RIVER RESEARCH AND APPLICATIONS

River Res. Applic. (2011)

Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/rra.1509

UPPER HUDSON RIVER ESTUARY (USA) FLOODPLAIN CHANGE OVER THE 20TH CENTURY†

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ABSTRACT

Detailed surveys of the upper Hudson River Estuary and its floodplain from the early 1900s and digital mapping of the same areas today provide an opportunity to evaluate changes over the 20th century. This study uses a geographic information system to quantitatively compare water areas and islands mapped by the United States Army Corps of Engineers in 1907 and 1911 along an approximately 60-km reach from Athens to Troy, NY, with the same features mapped in the late 20th century. The comparison shows a substantial decrease in total water area approximately 30% less than the 1907–1911 quantity, with secondary channels disproportionally affected (~70% less). The number and total area of islands has also dramatically decreased by approximately 65% and 85%, respectively. These changes primarily reflect the success of navigation improvement projects undertaken since the 19th century that transformed a shallow, island-braided river in the study reach to one characterized by a deeper, single-thread channel. Dredge spoils from the main channel were used to fill secondary channels and other backwater areas, a practice with implications for reproduction, growth and/or survival of native plants and animals. Published in 2011 by John Wiley & Sons, Ltd.

KEY WORDS: geomorphology; floodplain; human impacts; Hudson River; navigation; geographic information system (GIS)

Received 6 August 2010; Revised 4 January 2011; Accepted 7 February 2011

INTRODUCTION

The upper Hudson River Estuary from approximately Athens to Troy, NY, was historically an island-braided, tidal channel that was generally shallow even along the deepest part of the channel, or thalweg, and had many secondary channels (Figure 1). Its physical character impeded navigation for deep draft, ocean going vessels to Albany, NY, which became an increasingly important transportation centre for the north-eastern and midwestern United States after the completion of the Erie Canal in 1825 (Miller *et al.*, 2006).

Early efforts to improve channel depths in this reach were primarily undertaken by New York State (NYS) and consisted of constructing spur dikes and closing dikes along with supplemental dredging. Dikes constructed to close side channel entrances and spur dikes oriented perpendicular to the channel in the main channel were intended to constrict the flow to a single, narrower channel and thus increase flow velocities. It was hoped that the increased velocities would induce channel bed scour, thereby improving channel depths (Chen and Simons, 1979; US Congress, 1885, 1888). Dredging was done where channel constriction was not sufficient (US Congress, 1888).

In 1831, the United States federal government assumed jurisdiction over the Hudson River, and thereafter the United States Army Corps of Engineers (USACE) became involved in navigation improvements along with the state (US Congress, 1888). Because the earlier system of spur and closing dikes did not achieve lasting navigability, the federal government began a programme of constructing longitudinal dikes parallel to the flow to constrict the channel. Again, this was supplemented by dredging, and the dredge spoils were placed behind the longitudinal dikes. This approach was successful at achieving greater control depths and was expanded in 1867 with a target of improving navigation depths to 3.4 m between New Baltimore and Albany and 2.7 m between Albany and Troy (US Congress, 1888). To accommodate increasingly larger and deeper draft vessels in successive decades, in 1925 and again in 1932, the US Congress authorized further navigation improvements to attain 8.2 m and 9.7 m channels, respectively (Miller *et al.*, 2006).

The success of the navigation improvement projects is reflected in the dramatic change to the river's floodplain morphology in the upper estuary over the last 200 years. The river today in this reach is a deep, single-thread channel.

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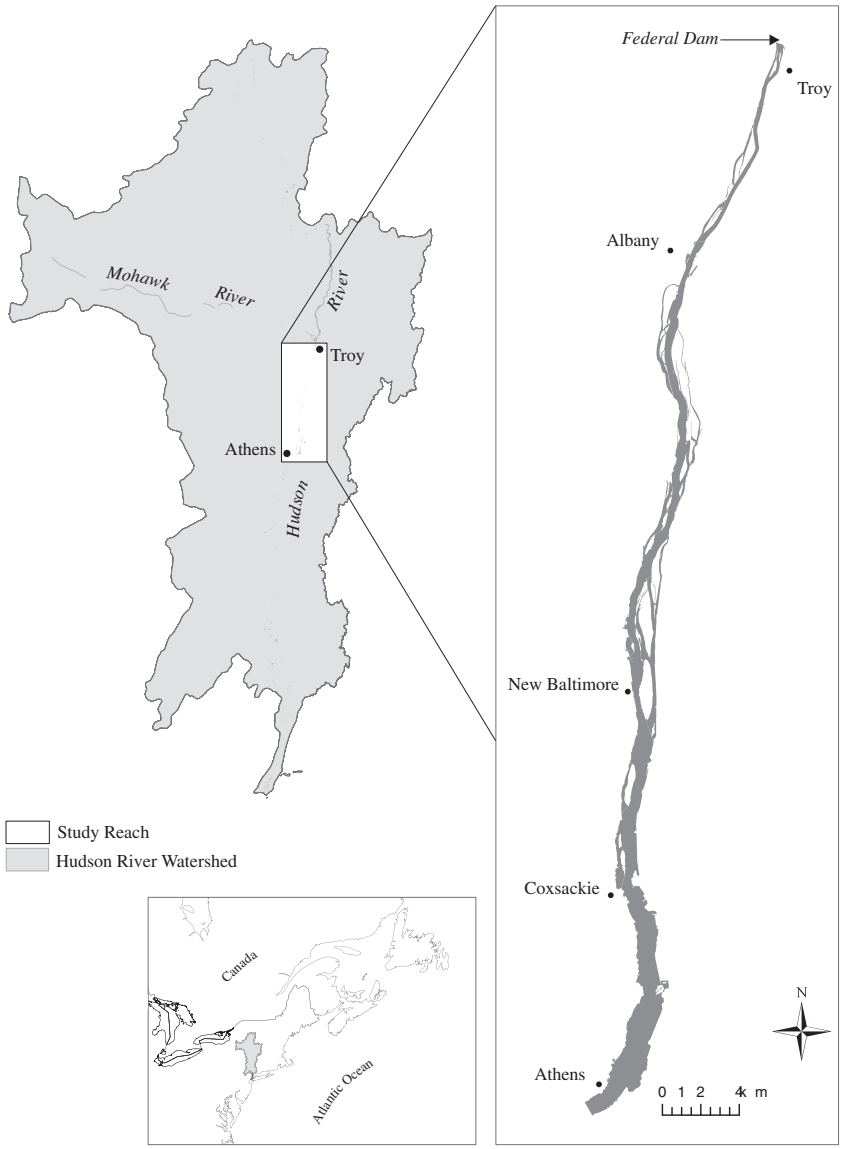

Figure 1. The Hudson River watershed and the nearly 60-km study reach from Athens to Troy, NY. The floodplain morphology shown was surveyed by the USACE in 1907 and 1911.

Many shallow areas adjacent to the thalweg are filled, many secondary channels are either fully or partially filled and thus many former islands are now part of the floodplain that is contiguous with the valley sides.

The floodplains and channels of large and small rivers around the world have been altered by humans for centuries for flood control, water and power supply, navigation, recreation and other uses. Direct impacts to floodplains and channels to achieve these objectives include dam construction, water and sediment extractions, channelization, channel modifications and diversions (Gregory, 2006; Simon and Rinaldi, 2006). For example, Hudson *et al.* (2008) documented extensive channelization and other direct modifications of the channels and floodplains of the lower Mississippi (USA) and Rhine (the Netherlands) Rivers accomplished over decades and centuries, respectively, for flood control.

Large-scale navigation improvement projects have been another important impetus for direct floodplain and channel modifications. Projects similar to those on the upper Hudson River Estuary were undertaken by the USACE on many of the United States' large rivers during the 19th and early 20th centuries to promote commerce in developing regions of the nation (Anfinson, 1993). With westward expansion, systematic navigation improvements of the type initiated on the upper Hudson River Estuary in the early 1800s were begun a few decades later on the upper Mississippi and Missouri Rivers, and brought similarly substantial geomorphic change (Chen and Simons, 1979; Hallberg *et al.*, 1979; Collins and

Knox, 2003). As with the Hudson River, the upper Mississippi River and Missouri River projects required many decades, and numerous congressional authorizations, to complete not only because of their scale but also because of changing navigation needs with further economic development and improved technology (Anfinson, 1993; Ferrell, 1993). The upper Mississippi River navigation improvements, for example, were attained by River and Harbor Acts of 1878, 1907 and 1930 that sought progressively deeper channels of 4.5, 6 and 9 ft (Chen and Simons, 1979; Anfinson, 1993).

Miller *et al.* (2006) identified changes in historic channel morphology (1820 – present) in the upper Hudson River Estuary by defining habitats by depth ranges and comparing historic and present day totals of intertidal and shallow habitat (< 2 m) and deep water (> 2 m). That analysis demonstrated that approximately 1335 ha of aquatic habitats were filled in the upper Hudson River Estuary from near Athens to Troy. They described a transformation from a system dominated by intertidal and shallow water habitats (< 2 m) to a system dominated by deep water channel (> 2 m). Native submerged aquatic vegetation communities can only exist in shallow water areas (< 2 m deep at low tide) because of light limitations in deeper water. These vegetation communities have been shown to be highly productive areas within the estuary that improve water quality by increasing dissolved oxygen and thus supporting a greater density and diversity of macroinvertebrates than non-vegetated areas (Findlay *et al.*, 2006; Strayer and Malcom, 2007). Relatively high dissolved oxygen and abundant macroinvertebrate communities of vegetated shallows are important components of forage and refuge habitat for native resident and migratory fishes. Shallow water habitat availability is also important for the growth and survival of many young fishes (Scheidegger and Bain, 1995; Freeman *et al.*, 2001).

Miller *et al.* (2006) did not, however, further quantitatively describe and compare habitat changes by other available morphologic and spatial metrics. For example, their analysis did not discriminate between shallow water areas that are flow-through secondary channels and those that are backwaters. Recent research describing the physical habitat characteristics of other large American rivers with multi-thread channels suggests that, when compared with flow-through secondary channels, backwaters have lower flow velocities, higher temperatures and finer substrates (Berry *et al.*, 2004; Welker and Scarnecchia, 2006). With higher temperatures and little to no flow velocity, it is also likely that backwaters have lower dissolved oxygen conditions compared to areas that receive moderate velocity through-flow. Velocity, temperature, substrate calibre and dissolved oxygen conditions are important discriminators between habitats for different fish assemblages (Hubbard *et al.*, 1993; Wilcox, 1993); thus, we expect that the native fish species that used flow-through secondary channels for some part of their life cycle in the Hudson River have been impacted by secondary channel filling and consequent losses or conversion to backwater environments (Daniels *et al.*, in press). Other fauna that use these areas have also likely been affected (Breisch, in press).

We use high-resolution surveys of the upper Hudson River Estuary from the early 20th century, modern maps of the same area and a geographic information system (GIS) to quantify for each time period specific aquatic feature types defined by their planform morphology and positions relative to the thalweg. We then estimate aquatic area losses and gains resulting from the 20th century navigation improvement activities, which are likely underestimates of the total change to the floodplain since European settlement because substantial floodplain change began in the early 19th century. We also briefly discuss potential implications of these changes for aquatic habitat.

METHODS

Study reach

The floodplain area surveyed in the early 20th century defines the extent of the study: an approximately 60-km river reach from Athens to Troy, NY (Figure 1). Our study reach is nearly the same as the reach analysed by Miller *et al.* (2006). The upstream boundary is just below the lock and dam at Troy, commonly referred to as the 'Federal Dam', which is operated by the USACE and separates the non-tidal river from the tidal estuary below. The watershed area immediately above the dam is approximately 21 000 km^2 and the average annual discharge there, calculated from a United States Geological Survey (USGS) daily discharge record beginning in 1946 that is continuous to the present (Hudson River at Green Island, NY, # 01358000), is about 400 $m^3 s^{-1}$. The USGS stage-recording gauge below the dam at Albany, NY (# 01359139), in operation since 1993, shows a modern tide range in the study reach of approximately 1.5 m. There have been no other operating stage gauges in the study reach to our knowledge; therefore, the relatively short record at Albany limits our ability to evaluate hydrology for this tidal section over the period for which we have floodplain surveys.

Data

The study reach's planform morphology in the early part of the 20th century was documented by the USACE in detailed surveys from Troy to Coxsackie in 1907 and Coxsackie to Athens in 1911 (USACE, 1907, 1911). They are available on 13, 1:5000 - scale historic map sheets that were registered and digitized by the NYS Department of Environmental Conservation (NYSDEC) from Tagged Image File Format (TIFF) images of the original maps (Figure 2). NYSDEC

DOI: 10.1002/rra

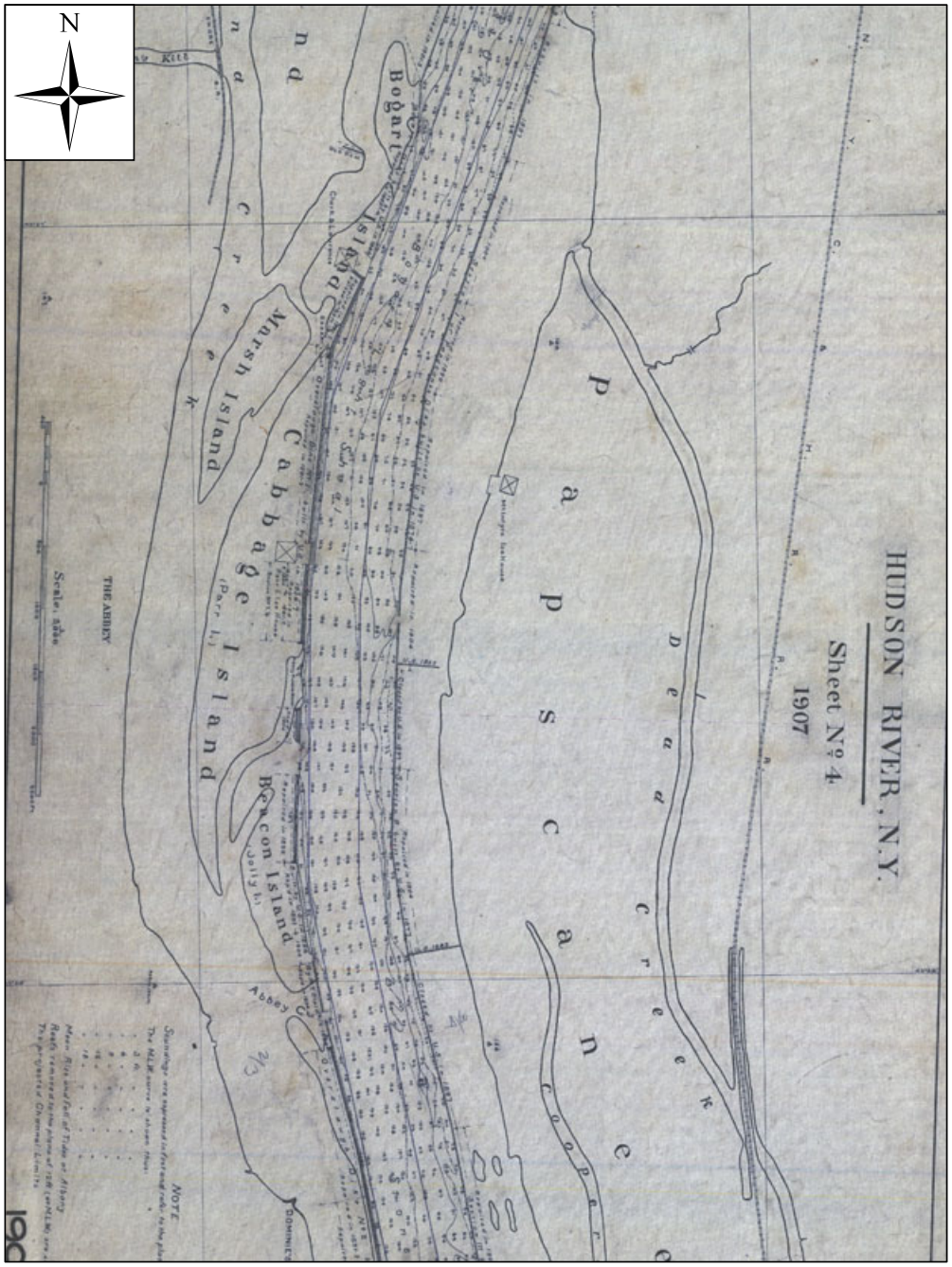

Figure 2. The island-braided Hudson River in the vicinity of Papscanee Island shown on Sheet No. 4 of the 1907 USACE survey.

reports that image registration was accomplished by using a combination of the existing latitude/longitude grid from the original maps and modern orthophotography showing lighthouses, bridges and other landmarks extant in both the historical surveys and the modern images (i.e. a 'rubber-sheet' transformation). Shoreline and island features were subsequently digitized to create one continuous layer from Athens to Troy. All digital data were captured in an ArcGIS 9.0 environment (Esri Inc., Redlands, CA, USA), referenced to the North American Datum 1983 (NAD83) and projected into the Universal Transverse Mercator (UTM) coordinate system (Zone 18, metres).

The modern planform of the study reach was digitized by the NYSDEC Hudson River Estuary Program from seven

adjoining NYS Department of Transportation (NYSDOT), 1:24 000-scale quadrangle maps (Lamont-Doherty Earth Observatory, 2004). NYSDOT quadrangle maps are updated versions of the original USGS quadrangle maps and show hydrography for this reach from 1993 to 1995. As with the historic map data, these data are referenced to the NAD83 and projected into the UTM coordinate system (Zone 18, metres).

Data reliability and limitations

When quantitatively comparing planimetric measurements of floodplain water areas and adjacent landforms at different time periods, it is important to understand if temporally variable water stages affect the measurements between survey dates. If the water's edge delimits measured water areas and/or floodplain landforms, any changes in stage between survey dates need to be understood and potentially accounted for in the analyses (Collins and Knox, 2003). Inspection of the USACE (1907, 1911) historic surveys of our study reach, and the modern NYSDOT quadrangle maps, shows that the water's edge was not the delimiter of the shoreline in either data set. Tidally exposed bars are clearly shown in all surveys with a well-defined, perennial shoreline on the landward side. This shoreline is described in the legend of the USACE (1907) map sheets as 'the projected channel limits' and is presumably analogous to a bankfull channel that contains daily tidal fluctuations and relatively frequent high stages (i.e. recurrence intervals less than approximately 1–2 years). It is the feature that was digitized in our GIS layers for the 1907–1911 and modern periods and defines the water areas, banks and islands. Thus, the reach's fluctuating tide stage and other freshwater discharge stage changes do not affect our floodplain landform or water area measurements.

Two other concerns arise when doing quantitative comparisons of planform features over time, especially when historic data are used: (i) the accuracy of the original survey work and (ii) georeferencing the surveys in the GIS. NYSDOT (2009) estimates the positional (horizontal) accuracy of their 1:24 000-scale quadrangle maps at approximately 12 m (40 ft). We have no accuracy estimates for the USACE (1907, 1911) surveys, but the relatively large scale at which they were compiled (1:5000) and our previous experience with USACE surveys from this time period suggest that they are at least as accurate as the NYSDOT quadrangle maps (Collins and Knox, 2003).

Quantitative estimates of georeferencing accuracy (e.g. root mean square error of control point registration) are also not available for either the 1907–1911 or the modern GIS data, but other existing information provides some insight. The 1907–1911 GIS layer was digitized from scanned images of the original USACE maps, a process that can introduce georeferencing errors if there are even slight wrinkles in the original map when it was scanned. Also, as described above, the images of the historic maps were registered via a rubber-sheet transformation, which can reduce positional accuracy.

Given the reported positional accuracy of the NYSDOT quadrangle maps and our concerns about the historic map georeferencing, our analyses simply quantify changes through time in the surface areas and numbers of classified floodplain features— quantities that are independent of exact location on the earth's surface. Our data support robust temporal analyses of these metrics.

Analyses

Water areas were delineated for both the historic (1907–1911) and modern river using a geomorphology-based, aquatic habitat classification system developed for the upper Mississippi River by Wilcox (1993) as modified by Collins and Knox (2003) [Figure 3(A)]. The areas and perimeters of natural polygons representing islands and isolated backwaters and delineated features including the main channel, secondary channels and contiguous backwaters were computed by the GIS. These quantities, as well as the total numbers, were tabulated by feature type for the historic (1907–1911) and the modern periods and compared. Our subsequent interpretations of habitat changes assume that all aquatic features other than the main channel were primarily shallow and intertidal areas, which is supported by inspection of the historic surveys and the analysis of Miller *et al.* (2006).

RESULTS AND DISCUSSION

Table I shows the total quantities of each aquatic feature type (number and total area) for the early and late 20th century, as well as the changes over time. The comparisons document a dramatic planform morphology transformation of the upper estuary over the 20th century. Approximately 1200 ha of the total water area was filled with dredge spoils during that time. A large proportion of the total water area lost was shallow areas bordering the main channel (approximately 975 ha). Secondary channels were also substantially affected. The modern quantity of secondary channels is approximately 70% less than it was in the early 1900s, a loss of about 550 ha. There has been a large increase in the total area of contiguous backwater. Although their number decreased by one, their area increased by approximately 300 ha (over 1000%). The increase in contiguous backwater area is directly related to the decrease in secondary channel area. In some cases, secondary channels were filled only at their upstream ends, converting the remainder from a flow-through secondary channel to a

DOI: 10.1002/rra

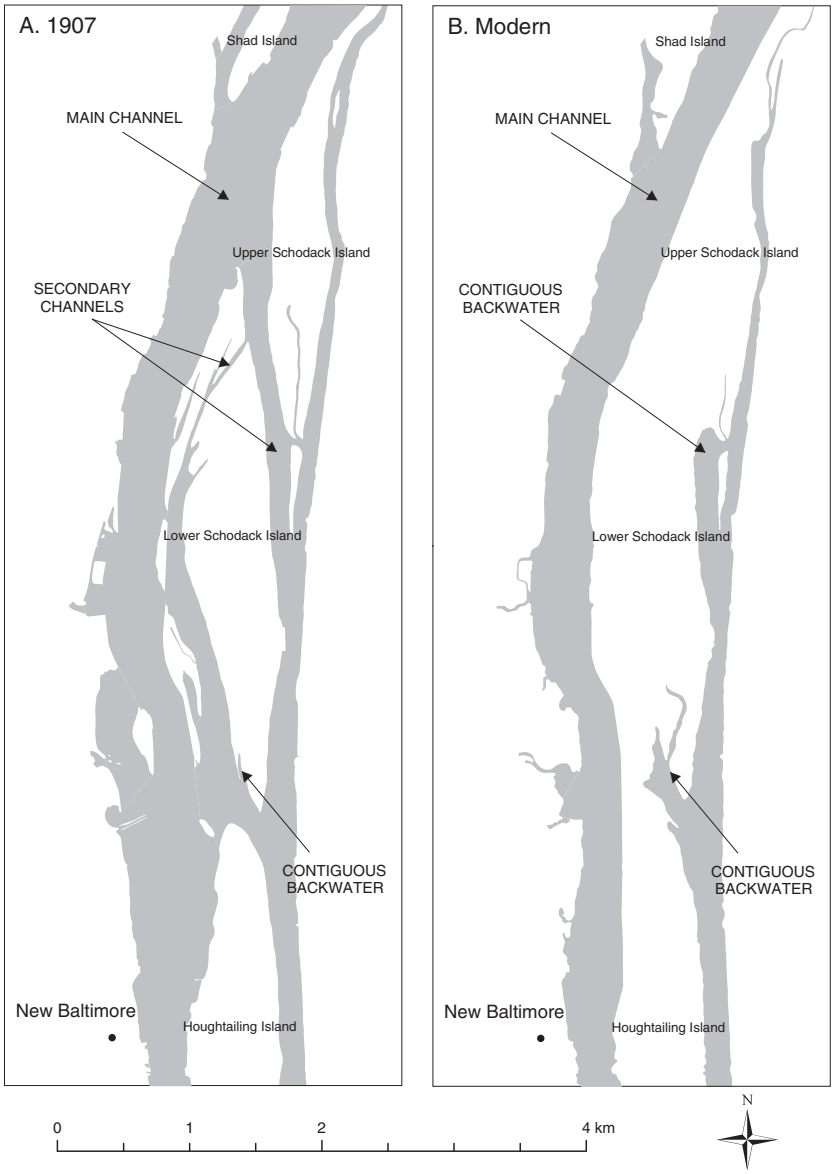

Figure 3. (A) Example water area delineations for a subsection of the study reach. Shown is the 1907 floodplain in an approximately 8-km reach from New Baltimore to Shad Island. (B) Modern water areas in the same river reach. Note the conversions of secondary channels to contiguous backwaters and narrowing of the main channel.

Table I. Total numbers and areas (ha) of aquatic feature types for the early (1907–1911) and late (modern) 20th century. Changes over time (Δ) are shown as changes in number and/or area (ha) and as relative change (%)

	Main channel	Secondary channels		Tributary channels	Contiguous backwaters		Isolated backwaters		Total water area	
	Area	No.	Area	Area	No.	Area	No.	Area	No.	Area
1907–1911	3479	14	765	24	24	28	1	0.6	40	4296
Modern	2504	6	213	46	23	325	0	0	30	3088
Δ	−975	−8	−552	22	−1	297	−1	−0.6	−10	−1208
Δ (%)	−28	−57	−72	93	−4	1064	−100	−100	−25	−28

DOI: 10.1002/rra

Table II. Aquatic feature types as a proportion (%) of total water area for the respective time periods, 1907–1911 and modern

	Main channel	Secondary channels		Tributary channels	Contiguous backwaters		Isolated backwaters		Total water area	
	Area	No.	Area	Area	No.	Area	No.	Area	No.	Area
1907–1911	81.0	35.0	17.8	0.6	60.0	0.6	2.5	0.01	100	100
Modern	81.1	20.0	6.9	1.5	76.7	10.5	0.0	0.0	100	100
Δ	0.1	−15	−10.9	0.9	16.7	9.9	−2.5	−0.01	0	0

contiguous backwater [Figure 3(A) and (B)]. There was only one documented isolated backwater (floodplain lake) in the study reach by the early 20th century, and by the late 20th century it was filled. Tributary channels show a nearly 95% increase in water area because many places where tributaries discharged to main channel border areas, and other shallow backwaters, were filled, and therefore these tributaries today flow through the new land to meet the Hudson—extending their overall length toward the river.

Table II shows the changes described above in relative terms. The main channel accounted for approximately 81% of the total water area in 1907–1911, and today it accounts for nearly the same proportion. However, it is very important to recognize that today's main channel is much different from the main channel of the early 20th century. At that time, the control depth of the channel in this reach was maintained at approximately 3.4 m [the reliable channel depth in 1819 was just over 1 m (US Congress, 1888)]. Since 1932, however, the navigation channel has been maintained at 9.7 m, and today there are many fewer shallow, main channel border areas (Miller *et al.*, 2006). Table II also shows an approximately 10% loss in the relative proportion of secondary channels and a corresponding 10% increase in the relative proportion of contiguous backwaters over the 20th century.

Islands have been severely affected by the navigation improvement projects (Table III). The total number of islands in this reach has been reduced by approximately 65%, and their areas and perimeters have been reduced by about 85%. This is a substantial loss of shoreline habitat—115 km [Figure 3(A) and (B)].

These physical habitat changes have likely had important implications for native aquatic plants and animals. There are many fewer shallow areas in this reach of the river to support the native submerged aquatic vegetation communities shown to be highly productive components of the estuary (Findlay *et al.*, 2006; Strayer and Malcom, 2007) and are important forage and refuge habitat for native resident and migratory fishes. Moreover, many of the remaining shallow areas were once moderate velocity, flow-through secondary channels that were partially filled and thus became contiguous backwaters. This physical alteration reduces or eliminates flow velocities and creates conditions that favour increasing temperatures, fining substrates and decreased dissolved oxygen (Berry *et al.*, 2004; Welker and Scarnecchia, 2006)—important habitat changes for the native aquatic species that were adapted to the secondary channel environments.

The results of Miller *et al.* (2006) are consistent with our water area results, despite using different historical map data and different analytical techniques. Miller *et al.* (2006) documented that approximately 1335 ha of the river's total surface area was filled over the period 1820–present by comparing polygon areas of shallow water habitat measured via planimeter for each time horizon. Our estimate of approximately 1200 ha of aquatic area loss was calculated via higher resolution GIS data for the 20th century. The slightly higher estimates of Miller *et al.* (2006) for habitat loss in the study area are expected because they analysed changes from the early 19th century forward. It is not surprising that the comparison between our results and theirs suggests that the large majority of floodplain change in the upper Hudson River Estuary brought about by navigation improvement projects was accomplished in the 20th century. As with other large American rivers over the last two centuries, navigation improvements, and the attendant morphological changes they brought, were generally small-scale operations throughout the early and mid-19th century. Large-scale efforts on the upper Mississippi River, the Missouri River and the Hudson River began in the late 19th century and were in full swing by the early to mid-20th century as commercial demand increased and technological advances permitted (US Congress, 1888; Anfinson, 1993; Ferrell, 1993; Collins and Knox, 2003; Miller *et al.*, 2006).

Table III. Twentieth century changes to islands in the Athens to Troy reach

	Islands		
	No.	Area (ha)	Perimeter (km)
1907–1911	68	1218	137
Modern	24	166	22
Δ	−44	−1052	−115
Δ (%)	−65	−86	−84

DOI: 10.1002/rra

CONCLUSION

The floodplain of the upper Hudson River Estuary, characterized by an island-braided morphology at the time of European settlement, has been substantially altered over the last two centuries by a series of navigation improvement projects. These projects, and the increasing scales of morphologic change they brought, were emblematic of similar efforts on other large US rivers over the 19th and 20th centuries—with similar implications for floodplain habitats. Our analyses, in light of earlier work, suggest that the large majority of upper Hudson River Estuary morphologic change occurred in the 20th century (Miller *et al.*, 2006). Since the early 1900s, approximately 1200 ha of aquatic area has been filled, much of which was shallow water, moderate velocity habitat. Nearly all of the loss is of main channel border area and secondary channels. Many secondary channels were converted to lower velocity, contiguous backwaters. Habitat alterations have been an important agent of Hudson River fisheries decline over the historical period, affecting human uses of the river and spurring human responses that have further modified the ecosystem (Daniels *et al.*, in press). Partially filled secondary channels provide opportunities to restore moderate velocity, shallow water habitat to the large contiguous backwaters that were created.

ACKNOWLEDGEMENTS

The authors would like to thank John Ladd, Larry Gumaer, Alan Lorefice and two anonymous reviewers whose comments improved the quality of the manuscript.

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