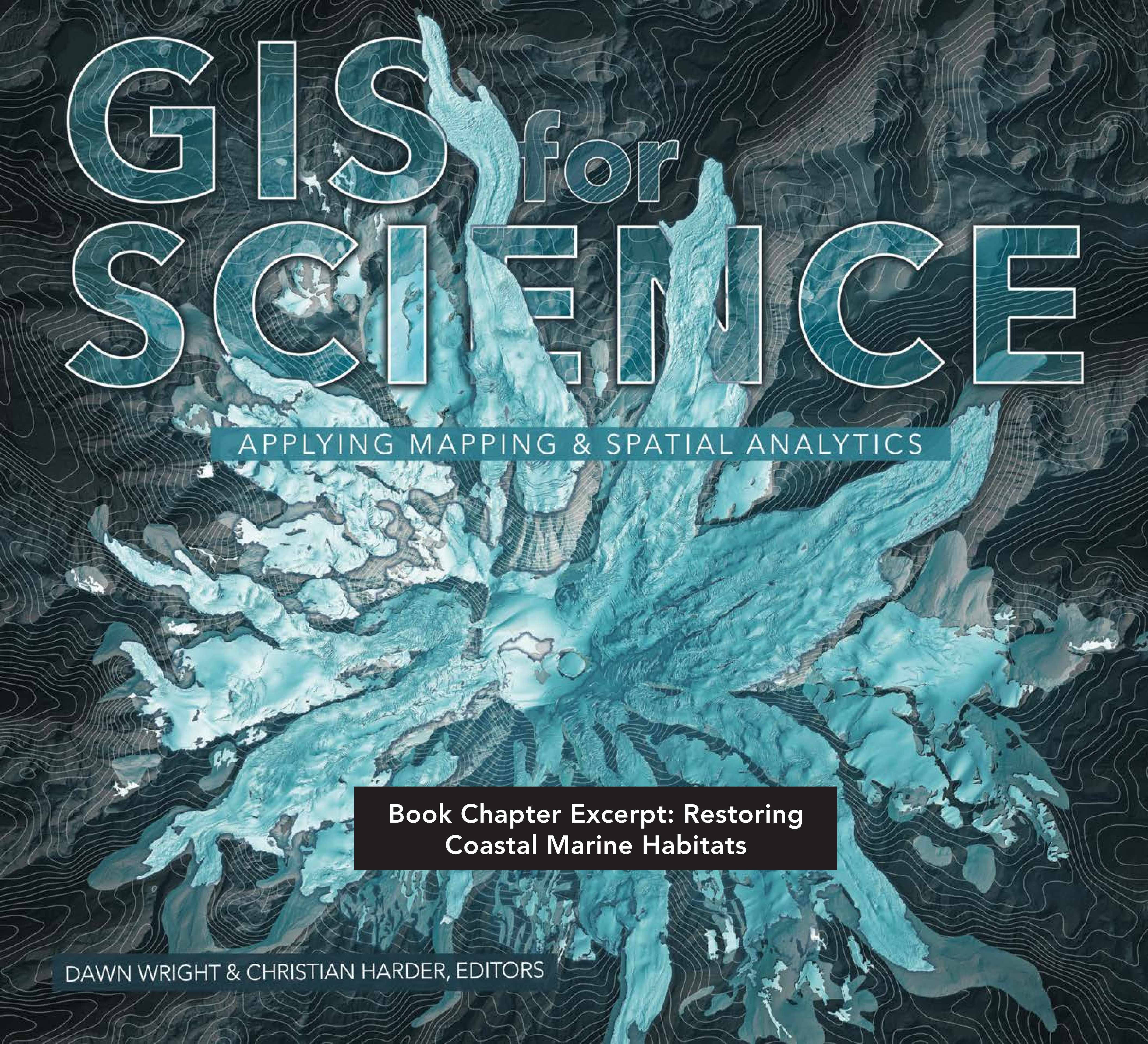

GIS for SCIENCE

APPLYING MAPPING & SPATIAL ANALYTICS

Book Chapter Excerpt: Restoring Coastal Marine Habitats

DAWN WRIGHT & CHRISTIAN HARDER, EDITORS

GIS for SCIENCE

APPLYING MAPPING AND SPATIAL ANALYTICS

DAWN J. WRIGHT AND CHRISTIAN HARDER, EDITORS

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The cover image shows a lidar-derived colored hillshade of glacial ice and snowfields on Mount Rainier in Washington State, United States, compared to the glacial extent of the same area from 1924. The lidar data is from a survey completed in 2008 by the National Park Service. Image by Daniel Coe, Washington Geological Survey. The lidar portion of the image was modified from Robinson, Joel E., Thomas W. Sisson, and Darin D. Swinney. 2010. Digital Topographic Map Showing the Extents of Glacial Ice and Perennial Snowfields at Mount Rainier, Washington, based on the LIDAR survey of September 2007 to October 2008: US Geological Survey Data Series 549. The 1924 extent of glacial ice was derived from: US Geological Survey, 1924, Mount Rainier Quadrangle, Washington: US Geological Survey, 1 sheet, map scale 1:125,000.

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“This beautifully illustrated and inspiring book brings home the power of today’s technology with unique effectiveness, telling and illustrating stories from the earth sciences in novel and powerful ways. A must-have book for anyone concerned about the planet’s future.”

—Mike Goodchild, distinguished emeritus professor and research professor of geography, UC Santa Barbara

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GIS FOR SCIENCE: A FRAMEWORK AND A PROCESS

by Jack Dangermond, Founder and President, Esri
and Dawn J. Wright, Chief Scientist, Esri

Science—that wonderful endeavor in which someone investigates a question or a problem using reliable, verifiable methods and then broadly shares the result, has always been about increasing our understanding of the world. In the beginning, we applied geographic information systems (GIS) to science—to biology, ecology, economics, or any of the other social sciences. It wasn't until around 1993, when Professor Michael Goodchild coined the term *GIScience,* that the world began to realize that GIS is a science in its own right. Today, we call this The Science of Where®. GIS incorporates sciences such as geology, data science, computer science, statistics, humanities, medicine, decision-support science, and much more. It integrates all these disciplines into a kind of metascience, providing a framework for applying science to almost everything, merging the rigor of the scientific method with the technologies of GIS. The study of where things happen, it turns out, has great relevance.

So why is this work all so important right now? We live in a world that faces more and more challenges. We see, we hear, and we read daily about such issues as growing population (some would say overpopulation), climate change, loss of nature, loss of biodiversity, social conflicts, urbanization, natural disasters, pollution, and political polarization. We also confront the realities of food, water, and energy shortages, and general overconsumption of resources. These concerns are not trivial for the individuals and organizations working in these fields. We must do everything we can to better understand these crucial issues and form better collaborations to address the challenges.

Our world at the same time is undergoing a massive digital transformation. Science always has been about increasing our understanding of the world. But it is also about using that understanding to enable innovation and transformation. It is about what we can measure, how we analyze things, what predictions we make, how we plan, how we design, how we evaluate, and ultimately, how we weave it all together in a kind of fabric across the planet.

What GIS provides is a language to help us understand and manage inside, between, and among organizations, to positively affect the future of the planet. It is also a framework in which we can compile and organize maps, data, and applications. We can visualize and analyze the relationships and patterns among our datasets, perform predictive analytics, design and plan with the data, and ultimately transform our thinking into action to create a more sustainable future. This technology also delivers a new way to empower people to easily use spatial information. As Richard Saul Wurman has said, "Understanding precedes action." Esri is driven by the idea that GIS as a technology is the best way to address the challenges of today and the future.

> Science itself is driven by the organic human instinct to dream, to discover, to understand, to create.

This book is full of examples that show how GIS advances rigorous scientific research. It shows how many science-based organizations use ArcGIS as a comprehensive geospatial platform to support spatial analysis and visualization, open data distribution, and communicate. In some cases, we use this research to preserve and restore iconic pieces of nature—revered and sacred places worthy of being set aside for future generations. These places belong to nature, and they also belong to science.

As scientists, the discipline of the scientific process is the central organizing principle of our work. But science itself is also driven by the organic human instinct to dream, to discover, to understand, to create. The Science of Where is a concept that brings these impulses together as we seek to transform the world through maps and analytics, connecting everyone, everywhere, every day through science. At Esri, we can't wait to see what you and your colleagues will achieve with geospatial technology.

INTRODUCTION BY THE EDITORS

This book is about science and the scientists who use GIS technology in their work. This contributed volume is for professional scientists, the swelling ranks of citizen scientists, and anyone interested in science and geography. Our world, now two decades into the twenty-first century, seems to be entering a crucial time in history in which humanity still can create a sustainable future and a livable environment for all life on the planet. But if we look critically at the facts, no informed observer can refute the reality that the current downward trajectory does not bode well.

Our first objective in assembling this volume was to select relevant and interesting stories about the state of the planet in 2019. We looked for a cross section of sciences and scientists studying a wide range of problems.

GIS has found its way into virtually all the sciences, but the reader will notice that earth and atmospheric sciences are especially well represented. Web GIS patterns and a simultaneous explosion of earth-observation sensors fuel this growth. Between all the satellites, aircraft, drones, and myriad ground-based and tracking sensors, the science community is now awash in data. Well-integrated GIS solutions integrate all this big data into a common operating platform—a digital, high-resolution, multiscale, multispectral model of our world.

Despite all these advances, science is under attack on many fronts. From fake news to political pressure, science is too often being used as a political tool at a time when level-headed, objective scientific thinking is required. We are convinced that GIS offers a unique platform for scientists to elevate their work above the fray. We invite you to read these stories in any order; the common thread is that all this work happens at the intersection of GIS and science. As you read through these stories, you'll see that GIS is a cross-cutting, enabling technology, whose use is limited only by our imaginations.

In some cases, like the fascinating work of the US Geological Survey in developing global ecosystem characterizations of the land and ocean, GIS and spatial analysis are at the core of the science. These innovations in science could only happen in the context of an advanced GIS. In other cases, like the story of glaciologists using ground-penetrating radar to measure ice loss in the high-country glaciers of Wyoming, GIS embeds itself in the science but is still mission-critical in terms of expedition planning, backcountry navigation, and analysis. GIS also serves as a vital storytelling platform that brings critical details of important research to stakeholders in the local community.

How the book and website work together

It's impossible to describe the full breadth and scope of what GIS means for science and scientists without showing digital examples. So we have created a companion and complement to this book online. You can access it here:

GISforScience.com

This unique website, comprising collections of ArcGIS® StoryMaps℠ stories, apps, and digital maps, brings the real-world examples to life and demonstrates the storytelling power of the ArcGIS® platform. The website also includes links to learning pathways from the Learn ArcGIS site (Learn.ArcGIS.com) and blogs related to the practical use of ArcGIS in each of the case studies.

RESTORING COASTAL MARINE HABITATS

Mapping the bond between people and nature, scientists are using geospatial technologies to build coastal resilience by addressing rising sea levels and other impacts of climate change.

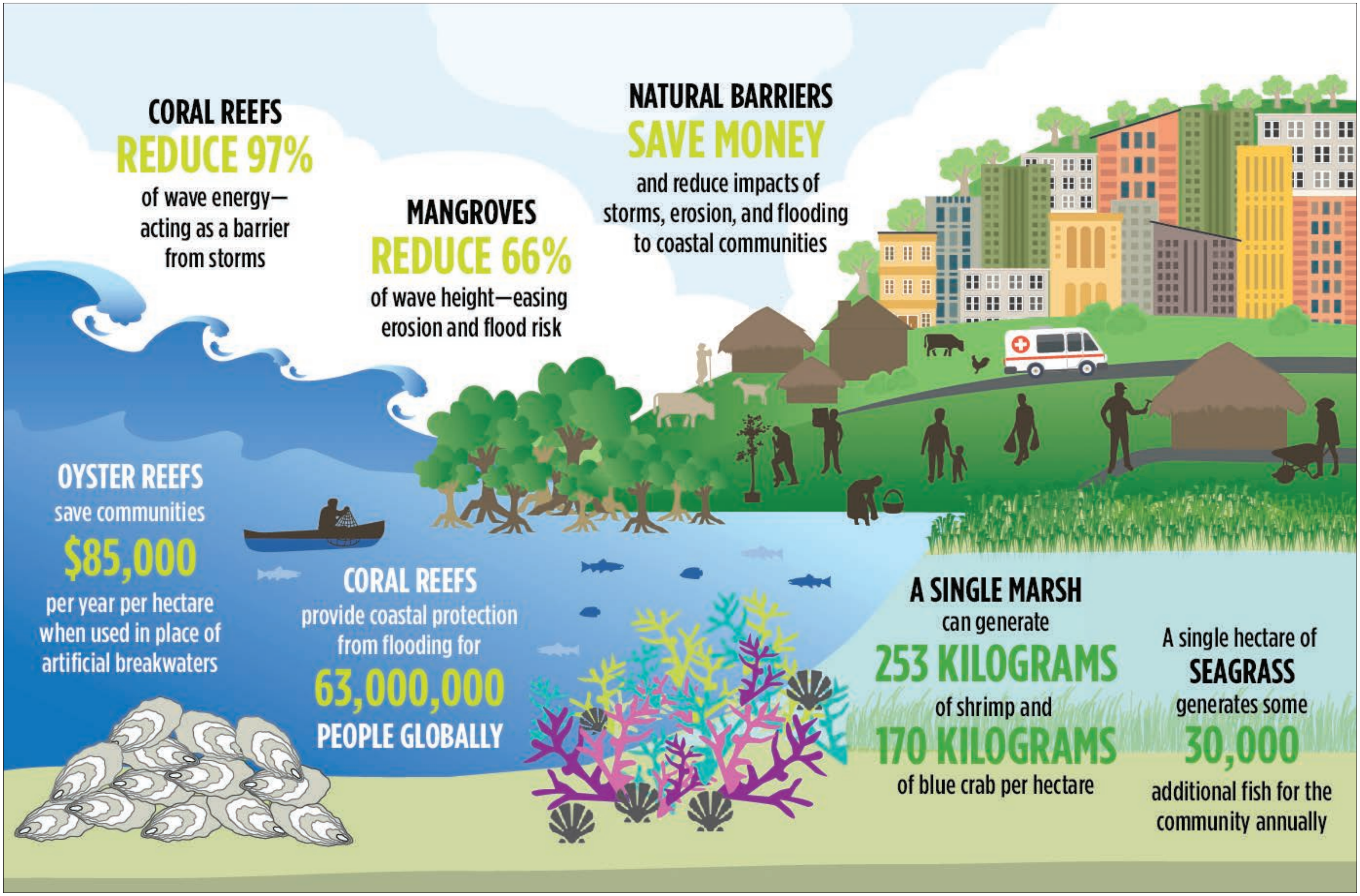
By Zach Ferdaña, Laura Flessner, Matt Silveira, and Morgan Chow, The Nature Conservancy; Tom Brouwer, FloodTags, and Omar Abou-Samra, American Red Cross

Nature reasserting its presence at a coral reef breakwater structure in Grenville Bay, Grenada. By understanding nature, marine scientists and engineers are devising ways to reverse the effects of habitat degradation and coastal erosion. Photo credit: Tim Calver

USING NATURE-BASED SOLUTIONS

Coastal communities around the world increasingly see and feel the impacts of climate change. More intense and frequent storms and hurricanes, coupled with rising seas, are changing the land and seascape and dramatically forcing cities, organizations, and nations to reconsider how and where to invest their coastal resources. Storms and floods affect hundreds of millions of people, important infrastructure, and tourism, causing significant losses to local and national economies and livelihoods. For more than 60 years, The Nature Conservancy (TNC), has been well known for acquiring, conserving and restoring coastal habitats and ecosystems around the world to protect nature now and for future generations.

Today, the Conservancy increasingly focuses on enhancing environmental protection to address disaster risk reduction (DRR). The United Nations defines this as any strategy which aims to reduce the damage caused by natural hazards like earthquakes, floods, droughts and cyclones, through an ethic of prevention. Since 2007, TNC has focused its attention on nature-based solutions, the conservation and restoration of degraded oyster and coral reefs, tidal marshes, and coastal mangroves as viable DRR alternatives. Working in public-private partnerships, the group has coined the term *Coastal Resilience*, the combined efforts to help address the devastating effects of climate change and natural disasters.



Some of the most effective strategies for reducing flood risk are rooted in restoring natural infrastructure that has always protected coastal environments.

WHAT IS COASTAL RESILIENCE?

Resilience is the capacity of a system to absorb disturbance and still retain its basic function and structure. With natural disasters and climate change, this definition should be expanded to recognize that our social and ecological systems must be nimble or adaptable in how we manage and sustain our communities and the natural world. This area is where GIS science and geospatial design, or geodesign, can help support this expanded concept of resilience. Geodesign is a design and planning method that tightly couples the creation of design proposals with impact simulations informed by geographic contexts (Flaxman 2010). Simply put, geodesign informs resilience to support communities in adaptive planning. The goal aims to empower stakeholders in this Coastal Resilience adaptive-management approach to help communities become more climate resilient using natural ecosystems as part of the solution.

The Coastal Resilience program led by TNC includes projects undertaken in the past decade in the Caribbean, Southeast Asia, Australia, Mexico, Central America, and in most US coastal states to continually examine nature's role in the reduction of coastal flood risk. The general ideas of an ecosystem-based approach are considered globally, but the use of GIS and online mapping decision-support systems allow pinpointed conservation and climate-resilience planning.

Geodesign supports this expanded concept of resilience. The Coastal Resilience approach allows stakeholders take a series of steps to reduce the ecological and socioeconomic risks of coastal hazards:

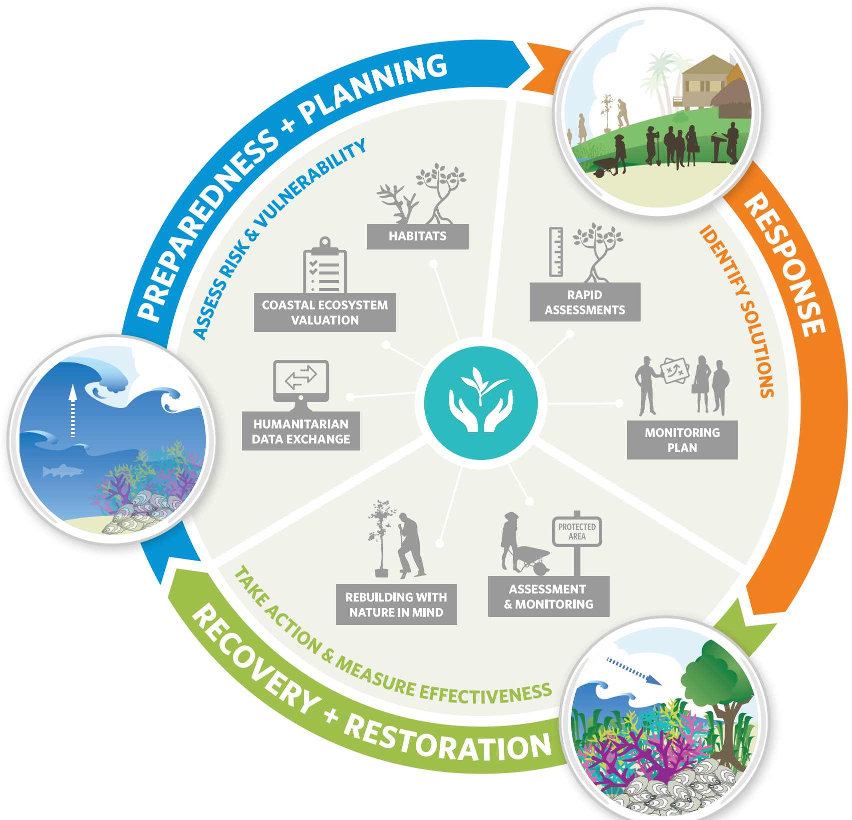
1. Assess risk and vulnerability to coastal hazards by including current and future storms and sea level rise.
2. Identify potential solutions for reducing risk that benefit social, economic, and ecological systems.
3. Act to help communities develop and implement these solutions.
4. Measure solution effectiveness to ensure that efforts to reduce risk through restoration and adaptation are successful.

The backbone of the approach is communicated through a decision-support system includes an online mapping tool that helps planners, government officials, and communities develop risk reduction, restoration, and resilience strategies. A data-viewing platform and suite of web-responsive apps are designed and tailored to meet specific planning needs, including coastal management policies, post-storm disaster decision making, community assessments, hazard mitigation plans, and cost-effectiveness evaluations.

The capacity of natural ecosystems to provide coastal protection and other services, including food production, water purification, carbon sequestration, and tourism and recreation, is critical yet highly variable (Hale et al. 2009; Hale et al. 2011; Spalding et al. 2012; Arkema et al. 2013). The science of nature- and ecosystem-based solutions in reducing coastal community flood risk is growing rapidly. Designers of coastal resilience strategies refer collectively to these nature-inspired strategies as "green infrastructure."

In contrast, built or "gray" (e.g., concrete) infrastructure such as seawalls and dikes helps safeguard coastal communities from flooding events but is often cost-prohibitive, massive building efforts that can take decades to get funded and built. Gray infrastructure also has socioeconomic and ecological drawbacks. These projects can block public access to natural areas, cause undesired erosion of beaches and coastal habitats, and interrupt natural coastal processes that prevent habitat migration and natural adaptation (Flessner et. al 2016). Natural adaptation can include green infrastructure, such as the creation of new beaches and dunes, marshes and mangroves, and coral and oyster reefs—so-called "soft-engineered" solutions, also called *nature-based* solutions.

Coupled with an increased effort to identify where coastal ecosystems can reduce flood risk, there has been a growing awareness of the need to develop collaborative partnerships and programs between humanitarian and environmental organizations. TNC, through its growing body of work in climate adaptation and mitigation, has formed a partnership with the International Federation of the Red Cross (IFRC). Explicitly incorporating the conservation of ecosystems into the risk reduction equation gives communities the information they need to find the most cost-effective and multi-beneficial adaptation solutions (Ferdaña et al. 2010; Ferrario et al. 2014; Groves et al. 2012; Halpern et al. 2012; Narayan et al. 2016; Whelchel and Beck 2016). Through collaboration on specific projects in the Caribbean and Southeast Asia that will be highlighted in this chapter, this initial round of work aims to help both TNC and Red Cross identify the most effective ways to integrate ecological disaster risk-reduction efforts within the humanitarian program cycle.



The Coastal Resilience program approach: Ecosystems are valuable for mitigating risk and supporting development and humanitarian goals. Incorporating conservation principles in risk-reduction plans gives communities the information they need to lower costs, discover benefits, and find creative solutions.

CASE STUDY: AT THE WATER'S EDGE

For decades on Grenada's eastern shore, climate change has adversely affected the communities of the Grenville Bay area (Telescope, Grenville, Soubise, and Marquis). Storms, rising seas, and changing temperatures threaten lives and property. A drastic decline in the health of the fringing coral reef and the overharvesting of mangroves exacerbate issues such as flooding and severe coastal erosion.

In 2012, TNC partnered with community members, nongovernmental organizations (NGOs), and government agencies to address these and other environmental challenges through the implementation of strategies aimed at building artificial coral reefs. (The word *artificial* is misleading: over time, what starts as artificial structures eventually become part of nature.) Using resilience and geodesign principles, this effort combined scientific data modeling and interactive mapping tools with traditional community knowledge. The goal was to answer this question: Can complex modeling of waves and wind, coupled with an online mapping tool, effectively support local communities and government ministers?

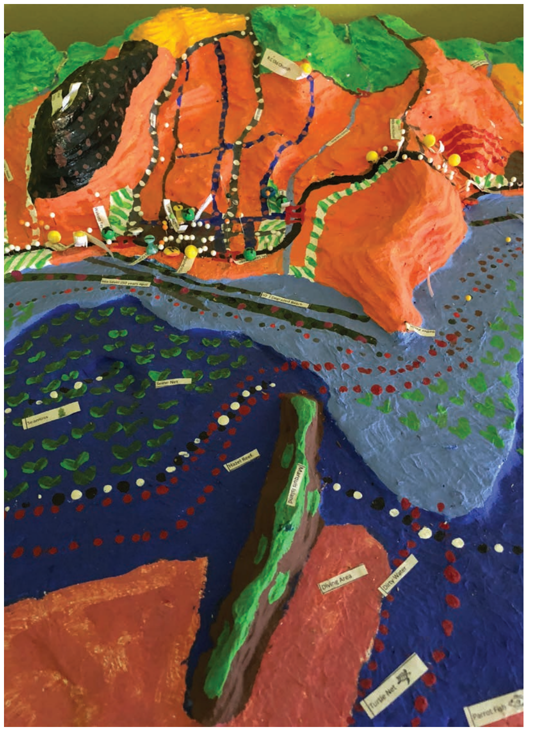
Accessing tools to identify solutions

Our initial efforts began with the development of the web-based, Coastal Resilience decision-support tool to help government planners and managers further understand specifically where they were most vulnerable. The tool enabled users to test scenarios using census data, data on storm surge occurrences, rise in sea level, existing natural resources, and other community assets, while developing practical restoration solutions that benefit people, nature, and infrastructure. The resulting maps and models helped users layer socioeconomic and vulnerability data to identify and compare areas of concern with areas of potential resilience. Despite national-level advancements in natural sciences and spatial analyses, high-tech, computer-based tools were inaccessible to many local decision makers, who are an integral part of the resilience approach. To further engage with the impacted communities, TNC teamed with local organizations, including the Grenada Fund for Conservation and Grenada Red Cross Society. Participatory 3D physical maps are a widely accepted method for capturing local knowledge and values through a 3D model of a specific site. By creating a large model of Grenville Bay, nearly 500 residents visualized their communities and highlighted important sites of cultural, economic, and historic value. The map captured and incorporated their knowledge into a dataset that informed the vulnerability assessment process. The dataset also informed the process of selecting cost-effective and culturally appropriate ecosystem-based adaptation strategies that would benefit the community and coastal landscape. Spatial indices such as adaptive capacity, social sensitivity, and critical infrastructure were created, identifying Grenville Bay as the target site because of its high vulnerability to coastal hazards and low adaptive capacity.

To identify and implement potential nature-based solutions in Grenville Bay, TNC collaborated with IH Cantabria to generate 3D digital models from more than 60 years of wave data. The models incorporated different coral reef breakwater design scenarios to understand the best position and placement of breakwaters for reducing coastal erosion and flood risk. The scenarios helped government officials and community leaders identify where breakwaters enhance shoreline protection and thereby improve social, economic, and cultural systems within the Grenville Bay communities. By coupling model results fed into the online decision-support tool with community participation, we empowered stakeholders to select options that best align with their community vision (i.e., prioritizing beach access and enhancing fisheries).

> "We are able to bring people together with nature, making them more resilient and able to adapt and combat the issue of climate change and even disaster hazards that would affect the community at the water's edge."
>
> —Terry Charles, Grenada Red Cross Society

Grenville Bay, Grenada, location of the coral reef breakwater project.



3D cardboard model developed and labelled by stakeholders and government officials highlighting Grenada's land and water resources.

Taking action

The community chose a solution that included the pilot installation of low-crested, hybrid breakwater structures along a degraded reef flat. To maximize economic and ecological benefits, the structures were engineered to meet these design criteria:

- Withstand hurricane wave forces
- Have a minimum lifespan of 30 years
- Promote coralline algae and coral growth
- Provide habitat for fish, lobster, and other commercially important species
- Use local material in their construction
- Be installed by local workers

In 2015, TNC worked with the communities to construct and deploy an initial 30 meters of constructed rebar baskets filled with rocks and hollow concrete blocks, using 15 local fishermen and a local commercial dive operator to transport the baskets. Coral fragments, termed *fragments of opportunity*, were affixed to the installed baskets.

Measuring effectiveness

The project team has monitored the structures to assess their ability to withstand forces, such as wave energy and sand blasting, and their capacity to host crustose coralline algae and other species. Reports indicate that most of the structures have crusted over with coralline algae, which adds to their strength and security. Coral recruits are prevalent, with fish and lobster preferring the steel rebar cages filled with cavernous blocks, as compared with the structures made with only rocks. This pilot structure is now helping inform the build-out of an additional 20 structures along the reef flat, totaling 300 meters.

The At the Water's Edge (AWE) project demonstrates that governments and communities of small island states can enhance their resilience to climate change by protecting, restoring, and managing their marine and coastal ecosystems through capacity building and adaptation. This flagship project between TNC and the Red Cross strengthened our understanding of community resilience using coral reef engineering solutions, setting the stage for more collaboration globally.

Coral reef growth on the breakwater structure one year after implementation, in 2015. The structures are designed to restore the wave-breaking function of the reef, and therefore reduce wave energy reaching the shore, which typically exacerbates coastal erosion and flooding. (Photo by Tim Calver.)

Divers survey the pilot breakwater structure for coral reef growth and structural integrity. (Photo by Tim Calver.)

CASE STUDY: RESILIENT COASTAL CITIES

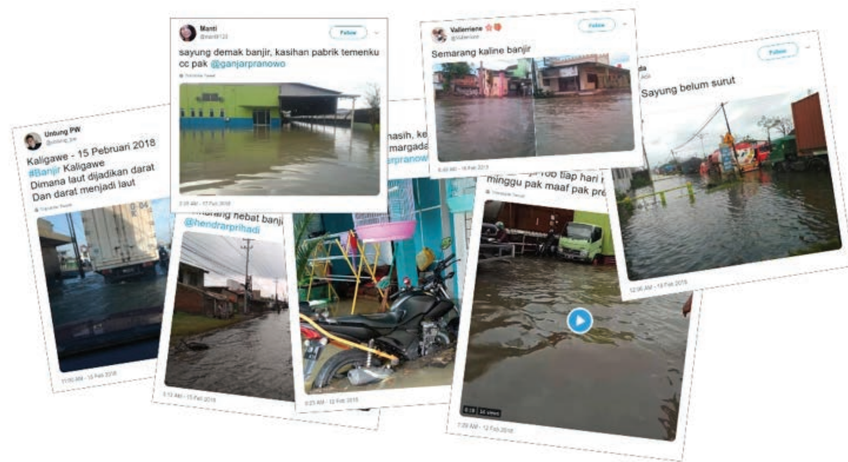
The Resilient Coastal Cities project builds local coalitions to identify and enhance community resilience. Led by the American Red Cross and the Global Disaster Preparedness Center (GDPC), the project builds on existing approaches to community assessment, problem-solving, and outreach on preparedness measures developed by the local Red Cross network in Indonesia. The Red Cross increasingly integrates environmental management within the humanitarian program cycle (preparedness, response, and recovery) in partnership with TNC, building green approaches to disaster-risk reduction.

In this use case, TNC's Coastal Resilience program leveraged geospatial technology to assess risk and vulnerability from flooding, identify nature-based adaptation solutions, take conservation and restoration action, and measure effectiveness of solutions. Here TNC studied the role of mangroves in protecting the coast from flooding in Semarang, Indonesia.

The geospatial framework aimed to combine real-time flood risk with community vulnerability and natural resource mapping into a replicable and scalable approach to help identify possible adaptation solutions for city planning.

Social media tools for real-time flood mapping

The coalition identified FloodTags, a social enterprise based in the Netherlands, as a critical component of the framework for identifying when and where floods are happening or have occurred. By monitoring flood-related information from social media and consuming flood reports through direct messaging apps, they detect floods in real time and provide practical information about floods. For this project, FloodTags analyzed flood reports from Twitter, which is popular in Indonesia, to detect flood events for Semarang and other places along the north coast of Central Java.



Examples of flood-related tweets for the north coast of Central Java, Indonesia.

> "We need to stay relevant and progressive, thinking creatively rather than just doing things how we have always done them."
>
> —Omar Abou-Samra, director, Global Disaster Preparedness Center (GDPC)

Workflow

This analysis included the following steps:

1. Collecting flood-related tweets from the Twitter streaming API, using Indonesian (Bahasa) flood-related keywords.
2. Tweets were classified using a machine-learning algorithm, extracting water depths from them, detecting locations from the text, and determining whether extreme rainfall occurred at these locations.
3. Flood events were detected by comparing the volume of tweets for each location to historical statistics.
4. Enriched flood reports and events were distributed through an API in real time.

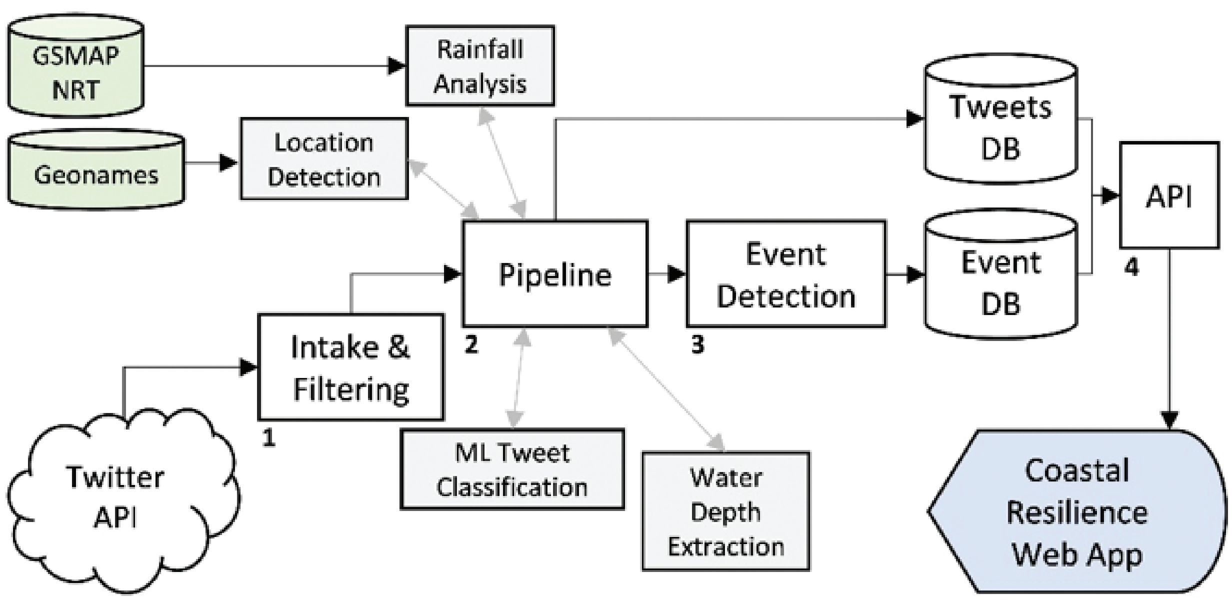
The coalition derived the locations from the text of the tweets. Since the location of the flood may not be the same as the location of the person tweeting about it, the GPS coordinates of a tweet were not directly used. Instead, the location names mentioned in the body text were geo-parsed using the Geonames database (see: Geonames, n.d.). Additional metadata from the tweets, including the location of the user, their time zone, GPS coordinates of the tweet, and the names of other locations referenced in the text were used to find the most likely location (in case a location name occurs in multiple places) (see De Bruijn et al. 2018). For this project, locations were derived up to level 4 administrative areas (called Kelurahans or Desas, small neighborhoods) on the north coast of Central Java.

Satellite-derived rainfall data (JAXA 2018) was also used to determine whether extreme rainfall occurred at the derived locations. For this analysis, a history of GSMAP data, dating back to 2008, was analyzed to derive rainfall statistics for each raster cell. Based on these statistics, the percentile of rainfall amounts was determined in near real time, which is an indicator of extreme rainfall. Each tweet with a derived location was then assigned the highest hourly rainfall percentile that occurred over the 24-hour period prior to the tweet being posted.

The tweet classification algorithm was trained using a system called the *Relevancer* (Hürriyetoğlu et al. 2016). TNC staff in Indonesia used this system to divide batches of similar tweets into "flood," "flood-related," "mixed," and "irrelevant" classes. After training the algorithm, it has since been implemented to classify tweets in real time.

To detect events, the number of incoming tweets for level 2 administrative areas (including underlying level 3 and 4 areas) were compared with historical statistics for these areas. In case a spike in the number of tweets is detected for an area, the system will flag this increase as a flood event.

The individual flood reports and the events are distributed through the FloodTags API. As floods occur, flood-event data from tweets will automatically update the Resilient Coastal Cities web app, which is connected to the API, allowing the coalition to monitor vulnerable flood areas by administrative unit in real time.

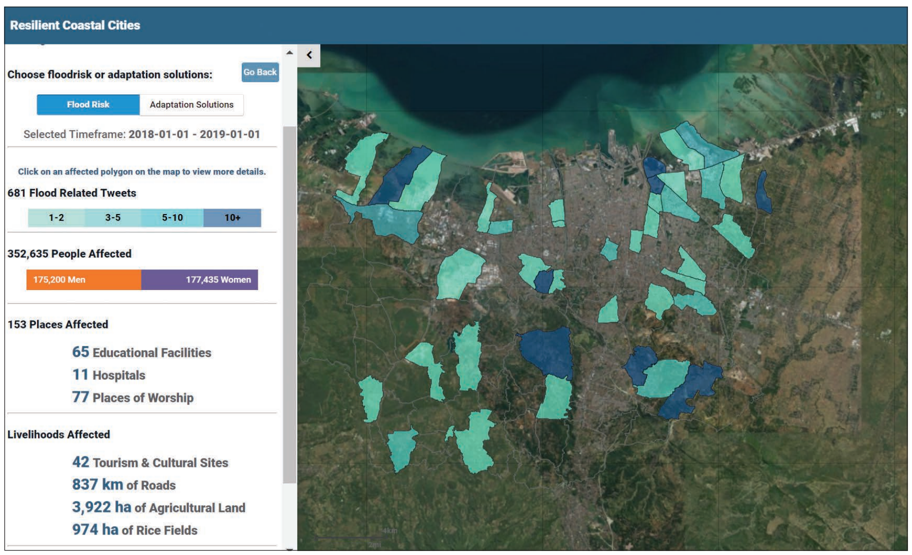


FloodTags performs several analysis steps on the flood related information collected from Twitter, to validate the information, detect locations from it and classify the messages. The analyzed messages as well as the flood events detected from them, are distributed through an API that's connected to the Coastal Resilience web app (preparecenter.org/rcc).

Socio-ecological urban analysis

The socio-ecological analysis supports two workflows within the decision-support tool: flood risk and adaptation solutions. The flood risk portion of the tool helps identify where the most people, places, and livelihoods are at risk from flooding within an administrative unit (kecamatan) and would therefore get the most benefit from nature-based adaptation solutions to reduce this risk. Key flood risk parameters were selected based on availability and scale of the data, summarized within each administrative unit, and spatially joined with the real-time flood reports extracted from FloodTags' API.

The user can view either the most recent flood event or a single selected past flood event, or can specify a date range to view cumulative flood reports. Viewing cumulative reports highlights the most vulnerable areas where nature-based solutions can be prioritized to reduce flood risk. Initially, the summary statistics are provided as a sum across all kecamatans; however, the user can click on an individual kecamatan or administrative unit on the map to visualize the summary statistics in their area of interest. Further, the tool implements the Open Street basemap, which allows users to zoom in to view infrastructure footprints and labels. With this information, a planner or disaster manager can quickly assess potential impacts of a single flood event or highlight areas that show trends of repetitive flooding over time to help prioritize both short-term response and longer-term adaptation actions.



Resilient Coastal Cities Explorer demonstrating tweet-derived floods by the city administrative unit in Semarang, Indonesia.

Theme	Metric per admin unit	Rationale
RISK: Potential flood impacts on people	Number of tweets related to flooding	Real-time social media data on observed flooding helps to ID chronic flooding areas to help prioritize response and recovery actions.
RISK: Potential flood impacts on people	Number of people potentially affected	The more people affected, the more potential socioeconomic impacts felt across the region.
RISK: Potential flood impacts on places	Number of educational buildings potentially affected	Schools and research facilities often provide shelter options during natural hazards. Interruption in educational activities could also have an economic impact if parents are forced to stay home with children.
RISK: Potential flood impacts on places	Number of buildings of worship potentially affected	Places of worship provide shelter and community support during and after natural disasters.
RISK: Potential flood impacts on places	Number of hospitals potentially affected	Could impact care and response time to emergencies.
RISK: Potential flood impacts on livelihoods	Length of roads potentially affected (km)	Flooding of major roads can shut down key routes to economic centers and prevent people from getting to work, negatively impacting their livelihoods and the businesses.
RISK: Potential flood impacts on livelihoods	Area of ag land potentially affected (ha)	Damage to ag land impacts farmers and consumers.
RISK: Potential flood impacts on livelihoods	Number of tourism and culturally important sites potentially affected	These areas provide rec/tourism benefits to the economy.
RISK: Potential flood impacts on livelihoods	Area of rice fields potentially affected (ha)	Damage to ag land impacts farmers and consumers.
ADAPTATION SOLUTION	Number of low production rice fields	Areas that have been deemed "low productivity" by the Ministry of Geospatial Agriculture (Kementrian Pertanian Geospasial) may be areas to prioritize for mangroves/wetland restoration if rice is no longer economically viable.
ADAPTATION SOLUTION	Area of convertible rice fields (ha)	Areas deemed as "rice fields that can be converted" by the Ministry of Geospatial Agriculture (Kementrian Pertanian Geospasial) may be areas to prioritize for mangroves/wetland restoration if rice is no longer economically viable.
ADAPTATION SOLUTION	Area of potentially restorable mangroves (ha)	Historical mangrove areas that have been identified as potentially restorable in prior analyses.

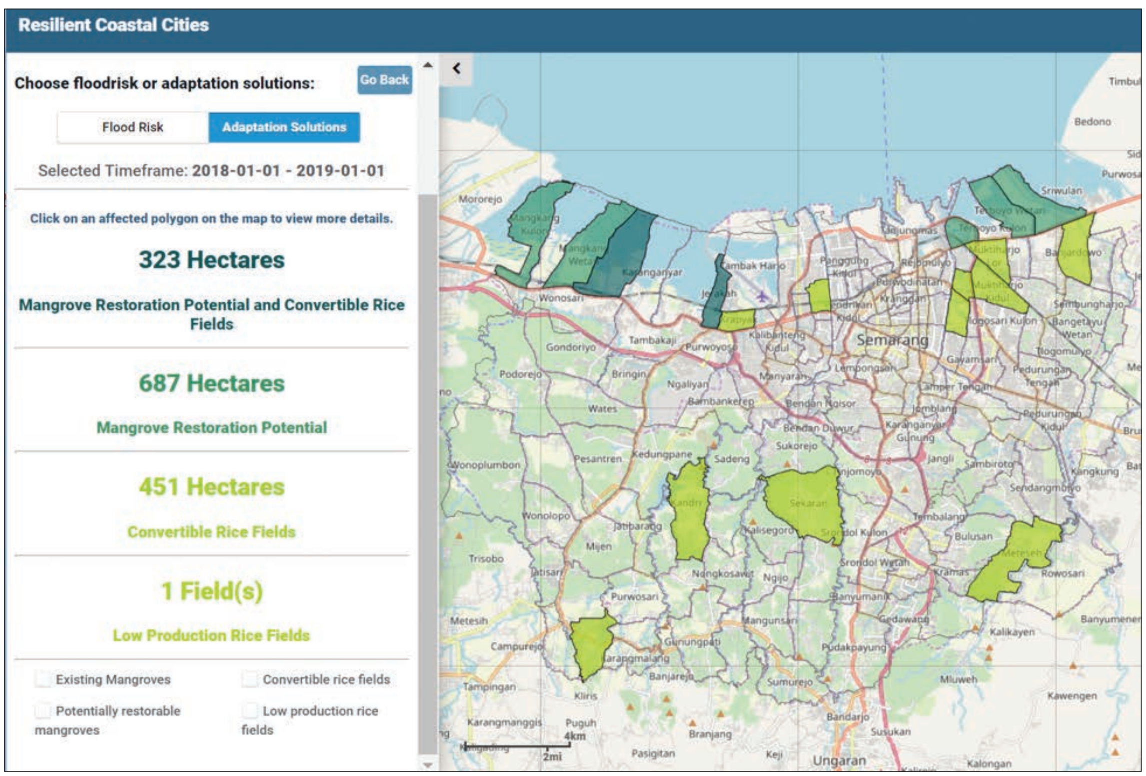
Flood risk and adaptation solution parameters summarized in the Resilient Coastal Cities Explorer decision support tool.

Once a user has explored a community's flood risk, the adaption solution workflow helps visualize where potential nature-based adaptation actions overlap with areas that are reporting flooding based on the selected flood event(s). Adaptation solutions were selected based on actions that are feasible in the region, namely mangrove restoration and open space reclamation/preservation. Key metrics for each parameter were summarized by kecamatans reporting flooding for the selected event(s) and displayed based on solution type with areas that have enabling conditions for more than one adaptation solution highlighted. The ability to view potential adaptation and flood mitigation opportunities alongside real-time flood risk enables planners to consider multiple green or green/gray solutions that will help their communities become more resilient to future flooding while also providing co-benefits back to the community.

Also contributing to the adaptation solutions component are 3D mangrove restoration simulations. The generation of these simulations was inspired by "Building with Nature," a program developed by an organization called Wetlands International. That organization aims to build a stable coastline in Central Java through the construction of permeable dams to support natural mangrove restoration and more sustainable aquaculture production for neighboring coastal communities.

This passive restoration approach uses partially submerged stick structures that allow water to flow through while trapping sediment to mimic the shoreline accretion and erosion control services provided by fully grown mangroves. Once erosion has stopped and the shoreline has accreted (two to five years), mangroves are expected to colonize naturally within three to five years and stabilize the shoreline without manual planting or regular maintenance. As part of the five-year Building with Nature project, the team installed pilot permeable structures in Demak (just northeast of Semarang) in 2015. Since then, they have been tracking progress, and the lessons learned from this case study are intended to be scaled up and leveraged in Semarang in collaboration with TNC Indonesia.

Permeable barrier to trap sediment. (Photo by Nanang Sujana for Wetlands International.)



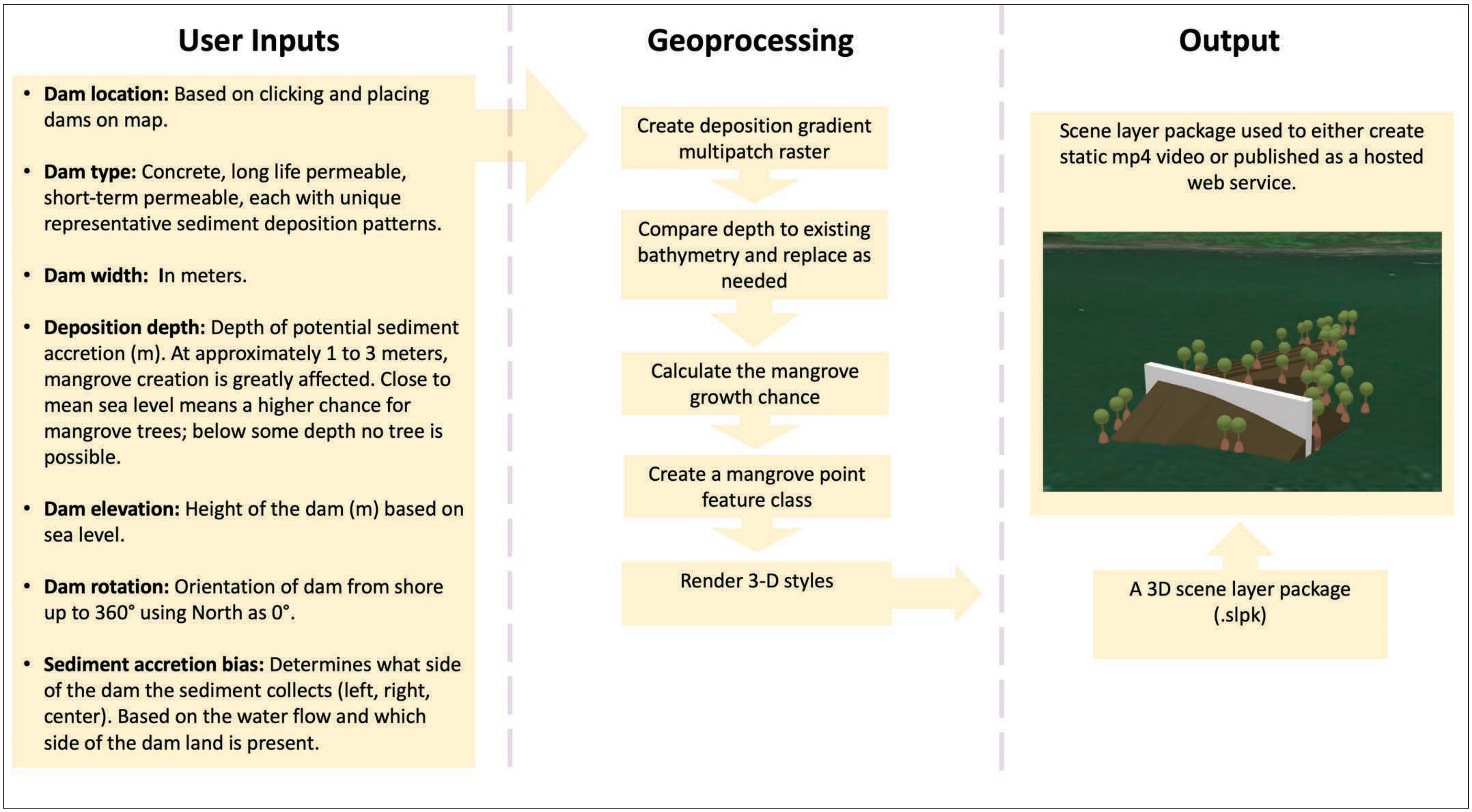
Resilient Coastal Cities Explorer demonstrating possible ecosystem-based adaptation solutions to reduce flood risk by city administrative unit in Semarang, Indonesia.

An ArcGIS Pro model

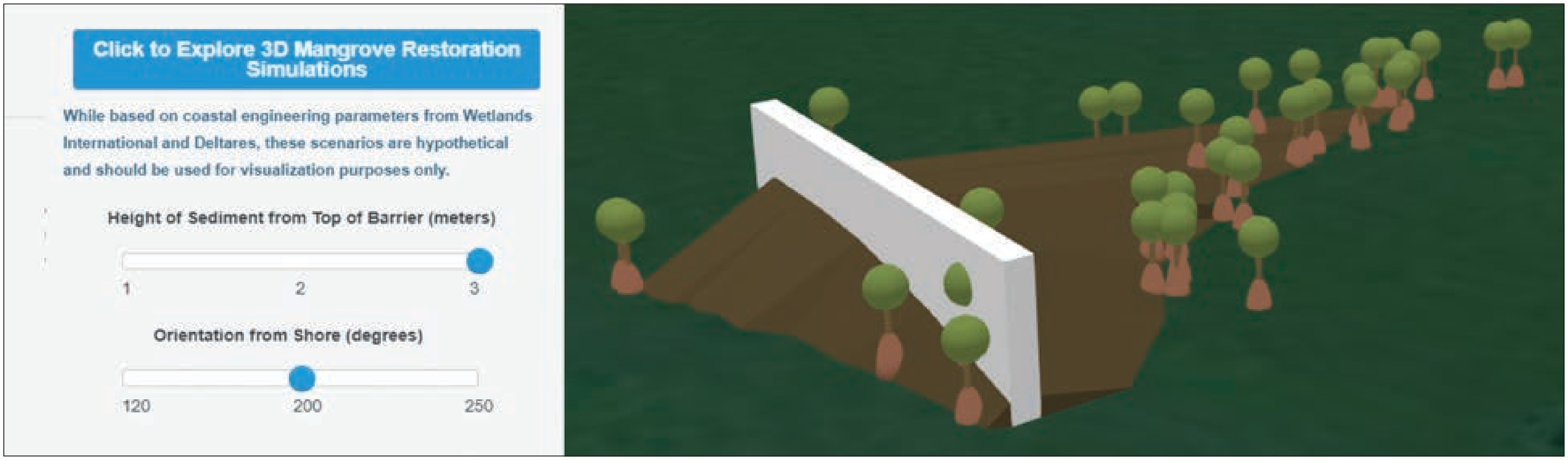
For a similar approach to be successful in Semarang, the Resilient Coastal Cities team identified the need for city planners to better visualize what a landscape-scale mangrove restoration might look like and how it would grow and provide benefits over time. TNC teamed with Esri to develop an ArcGIS Pro 3D geoprocessing model that simulates permeable dam mangrove restoration scenarios based on known coastal engineering parameters from the Demak case study.

User input parameters included dam location, type, width, deposition depth, elevation from mean sea level, rotation from shore, and sediment accretion bias. Using the Multipatch To Raster tool in ArcGIS Pro, the selected deposition gradients were converted to a raster. The model then compared the output deposition gradient raster to existing bathymetry and, through a conditional statement, found where deposition values are higher than the existing bathymetry and replaced it with the higher value.

For each cell replaced, the model calculated the chance of mangrove growth based on depth, where close to mean sea level means a higher chance for mangrove growth, and no mangrove tree is feasible below a certain depth. A point feature class was created based on the resulting probability of mangrove growth, and its elevation was set to mean sea level. The model then displayed the point feature class as green mangrove trees and the multipatch raster as brown sediment using 3D render classes. The result was a 3D scene layer package depicting sedimentation and mangrove growth behind the dam. The model could then be rerun using different parameters to create scene layers across various scenarios. The output from the mangrove model served two different audiences.



Workflow of the ArcGIS Pro 3D mangrove restoration geoprocessing model created to simulate sedimentation and mangrove growth due to permeable dam structures. With the interactive model, users can select the placement and characteristics of the dam structure, set sediment accretion rules, and visualize how those parameters might impact large-scale mangrove growth over time.



ArcGIS Pro model within Esri Javascript 4x API simulating mangrove restoration scenarios.

For the primary audience of planners and decision makers, a "fly through" style video was created within the ArcGIS Pro model, and then exported to an mp4 viewable in the introduction splash page of the Resilient Coastal Cities app. This capability allows a general audience to virtually observe the benefits that mangrove ecosystems provide to communities over time and influences the audience to consider ecosystem-based adaptation solutions to flood risk. The secondary audience, coastal engineers and scientists, can view scenarios published as web services to TNC's ArcGIS® Enterprise portal, where the scenarios are consumed by an Esri JS 4.x version of the Resilient Coastal Cities app.

This version is currently not publicly accessible, as it is still being adjusted with empirical data collected from pilot projects such as Demak. Once the model is vetted, this version will allow users to assess mangrove restoration project siting, feasibility, and implementation in the Central Java region.

Resilient Coastal Cities Explorer web apps

The Resilient Coastal Cities Explorer web app was built in both 3.25 and 4.0 versions of the ArcGIS® API for JavaScript™ to test the new 3D functionality offered in version 4.0 while still taking advantage of the feature-complete 3.25 version. Both versions incorporate the FloodTags API, which uses flood reports from Twitter returned as JavaScript Object Notation (JSON) data, parsed, and displayed on the web map. Whenever the site is loaded, a query is made to FloodTags for the most recent data, giving the user the feel of a "real time" dashboard.

The 3.25 version of the Explorer app uses a combination of dynamic map service layers and graphic layers to display the data on the web map. The dynamic map service layer consumes vector data from an ArcGIS Server map service and displays it on the map as static reference data. The graphic layers allow user interaction such as hovering and clicking to retrieve information about a specific feature. When a user clicks on the map (graphic layer), a Query function is used. The query returns the graphic's attributes as JSON, which is used to update the data (charts and text) on the app panel.

The 4.0 version of the Explorer app is built differently due to changes within the API that allow 3D data to be displayed on the web map where the user can switch between a scene view (3D) and a map view (2D). An ArcGIS feature layer displays vector data from an ArcGIS Server map service, while a graphics layer leverages a new SimpleRenderer to create 3D graphics by adding a z-value to appropriate points and polygons. The mangrove barrier 3D scenes were created in ArcGIS Pro, published in ArcGIS Online, and consumed in the app with Scene View. Both versions of the web app informed a coalition of primary and secondary audiences to consider the value and critical role that mangroves play in the humanitarian cycle of preparedness, response, and recovery from flooding.

Coalition and community engagement

Integrating the geospatial analysis, model, and simulated mangrove restoration scenarios, we presented the 3.25 version of the Explorer app as the final product to the local Red Cross Society in late October 2018 (preparecenter.org/rcc). The goal of the workshop was to review and solicit feedback on the Resilient Coastal Cities Explorer app to the coalition, with a particular focus on how it could be applied to city planning and coastal management in Semarang and Central Java. For the local Red Cross Society, demonstrating the relationship between coastal flood mapping and the identification of where mangroves could reduce risk in the city provided a fresh perspective to preparedness and recovery planning. Community and stakeholder engagement through tools like FloodTags demonstrated how social media-derived information can highlight the vulnerability of critical infrastructure and illustrate repeat flood areas over time. The Explorer app provides city-specific ecosystem data alongside community assets that can help city level planners and stakeholders make more informed decisions. Presented in relationship to disaster management, appropriate ecosystem-based adaptation solutions became a viable option and a critical part in disaster risk reduction. Workshop attendees were trained on the web-responsive app designed for phones, providing valuable feedback on the application's use for local decision support. A first-of-its-kind ArcGIS Pro mangrove model was built for replication for other coastal cities as part of the greater Resilient Coastal Cities project in Southeast Asia.

Conclusion

The state of the environment lies at the heart of humanitarian action. As coastal development increases and people continue to move to the coasts, we need new and improved strategies and tools for risk mitigation to support growth and minimize stress on the environment. Ecosystems are valuable for mitigating risk and supporting development and humanitarian goals. However, the environment is not systematically considered in global humanitarian action. Failing to integrate the environment within the humanitarian program cycle will further exploit natural resources and limit the safety and prosperity of coastal communities. Only by forming alliances between humanitarian and environmental sectors, as illustrated here with ecosystem-based approaches coupled with geospatial technology, can we achieve viable adaptation solutions in response to coastal climate change.

Through collaborations between TNC and the Red Cross, resilience coupled with geodesign provides critical decision support across communities, nature, and geospatial technology. No longer can we separate our reliance on technology from our place in nature. We must use technology to enhance and promote nature as our communities adapt to ever-changing climate conditions. Our tools for decision support must accommodate relevant information to best respond and meet communities' needs with intuitive design, effective communication, and optimal performance. We must integrate these tools into community engagement and coalition-building to achieve feasible and lasting solutions.

The program of Coastal Resilience has evolved over 11 years of scientific research, tool and web app development, and policy implementation with significant investments in a network of successful conservation and restoration sites. Coastal resilience practitioners have trained and supported more than 100 communities worldwide on the uses and applications of the approach, as well as of the decision-support tool, focusing on the identification of ecosystem-based adaptation and risk mitigation solutions. In partnership with the local Red Cross Society in Grenada, we connected coral reef and seafloor data with wind and wave models to plan for the construction of breakwaters that reduce the threat of coastal erosion while enhancing local fisheries. With accessible science via tools and apps, the community of Grenville Bay moved toward mainstreaming nature-based solutions to increase resilience through restoration in the water. In collaboration with the GDPC, we generated mangrove restoration scenarios to help make important planning decisions for communities faced with flooding and erosion.

Translating complex coastal engineering principles to geospatial models communicated through a web-responsive app provided the City of Semarang with viable solutions to address increasing flood events. The best solutions to climate change and disaster risk reduction may depend less on built infrastructure such as seawalls, groins, and levees, and more on rethinking how we value existing natural resources as part of the equation in achieving coastal protection.

"Impossible is not a fact, it is an attitude."

—Christiana Figueres, Secretariat United Nations Framework Convention on Climate Change

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