CLIMATE ADAPTATION

Evaluating Flood Resilience Strategies for Coastal Megacities

Integration of models for storms and floods, damages and protections, should aid resilience planning and investments.

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Recent flood disasters in the United States (2005, 2008, 2012); the Philippines (2012, 2013); and Britain (2014) illustrate how vulnerable coastal cities are to storm surge flooding (*1*). Floods caused the largest portion of insured losses among all catastrophes around the world in 2013 (*2*). Population density in flood-prone coastal zones and megacities is expected to grow by 25% by 2050; projected climate change and sea level rise may further increase the frequency and/or severity of large-scale floods (*3*–*7*).

Despite trillions of dollars of assets located in coastal flood-prone areas, investments in protection have often been inadequate (*8*), postponed for short-term economic reasons, for lack of consensus on how to properly evaluate the return on investment, or from the fear of making irreversible choices that become suboptimal over time. To help inform policy decisions, we have developed a multidisciplinary scientific approach to evaluate flood management strategies. It combines probabilistic risk assessment of hurricanes and storm surge with vulnerability determination of exposed assets at a census level, accounting for sources of uncertainty and the timing of investments in storm-surge flood-risk protection. We applied this methodology to New York City (NYC)—one of the most exposed coastal megacities—working with local policy-makers.

Barriers and Building Codes

A wealth of ideas about protecting NYC from floods has been proposed (*9*, *10*), including barriers, levees, wetland restoration and beach strengthening that are effective in reducing flood occurrence in large parts of the city. However, as in other cities, some of these large-scale engineering options have been criticized because they are costly or may harm the environment. Other measures, such as reducing exposure and vulnerability (e.g., by enacting zoning regulations and enhancing building codes), may considerably reduce flood damage and entail lower investment costs, but they do not prevent flood waters from entering the city.

We present three main classes of strategies that focus on reducing vulnerability or avoiding flooding or a combination of both [see the figure and supplementary material (SM)]. The Resilient Open City strategy (S1) is a cluster of measures to enhance building-code strategies in NYC (*11*) by elevating, or dry or wet flood-proofing, both existing and new buildings. Storm surge barrier strategies (S2, a, b, and c) aim to lower flood probabilities in NYC and parts of New Jersey (NJ), with barriers, levees, and beach nourishments. "Environmental dynamics" (S2a) consists of three barriers to close off parts of NYC and NJ that preserve wetland dynamics of Jamaica Bay. "Bay closed" (S2b) expands on S2a by adding a fourth barrier that closes off Jamaica Bay. "NJ-NY connect" (S2c) replaces three barriers from S2b with one large barrier in the outer harbor to protect a larger area (see the figure). The barrier systems are designed to withstand an extreme surge of 8 to 10 m (25 to 30 feet).

The "hybrid solution" (S3) (see the figure), reflecting many measures in (*9*), combines building code measures of S1 that turned out to be cost-effective according to our analysis (SM) only in high-risk 100-year return flood zones (defined by the U.S. Federal Emergency Management Agency), with protection of critical infrastructure to reduce economic loss due to business interruption. S3 includes moderate local flood protection measures, such as levees and beach nourishment that are also part of S2c. The local protection measures and building codes for new structures are adjustable to future climate change, as they can be upgraded if flood risk increases in the coming decades.

Modeling Flood Risks, Estimating Costs

The heart of the method is a probabilistic flood-risk model developed for the city (*12*–*14*) (SM §1). We simulated 549 storm-surge simulations, varying from extremely low probability events to more frequent storms, using a new coupled hurricane–hydrodynamic–inundation model (*15*) (SM). Then we applied flood depth–damage curves to calculate potential damage to buildings and vehicles at the census block level. In addition to flood risk to buildings, the risk to other categories (like infrastructure), the risk to parts of NJ, and indirect economic effects were added, based on observed consequences of Hurricane Sandy in 2012 (*13*).

We estimate the average annual expected flood loss for NYC alone at $174 million/year, if no flood management measures are implemented. Flood losses with a 100- and 1000-year return period are $2.2 billion and $25.4 billion, respectively. Our loss estimates for an extreme event of return period similar to Sandy are very close to the actual damages it triggered (SM §1.11).

The future risk in 2040 and 2080 is also calculated, accounting for estimated changes in surge probabilities (*15*) and projected sea-level rise under future climate change scenarios, as well as the increase in urban exposure due to new construction in flood zones (SM §1.3). Flood defenses in the storm surge barrier strategies (S2, a, b, and c) are assumed not to fail. A benefit-cost analysis (BCA) of flood risk–management strategies was conducted for NYC over a 100-year period to evaluate the benefit (avoided risk) of each strategy and its cost (*13*), under future scenarios (SM §2). We tested the robustness of the

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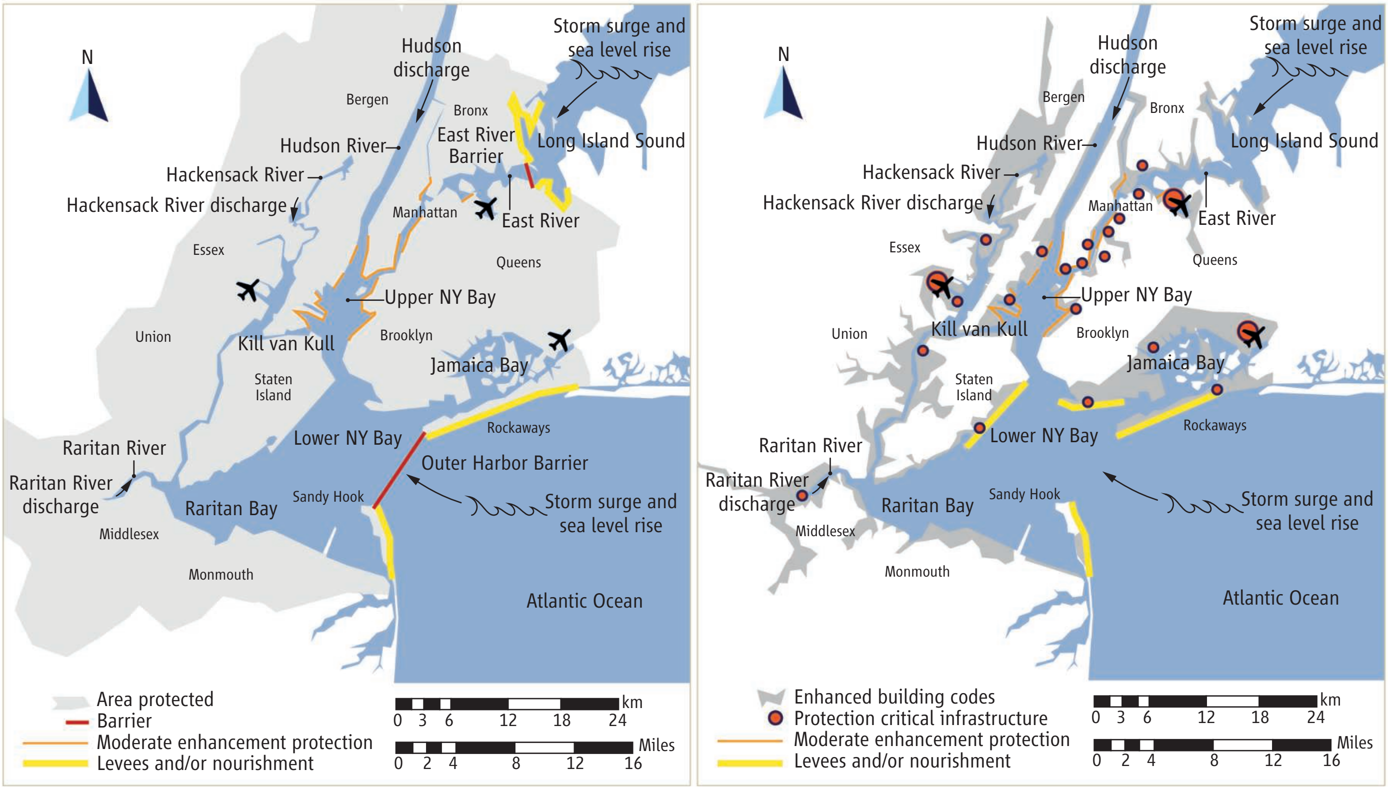
Published by AAAS



Strategies for protection vs. reducing vulnerability. (Left) Strategy S2c reduces the length of the coastline of the NYC-NJ area as much as possible, to minimize flood protection costs. Two storm-surge barriers are developed: one large barrier that connects Sandy Hook in NJ and the tip of the Rockaways in Queens, NY, and a barrier in the East River. Some lower spots (bulkheads, levees, or landfill) on the inside of the protection system will be elevated to accommodate rising water levels caused by Hudson River peak discharges during a storm event. **(Right)** Strategy S3 combines cost-effective flood-proofing measures with local protection measures of critical infrastructure. Such a "hybrid solution" aims at keeping options open: either (a) building codes can be enhanced in the future with additional local protection measures or (b) storm-surge barriers can be developed. See SM for details.

BCA by considering various scenarios of climate change and different assumptions about the discount rate (SM §2) and by propagating uncertainty in water depth and damage estimation (SM §1.9) into the final risk assessment. For the barrier strategies, often seen as an irreversible choice, we also tested different investment timings.

Combined investment costs for NYC and NJ are a maximum of $14.7 to $23.8 billion for S2, a, b, and c, and $11.6 billion for S3 (see the table) (*11*). Yearly maintenance costs are much higher for the barrier strategies than for S3. BCA results of different building-code strategies (S1) are given in the SM. Cost-effective strategies from S1 are incorporated into S3: elevation of new houses (4 feet or 6 feet, depending on flood zone) and wet flood-proofing (2 feet) of existing buildings.

None of the flood protection–barrier strategies is economically attractive [their benefit-cost ratios (BCRs) are less than 1] under current climate conditions or a low climate change scenario. S2c and S3 have a BCR higher than 1 in a middle climate change scenario. All barrier strategies and the hybrid strategy are, however, economically attractive if flood risk develops according to a high climate change scenario (rapid ice melt and significant increase in storm activity), with the highest net present value of $64 billion for S2c and $50 billion for S3 (SM §3.2). Investment strategies are slightly more economically attractive if a 150-year lifetime is used (SM §3.2).

For a given discount rate and climate scenario, there is inherent uncertainty in the models, which influences the BCA results (see the table). But, the impact of this within-scenario uncertainty on the results is smaller than the impact of selecting a different discount rate and/or climate scenario. The latter is particularly challenging for policy-makers because trends in climate change–caused flood risks are still highly uncertain (*16*, *17*).

Making Policies, Making Payments

Our study provides economic rationale for some measures proposed by the City of New York in (*9*). Implementing improved cost-effective building codes (parts of S3)—such as elevating new buildings and protecting critical infrastructure by including adaptation measures into maintenance works—is the most cost-effective strategy. Given the large existing building stock in NYC, this might only have marginal impacts if another hurricane occurs in the next few years though. A challenge with flood-proofing buildings is to incentivize those at risk to make such investments and to monitor compliance with building code regulations, which has been shown to be an important behavioral issue internationally.

BCA results of delaying investment in barriers by 25 years show that independent of the discount rate, it is economically effective to invest in a storm surge barrier system in 2040 if climate change develops according to the middle scenario; still this strategy needs to be studied now (SM §3.3).

Now comes the big policy question: Who should pay to make NYC (or any city) more resilient to future flood disasters? A small part of the investment costs of S3 will have to be paid directly by homeowners for flood-proofing their houses, whereas the largest costs of flood defenses are supposed to be paid by the city (through new taxes, increased debt or reallocation of the current budget). If estimated benefits to the rest of the United

States and the international economy of preventing future flooding of NYC are effectively captured though (positive externalities), costs could arguably be shared by city, state, and federal government and the private sector, which would mean that protection costs are distributed more widely. For instance, with more than 50 million tourists visiting the city every year, a simple $10 resilience fee—equivalent to the maximum September 11 airline security fee anyone traveling in the United States is now paying for a roundtrip ticket—could help. If the financial burden on the NYC budget is offset by such complementary funding and spread over time (for instance, by issuing a dedicated resilience bond paid back over 15 years), protecting the city becomes more financially appealing to local policy-makers.

	Where/ how much	Environ.dyn. S2a	Bay closed S2b	NJ-JY connect S2c	Hybrid solution S3
			Costs		
Total investment	NYC	$16.9–21.1 billion	$15.9–21.8 billion	$11.0–14.7 billion	$6.4–7.6 billion
Total investment	NJ	$2 billion	$2 billion	n/a	$4 billion
Total investment	NYC+NJ	$18.9–23.1 billion	$17.9–23.8 billion	$11.0–14.7 billion	$10.4–11.6 billion
Maintenance	NYC+NJ	$98.5 million	$126 million	$117.5 million	$13.5 million
			BCR for current climate		
BCR	4% discount	0.21 (0.11; 0.35)	0.21 (0.11; 0.34)	0.36 (0.18; 0.59)	0.45 (0.23; 0.73)
	7% discount	0.13 (0.07; 0.21)	0.12 (0.07; 0.20)	0.23 (0.12; 0.37)	0.26 (0.13; 0.43)
			BCR for middle climate change scenario		
BCR	4% discount	1.32 (0.67; 2.16)	1.29 (0.65; 2.11)	2.24 (1.14; 3.67)	2.45 (1.24; 4.00)
	7% discount	0.60 (0.30; 0.98)	0.60 (0.30; 0.97)	1.06 (0.54; 1.74)	1.09 (0.55; 1.78)

Costs and main BCA results of flood management strategies.(**Top**) Total costs. Environ. dyn., environmental dynamics; inv., total investment as billions of U.S. dollars; maintenance, maintenance costs as millions of U.S. dollars per year; n.a., not applicable. (**Bottom**) BCA results with modeling uncertainty as 95% confidence intervals (in parentheses). If BCR > 1, then the measure is cost effective. For S3, BCA results are shown for the scenario of high effectiveness of wet flood-proofing. See SM for details.

Additional policies are needed to support the involvement and commitment of stakeholders to flood resilience. Enhancing financial protection is critical, too. That 80% of households and 95% of small businesses in the area inundated by Sandy did not have flood insurance is disturbing, as it is available from the federal government at a subsidized rate for many. Recent legislation passed by the U.S. Congress phases out some of these subsidies over time, which is likely to make investment in risk-reduction measures even more appealing in order to lower the cost of more expensive flood insurance (*3*, *9*, *18*).

Physical and financial protection can also be linked creatively. For example, the U.S. federal government provides premium reduction for residents in a community that actively participates in the Community Rating System program, which requires specific flood resilience activities. About 1300 communities participate today; NYC does not as yet.

Transferability to Other Coastal Cities

Elements of our methodology are applicable for coastal megacities around the world, where flood resilience plans are currently debated (*19*). Many strategies that were implemented have thus far been the result of long learning-by-doing processes, such as elements of large-scale flood protection that have been employed with substantial economic and environmental benefits in the Netherlands (*20*). International examples can serve as an inspiration for designing effective flood resilience policies elsewhere (*21*), but flood risks and management approaches require location-specific analysis.

Climate and hydrological models for creating flooding scenarios are available at research institutes and meteorological services, but often need to be tailor-made for application at the regional or city level. In estimating risks from flooding scenarios, cities play an important role as they have access to (spatial) data on the assets—such as buildings, infrastructure, and environmentally protected areas—and socio-demographics of flood zones. Catastrophic modeling expertise from the insurance industry can be useful for cities, and new knowledge partnerships are needed between city agencies, research institutes and private sector specialists (*22*). The "100 Resilient Cities" challenge of the Rockefeller Foundation, the Zurich Insurance's "Flood Resilience Alliance" initiative and the European "Enhance program" on managing natural hazards are excellent examples of the initiation of such new partnerships (*23*–*25*).

In order to better inform decision-makers about the robustness of their investment choices, scientists have to accompany BCAs with a broad range of (future) scenarios, different discount rates, and an interval of model outputs representing model uncertainty and sensitivity results. It is also important to maintain the flexibility to change policies when new information on future scenarios becomes available (*26*). Most BCAs address one of these issues in isolation, and we recommend that all should be included in an integrated analysis. Uncertainty is inherent to such estimations, but it should not be used to justify not doing anything.

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Acknowledgments: See the supplementary materials for funding sources.

Supplementary Materials

www.sciencemag.org/content/344/6183/473/suppl/DC1

10.1126/science.1248222