The Importance of Digital Twins for Resilient Infrastructure

A Bentley White Paper

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Abstract

Many city governments have realized that their priority is making their cities resilient from natural disasters. In addition to chronic stresses that governments must address-such as social, economical, and financial-natural disasters have been in the spotlight, becoming a top priority for cities as they become resilient.

It is vital that cities take preventive measures to minimize the disruption caused by these extreme events with proactive actions. Establishing a digital twin can provide solutions to the complex issues that cities face. A digital twin is a digital representation of the city, as well as the engineering information that allows people to understand and model its performance.

Predicting floods in a city is challenging because “compound” flooding (which are not specifically coastal, rain-related, or river floods) can result from a combination of origins, such as river, rainfall, storm surges, sea-level rise, and soil sealing. It is only possible to face these types of flood events with a holistic approach with software capable of integrating the different flood origins, such as flood modeling and simulation solutions. The results that these solutions generated can then serve as a simulation input to a city’s digital twin.

Advanced integrated flood modeling applications enable users to take a complete, multiscale approach with geospatial analysis capabilities. These capabilities are specifically designed for dynamic modeling of the complex, interconnected processes related to flooding in urban, riverine, and coastal systems. Resilience platforms are accelerating city digital twins’ application, increasing smart cities’ preparedness for natural and human-made hazards. With a city digital twin, experts can now perform real-time resilience testing to see how its infrastructure is performing with challenges like global climate change. A more effective communication is achieved through the integration of innovative immersive 3D or 4D (which is 3D plus time) visualization, allowing users to visualize high-definition animations of virtual flood events from different perspectives.

The following sections will present how resilient cities should move toward a holistic perspective on flood risks. The sections also define a digital twin and discuss the existing digital collaborative workflows, which allow users to efficiently integrate processes and scales, moving from a fragmented and disciplinary perception to a multidiscipline perception without forgetting how relevant it is to effectively share information and communicate risk in an easily understandable way.

> “Flood resilience refers to comprehensively managing flood risks to minimize impacts and rapidly recover from disruptions caused by a flood event. Flood resilience solutions for urban, river, and coastal systems bring accurate and reliable risk and analysis data to agencies involved in flood preparedness, response, recovery, and mitigation.”
>
> *– Robert Mankowski,*
> *vice president,*
> *digital cities business unit,*
> *Bentley Systems*

1. Context, Definitions, and Challenges

In the past five decades, the world has experienced a larger population growth compared to the growth from the year 0 to 1970 A.D.[1] Most of today’s infrastructure was built quickly to accommodate this sharp increase, and stakeholders were obligated to take quick action. Unmeasured population growth made it a challenging task for stakeholders to properly allocate population and apply effective governance, requiring e increases in infrastructure capacity. In addition, society has been facing the impacts of climate change, and cities are playing an important role in response and improving preparedness.

As argued by Leichenko, one focus for urban resilience is for cities and infrastructure owners to improve recovery from natural and human-made hazards.[2] The growing risk of flooding is one of the most important environmental issues facing stakeholders, which can be aggravated by mismanagement of cities, inadequate collection of waste, and poor drainage systems. When it comes to the development of sound governance for the continuous and unrestrained growth, cities’ stakeholders must avoid reactive and palliative actions and start looking from a proactive perspective. This practice means that cities need to be resilient enough to simulate, predict, measure, and access risk, anticipating uncertainties and using technology as an opportunity to mitigate impacts on both infrastructure and society. The best way that cities can anticipate hazards and their impacts is with digital twins that enable them to be more resilient and avoid adverse consequences.

1.1. Definition of floods and flood types

Any water overflow that submerges dry land or infrastructure can be classified as a flood event. Floods are the most common of all natural disasters and one of the most impactful for infrastructure, undermining buildings and bridges, eroding shorelines and riverbanks, tearing out trees, washing out access routes, and putting lives at risk.

Floods can also cause power outages and destabilization of infrastructure. For example, a flood can cause landslides or shifting and sinking of the ground, causing serious failures or risk of failure in the building structure. It can also disrupt transportation infrastructure, including airports, railroads, and roadways.

Floods are a result of many events, including heavy rainfall and melting snow, obstruction of natural waterways, soil impermeabilization, broken levees or dams, storms, and high tides. Often, floods occur as a combination of these events.

There are different kinds of floods based on the area where they occur, and each one differs in how it occurs, the damage it causes, and how it is forecasted.

> "Through infrastructure digital twins, cities get advanced and integrated flood modeling and simulation that facilitates the understanding and mitigation of flood risks due to the complex array of interconnected processes from urban, riverine, and coastal systems. Reality modeling solutions, along with open simulation applications, provide the ability to perform risk assessment at city scale, including what-if scenarios and post-event emergency triage."
>
> *– Robert Mankowski, vice president, digital cities business unit, Bentley Systems*

Flash Flood

Flash flooding is a term used for any rapid flooding that occurs in less than six hours, usually caused by a combination of intense rainfall (the most common origin) and fast runoff. This type of flood is classified based on the event speed. Flash flooding occurs so quickly that people are often caught off-guard. The situation may become dangerous if people encounter high, fast-moving water while traveling. If people are at their homes or businesses, the water may rise quickly and trap them, or cause damage to the property without them having a chance to protect it. These events can also occur due to failures in hydrotechnical devices, and/or mudslides. While failures in hydrotechnical devices are usually more connected to fluvial flooding, they can also cause flash flooding in urban areas, which are prone to that type of flooding.

If flash floods due to hydrotechnical device failures are almost impossible to anticipate, then flash floods due to rainfall are also very difficult to predict. Many factors determine how quickly a flash flood may occur, including the intensity, location, and distribution of the rainfall; the land use and topography; vegetation types and growth/density; soil type; and soil-water content. These factors also determine where this type of flood may occur. The factors that influence water removal from the surface (the vegetation, soil type, and soil-water content) are important to attenuate flash flooding; however, they might not be enough to avoid these extreme events.

Heavy rainfall that potentially generates flash floods is often very rapid and localized. This situation means that ultra-high weather resolution forecasting systems, which assimilate as much real-time data as possible, are necessary to properly set up the flood model. Information that must be included in a model – such as land use, topography, soil type, and vegetation – are usually obtained from remote-sensing technologies. Some artificial intelligence (AI) techniques applied to reality modeling are already available for automatic data classification and segmentation, as well as to add semantic information.

Urban Flood

Urban flooding is the inundation of land or property in a built environment, particularly in more densely populated areas. This type of flooding is caused by surface water overwhelming the capacity of natural and artificial drainage systems, as well as the capacity of water retention systems. In this case, a flood is classified by the affected area.

The overland flow can be difficult to predict in urban flooding because it is affected by urban features, such as stormwater pipes, roads, fences, and walls. The actual depth and impact of overland flow varies depending on local conditions, but it generally occurs quickly.

Thus, flash flooding in urban areas is also a possibility. Sometimes, rainfall over an urban area will cause faster and more severe flooding than in the suburbs or countryside. The impervious surfaces in the urban areas do not allow water to infiltrate the ground, and the water quickly runs off to the low spots. Thus, urbanization modifies the hydrologic cycle, resulting in increased runoff rates, volumes, and peak flows in the drainage network.

The entire drainage network needs to be known to properly understand and model the correct interaction between the stormwater drainage system and the surface runoff. City planners need high-resolution topographic and planimetric mapping, as well as 2D surface runoff, to properly discretize the overland flow and water column in the buildings and streets.

Fluvial/River Flood

Fluvial, or river, flooding occurs when the river flow rate exceeds the maximum river capacity. This situation causes the water to breach the river's banks, overflowing the surrounding area. In this case, the flood is classified by the flood source. The main causes for these types of floods are usually excessive rainfall over an extended period, snowmelt, or a combination of both.

The risk of fluvial flooding can increase or decrease based on the same parameters as flash flooding. In addition, if any hydraulic structure exists, then the retention capacity and/or operation rules of those structures will also influence a potential fluvial flood.

One of the biggest challenges in fluvial flood forecasting is anticipating and estimating hydraulic operation rules of multipurpose reservoirs, which may depend on many different variables and purposes, including maximization of energy production. However, these rules are not always pre-defined or well-known. If there is no way to obtain the exact operating rules from a reservoir's non-operator perspective, it is possible to use AI approaches to predict rules based on historical information. From a reservoir operator's point of view, a flood forecasting system can also help make operational decisions toward increased safety or even optimization of energy production.

> "Using digital twins for flood resilience provides decision makers with real, actionable information toward anticipated early warnings and prompt responses, which can be used in the emergency management cycle of preparation, response, recovery, and mitigation."
>
> *– Robert Mankowski, vice president, digital cities business unit, Bentley Systems*

Coastal/Onshore Flood

A coastal flood occurs in areas that lie on the coast of a sea, ocean, or other large body of open water, such as an estuary or coastal lagoon. In this type of flood, water overwhelms low-lying land and often causes devastating loss of life and property.

These types of floods can be caused by storm surges and exacerbated by high upstream river flow (in the case of an estuary or a coastal lagoon). Many times, they occur in combination with astronomic high tides.

Storm surges are the leading cause of coastal flooding and often the greatest threat associated with a tropical storm. A storm surge can be caused by waves, low barometric pressure, and extreme on-shore winds that push water onshore. Tsunamis can also cause coastal flooding.

The severity of a coastal flood is determined by several factors, including the strength, size, speed, and direction of the storm. The onshore and offshore topographies also play a role.

Pluvial/Rain-related Flood

A pluvial, or rain-related, flood is caused when heavy rainfall creates a flood event independent of an overflowing water body. These floods can happen even in higher elevation areas that lie above coastal and river floodplains.

There are two common causes of pluvial flooding:

- **Intense rain:** The rain saturates an urban drainage system and the system becomes overwhelmed, with water flowing into streets and nearby structures.
- **Run-off or flowing water from rain falling upstream:** The hillsides are unable to absorb the water.

Regions affected by forest fires, as well as suburban communities located upstream, are notorious sources of pluvial floods. Although typically only a few centimeters deep, a pluvial flood can cause significant property damage.

"Compound" flooding

According to Mangor, Drønen, Kaergaard, and Kristensen, 60% of the world's population lives in coastal areas, while 65% of cities with populations above 2.5 million are located along the world's coasts.[3] With many cities also located along rivers, urban floods can be a result of the combination of all three types of flooding. These possibilities bring great challenges in the implementation of a proactive flood risk management, as a proper flood model and flood forecasting system involve different scales and processes.

1.2. Definition of digital twins to support resilience

A digital twin is a digital representation of a physical asset, process, or system, as well as the engineering information that allows people to understand and model its performance. Typically, digital twins can be continuously updated from multiple sources, including sensors and continuous surveying, to represent near real-time status, working condition, or position. A digital twin enables users to visualize the asset, check the status, perform analyses, and generate insights to predict and optimize asset performance.

1.3. Smart, Resilient, and Sustainable Cities

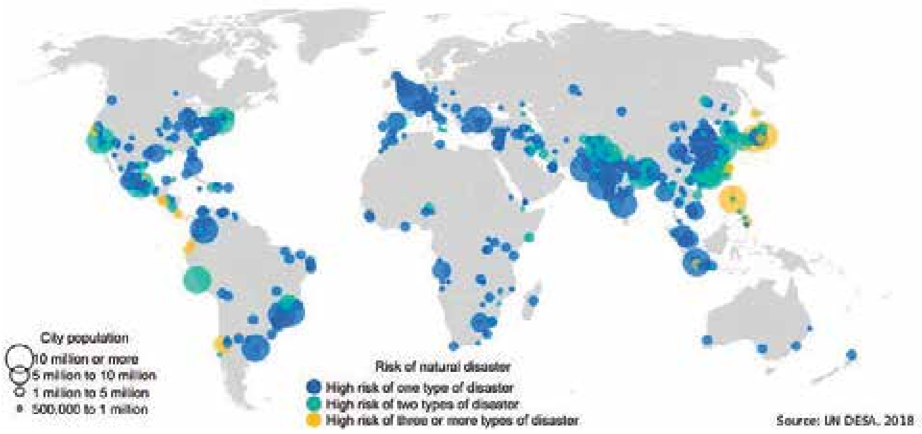
The term "smart cities" has been used extensively. According to Hall, a smart city is "a city that monitors and integrates conditions of all of its critical infrastructures, including roads, bridges, tunnels, rails, subways, airports, seaports, communications, water, power, even major buildings, and can better optimize its resources, plan its preventive maintenance activities, and monitor security aspects while maximizing services to its citizens."[4] Being a smart city is not the first step toward the future; but, rather, the final utilization of this information is what makes being a smart city so important.

The future is clear: cities can be resilient and sustainable through the application of smart city's strategy combined with digital twins. Resilient cities are smart cities that focus on mitigating urban hazards, withstanding threats, and rapidly recovering from such incidents. To recover from these types of events, resilient cities use multisource data integration – such as computer-aided design (CAD), building information modeling (BIM), geographic information system (GIS), digital twins, and near-real-time data – streamlined into comprehensive workflows that generate actionable insights. These insights help improve the population's quality of life, supplied services, and critical infrastructure availability. Along with these benefits, this workflow helps mitigate risk and associated monetary losses.

2. Resilience and Vertical Markets: What is the opportunity for resilience market?

The World Economic Forum (WEF) ranked "extreme weather events" as the leading and most likely risk to materialize over the next 10 years.[5,6] In the top five most likely global risks, the second was the failure of climate-change mitigation and adaptation while the third was natural disasters. According to the insurance company Munich RE, natural disasters and extreme weather caused around USD 160 billion in damage worldwide in 2018.[7] Yohe mentioned that the United States economy would lose USD 1 trillion over the next decade as a result of these extreme weather events.[8] China will be the second-most affected country, losing USD 389 billion over the next two decades.[9] Since 1980, European countries have also been affected by nearly half a trillion euros.[10] The average annual loss across the European Union has been EUR 4.5 billion.[11] India has an average annual loss from floods of USD 7.4 billion.[12]

About three in five cities worldwide with at least 500,000 inhabitants are at high risk of a natural disaster, cautions the United Nations Department of Economic and Social Affairs (UN DESA) in its latest report The World's Cities in 2018. Collectively, these cities are home to 1.4 billion people, or around one-third of the world's urban population. The UN DESA report shows that 679 of the 1,146 cities with a population of at least half a million people were vulnerable to either cyclone, floods, droughts, earthquakes, landslides, or volcanic eruptions – or a combination of these events, as seen in Figure 1.[13]



Source: UN DESA, 2018

Figure 1: Cities risk of exposure to natural disasters

From 1998 to 2017, disaster-hit countries also reported direct economic losses valued at USD 2.908 trillion, of which climate-related disasters caused USD 2.245 trillion or 77% of the total. Over the past 20 years, the United States and China recorded the biggest losses of USD 945 billion and USD 492 billion, respectively. These numbers reflect the high asset values, as well as the frequency of these events. While most fatalities were due to geophysical events – mostly earthquakes and tsunamis – floods, storms, droughts, heatwaves, and other extreme weather events caused 91% of all disasters , as seen in Figure 2. In the United States, almost half of the natural disasters were storms.[14]

Figure 2: Numbers of disasters per type 1998-2017 (CRED. UNISDR. 2018)

Resilient cities, campuses, and critical infrastructures need a more holistic approach to confront escalating flooding damages. As mentioned by EU-Circle, critical infrastructures – such as telecommunications, electric power generation and transmission, water supply systems, transportation, and emergency services – have become the components of a larger interconnected system (Figure 3).[15] Infrastructure currently designed for historical climate conditions is more vulnerable to future weather extremes and climate change. Climate-related hazards can substantially affect, or even severely damage, the lifespan and effectiveness of these critical infrastructures, particularly in energy, transportation, marine, and water management industries. Forecasting and resilience technology are important, as it has been demonstrated that flood forecasting reduce up to 35% of average annual flood damages and the impact on infrastructures.[16]

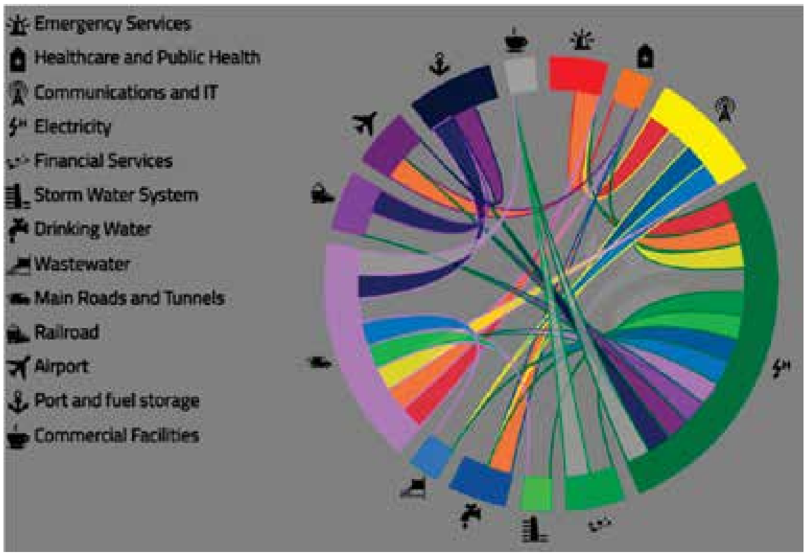
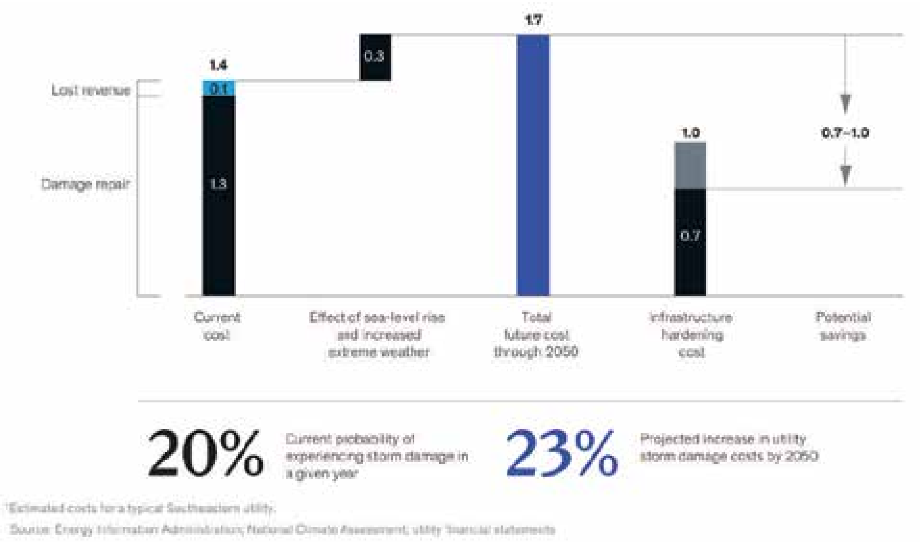


Figure 3: Illustration of the critical infrastructure (CI) dependencies in a circle diagram[17] (Bruijn et al. 2019)

Kandel explains that, upon an extreme environmental hazard, infrastructure plays an important factor for whether or not it becomes a disaster.[18] High-quality power and transportation networks can limit the impacts that natural hazards can cause, both in terms of life loss and socioeconomic damage. At the same time, the breakdown of nodal points in infrastructure – such as airports and power plants – can also cause impacts that reach far beyond the actual hazard. According to Brody et al., the United States has 8,625 power plants deliberately sited near shorelines to have access to water. The utility segment saw USD 1.4 billion in storm-damage costs and lost revenues due to outages caused by storms over 20 years, as seen in Figure 4. Moreover, infrastructure that is currently designed for historical climate conditions is more vulnerable to future weather extremes and climate change.[19]



¹Estimated costs for a typical Southeastern utility.

Source: Energy Information Administration; National Climate Assessment; utility financial statements

Figure 4: 20 years of storm-damage costs compared with adaptation costs for a southeastern utility, $billion

The insurance market wants more accurate risk estimates, as overall losses are often greater than the insurance coverage amount. Global natural catastrophes and human-made disasters resulted in USD 144 billion worth of insured losses in 2017. The top three events that caused the most insured losses were hurricanes Maria, Irma, and Harvey, which accounted for a total of USD 92 billion. The next highest insured losses came from two wildfires that resulted in almost USD 10.5 billion, as seen in Figure 5. In 2018, the overall economic impact was USD 160 billion, of which USD 80 billion was insured.[20]

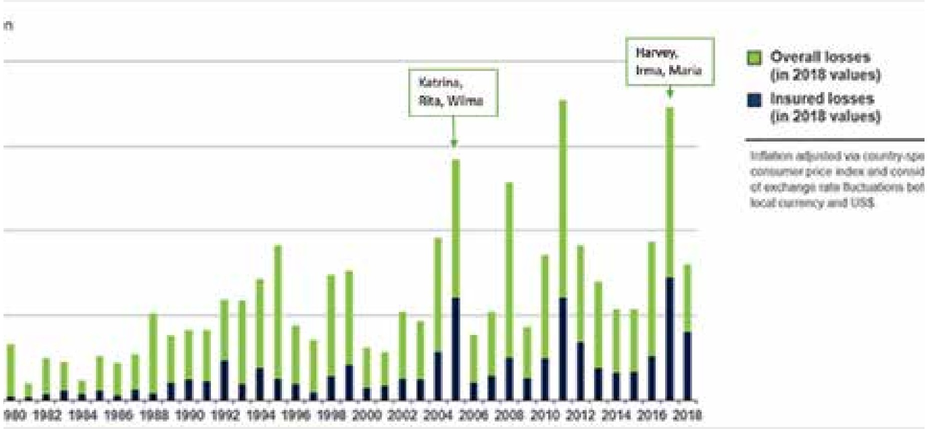


Figure 5: World Natural Catastrophes by Overall And Insured Losses, 1980–2018

3. Resilience Technologies, Solutions, Design Guidelines, and Approaches

By using digital twins, cities get advanced flood modeling and simulation that enables them to better prepare for flood risks. Digital twins provide comprehensive and actionable insights to flood risk assessment and mitigation.

Resiliency teams can make the right decisions by using actionable insights to anticipate early warnings and promote response to increase public safety and decrease damage to infrastructure while minimizing service interruption, avoiding additional mitigation cost and improving response times.

> "At Bentley, our core competency is in engineering technologies (ET) – but we are converging ET with operations technologies (OT) and information technologies (IT) to deliver an open, connected data environment that enables digital twins."
>
> *– Gregg Herrin, senior director, water infrastructure, Bentley Systems*

4. Examples of Operational Resilient Digital Twin

Lisbon, Portugal created a digital twin for urban flood simulation that enabled the city to comprehensively model alternative scenarios and develop a plan for several return periods. This feature will help Lisbon avoid 20 major floods over the next century.

Lisbon's city government is ready to manage against changing climate conditions and urbanization with its drainage master plan. Rising sea levels and frequent extreme rainfall events have increased flood risk. The region around Lisbon has been urbanizing rapidly, leading to soil imperviousness and more flooding in the region. Lisbon's existing infrastructure is not adequate to ensure efficient drainage during extreme storm events. Between 1900 and 2006, Lisbon registered 84 inundations; between 2008 and 2014, 15 inundation events occurred. The Lisbon city government created a digital twin for urban flood simulation that lets it comprehensively model alternative scenarios and develop a plan for several return periods. This digital twin helps the Lisbon project team create a drainage master plan that guards against changing climate conditions and urbanization.

The Lisbon city government has shifted from a reactive to a proactive mindset with goals to mitigate flood risk through intervention with existing infrastructure. This practice will enhance the drainage capacity of existing stormwater systems, resulting in a new mitigation strategy that will avoid 20 floods over 100 years and save hundreds of millions of euros.

Another example is a large chemical plant construction project happening in Pennsylvania, United States. The project team is flying drones over that site weekly to process these images in 2D and 3D so that team members have an updated reality model of the entire site. Bentley generates automated 2D flood simulations using the most updated digital surface model derived from the reality model. Flood simulations and high-resolution rainfall forecasts are provided via cloud-based web services and a mobile-friendly, web-GIS platform (Figure 6).

The main purpose of this project is to improve planning efficiency and asset management in relation to the ongoing construction and operation, minimizing potential impacts that flooding can bring to machinery, critical infrastructure, and people.

Figure 6: WebGIS platform providing visualization of flood simulation scenarios for a chemical plant

> "By bringing IT, OT, and ET together, we can create true intelligent and connected digital infrastructure, supporting planning, design, construction, and operations for smart water networks. Through the open, connected data environment, we can enable faster, better workflows that address the overall challenges of a utility better than individual tools can."
>
> *– Gregg Herrin, senior director, water infrastructure, Bentley Systems*

5. Final remarks: The future of resilience digital twins

City governments must be leading the way for the development of digital twins and understand that its application for resilient cities and critical infrastructure is key. Bentley Systems believes that addressing resilience problems by bringing together key technologies – such as OpenFlows™ FLOOD for flood modeling and simulation, remote sensors, and digital twins – is the unequivocal future. The same approach can be followed for addressing resilience to landslides, including geotechnical and hydrological analysis software – such as SoilVision™ – in the workflow. In addition, external data from crowdsourcing, nowcasting, and forecasting plays an important role in making monitoring and analyzing as dynamic and vivid as possible. Lastly, immersive visualization applications, such as LumenRT™ and OpenCities™ Planner, can improve risk communication and situational awareness to stakeholders.

For resilient cities, the way forward should come from interconnecting all the processes and scales involved in both natural and human-made disasters, without excluding all the social interactions.

Digital collaborative workflows allow users to efficiently integrate processes and scales, moving from a fragmented and disciplinary perception to a transdisciplinary perception. A digital twin is only reliable and relevant for situational awareness and to project the future if it is dynamic, reflecting the whole context evolving in real time. This dynamic digital twin approach is only possible and efficient if it is continuously gathering, integrating, and processing information from multiple data sources in an automated fashion. The involved information comes from remote sensing, in-situ stations, without forgetting the flood models and social media analytics.

Digital twins will eventually be high-fidelity reproductions of real urban environments and infrastructures that can even integrate weather conditions. In the future, city governments hope that any likely impacts caused by urban planning or natural hazards can be foreseen, evaluated, and mitigated using these digital twins. These features will result in substantially lessened effects to the population and infrastructure owners. This new multisource, crossdomain, and data-driven approach is a centralized workflow for resilient cities and infrastructure real-time health assessment, generating intuitive and data-rich conclusions for stakeholders and engineers. It funnels a complex array of different data sources, and also interconnected processes, into accurate and reliable insights.

Finally, the importance of effective risk communication is that the information must be quickly and effectively shared, adapted to the stakeholders. Dynamic dashboards, geo-targeted notification, and mobile-friendly websites can all contribute to that purpose – but 4D immersive visualization of flood-modeled scenarios from any user point of view is innovative, distinctive, and a game-changer.

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> "Connecting processes and data allow us to connect reality models with simulation features and connect functional design capabilities with physical design capabilities. These connections make it easier to ensure that our infrastructure performs the way it is intended to, that it fits within the real-world the way it needs to, and that its impact can be shared effectively with all types of stakeholders, within all corners of a utility, and even beyond to city officials and the public."
>
> *– Gregg Herrin, senior director, water infrastructure, Bentley Systems*

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