POLLUTION AND DISEASES
Research Article

Engineering Transformations of the New York State Canal System and Long-Term Environmental and Public Health Implications

Kenneth R. Olson [1]

Professor Emeritus of Soil Science, Department of Natural Resources and Environmental Sciences, University of Illinois, Urbana, Illinois, USA.

DOI: https://doi.org/10.66659/f33ysb84

Published: August 18, 2026

Vol. 2, pp. 103–146.

How to cite: Olson Kenneth R. Engineering Transformations of the New York State Canal System and Long-Term Environmental and Public Health Implications. Pollution and Diseases. 2026; Volume 2: 103–146.

DOI: https://doi.org/10.66659/f33ysb84

Abstract

Three major rivers—the Hudson, Mohawk, and Passaic—together with the New York State Canal System form an interconnected set of waterways that helped shape settlement, transportation, industry, and urban growth in the northeastern United States. Over the past two centuries, canals, channels, locks, dams, floodwalls, reservoirs, and repeated dredging transformed natural drainage systems and connected water bodies that had previously been separated. This review examines three linked case studies: the Hudson River and its legacy of polychlorinated biphenyl (PCB) contamination; the New York State Canal System and its economic, ecological, and public-health consequences; and the Passaic River, where Agent Orange manufacture contributed to long-term dioxin TCDD contamination of river sediments. The canal system accelerated commerce and migration but also created pathways for waterborne disease and invasive species, including the nineteenth-century spread of cholera and the movement of sea lamprey into inland waters. Industrialization along the Hudson produced persistent PCB contamination that required extensive dredging, monitoring, and Superfund remediation. Along the lower Passaic River, dioxin TCDD, PCBs, and mercury remain associated with contaminated sediments, fish and crab consumption restrictions, and multi-billion-dollar cleanup and natural-resource restoration efforts. Taken together, these cases show that hydrological engineering can create major social and economic benefits while also redistributing pollutants, biological agents, and ecological risks across connected water systems. Long-term management therefore requires integrated

[1] Corresponding author krolson@illinois.edu

attention to hydrology, sediment, ecology, public health, monitoring, remediation, and governance.

Keywords: Hudson River, Mohawk River, New York State Canal System, Erie Canal, Passaic River, polychlorinated biphenyls (PCBs), Agent Orange, dioxin TCDD, hydrological connectivity, public health.

Key Points

1. Canal construction, river regulation, and dredged channels transformed regional settlement, commerce, transportation, and the physical organization of northeastern U.S. waterways.
2. Engineered hydrological connectivity also created pathways for pollutants, waterborne disease, and invasive species across previously separated river and lake systems.
3. The Hudson River case demonstrates the persistence of PCB contamination and the long duration and high cost of sediment remediation and ecological recovery.
4. The Passaic River case links Agent Orange manufacture to persistent dioxin TCDD contamination, fish and crab restrictions, and multi-billion-dollar cleanup obligations.
5. Long-term waterway management requires integrated hydrology, sediment science, ecology, public health, monitoring, remediation, and governance rather than navigation engineering alone.

1.0 Introduction

The large-scale transformation of natural systems through engineered interventions, such as the New York State Canal System, is a defining feature of European settlement and economic development in North America. Rivers and lakes were extensively modified through the creation of channels, canals, locks and dams, cuts across drainage divides, and repeated dredging. These interventions addressed major societal needs, including navigation, industrial development, chemical manufacturing, and urban sanitation, but they also generated complex, cumulative, and often unintended environmental and public-health consequences. Pollution should therefore be understood as a dynamic process shaped by interconnected environmental pathways, including the Erie Canal, Oswego Canal, the New York State Canal System, and the Kill Van Kull channel. Hydrological engineering can alter the spatial redistribution of pollutants, nutrients, and biological agents across previously separated systems, affecting water quality, ecosystem stability, and human exposure pathways. Artificial connections among Lake Erie, Lake Ontario, the Mohawk River, Lake Champlain, the Hudson River, the Passaic River, and the Atlantic Ocean provide a major example of large-scale hydrological intervention. These cases show how engineering solutions designed for navigation, industrial development, and sanitation can reduce immediate constraints while creating long-term ecological and epidemiological consequences. Inter-drainage-basin connectivity has also contributed to the spread of invasive species, altered nutrient cycles, and broader ecological transformation. Addressing these long-term and cumulative effects requires an interdisciplinary approach integrating soil and water science, hydrology, ecology, epidemiology, infectious-disease ecology, and governance.

1.1 Case Study 1. Hudson River

Natural and anthropogenic changes in these river systems have repeatedly reshaped the landscapes through which they flow and the confluences where sediment-laden and polluted waters mix with tributaries on their way to the Atlantic Ocean. Climate variability and extreme events have altered channels and floodplains over millennia, while human engineering and industrial development have produced a second layer of landscape transformation. The Hudson River provides a particularly clear example: its abundant water supply and transport capacity supported industrial growth, but that growth also introduced persistent chemical pollution, including PCBs, into a river long celebrated for its scenic and ecological value.

The mid-nineteenth century Hudson River School of painting reflects artists' views of American paradise, a glorified Hudson River landscape where the disappearing wilderness, agriculture, and human settlements coexisted along the river in perfect harmony (1). The romantic, peaceful coexistence of nature and humans became an unsustainable illusion as the twentieth century 507 km Hudson River became a major transportation route to the northern and western interior of the United States (Figure 1). Like many rivers throughout history, navigation of the Hudson River waters fostered tanneries, paper mills, factories, chemical and electrical plants, and other enterprises along its coastline (2). Rivers, with their abundant water supply and capacity to transport raw materials and finished goods, fueled the Industrial Revolution of the 1800s, and the Hudson River was exemplary in its contributions. Settlements and industries along the Hudson River valley flourished, creating jobs, expanding communities, and bringing economic prosperity to the region and the nation. In its wake an era of industrial pollution left an ugly mark on the river celebrated for its beauty and pristine waters.

Morton and Olson (1) noted *"The development, degradation, and recovery of the Hudson River, its riverbanks, and the New York City (NYC) harbor is the story of a new country taming a wilderness, the growing pains and unintended consequences of uncontrolled economic entrepreneurship, and an emerging environmental ethic. As early as 1890, the US Army Corps of Engineers improved river navigation with dikes to narrow and deepen the river for larger boats to transport raw and finished products. The deepened channel eliminated shallow waters and the habitat that native river plants and animals needed to survive and thrive (2). The river ecosystem was further compromised as industries along the Hudson released by-products of their processes—oil, solvents, cleaning fluids, heavy metals, and paints into the river (3). Following World War II, the river's coastline included factories producing synthetic chemical compounds for electrical components and consumer products that became central to the modern economies of the world. One of these compounds was a synthetic chlorinated hydrocarbon called polychlorinated biphenyls (PCBs). PCBs were commercially produced from 1929 to 1977 when they were banned by the*

USEPA (4). PCBs unintentionally entered the food chain of rivers and have persisted throughout the environment despite extensive dredging and continued monitoring.”

Figure 1. The Hudson and Mohawk River basin in the State of New York, United States (1).

“By the 1960s, the health and safety issues connected with industrial pollution became too large to ignore. The Hudson River was polluted with sewage, heavy metals, butcher waste, and industrial chemicals (PCBs) (3). Swimming in the river was a risky action; eating the fish catch was even riskier (5). The glaring evidence of human disregard and negligence to the conditions of US waters generated an outcry from local citizens and media across the United States. Environmental activists protested

smog and poor air quality, water contamination, and careless disposal of hazardous wastes from American industries (6). The creation of the USEPA in 1970 and the Clean Water Act in 1972 were just the beginning of efforts to address industrial air and water pollution via monitoring, regulation, and enforcement. In 1980, the USEPA Comprehensive Environmental Response, Compensation, and Liability Act (also known as "Superfund") was authorized by Congress to clean up abandoned hazardous waste sites that contaminate the environment and are a threat to human health (7). Under the oversight of USEPA, billions of industry and government dollars are spent to clean up waste sites and rivers like the Hudson. The primary objective of this article is to discuss the geology of the Hudson River, early settlement, and industrial growth with a focus on PCBs and the cleanup investments to initiate the recovery of a valuable water resource" (1).

1.2 Geography and Geology of the Hudson River

The headwaters of the 507 km Hudson River emerge from the Appalachian Mountains of Upstate New York and flow from north to south where they are joined by a major tributary, the Mohawk River at Troy, New York (Figure 2), to form the Mohawk-Hudson River basin in eastern New York State (Figure 1). Near the end of the Wisconsin glaciation, the large glacial lake called Lake Iroquois (encompassing present-day Lake Ontario) drained toward the Mohawk Valley and then south through the lower Hudson River (8).

Figure 2. The confluence of the Hudson River (background) and the Mohawk River (far right), and the Erie Canal (front and center) near Troy, New York (1).

Morton and Olson (1) found that "*As the modern-day Hudson River flows south, the mountains of the Catskill Escarpment, a forested ecosystem with 1,000 m peaks, rise high above the Hudson Valley on the west. East of the river are the Taconic*

Mountains that form the boundaries of eastern New York State and western Massachusetts and Connecticut. South of the Catskill Mountains on the Hudson is the city of Newburgh, located in a valley comprised of lower Silurian or Cambrian slate and limestone. Below Newburgh, the Hudson Highlands tower over both sides of the river as high as 549 m where the river has cut a 32 km long gorge between Fishkill and Peekskill. Continuing southward, the Hudson flows into the upper and lower New York Bay and the Atlantic Ocean south of NYC. Here the tidal river becomes an estuary (Figure 3) formed during North American glaciation, 26,000 to 13,300 years ago. This deep, fiord-like strait cut from glaciation enables the bays and lower Hudson River to accommodate ocean vessels."

The lower Hudson Valley was filled by a glacier that carried great quantities of glacial till, and as it melted, it left behind what is now known as Long Island and Staten Island. The lower Hudson River cuts through Triassic sandstones and outcroppings of Precambrian gneiss that are not easily eroded. In 1890, James Macfarlane published the American Geological Railway Guide, which beautifully elaborates the geology of the Palisades, a high mountain ridge 122 to 183 m along the western edge of the river with the highest point in the range opposite Sing Sing, 244 m above the river. His comments echo the Hudson River School of landscape artists (9).

Viewed from the railroad or from a steamboat on the river, this lofty mural precipice with its huge, weathered ;kmasses of upright columns of bare rock, presenting a long, straight unbroken ridge overlooking the beautiful Hudson River, is certainty extremely picturesque. Thousands of travelers' gaze at it daily without knowing what it is. This entire ridge consists of no other rock than trap traversing the Triassic formation in a huge vertical dike… The materials of this mountain have undoubtedly burst through a great vent or fissure in the strata, overflowing while in a melted or plastic condition the red sandstone, not with the violence of a volcano, for the adjoining stratus are but little disturbed in position, … but forced up very slowly and gradually and probably under pressure… The rock is columnar basalt, sometimes called greenstone, and is solid, not stratified like water-formed rocks, but cracked in cooling and of a crystalline structure…On the east side of this river the formations belong to the first or oldest series of Primary or Crystalline rock, while on the west side they are all Triassic…" (1).

The rising Atlantic Ocean levels after the Wisconsin glaciation resulted in a marine incursion that buried the coastal plain and resulted in saltwater flowing north into the Hudson River as far as the upper New York Bay (Figure 3). The Hudson Canyon, a deeply eroded old riverbed extends beyond the current shoreline. When Staten Island and Long Island were connected, the Hudson River drained west into New Jersey (Figure 3), through the current Kill Van Kull (Figure 4) into Newark Bay (Figure 5), and then south into the current Arthur Kill between the Watchung Mountains and Staten Island into Raritan Bay and the Atlantic Ocean. The Narrows were formed 6,000 years ago at end of the glacial period when the Hudson River breached the terminal moraine and separated Staten Island from Long Island (Figure 3). Thus, the present course of the Hudson drains into the lower New York Bay between Staten Island and Long Island and into the Atlantic Ocean.

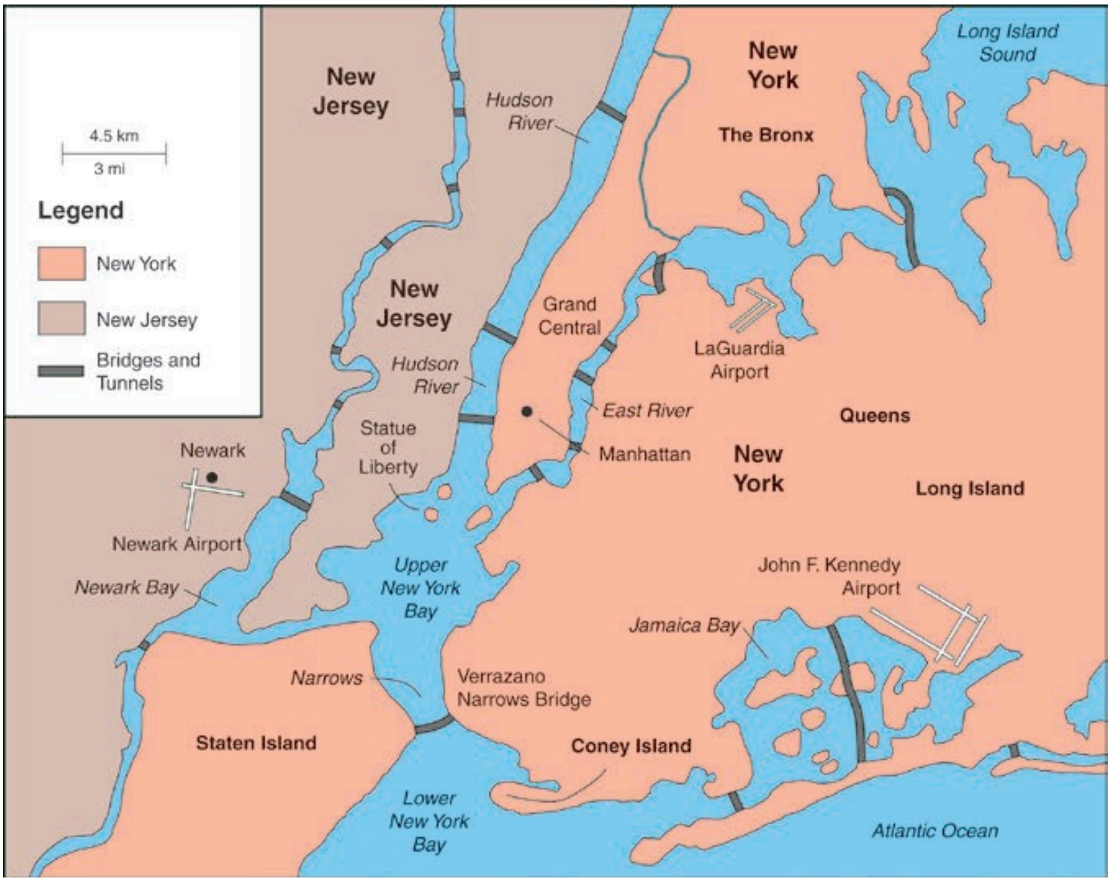

Figure 3. The lower Hudson River drains into the upper New York Bay and through the Narrows between Staten Island and Long Island into the Atlantic Ocean (1).

Figure 4. A view of East Kill Van Kull. Photo credit: Jim Henderson.

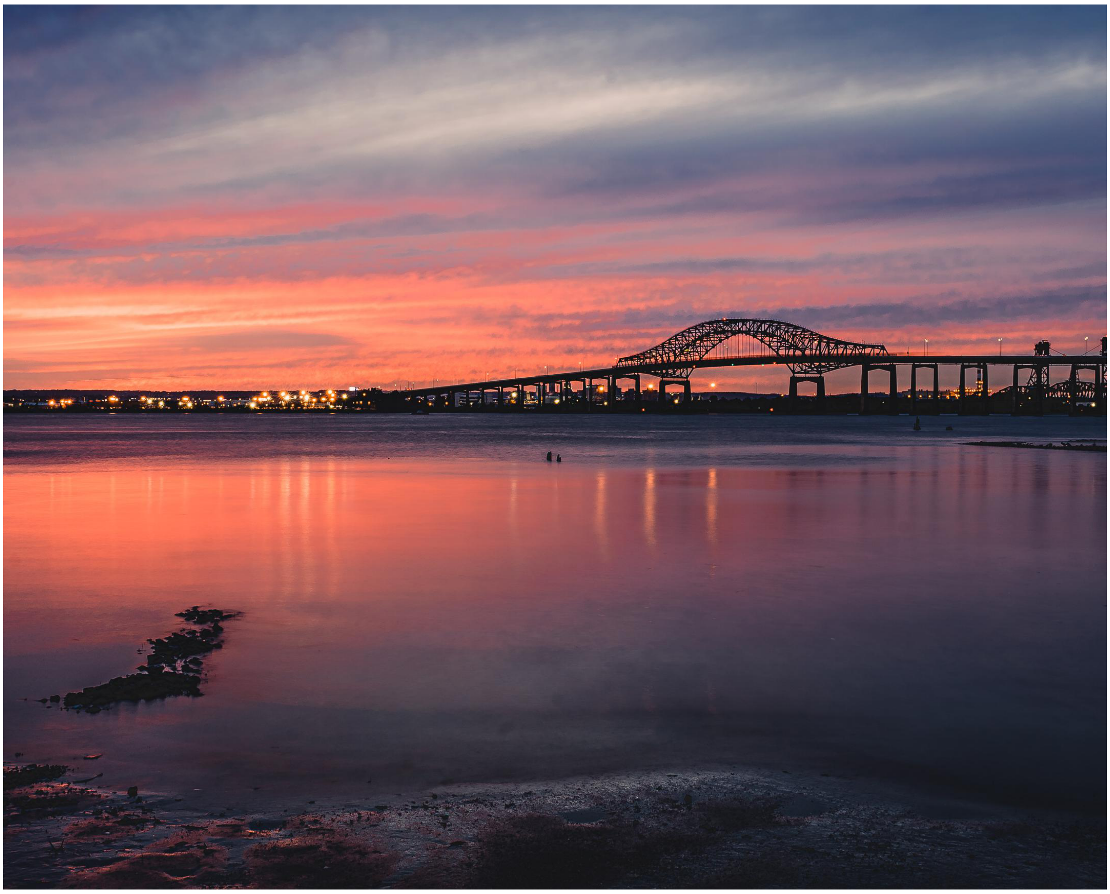

Figure 5. View of the Bayonne Bridge from Newark Bay at sunset. Photo credit: istock.

1.3 Native Americans in the Lower Hudson Valley

Levine (10) noted "*The lower Hudson Valley was the territory of the Acquackaronk and Hackensack Indians, members of the Lenape tribes. These Native Americans were primarily fishers and built weirs (overflow dams) on the Hudson and tributary rivers to create pools to trap fish. The Lenape spoke the dialect known as Munsee and were known as Munsee Indians. The Munsee Indians greeted the French explorer Glovanni da Verrazano who discovered the Narrows in 1524 and later interacted with explorer Henry Hudson who traveled the Hudson River north in 1609 in search of a northwest passage to the Pacific Ocean.*"

"The Munsee Indians grew beans, corn (Zea mays), and squash, and gathered nuts, hickory (Carya), butternuts (Juglans cinereal), walnuts (Juglans), chestnuts (Castenea), acorns (Quercus), and berries. They hunted and ate elk (Cervs elapus), bear (Ursidae), rabbits (Oryctolagus cuniculus), white-tailed deer (Odocoileus virginianus), turkey (Meleagris gallopavo), squirrels (Sciuridae), and river otters (Lontra canadensis). They fished the Hudson River for sturgeon (Acipenser oxyrinshus oxyrinchus), shad, herring, and striped bass (Morone saxatile), which were smoked, dried, or roasted."

"The Atlantic sturgeon was an abundant fish in the Hudson River and excellent source of protein for the Indians. Sturgeon hatch in freshwater coastal rivers like the

Hudson and head out to sea as juveniles, reaching 5 m and up to 363 kg at maturity. They return to the river of their birthplace to spawn and lay eggs at adulthood (11). Northern adults spawn during late summer and fall, with females exiting the river for the ocean four to six weeks after spawning, and males remaining in the river or lower estuary until fall (11). Sturgeon are bottom feeders eating crustaceans, worms, and mollusks. After hatching, the larvae hide in sediments and drift downstream until they reach brackish waters where they grow toward adulthood and then swim into coastal waters."

"This unique fish has bony plates (scutes) that run along its body, a shark-like tail, and a snout with barbells in front of its mouth. In the late 1800s, Atlantic sturgeon eggs, known as black gold, produced a high-quality caviar that was in high demand in the colonies and for export. National Oceanic and Atmospheric Administration Fisheries (11) reports almost 3,175 t of sturgeon caught in 1887, with a significant decline in the catch to 9 t by 1905 and less than 0.2 t by 1989. Once plentiful, this slow growing fish today is an endangered species. Population declines are attributed to habitat degradation, such as chemical contamination of river sediments in rearing areas and dredging as well as entanglement in fishing gear" (10).

1.4 Settlement of the Hudson River Valley

Morton and Olson (8) discovered "*The Hudson Estuary was a natural harbor for ocean vessels and their passengers: explorers, traders and settlers coming to the New World. Like the Lenape Indian tribes, the newcomers used the Hudson River as a navigation route between the ocean and interior lands. In the 1600s, the Dutch began to colonize the Hudson Valley and built Fort Orange (present-day Albany, New York) on the west bank of the Hudson River in 1624 as a trading post. The Dutch established two other fur-trading posts, one at New Amsterdam on the southern tip of Manhattan Island and Wiltwyck (present-day Kingston) on the Hudson River about halfway between Fort Orange and New Amsterdam. The British navy invaded the colony of New Netherlands and its capital city, New Amsterdam, in 1664, and the Dutch surrendered the defenseless city of traders. New Amsterdam was renamed New York (NYC) in honor of the Duke of York who sponsored the expedition."*

"The lower Hudson Valley became an agricultural hub under the British colonial rule. During the Revolutionary War, the Hudson River became a major battlefield as the British controlled the river north and its tributaries as well as Lake Champlain waterways, giving them control from Montreal, Canada, to NYC. As the new nation won its independence and pushed westward, NYC grew in population and commerce. The construction of the New York State Canal System (1817 to 1880) accelerated the US Industrial Revolution and spread new ideas, inventions, and prosperity throughout New York State. The canal system was built on the backbone of the Hudson and Mohawk rivers, connecting NYC harbor to the capital at Albany and to points west to Lake Ontario and north to Lake Champlain and the St Lawrence Seaway. This made the Hudson River, with its abundance of water, nearby forests for fuel, and a waterway that easily and inexpensively transported raw and finished products and labor, an ideal place to locate factories and new enterprises." (8).

1.5 New Industrial Products: Polychlorinated Biphenyls

A few short decades after Thomas Edison lit up a public street with the incandescent light bulb (1879), the concept of electricity was transformed from a novel scientific experiment to an essential infrastructure needed for everyday living. Factories, office buildings, and homes demanded electricity. Innovations and markets for new consumer appliances using electricity, like the electric refrigerator (invented in 1913), grew quickly. Cities and their industries invested heavily in the infrastructure necessary to ensure reliable and abundant supplies of electricity that underlie today's economic prosperity. The 1964 to 1965 New York World's Fair showcased the entrepreneurial spirit and success of American manufacturing, mass production, and Dupont's "Wonderful World of Chemistry." Innovations produced an amazing array of consumer products, electrical gadgets, futuristic car designs, nascent computer technologies, and expanded capacities to apply chemistry. The New York Power Authority (NYPA), the largest state public power organization in the United States, with more than 2,253 circuit km of transmission lines and 16 generation facilities, featured an 8 m scale reproduction of the NYPA St. Lawrence hydroelectric plant.

Faroon et al. (12) stated "*New York State and Hudson River industries were on the leading edge of research and development of products from synthetic chemicals. Between 1929 and 1977, PCB synthetic compounds were used in the production of lubricants, hydraulic fluids, plasticizers, capacitors and transformers, paints, inks, flame retardants, and adhesives (4) (13). Two General Electric (GE) capacitor manufacturing plants were built at Fort Edward and Hudson Falls, New York, on the Hudson River north of Albany and used PCBs from 1947 to 1977 in their production processes.*"

"Capacitors and transformers are basic components of electric circuits. The electric circuit enables electric charges to flow along a closed path. The capacitor is connected to a voltage supply and can store electrical charge making it available on demand. The rate at which electric energy is transferred by an electric circuit is called electric power. The transformer enables electrical power to be transmitted more efficiently at higher voltage but lower current. Dielectric fluids prevent electric discharges, thus acting as insulators in high voltage equipment. The properties of PCBs are especially well-suited for use in the dielectric fluids of capacitors and transformers. These properties include taking the form of either an oily liquid or a clear to yellow solid with no smell or taste. PCBs are relatively stable chemical mixtures resistant to acids and alkalis and extreme temperatures and pressures (4). PCBs have a similar basic chemical structure of carbon (C), hydrogen (H), and chlorine (Cl) atoms that can be combined to form 209 different PCB molecules (13) (Figure 6). Some of these forms are more harmful than others and persist in the environment, often depending on the degree of chlorination (number of Cl atoms) and the structural uniformity of the chlorination pattern."

"The release of PCBs in the environment can happen through manufacturing spills, improper disposal and storage, leaks from electrical equipment, and landfills of obsolete products containing PCBs. Environmental contamination can occur

through volatilization and/or adsorption to soil and sediments. When adsorbed to soils and sediments, the half-life can run from months to years. The strength of attachment to soils and sediments increases with the extent to which H atoms on the biphenyl molecule are replaced with Cl. In PCBs, chlorine atoms (ClnH(10–n)) can replace some or all the H atoms on a biphenyl molecule (Figure 6). At very high temperatures, PCB compounds are combustible, creating highly hazardous by-products. The pyrolysis of PCB mixtures with chlorobenzenes can produce polychlorinated dibenzodioxins" (12).

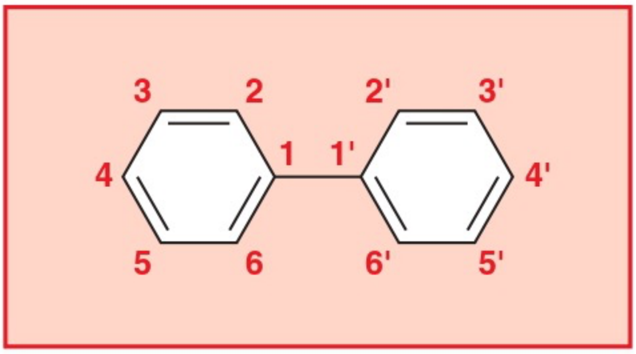

Figure 6. Biphenyl molecule with the numbering system. In polychlorinated biphenyls (PCBs) some or all of the 10 hydrogens (attached to carbon atoms numbers 2 to 6 and 2' to 6') are substituted with chlorines, thereby creating groups of chlorinated compounds (congeners) (1).

1.6 Impact of Hudson River Polychlorinated Biphenyls

Madden and Skinner (14) found that *"PCBs are a persistent organic pollutant found in air, water, soils, and sediments throughout the US environment and globally (4). They adhere strongly to soils and sediments, and water can transport them long distances. When ingested by humans, animals, fish, and aquatic animals, PCBs accumulate in fatty tissues and eggs and become biomagnified (concentrated) as they travel up the food chain. Fish, waterfowl, and aquatic animals usually contain higher PCB concentrations than the aquatic plants and invertebrates they feed on. For example, 2008 research by explain high PCB concentrations in newly hatched mallard ducks (Anas platyrhynchos) downstream of the GE plant sites as the result of ducks feeding on organisms from the river and ingestion of contaminated river sediments."*

"Most people are exposed to PCBs when they eat fish, milk products, and aquatic animals. Direct contact with PCBs does not automatically create a health problem. Health impacts occur from a combination of (1) length of time a person is exposed, (2) the amount of PCBs that enter and concentrate in the body (they are not easily eliminated); and (3) body sensitivity to PCBs (4). Visible effects of PCB toxicity are evidenced by yellow skin lesions, a condition called chloracne, and short-term changes in liver function. PCBs are neurotoxins—meaning they affect the nervous system and the brain as well as reproductive and endocrine systems (7). Development of lesions, adverse effects on survival, and reduced reproductive capacity have been associated with PCB exposure in fish (5). Human studies find PCBs probable carcinogens with increased risk of digestive system, liver, and skin cancers. There

are also concerns that high concentrations of PCBs may have neurological health effects, lead to reduced fertility, and be a cause of low birth weights."

"GE manufacturing plants at Fort Edwards and Hudson Falls released into the Hudson River over 590,000 kg of PCBs from 1940 through 1977 when USEPA banned the production of PCBs (5). Sediments and biota were contaminated the entire length of the Hudson River from Fort Edward south to NYC. More than two-thirds of the PCBs in sediments deposited between early 1970 and 1989 in NYC Harbor traveled almost 300 km downstream from the two upstream GE capacitor manufacturing plants (5). Recreational fishing (Figure 7) of the Hudson was banned from 1976 to 1995, and a fish consumption advisory continues in effect in the contaminated reach. Over 90% of ducks tested in 2008 downstream of the GE plants but above the Hudson tidal river influence exceeded the US Food and Drug Administration 3.0 mg m–1 tolerance level for PCBs in fatty tissues. In 1984, the USEPA designated 322 km of the Hudson River a PCB Superfund Site" (14).

Figure 7. Recreational fishing boats on the lower Hudson south of the Troy Federal Dam. A fish advisory remains in effect with cautions against eating them (1).

1.7 Hudson River Cleanup to Address the Polychlorinated Biphenyls Contamination

USEPA (7) (15) (16) (17) sponsored "*The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (amended 1986; Superfund) is charged with addressing top priority hazardous waste sites with high levels of potential threat to public health and the environment (7) (15). Funded by industry and federal and state governments, Superfund cleans up sites where responsible parties cannot be determined or cannot afford to pay for the cleanup. Although the Hudson River was placed in 1984 on USEPA's National Priorities List of the country's most contaminated* *hazardous waste sites, it was not until 2002 that USEPA determined that targeted environmental dredging would be necessary (5). Dredging was begun in 2009 on a 64 km stretch between Fort Edward and Troy, New York, to remove an estimated 2.03 × 106 m3 of PCB-contaminated sediments (16). GE's financial contribution to the cleanup project was reported April of 2019 to exceed US$1.7 billion (17)."*

"Prior to the dredging decision, the federal government and New York State monitored and evaluated the water quality, sediment, air quality, fish, and wildlife of the lower Hudson River from the Federal Dam at Troy to the southern tip of Manhattan at the Battery in NYC to determine if the river was cleaning itself. This evaluation revealed the river could not clean itself, and the PCB contaminated sediment was a serious risk to human health and the environment. The USEPA dredging project consisted of three river sections in the upper Hudson River (upstream from Troy): Section 1 from the former Fort Edward Dam to the Thompson Island Dam; Section 2 from the Thompson Island Dam to the Northumberland Dam; and Section 3 from the Northumberland Dam to the Federal Dam in Troy. To manage the complexity of the project, dredging of the upper Hudson area was partitioned into "certification units" of approximately 2 ha."

"River sediment dredging (2009 to 2015) occurred after winter ice melt (May) and before the onset of winter weather (November). In the first year, a 9.7 km stretch of contaminated sediment near Fort Edward was removed (~216,369 The Passaic River name was derived from an Algonquin word meaning "peaceful valley". In the mid-1900s, this peaceful valley in New Jersey, United States, became a major exporter of a powerful herbicide, Agent Orange, which was used as a chemical weapon during the Vietnam War (37). The unintended consequences of the use of this deadly herbicide were often fatal to military personnel, tetrachlorodibenzodioxin (C12H4Cl4O2; TCDD) pollution in the Passaic River dates to the 1940s, well before the Vietnam War when the US military used Agent Orange to kill jungle vegetation and Vietnamese food crops including cassava (Manihot esculenta), maize (Zea mays), sweet potato (Ipomoea batatas), and nuts. However, Agent Orange was ineffective when sprayed on the South Vietnam rice (Oryza sativa) crop. Agent Blue, the arsenic (As) based rice killer was used on the rice paddies. A company called Diamond Alkali manufactured Agent Orange in its Newark factory, which was next to the Passaic River. The dioxin contaminants—spilled, washed, or leaked Agent Orange—drained into the Passaic River via trenches and pipes. The Passaic River carried dioxin TCDD both upstream and downstream, creating a dioxin hotspot and contaminating a 27 km-section of the riverbed in one of New Jersey's most populated areas and was transported into Newark Bay, Arthur Kill, Kill Van Kull and New York Bay which is adjacent to New York City (Figure 14). The dioxin-contaminated sediment has reached Newark Bay, which is connected by the Kill Van Kull to New York Bay just north of Staten Island. The chemical plant has now been destroyed and contaminated soil incinerated. However, the Passaic River has become a Superfund site, and cleanup costs to date total US$1.3 billion with a need for US$6 billion more for cleanup and another US$6 billion for natural resource restoration. The dioxin TCDD-contaminated sediment in the Passaic River has a very long half-life in sediment (46)

(47) and remains an environmental and food supply problem in the Passaic River, Newark Bay, Arthur Kill, Kill Van Kull channel and New York Bay. To this day, the harvesting of fish and crabs from the lower Passaic River is banned (48). The sediment is still too contaminated with dioxin TCDD and remains a threat to both the food supply and human health). Additional evaluation in 2010 by an independent scientific panel of scientists and stakeholders guided USEPA in planning for the next phase of the cleanup (18). The second phase (June 2011 to 2015) removed ~ 1.9 × 106 m³ of PCB-contaminated river sediment for a total ~2.1 × 106 m³ of sediment dredged and processed for disposal."

"In April of 2019 USEPA reported continuing efforts to evaluate human and ecological risks and mitigation options of PCB sediment contamination in the 69 km floodplain from Hudson Falls to Troy. This included ~8,000 soil samples collected from over 500 floodplain properties. Where elevated PCB concentrations are found, signage and temporary soil cover with turf grasses will be planted until floodplain cleanup plans can be finalized" (7) (15) (16) (17).

1.8 An Urbanized Waterway

Rodenburg and Ralston (19) found "The Hudson River is an urbanized waterway that received PCBs from many sources over a long period of time. USEPA from 1999 to 2003 measured PCB sediment deposits in the NYC/New Jersey Harbor to estimate PCB loads in the harbor prior to dredging the upper Hudson River. These dated sediment cores enabled them to identify sources of contamination and timelines of sediment deposition. Findings showed that GE capacitor plants above the Federal Dam at Troy contributed almost half of the total PCB Harbor load. They also revealed the following timeline: (1) during the 1970s, 75% of PCBs in the harbor were from the upper Hudson River; (2) between 1970 and 2000 about 30% to 50% of PCBs in the lower Hudson River were distributed throughout the harbor; (3) in the 1980s, when local PCB manufacturing peaked, PCB harbor sediment cores revealed almost equal sediment deposits from the upper Hudson River and local sources; and (4) from 1970 to 2000, local PCB sources declined, thereby increasing the concentration of PCBs from the upper Hudson River."

"PCBs were a component of many products made by several companies for almost 50 years. The oldest PCBs found in the deepest sediment core in NYC/ New Jersey Harbor are thought to have occurred unintentionally with the inadvertent production of PCBs during the manufacture of titanium dioxide and in foundry wax processes, perhaps associated with color organic pigments (17). The NYC/New Jersey Harbor 1999 to 2003 sediment cores show a historical legacy of PCB contamination from a variety of sources: wastewater, storm water, and combined sewer overflows as well as redistributions from the upper Hudson River (17). With the completion of upper Hudson dredging in 2015 and the subsequent five-year review, USEPA is monitoring fish, water, and sediments of the lower Hudson River to determine possible cleanup action" (19).

1.9 Discussion

The Hudson River story of exploration, settlement, despoilment, reclamation, and recovery could be the history of other rivers throughout the United States and the world. Economic progress has not coexisted well with wise protection of soil and water resources. New York State has made huge efforts to address the complex and difficult issues of managing their river landscapes while ensuring economic and environmental well-being (8). Recognizing the need for river and land use planning along the Hudson River, the New York State Department of Environmental Conservation and Cornell University's Department of Natural Resources in 2001 implemented a Hudson River Conservation, Estuary, and Land Use Program. The intent is to provide communities with tools, training, and technical support to better balance protection and conservation of at-risk natural resources with present and future economic growth.

The Guardian, a British daily newspaper headlined in March of 2019 "startling evidence" of the Hudson River's recovery from "decades as New York's sewer" (3). University of Delaware geologist, John Madsen reported sonar images of an "enormous" 4.3 m Atlantic sturgeon about 110 km north of NYC. This 80-year-old female is part of a very small population of sturgeons known to spawn near Hyde Park. While their populations have not rebounded from the early days of colonial settlement, this is an encouraging sign that the river ecosystem can be returned to better health. However, a fish advisory remains in effect with cautions against eating. USEPA fish tissue testing post upper Hudson dredging also remains inconclusive.

Recovery of the Hudson River has been a long and complex process that is not yet fully realized. It will require continued vigilant local environmental advocacy and strong state and national government partnerships. The Clean Water Act and the Superfund legislation that authorized USEPA has played a critical role in the success of PCB contamination removal and persistent investments to restore the Hudson River. The built environment—commercial and residential buildings—that extends beyond the Hudson River shores and the burgeoning NYC population have obscured the natural flow of the Hudson River and its visibility to daily life. The challenge will be to keep the vision of a clean river visible. The Hudson serves cultural, aesthetic, recreational, functional, economic, and commercial needs. The struggle to meet these complex, multifunctional roles will be ongoing. The coexistence of humans and nature will need constant vigilance to produce a landscape worthy of the next generation of landscape painters.

2.0 Case Study 2. New York State Canal System

2.1 Introduction

Over the past two centuries, the New York State Canal System became an important economic engine as rivers and streams were reengineered through canals, channels, locks and dams, flood-control structures, reservoirs, and repeated dredging (8). The canal system was cut across uplands from the Mohawk River toward Lake Erie and Lake Ontario. The Kill Van Kull channel was dredged and deepened between Newark

Bay and Upper New York Bay, linking the Passaic-Newark Bay system with New York Harbor.

The rivers and canals of the northeastern United States were early transportation networks that settled interior "wildlands" and opened the subsistence farm economy to eastern markets (20). Industries and cities grew along these watercourses, and although canals were replaced by railroads, it was the canal-river infrastructure of the early 1800s that transformed occupations, markets, and settlement patterns of the new country (21). Growing urbanization modified rivers and their watersheds to achieve new uses and goals. The processes of population growth and settlement create massive changes in the social-ecological dynamics of river uses, habitats, and landscapes (22). About 3% of the world population in the 1800s lived in urban areas; by the 1900s urban populations grew to 14% (22), and today over half (55%) of the world population lives in urban environments with a United Nations projection of 68% by 2050.

The spatial changes in settlement patterns and spider-like intrusions into "wildlands" along river landscapes are historic, modern and are present and future challenges to water conservation and management at the rural-urban interface (22). These changes are concurrent with the growth in scientific knowledge about water ecologies and shifts in human perspectives and values about the uses of rivers, lakes, and human-made water bodies. Nowhere is the shift in scientific understandings, innovation, and human views of the functional uses of watercourses more apparent than a backward look brought forward of the New York State (NYS) Erie Canal System. Widespread post–Civil War canal infrastructure investments were important engines of economic development and growth (22). Economic analysis of canal impacts on local and national economies from tolls, construction, wage labor, new technologies, and reduction in freight costs of raw commodities and finished manufactured products reveal net social and economic benefits at their peak (22). Today the canal system is no longer a commercial navigation system, but it is a critical water ecosystem and green open space that draws thousands of people annually to the unique and varied natural landscape of NYS.

Canals throughout NYS were constructed on the backbone of abundant rivers and lakes and the port of New York City (NYC) strategically located on the Atlantic Ocean (Figure 8). Completed in 1825, the Erie Canal System linked major rivers, the Hudson, Mohawk, Oneida, Seneca, and Oswego, and the Finger Lakes to the US Great Lakes via canal ports on Lake Ontario and Lake Erie. The NYS Canal System cut in half travel time from Buffalo to Albany, reduced freight rates 10%, and made NYC the commercial center of the United States for many years (22).

Along with canal-river transport, economic development, human migration, and settlements came water pollution; untreated human sewage; and cholera, a deadly disease that spread rapidly in 1832 across lower Canada and eastern United States by travelers on the NYS waterways (23). It was not until the late 1800s that public health institutions realized that polluted water was the carrier of cholera and began to press for cleaning up canal-river systems and establishment of sanitary water supplies and wastewater treatment systems in densely populated canal-river settlements. An unintended consequence of the canal system was the introduction of the nonnative sea lamprey (Petromyzon marinus) into the ecology of the Great Lakes and Lake Champlain. The canal became a migration pathway for sea lamprey populations from the Atlantic Ocean, up the Hudson River and via connecting canals to Lake Ontario and Lake Champlain by early 1900s (24). The arrival of the invasive parasitic sea lamprey into the Great Lakes altered the native fish stocks of Atlantic salmon (Salmo salar), lake trout (Salvelinus namaycush), and lake whitefish (Coregonus clupeaformis); and led to widespread loss of commercial fisheries (24).

Figure 8. The New York State Canal System (built and enlarged 1817 to 1880) runs west-east from Buffalo on Lake Erie to Albany where it meets the Hudson River. At Albany the canal system runs north-south, connecting the headwaters of the Hudson to Lake Champlain by canal and flowing south to the mouth of the Hudson River, the port of New York on the Atlantic Ocean (8).

By the twenty-first century, the lifecycle of the canals as a transportation network for settlers and market exchanges had matured and become obsolete (25). Today there are 234 cities, villages, and towns and a population of almost three million people along the Erie Canal corridor (26). The heritage of the canal system has left a large imprint on the people and rivers of NYS, and these water resources now represent a different kind of valued asset at the rural-urban interface (27). We look at the history of the Erie Canal System; how it transformed the physical, social, economic, and environmental landscape; and the new opportunities this unique water resource offers in an age of diminished natural resources, population growth, and increased need for protecting river ecosystems, blue-green spaces, and watershed management.

2.2 Canals and Waterways

Canals, human-made channels connecting rivers and lakes, were major innovations in the United States during the early 1800s (Figure 8). They expanded natural inland navigation far into the interior "wildlands" of America (28). The lower Hudson and Mohawk rivers became the major migration route for Europeans settling in western NYS, northeastern Pennsylvania, and the northern section of the Ohio territory in the late 1700s and 1800s (Figure 8). When American settlers arrived in the port of New York, they migrated west using the river valleys which offered a much easier route than traversing the Catskill and Appalachian Mountains. However, once the early settlers reached the western extent of the Mohawk River they traveled overland on poorly developed roads and paths to reach Lake Erie. By the early 1800s the State of New York funded construction of the Erie Canal (Figure 9) from the Mohawk River to the Niagara River. This enabled European people and goods to be transported by barges on the Erie Canal and rivers from NYC to Buffalo on Lake Erie and Lake Ontario. It fueled the economic and social development of the state, decreased travel time, lower freight costs, and opened new markets.

Figure 9. The gates are closed at Palmyra Lock 29 creating slack water in the foreground as canal boats approach the lock from the east (8).

During the canal building years, 1817 to 1880, existing rivers and creeks were used to create the Erie Canal. The engineering goal was to use the lowest watercourses (rivers and creeks) and the natural elevation of the landscape rather than building artificial channels along the higher ground. Watercourses included the Mohawk River;

Oneida Lake; the Oneida, Oswego, Seneca, Clyde, and Niagara rivers; Tonawanda Creek; and Wood Creek.

Canals became extensions of rivers with water elevations controlled by building dams and locks (Figure 9) and dredging channels. The dredging provided uniformity in width and channel depth, and dams maintained the surface of the water at a fixed elevation above the streambed turning the rivers into a series of pools between dams. These dams controlled the water levels on the canalized rivers at strategic locations such as the dam on the Mohawk River between Schenectady and Cohoes. The dams at Schenectady and Little Falls had gates that could be lowered or raised to adjust water levels. A series of five lifts near Waterford moved boats up and downstream a total of 52 m, twice the lift of the Panama Canal, which opened in 1914.

Canals need a continuous supply of water to provide a dependable watercourse that could be manipulated for navigation. The Niagara River was adequate for the western part of the Erie Canal, but the eastern part, between Rome and Troy, lacked sufficient water in dry summers (Figure 8). Two very large 11.7 km^2 reservoirs, the Delta and Hinckley dams built near the head- waters of the Mohawk River, had feeder canals that kept the Erie Canal supplied with water during dry periods.

2.3 Geography of the Lake Ontario Basin and the Lake Champlain and Mohawk Valleys

The Ontario Lake basin, made of soft Silurian-age rocks, was created in the last ice age by the Wisconsin glacier. The Ontarian River valley prior to the glacier had a similar east-west orientation as the current land and drainage basin (Figure 10). A southward moving ice sheet altered the region's drainage system as it scoured the lake bottom and pushed glacial till into drumlins and moraines; and left behind the eskers, kames, and kettle lakes of the present landscapes when it melted and receded (29).

While the southern end of the ice sheet melted, the northern section of the glacial ice sheet remained frozen for many years and dammed the St. Lawrence valley outlet. This made the lake surface a higher level than it is today. The enlarged postglacial lake, known as Lake Iroquois, drained through present-day Syracuse (Figure 3) and carved out the 160 km Mohawk River valley (29) as it drained east and south toward the Hudson River. The enormous discharge of water during this stage scoured the area deeply and deposited sand and gravel in an area known today as the Great Flat Aquifer (28). The shoreline of ancient Lake Iroquois can be observed as a dry beach ridge 15 to 40 km from the present Lake Ontario shoreline.

The Mohawk River watershed drained a portion of the Catskill Mountains, which is a subarea of the southern Adirondack Mountains. This watershed developed in Paleozoic sediment rocks overlying 1.1-billion-year-old Proterozoic metamorphic rocks. During the Pleistocene (ca. 1.8 to 0.01 million years ago), glaciation modified the basin and left behind surficial deposits of boulders and clay-rich glacial till approximately 13,350 years ago. The headwaters of the Mohawk River begin in Lewis County and meet the Hudson River near Cohoes Falls (Figure 11) and the city of Cohoes. The Lake

Iroquois foot- print and its glacial meltwaters offered a natural path to engineer the Erie Canal system from Lake Ontario to the Hudson River via the Mohawk River.

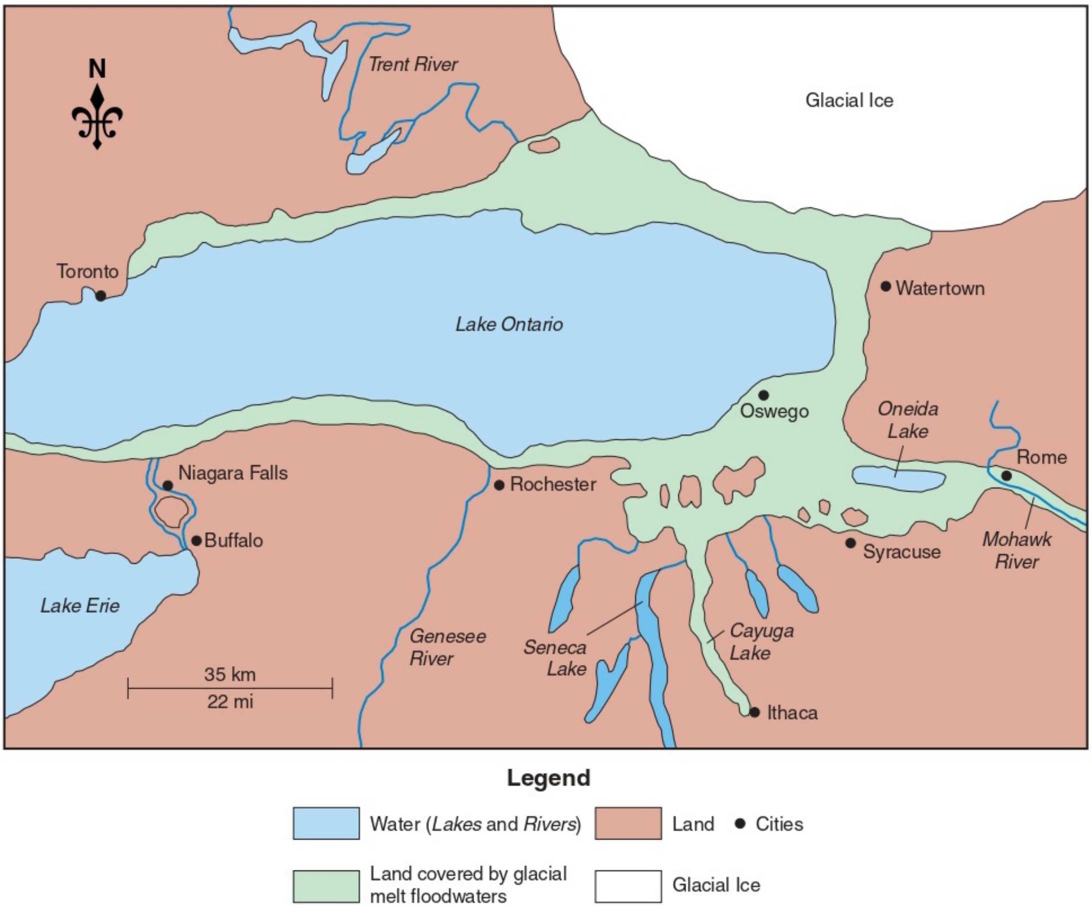

Figure 10. Lake Iroquois, a post-glacial lake, and its melt floodwaters carved out the Mohawk River valley creating a natural path to engineer the Erie Canal (8).

The first waterway improvements made in NYS were begun by a private company in 1791 to facilitate navigation on natural rivers. Military transportation problems during the War of 1812 gave momentum to the idea of constructing a canal across the state. By 1816, it became apparent that financial aid from the federal government was not coming, so the NYS legislature passed an act in 1817 authorizing a canal from the Hudson River to Lake Erie. The Project was divided into Hudson River to Rome, Rome to Seneca River, and Seneca River to Lake Erie. The canal required the digging of a 580 km long ditch that was 12 m wide at top and 8.2 m wide at bottom with a depth of 1.2 m. Fortunately, most of the digging was in alluvial, lacustrine, and glacial till. Lake Erie is 172 m higher than the Hudson River, and the waterway originally required 83 locks, each 26 m long by 4.5 m wide with an average lift of about 2.4 m. Locks are structures used to raise and lower boats from one canal or river to another stretch of water that is at a different level; or to bypass falls and rapids (30). The lock and dam engineering created pools of water a specific water depth (originally 1.2 m later deepened to 2.1 m) for navigation between dams. These pools were called slack-water canals. They had less current than a running stream and were flanked on one side by an elevated towpath where a team of mules pulled the packet boats along the canal.

Figure 11. Where the Mohawk River runs between Schenectady and Albany there is a 127 m drop that creates Cohoes Falls. Canal engineers originally constructed 27 locks around these falls (8).

All the construction was done by pick and shovel labor and animal power. Gunpowder was packed into hand drilled holes to blast areas of bedrock since dynamite was not invented until 1867, long after the canal ditches were dug. The heavily forested landscape made tree and stump removal a big challenge. Other challenges included valleys that had to be spanned; ridges to be excavated; and swamps, including the Cayuga marshes (Montezuma Swamp), that had to be drained in the summers of 1820 and 1821. Contractors paid Irish workers US$1.25 d–1 to do this backbreaking work. One major problem in constructing stone structures for canal locks and aqueducts was locating a source of hydraulic cement that could harden under water. Both locks and waste weirs required use of cement to hold the stone in place. Common quick lime did not work underwater, so initially European hydraulic cement was used. However, when Canvass White discovered a limestone near Chittenango that when burned, pulverized, and mixed with sand produced a cement that would harden underwater, the cost and timely availability of cement was solved. At Rochester, contractors encountered the Irondequoit Creek Valley and the fast-flowing Genesee River. They constructed a 0.40 km earthen embankment 21 m above the valley to support the canal and a 240 m long masonry aqueduct to carry canal water over the Genesee River.

The entire NYS Canal System, also called the NYS Barge Canal, was a 845 km system composed of the Erie Canal connecting the Hudson River via the Mohawk River to Lake Erie at Buffalo; the Oswego Canal connecting the Erie Canal directly north to

Lake Ontario; the Cayuga-Seneca Canal running south from the Erie Canal to Seneca and Cayuga Finger Lakes; and the Champlain Canal connecting the Hudson River north to Lake Champlain, the Richelieu River, the Chambly Canal, and ultimately the St. Lawrence River (Figure 8).

Originally, the port of Oswego on Lake Ontario was proposed as the western terminus for the Erie Canal. However, the Welland Canal Company incorporated by British Canada began to construct a canal in 1824 between Lake Ontario and Lake Erie. New York State decided to make Buffalo, New York, the terminus for the Erie Canal to have more control of Lake Erie. The Oswego River flowing north to the port of Oswego (Figure 12) formed a major portion of the 61 km Oswego Canal that connected to the Erie Canal in Syracuse (Figure 13). Completed in 1828, slack water in the Oswego River was created by the construction of 18 locks (27).

Figure 12. New York State funded construction of two modern grain elevators in the early 1900s. One was built at the port of Oswego on Lake Ontario enabling the transfer of agricultural fertilizers, grains, and other commodities; the other was the Gowanus Bay terminal in New York City (8).

The canal cost less than US$600,000 to build. Subsequent enlargement made it one of the most profitable canals in the system because it allowed trade with Canada via the Great Lakes all the way to the port of NYC and the Atlantic Coast. The last improvement made in the 1900s increased the draft to 4.3 m with 6.4 m clearance under bridges (air-draft), which today allows recreational cruisers to travel from the ocean to Lake Ontario. West-central NYS has the two largest Finger Lakes in the state, the 61 km long Cayuga and the 56 km long Seneca. These lakes offered access to sizable territory, and their value was enhanced by connecting the Seneca River to the Erie Canal. Part of the Three River confluence north to Lake Ontario. West-central NYS has the two largest Finger Lakes in the state, the 61 km long Cayuga and the 56 km long Seneca. These lakes offered access to sizable territory, and their value was enhanced by connecting the Seneca River to the Erie Canal. Part of the Three River confluence north of Syracuse, the Seneca River flows north from Seneca Lake until it joins with the Oneida River to become the Oswego River. In 1792, the right to improve navigation along the watercourse to Seneca Lake was granted, and by 1821 improvements were made in a water route connecting Seneca and Cayuga lakes. The 35 km Cayuga Canal was completed in 1828 (Figure 11), enabling travel between the two Finger Lakes and eastern and western NYS markets via the Erie Canal. The western part of the link from Albany followed Wood Creek from Rome to Oneida Lake, across the lake to an outlet on the Oneida River, through 16 km of river to its confluence with Seneca River, and 32 km down the Oswego River to Oswego. It is still used by recreational boaters today.

Figure 13. Canal tolls were assessed by weight. A canal boat sits in the Syracuse weigh lock where water is drained through a sluice gate at the bottom, leaving the boat to rest on a cradle scale at the Erie Canal Museum. The empty weight of the boat, on record as part of the annual state registration, was subtracted from the full weight of the boat with goods on board (8).

The confluence of the Mohawk River and Hudson River is near Cohoes Falls (Figure 1) and (Figure 4) and Cohoes, NYS. From Utica east to Schenectady, the Erie Canal followed the south bank of the Mohawk River. At Little Falls, a 360 m stone aqueduct feeder canal crossed the Mohawk River enabling boats to use the north side of the Erie Canal and to feed water into the canal to maintain navigation depth. The lower part of the Mohawk River had five permanent dams, nine seasonal dams, and five active hydropower plants. Schoharie Creek and West Canada Creek were both tributaries with large dams including Hickley Dam on West Canada and Gilboa Dam on Schoharie Creek. The Gilboa Dam was completed in 1926 as part of the NYC water supply system.

2.4 Lake Champlain Canal

Changes in the watercourse between Hudson River and Great Lakes were discussed during the seventeenth century, but it was not until 1792 that Western Inland Lock Navigation Company started improving the waterways. One of the first tasks was to clear Wood Creek and create a lift lock at Little Falls to circumvent the falls of the Mohawk River. Funding soon became a major problem. However, with the onset of war in 1812, the NYS commissioners decided a canal between Lake Champlain and the upper Hudson River was of national importance, and the legislature provided financing to keep the company solvent. Champlain Canal was authorized on April 15, 1817. A total of 19 lift locks on the 106 km route between Whitehall and Lake Champlain was completed on September 23, 1823, at the cost of US$921,000. Champlain Canal was a huge success. Lands around Lake Champlain and Lake George (west of Lake Champlain) had valuable timber and there were extensive and rich deposits of iron (Fe). Both commodities were shipped by canal along with Vermont marble. More than 19,000 boats passed through in the first year. The Champlain Canal took the primary share of the western Massachusetts and Vermont trade to NYC via the Hudson River. The Lake Champlain Canal linked with the Erie Canal via the Hudson River and later became part of the New York State Canal System.

2.5 Cost and Economic Benefits of the Erie Canal

In the nineteenth century the Erie Canal brought business to the state as well as more than US$120 million in tolls, which paid for the original construction cost, the first enlargement, and the first 75 years of maintenance. The success of the Erie Canal resulted in 10 laterals being built in the first 14 years (31). By 1862, the Erie Canal had been enlarged and deepened to 2.1 m depth. In 1882 yearly tolls were abolished; it had earned US$42 million, more than it originally cost, including the cost of enlargements, maintenance, and operations. The NYS legislature in 1903 authorized the construction of the New York State Barge Canal as the "Improvement of the Erie, Oswego, Champlain and the Cayuga and Seneca Canals." Construction started in 1905 and finished in 1918, at a cost of US$ 96.7 million (32). The Erie Canal reduced freight costs by a factor of 20 and took half the time of ox-pulled wagons. In 1840 most goods went west, but by the 1860s much of the freight went east. Competition with railroads caused canal traffic to diminish. Regardless, the Erie Canal had its greatest tonnage in 1880, after 50 years of railroad construction.

2.6 Innovative Infrastructure, Social, and Ecological Impacts

Like America, the Erie Canal was bold, innovative, and huge. Nothing of its magnitude had ever before been attempted" (32). This remarkable navigation infrastructure created new towns and cities along its banks; provided hydro- electric power for new industries and residential homes; created vast new markets for agricultural, forestry, and mining commodities; and made household products less expensive and more accessible. Community building is difficult without people, raw materials, big equipment, and simple necessities. The Erie Canal brought them all together; forests gave way to sawmills and hamlets grew into villages as the settlers migrated westward.

Not only did the canal project alter systems of transportation, expand the economy, and elevate civil engineering into a well-regarded profession, it transformed other aspects of society. Canal towns became the conduit for the mixing of diverse people and fostered social reform. The canal towpath became one of the main Underground Railroad routes, which slaves used to escape to Canada. Along with abolition of slavery, other social movements emerged with women's rights (Seneca Falls) and religious revivals originating in upstate NYS. During these canal years, evangelicals had a "great awakening," a revival that gave western NYS the label the "Burned-Over District." The Seventh-day Adventist church rose from this "awakening" in upstate New York and today has over 20 million members globally. The Mormon (Latter Day Saints) religion began in Palmyra, a small town on the canal, which has become a major pilgrim destination for Mormons worldwide. The canal altered the ecology of every water body in New York State: major rivers, the Finger Lakes, the Great Lakes, and smaller inland lakes. The migration of the sea lamprey, a nonnative fish species into Lake Champlain and the Great Lakes, and water-borne diseases from canal-river water in the cities along the canal were two unexpected consequences, the growth of small towns and cities along the canal increased industrial and residential water pollution. As cities grew, human and industrial waste were flushed into rivers and canals causing typhoid and cholera epidemics (23). The North American cholera epidemic of 1832 began in Quebec City and Montreal and quickly spread along waterways, including the recently completed Erie Canal. Lewis Beck's 1832 report documented outbreaks that occurred in sequence, "… starting with the disembarkation of infected individuals from boats plying the canals and rivers of New York" (23). Cholera cases clustered among the poor, immigrants, and laborer populations, and early medical theories proposed it was poor people who had intemperate habits that made them vulnerable to disease (23). Environmental knowledge and attitudes about garbage removal, waste disposal, and water pollution were not well understood in the nineteenth century. There was uncertainty on ecological and human health grounds about whether to treat sewage before discharging it into water. Scientific theories of the mid-1800s, proposed that running water would purify itself, and that disease epidemics like cholera were caused by contaminated air (33) (34). There was no consensus that cholera was contagious or caused by untreated wastewater. It was not until the later 1800s that germ theory prevailed, and it became generally accepted that cholera was caused by invisible microbes in water. This new scientific knowledge spurred public health institutions to establish sanitary sewers to protect public drinking water supplies. As the cities and towns along rivers and canals-built sewer systems, the smelly stench of the waterfront lessened, city drinking water tasted better, and water-borne contagious diseases were almost eliminated (33).

The marvel of an interconnected waterway had another unintended consequence: it bridged drainage divides and created new routes for ocean, river, and lake aquatic species to intermingle. As the canal-river system extended navigation beyond the Hudson River, it opened a water path to nonnative fish species, the sea lamprey, to migrate upriver from the port of New York to Lake Champlain and the Great Lakes (24). After spawning up coastal rivers, sea lamprey larvae take four or more years to fully develop into adults that parasitically suck the blood and body fluids of fish (24). First observed in Lake Ontario in 1835, the sea lamprey quickly spread into all the Great Lakes with improvements to the Welland Canal that bypasses Niagara Falls (34). Native fish—lake trout, lake whitefish, and Atlantic salmon—virtually disappeared, as did thriving fishery occupations and industries, when sea lamprey populations, without natural predators, exploded. The lake trout harvest in the upper Great Lakes in the early 1960s was 2% of the 7 × 106 kg before the sea lamprey invasion (34). Today, there is an extensive sea lamprey control program using a combination of barriers and traps to prevent upstream migration and lampricides (pesticides) that selectively kill larvae and adults.

2.7 The New York State Canal System Today

Trains and trucks have taken over the transport of most cargo that once moved on the barges of the NYS Canal System. Now pleasure boats, tour boats, cruise ships, canoes, and kayaks are the majority vessels that use the waterways of the Erie, Oswego, Cayuga-Seneca, and Champlain. The canal system serves historical and recreational purposes and provides important wetland and river habitats. The current canals are 3.7 m deep and 37 m long (Figure 9) with 57 electrically operated locks, which can accommodate vessels up to 1,800 t. The canal system is open from May 1 to November 15, and motorized craft pay a fee to traverse the locks and lift bridges. The NYS Canal System reported the shipment of 10,000 t of cargo valued at approximately US$102 million in 2004 and documented 122,000 recreational vessels locking on the canal. By 2012, the system annual cargo volume reached 38,000 t with future protection of 180,000 beyond 2017. Hydropower continues to provide electricity to the canal system and adjacent rural and urban communities. In January of 2017, the New York State Canal Corporation became a subsidiary of the New York Power Authority.

2.8 Canals, a Public Trust

In NYS, the canal system, its lands, and waters were "recognized, treated, and protected 'for the commercial advancement and prosperity of the state and its people'" in 1921 (35). New York State courts have upheld this vision and reaffirmed state ownership of canal lands as a trust for public purposes. This has state and national significance for future uses of canal-river watercourses ranging from open space conservation, watershed and habitat protection, recreation, and tourism (35) in a state and nation with expanding populations. In 2017, the canal system had over 3.3 million visits and total revenue just under US$1 billion. Boaters, cyclists, hikers, and paddlers are active users of the canal system, and festivals, museums, and other events are major sources of revenue (36). The multi-uses of rivers, canals, and lakes play central roles in bringing the lives of rural and urban peoples together. They provide critical habitats for plants, fish, waterfowl, animals, and people who derive their livelihoods from their water resources. They are sources of past, present, and future economic prosperity, human health, and well-being. Competing and complementary values and preferred uses give urgent meaning to water as the "new gold" and will require continued science and innovation to meet complex challenges as water resources become more limited and degradation affects all populations.

3.0 Case Study 3: Passaic River

3.1 Introduction

The Passaic River valley, linked to New York Harbor through Newark Bay and the Kill Van Kull channel, became a major industrial corridor that created jobs and supported regional economic growth. The same industrial development left a severe pollution legacy. Diamond Alkali manufactured Agent Orange at its Newark facility on the Passaic River, and dioxin TCDD associated with production wastes entered the river through spills, washing, drainage systems, and contaminated sediments. Because the lower Passaic is tidal, contaminated water and sediment were redistributed upstream and downstream and into Newark Bay. The lower river later became a Superfund site, with continuing fish and crab restrictions and remediation and natural-resource restoration costs measured in billions of dollars. This case study examines the interaction of chemical manufacturing, tidal sediment transport, navigation infrastructure, remediation, and public-health risk within the larger Hudson-Passaic-New York Harbor waterway system.

The Passaic River name was derived from an Algonquin word meaning "peaceful valley". In the mid-1900s, this peaceful valley in New Jersey, United States, became a major exporter of a powerful herbicide, Agent Orange, which was used as a chemical weapon during the Vietnam War (37). The unintended consequences of the use of this deadly herbicide were often fatal to military personnel, tetrachlorodibenzodioxin ($C_{12}H_4Cl_4O_2$; TCDD) pollution in the Passaic River dates to the 1940s, well before the Vietnam War when the US military used Agent Orange to kill jungle vegetation and Vietnamese food crops including cassava (Manihot esculenta), maize (Zea mays), sweet potato (Ipomoea batatas), and nuts. However, Agent Orange was ineffective when sprayed on the South Vietnam rice (Oryza sativa) crop. Agent Blue, the arsenic (As) based rice killer was used on the rice paddies. A company called Diamond Alkali manufactured Agent Orange in its Newark factory, which was next to the Passaic River. The dioxin contaminants—spilled, washed, or leaked Agent Orange—drained into the Passaic River via trenches and pipes. The Passaic River carried dioxin TCDD both upstream and downstream, creating a dioxin hotspot and contaminating a 27 km-section of the riverbed in one of New Jersey's most populated areas and was transported into Newark Bay, Arthur Kill, Kill Van Kull and New York Bay which is adjacent to New York City (Figure 14). The dioxin-contaminated sediment has reached Newark Bay, which is connected by the Kill Van Kull to New York Bay just north of Staten Island. The chemical plant has now been destroyed and contaminated soil incinerated. However, the Passaic River has become a Superfund site, and cleanup costs to date total US$1.3 billion with a need for US$6 billion more for cleanup and another US$6 billion for natural resource restoration. The dioxin TCDD-contaminated sediment in the Passaic River has a very long half-life in sediment (46) (47) and remains an environmental and food supply problem in the Passaic River, Newark Bay, Arthur Kill, Kill Van Kull channel and New York Bay. To this day, the harvesting of fish and crabs from the lower Passaic River is banned (48). The sediment is still too contaminated with dioxin TCDD and remains a threat to both the food supply and human health.

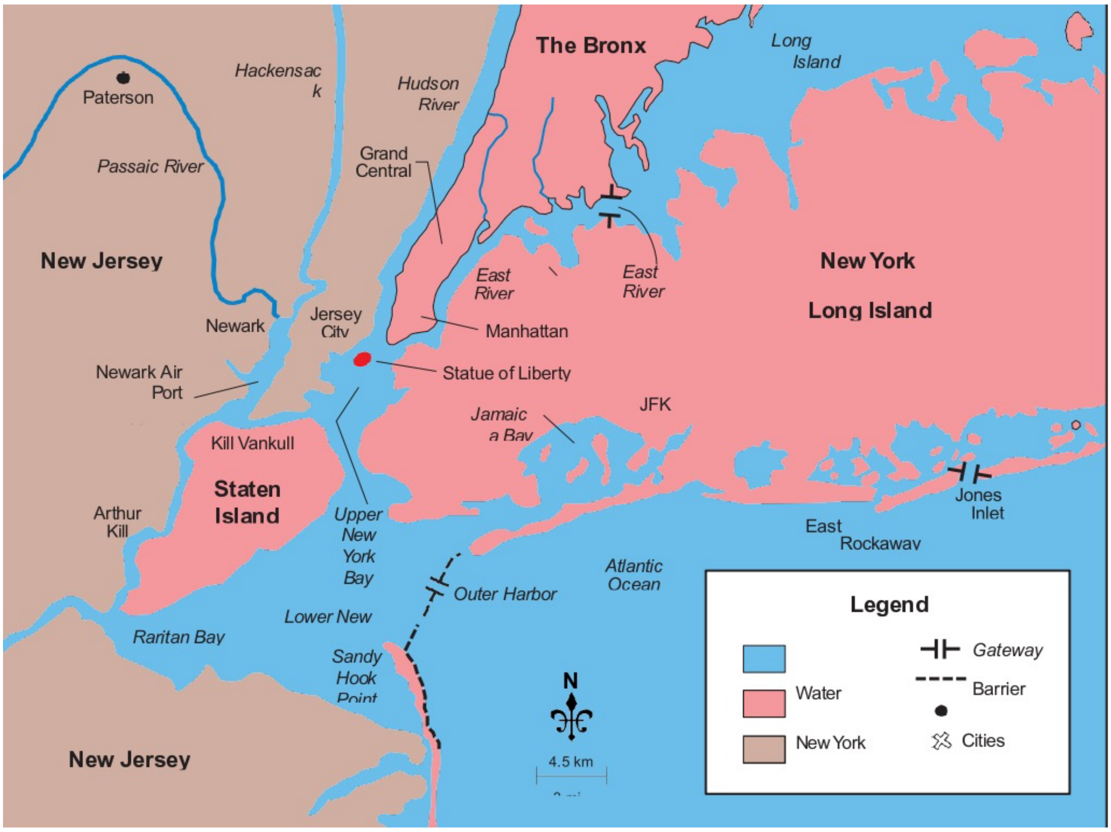

Figure 14. New York Harbor and the location of Kill Van Kull channel and storm surge barrier in Long Island Sound and Lower New York Bay (37).

3.2 Passaic River Geology and History

The Passaic River formed from a massive proglacial lake that developed in northern New Jersey approximately 13,000 years ago. The glacial ice sheet blocked the normal drainage path to the north. The overflowing lake drained out through the new path (Figure 14), the present-day waterway to the ocean. The Passaic River now drains into the Newark Bay and flows parallel with the lower Hudson River along the west side of Staten Island and into Raritan Bay and the Atlantic Ocean.

The river is 120 km long with a 2,422 km^2 watershed and has been developed as a source of power and water. It flows into the Great Swamp lowland between the ridge hills of rural and suburban northern New Jersey. The Passaic River headwaters are in Mendham. The river flows south into Morristown Natural Historical Park, passes through Lord Stirling Park, and then along the western side of the Great Swamp. The Passaic River drains northeast to Paterson and over the Great Falls of Passaic (Figure 15) and into Dundee Lake. The Dundee Dam was built in 1845. Approximately 4 km below the dam, the river is navigable to Raritan Bay before emptying into the Atlantic Ocean.

The Passaic flows through the most industrialized and urbanized areas of New Jersey. The lower river suffered industrial abandonment (Figure 16) and severe pollution in the twentieth century. The chemical manufacturing site is on the floodplain and subject to erosion of the soil and sediment contaminated by toxic waste including dioxin TCDD, polychlorinated biphenyls (PCBs), and mercury (Hg) (49) (50). During periods of heavy rainfall or snowmelt, the Passaic River has flooding problems—especially at the confluence of the Pompton and Passaic rivers. Historically, building has been allowed on these floodplains, which has resulted in homes and businesses now being frequently flooded. A plan has been proposed to build a 32 km-long flood tunnel to divert the periodic floodwaters directly into Newark Bay (51).

Figure 15. The Great Falls of the Passaic River (37).

Figure 16. The gravel parking lot where the chemical plant was removed in Newark, New Jersey, along the Passaic River. The floodwall is visible in the background (37).

3.3 Kill Van Kull Tidal Channel

Morton and Olson (1) determined that "When Staten Island and Long Island were connected, the Hudson River drained west into New Jersey, through the current Kill

Van Kull into Newark Bay, and then south into the current Arthur Kill between the Watchung Mountains and Staten Island into Raritan Bay and the Atlantic Ocean. The Narrows were formed 6,000 years ago at end of the glacial period when the Hudson River breached the terminal moraine and separated Staten Island from Long Island. Thus, the present course of the Hudson drains into the lower New York Bay between Staten Island and Long Island and into the Atlantic Ocean."

The Kill Van Kull strait (Figure 17) between the Borough of Staten Island, New York City and Bayonne, New Jersey connects Newark Bay with the Upper New York Bay (Figure 18). It is one of the most heavily travelled waterways in the Port and has provided principal access for ocean-going container ship to Port Newark-Elizabeth Marine Terminal, the busiest port facility in the eastern United States, and the New York Container Terminal at Howland Hook (52). The Kill Van Kull Channel is 4.8 km long and 305 m wide and spanned by the Bayonne Bridge (Figure 5). The bridge was raised in 2017 so that New Panamax ships could travel the Kill Van Kull.

The USACE completed the last major Kill Van Kull 17-m-deep dredging (Figure 19) in 2011. Since 1896 the dredgers have been deepening the Kill Van Kull strait.

Figure 17. A view of west Kill Van Kull. Photo credit: Jim Henderson.

3.4 Discovery, Formulation, Creation, and Manufacture of the Herbicide Agent Orange Dioxin TCDD in the Passaic River Valley

Hitchcock and Zimmerman at Boyce Thompson Institute (53) found absorption and movement of synthetic growth substance from soil resulted in a response by the aerial part of the plant. In the 1940s botanists tried to initiate flowering by applying small quantities of various chemicals to different plants. Zimmerman and Hitchcock (54) found that 2,3,5-triiodobenzoic acid (TIBA) induced flowering in tomato (Solanum lycopersicum L.) plants when either applied to soil or used as a spray on the leaves of the plants.

Arthur W. Galston's 1943 University of Illinois (botany) PhD thesis research focused on the use of TIBA to make soybeans (Glycine max [L.] Merr.) flower and fruit sooner so they could mature before the end of the growing season (55).

Figure 18. Ships waiting in New York Bay to enter the Kill Van Kull. Photo credit: Jasmile.

Figure 19. Deepening the Kill Van Kull channel to 17 m. USACE dredge brings up debris from bedrock broken by dynamite. Photo credit: Bob King.

Galston also noted that in higher concentrations, it would cause soybeans to lose leaves. Galston's discovery led to the development of a precursor (TIBA) to Agent Orange (47). In 1943, Galston moved to the California Institute of Technology to work with Nobel Prize winner George Beadle on World War II defense-related research. Galston joined the Navy in 1944 and served as a natural resources officer while stationed in Okinawa, Japan, until World War II was over.

In 1951, biological warfare scientists at Fort Detrick, Maryland, began investigating the possible uses of defoliant herbicides based on Galston discoveries while working with TIBA. US military researchers eventually produced the toxic defoliant Agent Orange, which was used in the 1950s by the British air force during the Malayan Emergency and later in the 1960s by the US Air Force, Navy, and Army during the Vietnam War.

Since the 1940s, the 2,4-dichloro phenoxy acetic acid, C8H6Cl2O3 (2,4- D), and 2,4,5-trichloro phenoxy acetic acid, C8H5Cl3O3 (2,4,5-T), herbicides were used separately in the United States (48). Agent Orange, a 50:50 mixture of 2,4-D and 2,4,5-T, was only produced for the US military. Both herbicides have a relatively short half-life when exposed to sunlight. Unfortunately, the manufacturing process used to make 2,4,5-T created a by-product or contaminant dioxin, TCDD, which has a much longer half-life (50 to 100 years or more) (47). The two herbicides, when buried under anaerobic conditions in the subsoil or attached to clay and organic matter particles transported as sediment, settle to the bottom of a river or lake. Initially, the dioxin TCDD contaminant levels were in the range of 0.05 ppm (56). However, to meet the needs of the US military, approximately 4.26 × 107 L, the Agent Orange combustion process was accelerated by increasing the temperature 5°C (47). Consequently, the dioxin TCDD levels in Agent Orange increased to as high as 60 ppm, or 3,000 times higher than the original Agent Orange by-product contaminant levels (56). Military field tests, including some in Florida, were conducted with Agent Orange that was manufactured in the 1960s (57).

The US government passed the Defense Production Act in 1950. The government, as a nation at war, compelled 11 companies to create, produce, and supply Agent Orange to the military. From 1965 to 1969, 11 wartime government contractors that manufactured Agent Orange only produced it for the US military (47), and it was not sold to the public. These companies included Dow Chemical, Monsanto Company, Hercules Inc., Diamond Shamrock Corporation (previously Diamond Alkali), Hooker Chemical Company, Riverdale Chemical Company, Ansul Chemical Company, Uniroyal Inc., Occidental Chemical Company, N.A. Phillips Chemical Company, and Thompson-Hayward Chemical Company. The US government also specified how Agent Orange would be produced and then controlled its transportation, storage, distribution, and use. During the manufacturing process, at all these Agent Orange chemical plants workers including at the New Jersey Diamond Alkali facility on the Passaic River were exposed to TCDD (58). Agent Orange was stored on site at Diamond Alkali in 205 L barrels painted with an orange stripe and then loaded on ocean-going ships (Figure 20) headed for the South China Sea and the coast of Vietnam. The barrels were shipped and stored on military bases for spraying the jungle and food crops or on navy ships (Figure 21) for use on stream banks and mangrove forests.

Figure 20. The loading of ocean-going ships at a port on the linked tidal Passaic and Hudson rivers system (37).

Figure 21. Navy ships that were used to transfer the chemicals from the commercial ships to the brown navy to spray on the stream banks (37).

In the 1950s, the Diamond Alkali facilities on the banks of the Passaic River in Newark, New Jersey (Figure 14), were used to manufacture Agent Orange. Diamond Alkali workers testified in court that they were exposed to Agent Orange, which contained the herbicide 2,4,5-T with by-product dioxin TCDD. These workers claimed that the chemical factory floors in the 1950s and 1960s were slick after Agent Orange was spilled or leaked and it was treacherous to walk on them. The contaminant dioxin TCDD which was in Agent Orange, was washed by poorly protected workers into trenches, drains and pipes, which emptied into the Passaic River (37).

In 1971, Diamond Alkali sold the Lister Avenue facility. The Passaic River, a tidal river, carried dioxin TCDD upstream and downstream, contaminating a 27 km section of the riverbed in one of New Jersey and New York's most populated areas. The river linked to Kill Van Kull and Hudson River, which flows adjacent to and past New York City (37). The dioxin-contaminated sediment has reached Newark Bay, which is connected by the Kill Van Kull to Hudson River just north of Staten Island.

The Passaic River (Figure 14), which parallels the nearby Hudson River, was an industrial river, with chemical plants that manufactured Agent Orange for use during the Vietnam War during the 1950s and 1960s (37). Stretches of Passaic River in Newark, New Jersey are post-industrial abandoned landscapes and the sediment in the Passaic River near Newark Bay remains contaminated with dioxin TCDD, PCBs, and Hg. The USEPA designated this 27 km stretch of the Passaic River as a Superfund site.

During the manufacturing process, the workers at the New Jersey Diamond Alkali facility were exposed to dioxin TCDD (37) as was the lower Passaic River and Newark Bay. Agent Orange was stored on site at Diamond Alkali in 208-liter barrels painted with an orange stripe, then loaded on ocean-going vessels on the Passaic River, and shipped via the Panama Canal Zone (59) to the South China Sea and the coast of Vietnam.

In 1983, sampling of soils and sediments, by the State of New Jersey and the U.S. Environmental Protection Agency (USEPA), near 80 Lister Avenue in Newark and the adjacent Passaic River west of Newark Bay, revealed high levels of dioxin TCDD (37). There were also high levels of PCBs and Hg because of the manufacture of other chemical products. In 2001, the USEPA, in partnership with New Jersey and other federal agencies, cleaned up the Lister Avenue manufacturing site on the Passaic River in Newark, New Jersey. The buildings were torn down and hauled to a landfill (Figure 16). The site became a gravel parking lot and the dioxin-contaminated soil was removed and incinerated. Today, only a gravel lot remains as part of an abandoned industrial complex (37). The remediation actions taken in the Passaic River included a pre-1998 floodwall and subsurface treatment system.

The contaminated sediment in the river originating from the Lister site and neighboring lots was covered to prevent additional release of dioxin TCDD into the river. Occidental Chemical Corporation (49) monitored the site (60). In 2005, the State of New Jersey sued Maxus Energy Corporation (the US unit of Argentina's oil giant YPF Sociedad Anomima) and OxyChem over a delay in the cleanup. The US$220 million that the state spent cleaning up a section of the river was recovered from Maxus and OxyChem partnership under terms of a court settlement. Cleanup activities by the partnership in 2012 and 2014 included the removal and disposal of dioxin TCDD, PCBs, and Hg-contaminated sediment from two areas along the Passaic River (61) (62).

Tierra Removal dredged the most concentrated inventory of dioxin TCDD contaminated sediment in the river adjacent to the Lister Avenue site. At river mile marker 10.9 the concentrated inventory of highly contaminated mudflat on the east bank of the river near Lyndhurst was dredged and capped (58) (63) (48). The Passaic River is one of the most polluted hotspots in the United States and site of one of the largest cleanup efforts ever conducted.

In 2014, the USEPA announced a US$1.7 billion plan to remove 3.2 × 106 m3 of toxic sediment contaminated with dioxin TCDD, PCBs, and Hg (6). The sediments in the lower 13 km of the Passaic River were found to be a major source of the contamination in other sections of the Passaic River and Newark Bay. In March of 2016, a remedy was chosen for the contaminated sediment of the lower Passaic River which included an engineering cap being installed from riverbank to riverbank.

To avoid increasing future Passaic River flooding hazard and to maintain the navigation channel, part of the dioxin TCDD-contaminated sediment had to be removed to make room for the cap. The removed dredge material was dewatered and transported by barge to a sediment permitted processing facility on the banks of Newark Bay for disposal (37) (50) (64). The estimated cost was US$1.38 billion. The USEPA estimated the cost of the cleanup of the lower 27 km of the Passaic River and Newark Bay to be US$6 billion, in addition to approximately US$6 billion in natural-resource damages. Cleanups for the remainder of Newark Bay and lower Passaic River are still being planned (49) (62).

Exposure to even low levels of contaminants through crab and fish consumption may have long-lasting health effects on people living along the lower Passaic River. The USEPA alerted the public about the prohibitions and advisories on harvesting crabs or fish in the tidal Passaic River and Newark Bay. The advisories and prohibitions, based on levels of Hg, PCBs, and dioxin in tested crabs and fish, are difficult to enforce.

In 2013, several corporations agreed to pay New Jersey US$130 million for ecological damages related to the Passaic River pollution (62). After 60 years, US companies, such as Diamond Alkali (now Diamond Shamrock), stopped manufacturing Agent Orange with the by-product dioxin TCDD. However, the contaminant has a very long half-life when attached to sediment under water (anaerobic conditions) and remains an environmental problem in the tidal Passaic River and Newark Bay. To this day, fish and crabs from the Passaic River are too contaminated with dioxin TCDD for human consumption and remain a threat to the food supply and human health (37).

4.0 Discussion

By the mid-1950s, evidence from chemical-plant accidents and occupational exposure had established serious concern about the human-health effects of dioxin TCDD. U.S. government agencies and American, European, and Canadian chemical companies had access to evidence linking TCDD exposure with chloracne and other serious health effects among workers, including incidents at the Monsanto 2,4,5-T plant in Nitro, West Virginia, in 1949 and the BASF plant in Europe in 1953. These events should have heightened concern about the risks associated with 2,4,5-T formulations contaminated with dioxin TCDD.

4.1 Recognition of Harmful Agent Orange Effects

Early in 1965, scientific organizations led by Arthur W. Galston, then a professor at Yale University, warned the U.S. government against the military herbicide program. Approximately 5,000 scientists, including members of the Federation of American Scientists and the American Association for the Advancement of Science, together with 17 Nobel Prize winners, petitioned the U.S. government and military to stop the use of chemical and biological weapons (65). Galston objected strongly to the military use of research related to his earlier scientific work and later described it as a misuse of science in a California Institute of Technology oral-history interview (66). He was recognized in 2004 by the University of Illinois Alumni Association for his scientific contributions and subsequent efforts to prevent their misuse.

By 1953, chemical companies including BASF had documented health effects among workers exposed to dioxin TCDD after an industrial accident (67). Questions remained, however, about how quickly and fully information on the magnitude of TCDD contamination in Agent Orange was communicated to government and military authorities, particularly after production conditions were intensified (47,56). TCDD was also a by-product in other Rainbow herbicides, creating additional environmental and human-health risks (40,55). By the late 1960s, the U.S. government and military had become more fully aware of the environmental and health consequences of TCDD contamination (41,67,68). In 1970, President Nixon ordered the U.S. military to stop spraying Agent Orange; the following year, the remaining Rainbow herbicide spraying program was terminated. Agent Orange barrels were collected at Bien Hoa Airbase and shipped to Johnston Atoll in the Pacific Ocean. Leaking containers and contaminated storage areas created additional exposure pathways for handlers, soils, runoff water, and nearby environments (47).

4.2 Bioaccumulation of Dioxin from Soils and Sediments

Dioxin TCDD can bioaccumulate in fish and shrimp tissue and enter the human food supply when contaminated aquatic organisms are consumed. Animal studies supported by the U.S. Department of Defense also contributed to evidence of developmental effects associated with TCDD exposure (40).

More than five decades after U.S. military spraying ended, fish and shrimp restrictions remain around heavily contaminated areas such as the Bien Hoa Airbase hotspot in Vietnam. Similar persistence is evident in the Passaic River system, where TCDD attached to fine sediment has been transported through the tidal river into Newark Bay and connected waterways. In both settings, long-term risk is controlled not only by the original release but by the later movement, deposition, resuspension, and biological uptake of contaminated sediment.

The Port Authority of New York and New Jersey has spent millions dredging dioxin TCDD-contaminated soil and sediment from the rivers, channels and ports. Dioxin TCDD binds to the clay and soil organic matter (47) and can be transported from

Passaic River during periods of heavy rainfall. Before 1998, floodwalls and slurry walls had been constructed (Figure 14) to reduce the runoff and dioxin-contaminated sediment transport into the Passaic River, Newark Bay, Arthur Kill, Raritan Bay, Kill Van Kull, New York Bay and the Atlantic Ocean.

4.3 The Source of Dioxin TCDD Contaminant in Passaic River Sediments: Diamond Alkali Facility in Newark, New Jersey.

The Diamond Alkali facility on the Passaic River in Newark manufactured DDT and other chemicals in the 1940s and later produced Agent Orange. Court testimony from former workers described substantial occupational exposure and repeated spills or leaks during production. Wastewater and contaminated material entered trenches, drains, and pipes connected to the tidal Passaic River. This manufacturing history provides the principal documented source for the dioxin TCDD hotspot associated with the Lister Avenue site.

4.4 Soils and Sediment Sampling for Dioxin TCDD

In 1983, sampling by the State of New Jersey and the U.S. Environmental Protection Agency (USEPA) near 80 Lister Avenue and in the adjacent Passaic River revealed high levels of dioxin TCDD, together with PCBs and mercury (Hg). In 2001, USEPA, New Jersey, and other federal agencies removed the Lister Avenue buildings, disposed of contaminated materials, and incinerated contaminated soil. River remediation also included a floodwall, subsurface treatment, and capping of contaminated sediments to reduce further releases. Occidental Chemical Corporation continued monitoring of the site (49,50).

In 2005, the State of New Jersey sued Maxus Energy Corporation and OxyChem over delays in cleanup. Under later settlements and remedial actions, contaminated sediments containing dioxin TCDD, PCBs, and Hg were removed or capped at several locations along the lower Passaic River (60,62,63). In 2014, USEPA announced a US$1.7 billion plan addressing approximately 3.2 × 10^6 m3 of contaminated sediment. The Passaic River remains one of the largest and most complex contaminated-sediment cleanup projects in the United States.

Sediments in the lower 13 km of the Passaic River were identified as a major continuing source of contamination to other parts of the river and Newark Bay. In March 2016, the selected remedy included installation of a bank-to-bank engineering cap. Some contaminated sediment had to be dredged first to preserve navigation depth and avoid increasing flood risk; the dredged material was dewatered, transported by barge, and processed for disposal (49,60,63). The selected lower-river remedy was estimated at approximately US$1.38 billion, while broader cleanup and natural-resource restoration estimate for the lower Passaic River and Newark Bay reached several billion dollars (49,50). Contaminated sediment has also moved into connected tidal waterways, although concentrations and remediation needs vary by location.

Exposure to even low levels of contaminants through crab and fish consumption may have long-lasting health effects on people living along the lower Passaic River, Newark Bay, Arthur Kill, Raritan Bay, Kill Van Kull, and New York Bay. The USEPA alerted the public about the prohibitions and advisories on harvesting crabs or fish in the tidal Passaic River and Newark Bay. The advisories and prohibitions are based on levels of Hg, PCBs, and dioxin in tested crabs and fish and are difficult to enforce.

4.5 Passaic River Case Study Summary

The Passaic River case demonstrates how industrial contamination can become a long-term problem for an entire connected estuarine system. Dioxin TCDD released from the Diamond Alkali manufacturing site entered the tidal river, became associated with sediments, and was redistributed through the lower Passaic River and Newark Bay toward connected waterways. Although the original plant was removed and contaminated soil was treated, river sediments continue to require monitoring and remediation. Fish and crab restrictions illustrate the continuing connection between contaminated sediment, the food supply, and public health. The scale and cost of the cleanup also demonstrate that short-term industrial benefits can generate environmental obligations lasting for many decades.

5.0 Summary

The Hudson, Mohawk, and Passaic Rivers, together with the New York State Canal System and the tidal channels of New York Harbor, form a highly modified waterway network. Natural landscape evolution created the basic river valleys, while two centuries of canal construction, dams, locks, dredging, urbanization, and industrial development transformed their hydrological and ecological connections.

The Hudson River case shows how industrial prosperity and technological innovation were accompanied by persistent PCB contamination, fish-consumption concerns, and a long Superfund cleanup. The canal-system case shows a different form of consequence: the same hydrological connectivity that supported migration, trade, and regional development also facilitated waterborne disease and the movement of invasive species between previously separated waters.

The Passaic River case adds the legacy of Agent Orange manufacturing and dioxin TCDD contamination. Contaminated sediments near Newark became a long-term environmental and public-health problem requiring extensive dredging, capping, monitoring, fish and crab restrictions, and multi-billion-dollar remediation and natural-resource restoration efforts.

Together, the three cases show that engineered waterways should be evaluated across long time scales. Navigation, industrial production, urban sanitation, ecological connectivity, pollution transport, and public health are not separate problems; they interact through the same connected water and sediment systems.

6. Conclusions

The creation of USEPA, the Clean Water Act, and the Superfund program established essential regulatory tools for addressing industrial and urban water pollution. The Hudson and Passaic River cases show, however, that recovery from persistent contamination requires decades of monitoring, sediment management, source control, public-health protection, and sustained financial investment. Legal and engineering responses are most effective when they are combined with long-term ecological assessment.

The broader conclusion is that pollution in engineered waterways is a dynamic process shaped by connectivity. Canals, dredged channels, locks, dams, and tidal waterways can redistribute pollutants, nutrients, invasive organisms, and disease risks across boundaries that were once more distinct. The Erie and Oswego canals, the New York State Canal System, and the Kill Van Kull channel demonstrate how hydrological engineering can create substantial economic and social benefits while also producing delayed environmental and public-health consequences. Future management should therefore treat navigation, water quality, sediment, ecosystem health, and human exposure as components of a single coupled system and should plan for long-term monitoring, remediation, and adaptive management.

Conflict of Interest

The author declares no conflict of interest.

Acknowledgments

The author acknowledges institutional support from the USDA National Institute of Food and Agriculture, Water Division; the Illinois Office of Research, College of Agricultural, Consumer, and Environmental Sciences, University of Illinois; and the Iowa Agriculture and Home Economics Experiment Station, College of Agriculture and Life Sciences, Iowa State University.

Funding

This work was supported by Hatch Project 875-979 and by the institutional support acknowledged above.

Data Availability Statement

No new data were created or analyzed in this review article; all sources used are cited in the reference list.

References

1. Morton, L.W. and Olson, K.R. (2020) Settlement, development, despoilment, and recovery of the Hudson River, New York, Journal of Soil and Water Conservation, 75(1):13A-19A, DOI: 10.2489/jswc.75.1.13A
2. Rothstein, E. (2019) Reflections on a river. The Wall Street Journal, July 9, 2019.
3. Milman, O. (2019) Hudson River shows signs of rebound after decades as New York's sewer. The Guardian. March 28, 2019.
4. IDPH (Illinois Department of Public Health) (2009) Polychlorinated Biphenyls (PCBs) Environmental Health Fact Sheet. Springfield, IL: Division of Environmental Health.

5. Pinkney, A.E., Myers, M.S., and Rutter, M.A. (2017) Histopathology of brown bullhead (Ameiurus nebulosus), smallmouth bass (Micropterus dolomieu) and yellow perch (Perca flavescens) in relation to the polychlorinated biphenyl (PCB) contamination in the Hudson River. Science of the Total Environment 575:1325-1338.

6. Hu, Z., and Morton, L.W. (2011) Region water quality concern and environmental attitudes. In Pathways for Getting to Better Water Quality, eds. L.W. Morton and S.S. Brown. New York: Springer.

7. USEPA (2019a) Summary of the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund) 42 US Code 9601 et seq. (1980). https://www.epa.gov/laws-regulations/summary-comprehensive-environmental-response-compensation-and-liability-act

8. Morton, L.W., and Olson, K.R. (2019) Corridor of migration, navigation and innovation: The New York State Canal System. Journal of Soil and Water Conservation 74(5):102A-108A, doi:10.2489/jswc.74.5.102A

9. Macfarlane, J. (1890) American Geological Railway Guide. New York: D. Appleton and Company. https://accessgenealogy.com/new-york/geology-hudson.htm.

10. Levine, D. (2016) Hudson Valley's Tribal History. Hudson Valley Magazine, June 24, 2016. http://www.hvmag.com/Hudson-Valley-Magazine/July-2016/The-Native-People-of-the-Hudson-Valley

11. NOAA (National Oceanic and Atmospheric Administration) (2019) Fisheries. Atlantic Sturgeon. Silver Spring, MD: National Oceanic and Atmospheric Administration Fisheries. https://www.fisheries.noaa.gov/species/atlantic-sturgeon

12. Faroon, O.M., Keith, L.S., Smith-Simon, C. and DeRosa, D.T. (2003) Polychlorinated biphenyls: Human health aspects. Agency for Toxic Substances and Disease Registry, Atlanta, Georgia. Concise International Chemical Assessment Document 55. Geneva: World Health Organization. http://www.inchem.org/documents/cicads/cicads/cicad55.htm#1.0

13. Green Facts (2006) PCBs: Polychlorinated biphenyls. Facts on Health and the Environment. Brussels: Cogeneris sprl. https://www.greenfacts.org/en/pcbs/

14. Madden, S.S., and Skinner, L.C. (2016) Polychlorinated biphenyls (PCBs) in adult and juvenile mallards (Anas platyrhynchos) from the Hudson River, New York, USA. Environmental Pollution 216:487-499.

15. USEPA (United States Environmental Protection Agency) (1981) EPA announces first 114 top-priority Superfund sites. USEPA Archives. Washington, DC: US Environmental Protection Agency. https://archive.epa.gov/epa/aboutepa/epa-announces-first-114-top-priority-superfund-sites.html

16. USEPA (2015) Sixth season of Hudson River dredging begins, historic dredging project draws to a close, next up: clean up floodplains. USEPA Archives. Washington, DC: US Environmental Protection Agency. https://archive.epa.gov/epa/news-releases/sixth-season-hudson-river-dredging-begins-historic-dredging-project-draws-close-next.html

17. USEPA (2019) After extensive consultation and analysis, EPA announces two actions on the Upper Hudson River PCB cleanup in New York. Albany, NY: US

Environmental Protection Agency. https://www.epa.gov/sites/production/files/2019-04/documents/hudson_news_release_final_0.pdf

18. Stainbrook, K. (2005) Anticipating Changing the Hudson River Watershed: An Economic and Ecological Risk Assessment: Applications to Watershed Management. Boca Raton, FL: CRC Press.
19. Rodenburg, L.A., and Ralston, D.K. (2017) Historical sources of polychlorinated biphenyls to the sediment of the New York/New Jersey Harbor. Chemosphere 169:450-459.
20. Kalabon, A., Loescher, E. Sommerville, A., and Delatte, N.J. (2013) Rise and fall of the Ohio and Erie Canal. Journal of Professional Issues in Engineering Education and Practice 139:3:226-234.
21. Grove, J.M. (2009) Cities: Managing densely settled social-ecological systems. In Principles of Ecosystem Stewardship, eds. F.S. Chapin III, G.P. Kofinas, and C. Folke, 281-294. New York: Springer.
22. Vitaliano, D.F. (2016). Benefits and costs of the Erie Canal: A new view. Eastern Economic Journal 42(4):581-593.
23. Tuite, A.R., Chan, D.H. and Fisman, D.N. (2011). Cholera, canals, and contagion: Rediscovering Dr. Beck's report. Journal of Public Health Policy 32:320-333.
24. Eshenroder, R.L. (2014) The role of the Champlain Canal and Erie Canal as putative corridors for colonization of Lake Champlain and Lake Ontario by sea lampreys. Transactions of the American Fisheries Society 143:634-649.
25. Lyons, C. (2008) Navigating the future of the Erie Canal. Planning 74(4):10-13.
26. Stevenson, D. (1838) Sketch of the civil engineering of North America: Comprising remarks on the harbors, rivers and lake navigation, light- houses, steam-navigation, waterworks, canals, roads, railways, bridges and other works in that country. London: Sabin Americana Gale, Cengage Learning.
27. Morgastein, M., Cregg, J.H. and Erie Canal Museum (2001) Erie Canal. New York: Arcadia Publishing.
28. Johnson, T.M. (2009) Responsible planning for future ground water use from the Great Flats Aquifer. In Proceedings from 2009 Mohawk-Watershed Symposium, Union College, New York, March 27, 2009.
29. Ridge, J.C. (1997) Discontinuity and Little Falls Gravel: Evidence for Erie interstage in central New York State. GSA Bulletin 109(6):652-665.
30. Olson, K.R., and Morton, L.W. (2016) Managing Mississippi and Ohio River Landscapes. Ankeny, IA: Soil and Water Conservation Society.
31. Whitford, N.E. (1922) History of the Barge Canal of New York State. Albany, NY: J.B. Lyons Company.
32. Karwatka, D. (2012) The Erie Canal. Tech directions October, p. 10. http://www.techdirections.com/
33. Johnson, S. (2006) The Ghost Map. New York: Riverhead Books.

34. Great Lakes Fishery Commission. (2018) Sea lampreys. Ann Arbor, MI: Great Lakes Fishery Commission. http://www.glfc.org/sea-lamprey.php

35. Bray, P.M. (1994) The role of the public trust doctrine in planning and management of the New York State Canal System. Albany Law Journal of Science and Technology 4(1):47.

36. Level 7 Market Research (2017) (Dec 15) Canal Event Analysis. Erie Canalway National Heritage Corridor. https://eriecanalway.org/

37. Olson, K.R. and Tharp, M. (2020) How did the Passaic River, a Superfund site near Newark, New Jersey, become an Agent Orange dioxin TCDD hotspot? Journal of Soil and Water conservation, 75(2) 33A-37A. https://doi.org/10.2489/jswc.75.2.33A

38. Thomas, T.L. and Kang, H.K. (1990) Mortality and morbidity among Army Chemical Corps Vietnam Veterans: A preliminary report. American Journal of Industrial Medicine 18:665-67.

39. Schecter, A., Dai, L.C., Thuy, L.T., Quynh, H.T., Cau, H.D., Phiet, P.H., Nguyen, N.T., Constable, J.D. and Baughman, R. (1995) Agent Orange and the Vietnamese: The persistence of elevated dioxin levels in human tissues. American Journal of Public Health 85(5):516-522.

40. NAS (National Academy of Sciences) (1974) The effects of herbicides in South Vietnam: Part A. Summary and Conclusions. Washington, DC: National Academy of Sciences.

41. Institute of Medicine (US) (1994) Veterans and Agent Orange: Health Effects of Herbicides Used in Vietnam. Washington, DC: National Academy Press.

42. Constable, J.D. and Hatch. M.C. (1985) Reproductive effects of herbicide exposure in Vietnam recent studies by the Vietnamese and others. Teratogenesis, Carcinogenesis, and Mutagenesis 5(4):231-250.

43. Stockbauer, J.W., Hoffman, R.E., Schramm, W.F. and Edmonds, L.D. (1988) Reproductive outcomes of mothers with potential exposure to 2,3,7,8-T dioxin. American Journal of Epidemiology 128:410-419.

44. Morton, L.W. and Culbertson, C. (2022) Persistence of Dioxin TCDD in Southern Vietnam Soil and Water Environments and Maternal Exposure Pathways with Potential Consequences on Congenital Heart Disease Prevalence in Vietnam. Open Journal of Soil Science, 12, 119-150. https://www.scirp.org/pdf/ojss_2022041916012920.pdf

45. Giang, H.T.N., Hai, T.T., Nguyen, H., Vuong, T.K., Morton, L.W. and Culbertson, C.B. (2022) Elevated Congenital Heart Disease Birth Prevalence Rates Found in Central Vietnam and Dioxin TCDD Residuals from the Use of 2, 4, 5-T Herbicides (Agent Orange) in the Da Nang Region. PLOS Global Public Health, 2, e0001050. https://doi.org/10.1371/journal.pgph.0001050

46. Olson, K.R., and Morton, L.W. (2017) Why were the soil tunnels of Cu Chi and Iron Triangle in Vietnam so resilient? Open Journal of Soil Science 7:34-51.

47. Olson, K.R., and L.W. Morton. (2019) Long-term fate of Agent Orange and dioxin TCDD contaminated soils and sediments in Vietnam hotspots. Open Journal of Soil Science 9(1):1-34. https://doi.org/10.4236/ojss.2019.91001

48. New Jersey Department of Environmental Protection (2009) Notice to general public – fish should not be eaten. Fish Advisory posted January 23, 2009.

49. Fallon, S. (2019) EPA targets Bergen, Passaic counties for Passaic River dioxin cleanup. But is it enough? July 30, 2019. NorthJersey.com.

50. Brickley, P., and Morgenson, G. (2018) Agent Orange legacy – A $12 billion cleanup and fight over who pays. Wall Street Journal, December 3, 2018.

51. Romano, J. (1992) Passaic Flood Tunnel: A turning point. The New York Times, November 8, 1992.

52. USACE (2011) Fact Sheet on Kill Van Kull Federal Channel. New York District, United States Army Corps of Engineers.

53. Hitchcock, A.E. and Zimmerman, P.W. (1935) Absorption and movement of synthetic growth substances from soil as indicated by the responses of aerial plant parts. Contrib. Boyce Thompson Institute 1:447-476.

54. Zimmerman, P.W., and Hitchcock, A.E. (1942) Flowering habit and correlation of organs modified by triiodobenzoic acid. Contrib. Boyce Thompson Institute 12:491-496.

55. Galston, A.W. (1943) The physiology of flowering with especial reference to floral initiation in soybeans. PhD Thesis. University of Illinois.

56. Sills, P. (2014) Toxic War: The Story of Agent Orange. Nashville, TN: Vanderbilt University Press.

57. Young, A.L. and Newton, M. (2004) Long overlooked historical information on Agent Orange and TCDD following massive applications of 2,4,5-T containing herbicides. Eglin Air Force Base, Florida. Environmental Science and Pollution Research 11:209-221. https://doi.org/10.1007/BF02979627

58. Olson, K.R. and D. R. Speidel 2022. Agent Orange Chemical Plant Locations in the United States and Canada: Environmental and Human Health Impacts. Open Journal of Soil Science 12(7): 363-426. DOI:10.4236/ojss.2022.128016. https://www.scirp.org/pdf/ojss_2022083014023480.pdf

59. Olson, K.R. and Tornoe D. (2021) Long-Term environmental Impacts of Pesticides and Herbicides Use in Panama Canal Zone. Open Journal of Soil Science 11, 403-434. https://doi.org/10.4236/ojss.2021.119021

60. Baxter, C. (2011) Second New Jersey chemical company held liable for lower Passaic River pollution cleanup. NorthJersey.com

61. Payne, M. (2021) Episode 2086-Vietnam Veteran News Podcast. PBS. Show Exposes Agent Orange Secrets. https://vietnamveterannews.com/episode-2086

62. USEPA (US Environmental Protection Agency). (2019) Case Summary: US$165 million settlement to start cleanup work on the Passaic River in New Jersey. Washington, DC: US Environmental Protection Agency.

63. Grant, M. (2011) Environmentalist, official argue intent of 130 million to be obtained from Passaic River Polluters. NorthJersey.com.

64. Mansnerus, L. (1998) Newark's toxic tomb; Six acres fouled by dioxin, Agent Orange's deadly byproduct, reside in the shadow of an awakening downtown. The New York Times. Nov. 8, 1998.

65. Galston, A.W. (2002) An accidental plant biologist. Plant Physiology 128(3):786-787. https://doi.org/10.1104/pp.900024

66. Cohen, S.K. (2002) Galston, Arthur, W. Oral History Project. Pasadena, CA: California Institute of Technology Archives.

67. Zober, A., Messerer, P. and Huber, P. (1990) Thirty-four-year mortality follow-up of BASF employees exposed to 2,3,7,8-T dioxin after 1953 accident. International Archives of Occupational and Environmental Health 62(2):139-157.

68. US Congress House of Representatives. (1992) Committee on Government Operations, Human Resources Intergovernmental Relations Subcommittee. Hearing on Health Risks of Dioxin. June 10, 1992.