aftershocks

Remodeling the Past for a Resilient Future

Quetzalcoatl, Aztec god of wind and wisdom

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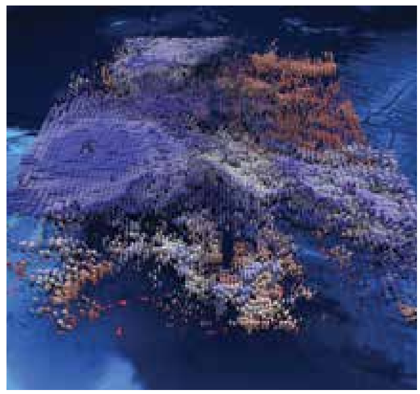


"THE PAST IS NEVER DEAD. IT'S NOT EVEN PAST."

—William Faulkner

FOREWORD

With the words of Faulkner in mind, we might argue that the disasters of the past are not past, as long as they have something to teach us.

The Global Facility for Disaster Reduction and Recovery (GFDRR) conceived of this publication as a thought exercise: what would the effects be if some of the iconic disaster events of the past were to happen in today's world? How have our actions mitigated or exacerbated their potential impacts? What if Mount Vesuvius erupted today, close to the heart of a modern European city? Or if Typhoon Wanda, which hit Zhejiang Province in China in 1956, were to strike again in the same area—now home to the world's third biggest conurbation, and more than 50 million people? To answer these questions, we turned to risk modeling.

Risk modeling distills earth sciences and technical knowledge into analysis of the potential impacts of adverse natural events, expressed in terms of casualties, damage to assets and infrastructure, or monetary loss. It is not an exact science, but when thorough and based on sound assumptions and analysis, it can provide useful insights and direction for action. Within this framework, scenario studies that reexamine possible consequences of past disasters can help guide interventions to address problematic development patterns.

Some of the events examined in these pages—for example, the 1815 eruption of Mount Tambora, or solar flares on a scale of the Carrington event of 1859—could have tremendous consequences if they happened in today's exponentially more populous and connected world, with massive loss of life and major disruptions to transport, communications, and commerce. As the 2011 Tohoku earthquake and tsunami demonstrate, events of this scale will always be with us. Modeling helps us imagine the potential impact of such events. Most of the disasters you will read about are comparatively recent—like the earthquake in Mexico City on September 29, 2017, which struck on the anniversary of the far more devastating 1985 earthquake. The reanalysis of such events creates an opportunity to disentangle cause and effect, providing essential information for future mitigation strategies.

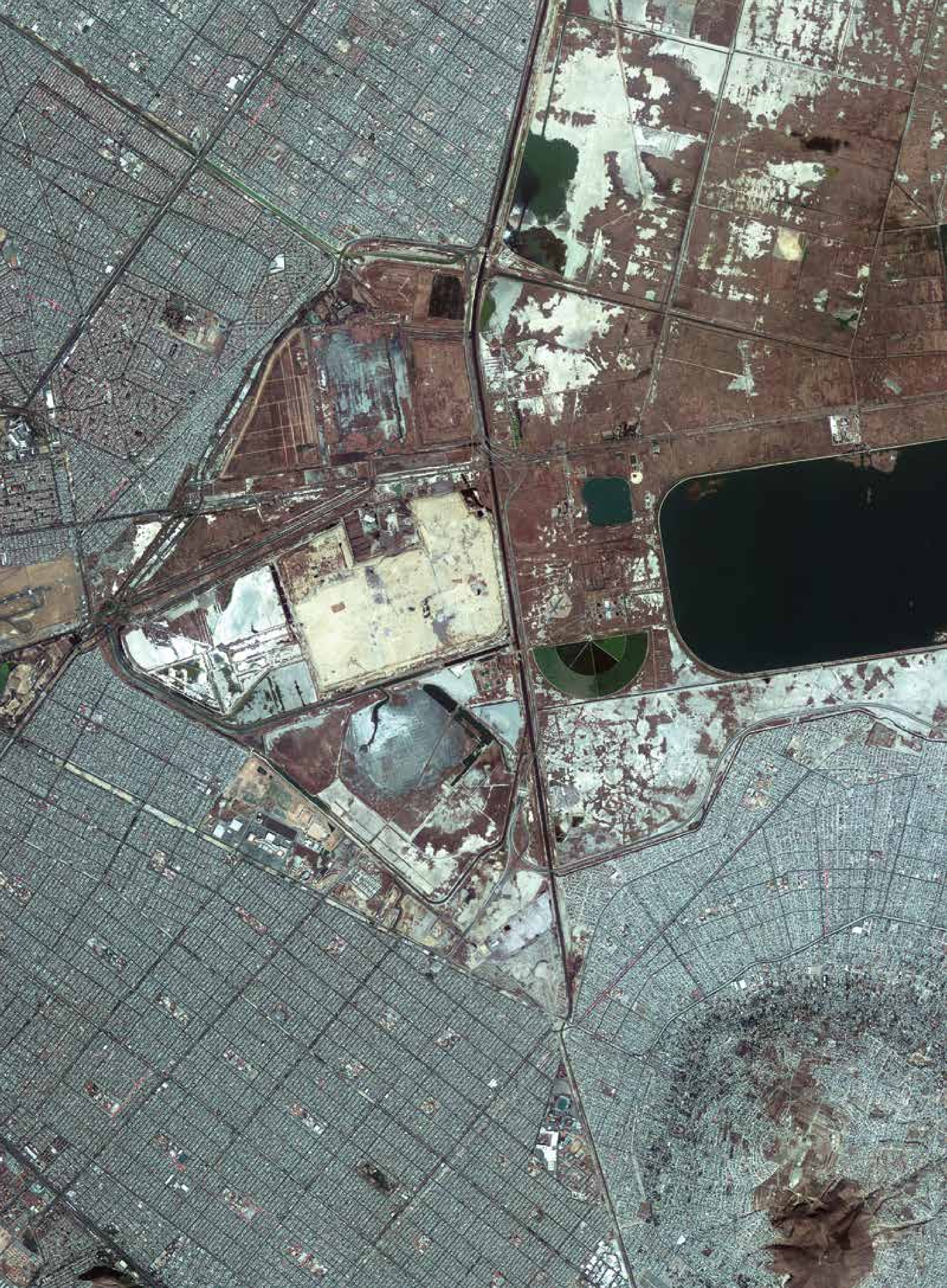
Disasters are of course inherently challenging to model, with uncertainties in what determines the probability of extreme events, and the need to understand all the potential causes and weaknesses leading to the losses. The challenges of risk modeling are great, but the rewards are significant. It provides valuable input in diverse areas, from the establishment of early warning systems to urban planning, from preparedness to financial protection and better recovery. It produces risk information that may be used across multiple sectors, from global supply chains to small-scale local agriculture, as examples from Thailand and Madagascar respectively illustrate.

As the world's population continues to grow, and to urbanize, so too does its exposure and vulnerability to hazards. With climate change, some of the hazards we face are also becoming more frequent, more intense, and more unpredictable; and the combination of these factors has the potential to increase risk exponentially. The scenarios in this publication remind us of the urgency of integrating better risk management and climate adaptation in all development programs. By fostering resilience through measures like improved building practices, better land use planning, and poverty reduction, we can strive to reduce the vulnerability of infrastructure and communities.

I personally would like to thank the team that led the work on this publication, as well as the partners who provided the model results used. The Disaster-Resilience Analytics and Solutions (D-RAS) team of the World Bank provided risk model results for six of the case studies we drew upon, and colleagues from AIR Worldwide, ERN, and JBA Consulting provided information on some of the other disasters modeled.

The past can be a powerful tool. As the stories you will read in these pages demonstrate, we need to learn its lessons, and apply them to plans for a better, more resilient future.

Francis Ghesquiere
Head, GFDRR Secretariat



OVERVIEW

Aftershocks aims to provide readers with an accessible look at what would happen today if we were to experience some of the iconic disasters of the past. The pages that follow look at how risk modeling can be used to analyze natural events that led to the major disasters of the past, and to understand how these events might impact today's more populous and connected world.

The events included in this publication were selected to represent a range of regions and hazards, and to illustrate the evolution of exposure and how vulnerability translates into risk. They were also chosen to illustrate the impacts of disasters on a range of sectors, including agriculture, infrastructure, the supply chain, and—in the case of the Carrington event—the vulnerable "digital cocoon" in which we have encased the world. Finally, the events were chosen to highlight diverse areas of engagement in disaster risk management.

The case studies of the earthquakes in both Chile and Haiti, for example, show the benefits of building back better after a disaster by analyzing the impact of improved building code enforcement and resilient urban planning to mitigate the impact of future events. The damage from Typhoon Wanda demonstrates both the impact of natural hazards on a rapidly growing economy and the benefits of effective risk identification and early warning systems. The two earthquakes in Mexico City illustrate the importance of integrating multiple areas of risk management, from risk identification and preparedness to civil and financial protection.

Most of the disasters documented here took place in the developing world, where population growth, rapid urbanization, and climate change are heightened, and where the impact of adverse events is exacerbated by the vulnerability of poorer communities, who are disproportionately impacted by disasters. This report makes the case for renewed support to the poorest of the poor.

This report is also part of an effort to bring about a better understanding of risk to a wider audience and community of practice. However, reporting in this publication is by no means comprehensive, and readers who prefer greater detail or a more technical account of the events described can consult the risk profiles and detailed analyses that are linked to the online version. Readers are also directed to the bibliography (p. 63).

Most of the disasters documented here happened in the recent past. Adverse natural events of a significant magnitude happen all the time, and will happen again. By 2050, population growth and rapid urbanization could put 1.3 billion people and $158 trillion[1] in assets at risk from river and coastal floods alone[2]—a reminder that the integration of risk management in our development programs is an urgent imperative. ◎

[1] All dollar amounts in this report refer to U.S. dollars.

[2] Jongman et al. Global Exposure to River and Coastal Flooding: Long Term Trends and Changes.

Mexico City, 2012. Photo: ESA

The Last Days of Pompeii by Karl Bryullov, 1830–1833. Image: Wikipedia

THE POWER OF HINDSIGHT

What If Vesuvius Erupted Today?

The eruption of Vesuvius in 79 AD destroyed two cities, claimed at least 1,500 lives, and left a vivid snapshot of a past disaster for posterity. What if the volcano erupted today, in an urbanized and connected world? Risk modeling can help assess the likely losses and guide actions that might mitigate the risk.

It is estimated that the eruption at times produced a column of ash 32 km tall, and that about 4 km^3 of ash was erupted in about 19 hours.

"You might hear the shrieks of women, the screams of children, and the shouts of men; some calling for their children, others for their parents, others for their husbands, and seeking to recognize each other by the voices that replied; one lamenting his own fate, another that of his family; some wishing to die, from the very fear of dying; some lifting their hands to the gods; but the greater part convinced that there were now no gods at all, and that the final endless night of which we have heard had come upon the world."

—Pliny the Younger, on the eruption of Vesuvius

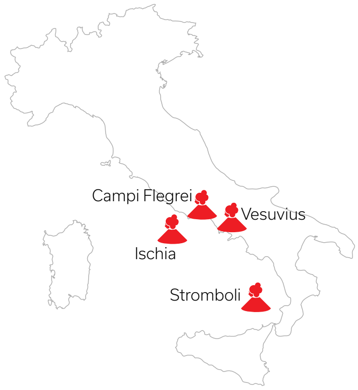
Ash-encapsulated remains of some of the victims of the Vesuvius eruption of 79 AD. Photo: © Floriano Rescigno | Dreamstime.com

Facing page: Aerial view of Mount Vesuvius with densely populated communities surrounding it. Photo: © DigitalGlobe

For a disaster that happened almost 2,000 years ago, the tragedy still seems fresh and poignant. The figures of Pompeiians preserved in volcanic ash—working people, families with children, even household pets—are evidence that things were not so very different then. The buildings, the preserved artifacts, and the murals all show a perfectly ordinary Roman town going about its business on a day like any other, oblivious to the impending cataclysm, and unprepared for disaster.

This lack of preparedness was not due to lack of interest in the natural world and its processes. Fifteen years before the eruption of Mount Vesuvius in 79 AD, the philosopher Seneca, advisor to the emperor Nero, had written on the causes of earthquakes in his *Naturales quaestiones*. He thought it likely that earthquakes in different parts of the world were interconnected, and even wrongly suggested that they were linked to stormy weather, but he drew no link with volcanic activity. Pliny the Younger experienced the eruption of Vesuvius and wrote an account of the death of his uncle—Pliny the Elder—in the eruption. Pliny the Elder had himself been the most

The volcanoes monitored by the Vesuvius Observatory



Monitoring room of the Vesuvius Observatory in Naples. The observatory monitors the activity of all the Campanian volcanoes (Ischia, Vesuvius, and the Phlegraean Fields, as well as Stromboli). Photo: Salvatore Laporta/KONTROLAB /LightRocket via Getty Images.

The Vesuvius Observatory, founded in 1841 on the slopes of the volcano but now situated in Naples, is the oldest volcanological observatory in the world.

Pliny the Younger

notable scientist and naturalist of his age, but he had failed to see the significance of seismic activity in the weeks leading up to the eruption.

The younger Pliny's descriptions of the eruption in the two letters to Tacitus are finely observed. "A cloud . . . was ascending," he writes,

the appearance of which I cannot give you a more exact description of than by likening it to that of a pine tree, for it shot up to a great height in the form of a very tall trunk, which spread itself out at the top into . . . branches; occasioned, I imagine, either by a sudden gust of air that impelled it, the force of which decreased as it advanced upwards, or the cloud itself being pressed back again by its own weight, expanded in the manner I have mentioned; it appeared sometimes bright and sometimes dark and spotted, according as it was either more or less impregnated with earth and cinders.

It is estimated that the eruption at times produced a column of ash 32 km tall, and that about 4 km^3 of ash was erupted in about 19 hours. Initially up to 3 m of tephra and pumice fell on Pompeii, followed by up to 1.5 m of extremely hot pyroclastic flow (also known as glowing avalanches), followed in turn by up to 1.5 m of tephra and pumice again. Eventually everything was buried except the roofs of some two-story buildings, while the port town of Herculaneum was buried under 20 to 23 m of extremely hot pyroclastic flow deposits. It is believed that the destruction of life and property was principally

due to the pyroclastic flows, whose extremely dangerous effects were not well understood at the time.

The Vesuvius Observatory, founded in 1841 on the slopes of the volcano but now situated in Naples, is the oldest volcanological observatory in the world. Run by the National Institute of Geophysics and Volcanology, it monitors all of the Campanian volcanoes (Ischia, Vesuvius, and the Phlegraean Fields, as well as Stromboli), enabling long- and short-term forecasting. The observatory monitors seismic activity, ground deformation, and gravimetric and magnetic field variations, as well as changes in the composition and temperature of the gases emitted from fumaroles, soil, and groundwater.

While the observatory can provide early warning of an impending eruption, it is through volcanic eruption modeling that we can gain a realistic sense of what would happen should Vesuvius erupt today. Such an eruption is by no means impossible. An eruption in 1631 killed over 3,000 people. Vesuvius's last eruption phase started in 1913 and culminated in March 1944, when it destroyed the villages of San Sebastiano al Vesuvio, Massa di Somma, Ottaviano, and part of San Giorgio a Cremano. An earlier eruption, on April 5, 1906, killed more than 100 people, ejected the most lava ever recorded from a Vesuvian eruption, and caused the 1908 Olympic Games to be held in London instead of Rome due to financial difficulties.

At present, around 1.7 million people live in the potentially affected area, with the value of properties at risk in excess of $80 billion. According to Italy's Department of Civil Protection, 25 separate towns would be at risk in the event of an eruption, and plans are in place for the evacuation of as many as 700,000 people. Without these preparedness plans, informed by detailed risk models, the risk to life would be substantially worse.

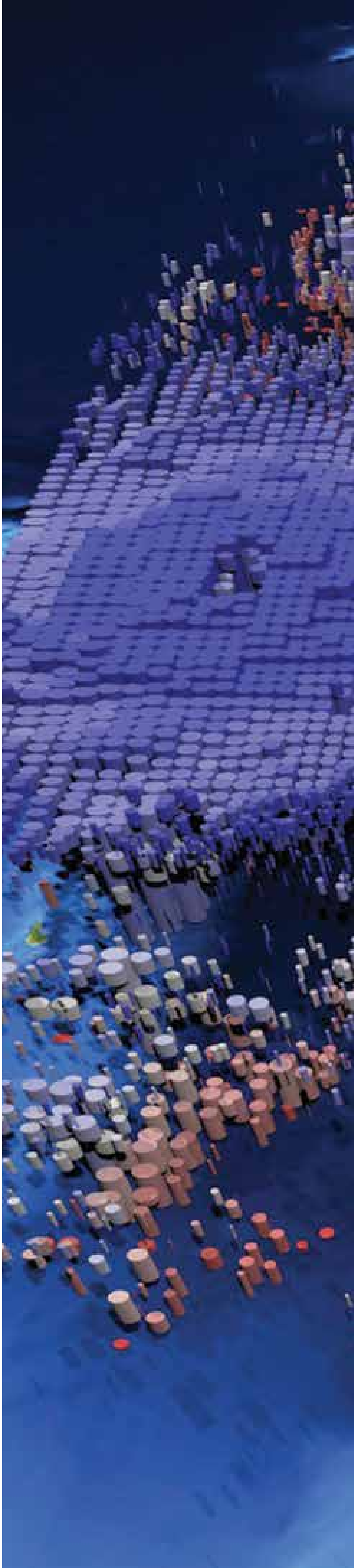
According to a 2009 Willis Research Network report, a major eruption of Vesuvius today—modeled on an approximation of the 1631 eruption—could result in 8,000 fatalities, 13,000 serious injuries, and total economic losses of more than $17 billion (2008 values).

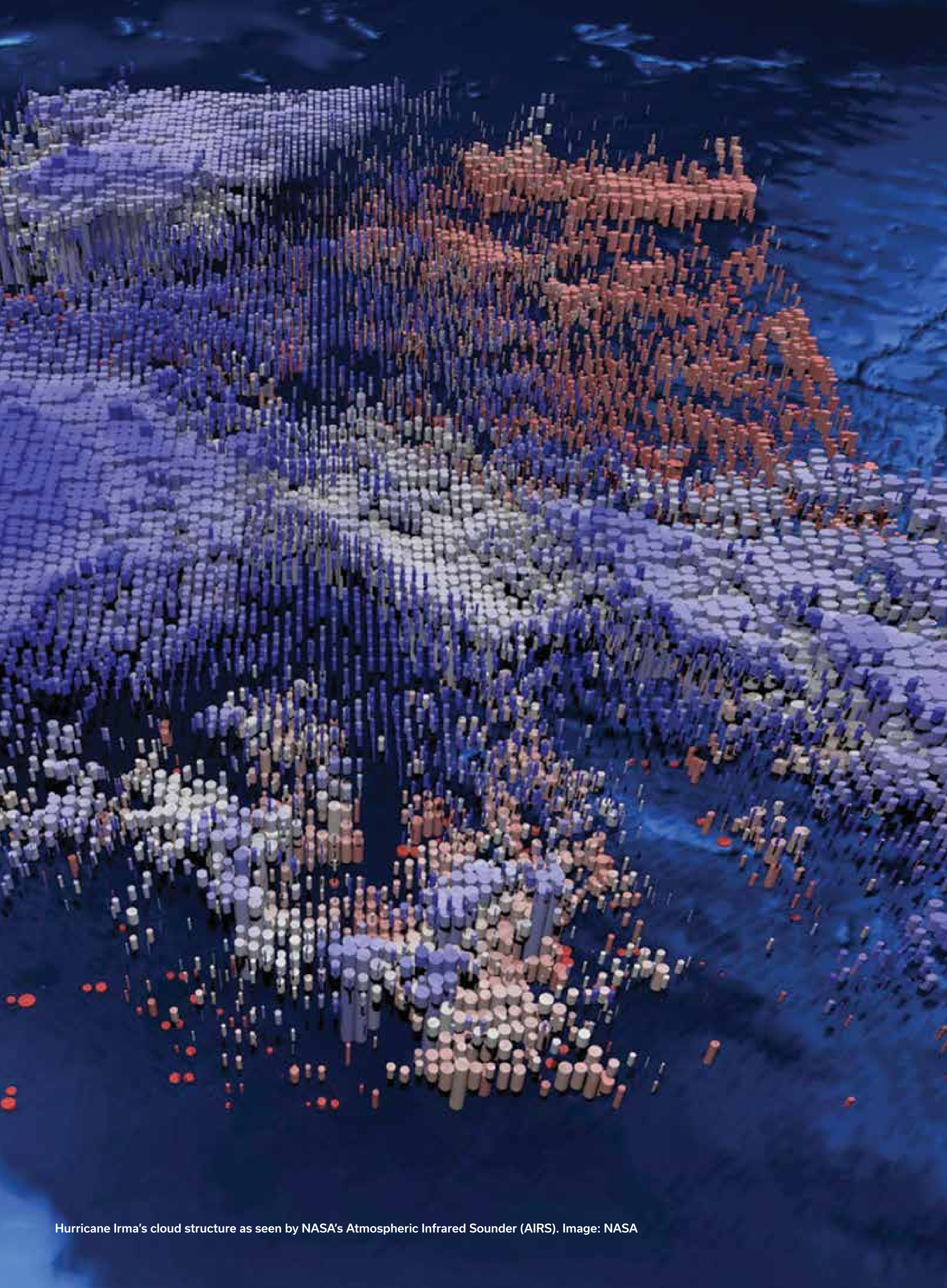
Visitors to Pompeii see the story of Vesuvius written in the ash and the ruins. The story of a new eruption could well be written in numbers like these. ◎

BUILDING ON EXPERIENCE

Risk Modeling

By understanding the possible effects of past disasters in today's world, we have a better chance of mitigating the impacts of future events. One of way of doing this is through the lens of risk modeling, which explains risk as a function of hazard, exposure and vulnerability.





Hurricane Irma's cloud structure as seen by NASA's Atmospheric Infrared Sounder (AIRS). Image: NASA

Risk models are created using a combination of science, technology, engineering knowledge, and statistical data to simulate the potential impacts of natural and man-made hazards. The interaction of the hazard event with the exposed population and assets (or built infrastructure) determines its impact. More specifically, the amount of damage experienced in an event is estimated using vulnerability relationships that translate the event intensity (e.g., wind speed or flood depth) and asset characteristics (e.g., construction type, year built, building height, etc.) into scale of damage.

Risk modeling requires that the scale and resolution of hazard, exposure, and vulnerability data are appropriate for the problem of interest. It also calls for the creation of multidisciplinary, multi-institutional platforms and the establishment of nontraditional partnerships around the technical analysis.

Hazard: What could happen?

A hazard is a *potentially destructive physical phenomenon* (e.g., an earthquake, a windstorm, a flood), and its *likelihood* is an essential measure in the quantification of risk. Once the hazards of interest are defined, the next step often involves acquiring a variety of hazard-related data. The most fundamental data define historical events, in particular their date, geographical location and extent, and maximum intensity.

When used probabilistically, risk models estimate the likelihood of extreme events and the probable severity of their impacts. The models simulate hazard events that occur over periods ranging from tens to hundreds of thousands of years. Overall, the simulated hazards have statistical characteristics that are consistent with observations from the historical record, and they are designed to include a wide range of possible hazard events, including those that aren't in the historical record.

When used deterministically, risk models simulate a single event, but multiple realizations of an event are used to account for uncertainty in spatial distribution and intensity. For example, there may be only a few accurate and precise measurements of an historical hazard event, but the complete spatial distribution of the event is needed to assess its impact on the exposed assets.

We need data on the various factors that influence a hazard in order to generate a hazard catalog. Knowledge of the distribution of soil types, for example, is required to model the spatial variation of ground acceleration (shaking) from an earthquake; values for surface roughness are needed to define the distribution of wind speed from a tropical cyclone; and topographic data from a digital elevation model (DEM) are needed to determine flood depth.

Exposure: What could be damaged?

Exposure describes the *location, attributes, and value of assets*—which for the purposes of this definition includes people—that are important to communities and that could potentially be affected by natural hazard events. Exposure modeling techniques have been developed to describe the distribution of multiple types of exposure at various geographic scales, from global to local. Global scale modeling tends to take a top-down approach, with work being carried out by governments or large institutions, whereas local scale modeling works from the bottom up by methods such as crowdsourcing and in situ surveys.

Data sources for exposure modeling might for example include household surveys, aerial photos, and architectural drawings at a local level; GIS data, investment listings, and business listings at a regional and provincial level; and census data, global databases, and remote sensing at a national level or above.

Vulnerability: How bad could the damage be?

Vulnerability describes the *characteristics that determine how susceptible exposed assets* are to the effects of a hazard. Methods of assessing damage vary greatly depending upon a number of factors. The first is the type of exposure under consideration; people, buildings, and livestock, for example, are susceptible to very different types of damage. The second is the resolution of the exposure information; damage information based on fine-grained site-specific data will differ from damage information for coarser aggregate data (at postal code resolution or lower). The method of assessing damage depends finally on the details available for a given resolution; the method used when detailed structural information is available will differ from that used when just occupancy is known.

Vulnerability functions are used to estimate the severity of damage, or probability of a certain level of damage, being sustained by a type of structural asset when exposed to a given intensity of hazard. Vulnerability indexes are also used to describe impacts on population or environment by relating hazard intensity to various measures of damage suffered by the population or system of interest.

Loss metrics: What is the potential loss?

The damage to each asset affected by an event is combined with all others to determine the total impact for an event. If the model is being used deterministically and there are multiple realizations of a single event, then the distribution of losses is a function of the uncertainties around the hazard characteristics. If a model is being used probabilistically, then losses from all the events in a hazard catalog are used to define a variety of statistical measures such as the average loss expected each year.

For a variety of reasons, modeled losses based on the simulation of a single event often differ from observed losses actually produced by the event—for example, modeled losses represent only losses that are captured by the model, and these losses depend upon the quality of the exposure data, the way that event intensity is modeled, and the quality of the vulnerability information. In reality, losses are often adjusted for a variety of additional factors, such as the need to replace a structure if damage exceeds a certain threshold or to account for business interruption costs for commercial or industrial properties. Another consideration is that actual loss data are difficult to collect in a comprehensive and accurate manner.

Better records of disaster losses would be extremely useful for managing disaster risk. To meet the need for more complete and systematic disaster information, the United Nations Office for Disaster Risk Reduction (UNISDR) developed the open source Sendai DesInventar Disaster Information Management System, a tool designed to systematically analyze disaster trends and impacts, and thereby help guide actions to reduce the impact of disasters on the communities.

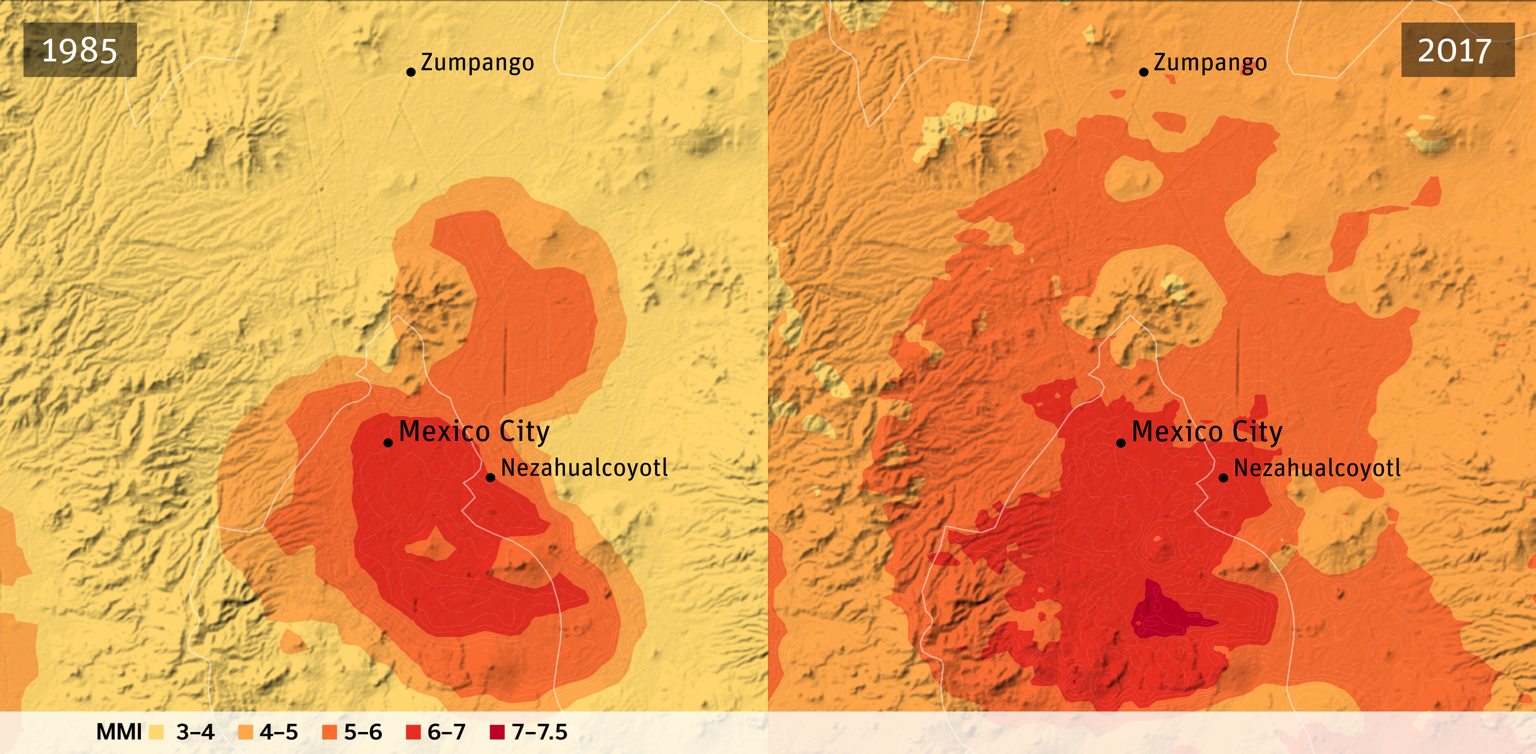
Different approaches can be used to estimate the uncertainty of modeled losses, and these uncertainties apply to the specific model used. Thus, in an ideal case, multiple models are used to estimate disaster risk. Using multiple models allows us to better represent—and make decisions in light of—the uncertainty in estimated loss. This includes the uncertainly due to our incomplete knowledge of hazard, vulnerability, and exposure data, but also the uncertainty introduced by our chosen modeling approaches. ◎

Mexico: Aerial view of rescue workers at the site of a collapsed building after the September 2017 earthquake in Mexico City. Photo: Manuel Velasquez/Anadolu Agency/Getty Images

FAULT LINES

The Mexico City Earthquakes of 1985 and 2017

A comparison of the earthquakes that hit Mexico City in 1985 and 2017 shows that much has improved since the first disaster. Remodeling the 1985 event helped identify buildings that were susceptible to damage in future events.



Shake maps showing the relative ground motions in terms of Modified Mercalli Intensity (MMI). Maps: USGS and Axis Maps

The 1985 Mexico City earthquake struck shortly after seven in the morning of September 19. It originated in the Pacific Ocean just off the coast of Michoacán state in the area of the Rio Balsas estuary, with its epicenter nearly 400 km away from Mexico City. This was a major earthquake, with a magnitude of 8 at a depth of just under 20 km. For a number of reasons, it was an historically devastating event for the capital.

Much of central Mexico City is built on Lake Texcoco's ancient, drained bed, whose poorly consolidated soils can cause an amplification effect of low-frequency ground motion during strong distant or deeper earthquakes. It was these low-frequency seismic waves that affected Mexico City the most, because of the distance from the source—most high-frequency ground motion in an earthquake is filtered out at relatively short distances from the epicenter. The 1985 earthquake demonstrated with great clarity the danger that distant earthquakes pose to medium- and high-rise buildings constructed on poorly consolidated soils, which amplify the type of ground motion to which they are already susceptible due to their longer period of vibration.

The earthquake shook the parts of Mexico City built on the old lakebed for over three minutes with strong seismic waves that repeated every to two to three seconds, while in the hilly parts of the city people barely perceived the motion. During the quake itself and the powerful (Mw 7.6) aftershock that occurred 36 hours later, 2,177 buildings were damaged to the extent that they were deemed not repairable, and 859 collapsed completely or partially, trapping thousands under the rubble.

Most of the collapsed structures were reinforced concrete framed buildings of between 6 and 15 stories, and most of them had been built prior to the 1976 Mexico earthquake code. Some of these buildings represented vital infrastructure: the partial collapse of the Ministry of Communication and Transportation with its tall microwave tower effectively cut off long-distance communications between Mexico City and the rest of the world. Thirteen hospitals were partially or totally destroyed, with the loss of one in four available beds. Two major hospitals—Juarez and General—collapsed entirely, causing the loss of 890 lives. Water and electricity supply and public transport were widely disrupted.

The destruction of two massive apartment blocks in the Tlatelolco housing complex was a particularly egregious loss, accounting for a part of the 30,000 residential units lost across Mexico City. The 13-story Nuevo Leon apartment block collapsed completely, killing

468 people. "I turned toward the Nuevo Leon and I saw that it was collapsing, first like a sandwich, and then twisting and falling," reported Cuauhtemoc Abarca, a neighborhood leader at the time. "I saw but couldn't believe it, and then a cloud of dust went up." It was believed at the time that somewhere between 10,000 and 13,000 lives were lost, although the official toll in 2015 puts the number at 7,500. Around 4,000 people were pulled out alive from the rubble. Damages were estimated at $4 billion in 1985 prices.

Building back better

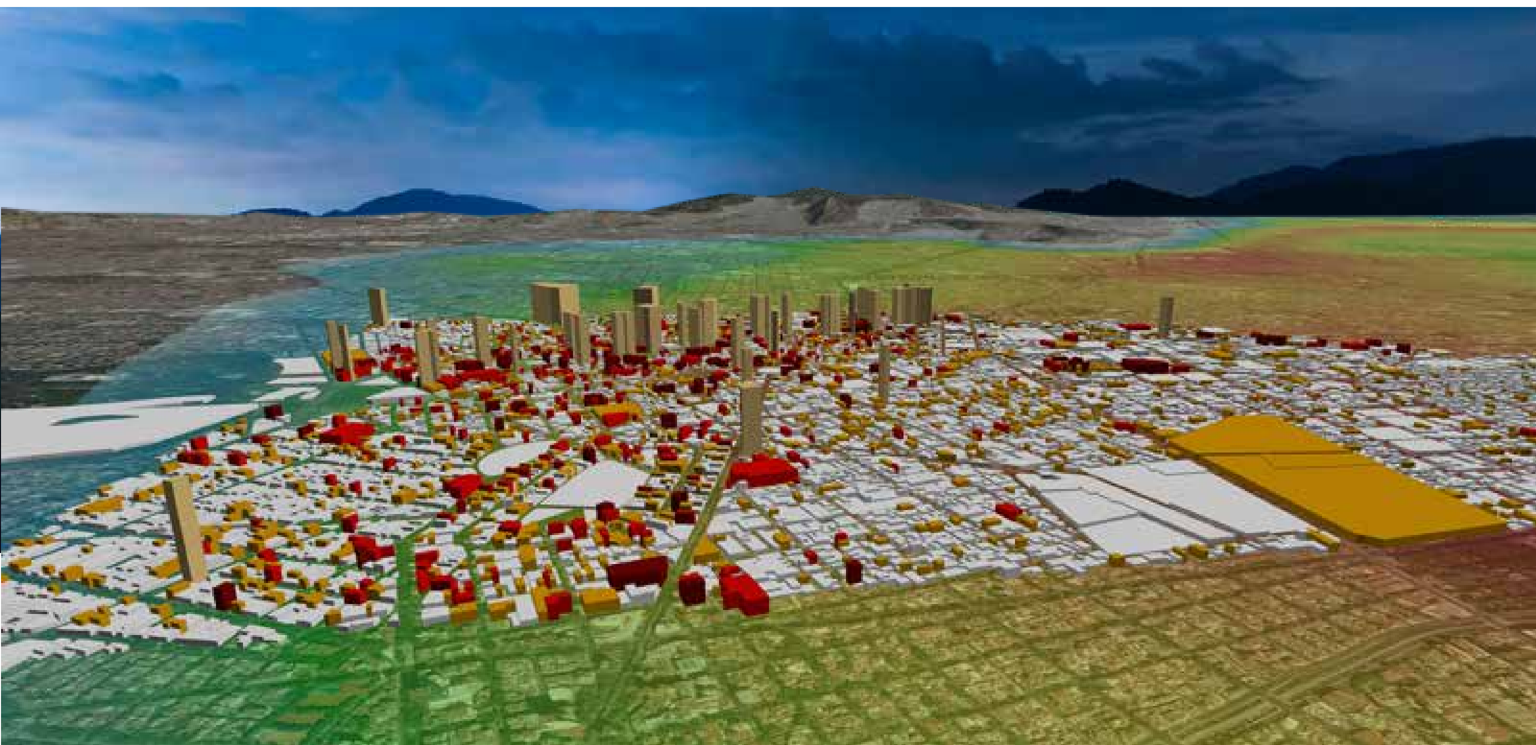
The damage and losses from the earthquake prompted the city to take some significant steps to mitigate the effects of future disasters. Mexico's National System for Civil Protection (SINAPROC) was established in 1986, the year following the earthquake. Initially designed to improve Mexico's planning, response, and recovery capacity, SINAPROC has evolved to focus on building an end-to-end disaster risk management system encompassing risk identification, prevention, reduction, and financing as well as post-disaster reconstruction. In 1988, Mexico established its National Center for Prevention of Disasters (CENAPRED), a federal agency tasked with warning citizens about possible disasters.

Mexico City's building code, established in the 1940s and repeatedly modified over the years, underwent significant changes in response to the 1985 earthquake. The code has proved an excellent first line of defense against earthquake damage, and has been used as a template for other codes, both within the country and abroad. However, like codes elsewhere in the world, it is not always adequately enforced. In 1995 Roberto Meli, director of CENAPRED, suggested that poor enforcement would eventually come to light: "The next temblor will be in charge of identifying where things were badly done," he said.

Modeling future losses

Rather than relying on an earthquake to identify poor building code enforcement, however, Mexico City took action on its own. In 2015, ERN, a

Map of expected damage (white, low damage; red, large damage) in downtown Mexico City due to an a Mw 8.0 earthquake in the subduction zone. The intensity map is also shown from blue (hill zone) to red (large amplification lakebed zones). Image: ERN



Tenochtitlan and Gulf of Mexico, 1524. Image: Wikimedia Commons

FATED TO FALL

Mexico City was originally built by the Aztecs on an island in the middle of Lake Texcoco, which was later drained by the Spanish to prevent flooding. The silt on which part of the city rests has a high water content, and the soft sediment resonates when affected by low-frequency seismic waves, such as those that reached the city from the distant earthquake in 1985. The motion of the sediments was amplified by this resonance, causing greater shaking on them; this shaking in turn had a particularly damaging effect on buildings of 6–15 stories, because those buildings also experience resonance at the same low frequencies. While Mexico City is not situated in the direct vicinity of a fault line (unlike San Francisco or Los Angeles), Mexico itself is located on the confluence of the North American, Cocos, and Pacific tectonic plates, whose movement against each other causes more than 90 tremors every year. The presence of soft lake sediments means that Mexico City could again experience amplified ground shaking during earthquakes that occur on these distant faults.

Mexican consultancy specializing in the evaluation of natural risks, conducted a survey of 150 buildings in Mexico City to assess their compliance with the code. The survey found that over 30 percent of the buildings did not comply with the regulations. ERN also built a model predicting future losses according to building type for an earthquake similar in magnitude to the 1985 event—an essential tool for businesses and institutions seeking to mitigate future loss in an urban area.

At the time of the 1985 earthquake, the extremely large amplification effect of the ancient lakebed was not fully anticipated, although it had been observed during the Mw 7.6 earthquake of July 28, 1957. “The engineers at the time did not know that the amplification of the motion was going to be that large,” says Dr. Eduardo Reinoso of ERN. “Nobody in the world did. This effect is now included in the models, and the code, so that there are no surprises.”

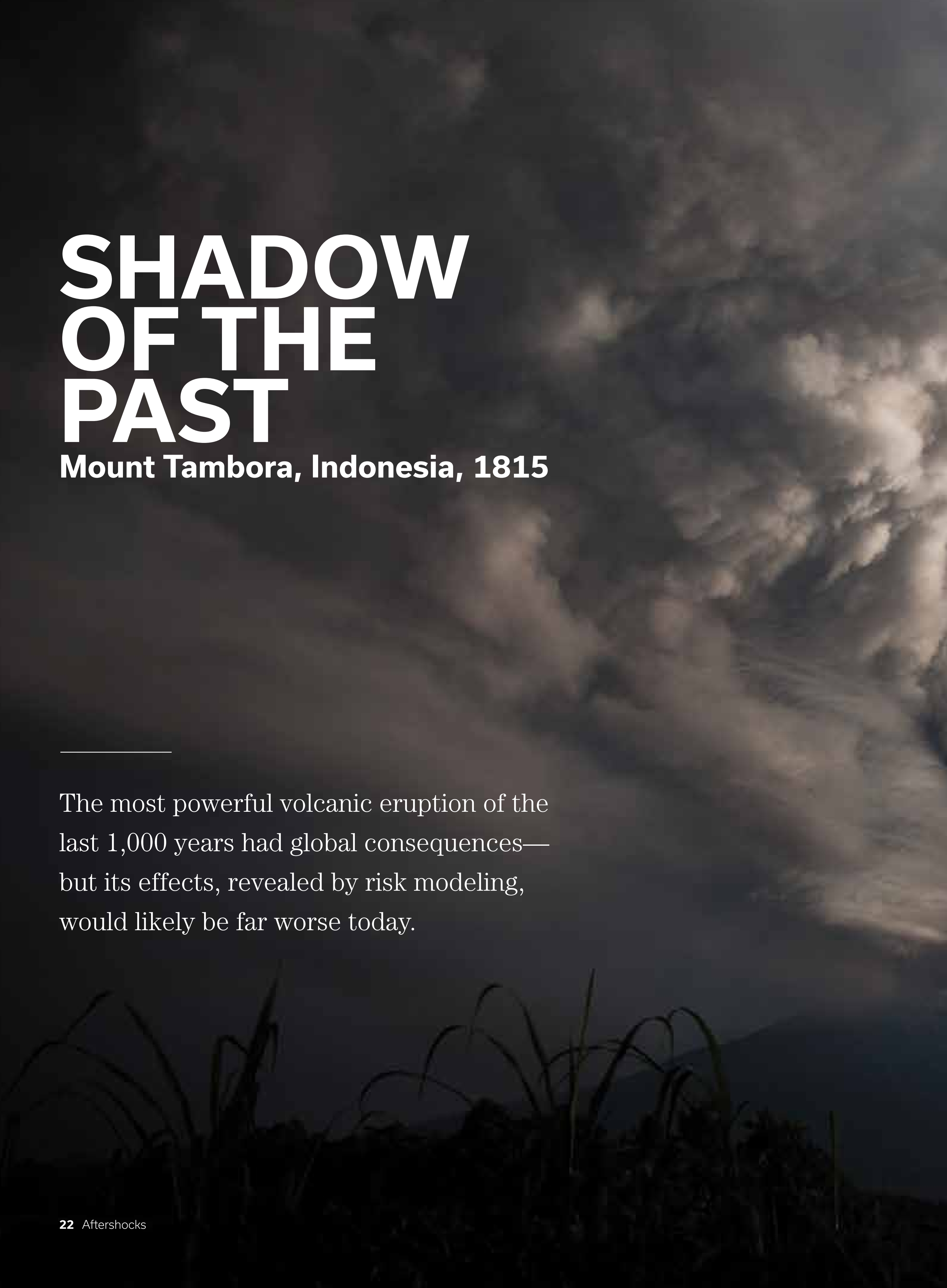
Testing the model

Occasionally, a risk model will be tested by an actual disaster. In 2017, 32 years to the day after the disaster of 1985, central Mexico was struck by an intermediate-depth earthquake of magnitude 7.1 and about 55 km deep—just two hours after an earthquake preparedness drill had been conducted in Mexico City. According to the Mexican Seismic Alert Early Warning System (SASMEX), residents received advance warning of 20 seconds as the epicenter was 120 km to the south-southeast of the city; some people reported that the warning time was less than that, while many believed the warning was simply part of the earlier drill.

The earthquake was again felt strongly on the old lakebed of Mexico City and caused the collapse of more than 30 buildings across the city. It killed 370 people, including 228 in Mexico City and 34 in the city of Puebla. Some of the characteristics of the collapsed structures had been identified as vulnerabilities in the ERN survey, and much of the damage followed the patterns identified in the risk model. “We already knew that these types of buildings were not going to behave well, and it is going to happen again in the future. The problem is it is expensive to mitigate the risk,” says Dr. Reinoso.

Overall, however, the September 2017 earthquake suggests that Mexico City’s implementation of the building code regulations (introduced in 1987, 1993, and 2008) had improved the resilience of the city, reducing significantly the number of lives lost and buildings damaged, although detailed analysis comparing the two earthquakes is yet to be completed. More work remains to be done to further improve buildings’ resilience. Much of the damage of the 1985 earthquake was caused by poorly designed or executed construction, in a city which at the time was the fastest growing in the world.

Rapid visual screening surveys on the ground can provide block-by-block information on high-risk structures, informing risk modeling and decision making and in turn building resilience into the city’s future growth.◎



SHADOW OF THE PAST

Mount Tambora, Indonesia, 1815

The most powerful volcanic eruption of the last 1,000 years had global consequences—but its effects, revealed by risk modeling, would likely be far worse today.

The eruption of Mount Agung, Bali, Indonesia, November 2017. Photo: Muhammad Fauzy/NurPhoto via Getty Images

In the early evening of April 5, 1815, the volcano Mount Tambora on the Indonesian island of Sumbawa began to erupt in a series of explosions that could be heard 1,200 miles away. After a lull in activity, a second and even stronger eruption occurred five days later, lasting until the evening of the 11th; by this time the top 3,000 feet of the mountain, then a graceful cone like Mt. Fuji in Japan, had collapsed into a caldera that is today 6 km across and 1 km deep.

The second eruption sent a plume of ash 20 km into the atmosphere and blocked out the sun across an 800-km area for at least two days. Forty-eight hours after the second eruption, the area covered by tephra of 1 cm thickness or more had reached around 800,000 km^2, equivalent to the size of Pakistan. It was the most devastating volcanic event of at least the past 1,000 years: measuring an estimated 7 on the Volcanic Explosivity Index (VEI), it was 10 times more powerful than the better-known 1883 eruption of Krakatoa, and 1,000 times more powerful than the eruption of Eyjafjallajökull in Iceland in 2010. The eruption produced around 50 km^3 of debris—enough to bury the island of Java under 35 cm of ash.

Actual loss of life from this event is not known, but it is estimated that around 12,000 people died during the eruptions on the island of Sumbawa. The indirect toll—related to famine and disease in Sumbawa and Lombok—was much higher, perhaps as high as 60,000, although numbers as high as 100,000 have also been proposed to allow for further possible loss of life in Bali and East Java. Thousands died from severe respiratory infections caused by inhaling the ash that remained in

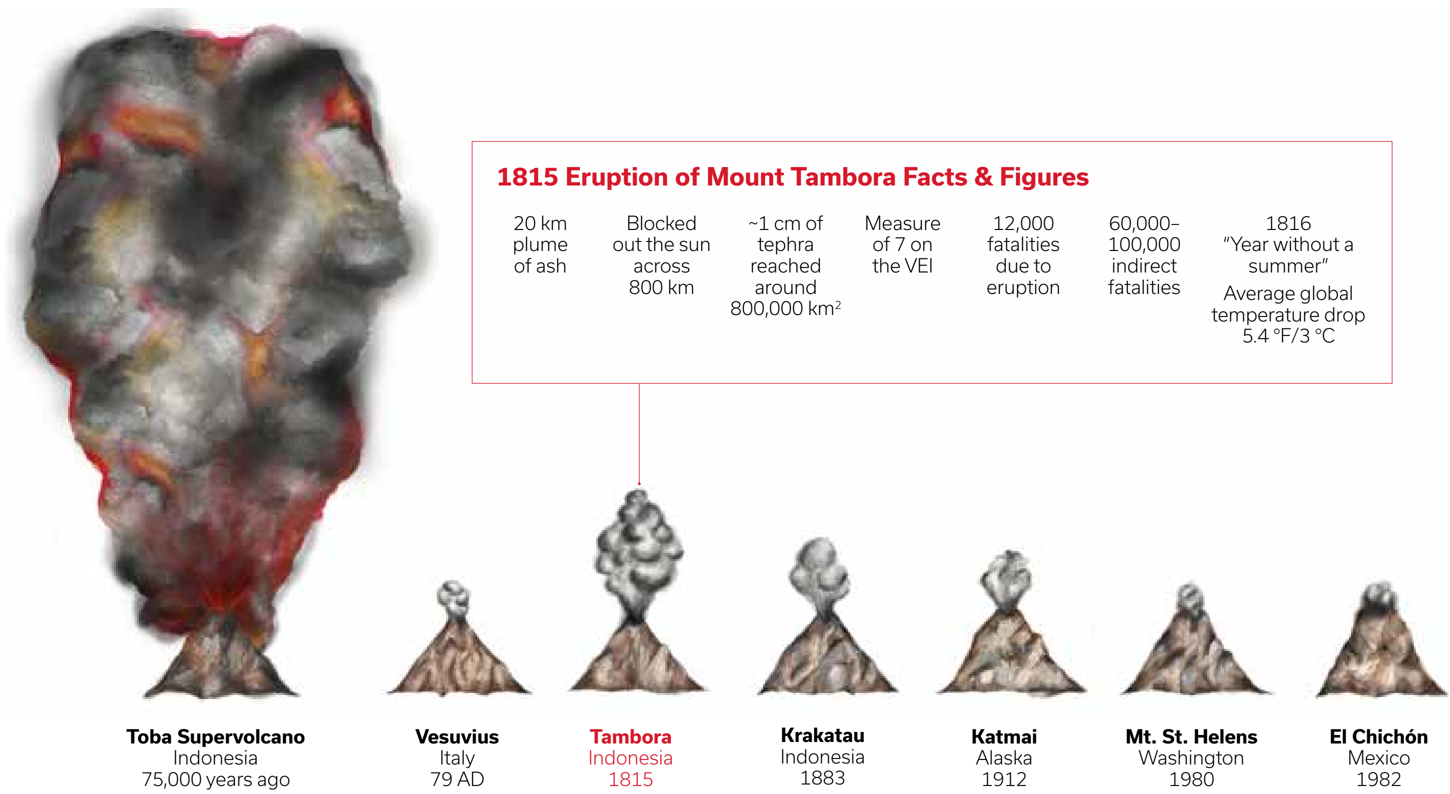


Illustration: Andrea Fernandez

The painter J. M. W. Turner's sunsets are thought to have been influenced by the "year without a summer" of 1816. Image: Wikipedia

the atmosphere, and thousands from diarrheal disease caused by drinking water contaminated with acidic ash. The same deadly ash poisoned crops, especially the vital rice fields, raising the death toll higher.

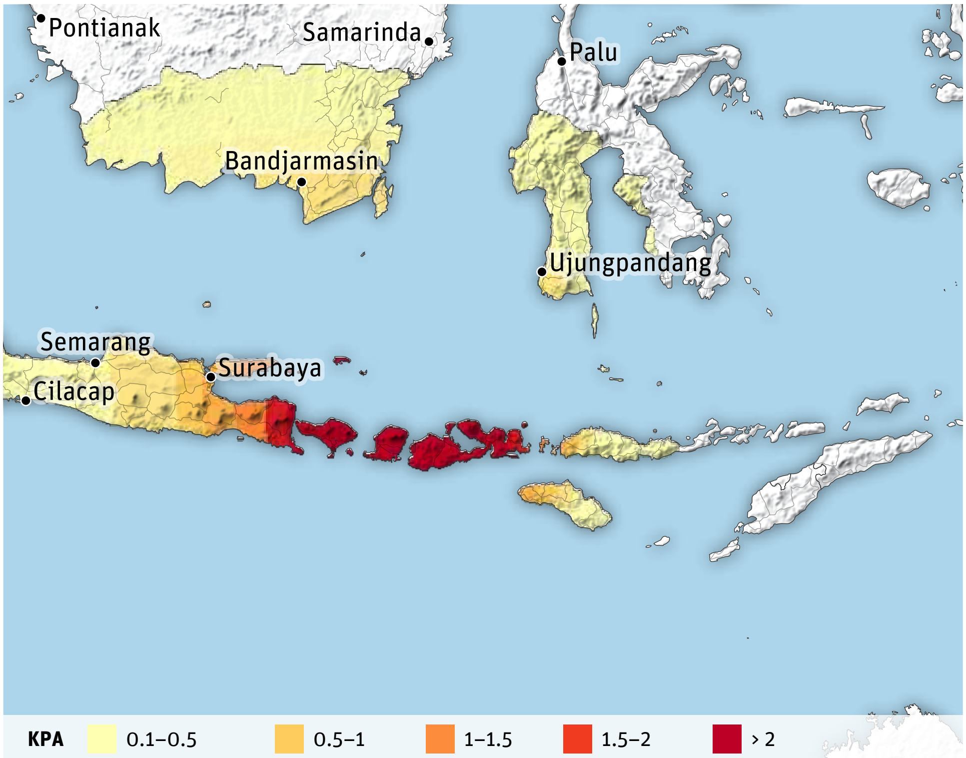
While the devastation in Indonesia was particularly severe, the eruption of Mount Tambora had lasting—even historic—global effects. The eruption flung an estimated 60 million tons of sulfur gas over 40 km into the stratosphere, where it combined with hydroxide gas to form particles of sulfuric acid. Within months, this was distributed globally throughout the stratosphere, reflecting sunlight and creating a global cooling effect that resulted in "the year without a summer" that was 1816, when it was estimated that the average global temperature was reduced by 3° Celsius.

The disruption to weather patterns resulting in part from the eruption caused crop failures and famine in Europe and North America, and may have accelerated the settlement of the American West by New England farmers seeking better growing conditions. In China and Tibet, the cold weather destroyed rice production and killed livestock, and surviving crops were destroyed by unseasonal flooding.

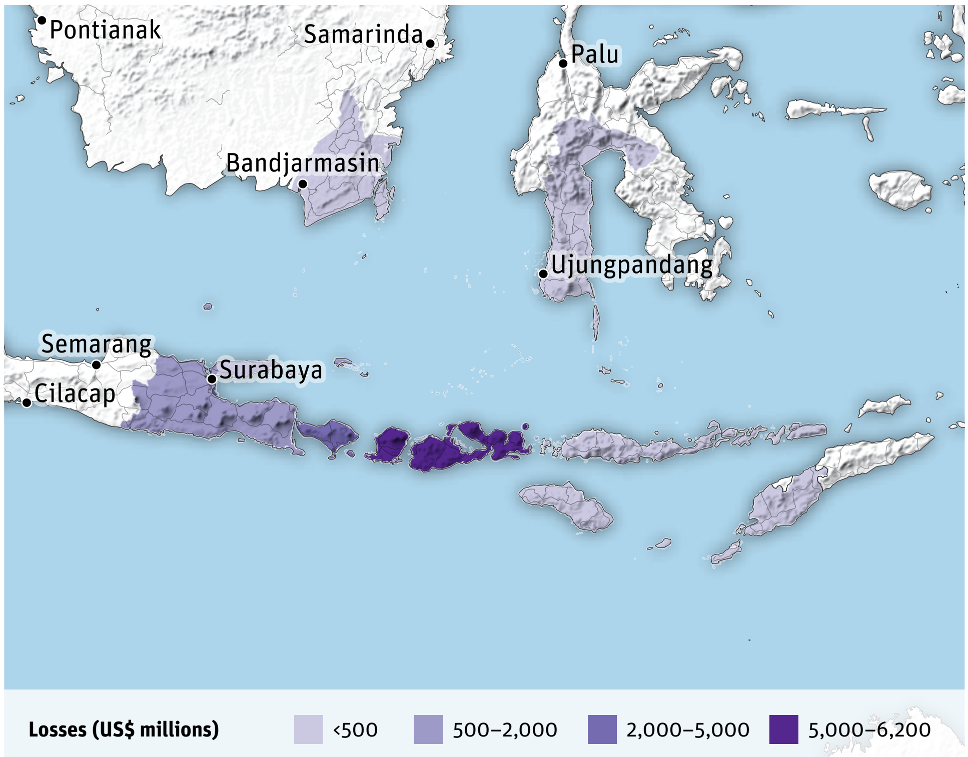
Another consequence of that gloomy year was its influence on some of the great art of the period, from Turner's rich sunsets, to Mary Shelley's *Frankenstein*, composed in the global shadow of the greatest volcanic eruption of the age.

What if a Tambora-scale eruption happened today?

Globally, the consequences of a Tambora-scale event would be far more disruptive if they took place today. The eruption of Eyjafjallajökull, with a VEI of 4 and one-thousandth of the ejected volume of Tambora, closed air space over northern Europe and disrupted air travel for eight days.



1815 Tambora reanalysis isopach with tephra loading measured in kPa.
Map: D-RAS, Axis Maps



Absolute losses aggregated to a province level for a remodel of the 1815 eruption.
Map: D-RAS, Axis Maps

The eruption grounded 107,000 flights, costing the aviation industry an estimated $1.7 billion. A Tambora eruption today would likely prove more disruptive, for a longer period, over a much wider area. Southeast Asia is one of the most densely populated regions in the world, with correspondingly busy air traffic routes. The regional economy would suffer devastating effects on food production, tourism, and commerce.

Tambora erupted before the advent of industrial farming, and at a time when the global population had just passed the 1 billion mark. A similar event now would likely have a more devastating effect on crop production and hence on global food security. In terms of loss of life, it's impossible to estimate the effect of a Tambora today. At the time, the region including Sumbawa, Lombok, and Bali was home to 750,000 people; today over 9 million people live there, 1.4 million of them on Sumbawa and its smaller offshore islands. While today there is a much improved capacity to deal with such events through timely warnings and evacuation ability, the global toll that might result from a loss of agricultural production would be considerable.

Every volcano is different, and each eruption produces a unique combination of the various forms of ejecta, including magma and volcanic gas. Of these hazards, volcanic ashfall and gases are the most far-reaching, and they can affect areas hundreds or even thousands of kilometers downwind of the volcano. Ashfall—such as that caused by the 1815 eruption—is perhaps the easiest to measure. Its effects are also particularly serious, ranging from an impact on agricultural production, to public health consequences such as respiratory disorders, to the disruption of public services through damage to equipment or infrastructure.

In order to estimate some of the economic damages and losses to the region in the case of a similar event, the World Bank Disaster-Resilience Analytics and Solutions (D-RAS) team remodeled aspects of the original eruption for 2017. Model results suggest that within the affected 300 km radius, damage to residential buildings alone would be in the order of $9.7 billion today.

What about the future?

Tambora-scale events are rare. And the 1815 eruption, at a comparatively recent point in the past, means that another eruption of such ferocity is unlikely to happen again at the same site. However, this model can also quickly analyze smaller-scale future events and be used to determine losses in the residential sector.

There are 127 active volcanoes in Indonesia alone, and over 1,500 globally—many of them situated on the densely populated Pacific Rim—the "Ring of Fire" that gets its name from the region's high levels of volcanic (and seismic) activity. The eruption of Mount Merapi in 2010 produced enough ashfall to cause buildings to collapse under its weight; data of the sort provided by the remodeling of Tambora might have allowed for better planning for the losses in that event.

What has changed?

Since the Indian Ocean tsunami of 2004, which devastated the province of Aceh, Indonesia has deliberately sought to develop and implement a complete and modern disaster risk management system. The country has enacted legislation on disaster management, established the National Disaster Management Authority (BNPB), and drafted the National Disaster Management Plan. The government has also prioritized the identification of risk: it has developed a national risk atlas to map exposure to natural hazards across all of the country's districts, assessed provincial- and local-level risk, and adopted open source software for community mapping projects. All this information on risk in turn is used to inform national and local planning and budgeting.

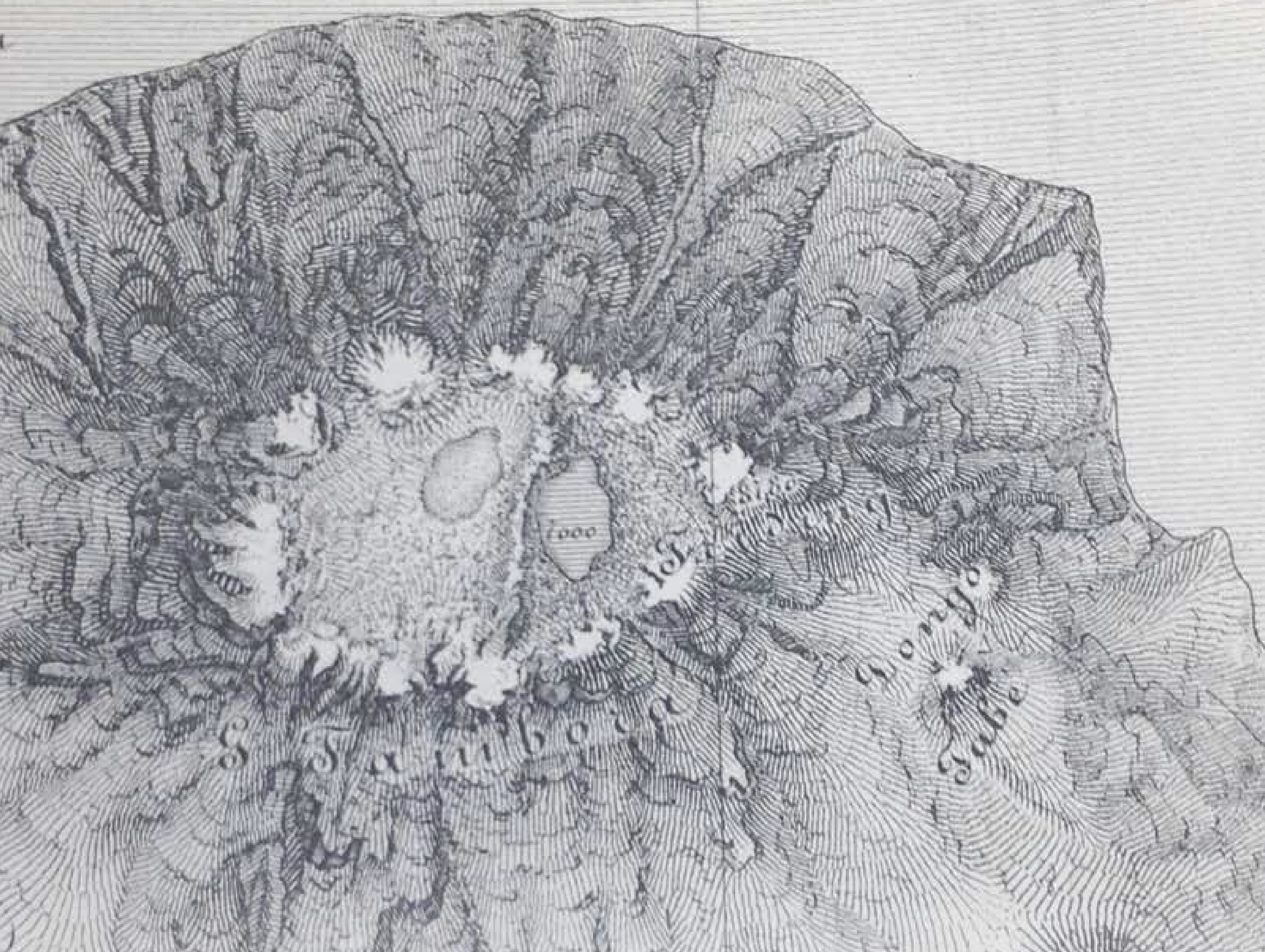
Following the devastation in 2004, with technical and financial support from the World Bank and other donors, the government of Indonesia also piloted REKOMPAK, an approach to large-scale reconstruction and rehabilitation designed to support community-based efforts to build back better after a disaster. The REKOMPAK model has been used after a range of disasters, including earthquakes, volcanic eruptions, landslides, and flooding. To cite two examples: it was used following the earthquake affecting Yogyakarta in 2006, and after the eruption of Mount Merapi in 2010, when it supported voluntary relocation of communities at risk.

The eruption of Mount Merapi provided an opportunity to test Indonesia's disaster risk management system. Before that event, the Indonesian Center for Volcanology and Geologic Hazard Mitigation had requested assistance from the Volcano Disaster Assistance Program of the U.S. Geological Survey (USGS) to improve volcano monitoring. The resulting advanced capacity—in the form of experts, training, and equipment—enabled accurate prediction of the 2010 eruption and the successful evacuation of 70,000 people.

This improved capacity was also evident during the threatened eruption of Bali's Mount Agung in 2017. At that time, manually activated early-warning sirens with a range of some 2 km were placed in several townships in the likely path of magma or pyroclastic flow, and 144,000 people were evacuated from particularly vulnerable areas to shelters established by the local disaster management agency (BPBD). One of the challenges was the reluctance of some community members to leave their homes or their livestock.

In 1815, news of Tambora spread at the speed of sail; the eruption of the much smaller Krakatoa some seven decades later was carried around the world by telegraph. Today, modern communications technology alone would dramatically mitigate the immediate loss of life from an eruption, and social media would screen it around the world in real time. ◎

Background: The Sanggar Peninsula and the crater of Tambora on Sumbawa, Indonesia. Map: Heinrich Zollinger



Thomas Stamford Raffles.
Engraving: James Thomson

EYEWITNESS: SIR THOMAS STAMFORD RAFFLES

Sir Thomas Stamford Raffles was the British lieutenant general resident in Sumbawa at the time of Tambora's eruption. A keen amateur scientist, he directed his representatives in the affected areas to send him detailed accounts of the eruption and its aftermath. The following is part of his own description:

At 10 pm of the 1st April we heard a noise resembling a cannonade, which lasted at intervals till 9 o'clock the next day, it continued at times loud, at others resembling distant thunder—but on the night of the 10th the explosions became truly tremendous, frequently shaking the earth and sea violently. On the morning of the 3rd April, ashes began to fall like fine snow, and in the course of the day they were half an inch deep on the ground; from that time till the 11th the air was constantly impregnated with them, to such a degree that it was unpleasant to stir out of doors . . . The sun was not visible till the 14th, and during this time it was extremely cold—the ashes continued to fall, but less violently, and the greatest depth, on the 15th of April, was 9 inches.

THE LESSONS OF VULNERABILITY

Spitak Earthquake, 1988

A ruined building near Mount Aragats in the aftermath of the 1988 Spitak earthquake, northern Armenia. Photo: Pascal Parrot/Sygma/Sygma via Getty Images

A remodeling of the 1988 Spitak earthquake in northern Armenia demonstrates how socioeconomic factors can worsen the damage and loss from a devastating event and impede recovery efforts.

Northern Armenia is located on a seismic belt that stretches from the Alps to the Himalayas, and as a result is vulnerable to large and destructive earthquakes. One such was the Armenian earthquake of 1988—also known as the Spitak earthquake—centered around the cities of Spitak, Leninakan (now Gyumri), and Kirovakan (now Vanadzor).

The Spitak earthquake, which struck in the late morning of December 7, 1988, was caused by a fault rupture 40 km south of the Caucasus Mountains. It had a shallow hypocenter, originating relatively close to the surface, and with a magnitude of 6.8 was one of the largest earthquakes ever to strike the region. Some of its effects, however, may be attributed to human error and economic neglect.

Around 350 multistory apartment buildings collapsed during the event, killing about 20,500 people (although other structures stood undamaged or only moderately damaged nearby, particularly the nine-story large precast reinforced concrete panel buildings). Several thousand low-rise, unreinforced stone masonry houses also collapsed across urban and rural areas, killing another 4,500 people. The city of Spitak in particular was almost entirely destroyed; it lost around half of its residents to the quake, and the rest were left homeless.

Most of the multistory apartment blocks that collapsed in the earthquake were poorly constructed Soviet-era building stock. Particularly devastating was damage in the health care sector. Most hospitals collapsed, killing two-thirds of the doctors in the region and limiting capacity to handle the critical medical needs after the disaster. The disaster also had long-term economic effects: aside from imposing immediate economic losses and the cost of rebuilding, the earthquake destroyed 130 factories, putting 170,000 people out of work.

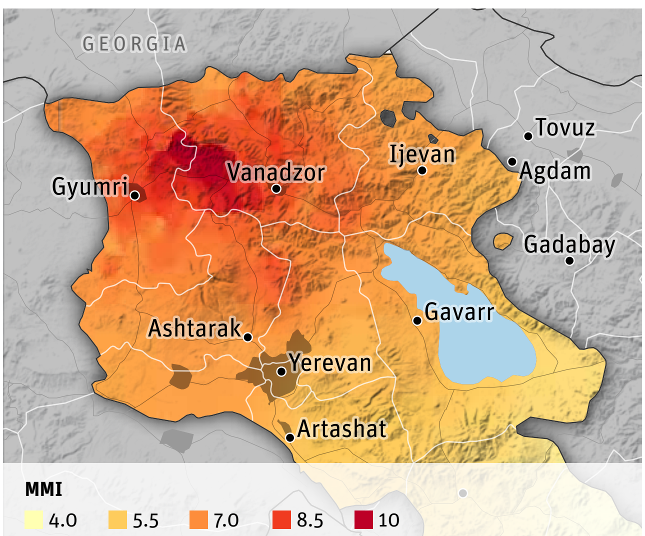
Revisiting the damage

The Spitak earthquake was marked by a large number of studies on post-disaster damage and loss. Unfortunately, these produced many conflicting numbers, including some huge overestimations of the economic losses. The valuation of losses was complicated by the constantly changing rate of the Soviet-era ruble, which in the construction industry was then around one-ninth of the U.S. dollar.

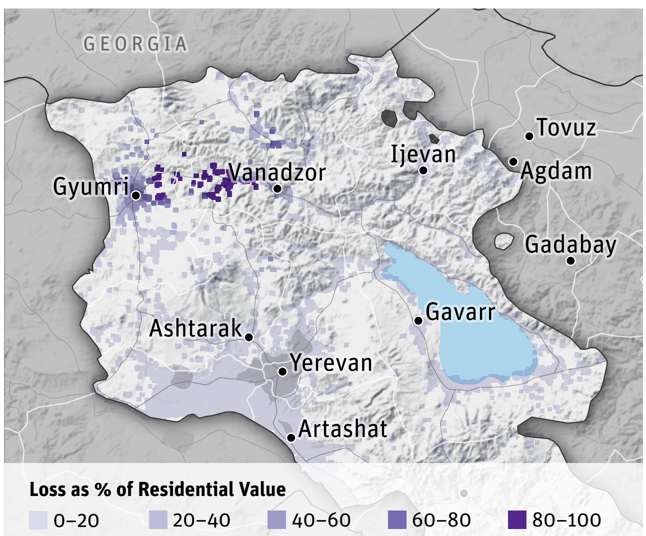
In 2017, the D-RAS team of the World Bank conducted a reanalysis of the event's effects on the residential sector, both to get a more accurate view of the original losses and to establish what damage would likely result from an earthquake of similar magnitude today. The team modeled exposure of buildings using a number of studies, mostly from the National Statistical Service of the Armenian government, and examined historical damage data, intensity maps, and ground motion maps in order to gain the best possible reanalysis of the scenario. This study produced the first definitive estimate of losses from the event.

Specifically, the study estimated that the earthquake caused $150–200 million[3] of damage to the residential sector as it was at the time of the event. The reanalysis for today's residential exposure suggests around $420 million in damages. In relative terms, this is a reduction in the ratio of loss to

[3] The figure is in 1988 U.S. dollars and assumes an exchange rate of 8.8 rubles to the dollar.

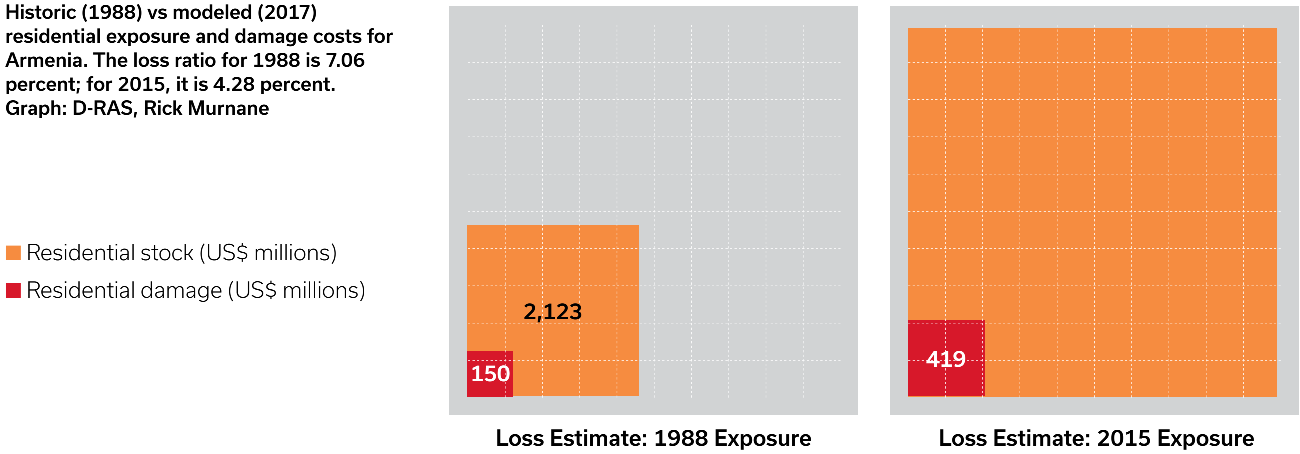


Hazard map showing Modified Mercalli Intensity.
Map: D-RAS, Axis Maps



Relative loss from the Spitak earthquake on a 1 km resolution for the reanalysis as a percentage of total exposed value.
Map: D-RAS, Axis Maps

Historic (1988) vs modeled (2017) residential exposure and damage costs for Armenia. The loss ratio for 1988 is 7.06 percent; for 2015, it is 4.28 percent. Graph: D-RAS, Rick Murnane



exposed value—loss ratio—as the figure above demonstrates.

Improving construction

The projected reduction in relative loss is due in part to changes in building construction. In the period after independence (starting in 1991), the construction typologies that fared poorly in 1988 were entirely discontinued and were replaced by superior cast-in-situ reinforced concrete construction. The reduction may also in part be attributed to the fact that fewer people and properties are now located in the regions of northern Armenia affected by the 1988 event. After the earthquake, there was a significant exodus, and cities have not recovered their earlier population levels: Gyumri and Vanadzor—Armenia's second- and third-largest cities—are each roughly half as populous at present as they used to be in 1988.

Despite these findings showing a reduction in relative loss, challenges remain. For various reasons, economic growth in Armenia has been muted, resulting in slow replacement of Soviet-era building stock and creating concern about the degradation of metal joints in the panels of large pre-cast concrete buildings. By 2016, post-1990 housing stock was estimated to make up only about 13 percent of the total built floor area. Should a similar event occur, reconstruction costs would likely be higher given the improved construction standards required for new buildings.

The return period of a quake of this magnitude in the affected region is estimated at around 250 years, equivalent to a 0.4 percent chance of it occurring in any given year. The Spitak earthquake showed the potential for severe consequences when so many residential apartment buildings and critical facilities such as schools, hospitals, and factories are destroyed in an earthquake. The same high levels of earthquake risk exist in other regions in Armenia: Armenia's capital Yerevan, for example, is threatened by the Garni fault, and most of its residents continue to occupy vulnerable pre-1988 buildings that may provide lesser safety during an earthquake.

This reanalysis supports the case for improvements in building stock and critical infrastructure across Armenia. It also suggests decreased economic loss ratios and improved life safety could result from the development of earthquake-resistant infrastructure and improved building design.◎

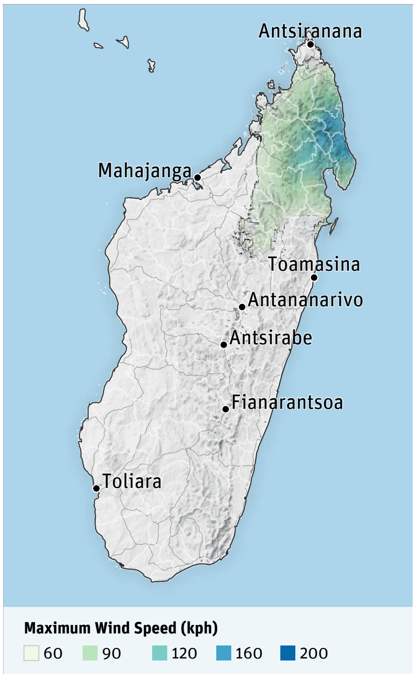
A Malagasy woman manually pollinates a vanilla flower near Sambava, Madagascar. Photo: © Pierre-yves Babelon | Dreamstime.com

A FRAGILE HARVEST

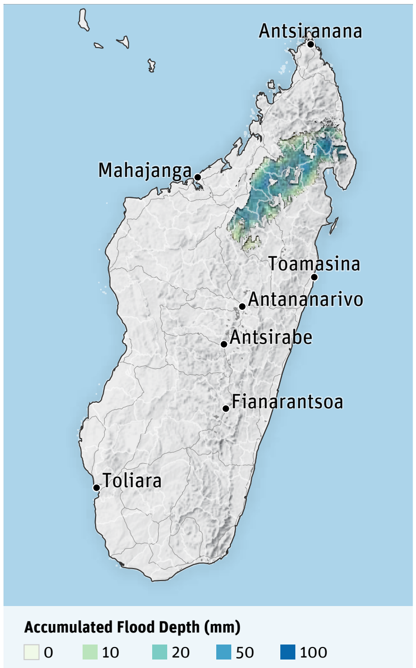
Tropical Cyclone Enawo, Madagascar, 2017

A tropical cyclone in Madagascar devastated vanilla production and disrupted the industry globally. Remodeling this event may help limit the impact of future extreme weather events.

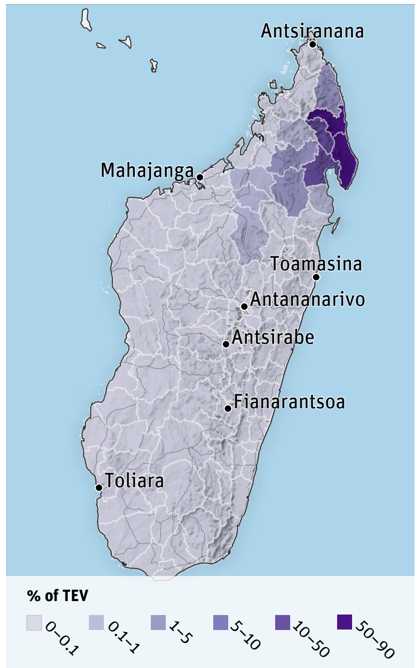
CYCLONE ENAWO 2017



Modeled Wind Hazard. Map: World Bank, Axis Maps



Modeled Flood Hazard Map. World Bank, Axis Maps



Agricultural Losses in Percentage of TEV. Map: World Bank, Axis Maps

In March 2017, Tropical Cyclone Enawo swept through Madagascar, making landfall in the northeast as a Category 4 cyclone and then moving southward as a tropical depression before exiting the country. Northeastern Madagascar suffered wind damage and widespread flooding, and the central and southeastern parts of the country were affected by heavy rains and flooding.

Enawo was the strongest cyclone to strike Madagascar since 2004; with maximum sustained wind speeds of 230 kph at landfall, it dropped up to 220 mm of rain on Sambava in 24 hours. Preliminary field assessments conducted by the government and partners estimate that close to 434,000 people were affected by the event, with 81 deaths and 250 injuries. More than 40,000 houses, 3,300 classrooms, and 100 health centers were damaged. But Enawo also had immense consequences for the economy of the country and for the vanilla industry worldwide.

A vulnerable market

After years of price increases, many farmers in Madagascar had become increasingly dependent on the crop, putting all of their resources into vanilla production. This left them particularly vulnerable to the effects of the cyclone. In the Antalaha commune of the Sava region, initial reports indicated that 90–100 percent of production was lost, threatening many families with ruin.

Madagascar produces almost 4,000 tons of vanilla every year, over one-third of the world's total. Vanilla's relatively limited global production makes the price of vanilla beans highly susceptible to bad news. Prices had increased from $100 per kg in 2015 to $500 per kg in early 2017, for a number of reasons, including rising global demand and speculative hoarding by producers. Enawo kicked this trend into overdrive: the modeled direct damage to the vanilla crop and its associated loss of productivity was estimated at $164 million out of a total production worth $1 billion in annual exports. By August 2017, the price of vanilla beans had soared to a record $600 per kg on global markets, and high prices seem likely to continue through 2018. As the Malagasy proverb

> "All who live under the sky are woven together like one big mat."
>
> —Malagasy proverb

suggests, everything in the world is connected, and the destruction of a local industry may have global consequences.

Three risk models

Three complementary approaches were used to model losses from Enawo and the risk from future events of a similar scale:

1. Using a quantitative risk modeling approach, AIR Worldwide estimated losses resulting from direct damage to buildings and infrastructure at around $208 million (2015 dollars), with a mean return period of around 11 years for similar events.

2. The African Risk Capacity (ARC) model is based on historical data for over 30 years and simulated data for over 1,500 years. It has produced risk profiles for the Comoros, Madagascar, Mauritius, Mozambique, the Seychelles, and Zanzibar, and is used to facilitate insurance payouts for events of varying magnitudes. ARC's model estimates the economic loss generated by Enawo at $50–60 million.

3. The D-RAS team at the World Bank developed an agriculture sector model to assess agricultural losses from an Enawo-scale event. These were estimated at approximately $207 million and were dominated by the impact on vanilla plantations, which amounted to losses estimated at $164 million in the Sava and Diana regions.

Communicating risk

Post-event loss calculations can complement damage and loss assessments involving on-the-ground evaluation. In the case of Tropical Cyclone Enawo, the modeled loss approach offered an early estimate of the economic impact of the cyclone, which the government has been able to use to start the recovery planning process. Access to state-of-the-art disaster risk models marks an important step forward in Madagascar's ability to understand the risk and mitigate the potential impact of cyclones. Model results can help the government develop rapid post-disaster contingency financing instruments; however, while such instruments help in managing the financial impacts, they do not actually reduce those impacts. If effectively communicated, risk information, derived from risk models, may also help Madagascar's vanilla farmers—as well as major producers—better prepare for future weather disasters by reducing the vulnerability of their crops and diversifying their livelihoods. ◎

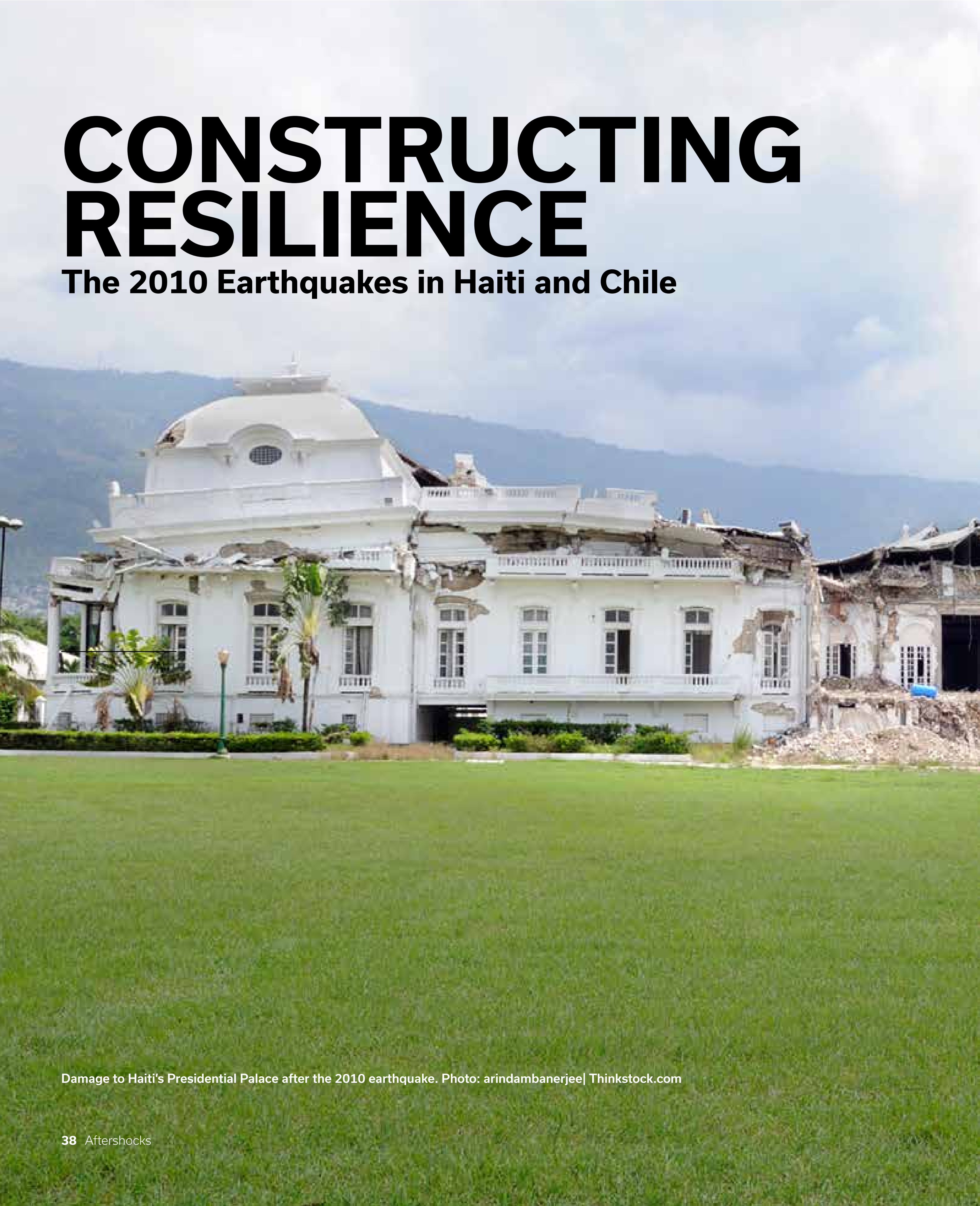
POD OF GOLD

Vanilla beans drying in Sambava, Madagascar.
Photo:© Sebastien Shauvel | Dreamstime.com

Vanilla is a type of orchid that requires pollination to produce the pods from which the flavoring is derived. Native to Mexico, where it was cultivated by pre-Columbian communities, vanilla was introduced to Europe in the 1520s. In 1841 Edmond Albius, a 12-year-old slave on the island of Réunion in the Indian Ocean, discovered that vanilla could be hand-pollinated, enabling its cultivation in suitable climates around the world. But hand pollination, together with the maintenance of the vines and the harvesting of the crop, means that farming vanilla is particularly labor-intensive, and explains why it is the second most expensive spice in the world, after saffron.

CONSTRUCTING RESILIENCE

The 2010 Earthquakes in Haiti and Chile



Damage to Haiti's Presidential Palace after the 2010 earthquake. Photo: arindambanerjee| Thinkstock.com

In 2010, Haiti and Chile were both struck by devastating earthquakes. The earthquake that struck Haiti had a lower magnitude, yet Haiti suffered far greater damage and losses. Why was this the case? Remodeling reveals the role that resilient urban planning and building codes can play in limiting earthquake damage.

It is tempting to compare two devastating earthquakes that occurred in the same general time frame, and indeed, many column inches have been devoted to the contrasts between the Haitian and Chilean earthquakes of 2010. Remodeling the former disaster, however, helps explain the significant differences in the losses and impact associated with the two earthquakes.

Devastation in Haiti

The Haiti earthquake of January 2010 was one of the most destructive earthquakes in recent times. The Mw 7.0 earthquake occurred on the eastern end of the Enriquillo-Plantain Garden fault zone very near the capital city of Port-au-Prince. It devastated many residential neighborhoods as well as the commercial district near the port.

A building-by-building damage survey carried out between February 2010 and February 2011 found that 79,500 buildings—approximately 20 percent of all buildings in the affected area—had either collapsed entirely or were damaged beyond repair, while an additional 102,000 buildings—approximately 26 percent—had repairable structural and/or nonstructural damage.

The focal origin of the Haitian quake was 13 km beneath the surface and just 25 km from the densely populated capital of Port-au-Prince—in earthquake terms, close to a direct hit on the capital.

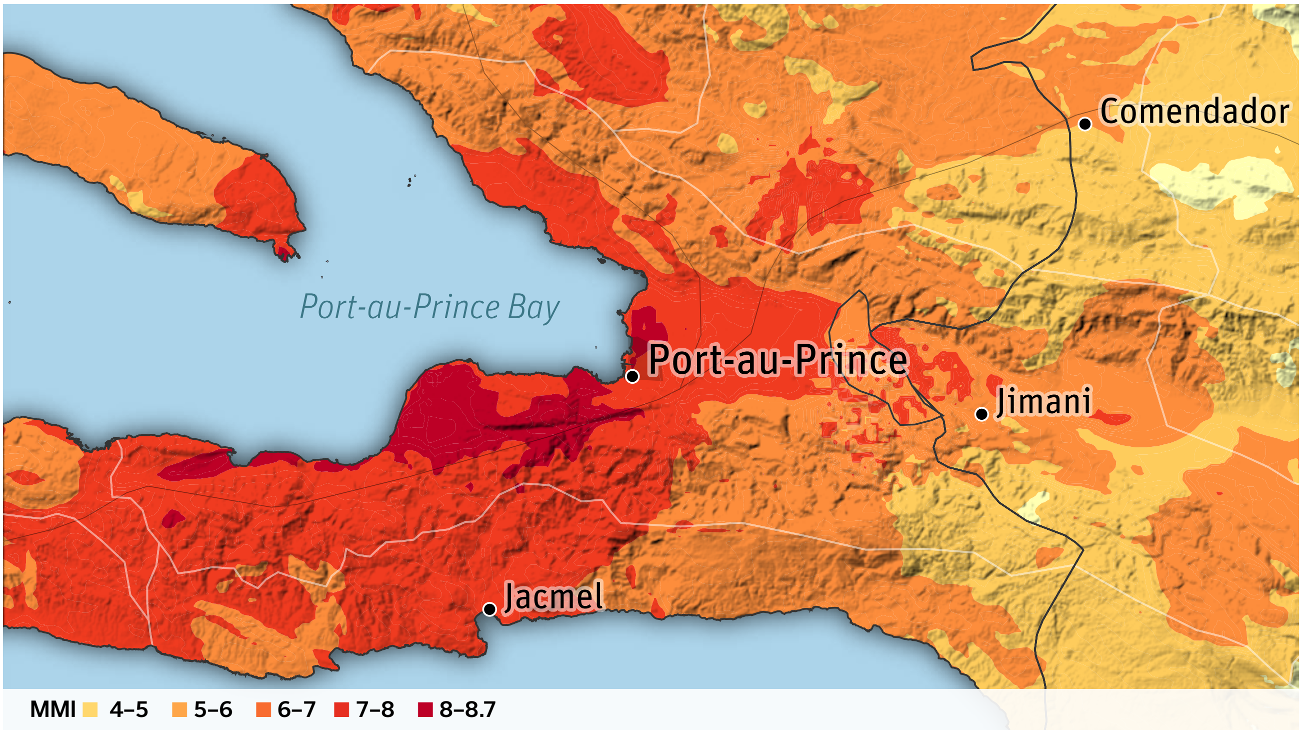
These tens of thousands of collapsed buildings led to extensive loss of life in this earthquake. An estimated 3 million people were affected by the earthquake, and death toll estimates ranged from 100,000 to the Haitian government's estimate of 316,000, though later studies emphasize that the former is the more likely figure. In the widespread devastation throughout Port-au-Prince and elsewhere, vital infrastructure necessary to respond to the disaster was severely damaged or destroyed. This included all hospitals in the capital; air, sea, and land transport facilities; and communications systems.

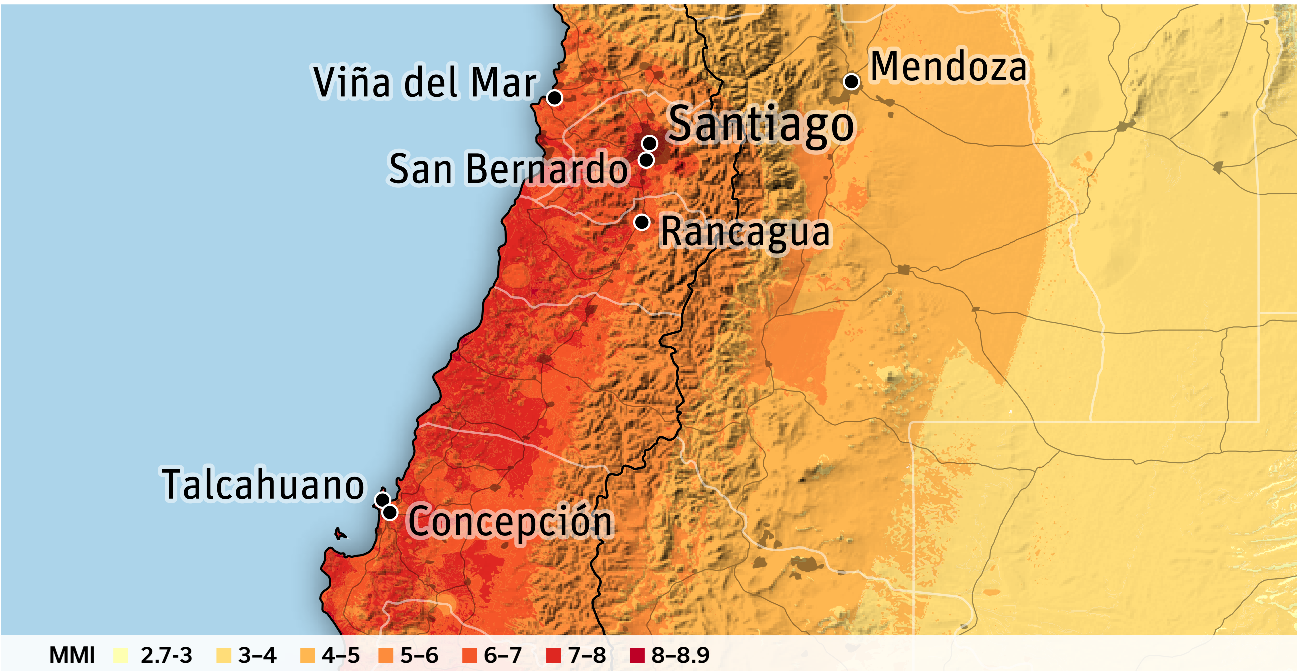
One of the challenges in understanding the loss and impacts of the 2010 Haiti earthquake has been the great degree of uncertainty over many of the relevant variables—including building costs, exposure, damage data, loss data, ground motion, and vulnerability. There has even been uncertainty around the intensity of the earthquake itself. Although there are a lot of uncertainties regarding actual ground motions from the Haiti earthquake, the modeled analysis of the earthquake has refined the available knowledge by comparing the original ground motion estimates with building damages.

In 2017, the D-RAS unit at the World Bank remodeled the Haiti event in order to obtain an accurate estimate of potential losses had this event taken place in the present time. This is a worthy endeavor, as the Enriquillo-Plantain Garden fault continues to accumulate strain that will be unleashed upon the Greater Port-au-Prince region in the future. The reanalysis provided an opportunity to investigate the vulnerability of existing buildings by reviewing what is known about the consequences of the 2010 event. The model concluded that should the event happen today, residential losses would be in the order of $3.2 billion, compared with the $2.3 billion estimated for 2010.

Comparison of catastrophes

Six weeks after the Haiti earthquake, Chile was hit by an earthquake with a magnitude of Mw 8.8—in energy release terms, 500 times more powerful than





Hazard maps of the Hait (above) and Chile earthquakes of 2010, showing Modified Mercalli Intensity. Maps: D-RAS, USGS, Axis Maps

	Haiti	Chile
Magnitude of earthquake	**Mw 7.0**	**Mw 8.8**
Depth of earthquake	13 km	35 km
Maximum recorded peak ground acceleration (PGA)	0.30–0.70g (estimated)	0.65g
Maximum recorded PGA near capital city	0.30–0.70g (estimated)	<0.30g
Population density of capital city	~25,000 people per km^2	~8,500 people per km^2
Estimated casualties	~100,000	550
PDNA-residential damage (2010)	$2.3 billion	$3.9 billion
Modeled residential damage (2017)	$3.2 billion	$6.8 billion

the Haiti event. The earthquake and tsunami claimed 550 lives—a tragedy, but a tiny fraction of Haiti's loss of life. In Chile, 6.5 percent of the housing stock was either damaged or destroyed, while in Haiti this ratio was more than double, at 13.7 percent.

Why was the scale of destruction and loss of life so much greater in Haiti than in Chile? The reasons are substantially geological in origin, and dependent upon both distant and local conditions. While the Chilean quake was much stronger, its epicenter was offshore and its focal origin deeper—about 35 km below the surface of the Pacific Ocean—and 325 km from the capital city of Santiago. By contrast, the focal origin of the Haitian quake was 13 km beneath the surface and just 25 km from the densely populated city of Port-au-Prince—in earthquake risk terms, close to a direct hit on the capital. Great subduction earthquakes, such as the one that struck Chile, last longer, as they involve a much bigger fault rupture zone (the 2010 event lasted for 1.5 to 2 minutes), and they produce longer period waves (affecting taller buildings) that reach over a greater distance. The seismic waves that shook Port-au-Prince, although not recorded, were shorter and due to the proximity more violent, with the strongest shaking occurring in

The Gran Torre Santiago is a 64-story tall skyscraper (299.92 meters) in Santiago, Chile, the tallest in Latin America, and the second-tallest building in the Southern hemisphere. Photo: © Tifonimages | Dreamstime.com

a narrow band of land of around 50 km east-west and 20 km north-south.

There are also historical reasons for the greater devastation in Haiti. Haiti has had far less experience with earthquakes than Chile—the last significant earthquake to hit Port-au-Prince had been in 1751. Before the 2010 earthquake, Haiti's seismic surveillance network was almost nonexistent, and seismic risk preparedness and education were likewise lacking. After the earthquake, the government, with assistance from the United States, installed five new seismometers and a surveillance network that transmits timely information through the Internet on seismic activities in Port-au-Prince and regions to the north.

The frequent occurrence of damaging earthquakes in Chile prompted it to develop stringent building codes, comparable to those of California (although as elsewhere in the world they are not always uniformly enforced). In recent decades, Chile has mandated earthquake-proofing for new engineered structures and has required architectural designs that include materials like rubber and features like counterweights to allow tall buildings to bend and sway rather than break during temblors.

Haiti, in contrast, has few building regulations in place and no integration of risk in urban planning. Residential buildings are still mostly informally constructed, and though the International Building Code (IBC) was introduced after the earthquake, it is not well enforced. There is also a shortage of licensed contractors, engineers, and architects to ensure regulations are adhered to during construction. As a result, Haitian buildings are often constructed with natural available materials, such as the traditional *clisse* mortar houses (with walls from sticks and twigs covered by mud or cement mortar). Contractors also cut costs by using less expensive and less resilient materials, including limestone dust and unrefined sand. In addition, many structures in Port-au-Prince are built on steep slopes, without adequate foundations.

Finally, population density in the affected areas helps to explain the different impact of the earthquakes. The population density in the city center of Port-au-Prince was over 25,000 people per km^2. In contrast, Santiago, the most densely populated area in Chile, has a population density of just under 8,500 people per km^2.

The earthquakes in Chile and Haiti are remarkable perhaps more for their differences than their similarities. However, if the juxtaposition of the two events is at all useful, it is because it highlights the value of resilient urban planning and strictly applied construction standards in areas of seismic risk. ◎

Devastation of Santo Domingo after San Zenon Hurricanem in 1930. Photo: Keystone-France/Gamma-Keystone via Getty Images

A DIRECT HIT

San Zenon Hurricane, Santo Domingo, 1930

A risk model developed for the 1930 San Zenon Hurricane in the Dominican Republic yields valuable data on the likely effects a similar storm would have on cities in the developing world in today's era of rapid urbanization.

In 1930, the value of the total residential and nonresidential stock was $110 million in 1935 dollars; today, it is over $150 billion.

What happens when an Atlantic hurricane at the height of its strength scores a direct hit on a major city in a developing country? Some answers to this question are offered by the San Zenon Hurricane, which struck Santo Domingo in the Dominican Republic in 1930, causing widespread destruction and the loss of up to 8,000 lives.

The storm—the second of three in one of the quietest hurricane seasons on record—originated in the mid-Atlantic in late August. It was still intensifying when it made landfall near Santo Domingo, with peak winds estimated at around 250 kph and gusts of up to 320 kph. The San Zenon Hurricane had a relatively small footprint: although it left a trail of destruction 20 km wide, much of this was concentrated in the capital city.

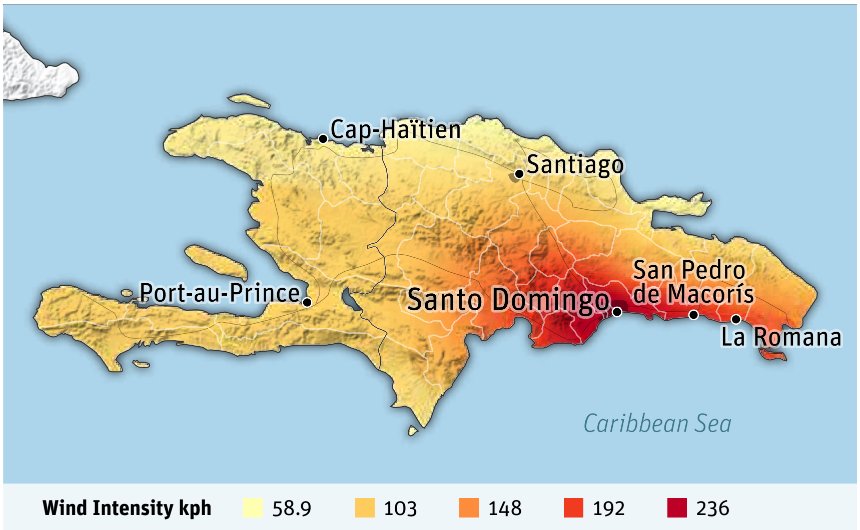
The storm hit with pinpoint accuracy in a particularly vulnerable location. Santo Domingo is located on an exposed coastal plain, susceptible to flooding from the Ozama River, which broke its banks during the storm; other damage resulted from high winds and mudslides. Three districts of the city were almost completely destroyed. Estimates of the lives lost vary, from as low as 2,000 to as many as 10,000.

How was the storm modeled?

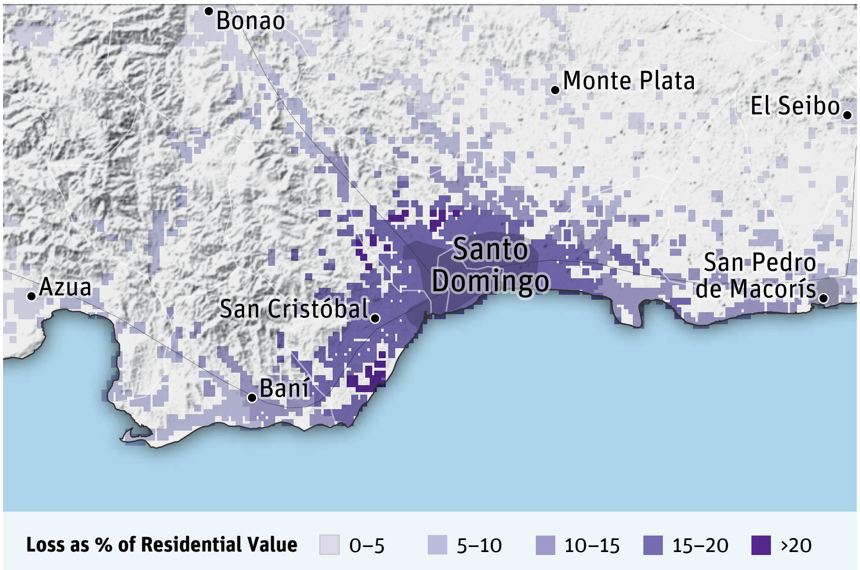
To establish an accurate view of the intensity and track of the storm, researchers examined the National Hurricane Center HURDAT data. Storm data were then compared against the exposure of residential building stock in the Dominican Republic, obtained from census and other data, and encompassing eight different types of construction with varying weather resistance, such as wood, steel, concrete block, and reinforced masonry. Spatially, the exposure was distributed over three types of development: the metropolitan Santo Domingo area, other urban areas, and rural areas, with differences in construction characteristics for each administrative zone.

Remodeling the 1930 hurricane proved challenging. There are limited and often conflicting historical observations—for example, estimates of the storm's radius of maximum winds start at 2 km, with other estimates higher. There are also limited data on the housing stock for the country.

The damage estimated in the reanalysis was compared in



Hazard map of the 1930 reanalysis scenario including wind speed per cell. Map: D-RAS, Axis Maps



Relative losses on a 250 m grid cell resolution from the 1930 hurricane scenario. Map: D-RAS, Axis Maps

absolute terms to the total existing value of the current residential stock in the Dominican Republic. In 1930, the value of the total residential and nonresidential stock was $110 million in 1935 dollars; today, it is over $150 billion.

The damage from the 1930 storm was estimated at $18 million in 1935 dollars. If today the same storm directly hit the city and moved through the rest of the country, it could cost as much as $15 billion. However, taking into account the value of current residential and nonresidential stock, this represents a decline in relative damages—from almost 16 percent of the value of residential exposure damaged in 1930 to 10 percent today.

There are several possible reasons for the reduction of relative loss. One may be the change in building construction practices, particularly since 1980. That was the year when a new building code was introduced to prevent serious damage from earthquakes, to which the Dominican Republic is also prone. Buildings that are more structurally sound are likely to better withstand high winds as well as strong ground motion. However, it should be noted that within a given type of construction, such as unreinforced masonry, vulnerability remained the same.

How does this model help?

Home to over 3.5 million people, Santo Domingo is the most populous metro region in the West Indies. The results from remodeling the San Zenon Hurricane provide a worst-case scenario in which a major metropolitan center is hit by a very intense hurricane. Such a scenario can be useful for disaster risk management and planning. It also facilitates the production of exposure, hazard, and vulnerability models for tropical cyclones occurring anywhere around the world, and allows future events to be quickly analyzed and losses to be more easily determined, both in the residential and nonresidential sectors.

San Zenon was a deadly outlier in a season that yielded just three storms. In 2017, there were 17 named storms—including Harvey and Irma. The total number of storms in a season is not important. All that matters is the one storm that strikes your community. Modeling the big storm can help decision makers and communities plan for the worst and be prepared. ◎

THE ANGRY GODS

The word *hurricane* derives from the Spanish *huracán*, which comes from *Juracán*, the name of the storm god of the Carib or Taino people native to the Caribbean region. Juracán is believed by scholars to be derived in part from the Mayan creator god, Huracan, who created dry land out of the turbulent waters, but who also destroyed the original "wooden people" of Mayan myth with a great storm and flood. The history of the region is punctuated by such cataclysms: in 1502, the new city of Santo Domingo was completely destroyed by a hurricane, and was then rebuilt on the opposite bank of the Ozama, which flows through it today.

WHEN THE RIVERS RISE

Thailand Floods, 2011

"The temple bell stops. But the sound keeps coming—out of the flowers"

—Basho, 17th-century Buddhist poet

The Thailand floods in 2011 exposed the vulnerability of global industries to local disasters, and highlighted the importance of Thailand in the global supply chains of the automobile and electrical hardware industries. Risk models could help businesses assess their resilience to such disruptive events, and help governments decide on flood mitigation strategies.

Arising at the confluence of the Ping and Nan Rivers, the Chao Phraya, Thailand's major watercourse, flows 372 km south before finding its way through Bangkok to the Gulf of Thailand. Many of the country's largest and most densely populated cities lie along its banks. It is the principal watershed for 35 percent of the nation's land and home to 40 percent of Thailand's citizens, employing 78 percent of its workforce; the regions it runs through generate 56 percent of the country's GDP. When it floods—as it often does, in a country with rainfall of over 1,400 mm annually—vast areas of the country are affected.

However, the floods of 2011 were the worst that Thailand had experienced in decades. Caused by heavier than usual monsoon rains and a spate of tropical storms from July through November, flooding quickly spread and affected provinces in the North, Northeast, and Central regions as rivers burst their banks. The basins of the Mekong and Chao Phraya were particularly affected, and flooding in the Chao Phraya basin was potentially exacerbated by flood management practices, specifically major releases of water from the Bhumiphol and Sirikit dams. A significant amount of damage occurred in areas that were protected by dikes that failed.

Local losses, global consequences

The disaster affected more than 13 million people in Thailand and left many neighborhoods underwater for months. Residential, commercial, and industrial sites were badly affected, and the World Bank estimated total financial losses of around $46.5 billion, making the floods the world's fourth most expensive disaster at that time. It is estimated that Thailand's GDP shrunk by more than 10 percent in the final quarter of 2011. The event also became the largest Asian flood re/insurance catastrophe; according to the reinsurance company Munich Re, $18 billion in losses was declared due to the significant flood damage experienced by industrial estates along the banks of the Chao Phraya.

Prior to the 2011 floods, the insurance industry did not consider Thailand to be a major source of disaster risk. There was also little awareness of how production disruptions in Thailand could affect the global supply chain. The flood event exposed the vulnerability of global industries to local disasters, and highlighted the importance of Thailand in the global supply chains of the automobile and electrical hardware industries, which experienced considerable disruption when factories and warehouses were flooded for

Extent of the 2011 flooding in Thailand. Map: JBA, Axis Maps

several weeks. The global insurance market was dominated in 2011 by insured losses—apportioned to both business interruption and contingent business interruption—from the floods in Thailand and the Tohoku earthquake in Japan.

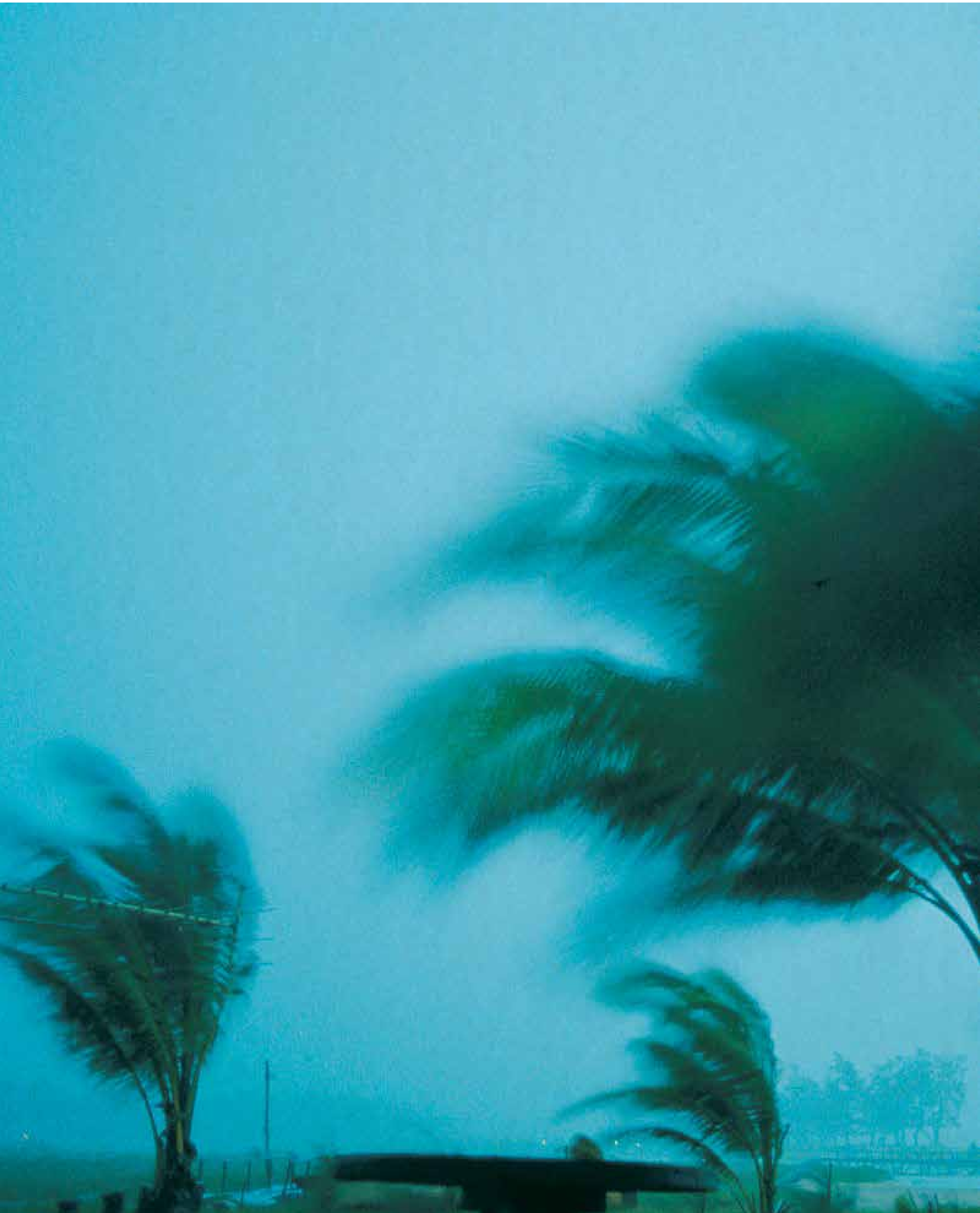
Uncertain predictions

Flooding is a highly complex phenomenon, contingent on an interplay of factors. These include soil moisture (or antecedent conditions), terrain characteristics (including gradient), and water and land management practices related to dams, reservoirs, and urbanization. Longer-term weather patterns are also critical. During the cold phase of the La Niña effect on the Pacific (which persisted through much of 2011), an atmospheric phenomenon called the Walker Circulation shifts farther west, aided in part by the stronger-than-normal northeasterly trade winds. This strengthens the monsoonal rains over Thailand. Since August 2010, Thailand has received on average 33 percent more precipitation annually than is typical; as a result, the soil has become saturated and has exceeded its capacity to absorb further moisture. Although Thailand is seldom affected by strong typhoon winds, the rains from tropical cyclones affecting the neighboring countries of Vietnam, Cambodia, and the Lao People's Democratic Republic often sweep across the country—particularly during a strengthening La Niña. All of these factors make predicting the likelihood and extent of flooding particularly challenging.

Modeling flood hazards is difficult, but this does not mean we should not try; a flood scenario taken from the catalog of synthetic events in JBA Risk Management Pte Ltd's Thailand flood model represents an approximation of the 2011 Thailand floods. This scenario considers meteorological and antecedent conditions similar to those associated with the 2011 event, but with a wider spatial extent of flooding, including Thailand's Central, Northern, and Eastern provinces (e.g., Udon Thani, Khon Kaen). It also factors in the mitigating effects of known flood defenses.

The model predicts that a similar event today would cause economic losses in the range of $60–80 billion, with insured losses of $20–28 billion. Less certain is the likelihood of a similar event: this scenario has an annual probability of occurrence of between one percent and 0.5 percent – or a so called return period of 100 to 200 years. An important contribution to the uncertainty lies in the flood management of the event—for example, the releases of water from the Bhumiphol and Sirikit dams.

Thailand may well experience similar events in the future, with similarly disruptive consequences globally. Risk models can help businesses anticipate the impacts of such events, and can help governments prepare effective mitigation strategies. ◎



THE SCARY WIND

Typhoon Wanda, Zhejiang, China 1956

A remodeling of Typhoon Wanda, which devastated China's Zhejiang Province in 1956, provides a clear illustration of how development can lead to potentially more costly disasters.

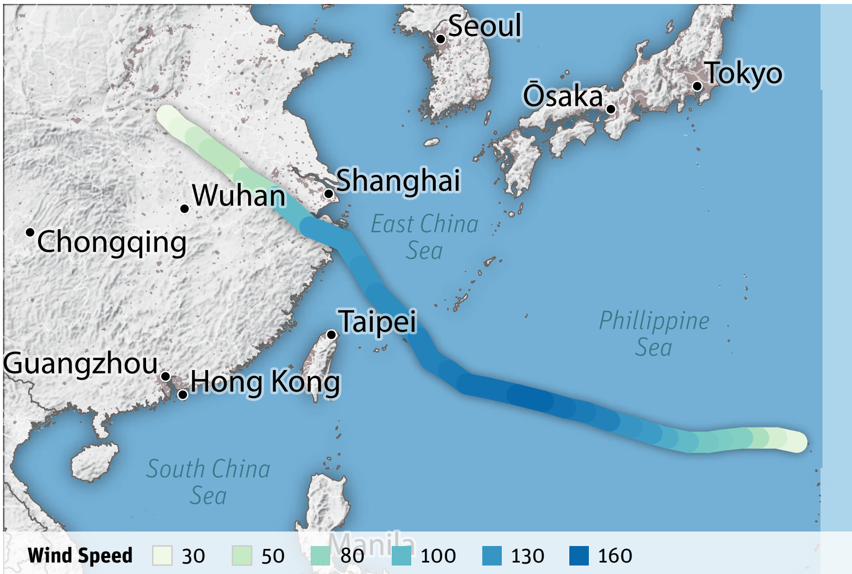
In early August 1956, Typhoon Wanda made landfall in eastern China near the city of Zhoushan, 250 km south of Shanghai. It weakened slowly as it proceeded northward through inland China and dissipated four days later. Along the coast of Zhejiang Province, Wanda produced a 5 m storm surge that destroyed almost 500 seawalls, sank over 900 boats, and damaged a further 2,233. The storm also flooded crop fields, destroying 20,380 tons of wheat. Across Zhejiang, 2.2 million houses and nearly 40 percent of the main roads were damaged during the storm. Ten sections of the Zhejiang–Jiangxi railway line washed away. Nationwide, Wanda killed over 4,900 people and injured over 16,500.

A similar typhoon in Zhejiang today would find a region in the midst of social and economic change. Host to the G20 summit in 2016, the province is home to over 55 million people, and in 2017 recorded GDP growth of 7.8 percent. Businesses like Alibaba are based in the provincial capital Hangzhou, and the city of Ningbo has the world's busiest port by throughput tonnage. The Ningbo Free Trade Zone is home to over 6,600 companies representing 60 countries and concentrated in three main industries: international trade, advanced manufacturing, and warehousing and logistics.

Development in risk-prone areas increases exposure, and it follows that the damages from a similar hazard today would be costlier. To estimate the potential impacts of such an event, AIR Worldwide modeled the typhoon winds and inland flooding resulting from a storm whose strength and track resembled Wanda's (storm surge was not modeled). The impact on residential and commercial building stock was modeled for three different years: 2006, 2012, and 2018. The 2006 building stock was based on AIR's industry exposure database (IED). The modeled damage to the 2006 building stock was $4.2 billion (in 2006 dollars). Values for 2012 and 2018 were extrapolated from the 2006 values using AIR's IED for China to account for inflation and changes in China's capital stock of buildings. With the adjustments to building exposure, the total modeled damage to buildings in 2012 was $11.5 billion (2012 dollars); for 2018, the figure was $26.8 billion (2018 dollars). If one corrects for inflation, the 2006 loss in 2018 dollars would be around $5.7 billion.

While the economic damage in 1956 has not been quantified, the change in value over a single decade makes clear that the area has seen a rapid increase in building values exposed to typhoon hazard. This increase underlines the fact that development in hazard-prone areas drives up disaster risk in absolute terms. The dramatic growth of the Zhejiang region has exposed ever greater amounts of property, of ever higher value, to typhoon wind and flood. This trend is repeated wherever we see urban growth across the world.

Location is a key factor in growth in *modeled* damage. Other things held equal, buildings further from the coastline will be less affected by coastal winds and storm surge than buildings nearer to the coastline. Property located close to rivers or in low-lying areas will be more prone to flood from typhoon-related rainfall than property on high ground. However, there are other factors—exacerbating or mitigating—not considered in this modeling exercise. Engineering advances over several decades can result in improved building design standards and construction practices. As the population becomes wealthier, a greater proportion of building stock is built to better standards, reducing the vulnerability of some buildings. Early warnings can help minimize the loss of life from a typhoon affecting land. For example, the Shanghai meteorological services and capacity for impact-based forecasts and early warnings are among the best in the world and serve as an example to many countries striving to reduce their hydrometeorological disaster risk.



Track of Typhoon Wanda, 1956, showing wind speed in kilometers per hour. Map: IBTrACS, Axis Maps

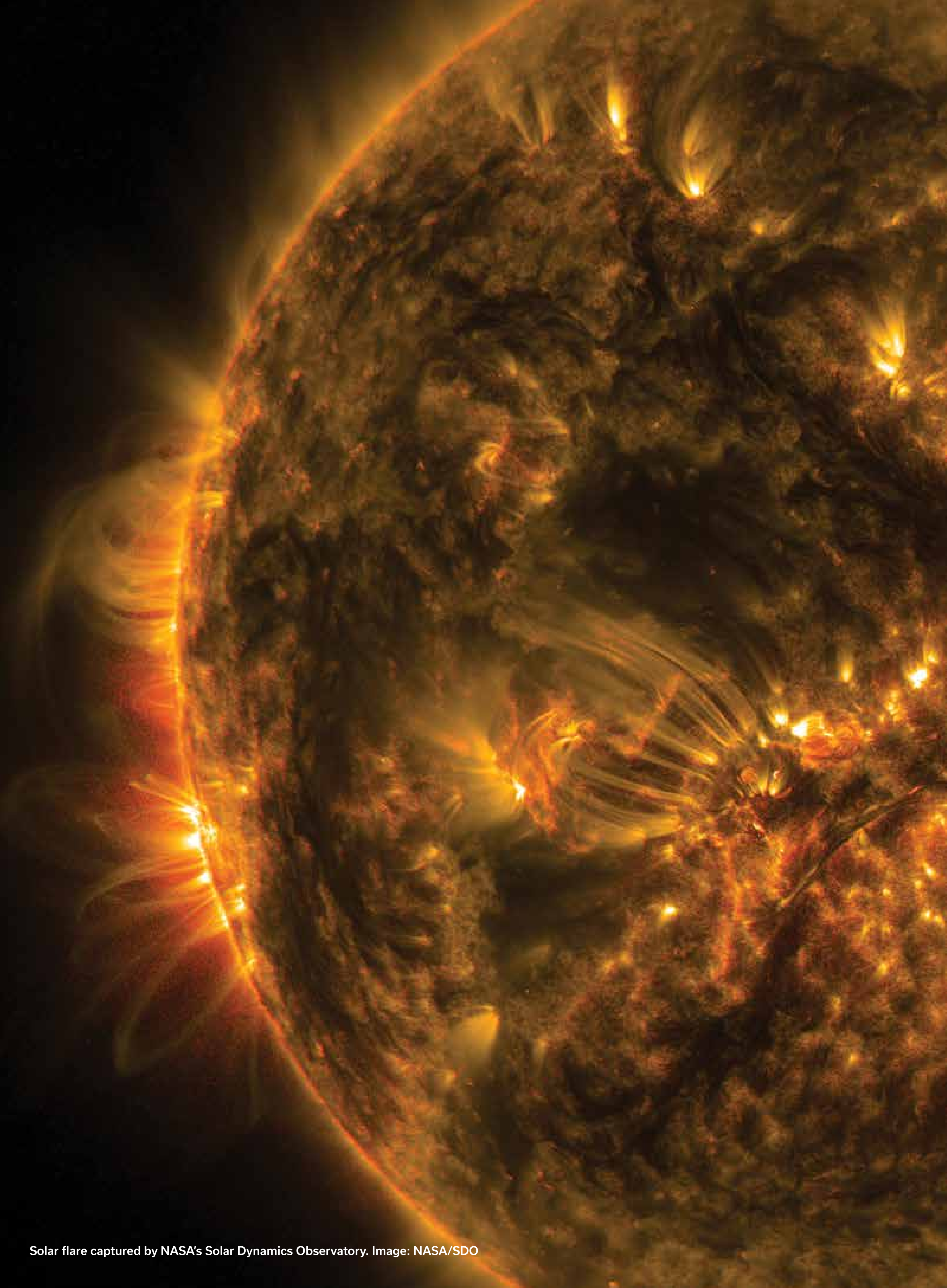
In typhoon-prone areas experiencing rapid urban growth, such as Zhejiang Province and other areas of coastal China, it is important to implement risk-informed land use planning when considering significant investment and development. That is, development in the highest-risk areas (particularly those with high value and high population or intensive use) should either be avoided or be constructed to withstand the effects of hazards locally present. This may be achieved through adherence to design and construction standards, investment in storm surge protection, use of early warning systems and evacuation plans, and support and training of communities in making homes and businesses more resilient to the effects of typhoon, storm surge, and floods. The location of critical infrastructure (such as water and waste treatment plants), and storage of hazardous chemicals should be taken into account, to avoid secondary impacts like contamination and illness.

Such systems and techniques are largely in place in China, and have no doubt reduced vulnerability in many cases since Typhoon Wanda occurred, but in rapidly developing high-hazard areas, the importance of integrating risk management should not be underestimated. ◎

THE EARLIEST RECORDS

The entirety of China's long history has been punctuated by the annual arrival of typhoon season. In around 450 AD, the author Shen Huai-yuan wrote the earliest known description of typhoons. "Many *jufeng* (typhoons) occur around Xi'an County. *Ju* is a wind that comes in all four directions. Another meaning for *jufeng* is that it is a scary wind. It frequently occurs in the sixth and seventh month. Before it comes, roosters and dogs are silent for three days. Major ones may last up to seven days. Minor ones last one or two days. These are called *heifeng* (black storms) in foreign countries." Some 400 years later, the first official record of a typhoon's landfall—near the city of Mizhou, now named Gaomi, in Shandong Province—was documented in the official history of the Tang Dynasty. "On the 15th day of the 8th month of the 11th year of Yuanhe Reign," wrote the unnamed author, "Mizhou reported that a typhoon occurred and the seawater damaged the city wall." No detailed account of the damage was given, unfortunately, making remodeling of this unnamed storm impossible.

Tang Dynasty fresco. Photo: Thinstock.com



Solar flare captured by NASA's Solar Dynamics Observatory. Image: NASA/SDO

RETURN OF THE BLACK SWAN

The Carrington Event, 1859

Not all disasters are earth-based. A solar storm like the Carrington event of 1859 could produce widespread damage on an unimaginable scale; risk modeling could help mitigate its effects.

In the morning hours of Thursday, September 1, 1859, the British astronomer Richard Carrington was taking routine observations of sunspots, with the image of the solar surface projected from his telescope onto a sheet of coated glass, when his attention was caught by something unusual.

"Two patches of intensely bright and white light broke out," he wrote in his report, "Description of a Singular Appearance Seen in the Sun," for the *Monthly Notices of the Royal Astronomical Society*. "My first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by which the general image is thrown into shade, for the brilliancy was fully equal to that of direct sunlight. But, by at once interrupting the current observation, and causing the image to move … I saw that I was an unprepared witness of a very different affair."

The phenomenon Carrington observed was a solar storm, of the sort which releases a combination of radiation, charged particles, and coronal mass ejections (CMEs) of magnetized plasma into space. In the days after the event, geomagnetic storms caused by the CMEs ignited a spectacular display of the aurora borealis—the northern lights—that was visible as far south as the tropics. Telegraph lines sparked, causing paper fires in some telegraph offices and shocking operators through their handsets.

The event was brief—Carrington left for a minute to call someone to witness it with him, and by the time he returned it was all but over—but its effects were global, and dramatic. If the same event happened today, its effects on power grids, computers, and all the systems that depend on them would likely be catastrophic on a scale it is difficult to imagine, much less quantify. While no remodeling of the Carrington event has been conducted, it is possible to infer from various studies the likely effects of a similar event in today's world.

Magnetic disturbances caused by CMEs are measured in nano-Teslas (nT) according to a parameter called Dst, short for "disturbance—storm time." Modern estimates put the Carrington event at around -850 nT on this scale. The most recent disruptive event, a magnetic storm in 1989 that knocked out the power grid across Quebec for 12 hours, measured -589 nT. And a CME event that almost hit earth in July 2012 was estimated to measure -1,200 nT, 40 percent stronger than the Carrington storm. Fortunately, the area of the sun on which the flare occurred was pointing away from the earth at the time of the storm. While the event missed the earth, it did hit a space-based solar observatory, which was able to collect a wealth of accurate data on it.

A real threat

The chances of a direct hit by a Carrington event are as high as 12 percent in the next 10 years, according to physicist Pete Riley of Predictive Science Inc., who in 2014 analyzed records of solar storms going back 50-plus years, extrapolating the frequency of ordinary storms to the extreme to calculate the odds. What would the likely effects of such a storm be? "What's at stake," says Tom Bogdan, director of the Space Weather Prediction Center in Colorado, "are the advanced technologies that underlie virtually every aspect of our lives."

Modern life is powered by interconnected energy grids, managed by computers. Most communications devices are integrated with the global GPS system, reliant on geostationary satellites. In the event of a major solar storm, X-rays and extreme UV rays would reach earth almost immediately, causing radio blackouts and GPS navigation errors. The charged particles could damage the circuits of satellites, knocking out the GPS system and major communications networks, including those responsible for credit card payments. Finally, the CME, which takes a day or more to reach the earth, could cause the failure of anything using or producing electricity, from household appliances to transformers in electrical grids. In a world where everything is reliant on the grid—including, for example, water supply systems and the food supply chain—the potential for immediate and widespread chaos is massive.

The cost of replacing transformers in the United States alone is estimated at between $0.6 trillion and $2.6 trillion. Damage to satellites is likely to cost between $30 billion and $70 billion. With these sorts of projected losses, the cost to the global economy is incalculable—and a recovery period of 4 to 10 years is likely.

Mitigating the risk

Better forecasting of a solar event could provide better outcomes. Current technologies are able to provide only about a day's notice of the arrival of a CME—putting the prediction of space weather about 50 years behind the science of meteorology. However, this window still provides enough time to mitigate some of the damage. For example, power companies could take transformers offline before the storm struck, protecting them and producing shorter, local blackouts rather than long-lasting damage. Longer-term measures would include expensive upgrades to the grid. In the meantime, detailed models of a Carrington-scale event would be a good start to mitigation efforts.

Space weather, like any other hazard, needs only human intervention or inaction to become a disaster. Richard Carrington described himself as "an unprepared witness"; in today's connected world, with the earth wrapped in a fragile cocoon of power grids and communications technology, being unprepared is a luxury we cannot allow ourselves. ◎

Solar Dynamics Observatory at NASA's Goddard Space Flight Center in Greenbelt, Md. Photo: NASA

Image: © Noiral | Dreamstime.com

MODELING THE FUTURE

From Statistics to Stories to Action

"The best qualification of a prophet is to have a good memory."

—The First Marquess of Halifax

Over the last three decades, as science and technology continue to develop, we have witnessed a tremendous growth in the field of risk modeling. Scientists have made great progress in quantifying risk for almost all natural hazards, including risk from flooding, earthquake ground shaking, high winds, coastal flooding due to tsunami or extreme storms, and a whole suite of volcanic hazards.

At the same time, engineers have been attempting to introduce more advanced construction regulations in the form of building codes and to develop flood and coastal protection solutions, while planners and geographers have focused their energies on mapping out areas at risk. With the growing appreciation that development should be risk-informed, social scientists have developed methods and tools to understand social processes and vulnerabilities. One positive result has been a tentative trend toward lower global risk to life from seismic ground motion.

Other types of hazard have not followed this trend: rapidly increasing coastal populations have revealed vulnerabilities to coastal and hydrometeorological hazards, for example. Rapid urbanization has continued unabated in developing countries, with settlements growing in harm's way, and the most vulnerable people continuing to build and live in new non-engineered houses. The disasters of 2017—from severe hurricanes, to forest fires and the ensuing mudslides—have provided ample evidence of this increasing vulnerability, in both developed and developing countries.

At the same time, we have entered a golden age for data collection, analysis, and sharing. Data can be collected in new ways: through community mapping efforts, by street cameras mounted on cars, or by drones, aircraft, and a variety of satellites. Advances in cloud computing and machine learning have made it possible to host and analyze copious amounts of data using approaches that have been developed only in the past few years. Inexpensive cell phones, social media, and other means of electronic communication provide novel methods for sharing risk results. Risk modelers are challenged to leverage this progress by improving their models and data sets.

These advances have prompted the development of new approaches to collecting risk-related data and novel methods for estimating risk. New private sector companies have already been formed to exploit such advances. Some use machine learning to develop and market site-specific exposure data for every building in the United States. Others use machine learning to develop novel approaches for use in new types of risk models.

It's also the case that more traditional approaches to risk modeling are being applied to new perils and to previously unmodeled regions. These efforts are particularly important for the developing world, which has lagged behind developed countries in risk modeling.

As illustrated in this publication, results from risk models can be used to inform disaster risk management planning—in the development of financial products, in improved and better-enforced building regulations, and for planning purposes. Some of the events described in these pages provide lessons that may be applied locally to reduce the impact of an extreme event—for example, the implementation of earthquake-resistant building codes by a city or regional government, or crop diversification by farmers in an area prone to flooding. Others, like a Tambora-scale eruption or another Carrington event, have global implications and require a global response in anticipating massive disasters and building resilient systems.

The combination of urbanization and climate change will be marked by an intensification in the frequency and severity of hydrometeorological hazards, with a dramatic increase in loss potential, especially in areas of increased social vulnerability or increased urban density and industrialization. The resulting challenges will require the deployment of every tool in the disaster risk management tool box—from the technologies of the present and the future, to the illuminating and instructive lessons of the past.

An important area where work remains to be done is in engaging non-practitioners, in part by communicating risk—and steps aimed at reducing risk—in an understandable and actionable way. This publication is part of that effort. Its goal was to offer stories of past disasters, and explore their implications for the present, in an interesting and accessible way. We hope readers have gained a new understanding of risk. We hope further that their knowledge will inform future discussions and actions related to disaster risk management, and ultimately contribute to a less risky future. ◎

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ABBREVIATIONS AND ACRONYMS

ARC	African Risk Capacity
BNPB	National Disaster Management Authority (Indonesia)
BPBD	Local Disaster Management Agency (Banda Aceh, Indonesia)
CENAPRED	National Center for Prevention of Disasters (Mexico)
CME	coronal mass ejection
CVGHM	Center for Volcanology and Geologic Hazard Mitigation (Indonesia)
DEM	digital elevation model
D-RAS	Disaster-Resilience Analytics and Solutions
ERN	Evaluación de Riesgos Naturales
GDP	gross domestic product
GFDRR	Global Facility for Disaster Reduction and Recovery
GPS	Global Positioning System
HURDAT	National Hurricane Center Hurricane Database
IBC	International Building Code
IED	industry exposure database
KSB	Knowledge Silo Breaker
MMI	Modified Mercalli Intensity scale
NDMP	National Disaster Management Plan (Indonesia)
nT	nano-Tesla
REKOMPAK	community-based approach for large-scale reconstruction and rehabilitation
SASMEX	Mexican Seismic Alert System
SINAPROC	National System for Civil Protection (Mexico)
TEV	total exposed value
UNISDR	United Nations Office for Disaster Risk Reduction
USGS	United States Geological Survey
VDAP	Volcano Disaster Assistance Program of the U.S. Geological Survey
VEI	Volcanic Explosivity Index

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GFDRR
Global Facility for Disaster Reduction and Recovery

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