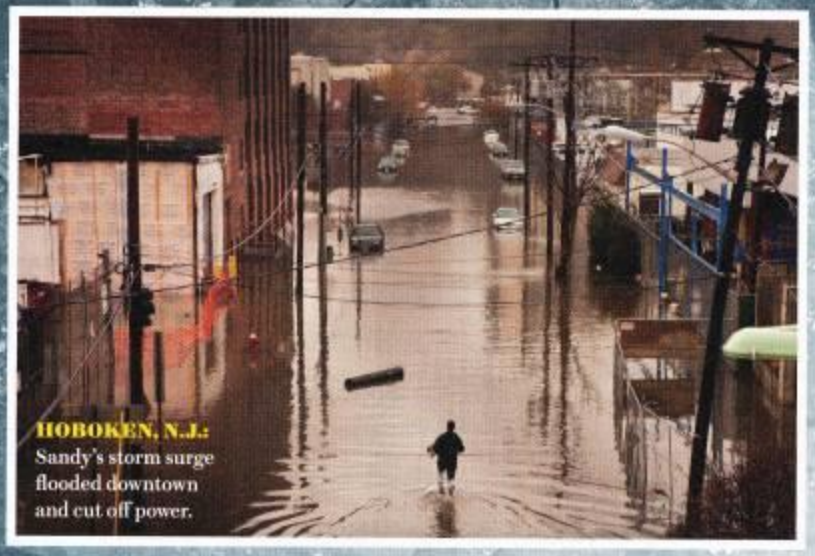


HOBOKEN, N.J.: Sandy's storm surge flooded downtown and cut off power.

STATEN ISLAND: At least 17 residents drowned despite protective levees.

MANHATTAN: Superstorm Sandy engulfed streets and filled subway tunnels.

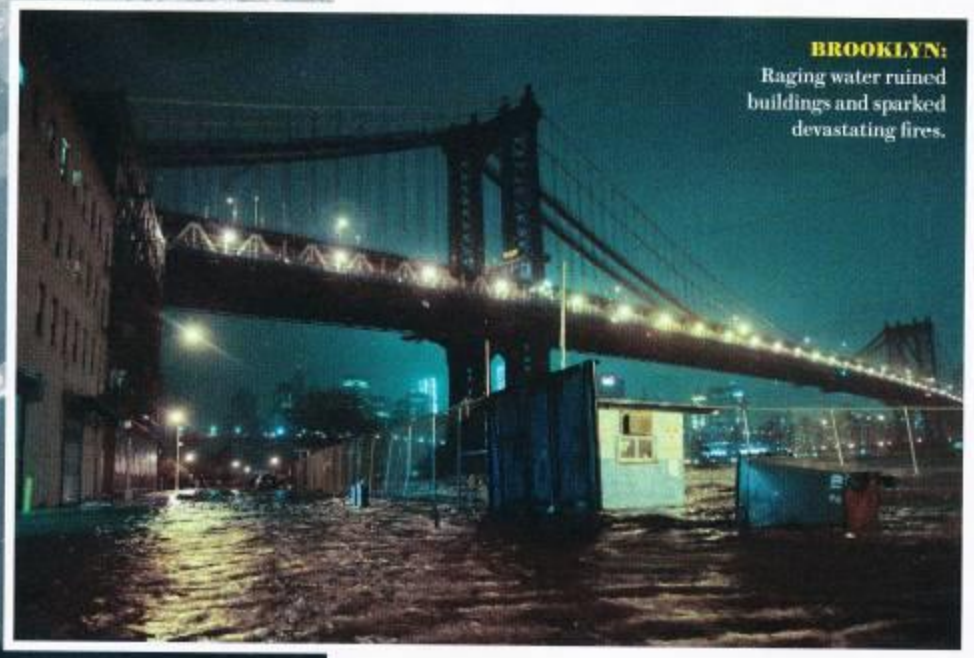
CLIMATE SCIENCE

STORM OF THE CENTURY*

*EVERY TWO YEARS

New York City and the entire U.S. East Coast could face frequent destruction unless the region takes drastic action

By Mark Fischetti *Maps by XNR Productions*



BROOKLYN: Raging water ruined buildings and sparked devastating fires.

THOMAS ABDALLAH HAS SEEN A LOT OF WATER in his 26 years of work for New York City's transit system. In December 1992 a nor'easter storm killed the subway's power, forcing rescue crews to evacuate passengers from flooding tunnels. In August 2007 a five-inch deluge that meteorologists called an "extreme climate event" shut down the system again. So did Hurricane Irene in August 2011. Then came Hurricane Sandy.

As Sandy's storm surge began to flood downtown Manhattan last October, dozens of New York City transit workers scrambled in the wind and rain to place plywood sheets and sandbags across subway entrances. But the oncoming water pushed right through the feeble barricades, pouring down stairwells until underground stations filled chest deep, in turn filling seven long train tunnels running under the rivers between the boroughs. Huge pumps in more than 300 man-made caverns deep below the city's subway line, which can push out 18 million gallons of water a day, couldn't possibly keep up.

After the deluge, Abdallah, who is the transit system's chief environmental engineer, assessed the damage with his colleagues. Saltwater had corroded electrical equipment throughout the subway system. Much of it had to be replaced. The transit authority chair at the time, Joe Lhota (now running for mayor), testified before Congress that fully restoring the system would cost $5 billion. And that would just bring the subways back to their pre-Sandy condition; the money would do nothing to enhance protection against the next hurricane or against rising seas.

That status quo is becoming increasingly costly in money and lives. Experts predict that damaging storms will get more severe and more frequent. According to the latest estimates, the chance of widely destructive flooding in New York City will be one in two each year by the end of the century unless significant infrastruc-

IN BRIEF

The chances of severe flooding in New York City will be as high as one in two each year by 2100, in part because the U.S. East Coast is a hotspot for sea-level rise.

Experts may be reluctant to recommend the ultimate protection measures for New York City: building massive barriers that would cost billions of dollars and moving communities out of the lowest-lying areas.

The primary way to protect long coastlines between cities is to pile sand along beaches every five to 10 years, but it is unclear whether enough quality sand deposits exist offshore.

Ending federal subsidies for flood insurance, so that beachfront residents must pay the full cost, might encourage people to move out of vulnerable areas.

EAST COAST

Sea-Level Rise: A Global Hotspot

Rising seas could drown a significant portion of the U.S.'s valuable and highly populated East Coast, including famous cities. The latest estimates indicate that global sea level could rise by at least one meter (3.3 feet) by 2080 (*red*), as warmer seas expand and glaciers melt. Yet the effect is not uniform around the world. The coast from Massachusetts to North Carolina is a hotspot; sea level there has risen three to four times faster than the global average over the past 40 years, in part because of changes in Atlantic Ocean currents caused by melting ice in the Arctic (*map at far right*). Furthermore, the land under most of the coast is sinking, making the sea relatively higher still (*green line*). Certain municipalities such as Atlantic City are subsiding even faster because they are rapidly extracting groundwater that helps to prop up land.

Lowest of the Low
New Orleans, much of which is below sea level, is the most vulnerable of all major U.S. coastal cities. A single meter of sea-level rise would swamp more than 90 percent of it unless levees and other barriers are improved.

Sifting Sand
The only practical way to protect hundreds of kilometers of shoreline between cities is to pump sand from offshore deposits onto beaches every five to 10 years to replace what tides wear away. It is unclear, however, if enough quality deposits exist to last more than a few decades.

PRECEDING IMAGES: COURTESY OF NASA VISIBLE EARTH (satellite image); GETTY IMAGES (map); CHRISTOS PATHIAKIS Getty Images (cars in flooded street); REBECCA MATTHEWS AP Photo (Manhattan Bridge); VICTOR J. BLUE Getty Images (left)

SOURCES: "IMPLICATIONS OF RECENT SEA LEVEL RISE SCIENCE FOR LOW-ELEVATION AREAS IN COASTAL CITIES OF THE CONTERMINOUS U.S.A." BY JEREMY L. WEISS, JONATHAN T. OVERPECK AND BEN STRAUSS, IN *CLIMATIC CHANGE*, VOL. 105, NOS. 3–4, APRIL 2011 (1-meter and 6-meter sea-level rise data); "HOTSPOT OF ACCELERATED SEA-LEVEL RISE ON THE ATLANTIC COAST OF NORTH AMERICA," BY ASHBURY H. SALLENGER, JR., KARA S. DORAN AND PETER A. HOWD, IN *NATURE CLIMATE CHANGE*, VOL. 2, 2012 (sea-level rise gauge data, USGS)

ture changes are made. Each decade from now until then, the "average" flood will become worse and worse. Billions of dollars in repairs will become commonplace.

New York City is not alone in facing a watery future. The U.S. East Coast—one of the wealthiest and most densely populated regions in the world—is a hotspot for sea-level rise. Melting Arctic ice is changing Atlantic Ocean currents in a way that raises water along the coast. At the same time, the land is subsiding. In 2012 Asbury Sallenger of the U.S. Geological Survey reported that for the prior 60 years, sea level from Cape Cod outside Boston to Cape Hatteras in North Carolina had risen three to four times faster than the global average. Using the data, Sallenger (who died in February) confirmed models by colleagues indicating that by 2100 the mid-Atlantic region would experience 4.7 to 9.4 inches of sea-level rise above and beyond the average global increase, which itself is expected to be several feet at least.

Sandy's damage has focused the minds of scientists, politicians and the public on the vulnerability of coastal areas to storm surges and sea-level rise. Experts are debating which actions could best protect the Eastern seaboard, especially as millions more people flock there. Turning the entire coastline into a fortress is prohibitively expensive and would ultimately be a losing proposition for many sandy coastlines. Yet the alternative—moving people away from the water—would be a political tinderbox and cause social and economic disruption.

This dilemma is being played out in New York City, where scientists and engineers are scrambling to present protection options to Mayor Michael R. Bloomberg by the end of May. They were expected to recommend steps to repel minor flooding, but it is not clear that they would be willing to recommend the only sure way to protect against an 11-foot surge like Sandy's: massive flood barriers that would cost $10 billion to $20 billion. It is also unclear whether they would recommend an end to federal subsidies for flood insurance and the evacuation of low-lying land, even though these steps are the ultimate long-term solutions to the sea-level rise that the latest climate science predicts.

The choices are even more stark for the long stretches of coastlines between cities—along New Jersey, Maryland, the Carolinas, Florida. The U.S. would have to build a wall 16 feet high—to handle storm surge on top of sea-level rise—along every inch of the East Coast. Even if the money for such work were found, the millions of people who live in beachside communities would never stand for it because it would block their ocean view and access. The only politically viable option is to continually pile sand along beaches, even though higher and higher seas will erode more and more of it away—a Sisyphean postponing of the inevitable retreat from the shore.

In interviews with dozens of experts, it is clear that extreme measures needed to harden the East Coast would take decades to complete, cost hundreds of billions of dollars and disrupt many lives, but they are necessary evils.

DEFENDING NEW YORK CITY

SINCE HURRICANE SANDY struck, all eyes have turned toward New York City to see how best to defend against rising water. The metropolis ranks in the top 10 port cities most exposed to flooding worldwide and has more than $2 trillion of coastal property at risk—first or second on the planet. When Cynthia Rosenzweig, a climate scientist at Columbia University, attended a global

NEW YORK CITY

Storm Surge: Block It or Abandon Shore

Storm surge and sea-level rise threaten New York City. Hurricane Sandy's 3.4-meter (11-foot) surge was the highest to hit the city's metropolitan area. Like most cities, New York bases protection plans on maps from the Federal Emergency Management Agency, which show where flooding most likely will occur if a one-in-100-year storm hits. FEMA updated New York's flood zones in January, but Sandy's surge flowed farther inland in many areas (*key below*). Two massive barriers could hold back surges, but residents might have to abandon the lowest-lying communities, which already flood regularly, as seas relentlessly rise.

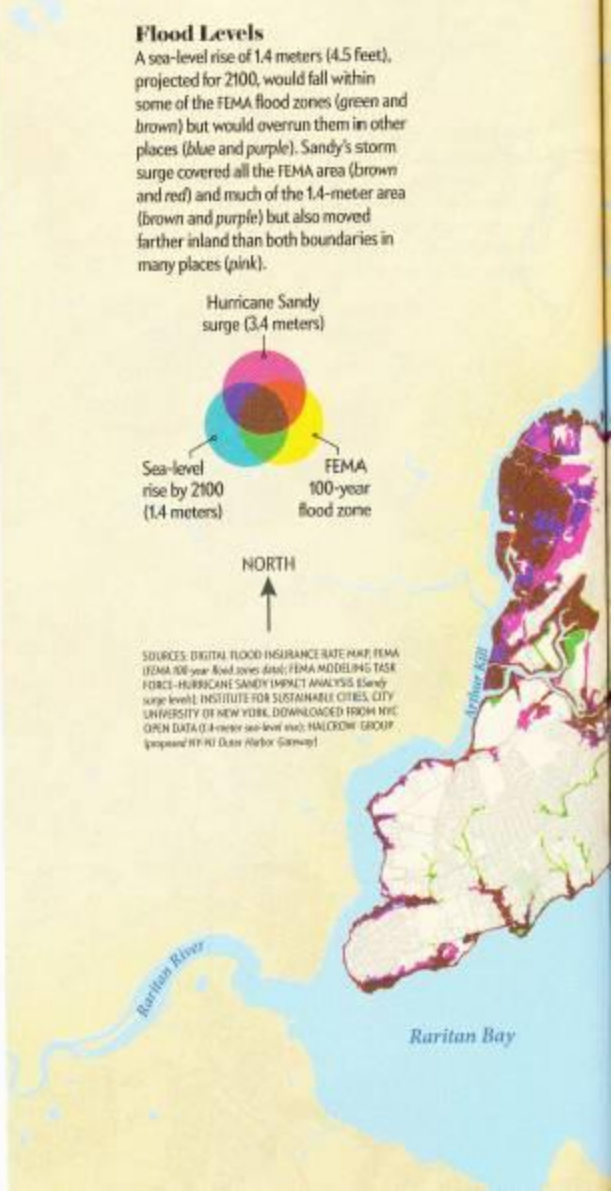
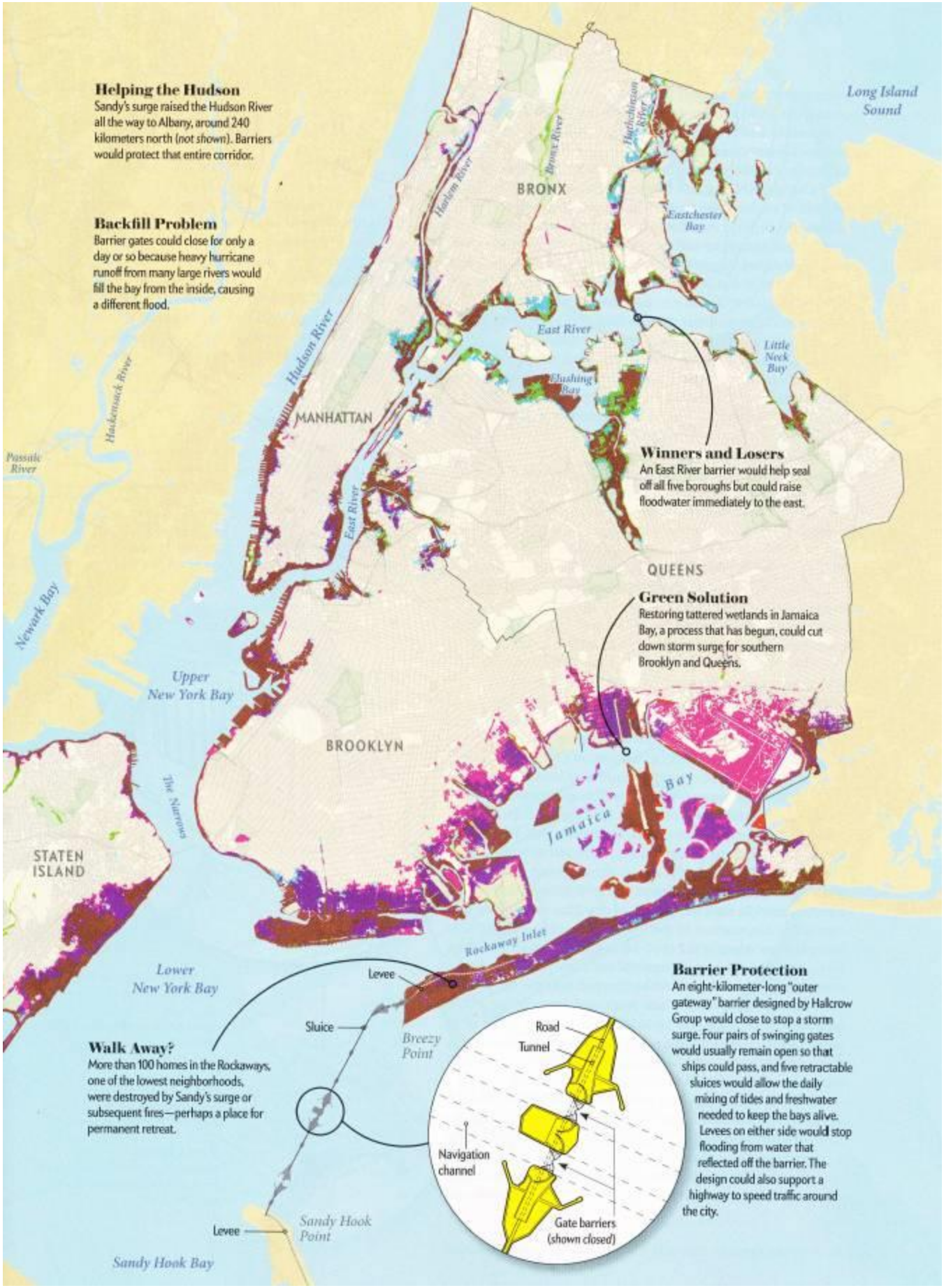


Illustration by George Retseck (inset)


Helping the Hudson
Sandy's surge raised the Hudson River all the way to Albany, around 240 kilometers north (not shown). Barriers would protect that entire corridor.
Backfill Problem
Barrier gates could close for only a day or so because heavy hurricane runoff from many large rivers would fill the bay from the inside, causing a different flood.
Long Island Sound
Bronx River
Hutchinson River
Harlem River
BRONX
Eastchester Bay
Hudson River
East River
Little Neck Bay
Flushing Bay
MANHATTAN
Hackensack River
Passaic River
Winners and Losers
An East River barrier would help seal off all five boroughs but could raise floodwater immediately to the east.
East River
QUEENS
Green Solution
Restoring tattered wetlands in Jamaica Bay, a process that has begun, could cut down storm surge for southern Brooklyn and Queens.
Newark Bay
Upper New York Bay
BROOKLYN
Jamaica Bay
The Narrows
STATEN ISLAND
Rockaway Inlet
Lower New York Bay
Levee
Sluice
Breezy Point
Walk Away?
More than 100 homes in the Rockaways, one of the lowest neighborhoods, were destroyed by Sandy's surge or subsequent fires—perhaps a place for permanent retreat.
Road
Tunnel
Navigation channel
Gate barriers (shown closed)
Barrier Protection
An eight-kilometer-long "outer gateway" barrier designed by Hallcrow Group would close to stop a storm surge. Four pairs of swinging gates would usually remain open so that ships could pass, and five retractable sluices would allow the daily mixing of tides and freshwater needed to keep the bays alive. Levees on either side would stop flooding from water that reflected off the barrier. The design could also support a highway to speed traffic around the city.
Levee
Sandy Hook Point
Sandy Hook Bay

environment meeting after Sandy occurred, city officials from around the world told her they were looking to New York to lead.

Scientists and engineers are scrambling because Sandy and new science have washed out the basic assumptions that the city had made. In 2009 a report by the New York City Panel on Climate Change (NPCC) stated that the city should plan for at least two feet of sea-level rise by 2100, based on conventional climate models. But in 2012 new information from various global sources showed that Antarctica and Greenland are melting quicker than models predicted. According to what scientists call the rapid ice-melt scenario, global sea level will rise four feet by the 2080s, notes Klaus Jacob, a research scientist at Columbia's Lamont-Doherty Earth Observatory. In New York City, by 2100 "it will be five feet, plus or minus one foot," Jacob says flatly.

The NPCC report also did not focus much on storm surges. Sandy's surge topped out at about 11 feet above average sea level at the lower tip of Manhattan. But here's the rub: Flood maps just updated in January by the Federal Emergency Management Agency indicate that an eight-foot surge would cause widespread, destructive flooding. So if sea level rises by five feet by 2100, a surge of only three feet is needed to inflict considerable damage.

Of course, rapid climate change would push the sea higher every decade until then. Jacob says the chance of what had been a one-in-100-year storm surge occurring in New York City will be one in 50 during any year in the 2020s, one in 15 during the 2050s and one in two by the 2080s. Scientists at the Massachusetts Institute of Technology say the chance of a one-in-100-year storm will be as great as one in three by 2100.

Despite the dire odds, none of the more than 20 scientists, engineers and city officials interviewed for this article would articulate a grand plan for protecting New York City against five feet of sea-level rise, plus an 11-foot surge, because that would require politically difficult choices. The lone exception is Jeroen Aerts, who served as an adviser to New York City's Office of Long-Term Planning and Sustainability and Department of City Planning, until they parted ways after Hurricane Sandy.

To Aerts, the necessary plan is straightforward. Immediately start flood-proofing buildings, which would harden them against events like the five-inch deluge in 2007. Begin to retrofit subway, train and automobile tunnels so water cannot get in. Armor power plants, wastewater treatment facilities and other "critical infrastructure." Meanwhile start the process of changing zoning laws to discourage construction in the lowest-lying areas. Add seawalls along the low edges of the city's boroughs to fend off rising sea level. And start doing environmental and cost-benefit studies for enormous barriers that would be dropped into the bay to hold back surges. Those studies take years, and construction would take years more, "so it will be 2030 before barriers would be in place," Aerts explains. "In the meantime, you start implementing the 'no regret' steps," such as raising subway entrances so floodwater cannot pour down the stairways onto the tracks.

Aerts was hoping New York would impose a regional plan such as the one he was developing, but in the aftermath of Sandy the groups he was advising told him that regional politics would make a centrally executed plan impossible. That is a far cry from how things work where Aerts comes from: he is a specialist in geographical risk management at the Institute for Environmental

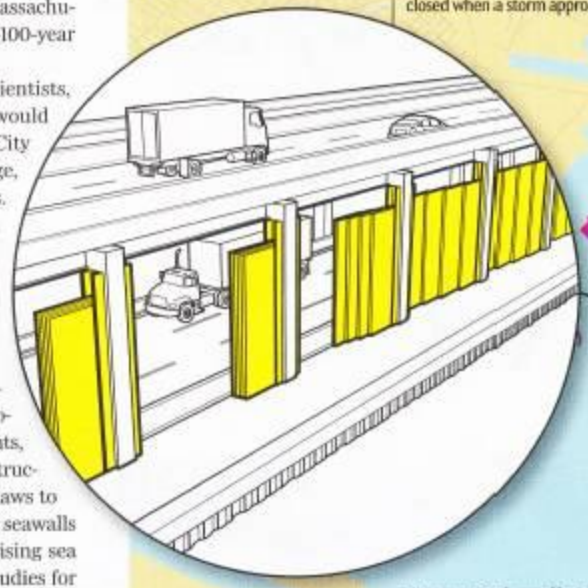
LOWER MANHATTAN

Flood Damage: Local Fixes Can Lessen Loss

As seas rise, tides and surges will invade farther into a coastal city, and even routine storms will cause more extensive flooding. Many street-level protection measures have been proposed for New York City and other municipalities; a variety of these proposals are shown here. Although quick implementation is tempting, experts warn that any mitigation measure should first meet standards and policies established in a region-wide protection plan, including a cost-benefit analysis for the short and long term. Otherwise, money could be wasted.

Install Retractable Floodwalls

If giant barriers are not built in the ocean outside a city to hold back a storm surge, high, retractable floodwalls could be installed between the pillars of a perimeter highway and closed when a storm approaches.



Frame Sidewalk Vents

Runoff from downpours can overtop the curb and flow into subway air vents that lie flush in sidewalks. Surrounding a vent with a simple vertical frame can divert the flow.

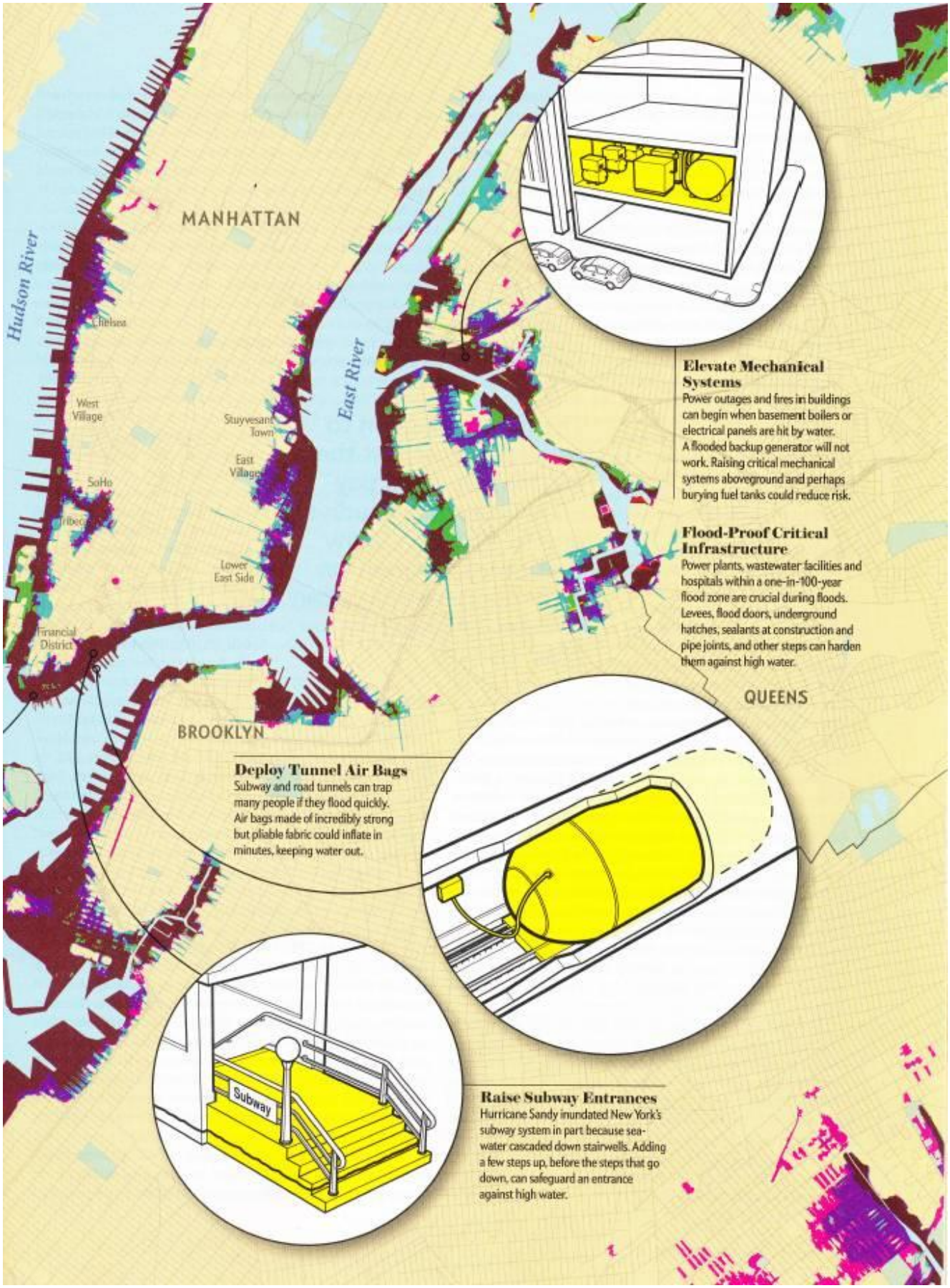
Bulk Up Boardwalks

Low-lying boardwalks and piers along the shore can be raised and fortified.

Erect Reefs

Artificial reefs or restored wetlands can break up waves and surges, reducing their energy.

Illustration by George Retseck (insets)



Elevate Mechanical Systems
Power outages and fires in buildings can begin when basement boilers or electrical panels are hit by water. A flooded backup generator will not work. Raising critical mechanical systems aboveground and perhaps burying fuel tanks could reduce risk.

Flood-Proof Critical Infrastructure
Power plants, wastewater facilities and hospitals within a one-in-100-year flood zone are crucial during floods. Levees, flood doors, underground hatches, sealants at construction and pipe joints, and other steps can harden them against high water.

Deploy Tunnel Air Bags
Subway and road tunnels can trap many people if they flood quickly. Air bags made of incredibly strong but pliable fabric could inflate in minutes, keeping water out.

Raise Subway Entrances
Hurricane Sandy inundated New York's subway system in part because seawater cascaded down stairwells. Adding a few steps up, before the steps that go down, can safeguard an entrance against high water.

The main objection to barriers is cost. Yet the investment could pay off handsomely. Studies of past disasters show that every $1 spent on protection measures can prevent $4 in repairs after a storm.