Adapting flood prediction for the climate crisis era

With the sensational and blockbuster-worthy destruction caused by wildfires, tornadoes, and earthquakes, it might surprise you to learn that floods are the most common and among the most deadly natural disasters in the United States[1]. Then again, it might not—major flood events have been so frequent and so devastating recently that hardly a week goes by without national media coverage of yet another of these natural disasters. Between 1980 and 2023, the United States saw an average of $4.3 billion in flood damage costs, while in 2016, the annual record for billion-dollar flood events doubled from two to four events per year. This astronomical financial cost amounts to roughly two-thirds of the financial impact of all natural disasters combined.[2]

These flood events are increasingly widespread and have devastating impact: Rather than being confined to coastal areas and major rivers, the number of major flood events is rising across the country. FEMA states that 99% of counties in the United States were impacted by some type of flooding between 1996 and 2019, and somewhere in the country has experienced an urban flooding event once every two-three days for the past 25 years.[3] This increase has compound effects for society—not only do floods pose a real and immediate danger to human life, they can also cause serious property damage, destroy vital food crops, undermine local business activity, destroy natural habitats, and drastically alter the physical landscape irreparably.

Why are severe flooding events becoming more and more frequent?

The answer is not simple. To begin with, flood events themselves are multifaceted, encompassing various types of flood sources like coastal surges, fluvial (river overrun), pluvial (flash flooding), urban flooding, and compound floods, where two or more traditional flood types combine to create a major event and which are growing in frequency. Moreover, a multitude of factors contribute to the creation and severity of flood events, including considerations such as rainfall and snowmelt, land use practices, changes in surface vegetation and soil moisture, infrastructure designs (and occasional failures), human behaviors, and many others. As a result, understanding and identifying the causes of even a single flood event proves to be a challenging task.

What is clear is that the global climate crisis, while not a comprehensive correlation to increased flood events, is having both a direct and indirect impact on changes to rates, types, scale, and severity of flood events around the globe. The climate crisis, again, is quite complex, but simply put, the

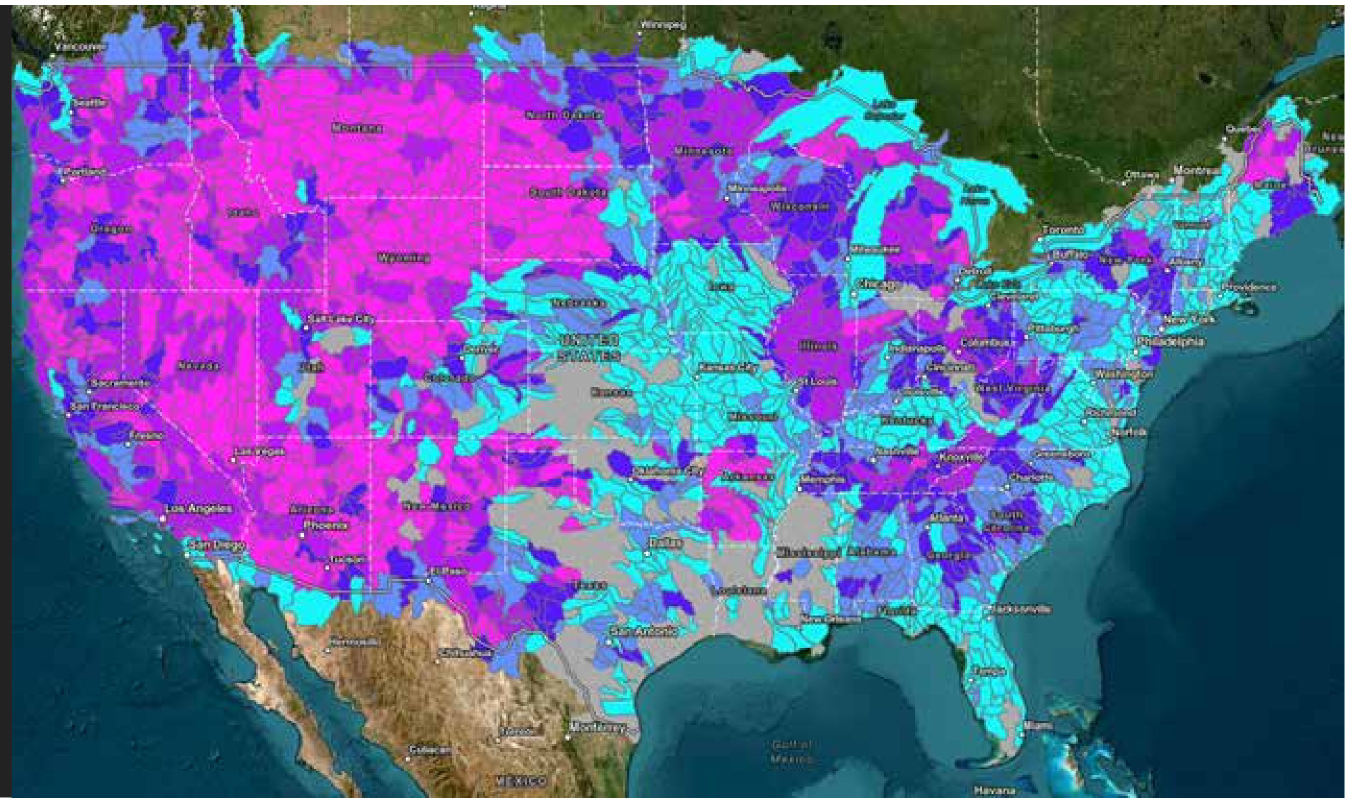
Earth's temperature, which has held relatively steady through a gentle cycle of warming and cooling since the beginning of human life, has begun a rapid climb. The global temperature has risen by an average of 0.14° Fahrenheit per decade since 1880, roughly 2° F in total. While the initial impetus for this warming is tied to the start of the industrial revolution, recent years have seen an even more drastic jump: The rate of warming since 1981 has more than doubled to 0.32° Fahrenheit per decade. The nine hottest years since records of the Earth's temperature started to be kept 143 years ago have been the past nine years—2014-2022.[4] This is the current trajectory of the Earth's climate. By 2050, the Earth's temperature is projected to rise by 2.7° Fahrenheit (1.5° Celsius), and an increase of between 3.6-7.2° Fahrenheit (2-4° Celsius) is predicted by the end of the century.[5]

While these numbers may not seem like much, even tiny increases in temperature can have catastrophic effects. It's also important to remember that these average temperature rises are just that—an average covering a very large and very diverse range of geographies and environments. A significant portion of the Earth is already experiencing temperature rises above the 1.5 degree Celsius target, and we are on a path to soon exceed the 2° Celsius limit set by the Paris Agreement in 2015. As a result, we are seeing widespread impacts: more extreme weather patterns that include heat waves, droughts, wildfires, and heavy precipitation events; snow, ice, and permafrost melt; rises in sea levels and the acidity of oceans; food shortages; extinction and biodiversity loss; and increased death rates, just to name a few.

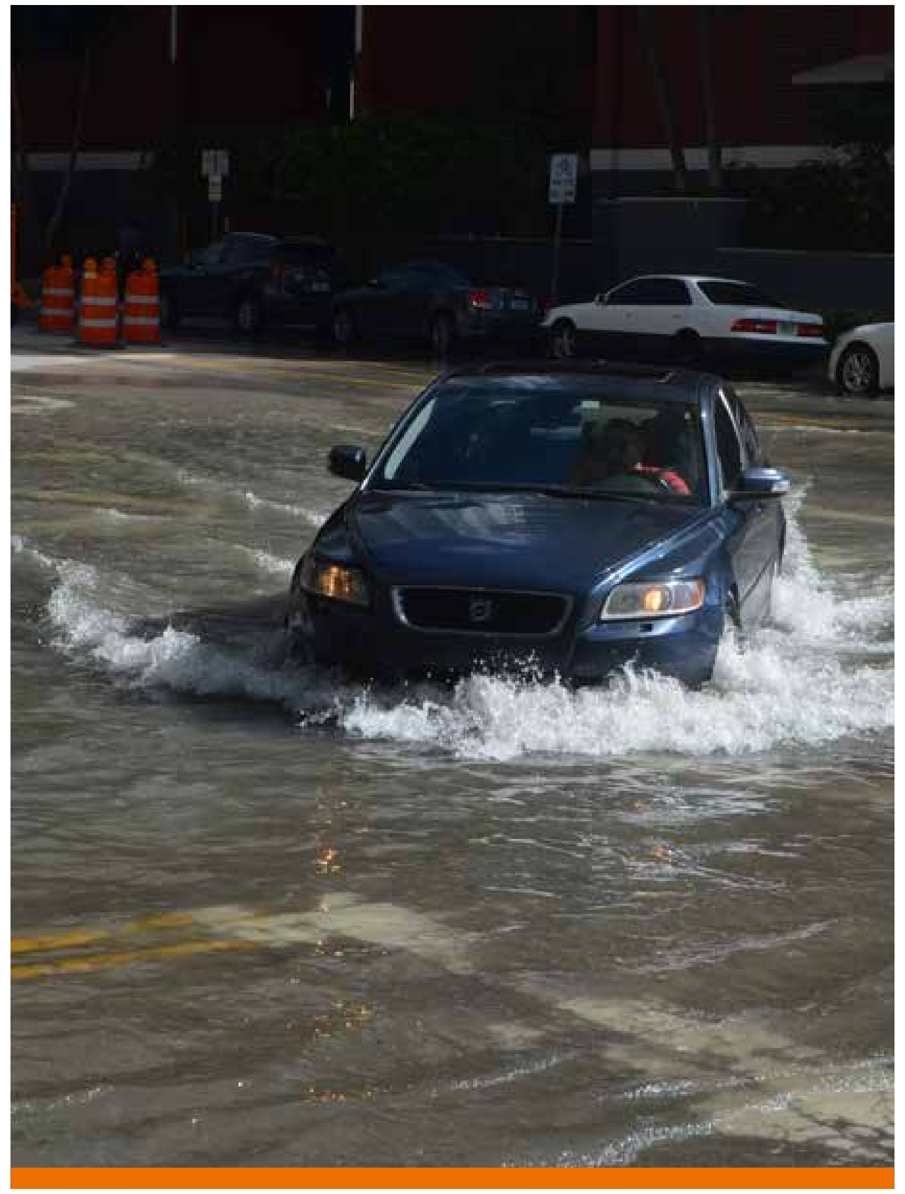
CNMS QUARTERLY PLANNING METRICS

- Highly Unmapped
- Medium High
- Medium
- Medium Low
- Low

Source: FEMA, FY23Q2, Unmapped Miles Normalized by HUC8 Watershed



THE NINE HOTTEST YEARS SINCE RECORDS OF THE EARTH'S TEMPERATURE STARTED TO BE KEPT 143 YEARS AGO HAVE BEEN THE PAST NINE YEARS—2014-2022.



Connection between climate crisis and flooding

What does this mean for current and future flood events? Floods, like all natural disasters, do not occur in a vacuum. Compound events are becoming more common, and we need to adapt our behavior to handle seemingly innumerable combinations of events. While it is difficult to directly link flood activity overall to climate change, given the many and complex natural and human causes of flood events, the IPCC has concluded that climate change has "detectably influenced" many of the factors that lead to flooding.[6] These influences are perhaps best summarized by the National Oceanic and Atmospheric Administration (NOAA) in a recent piece of research conducted through the Princeton University Geophysical Fluid Dynamics Laboratory that focused on climate change and the hydrologic cycle: "Climate change undermines the commonly-held notion that past behavior of elements of our water supply—rivers, floods, droughts—provides us with statistics directly transferable [and] applicable to the future. As changing climate alters the behavior of water, climate science is called upon to provide information about the future of the water cycle."[7]

The problem here is that the majority of flood prediction is based only on historical data and assumes a stationary climate. By law, FEMA is only allowed to consider past data when creating flood insurance studies. Michael Grimm, acting deputy associate administrator of FEMA's Federal Insurance and Mitigation Administration, in an interview with The Washington Post, made clear one of the major shortcomings of our current approach to flood prediction—simply that FEMA maps are designed to indicate flood risk, not in any way consider prediction of future flooding situations. "Maps do not forecast flooding," Grimm said. "Maps only reflect past flooding conditions and are a snapshot in time. They do not represent all hazards and do not predict future conditions."[8] This means that the main source of the floodplain maps and models used in flood prediction is inherently inadequate for long-term resilience. Both the scientific community and the federal government have acknowledged that this needs to change. NOAA is addressing this issue, which is often called nonstationarity, in their forthcoming rainfall data, Atlas 15.

Luckily, climate scientists have been hard at work doing just what NOAA's research calls on them to do, and we are rapidly developing a more complete and proactive understanding of how climate change is specifically influencing each of the five different flood types, as well as how it will potentially affect them in the future. Only through this detailed understanding will we be able to move forward—to go from "something needs to change" in our flood prediction approach to a clearly defined method.

Through this, we are able to ascertain exactly what a new, data-driven approach to flood prediction will need to look like in order to succeed.

THE MAJORITY OF FLOOD PREDICTION IS BASED ONLY ON HISTORICAL DATA AND ASSUMES A STATIONARY CLIMATE.

SPECIFIC IMPACTS OF CLIMATE CHANGE FACTORS ON FLOODING

	Fluvial	Pluvial	Coastal	Urban	Compound
Extreme Precipitation	X	X		X	X
Drought		X			X
Snowmelt	X	X			X
Sea Level Rise			X	X	X
Erosion / Devegetation	X	X	X	X	X

SPECIFIC IMPACTS OF CLIMATE CHANGE FACTORS ON FLOODING

Extreme Precipitation

The intensity of extreme weather, like storms, floods, and rainfall, depends on the moisture in the air. For every 1°F increase in temperature, the atmosphere can hold 7% more water, while warmer oceans also increase evaporation, adding even more humidity; since 1901, the United States has become 4% more humid overall.[9] When moisture-laden air moves over land or converges into a storm system, it leads to heavier precipitation. In the latter half of the 20th century, there was a rise in intense precipitation events, even in areas with reduced overall rainfall due to environmental warming. In the Northeast, extreme storms now generate about 27% more water than a century ago.[10] We can observe this in events like the destructive Vermont floods in July 2023, when 6-9 inches of rain fell across the northeastern US, causing widespread damage.[11]

Drought

Drought alters how water enters the soil, affecting how rainfall is partitioned into runoff, evaporation, and storage. Additionally, drought can render soils more water repellent. A recent study conducted in Germany linked drought to a notable increase in the water repellency of forest soils. When researchers measured water repellency by monitoring the time it took for a water droplet to be soaked up by forest soil, they made the alarming discovery that after experiencing conditions equivalent to a 40-year drought, certain soil areas took more than an hour to absorb a water droplet after it made contact.[12] In 2022, a study found climate change drought conditions have doubled the chance of a California megaflood, the scale of which has never been seen before;[13] then, in 2023, following yearslong climate-change-fueled drought conditions, California was hit with a succession of intense storms, and while the rainfall was enough to cause flood risk in any circumstances, the prolonged drought exacerbated the impacts exponentially, creating deadly events.

Snowmelt

Increased global temperatures mean earlier snowmelt and an overall increase in the amount of snow and glacier melt that is experienced globally, as well as increasing the probability of rain-on-snow events, which cause snow to melt more rapidly and lead to downstream flooding. An extreme rain-on-snow event captured headlines in 2022 as it struck one of the United State's most iconic locations, Yellowstone National Park. As roads, bridges, and buildings were swept away by flash floods, park rangers evacuated more than 10,000 visitors.[14] Snowmelt can affect individual flood events and contribute to rising global sea levels, affecting storm surges and coastal flooding. In areas not accustomed to such floods, primarily in the north, snowmelt poses a threat, especially when it comes to pluvial or fluvial flooding. These communities may lack the awareness and resources to prevent and address flood damage, making the risk particularly hazardous.

Sea level rise

Global sea level rise has sped up, from 1.7 mm/year for most of the 20th century to 3.2 mm/year since 1993. Since 1880, global sea levels have gone up by 8-9 inches in total. Even though this might seem like a small change, it's already causing severe problems. These include major increases in coastal erosion, shifts in coastal ecosystems, and serious consequences for storm surges. High tide flooding—which is rarely dangerous but can cause significant damage and impact daily life from human behavior to infrastructure design and insurance policies—is now between 300% and 900% more likely than it was just 50 years ago.[15] This is particularly relevant when you consider that roughly 30% of the population of the US lives in high-density coastal communities that are at risk of high tide flooding and more dangerous flood events during a storm surge.

Deforestation/Devegetation

Clearing forests and vegetation has a multifaceted impact on runoff generation and routing. The effects hinge on factors such as the type of vegetation being cleared, groundwater table depth, and the predominant land cover following clearance. Trees specifically play a vital role by intercepting rainfall, with a medium-sized tree capable of capturing up to 2,380 gallons of rainfall annually.[16] They reduce both the quantity of rain reaching the ground and its subsequent impact; when they are cleared, the potential for flood events increases drastically. The exponential impact of flood events in areas without vegetation can most often be seen in environments that have suffered from vegetation-clearing wildfires. Santa Clara Pueblo, a Native American community in New Mexico near the Rio Grande, has suffered cyclical wildfires regularly since 2000, leaving the land void of substantial vegetation. Two of the major wildfires in 2013 and 2015 were followed by 500-year flood events, resulting in severe damage to bridges and dams, and complete devastation of the essential local fishing economy.

A SIGNIFICANT INCREASE IN COMPOUND FLOODING EVENTS OVER RECENT YEARS IS ONE PARTICULARLY STRONG ARGUMENT FOR ASSESSING FLOOD RISK THROUGH A NONSTATIONARY FRAMEWORK.

A closer look at urban and compound flooding risks

A significant increase in compound flooding events over recent years is one particularly strong argument for assessing flood risk through a nonstationary framework. Compound flooding is a fairly simple concept: When storm surges and heavy rainfall happen at the same time, the risk of flooding in low-lying coastal areas is much higher compared to each event occurring alone. The impacts of these two events are felt either through pluvial surface flooding from runoff or from fluvial flooding from increased river discharge. This phenomenon is particularly challenging for coastal cities, where factors such as high population density, highly susceptible and concentrated levels of public transportation and infrastructure systems, and the high occurrence of physically impermeable or even hydrophobic surfaces inevitably multiply the repercussions of flood events. On August 21, 2021, New York City saw a record 1.94 inches on rain in one hour as the remnants of Hurricane Henri battered the city, causing flooding in streets, subways, and buildings across all five boroughs. Two weeks later, the remnants of Hurricane Ida, which had already left catastrophic destruction in its wake as it traveled up the country from New Orleans, dropped an astonishing 3.15 inches in Central Park in a single hour, obliterating Henri's recent record-breaking totals. For the first time, the National Weather service declared a flash flood emergency in New York City.[17] The response from local and federal officials felt a bit like déjà vu: President Biden called extreme weather events "one of the greatest challenges of our time," while New York State Governor Kathy Hochul stated, "I don't ever want again to see Niagara Falls rushing down the stairs of one of the New York City subways. I can't prevent it right now, but I know we have to take action to mitigate that."[18]

What is needed?

The harsh reality is that this is likely our "new normal." If we can't, at least in the near future, do anything to significantly curb these climate change factors, it becomes evident that we must act swiftly to enhance our flood prediction practices. But what exactly does "improved" flood prediction entail? For starters, as noted above, we must implement a flood risk assessment approach that is nonstationary. Considering this alongside the many specific climate change factors and their impacts, the following criteria serve as the baseline for a new, enhanced flood prediction method:

1. Inclusion of future trends and predictions

As noted, current practices of predicting flood risk are based solely on past data and therefore are often woefully inaccurate given the significant and ongoing changes to watershed behavior as a result of climate change. Future practices need to be able to account for nonstationarity of climate data and run several risk scenarios to provide a comprehensive prediction of the other factors that influence flooding (soil moisture, land use, fragility of flood control structures).

2. Faster mapping and more regularly updated maps

Understanding that using FEMA floodplain mapping for flood prediction is already inherently flawed because the maps were never intended to be used for prediction purposes, there are still more limitations. FEMA is currently required to reassess their flood maps every five years, but despite their best efforts to keep up with the growing impacts of climate change and other factors on flooding, they are destined for difficulty before they even begin: While flood maps are reassessed every five years, it takes an average of seven years to issue a new one because of the level of detail and due process required. FEMA are, through no fault of their own, perpetually on the back foot.

3. Inclusion of pluvial and compound flood types

As the impacts of climate change continue to alter watershed behavior, different types of floods are posing different levels of risk. Historically, the focus has been on fluvial and coastal floods, and consequently, up until now, FEMA has rarely studied pluvial flood risk. As this is now a major risk area, they are working on assessing pluvial risk for floodplain management and insurance purposes, but using traditional flood prediction methods, this is proving both an expensive and lengthy exercise. W. Craig Fugate, FEMA administrator under President Barack Obama, acknowledges this point blank in a 2022 article for the Washington Post: “Climate has changed so much that the maps aren’t going to keep up for some time. They are not designed for extreme rainfall events.”[19]

4. Coverage of unmapped areas

Currently, FEMA has not mapped about 1.3M miles of streams within the United States, leaving a significant portion of the country unmapped. Areas may be unmapped for a variety of reasons, ranging from lack of financial and physical resource to the fact that some areas were historically categorized as "too small" or "low risk" but over time and with the increased impact of climate change have developed into high-risk areas, especially for flash flooding.

5. Estimation of impacts of flooding

Beyond addressing the above fundamental issues with flood prediction practices, future flood prediction needs to add an additional level of detail, providing insights around the potential severity of a flood (e.g., depth, velocity, or damage of floodwater), as opposed to just the risk of being flooded. Anticipating severity allows us to make proactive informed decisions about planning, building, and infrastructure design, as well as local flood impact mitigation measures, real-time choices regarding evacuations, and the use of response and emergency resources.

6. Prioritize access

As the old adage goes, “Knowledge is power.” Improved flood prediction practices and the relevant actions in response to those improved insights are dependent upon shared access to the information. Only by ensuring the same high-quality insights to all relevant stakeholders can we achieve the necessary collaboration on preventative solutions and be aware of changes in as close to real time as possible. The group of relevant collaborators is vast and might surprise you, ranging from the more obvious government agencies and emergency services to individual local citizens and businesses, and developers, planners, engineers, and architects.

7. Maintain accuracy and quality

Thus far, this may all sound fairly straightforward. The final and arguably most important point is to do all of the above with a high degree of accuracy and quality. FEMA’s flood studies have been the gold standard for attention to detail in the floodplain mapping community. While it may be tempting to want to fill in any available floodplain map for an unmapped area or an unmapped flood type, the reality is the danger in generalizations or cutting of corners in the already complex and uncertain process of flood hazard studies. Decisions that are made and actioned with a high degree of confidence but based on inadequate data or knowledge often create a much higher risk than simply living in the unknown. Communities need to be able to trust the engineering data that supports these types of decisions for the long term.

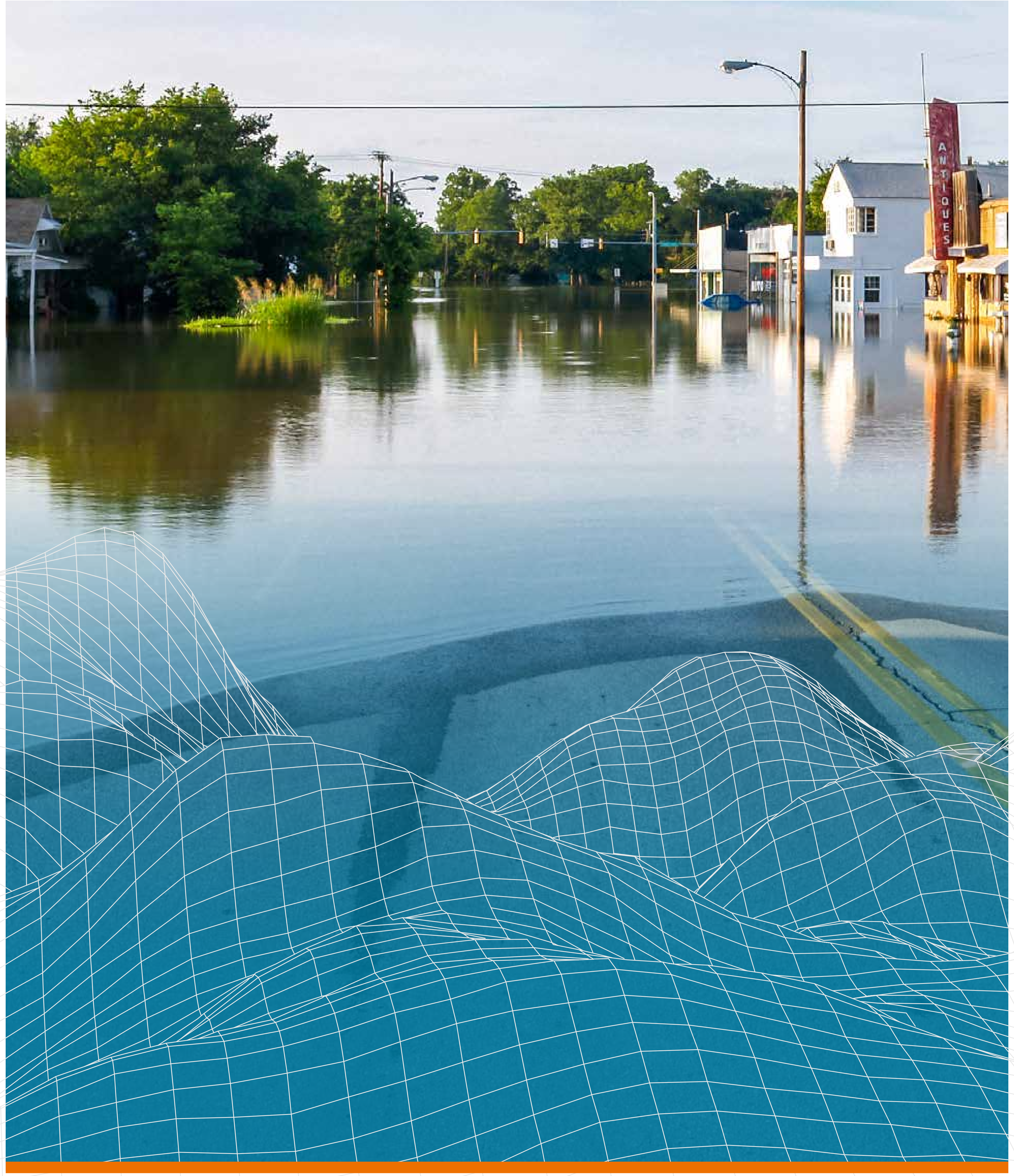
How? A paradigm shift

The above criteria equate to a single, simple concept: a fundamental paradigm shift from manual to digital flood prediction. This may seem obvious, and you may argue that we are already working in a digital realm with our flood prediction—after all, current floodplain maps are created and stored in digital form. When we dig one layer deeper, however, we realize the process is still grounded in manual-driven practices. Starting with data collection and surveys, engineers then develop a hydraulic model to represent on-the-ground conditions, followed by development of rainfall runoff, flow input, and model calibration before finally getting to floodplain mapping and post-processing.

We believe we haven't yet tapped into the full potential of a data-driven, machine-learning based flood prediction solution. But not all digital solutions are created equal. Our industry is seeking an approach that provides the confidence in results of a highly detailed, engineered physics-based model, but with the speed and universality of application of an empirical equation. Digital solutions are only as good as the data and science put into them, just as manual processes rely on the effort applied to complete them. But it's also not just about good data. What is needed is a careful and expertly designed balance between data and scientific theory—a process that is grounded in engineering principles that are trained on, and responsive to, big data inputs.

We're not the first to attempt to harness data-driven methods for flood prediction, but we're bringing a novel approach that redefines how the machine learning algorithm sees the raw data inputs (terrain, land use, etc.) in order to better represent the characteristics that influence how a watershed will respond to a given flood event. This new method of using engineering theory as a lens for how the raw data is analyzed by machine learning unlocks significant improvements in flood prediction—specifically, being able to match and correlate data-driven predictions to physics-based models like those developed by FEMA. Even with today's data and technology, this approach is able to generate highly detailed results for any watershed within minutes, giving users the best of both worlds. The promise of this new approach is multiplied, however, when considering where data collection and machine learning advancements are heading.

The list of benefits of this approach may induce déjà vu, as it closely resembles our list of baseline criteria for a new flood prediction methodology. By grounding flood prediction in a fundamentally digital process with machine learning, several advantages emerge. First, it enables the mapping of previously unmapped areas. Second, its speed ensures regular updates and provides current prediction data. Third, it offers easy access to high-quality information for multiple stakeholders. Fourth, the level of detail it provides addresses the potential scale and impact of a flood event. Furthermore, this approach proves significantly more cost-effective than traditional methods, allowing for regular maintenance and updates of maps or even running on demand to consider impending risk scenarios.



What does a future with better flood prediction and flood management look like?

While every effort should be made to not only halt but reverse the climate change factors that are leading to this “new normal” for flooding, we simply cannot wait for that to happen. We need to find a way to respond to and anticipate our new flood event reality now. With a new approach to flood prediction, even with the impacts of climate change, our future could look a lot more positive: intelligent land use, efficient distribution of resources, improved public health and well-being, and enhanced physical and community resilience.

Improved data and longer-term predictive flood monitoring practices are guiding planning and land-use decisions. This involves not only limiting development in high-risk areas but also prioritizing the preservation of natural flood-protection environments. When prediction processes are agile enough to provide predictions for various scenarios, it enables engineers and designers to consider multiple environmental factors when planning new buildings and infrastructure. By running simulations for all probable climate scenarios and accounting for nonstationarity, they can make well-informed decisions about approaching new and retrofit projects with reduced risks. Furthermore, combining nature-based solutions with designed approaches enhances overall environmental resilience. Preserved wetlands and increased vegetation improve groundwater absorption and slow down surface water runoff, significantly reducing pollution from runoff. As a result, ecosystems, from natural environments to human communities, experience a substantial decrease in health risks.

In addition to gaining valuable insights and sufficient time to conceptualize and implement resilient building and infrastructure design decisions, considering the watershed's response to the changing climate ensures that assets can be assessed annually. This proactive approach helps avoid surprises and allows for timely updates or necessary mitigation efforts. As a result, not only does the built environment become less susceptible to the impacts of flood events, but also, society as a whole becomes more resilient. The integration of improved approaches to both the built and natural environment effectively mitigates the physical, financial, and emotional impact of flood damage. Moreover, these enhanced predictive practices foster more collaborative efforts to manage flood impacts as they occur. With fewer critical services being disrupted during major flood events, such as water and power utilities, roads, and public transportation systems, efficient collaborative responses become more feasible. Consequently, resources can be directed more effectively to high-risk areas, significantly reducing the strain on emergency and recovery resources.

Before the adoption of new and improved flood prediction practices, climate change-induced flood events used to have a disproportionate impact on socially and economically vulnerable populations. These groups often reside in higher-risk areas, like Hoboken, New Jersey's affordable housing developments in wetland regions, and rely heavily on public transportation, which is susceptible to quick disruptions and slow recovery. As a consequence, marginalized communities consistently faced elevated risks during major flood events.

However, by enhancing the resilience of the built environment and improving preventative decision-making and real-time response strategies, we can create a more equitable society. Because these historically disenfranchised groups are no longer facing such intense risk to their basic human needs during flood events, they can direct their financial and emotional energy toward other areas that significantly improve their overall quality of life. The outcome is a more inclusive and productive community with a stronger economic and social fabric.

By now, it should be evident that this envisioned future, empowered by enhanced flood prediction based on engineering theory and big data analysis, offers numerous direct and indirect benefits. In essence, it saves lives, time, and money; redirects resources to areas of necessity; and enables us not only to mitigate but also to proactively combat and even reverse the impacts of climate change on our communities. As we strive for a sustainable and resilient future, harnessing the power of improved flood prediction through data-driven engineering lays the foundation for a brighter, safer world.

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