NOAA Technical Report NOS 93

Is the East River, New York, a River or Long Island an Island?

Rockville, Md.
June 1982

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National Oceanic and Atmospheric Administration
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Others will enter the gates of the ferry and cross from shore to
    shore,

Others will watch the run of the flood-tide,

Others will see the shipping of Manhattan north
    and west, and the heights of Brooklyn to the south and east,

Others will see the islands large and small;

Fifty years hence, others will see them as they cross, the
    sun half an hour high

A hundred years hence, or ever so many hundred years hence,
    others will see them,

Will enjoy the sunset, the pouring-in of the flood-tide,
    the falling-back to the sea of the ebb-tide.

Walt Whitman
from *Crossing Brooklyn Ferry;* 1856

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IS THE EAST RIVER, NEW YORK, A RIVER OR LONG ISLAND AN ISLAND?

by

R. Lawrence Swanson,[1] Charles A. Parker,[2]
Michael C. Meyer,[1] and Michael A. Champ[3]

ABSTRACT—The State of Rhode Island is disputing (United States versus Maine) the delineation of the closing line (a part of the baseline that crosses a body of water from which marginal seas are measured) separating the waters under Federal jurisdiction from State waters in the vicinity of eastern Long Island Sound. Jurisdiction over some 595 km^2 (172 nautical miles^2) of the continental shelf is in question. The United States legally considers Long Island Sound as historic inland waters. Rhode Island contends that Long Island is part of the mainland, thus moving the baseline seaward. The fundamental issue revolves around what constitutes the mainland, as determined by whether the East River is a river or a tidal strait.

This paper examines the definitions of rivers and straits and develops working definitions for them. The physical characteristics of the East and Harlem Rivers are examined and compared with the working definitions as part of the litigation in this case.

INTRODUCTION

Economic resources in the oceans continue to grow in importance, and the technology to develop these resources is more accessible. Territoriality, as exemplified by the complex and polemical Law of the Sea Treaty, is a major issue. Closer to home, the States and Federal Government vie for taxable revenue from resources in our coastal waters. Delineation of coastal boundaries is thus an extremely important and often controversial issue.

Such a dispute is now occurring in the case of United States versus Maine (Massachusetts, Rhode Island, and New York). The issue involves the location of the baseline between eastern Long Island and the New England mainland (fig. 1).

The United States considers Long Island, N.Y., as an island and not part of the mainland. Thus, Long Island Sound is not a juridical bay. However, the Sound is treated as historic inland waters (Strand,[4] personal communication).

With this interpretation, the closing line (a part of the baseline that crosses a body of water from which marginal seas are measured) (fig. 2) runs from Culloden Point to Orient Point, thence to Plum Island, to Race Point on Fishers Island, and from East Point on Fishers Island to Napatree Point, R.I. Block Island is considered to be an offshore island.

The State of Rhode Island, however, contends that Long Island is part of the mainland. In this scenario there are three possible solutions (fig. 2). In the extreme, the closing line would run from Montauk Point, N.Y., to Southwest Point, Block Island, and then from Sandy Point, Block Island, to the mainland of Point Judith, R.I. (Strand, personal communication).

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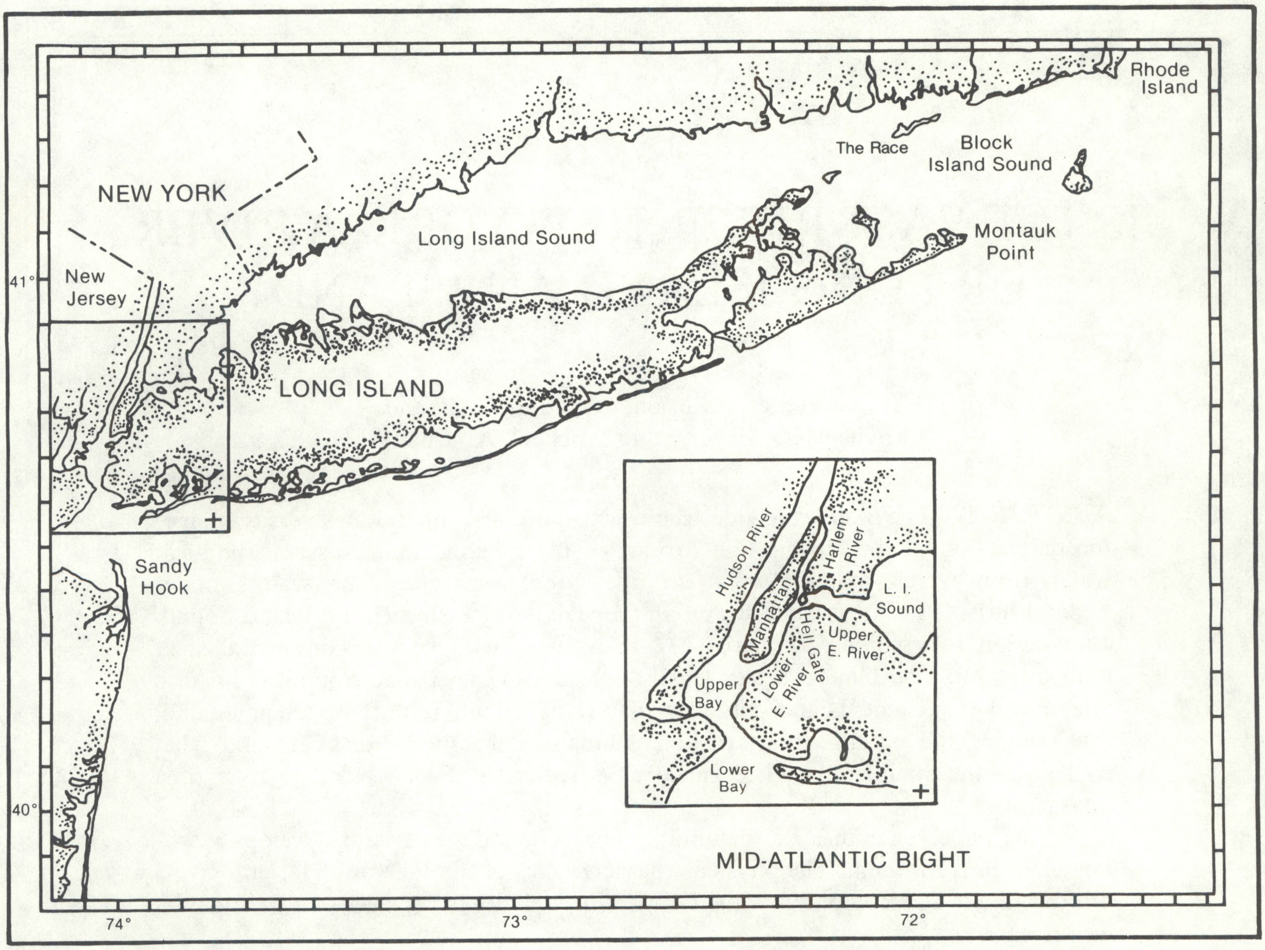

Figure 1.—Locator map of Long Island and vicinity

Thus, jurisdiction over some 595 km^2 (172 nautical miles^2) of continental shelf by the Federal Government and the States of New York and Rhode Island is in question. The fundamental issue, however, revolves around what constitutes the mainland, as determined by whether the East River (and possibly by implication, the Harlem River) is a river or a tidal strait.

The ultimate decision in the case resides in the courts and it may be decided considering any number of issues, including physical characteristics, historical usage, and physical and institutional ties between Manhattan and Brooklyn. The National Oceanic and Atmospheric Administration (NOAA) was requested by the U.S. Department of Justice to review the physical characteristics of the East and Harlem Rivers and to determine the nature of these bodies of water as part of the judicial process. This report summarizes our analysis and findings.

GENERAL DESCRIPTION

The 25.8 km (13.9 nautical miles) water body connecting western Long Island Sound with the New York Upper Bay is named the East River [National Ocean Survey (NOS) Charts 12339 and 12366] (fig. 3). The Sound entrance is between Throgs Neck and Willets Point; the Upper Bay entrance is in the vicinity of The Battery and Governors Island. The tidal cycle in the East River is derived from the tides in these two larger bodies of water. The tide at Throgs Neck has a range that is approximately 1 meter greater than that at The Battery, and it lags that of The Battery by about 3 hours. A Federal project provides for main-channel depths from 10.7 m (35 ft) at the northern end of the East River to 12.2 m (40 ft) at the southern end (NOAA, 1981). Authorized shipping channel widths range from 167.8 m (550 ft) to 305 m (1000 ft)

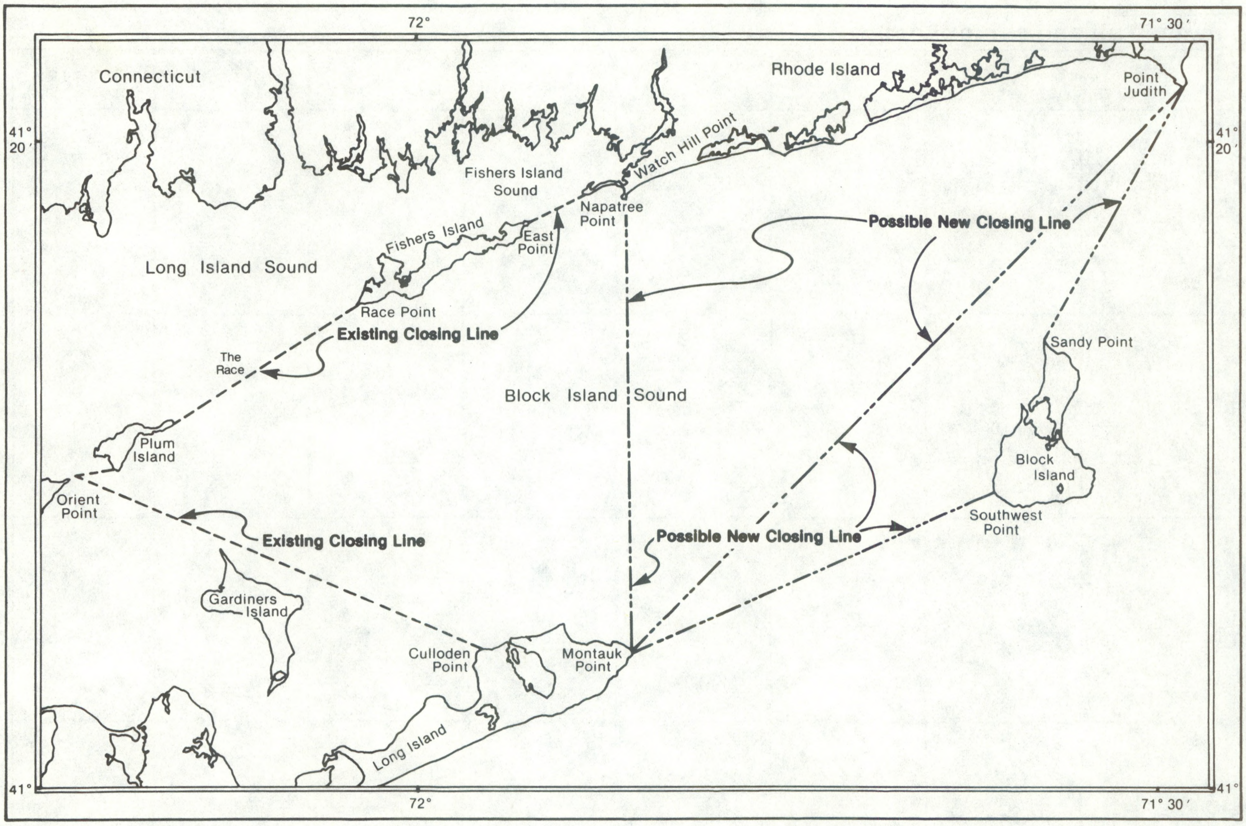

Figure 2.—Detailed map of Block Island Sound showing disputed closing line

(Hammon, 1976). The East River has been an important navigable waterway for several centuries and has played an essential role in the commercial development of the Port of New York.

The Harlem River is a 12.4 km (6.7 nautical miles) channel connecting the Hudson River at the north end of Manhattan Island with the East River near Hell Gate (figs. 1 and 3). Marmer (1935) states that the Harlem River originally connected with the Hudson River through a narrow channel known as Spuyten Duyvil Creek. However, in 1895 a navigable channel was cut through the marsh. The controlling depth in the channel is 4 m (13 ft) and the width is generally about 114 m (375 ft).

The early geological theories on the origin of the East and Harlem Rivers have been reviewed by Hobbs (1904). Early geologists attributed the location of the East River Channel to the distribution and dissolution or erosion of limestone beds. Hobbs refuted these theories with evidence of harder rock underlying the river, the direction of which was largely determined by lines of jointing and displacement. Fuller (1914) reported that the rock channel was produced by the mechanical erosion of streams, rather than solution (due to lack of limestone in the area), with the form of the tidal channel most likely controlled by joints (or possibly fault planes) or by the strike of the beds, with no contribution due to downfaulting. The northern part of the East River channel seemed to arise before the Manhasset Period (Fuller, 1914), which is now thought to be part of the Wisconsin sequence, possibly more than 55,000 years BP (Flint, 1971). The ice melt from the retreating ice sheet and subsequent tidal scour removed the deposits left by glaciers (Fuller, 1914).

Hell Gate (Dutch—"Helle Gat"—literally translated, "hole through hell"), a natural rock sill, divides the East River almost exactly in half (fig. 4). Hell Gate was an appropriate designation, especially in the early days when rock reefs, swift currents, and the tortuous channel rendered navigation extremely dangerous. It was notorious and dreaded by early mariners. However, the Long Island Sound approach to New York Harbor became attractive as the draft and tonnage of the growing steam power fleet increased in the second quarter of the 19th century. Crossing the bar, with a depth of only 7.3 m (24 ft) at mean low water, off Sandy Hook limited the access of these larger vessels to the Harbor, and ocean dredging was not technologically feasible at

Manhattan and surroundings

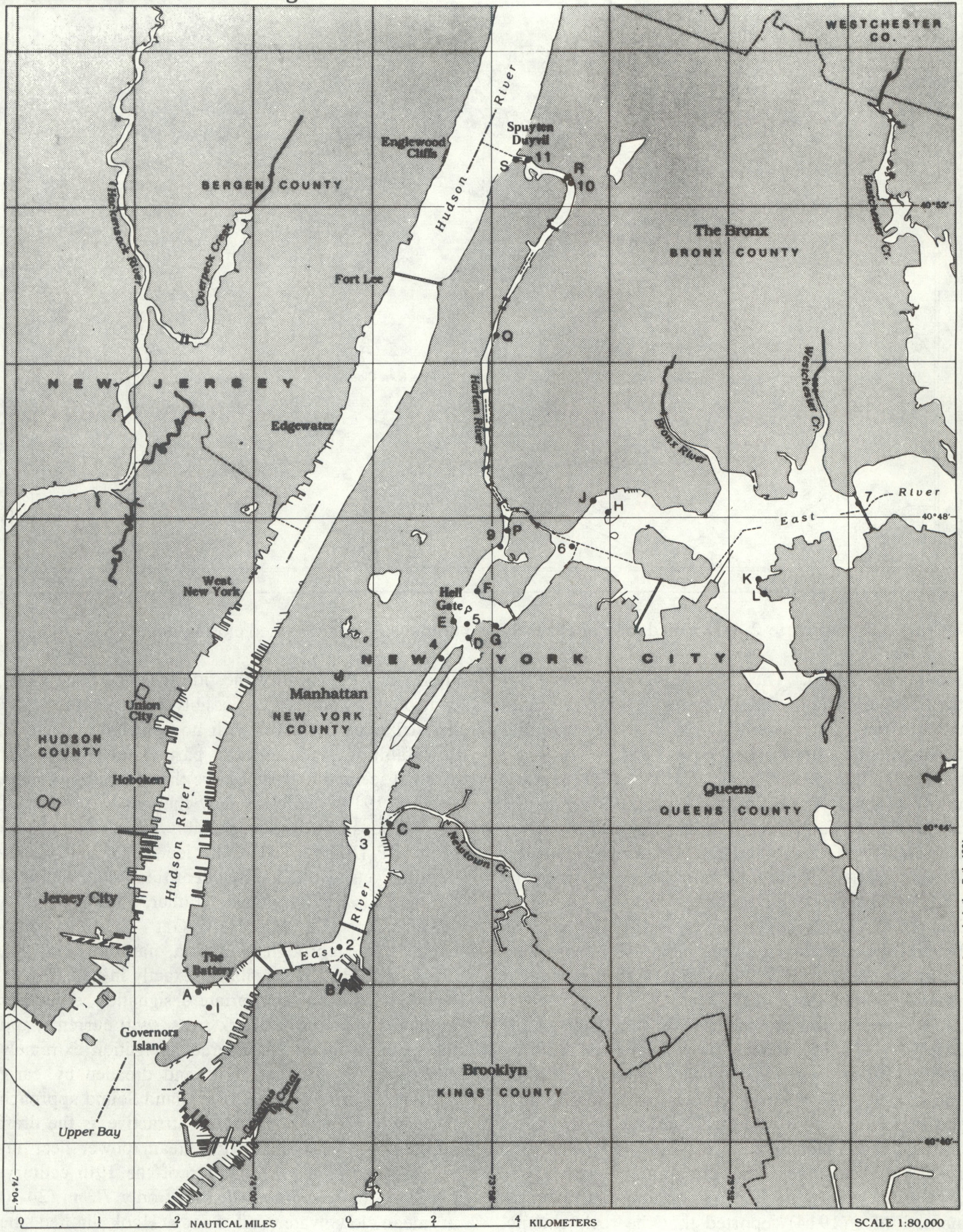

Figure 3.—Manhattan and surroundings showing locations of tide and tidal current stations

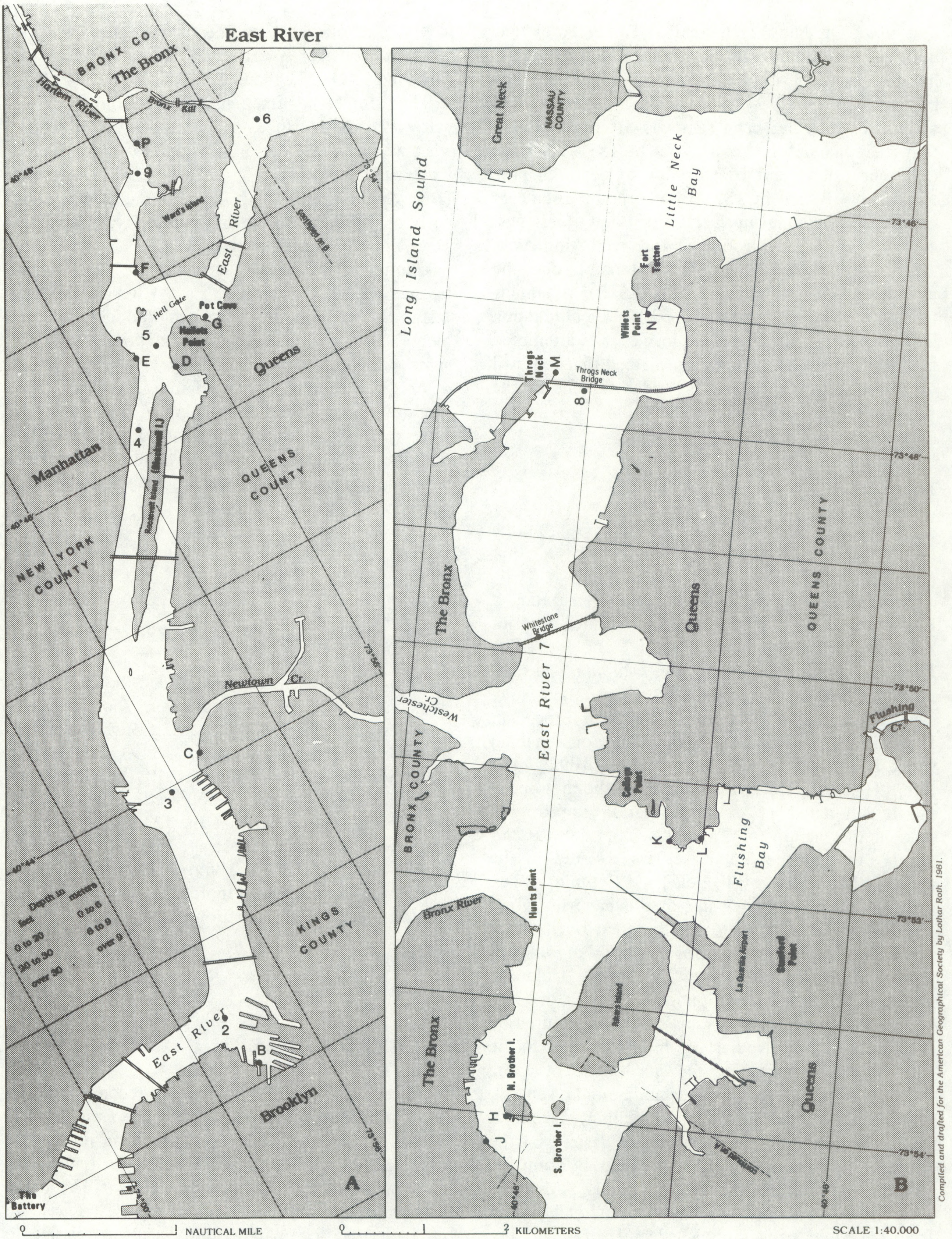

Figure 4.—East River showing locations of tide and tidal current stations

that time. Dredging a channel at Sandy Hook did not commence until 1885. Thus, removal of the hazards in the East River became extremely important (Klawonn, 1977). Since 1851 a considerable amount of rock has been removed at Hell Gate, so that the channel is about 262 m (850 ft) wide (Marmer, 1935) and 10.7 m (35 ft) deep. Of particular note is that in 1876 the Corps of Engineers completed tunneling under Hallets Point Reef (figs. 4 and 5) and then blasting of the overlaying rock. After the removal of over 90,000 tons of rock, the channel was deepened to 7.9 m (25 ft). A similar technique was employed at Flood Rock culminating in "the greatest quantity of explosives ever attempted in a single operation." It was projected that removal of the rock would reduce the tidal current in the vicinity from 18.5 to 8.3 km/hr (10 to 4½ knots) (Klawonn, 1977).

HISTORICAL PERSPECTIVE

In April of 1524, Giovanni da Verrazano, a Florentine sailing in the interest of the King of France, sailed through the Narrows and into New York Harbor. From his ship, the *Dauphine,* he took a smaller boat into the New York Upper Bay. However, it was not until 1614 that Adrien Block, an Englishman, pushed through the hazardous channel which is now called Hell Gate (Wilson, 1892). The term "Helegatt" appears on a map of the metropolitan region dated 1616. The notation appears on land in the vicinity of Throgs Neck. Laet (1625) points out that the Dutch settlers referred to the present East River as Hellegat. Captain Block described this body of water as flowing from great bay (Long Island Sound) into the great river (Hudson River) and the current of this body of water as coming a distance of about 111 miles (from the entrance of Long Island Sound).

The Remonstrance of New Netherland, drafted by the people of New Netherland in 1649, refers to the East River as bordering the north side of Long Island (i.e., the present Long Island Sound), separating it from Manathans (Dutch spelling) Island as far as the Hellgate and being highly desired by the English "on account of its convenient position, its suitable harbors, and anchorage grounds." Also, the East River was so named, "because it stretches East from the Manathans. This is esteemed by many not a river but a bay, because 'tis very wide in some places, and opens at both ends into the sea. We, however, consider it a river, and it is generally so reckoned" (O'Callaghan, 1856).

Thus, for some time, just as the Hudson River was called the North River because of its direction, what we know as Long Island Sound was considered the East River because of its east-trending direction. However, the term Long Island Sound was used as early as 1670 on a map by Robert Ryder (on file, New York Historical Society).

Confusion over the nomenclature and actual boundaries of the present East River and Long Island Sound stems from the exploration and settlement of this region by two nationalities during the same period. The failure of the New Netherlands colonists to correct their misnaming the East River, presently Long Island Sound, knowing it was not a river, probably reflects the harshness of colonial life and the subsequent importance placed on survival versus proper delineation and description of water bodies.

POST-COLONIAL PERSPECTIVE

The early residents, who regarded the East River as something other than a river, showed "little propriety in denominating it [East River] a river" according to Haskel and Smith (1849). Engineering and scientific studies of the East River in the latter half of the 19th century are followed by the assertion or parenthetical caveat that the East River is not a true river but rather a strait, tidal strait, or hydraulic strait [Mitchell, 1869, 1887; Harris, 1966 (reprinted from a 1900 report); Marmer, 1935; Jay and Bowman, 1975; and Bowman, 1976].

EXTANT RELEVANT DEFINITIONS

Since our objective is to make a recommendation as to whether, on a physical basis, the East River is a river or a strait, it is appropriate to review the accepted definitions or axioms for such terms as *river, strait, tidal strait,* or *hydraulic strait.* The actual physical processes that occur in the East River are characterized, compared, and discussed relative to these definitions.

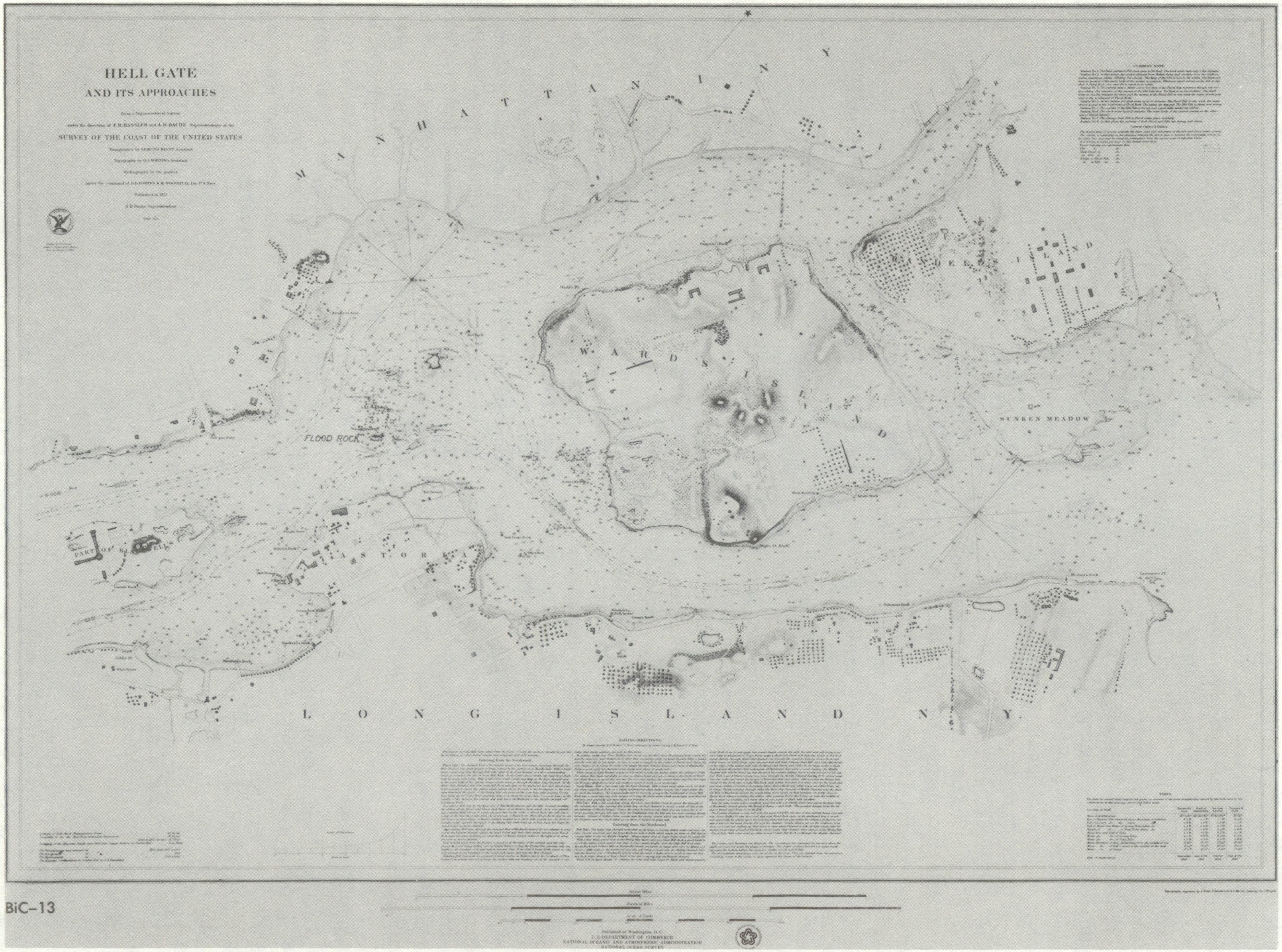

Figure 5.—1851 nautical chart depicting Hell Gate and approaches

Legal Definitions

Definitions for river and strait may be found in Shalowitz's *Shore and Sea Boundaries,* Vol. 2 (1964) and Vol. 1 (1962), respectively:

River: "A river has been defined legally as 'a natural stream of water, of greater volume than a creek or rivulet, flowing in a more or less permanent bed or channel, between banks or walls, with a current which may either be continuous in one direction or affected by the ebb and flow of the tide' (Black, Law Dictionary (4th ed.) 1491 (1951), citing *Alabama v. Georgia,* 23 How. 505, 513 (64 U.S., 1860) and *Motl v. Boyd,* 286 S.W. 458 (1926) (Tex.).")

Strait: ". . . the International Court of Justice laid down the doctrine that the decisive criterion for a strait being open to the passage of vessels of other nations is 'its [the strait's] geographical situation as connecting two parts of the high seas and the fact of its being used for international navigation'." However, a strait in the geographical sense is "defined as a relatively narrow waterway connecting two larger bodies of water."

In the Acts of the 1930 Hague Conference, the report of the Second Sub-Committee contains the following: "When a river flows directly into the sea, the waters of the river constitute inland waters up to a line following the general direction of the Coast across the mouth of the river, whatever its width. If a river flows into an estuary, the rules applicable to bays apply to the estuary." The recommendation of the Special Master of the 1958 Geneva Convention was substantially the same, except that no mention was made of rivers that flow into estuaries.

Common Definitions

The *Oxford English Dictionary* (1970 Edition) is taken as the most comprehensive and authoritative source for the English Language:

River: "A copious stream of water flowing in a channel towards the sea, a lake, or another stream."

Stream: "A course of water flowing continuously along a bed of earth, forming a river, rivulet, or brook."

Strait: "A comparatively narrow waterway or passage connecting larger bodies of water." In the adjective form, strait was listed in the physical sense as "tight, narrow. . . . 3. of a way, passage or channel; so narrow as to make transit difficult."

In general, the definition for "strait" in several common usage dictionaries consulted is equivalent; however, several deviations are observed for "river":

"A natural stream of water of considerable volume" (*Webster's Seventh New Collegiate Dictionary,* 1970).

"A large natural stream of water emptying into an ocean, lake, or other body of water, and usually fed along its course by converging tributaries" (New College Edition, *The American Heritage Dictionary of the English Language,* 1976).

"A natural stream of water of fairly large size flowing in a definite course or channel or series of diverging and converging channels" (*The Random House College Dictionary,* 1980).

Scientific Definitions

The *Glossary of Oceanographic Terms* (Baker et al., 1966) defines:

Strait: "A narrow sea *channel* which separates two landmasses;" and

Channel: "A natural or artificial waterway which either periodically or continuously contains moving water or which forms a connecting link between two bodies of water."

These two definitions in combination seem to carry all the properties of a geographical strait as defined in dictionaries and in Shalowitz (1962). They also imply the movement of water between the two connected water bodies via the strait, at least intermittently if not continuously. There is no sense of directionality of this flow. The possibility of net flow in both directions is not excluded nor is any driving force (tidal, gravity, etc.) implied for this flow. At first glance, the character of the water bodies being connected by the strait is not specified except that they be larger than the narrow strait, presumably in width. Most oceanographic glossaries and dictionaries do not venture a definition for "river," probably because it is not considered an oceanographic feature associated with salt waters; however, Baker et al., (1966) defines river discharge:

River Discharge (also called river outflow, river runoff) "The rate of flow of water past a point in a stream, expressed as volume per unit time. More specifically, the volume of river water that flows into the sea is usually measured in cubic kilometers, cubic miles, cubic meters, or cubic feet, and sometimes acre-feet."

"River discharge may affect tidal currents considerably, especially during rainy seasons, by increasing the strength and duration of ebb and decreasing the strength and duration of flood."

Although the "fresh" (versus "salt") quality of the water is not explicit in this definition, the distinction of river (fresh) water flowing into the sea (salt water) seems to imply this. Certainly freshwater input is a major oceanographic consideration in determining the distribution of salt (thus density) in estuarine and coastal waters. Apparently, geographers also generally recognize the freshwater quality of river sources. According to William Garren of the Defense Mapping Agency and a member of the Board of Geographic Names, the Board's working list of "Definitions and Designations" (internal, June 1979) does not directly list "river," but lists "stream":

> *Stream*—"a river or other running freshwater body, perennial in all or a part of its course."

A Glossary of Geographical Terms, a comprehensive treatment prepared by a committee of the British Association for the Advancement of Science (Stamp, 1966), presents:

River

> *Oxford English Dictionary:* "A copious stream of water flowing in a channel towards the sea, a lake or another stream."
>
> *Webster:* "A natural stream of water larger than a brook or a creek. A river has its stages of development, youth, maturity, and old age. In its earliest stages a river system drains its basin imperfectly; as valleys are deepened, the drainage becomes more perfect, so that in maturity the total drainage area is large and the rate of erosion high. The final stage is reached when wide flats have developed and the bordering lands have been brought low."
>
> *Swayne* (in Stamp, 1966): "A large body of fresh water which flows with a perceptible current in a certain definite channel or course, usually uninterruptedly throughout the year."

"River" is a very general term, and the *Oxford English Dictionary* definition is too narrow; the water is often far from "copious", and many rivers are reduced to a string of pools in the dry season. Further, in hydrology it is more customary to discuss stream flow rather than river flow. Stream flow is "the movement of (fresh) water under the force of gravity through well-defined, semi-permanent surface channels" (Linsley, et al., 1949).

Pritchard (1967), in his treatment of estuaries, argues that one of the key determinant factors physically establishing a body of water as an estuary is that there is a measurable dilution of sea water by fresh water. He identifies three major segments of a river-estuarine system: (1) an estuarine segment with measurable sea salt which is under the influence of tides; (2) a freshwater tidal segment (with no measurable sea salt) generally extending above the front of the salt wedge (toward the river's sources), and (3) implicitly a non-tidal segment above the tidal segment influenced predominantly by gravity flow of fresh water.

DISTILLATION OF WORKING DEFINITIONS

In summary, the definition of *river* in Shalowitz (1964) is satisfactory as far as it goes, but it is too general a term for a physically discriminant determination of most water bodies. The following physical characteristics should also be incorporated:

1. having a source of fresh water which flows in one direction down river toward a sea, lake, or other river under the influence of gravity throughout its length;
2. in the tidal and estuarine segments of its length, this flow may be affected by the ebb and flood of the tide, but the net transport of this fresh water is unidirectional, down river, caused by a topographic change in the head of water between the source and the receiving waters (sea, lake, or other stream); and
3. in the estuarine segment, there is a measurable quantity of sea water which may be carried up river within this segment via the estuarine circulation; however, the net transport of salt over appreciable periods must be zero (to do otherwise indefinitely would result in ever increasing salinity in the river at the source of fresh water).

Thus, we have chosen the following working definition for a river:

> **A natural stream of greater volume than a creek or rivulet, having a freshwater source flowing, in general, in one direction toward a sea, lake, or other river, in a more or less permanent bed or channel, with a current which may either be continuous in one direction or affected by the ebb and flow of the tidal current. The freshwater flow is controlled by the topographic difference in the head of water between the source and the receiving body of water. Where under the influence of tidal currents, the long-term flux of salt up river must be zero.**

The geographic definition of a strait given by Shalowitz (1962) is almost universally accepted with relatively small variations in the wording, with the exception of the oceanographic definition, which implies the connection of marine (sea salt) bodies of water, and through which (the strait) waters of the two bodies are exchanged.

Thus, our working definition of a strait is:

A relatively narrow waterway connecting two larger bodies of water in which water movement is determined by the interconnected bodies.

PHYSICAL OCEANOGRAPHY OF THE EAST AND HARLEM RIVERS

Overview of Tides, Tidal Currents, and Transport

Before examining the tides and currents of the East and Harlem Rivers in any detail, it is appropriate to provide an overview of the various nested systems within which they reside. The Long Island Sound-New York Harbor system communicates with the open sea within the Middle Atlantic Bight through two connections—The Race at the eastern end of Long Island Sound and the mouth of the Lower Bay entering into the Bight at Sandy Hook, N.J. (fig. 1). The semidiurnal nature of the Bight tides is basically preserved throughout the Harbor-Sound system, but tidal waves develop within these two water bodies in distinctly different ways. Specifically, the tidal wave in the Harbor is predominantly a progressive wave with tidal heights and currents tending to be in phase, whereas in the Sound it is more like a standing wave with tidal heights and current about 90° out of phase (i.e., strength of current [1] occurs near mean tide level rather than at high or low waters as is the case for a progressive wave) (Swanson, 1976). These wave forms meet and interfere within the reaches of the East River, causing the East/Harlem Rivers to exhibit a permanent, oscillatory (at semidaily frequency) hydraulic flow regime driven by the two dissimilar wave forms in the larger water bodies at the opposite ends of these passages (Marmer, 1935). Other physical phenomena (such as meteorological and hydrological disturbances) occurring within the Middle Atlantic Bight or Harbor/Sound bodies also communicate through the same routes as the tides and affect sea level and flow through the East/Harlem River system.

It is important here to establish some definitions and sign conventions regarding the East/Harlem River system. As Marmer (1935) points out, the common usage of the terms "the tide," "the tides," and "ebb and flood" is rather indiscriminately applied to both horizontal and vertical tidal motions, and in general to the tidal phenomena, only to be understood in the context of usage.

Hicks (1975) revised Schureman's (1949) definition of ebb (flood) current to include estuaries: "The movement of a tidal current away from shore (toward the shore) or down (up) a tidal river or estuary"; but otherwise, these long-established definitions have remained unaltered and do not satisfactorily apply to straits. This has long bothered hydrologists and oceanographers and led Mitchell (1869) to state with regard to Hell Gate: "I propose not to use these terms (ebb and flood) because they cannot be properly applied to interference currents whose epochs bear no necessary relations to high and low water." With regard to the East/Harlem Rivers which Marmer (1935) labels *straits,* "upstream and downstream, therefore, have no precise meaning . . . and the designations of the flood and ebb currents here must be made with reference to the time relations between local currents and tides." Regardless of these reservations, conventions have been established based on the criteria given by Marmer. Specifically, flood is defined as the direction of maximum current occurring on the rising tide, ebb being generally directed opposite to flood.

Figure 6 presents schematically the conventions for various water bodies around New York Harbor. Where applicable in mathematical or numerical terms, ebb is considered positive and flood negative. It is interesting to note that ebb in Upper Bay, Hudson and East Rivers points to the sea by way of the mouth of Lower Bay at Sandy Hook, N.J., while in Long Island Sound, it points to the sea through The Race. The consequence of this is a discontinuity in the sense of direction, separating the upper East River from Long Island Sound. This is indicated by the dashed line in figure 6 located along a section between Willets Point and Throgs Neck.

In classical rivers and estuaries, the nontidal gravity flow of fresh water is down river to the sea and overrides salt water which may also, within the estuarine segment of the river, move up river with considerable strength. This interaction has a number of consequences in modifying the tidal currents as well as the tides themselves. Table 1 summarizes Marmer (1935) and lists some of these notions regarding tidal currents, with the Hudson River representing the classic example of a true tidal river for comparison to the East/Harlem Rivers.

[1] Maximum current.

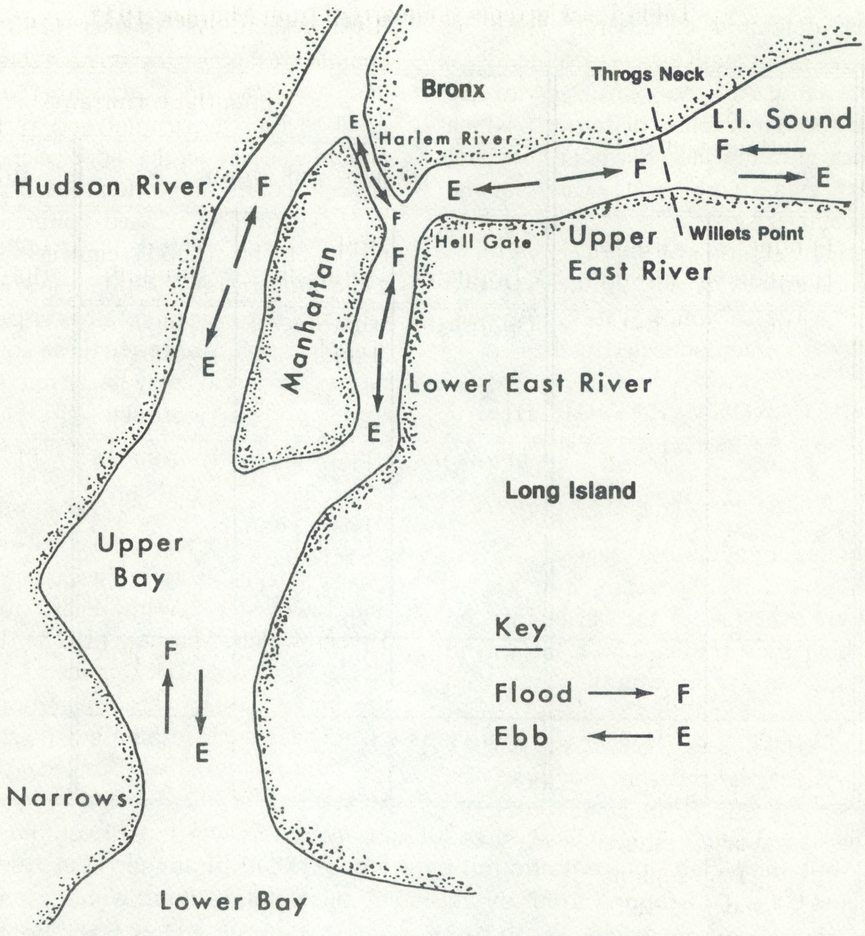

Figure 6.—Conventions used to describe flood and ebb tidal current patterns

According to Marmer (1935), the upper East River clearly exhibits the effects of the freshwater flow on the current, whereas these effects are absent in the lower East River. It is interesting to note that the flood carries the fresh water to the sea (via Long Island Sound) in contrast to the ebb in classical tidal rivers. Hardy (1972) and Jay and Bowman (1975) upon the examination of more recent data, reported an estuarine character in the upper East River and western Long Island Sound density structure and currents. For this to be the case, one might expect the bottom current in the upper East River to be of longer duration and greater strength on the ebb, which is not the case according to Marmer (table 1).

In a true river the long-term net transport through any cross section must be down river, with fresh water derived from the river and its tributaries. There can be a transport of salt water up river in bottom waters, but this increased volume must be reflected in increased surface flow carrying an equal amount of salt down river, so that, in the long term, there is no net transport of salt up river. That is, net transport of water equals the net transport of fresh water in a true river estuary.

However, in straits connecting larger bodies of water, transport processes are very complex and the net freshwater transport (if existent) depends on factors within the larger bodies and their relative influence on channel hydraulics. Likewise, a long-term net salt transport may exist, the direction of which exhibits similar complex dependence on the external water bodies and may be independent of the direction of freshwater transport. It will be shown later that the movement of water through the East/Harlem Rivers can be explained quite well by considering that the independent tides at each end determine the slope of an oscillating sea surface causing the ebb and flood currents in the channels. A net water transport from Long Island Sound to the Upper Bay occurs due to a higher stage and longer duration of ebb throughout the channel.

Table 1.—Currents summarized from Marmer, 1935

	Surface Currents		Subsurface Currents				
			Change with Depth			Bottom Currents	
	Longer Duration	Greater Strength	Ebb Duration	Ebb Strength	Flood Strength	Longer Duration	Greater Strength
Hudson River	Ebb	Ebb	Decreases D	Decreases rapidly	Slow decrease; may increase	Flood	Flood
Upper E. River (mid channel only)	Flood A	Flood	Increases E,H	Increases to mid depth, then decreases slowly to bottom	Decreases relatively	Flood I	Flood I
Lower E. River	Ebb B,F	Ebb B,F	Increases E,F	Decreases	Decreases	Ebb	Ebb
Harlem River	Equal C	Ebb	Increases G	Decreases	Decreases	Ebb	Ebb

Notes to Table 1: A) Equal at Hell Gate, duration increases eastward. B) Might imply fresh water flow to Upper Bay but subsurface currents do not bear this out. C) Ebb longer near Hudson River; flood longer near Hell Gate. D) Brought about by an earlier slack before flood with increasing depth; time of slack before ebb non-changing. E) Brought about by both a later slack before flood and earlier slack before ebb with increasing depth. F) Also highly variable due to effects of curvature and momentum. G) Brought about by a later slack before flood with increasing depth; time of slack before ebb non-changing. H) Constant at Hell Gate. I) Highly variable, not well determined.

Similarly, the Harlem River exhibits a net transport of water from Hell Gate to the Hudson River. These net transports not only reflect the effects of the dissimilar nature of the astronomic tides at both ends but also the effects of some of the other factors influencing the net transports of salt and fresh water. As indicated above, the direction of the transports of salt and fresh water cannot be inferred from the net water transport alone.

In actuality, the situation is more complex in that the Harlem River intersects the East River at its midpoint, resulting in a system of three hydraulic channels with their junction at Hell Gate (fig. 3). One end of both the Harlem and lower East Rivers adjoins the Hudson River at locations separated by approximately 21.7 km (11.7 nautical miles) along its length (the northern and southern ends of Manhattan Island), while their other ends are essentially co-located at Hell Gate. Differences in the mean range and time of tide between the two Hudson River ends are relatively small, being about 0.21 m (0.7 ft) and slightly less than 1 hour, respectively. The upper East River, on the other hand, has one end also in common with the other two channels at Hell Gate, but its opposite end at Throgs Neck (Willets Point) is under the influence of Long Island Sound tides which are distinctly different from the tides in the Hudson River.

Examination of tidal current charts illustrates that the three component channels (excluding the stretch in the upper East River from Hunts Point to Throgs Neck) make up a harmonious current system ebbing and flooding more or less in unison. Figure 7 presents total phase information for the East River for a given day. Although the range and the times of occurrence of tide phases change throughout the system, including a hydraulic jump (a sudden, usually turbulent, rise in water flowing in an open channel where it encounters an obstruction or change in channel slope) at Hell Gate, current phases vary

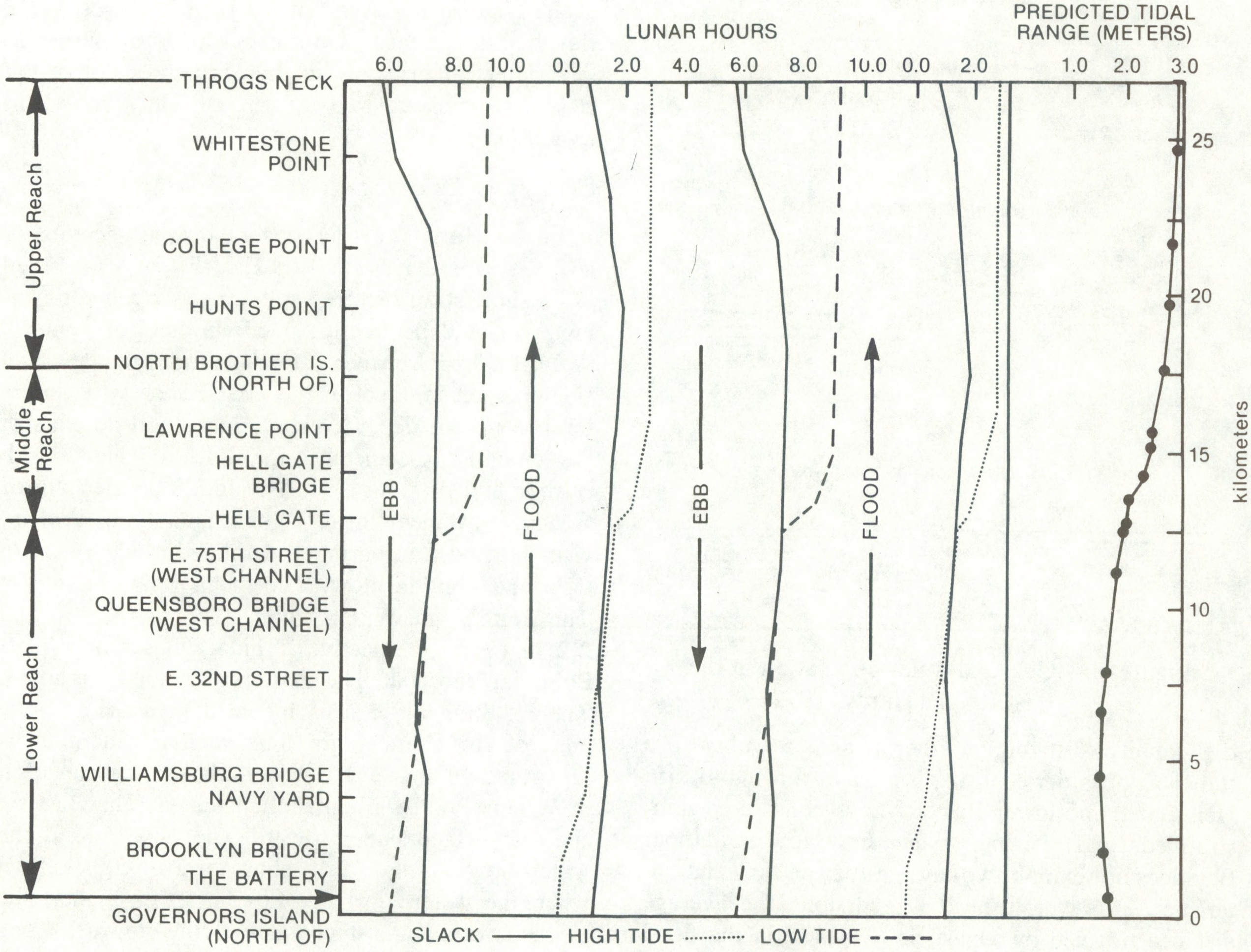

Figure 7.—Time of tides and currents in the East River, September 23, 1972 (modified from Jay and Bowman, 1975)

slowly and occur more or less simultaneously throughout the system. From Hunts Point east, however, slack water [when tidal current changes from flood (ebb) to ebb (flood) and the velocity of the current is zero] comes considerably earlier. It should be noted that the Hudson River tides are not in phase with the channel system. There are periods when the Hudson River both ebbs and floods while the channel system floods, and again the Hudson River floods and ebbs while the channel system ebbs. Therefore, from Hunts Point west, the channel system acts as though Hunts Point were the "upriver source" of the net transports, except that this obviously could not be a freshwater stream as in a true river. Further, this situation does not preclude a net freshwater transport through the upper East River to Long Island Sound from the Harlem or lower East Rivers. During the last 2 hours of the Hudson River ebb, the East River has already begun to flood and low salinity surface waters are carried around The Battery and into East River. This water, along with the flood-transported water from the Harlem River, is vertically mixed by turbulence at Hell Gate before entering the upper East River.

Hardy (1972), in his examination of the water quality of Long Island Sound, developed a conceptual model (fig. 8) of the general circulation and transport in the East River to explain the distributions of salinity and contaminants in western Long Island Sound. The model relied heavily on his synthesis and interpretation of the wealth of information presented by Marmer (1935) as well as his independent measurements of water properties. The model portrays a two-layer flow in the upper East River, with a net transport of fresh water in the surface layer into Long Island Sound maintaining

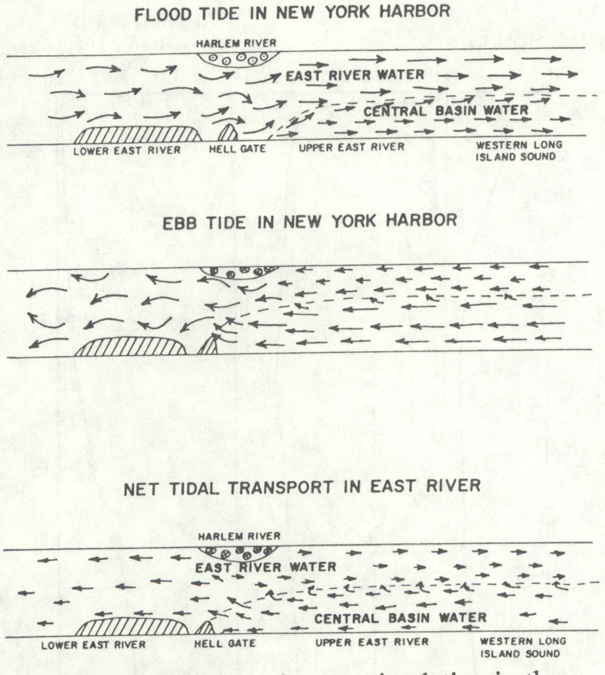

Figure 8.—Genreral water circulation in the East River (Hardy, 1972)

the salinity distribution there; and a subsurface transport of saltier central basin water flowing toward Hell Gate. The lower East River is considered nonstratified, and the net water flow toward Upper Bay does not exhibit two-layer estuarine flow characteristics. However, the tidal excursion [the average distance traveled by a particle of water on the flood tide (Harleman, 1966)] exceeds the length of the lower East River; therefore, it is possible for fresh water to be transported from Hudson River and over the Hell Gate sill during the flood.

Although the net water transport in the Harlem River is portrayed as directed from Hell Gate to the Hudson River, this shallow and narrow channel injects its relatively small flow into larger, swift-moving water bodies. This, coupled with the fact that the tidal excursion is approximately equal to its length, results in two oppositely directed net transports (salt and fresh water). During the ebb the saltier Hell Gate water is transported to the Hudson River water at Spuyten Duyvil; conversely, during the flood, fresher Hudson River water is transported to Hell Gate. Considerable turbulence at Hell Gate effectively mixes the waters passing over the sill. Jay and Bowman (1975) examined additional hydrographic data and direct current measurements and found further support for the Hardy conceptual model (fig. 8). Figure 9 shows the tide and tidal current phase relationships in the Harlem River. High water occurs slightly earlier (about 0.7 hours) at the Hudson River end of the Harlem River. Slack water occurs almost simultaneously with high and low waters. Thus, flow in the Harlem is not of the classic progressive wave form typically found in rivers.

Characteristics of the Mean Hydraulic Strait

In the Harris (1966) system of classification of rivers, straits, bays, etc., the East River is classified as "a short strait of very small cross section connecting two independently tided bodies of water." According to Marmer (1935), the primary tidal phenomenon in effect in the East River is the interference of two tide waves entering opposite ends of the channel, specifically, the tides of New York Harbor and of Long Island Sound. The mechanism of tidal movement through the channel can best be visualized by considering a simplified model of mean tidal and nontidal flow. The mean range of tide at The Battery and Willets Point is 1.4 m (4.5 ft) and 2.2 m (7 ft), respectively. Tidal phases at Willets Point lag those at The Battery by about 3 hours. The resulting differences in elevation (ΔH) of the ends of the channel are thus seen to fluctuate as illustrated in figure 10. When the water elevation at Willets Points is higher than that at The Battery, the sea surface slopes toward The Battery and the water flow in the strait ebbs toward Upper Bay; when the water level at The Battery is higher, the slope reverses and the water floods toward Long Island Sound. The vertical dashed lines (fig. 10) indicate the time when the sea surface is level (i.e., at slack water beginning a reversal in the direction of the tidal current.)

In this simplified model of hydraulic flow (fig. 11), the sea surface slope is assumed to be linear. Under this condition, the mean stage of the entire channel during an ebb or flood current can be obtained by the equal-area graphical method from the mean level curve (fig. 10). The mean slope during the flood approximately equals that of the ebb and the duration of the ebb is only slightly longer than the flood. All other things being equal (i.e., if velocity is dependent solely on the slope), the mean ebb and flood currents should be equal with a slightly larger ebb transport due to the longer duration of the ebb. However, the mean water stage throughout the East River during the ebb is higher than the flood by about 0.5 m (1.6 ft). The consequences of this are to increase the cross-sectional area of the channel during the ebb, reducing the resistance to flow, to further increase the ebb transport over that of the flood.

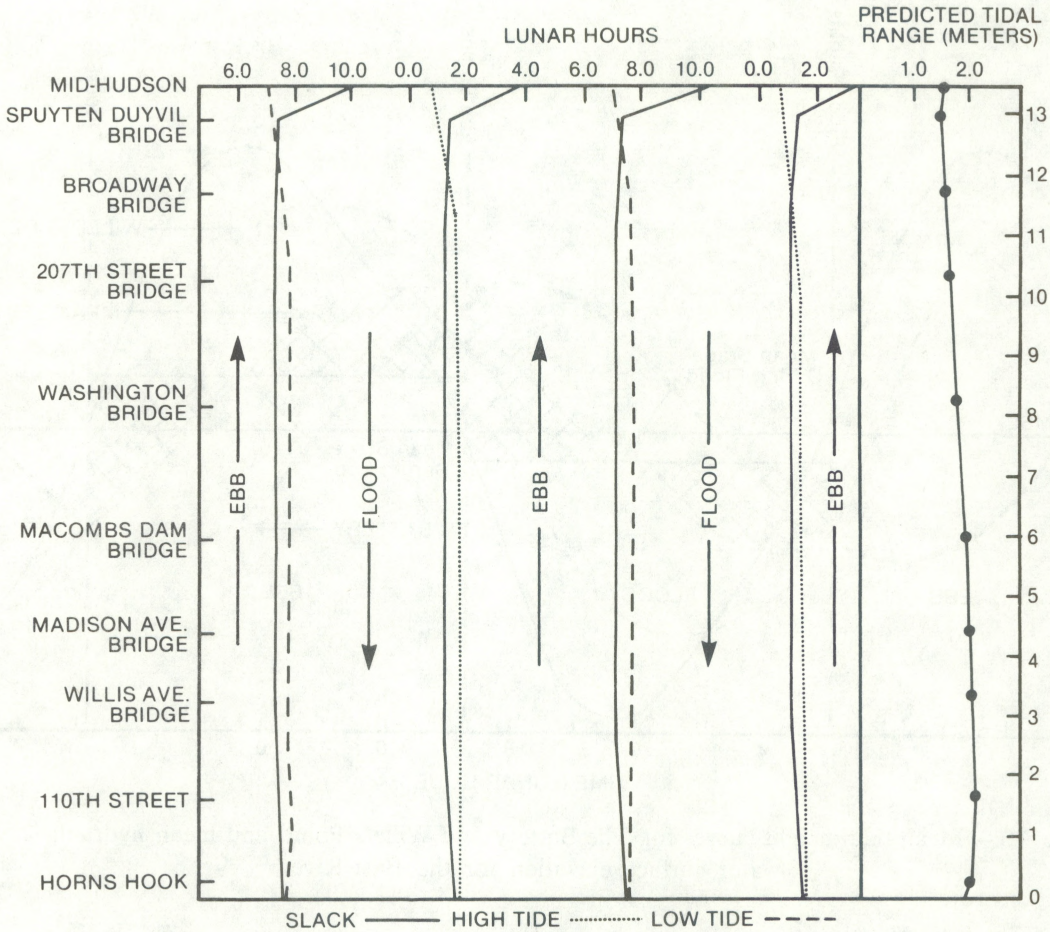

Figure 9.—Time of tides and currents in the Harlem River, September 23, 1972 (modified from Jay and Bowman, 1975)

Redfield (1978) has analyzed a number of the semi-enclosed bodies of water along the coast between New York and the Bay of Fundy. The East and Harlem Rivers were included in the analysis. Theoretical equations for the interference of two progressive waves were used to describe the tide throughout the channels. Parameters dealing with amplitudes of the two interfering waves and an attenuation coefficient for the amplitude of the combined wave were defined as characteristics for tidal straits.

The East River, according to Redfield, can not be considered as a single hydraulic strait as suggested by Marmer (1935). On the basis of his analysis, Redfield characterized the East River as consisting of three segments (fig. 7): Lower Reach, from Governors Island to Hallets Point; Middle Reach, from Hallets Point to North Brother Island; and Upper Reach, from North Brother Island to Throgs Neck. The numerical values of the characteristic parameters for each of the three segments of the East River were consistent with those specified for tidal straits. Furthermore, the Lower and Middle Reaches have flow regimes suggestive of hydraulic currents (flow resulting from a difference between water levels of the two ends of the channel). Hydraulic currents were not judged to be a prominent feature of the Upper Reach. The Harlem River was classified as a strait with hydraulic currents in the Redfield analysis.

Estimates of Net Water, Saltwater, and Freshwater Transports

The processes involved in saltwater and freshwater transport are more complex than the mere transport of water; this is particularly true in the upper East River, which exhibits an estuarine character. In addition to the salt water or fresh water carried by long-term mean flow, diffusive and estuarine transport processes are also operative. In general, the

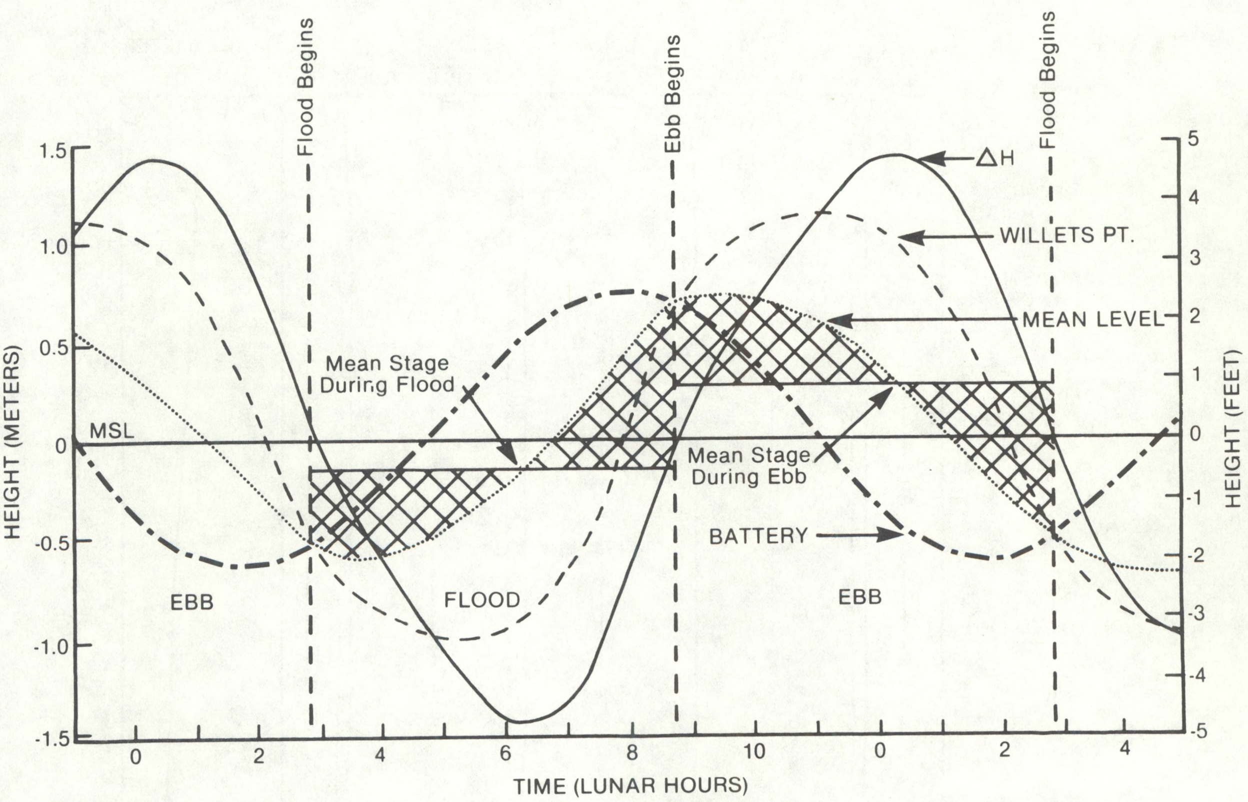

Figure 10.—Mean tidal height curves for The Battery and Willets Point, and mean hydraulic head and water surface elevation for the East River

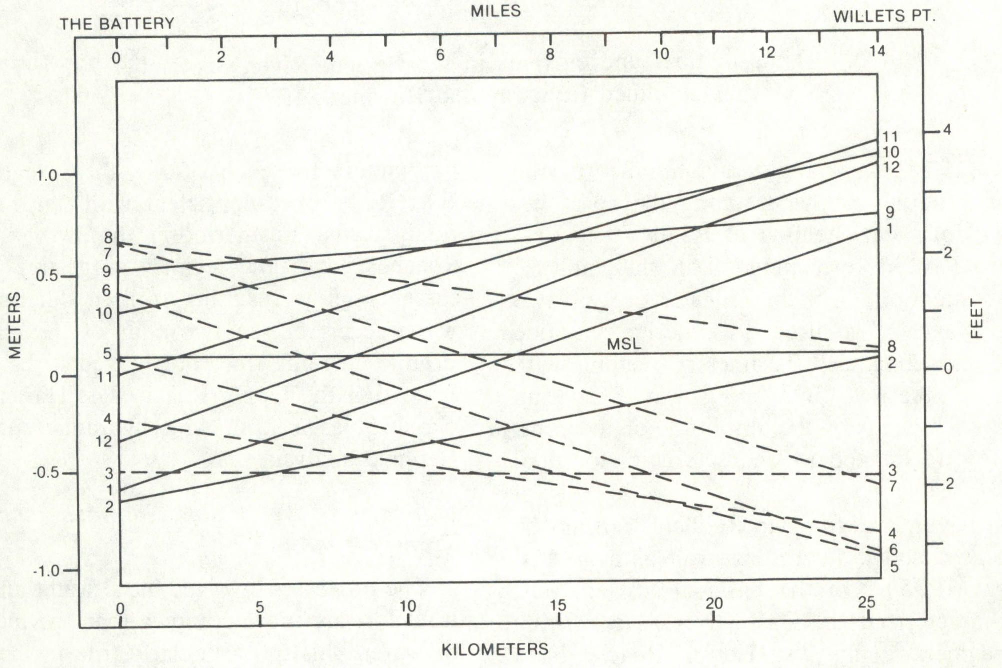

Figure 11.—The simultaneous tidal heights at The Battery and Throgs Neck are connected by straight lines for each lunar hour of the tidal cycle. The envelope of the bundle gives the approximate elevation of the MHW and MLW surface at each point along the River.

long-term net effects of these latter two processes cannot be evaluated due to a paucity of data. However, some general statements based on oceanographic understanding regarding the direction of the long-term net transports of these fractional components can be made.

Jay and Bowman (1975) made some calculations for these component flows through a section located between Throgs Neck and Willets Point during September 1972, a period of relatively low freshwater runoff. Through the entire vertical section, a total volume of water was transported at the rate of 560 m^3/s toward New York Harbor. Also 1.56×10^4 kg/s of salt were transported through the section to the Harbor; however, 13 m^3/s of the freshwater flow were directed toward Long Island Sound. The surface transport above 7 m was 103 m^3/s of water, 1.56×10^2 kg/s of salt, and 32 m^3/s of fresh water, all directed toward Long Island Sound.

Examination of the historical (1947-65) surface salinity data for Willets Point and The Battery yields a value for the mean salinity for Willets Point to be 25.2°/oo and at The Battery 21.4°/oo, resulting in a mean salinity difference along the East River of 3.8°/oo. The monthly mean difference ranges over the year between 2.1 – 2.2°/oo in July through October to 7.5°/oo in April during the spring freshet. Jay and Bowman (1975) assert that only during very low runoff periods is there any possibility of The Battery salinity exceeding that at Willets Point. Most of the variability in the differences is due to salinity changes in the Harbor, since the range of mean monthly salinity at Willets Point is only 1.9°/oo.

Actual sea surface elevation at either end of the East or Harlem Rivers varies from tidal cycle to tidal cycle, day to day, week to week, month to month, and even for longer averaging periods, due to many factors such as variations in river discharge, wind stress, direct atmospheric pressure, and salinity distribution. Jay and Bowman (1975) have evaluated many of these variable factors and have determined that, on any given day, the mean slope or hydraulic head produces a net flow in the East River which may be either toward Long Island Sound or toward the Upper Bay of New York Harbor, depending on the direction of the average slope. The predominance of the slope towards The Battery increases as the period of averaging increases. They estimate long-term average net flow in the East River to be about 340 m^3/s directed toward The Battery. However, examination of all available estimates of the net flux based on historical current measurements ranges from −324% (toward Long Island Sound) to +182% (toward Upper Bay) of this value. Unfortunately, these estimates are based on current measurements of only a few tidal cycles duration and cannot represent a stable long-term mean. They do, however, illustrate the point made above with regard to the variability over short averaging periods.

Generally, in the long term, the mean salinity gradient (down toward The Battery) and estuarine character of upper East River and western Long Island Sound are persistent features of the region. Consequently, one would expect a diffusive transport of salt to augment the advective salt transport to the Harbor due to the longitudinal salinity gradient. The estuarine transport of salt in the bottom water layer would also operate in the same direction. Since all of the transport processes are operating in the same direction, it is concluded that there is a long-term net salt transport to the Hudson River from Long Island Sound.

Jay and Bowman (1975) examined the freshwater sources and transport processes and concluded that the Hudson River provided the freshwater source necessary to maintain the estuarine character of the upper East River and Long Island Sound. The mechanism of transport, however, is not riverine as per the definition of a river. Further, sources (such as urban runoff and sewage treatment plant effluent) local to the reaches of the East River can be of the same order of magnitude as the Hudson River input during low runoff periods. In general, this would be expected to augment the estuarine transport of fresh water from Hell Gate to Long Island Sound.

EFFECTS OF MAN-MADE MODIFICATIONS

The East and Harlem Rivers have been considerably modified as the Port of New York has developed, particularly over the past century. The Harlem River was dammed in the early 19th century, dredged, and its course even modified in the vicinity of Spuyten Duyvil.

The channel in the East River has been considerably deepened but the metropolitan area has also encroached beyond the precolonial channel banks. In the Port's earlier years, the slips [with piers up to 122 m in length (400 ft)] gradually shoaled due to sedimentation and trash accumulation. Eventually, the slips were filled and piers extended further into the river (Klawonn, 1977). Much of East River Drive is constructed on fill derived from ballast carried as part of our trading with Europe (Delaney, 1965). In addition to the extensive topographic

Table 2—Comparison of 19th and 20th century tide and tidal current observations (modified Marmer, 1935) (See Figure 3 for station locations)

	19th century			20th century		
Tide station*	Year	Mean range m (ft)	Time of high tide relative to Willets Point	Year	Mean range m (ft)	Time of high tide relative to Willets Point
A The Battery (Manhattan)				1921-26	1.35 (4.45)	−3.05
B Brooklyn Navy Yard (Brooklyn)	1869	1.25 (4.10)	−2.42	1943-45	1.25 (4.11)	−2.21
C Greenpoint Dupont St. (Brooklyn)	1855	1.35 (4.43)	−1.87	1932	1.30 (4.25)	−1.90
D Astoria Blvd (Queens)	1868	1.46 (4.80)	−1.32	1932-33	1.49 (4.89)	−1.28
E Horns Hook E. 90th St. (Manhattan)	1868	1.45 (4.77)	−1.14	1940-42	1.48 (4.84)	−1.29
F S.W. end Wards Island	1866	1.56 (5.11)	−1.25	1932	1.54 (5.06)	−1.12
G Pot Cove, Astoria (Queens)	1868	1.85 (6.07)	+0.13	1932	1.60 (5.25)	−0.66
H North Brother Is. (West Side)	1847	1.91 (6.27)	−0.89	1933	1.97 (6.47)	+0.01
J Port Morris 141st St. (The Bronx)	1886	2.08 (6.84)	+0.49	1952	1.93 (6.34)	+0.21
K College Pt. East River (Queens)	1883	2.09 (6.85)	+0.49	1932-33	2.09 (6.85)	+0.14
L College Pt. Flushing Bay (Queens)	1886	2.20 (7.21)	+0.63	1933	2.03 (6.67)	+0.35
M Throgs Neck Fort Schuyler (The Bronx)	1847	2.12 (6.96)	−0.72	1960-78	2.18 (7.14)	+0.04
N Willets Pt. Fort Totten (Queens)	1886	2.13 (6.99)	0	1932-33	2.16 (7.10)	0
P Randalls Island Harlem River	1886	1.59 (5.24)	−1.03	1932	1.54 (5.06)	−1.31
Q South of High Bridge Harlem River (The Bronx)	1856	1.36 (4.45)	−0.25	1927-32	1.34 (4.41)	−1.37
R Broadway Bridge Harlem River	1886	1.21 (3.96)	−2.06	1932-33	1.19 (3.89)	−1.77
S Spuyten Duyvil Harlem & Hudson Rivers				1928-32	1.15 (3.78)	−2.07

Table 2.—con.

Current station*	19th century Year	Mean strength of flood km/h (kts)	Mean strength of ebb km/h (kts)	20th century Year	Mean strength of flood km/h (kts)	Mean strength of ebb km/h (kts)
1 Off Governors Is.	1858	2.6 (1.4)	3.5 (1.9)	1932	1.8 (1.0)	2.2 (1.2)
2 Off Brooklyn Navy Yard	1855	8.3 (4.5)	7.2 (3.9)	1920	7.2 (3.9)	6.1 (3.3)
3 Greenpoint Dupont St. (Brooklyn)	1854	4.3 (2.3)	3.0 (1.6)	1920	3.9 (2.1)	3.3 (1.8)
4 Off 80th St. (Manhattan)	1845	7.8 (4.2)	8.9 (4.8)	1920	8.9 (4.8)	9.3 (5.0)
5 Hell Gate	1845	4.4 (2.4)	7.8 (4.2)	1932	5.9 (3.2)	6.7 (3.6)
6 Lawrence Point (Queens)	1858	5.7 (3.1)	4.4 (2.4)	1932	7.0 (3.8)	4.6 (2.5)
7 Old Ferry Point (The Bronx)	1885	3.7 (2.0)	2.8 (1.5)	1932	3.1 (1.7)	3.0 (1.6)
8 Between Throgs Neck & Willets Point	1858	1.8 (1.0)	1.5 (0.8)	1929	1.7 (0.9)	1.1 (0.6)
9 Randalls Island Harlem River	1856	0.9 (0.5)	1.1 (0.6)	1932	2.4 (1.3)	0.4 (0.2)
10 Broadway Bridge Harlem River				1920	3.9 (2.1)	4.4 (2.4)
11 Spuyten Duyvil				1932	2.8 (1.5)	4.1 (2.2)

* See Figure 3 for station locations.

modifications associated with removing obstructions and deepening the channel in the Hell Gate region, there has also been considerable filling, much of the material being derived from these other navigational projects. Wards Island, Randalls Island, and Sunken Meadow have been made one and actually joined to the mainland. Sanford Point has been built out to accommodate LaGuardia Airport and now practically joins Rikers Island (fig. 4).

These numerous modifications have had a considerable effect on local flow conditions in the two channels of concern. But have the changes been enough to alter their fundamental flow characteristics? There were some measurements of tides and tidal currents prior to the major period of modification. Comparison of early data with more modern information can provide some insight into the extent of change.

One-to-one geographic comparisons are for the most part not possible because of physical changes. In addition, our ability to measure tides and tidal currents (and for longer periods of time) has greatly improved over the last century so that there is undoubtedly considerable measurement error to be considered. Nevertheless, in this study we are concerned with the broad issue of whether the East and Harlem Rivers are characteristically driven by the same flow conditions as in years past. We are fortunate to have actual measurements to help in the decision process.

The 19th and 20th century values of mean range and arrival times of high water are tabulated for locations on the East and Harlem Rivers where repeat observations have been made (Table 2 and fig. 3). The greatest change in mean range was at Pot Cove, in proximity to where the reef was removed off Hallets Point. Here the mean range is reported to have decreased 0.25 m (0.82 ft). At College Point site (L), the range is shown to have decreased 0.17 m (0.54 ft), while only 0.46 km (0.25 nautical miles) away there has been apparently no change in mean range.

The greatest change in the time of arrival of high tide in the East River also occurred at Pot Cove. High tide now arrives some 47 minutes earlier than determined in 1868. While the data are not tabulated by Marmer (1935), he states that the tide in the Harlem River, near the Hudson, arrives considerably earlier than before navigational improvements. High water is about 1 hour earlier, and low, 2 hours earlier.

There are fewer current measurements. The comparisons of maximum currents are actually quite close, considering the difficulties of measurement. The greatest change is noted in the 1.5 km/h (0.8 knots) increase in flood near Flood Rock in Hell

Gate. It is interesting to note that the greatest reported mean strength of flood by Marmer (1935) is 10.6 km/h (5.7 knots), observed in 1845, although a note on the 1893 edition of the Hell Gate chart states that 14.8 km/h (8 knots) was measured on the flood between Hallets Point and Hog's Back. One must question the early statements concerning 18.5 km/h (10 knots) currents in the East River.

Comparison of data from the two centuries, however, indicates that the general flow characteristics reported today were observed prior to the major channel modifications. There are local changes in tidal characteristics and probably considerable reduction in turbulence as a result of navigational improvements. Even in the case of the Harlem River, where navigation was limited prior to 1895, there was apparently restricted flow between the Hudson River and Hell Gate. Klawonn (1977) states that settlers around 1700 reported that the Harlem and Spuyten Duyvil streams were navigable (probably at high tides). In precolonial times, the area in the vicinity of Broadway and west of 230th Street was known as the Wading Place (McNamara, 1978), where the Indians forded (Fordham) the marshy confluence of the Spuyten Duyvil, Tibbets Creek, and the Harlem. Early colonists mentioned a double tide in the marsh area where the Harlem River and Spuyten Duyvil met (McNamara, 1978). This probably occurred as a result of the tide rising from flow in the Hudson, beginning to fall, and then rising again as a consequence of the rising tide in the Harlem. Thus, four high-water peaks might have occurred in one tidal day. This mechanism would have resulted in a limited exchange of fresh water from the Hudson River to the Harlem River and conversely a limited exchange of saltier water from the Harlem into the Hudson.

The governing processes, however, are the same today as before. The effects of modification have been to reduce the frictional drag and to allow a free exchange of water, particularly in the case of the Harlem River. Man has not altered the East and Harlem Rivers to the extent that what was once a purely riverine system is now a system of tidal straits.

CONCLUSIONS

The definition of *river* and *strait* generally accepted for common usage in the legal or scientific professions are not sufficient to clarify the physical nature of the East and Harlem Rivers. Consequently, we have further developed the existing definitions in terms of the physical processes controlling flow in these types of water bodies. Examination of the flow and processes controlling the flow in the East and Harlem Rivers permits us to distinguish whether they are more typical of rivers or straits. The modified definitions are repeated here:

River: A natural stream of greater volume than a creek or rivulet, having a freshwater source flowing, in general, in one direction toward a sea, lake, or other river, in a more or less permanent bed or channel, with a current which may be either continuous in one direction or affected by the ebb and flow of the tidal current. The freshwater flow is controlled by the topographic difference in the head of water between the source and the receiving body of water. Where under the influence of tidal currents, the long-term flux of salt up river must be zero.

Strait: A relatively narrow waterway connecting two larger bodies of water in which water movement is determined by the interconnected bodies.

Based on these definitions and a review of the flow characteristics in the East and Harlem Rivers, we conclude that these "Rivers" are in fact a complex network of interacting tidal straits connecting the Hudson River, Upper Bay, and western Long Island Sound. While there have been considerable manmade modifications to these channels, particularly over the last 120 years, there is no indication that the basic characteristics have been modified from that of rivers to straits.

The controlling mechanism in the flow regime of the East and Harlem Rivers is due to a mismatch in the heights and phases of a primarily progressive tidal wave moving from Lower Bay into Upper Bay and the Hudson River, and that of a primarily standing tidal wave in Long Island Sound. Throughout most of this system (the lower and middle reaches of the East River and the Harlem River) the flow is hydraulic. In the upper reach of the East River the flow may be more characteristically estuarine. There is no apparent topographically controlled head of water in the channels between the connected bodies of water. In both the East and Harlem Rivers, there is net flux of salt directed oppositely to that of fresh water which is also contrary to our definition of river.

It is with confidence that we state that, based on the physical processes, the East and Harlem Rivers are straits. It is also nice to know that, based on these findings, Long Island is still an island and not part of the mainland.

ACKNOWLEDGMENTS

Preparation of this paper has been a considerable challenge but nevertheless enlightening and fun. Numerous people have assisted in locating source material and interpreting the historical information in terms of what we now know about the geography and oceanography of the area. Donald Squires of the New York State Sea Grant Institute, Michael Kawka and Steven Collins of the Office of Marine Pollution Assessment, and Bruce Parker and Charles Harrington of the National Ocean Survey have been particularly helpful in this regard. We also appreciate the critical reviews provided by Steacy D. Hicks, Dana Swanson, and Margaret Strand. Dorothy Newman deserves special recognition for typing the many drafts of the manuscript.

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