently detected on the lee side of the ebb spit of Jinks Creek.

26 June, Noon Low Tide. Three days after introduction, zones of concentration remained detectable; however, tracer had been dispersed over most of the eastern intertidal flat as seen in Figure E5. The blue tracer from Jinks Creek was prominent on the western side of the inlet. Tracer sand was also detected on the swash bars (channel-margin linear bars) west of the seaward mouth. Fire orange tracer was found to surround the recurved spit of the eastern flat and was concentrated near the high water shoreline and in the ebb-oriented bedforms of the intertidal channel. Blue tracer was also detected in medium concentration near the low-water shoreline on the eastern beach. Sufficient fire

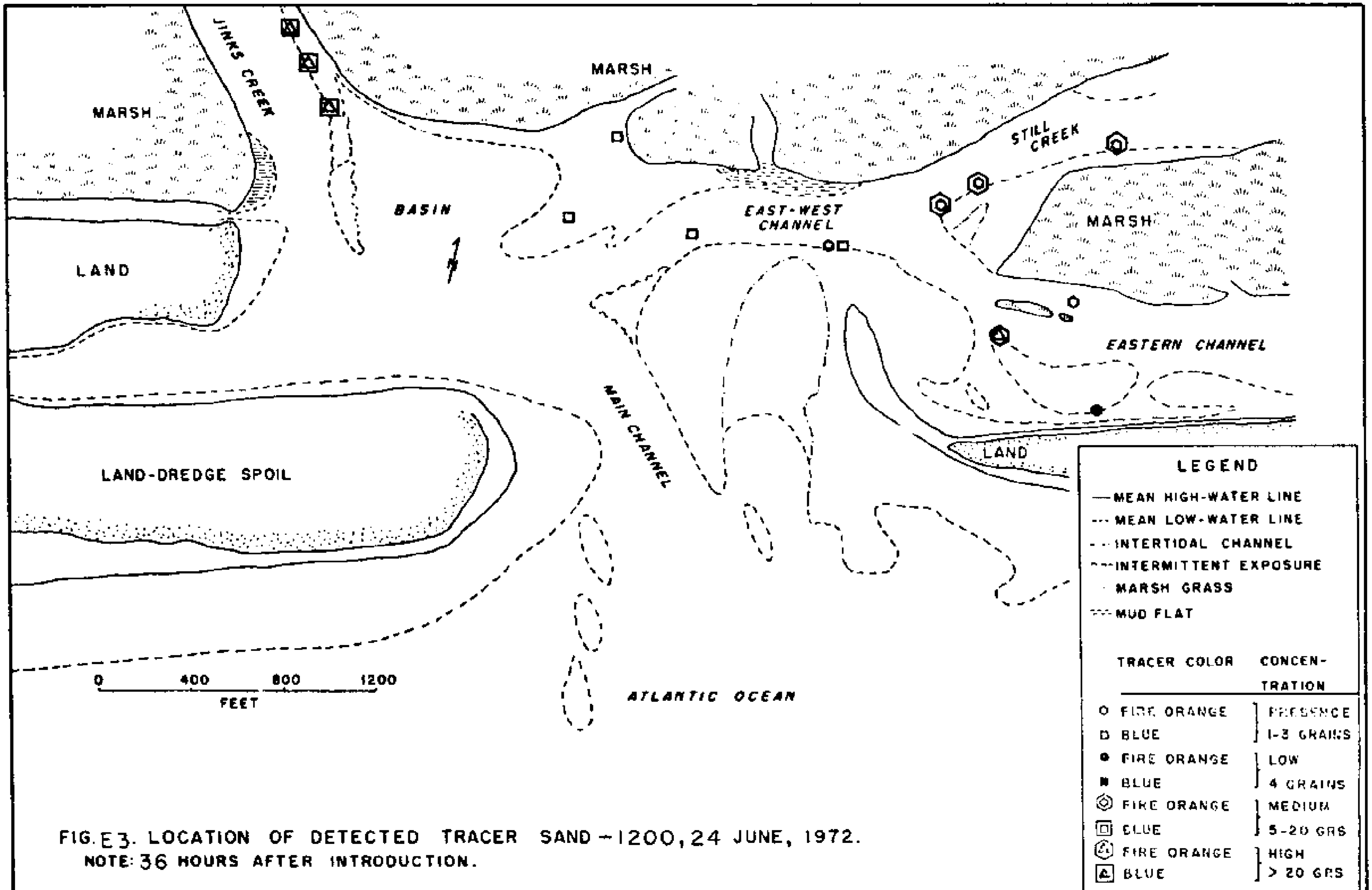

FIG. E3. LOCATION OF DETECTED TRACER SAND - 1200, 24 JUNE, 1972.
NOTE: 36 HOURS AFTER INTRODUCTION.

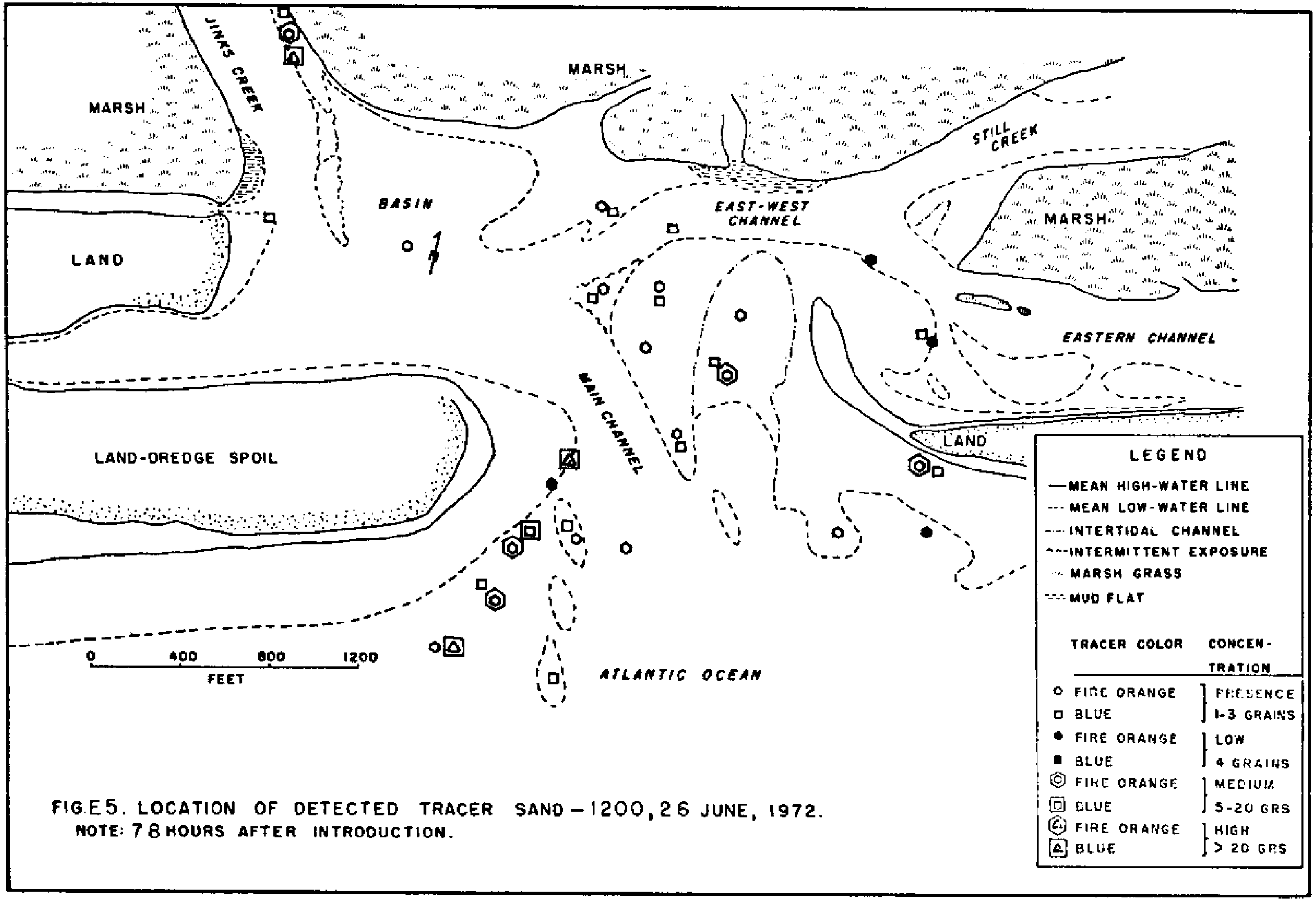

FIG.E5. LOCATION OF DETECTED TRACER SAND – 1200, 26 JUNE, 1972.
NOTE: 78 HOURS AFTER INTRODUCTION.

orange tracer had entered Jinks Creek to become concentrated in the ebb-oriented bedforms of that channel.

Flood Movement Test

Initial Movement - 1 July AM Flood Tide. Blue and fire orange tracers from the ebb movement test were recovered but were disregarded in this discussion.

Sampling began in the channels at approximately 0730, 1 July, and on the intertidal portions at 0830 and continued until about 1600. By 0800, all three color tracers had been found on the subtidal bottom near the point of the flood-tidal delta (Figure E6, Stations 10 and 11).

Sampling during slack high water (noon, 1 July) detected green and blaze orange tracers in the mouth of Still Creek and green tracer in the flood-oriented bedforms on the northern side of Still Creek. Stations 10 and 11 (Figure E6) mark the limit of yellow tracer into the inlet during the first flood tide.

Yellow tracer was detected on card samples at Station 7 (Figure E6) about two hours into the following ebb cycle.

Subsequent Movement - 1 July, PM Low Tide. Figure E6 shows that after 12 hours from introduction, green and blaze orange tracers were detected over much of the inlet system. Concentrated green tracer was detected west of the green tracer introduction point near the low-water shoreline. Green tracer had moved further along the recurved spit into the inlet in the high-water surf and swash zone. Green tracer was detected across the main channel on the western beach and swash bars. No tracer was detected in Jinks Creek after 12 hours.

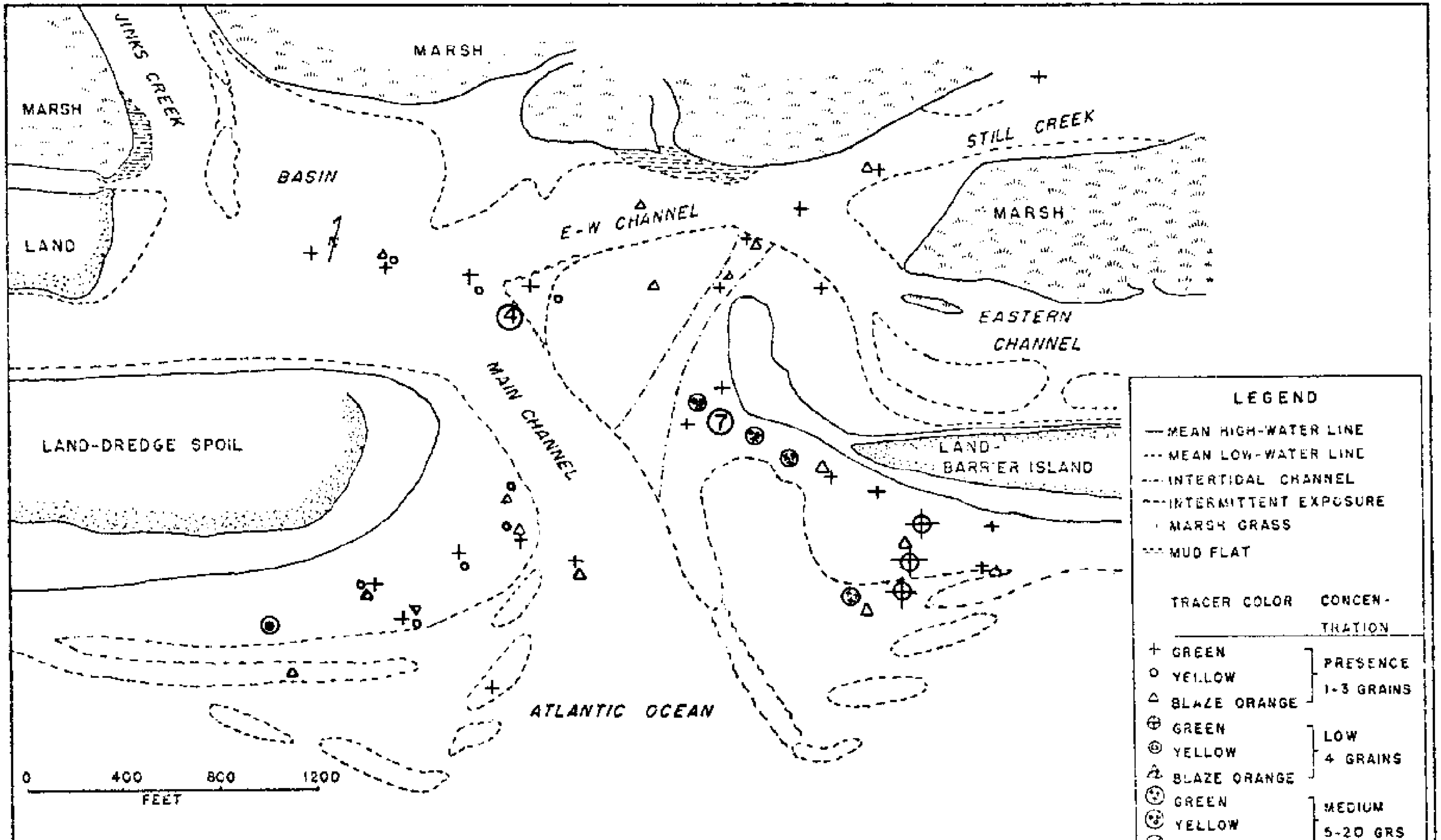

FIG. E6. LOCATION OF DETECTED TRACER SAND – **PM**, **1** JULY, 1972.
NOTE: **12** HOURS AFTER INTRODUCTION.

Yellow tracer was detected in concentrated amounts across the main channel on the eastern intertidal flat in the vicinity of the intertidal channel at Station 7, as shown in Figure E6. Yellow sand was also detected in numerous samples along the southern portion of the western tidal flat.

Blaze orange tracer from the main channel was found to be present over much of the intertidal environment, in the basin, and in E-W channel.

2 July - AM Low Tide. Sampling at low water, the morning of 2 July (24 hours after introduction), revealed that green tracer was highly concentrated in the same location as 12 hours previous. (See Figure E7 for these locations). Green tracer was also concentrated at the end of the spit and on the western point of the flood-tidal delta (Figure E7, Station 4).

The concentrated yellow tracer of 1 July AM low tide at Station 7 was not detected. The transport of sediment through the main channel to the northern shore of the inlet was indicated by the concentration of blaze orange tracer on diamond shoals. Blaze orange tracer, which was present in samples from eastern beach of 1 July PM, was found in concentrated amounts by 2 July AM. Unfortunately, only one sample from the western beach was obtained at this time. This one sample did contain yellow tracer.

2 July - PM Low Tide. Figure E8 shows tracers detected in samples collected 36 hours after introduction. The green tracer was not detectable in medium or high concentration along most of the intertidal

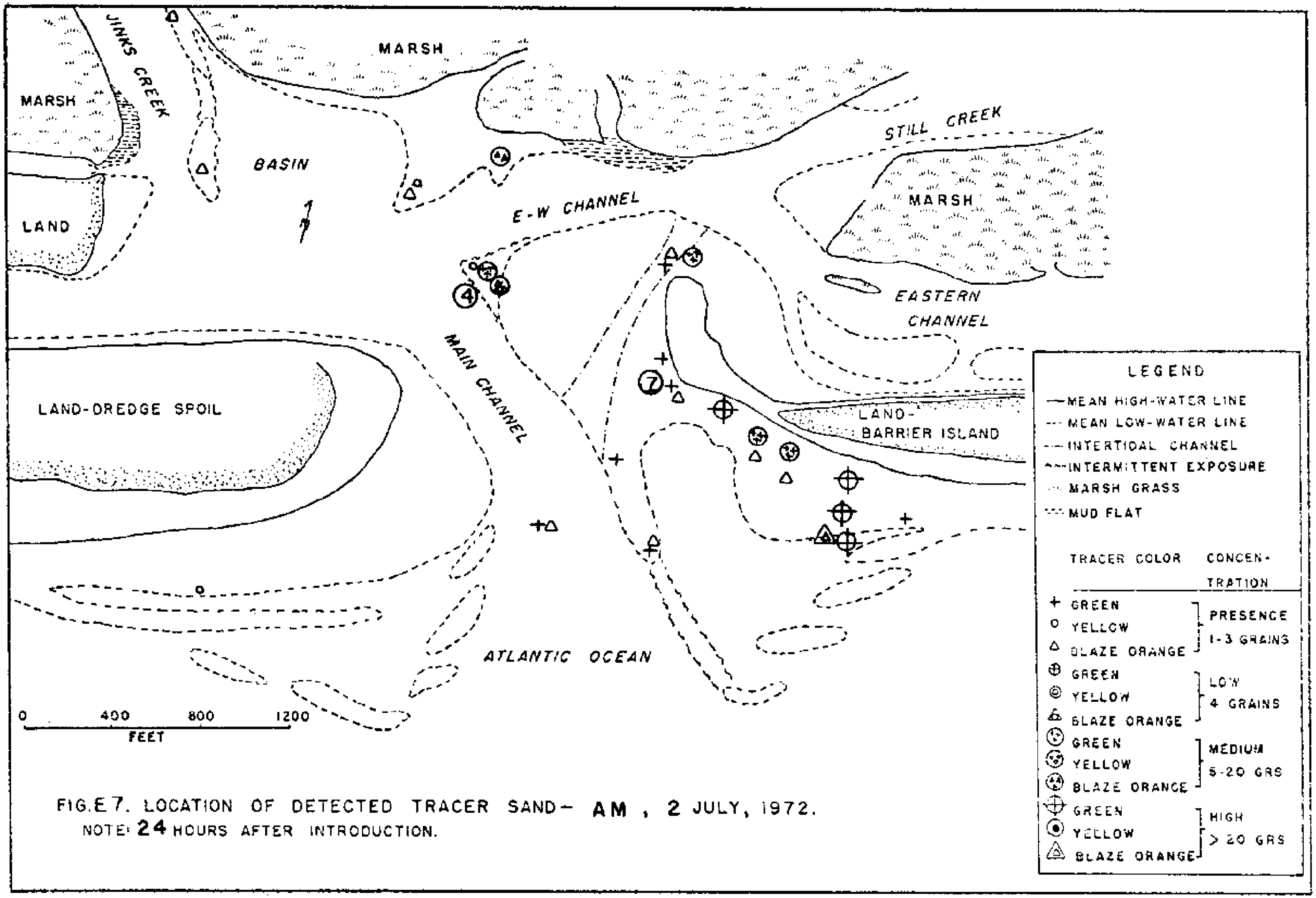

FIG. E 7. LOCATION OF DETECTED TRACER SAND – **AM**, 2 JULY, 1972.
NOTE: **24** HOURS AFTER INTRODUCTION.

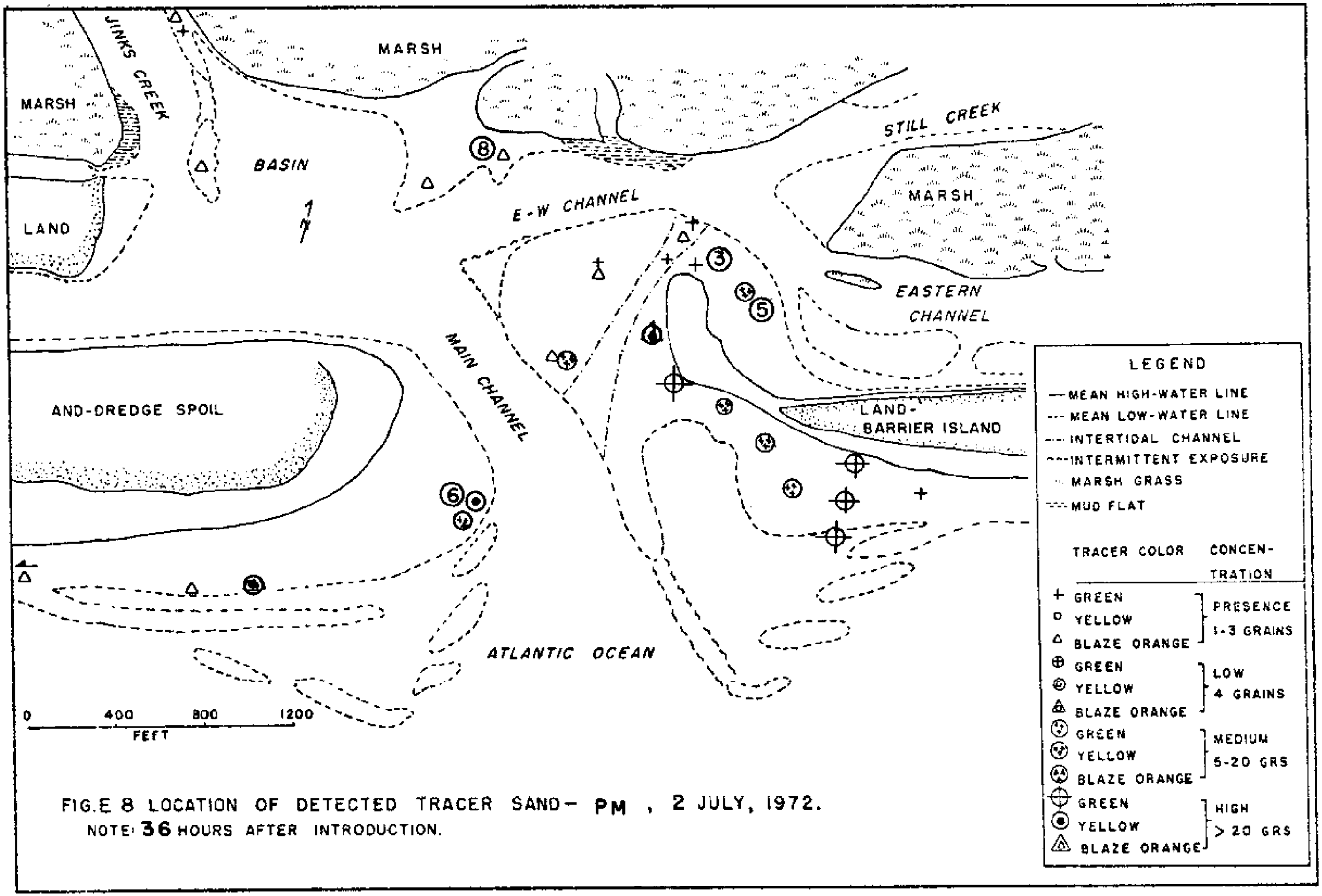

FIG.E 8 LOCATION OF DETECTED TRACER SAND– PM , 2 JULY, 1972.
NOTE: 36 HOURS AFTER INTRODUCTION.

zone on the eastern beach corresponding to high-water swash and surf zones. Sufficient green tracer had migrated around the end of the spit (Station 3) to become concentrated in the back barrier sand flat (Station 5). Green tracer had also become concentrated on the eastern end of the western tidal flat (Station 6). Jinks Creek received green and blaze orange tracers during the previous flood tide.

The concentration of yellow tracer was again detected near the spit (south of Station 3) on the east intertidal flat. Yellow tracer was detected in concentration along the low water area of the western beach. It was also present in samples from the vicinity of Station 8.

No concentration of blaze orange tracer was detected. Blaze orange tracer was present in one sample collected 0.3 NM to the west of the inlet. The fact that blaze orange and green tracers were detected west of the yellow introduction point without any yellow tracer may indicate material moving around or bypassing the western beach area. Green tracer was detected east of the green tracer introduction point indicating slight movement to the east away from the inlet.

3 July - AM Low Tide. Green tracer remained detectable in concentrated amounts along the spit with the high concentration zone low on the beach profile shown in Figure E9 (SE of Station 1). No tracer sand was found in the back barrier sand flat or Eastern Channel areas. The concentration zone was on the flood-tidal delta indicating movement across the intertidal channel rather than along the spit front. Green tracer was no longer detectable at the introduction site near the high

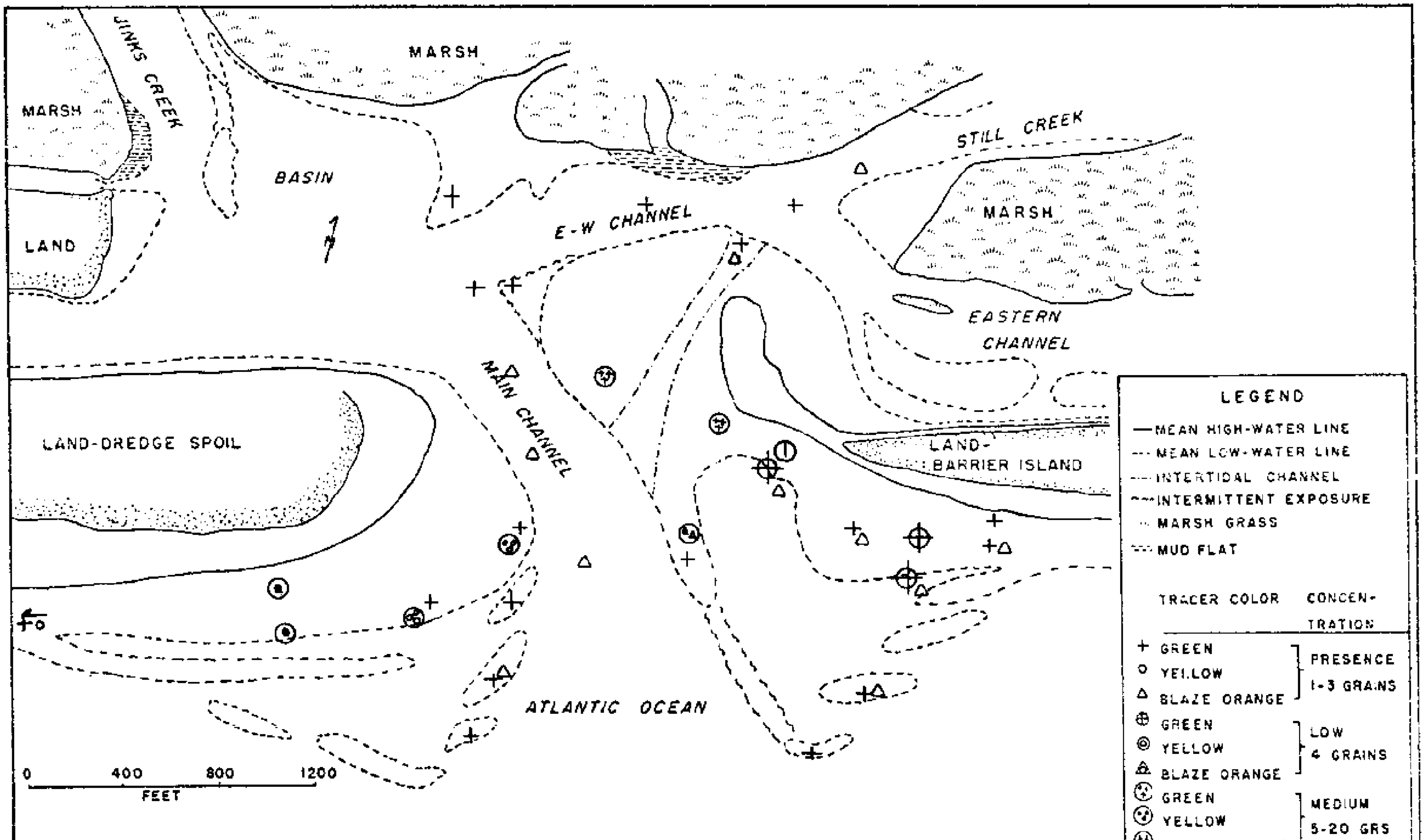

FIG. E9. LOCATION OF DETECTED TRACER SAND- **AM , 3** JULY, 1972.
NOTE: **48** HOURS AFTER INTRODUCTION.

water surf and swash zone, but remained detectable midway between the high and low water lines and down to the low water shoreline.

Green and blaze orange tracers were detected (one to four grains per sample) on the ebb-tidal delta for the first time. This indicated that the adjacent beaches were not a primary source of sand for the nourishment of these bars. If so, tracer would have been detected sooner suggesting a more direct travel path.

Yellow tracer remained detectable in concentration along the western beach, near the low-water shoreline. Blaze orange tracer was found concentrated on the eastern channel-margin linear bar. Green and yellow tracer grains were recovered in a sample 0.3 NM west of the inlet. No tracer was detected in the vicinity of Jinks Creek and Crane Bar (Jinks Creek ebb spit).

3 July - PM Low Tide. Tracer dispersion had removed most of the concentrated tracer except for the rather consistent medium concentrated zone of green tracer along the spit front as shown in Figure E10 (Station 7). Note that in every sampling period green tracer was detected at the point at which the spit bends sharply to the north.

Yellow tracer remained detectable on the western beach; however, no such tracer was found at the introduction point. Yellow tracer was detected for the first time along the western linear marginal bars. This was possibly due to the redistribution of the large amount of yellow tracer which had accumulated on the end of the western tidal flat. The deposition of sand and resulting eastward progradation of the western tidal flat was reflected by the concentration of yellow and green tracer detected by samples from this area.

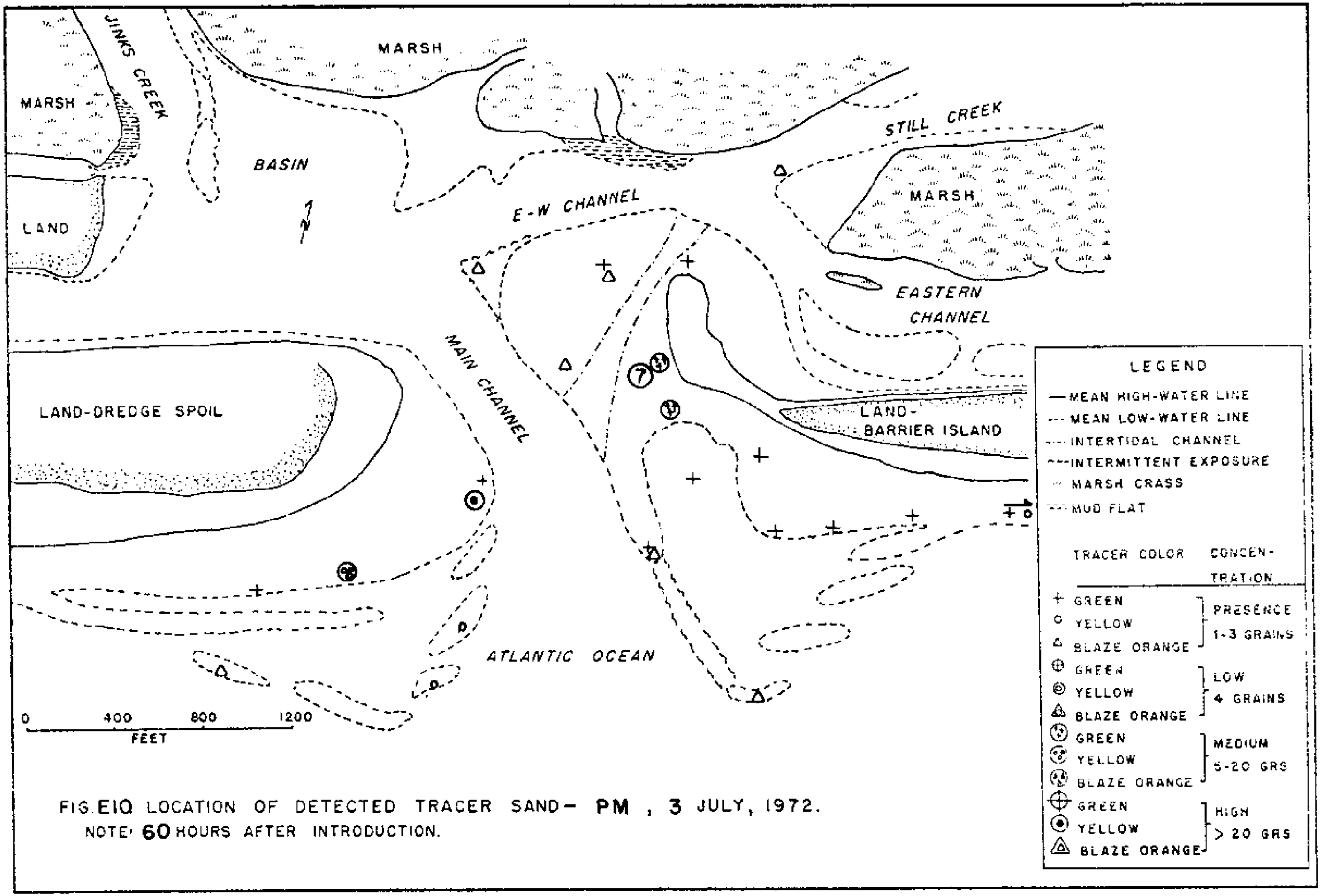

FIG. E10 LOCATION OF DETECTED TRACER SAND– **PM , 3** JULY, 1972.
NOTE: **60** HOURS AFTER INTRODUCTION.

Blaze orange tracer was detected in the western linear marginal bar. Green and yellow tracers were detected for the first time 0.3 NM to the east of the inlet.

4 July - AM Low Tide. Sampling at this time, 72 hours after introduction, detected only one medium concentration zone of green tracer near the northern end of the intertidal channel as shown in Figure E11. The tracer found at that station may have reflected the concentration of tracer previously dispersed over the intertidal flat. No green tracer was detected along the front of the spit.

Yellow and blaze orange tracers were detected on diamond shoals (vicinity of Station 8). Yellow tracer continued to be present along the western tidal flat. Blaze orange tracer was again detected in the swash bars seaward of the inlet.

4 July - PM Low Tide. Continued dispersal of the tracer resulted in only one sample recovering tracer which was a medium concentration of yellow tracer at the end of the western beach/flat as shown in Figure E11.

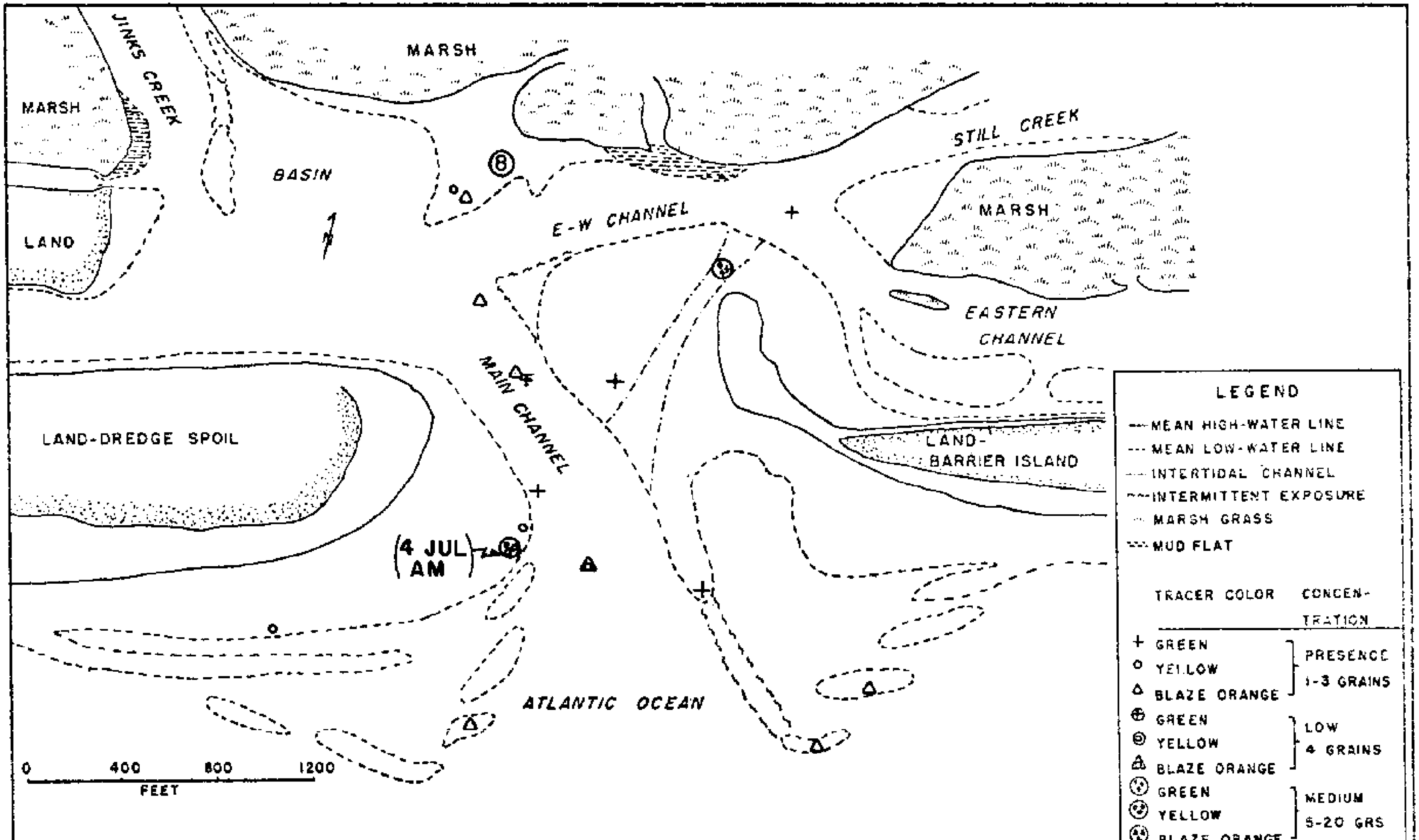

FIG.EII. LOCATION OF DETECTED TRACER SAND– **AM** , 4 JULY, 1972.
NOTE: **72** HOURS AFTER INTRODUCTION.