1 The Hudson River Estuary: Executive Summary

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From the Tear of the Clouds to the Verrazano

The ecological and cultural importance of the Hudson is surely not revealed by its size. Its drainage basin is about 34,000 square kilometers (km) (13,000 square miles), which is less than one percent of the United States. In contrast, the Mississippi drains about half of the area of the lower 48 states. Compared to the mighty Mississippi's length of 3,700 km, the Hudson, originating in the Adirondacks and pulsing to the sea through the Verrazano Narrows, flows over a main course of only 500 km (ca. 300 miles).

Henry Hudson and his crew first saw the mouth of the Hudson in 1609, but it wasn't until the 1870s that its origin was declared, at tiny Lake Tear of the Clouds, near Mt. Marcy in the Adirondacks. The small rivers and streams flowing from Adirondack peaks over 1000 meters (m) in elevation descend to a lowland drainage usually less than 100 m above sea level. Below Troy the river is navigable to the Narrows entrance to the ocean.

The Terrane

The Hudson River drains New York, and parts of Vermont, Massachusetts, Connecticut, and New Jersey. The basin contains three subareas: the upper Hudson from Mt. Marcy to Troy, the Mohawk from Rome to Troy, and the lower Hudson from Troy to New York Bay (we try to stick to this terminology throughout the book, but some authors have failed us). The Hudson and Mohawk basins are fresh water; the lower Hudson is an estuary, with water greater than 1 practical salinity unit (psu) usually below West Point.

The drainage and flow pattern of the upper Hudson is complex and consists of a number of streams coursing through the Precambrian and early Paleozoic rocks of the Adirondacks (Chapter 2). By contrast, the lower Hudson takes a reasonably straight shot to its terminus (Figure 1.1a, b, c). The regional geological lineations seem oblivious to the Hudson's flow, which slices across a series of complex terranes. The mid-Hudson cuts through early and middle Paleozoic sedimentary rocks, with the Catskills to the west and the Taconics to the east. Most notably, the river then runs through the Hudson Highlands, early Paleozoic geological formations that trend directly east-west across the Hudson's flow path in the vicinity of West Point. The river's erosion simply cut downward through this cross-cutting terrane with no notice of its geological contrariness.

Below this region the river passes the Triassic volcanic cliffs of the Palisades and then moves past the New York group, a series of Proterozoic and early Paleozoic metamorphic rocks and then a series of terminal deposits of the last glacial epoch. Along the entire stretch of the lower Hudson, one is impressed by the steep banks and even cliffs along the shoreline. Most other estuaries in the United States meander to the sea along a broad low-relief flood plain. The Hudson clearly has cut down through a great deal of bedrock and yet, owing to its relative youthful erosional history, has not formed a large depositional plain near its mouth.

The Hudson's straight southerly course has cut through these disparate geological terranes and, during the time of the glacial ages, formed a classic U-shaped cross section, much like the glacial fjords of southwestern Norway. During the height of the most recent glacial advance during the Pleistocene Epoch, the glaciers scoured the Hudson to a depth of 150–200 m (488–650 feet). Then, as the glaciers retreated, the Hudson obtained the shape of a fjord, with a deep U-shaped valley. Glacially-derived sediment filled the now quiet-water Hudson so that today it is rarely more than 50 m deep, although

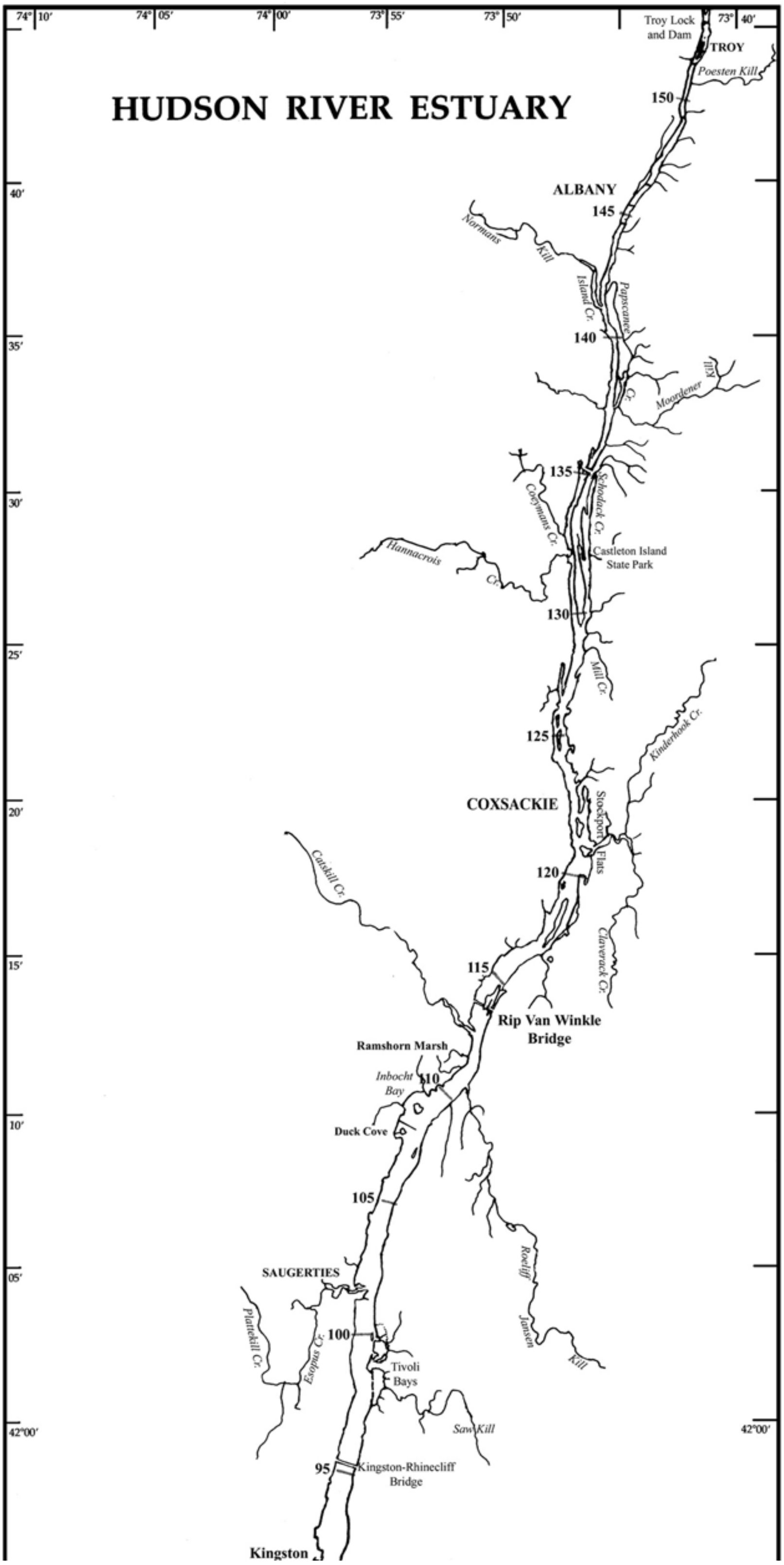

Figure 1.1. The Hudson River Estuary (*continued on next two pages*).

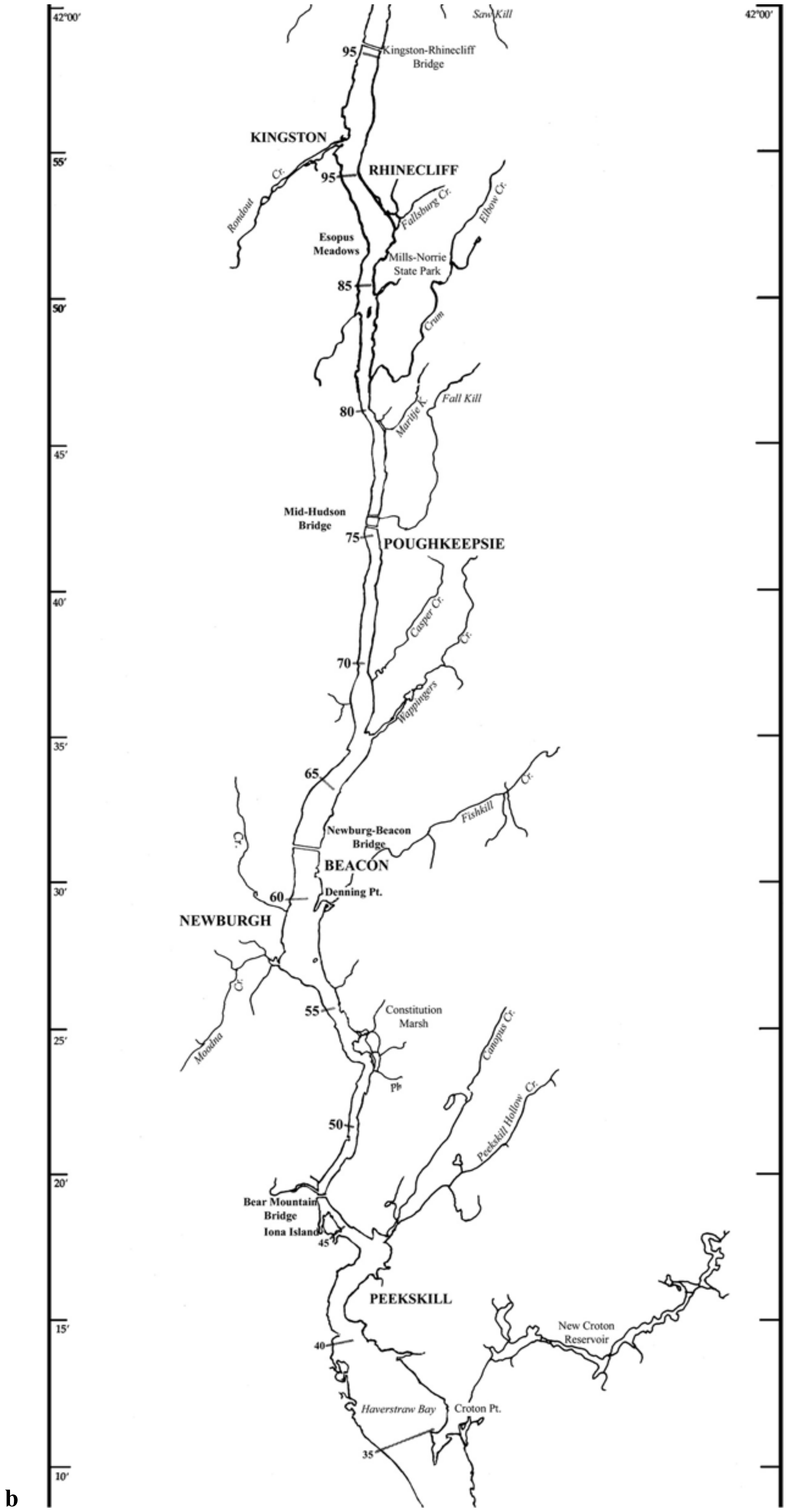
42°00′
Saw Kill
95
Kingston-Rhinecliff Bridge
KINGSTON
RHINECLIFF
55′
Rondout Cr.
95
Fallsburg Cr.
Elbow Cr.
Esopus Meadows
Mills-Norrie State Park
85
50′
Crum
Fall Kill
80
Maritje K.
45′
Mid-Hudson Bridge
75
POUGHKEEPSIE
40′
Casper Cr.
Cr.
70
Wappingers
35′
65
Cr.
Fishkill
Newburg-Beacon Bridge
BEACON
30′
60
Denning Pt.
NEWBURGH
Cr.
Moodna
55
Constitution Marsh
25′
Canopus Cr.
50
Peekskill Hollow Cr.
20′
Bear Mountain Bridge
Iona Island
45
PEEKSKILL
15′
New Croton Reservoir
40
Haverstraw Bay
Croton Pt.
35
10′
b

Figure 1.1.

c

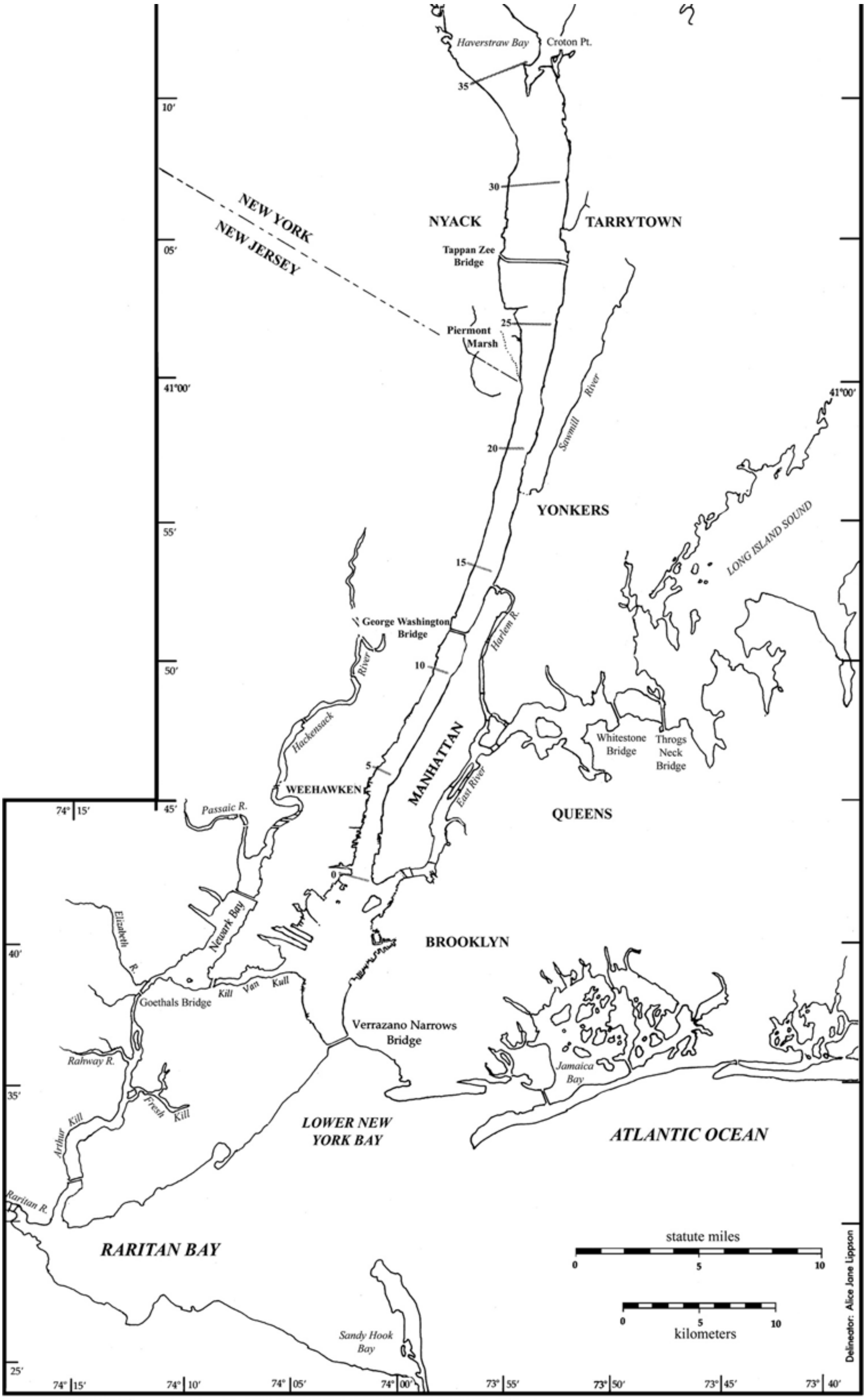

Figure 1.1 (*continued*). The Hudson River Estuary.

it reaches greater depths at World's End in the Highlands.

Thanks to the post glacial rise of sea level, the Hudson River Estuary is now a drowned river valley falling only 1.5 meters along the 240 km between Troy and the Battery. The estuary is maintained as a shipping channel, and dredged to a minimum depth of 9–11 m, although portions of the river are much deeper. Slightly more than half the estuary is fringed by marshes and wooded swamps; the remainder consists of mud flats that are flooded at high tide. Wetlands such as tidal marshes are in greatest abundance in the upper third of the estuary (Chapter 20).

The River That Flows Both Ways

The Hudson River is, in the parlance of estuarine scientists, a *partially mixed estuary*, which means that a distinct mixing occurs between the ocean and the freshwater river, leading to a layered structure. Higher salinity water is overlain by lower salinity water (Chapter 3) over a broad stretch of mixing between the river and the ocean. The estuary can be divided into four salinity zones: polyhaline (18.5–30 psu), mesohaline (5–18), oligohaline (0.3–5), and limnetic (<0.3). The location of these zones varies seasonally as well as daily depending on tidal and freshwater inputs. In New York Harbor, between the Verrazano Narrows and approximately the George Washington Bridge, the distinct two-layer vertical structure occurs, with a saline bottom layer overlain by a freshwater surface lens. Wind and tide mix the two layers so there is a vertical salinity gradient from fresh to saline, as one goes from the surface to bottom waters. At some point upstream the Hudson is fresh water from surface to bottom.

Although this basic salinity structure is always present, it varies radically with season and weather. After the spring freshet, when snows melt in the upper part of the watershed and spring rains increase freshwater flow downstream, the surface freshwater lens in the mixing zone extends much further down into New York Harbor. Thus, the three-dimensional distribution of salt is complex and dynamic. Water circulation also differs from bank to deepest depth to opposite bank and this also affects the distribution of salt in the river.

North and above the Federal Dam at Troy, the Hudson has a conventional river flow, with a series of rivers and streams feeding from eastern and western uplands into the main course of the river. Below the dam the river is tidal. It must be upsetting for a stranger to see the river flowing opposite ways, depending upon the movement of the tide. The surface of the river at Albany is not much more than a meter higher than at the narrows, 240 km downstream. Thus tidal currents propagate a surprisingly large distance upstream.

Tides are caused by the gravitational interaction of the sun, moon, and the waters of the earth. In our region, the rotation of the earth, combined with gravitational attraction, results in approximately two high and two low tides per day at the coast. In the transitional zone in New York Harbor, where fresh or very low-salinity water becomes salty, the tide exerts a major vertical mixing effect. During spring tides this mixing is nearly complete and the salinity in New York Harbor is relatively homogeneous from surface to bottom. During neap tides flow is more reduced and one sees a more distinct lower salinity later overlying a higher salinity bottom layer.

As the tide rises, a tidal current moves northward up the Hudson. The time taken for the propagation of this current results in a significant delay between the time of high tide at the Verrazano Narrows and points upstream. High tide at West Point is a full three hours later than at the Narrows. The propagation is so drawn out that it can be high tide at one part of the length of the Hudson while being dead low at another. This makes for complex flow patterns. Flow is further complicated by the changing width and depth. As the width decreases a greater volume of water is forced through a narrower channel, which increases the flow velocity. Thus water flow through the narrow throat adjacent to the Hudson Highlands is far greater than in the broad width of Haverstraw Bay in the vicinity of Indian Point Power Plant.

On the shortest time scale, tidal flow is the controlling factor of water motion. But over longer seasonal time scales, the inevitable flow of fresh water from uplands to the oceans creates a net movement of fresh water downstream. This flow varies strongly and is generally strongest during the late winter and spring. On the still longer decadal time scale, one encounters some years with far more freshwater flow than others, with an inevitable shifting of fresh water downstream into New York Harbor.

A Dynamic Sedimentary Environment

The first impression one gets of the Hudson is its turbidity and the abundance of soft sediment. As a Secchi disk (the aquatic scientist's traditional indicator of turbidity) is dropped below the surface, one is impressed at how the disk quickly fades from view, usually only a half meter or so below the surface. As a large barge moves upriver, one immediately sees silt and mud stirred from the bottom adjacent to the shore. Both these phenomena combined indicate that the Hudson is dominated by suspended particles and is very dynamic as a sedimentary environment. It is not unusual to find sites where 10–20 cm or more of sediment may be deposited in a matter of days, and where similar amounts can be eroded away.

The Hudson's load of suspended sediment derives principally from clays eroded from surficial glacial lake and glacial outwash deposits (Chapter 4). Otherwise, the main stem of the Hudson flows through relatively resistant rocky terrane, which does not supply a great deal of sedimentary material. While turbid along its entire main channel, peaks of suspended sedimentary particles are found at the northerly extent of saline water and in the mid-Hudson. Because of the two-layered flow of the Hudson in the New York Harbor region, upcurrent flow in the deep layer transports sediment from the ocean to within the estuary.

The strong tidal mixing throughout the estuary results in strong current conditions at the bottom. Recently, a bottom survey using multibeam scanning sonar has detected a truly fantastic system of sand ripples with wave lengths of many meters and ripple amplitudes of a few meters (Chapter 5). The New York-New Jersey Harbor region is also a dynamic sedimentary environment and water movement and sediment deposition is complicated by extensive dredge channels that are maintained for shipping traffic.

A River Contaminated

Sediments in the Hudson are repositories for a vast array of toxic substances, which have been discharged from industrial pipes, sewage treatment plants, and general runoff over many decades. Persistent contaminants include PCBs, dioxins, chlorinated hydrocarbon pesticides, and trace metals such as copper, lead, zinc, cadmium, chromium, and mercury (Chapters 7, 24, 25, 26). In recent years alkylphenol ethoxylate (APEO) metabolites have been found and are believed to act as endocrine disruptors. Most famous are the high concentrations of dioxins and other substances in sites such as the Raritan River and high concentrations of PCBs in sediments above and below the Federal Dam in Troy. A 2001 EPA decision will result in the eventual dredging and disposal of PCB-laden materials. The Hudson River is the second most contaminated large estuary in the United States with metals, including mercury and copper.

In 1995, a Superfund cleanup removed cadmium-laden sediments in Foundry Cove near Cold Spring (Chapter 30). Many areas, however, still have high concentrations of toxics and proposed New York Harbor dredging therefore raises the important question of disposal. Extensive studies of dated sediment cores provide important evidence of contaminant deposition histories and insights into degradation processes (Chapters 25, 26).

A Rich Array of Habitats

The Hudson River Estuary is an ecologically heterogeneous environment with a diverse array of habitat types (Table 1.1). It is essential to have an inventory of these habitats in order to understand their relative impacts on water characteristics of the Hudson and to develop management, conservation, and restoration plans. Most of the Hudson consists of deep water habitats that are dynamic hydrological and sedimentary environments. We know far too little about these areas, which is a problem when considering deep-water populations, especially those of shortnose sturgeon and Atlantic sturgeon. Recent surveys using remote sensing and direct sediment coring have provided a complete sediment-habitat map of the freshwater part of the estuary (Chapter 5).

Among the most ecologically important and poorly understood habitats are tidal wetlands, which include freshwater and salt marshes (Chapter 20). Both are biologically diverse and are locations of sedimentation, which is strongly

Table 1.1. Habitat types of the Hudson River Estuary; Troy Dam to the Battery

Habitat type	Percent
Shallows	34
Tidal wetlands	9
Submerged attached vegetation	6
Floating vegetation	2
Non-vegetated bare bottom	17
Deep-water bottom >3m depth	66

Source: Courtesy of Elizabeth Blair, New York State Department of Environmental Conservation and Hudson River National Estuarine Sanctuary.

regulated by intertidal vegetation such as cattails (fresh water) and cord grasses of the genus *Spartina* (salt water). The vegetation harbors many animal species and also protects a series of channels, which are hotspots for aquatic animal diversity and often nursery grounds for juveniles of many fish species. Tidal marshes often dominate the large number of coves, whose hydrodynamics and overall ecology are strongly affected by the enclosing peninsulas created by railroad construction in the nineteenth century. The marshes may be sources of labile organic matter for the open Hudson River estuarine food web.

Shallow coves and bays are often covered by submarine attached vegetation, which includes at least twelve species, but is dominated by water celery. A number of coves have been successfully invaded by the floating water chestnut, a continuing source of annoyance to Hudson River residents. Despite this large amount of vegetation cover, most shallow areas consist of bare bottom and harbor a diverse benthic fauna (Chapter 19).

An extremely important but poorly understood habitat component of the Hudson River Estuary is the large suite of at least seventy-nine tributaries aside from the large Mohawk River, including rivers such as Indian Brook near Cold Spring and the Saw Mill River, which enters the river in Yonkers. The tributaries contribute approximately 20 percent of the water to the Hudson, a significant amount of particulate carbon and sedimentary material, and are crucial habitats for a wide variety of invertebrates and fishes. Alewifes use the tributaries extensively but we still do not know nearly enough about the importance of tributaries to the life cycles of a number of other fish species (Chapter 15). Interest in the Hudson's tributaries has heightened because urbanization has taken its toll on water quality and there is some evidence that the most urbanized tributaries contain greatly reduced fish populations.

The Base of the Food Web

Estuaries are among the most productive of marine environments, although food abundance does fluctuate greatly over space and time. This extraordinary productivity is a product of the large amounts of nutrients that enter the estuary seasonally and their extensive recycling between the overlying water and the biologically active sediments. The Hudson has some interesting complications that create exceptions to these generalizations. Most importantly, the Hudson bears a large sediment load, coming from its drainage system and consisting of materials ranging from clays derived from erosion of glacially derived deposits to organic particles derived from substances such as leaf litter. The combination of materials reduces light penetration in the water column, which in turn reduces photosynthesis of phytoplankton and restricts subaquatic attached vegetation to very shallow depths. The high particle concentration is complicated by strong vertical mixing, owing to tidal and wind mixing. Thus, phytoplankton cells spend much of their time in suboptimal light conditions.

Owing mainly to light limitation, the Hudson is not a river with high primary production in the water column (Chapter 9). Primary production is seasonal, with a peak in spring. Respiration, however, is a dominant process and little production is available for higher trophic levels in the Hudson. The freshwater phytoplankton are not limited by nutrients, but by light. In recent years the invasion of the zebra mussel has strongly reduced phytoplankton populations, which has further reduced the potential for oxygen production from photosynthesis. The respiration of the zebra mussels has lowered oxygen concentrations in the freshwater Hudson, which may be stressful to active organisms such as fish under some circumstances.

In the saline part of the Hudson in the vicinity of New York Harbor nutrient concentrations increase greatly as a result of dissolved sources from sewage. Nutrients are so concentrated that phytoplankton production is not limited by nutrients, but by light and temperature. Nutrient input in the saline part of the Hudson is among the highest of any coastal water body in America. Before the 1990s, organic matter input from untreated sewage resulted in anoxic or strongly hypoxic waters in New York Harbor. Since then, water quality has improved greatly, as has oxygen levels (Chapters 10, 23).

Zooplankton are abundant in both the freshwater and saline parts of the Hudson estuary, but in neither part of the estuary do they exert major grazing effects on the phytoplankton (Chapter 16). The zooplankton in the freshwater part of the Hudson are dominated by copepods, rotifers, and cladocera. Occasionally ciliates and flagellates are very abundant. While they may not be important in the cycling of nutrients, the zooplankton, nevertheless, are crucial food sources for larval and juvenile fish. It is notable, therefore, that the invasion of the zebra mussel resulted in strong decline of some zooplankton, particularly rotifers. It is not clear whether the decline was due to direct consumption by the mussels or by a shortage of phytoplankton food caused by zebra mussel feeding. In the saline portion of the Hudson, copepods dominate the zooplankton and feed mainly on phytoplankton.

Heartbeats in the Muck

The benthos of the Hudson is dominated by species capable of living in soft bottoms. In freshwater areas the benthos consists mainly of diminutive animal species such as larvae of chironomid flies, oligochaete worms who depend upon organic detritus and sediment microbes for food (Chapter 19). Predatory fly larvae and amphipods are also common. In the saline reaches of the estuary, these species are supplanted by abundant polychaete annelids, amphipods, and patchy occurrences of mollusks such as clams. Again, a dependence on particulate organic matter and sediment microbes is widespread (Chapter 18). These animal species form rich populations that burrow in the sediment and accelerate the breakdown of organic matter and recycling of this material back to the water column. A few invertebrate species are specialized and are confined to the low salinity (oligohaline and mesohaline) parts of the Hudson and are neither common in open marine nor purely freshwater habitats.

Both the freshwater and saline parts of the Hudson Estuary were once far more dominated by native suspension-feeding bivalves. In the limnetic region, freshwater mussels (members of the bivalve family Unionidae) were common in both the tributaries and in the main course of the Hudson, but they have been decreasing for decades, probably owing to habitat alteration. The invasion of the zebra mussel has probably further accelerated the decline of this group. In the saline part of the estuary, oyster beds were once ubiquitous, and the Fresh Kills area of Staten Island was one of the most productive oyster grounds in the United States in the early part of the nineteenth century. Pollution and exploitation have taken their toll, however, and oysters remain uncommon in New York Harbor. Clams are still exploited in Raritan Bay but they have recently suffered from disease.

Fisheries, Past and Present

The Hudson River is blessed with high fish biodiversity for a temperate estuary, with more than 210 species recorded from its entire watershed (Chapters 13, 14). The Hudson once supported rich commercial fisheries throughout its tidal waters. American shad were landed along the entire river, even across from Manhattan. Today, nearly all of its native fishes survive – some in robust numbers – but its commercial fisheries are almost extinct, shut down in 1976 because of contamination with PCBs. Among finfish, only American shad (a species that spends most of its life outside the system) are still harvested for profit, albeit in limited numbers as both fish and fishermen dwindle. Blue crabs, at the very northern limit of their range, also are caught by commercial and recreational fishers alike.

Other formerly important commercial fishes are protected from any harvest or from commercial fishing alone. Shortnose sturgeon appear to have quadrupled in stock size since the 1970s, yet remain off limits to all fishing because of their listing as a federally endangered species. Atlantic sturgeon – the behemoth of the river, once reaching 12 feet and 800 pounds – have been protected from all harvest in U.S. waters since 1998. Striped bass, formerly a major commercial species, can only be legally taken by anglers. However, the Hudson's striped bass population has grown enormously over the past two decades and it now supports a regionally-important recreational fishery during springtime for large, spawning-size fish.

Resident freshwater fishes such as channel catfish, white catfish, brown bullhead, yellow perch, and white perch are fished recreationally despite consumption advisories. The two non-native black basses – largemouth and smallmouth bass – are also avidly sought in the Hudson, where they form the basis of catch-and-release tournament fisheries.

Electric generating stations that withdraw Hudson River water for cooling purposes have caused considerable mortality of young life stages of Hudson River fishes, but their eventual replacement with modern facilities which use far less water should reduce these effects. Long-term reductions in PCB levels should allow for greater enjoyment of the river's fish resources.

Invasion of Exotic Species

From the time of the settlement of the Dutch colony of New Amsterdam to the digging of the Erie Canal, New York Harbor and the Hudson estuary became a major focus of long-distance commerce, which has made this region a target for the introduction of exotic species (Chapter 21). The Hudson estuary has over 100 alien species in continuing residence, some of which have had major effects on structural habitats and ecosystem functioning. While some species were introduced purposefully, most arrived owing to the water-borne access to Great Lakes and New York Harbor shipping. In the nineteenth century, the use of solid ballast brought a number of aquatic plants to the region. In recent decades, solid ballast was replaced by water, but this has brought a new batch of alien species in the form of plankton and larvae of benthic species. Most alien species derived from Europe or from the interior of North America.

In some cases, the arrival of alien species has been perceived as desirable by residents of the region surrounding the estuary, as witnessed by the widespread black bass fishing tournaments. But in other cases, aliens are noticeable intruders. The water chestnut, a Eurasian native, was introduced purposefully into a lake but soon escaped into the entire estuary. It produces a nearly impenetrable mat of vegetation, which often reduces oxygen in the waters beneath, enhances sedimentation, and impedes navigation by small boats. Its sharp spiny nut is a hazard to swimmers and barefoot walkers. In some shallow bays it has displaced native vegetation. Another notable example is the zebra mussel, which arrived in the estuary in 1989 and has spread throughout the entire freshwater portion of the estuary, colonizing shallow, subtidal hard surfaces. The planktivorous and rapidly dispersing plankton larval stage has facilitated its invasion of the river. Its high rate of suspension feeding has resulted in dramatic reductions of phytoplankton and its abundance and respiration resulted in sharp reductions of dissolved oxygen. Its clearance of particles, however, has had a slightly beneficial effect on shallow-water attached subaquatic vegetation, which can live at deeper depths owing to higher light penetration.

In the saline part of the estuary, a number of alien species have become very abundant. The green crab invaded our East Coast and spread in the early part of the last century but in recent years the Asiatic shore crab *Hemigrapsus sanguineus* has become dominant in the intertidal zone. Both species may be responsible for high mortality of juvenile mollusks, including young of harvestable shellfish species.

The Present and Future State of the River

Surely among the most predictable questions asked about the Hudson River are: what is its current state? And, given its historical reputation for being polluted, is it improving?

To provide answers, we face the question of which metrics to use, i.e., how do we establish a scoring system that reliably characterizes the Hudson's environmental condition and trajectory? This is not a trivial problem. The indicators chosen should represent the system in question and not geographically broader effects, should encompass its full breadth at numerous physical and biological levels, and should be sensitive to both gradual and episodic environmental impacts.

The New York-New Jersey Harbor Estuary Program tackled this issue with a report issued in 2003 that found nine of twenty-four proposed environmental indices showing improvement, including sediment loading, benthic community health, contaminant loadings, and the areal extent of shellfish beds. But meanwhile, harmful algal blooms were on the rise and abundances of some important resource species were on the decline. Other indicators, such as abundances of striped bass, forage fish, and winter flounder revealed no appreciable changes. On the whole, the weight of the evidence is positive, particularly indicators of toxic substances, but biological resources are still in need of upgrading.

Perhaps the most exciting results reported in this volume involve the great progress made in relating ecosystem processes to environmental change and human efforts at environmental restoration. The chapter on the benthic communities of New York Harbor (Chapter 18) shows a clear recovery over decades in response to reductions of contaminant inputs. The clean up of Foundry Cove has removed the major source of metal pollution to the Hudson, which will decrease trophic transfer of metals through food webs (Chapter 30). Follow through on current plans to dredge PCB hotspots should have similar effects for this contaminant (Chapters 24, 25), the limiting factor for unfettered consumption of Hudson River finfish.

Radically improved sewage treatment in the 1900s, particularly since the Clean Water Act of 1972, has led to major improvements in water quality throughout the estuary (Chapter 23). Indeed, a focus on this baseline issue has generated considerable new knowledge of how the system functions ecologically from nutrients upward to the watershed level (Chapters 9, 10). It may be argued that successes achieved in the water quality arena have allowed the recent focus in the estuary on habitat evaluation and restoration – an initiative that would not merit serious attention in the absence of adequate dissolved oxygen levels.

But all is not well and vigilance is required to prevent environmental backsliding. The recent invasion of zebra mussels (Chapter 21) has resulted in major declines in freshwater phytoplankton and noticeable decreases in oxygen. Much earlier misguided introductions of organisms such as water chestnut, common carp, and others (Chapter 21) have had profound effects in portions of the estuary and are reminders that such mistakes usually are irreversible. Pollution inputs have been lowered dramatically (Chapter 22), but intermittent episodes may still occur, such as oil spills. And non-point sources of contaminants still leach into the system.

Do we know all we need to know about the Hudson? No, although we've made great strides. Despite a volume filled with exciting progress and results, we still require more knowledge of the River's flow patterns and how they distribute sediments and contaminants. We still are in need of comprehensive modeling approaches to fisheries that relate physical variables and human impacts to fish production, and to how species abundances are affected by interactions with other species. We still know relatively little about the importance of tributaries to Hudson River fishes, sediment transport, and water quality. These and many other realms of study can only benefit from periodic syntheses, such as this one, of what we continue to learn about this great river, which will help steer future research efforts.