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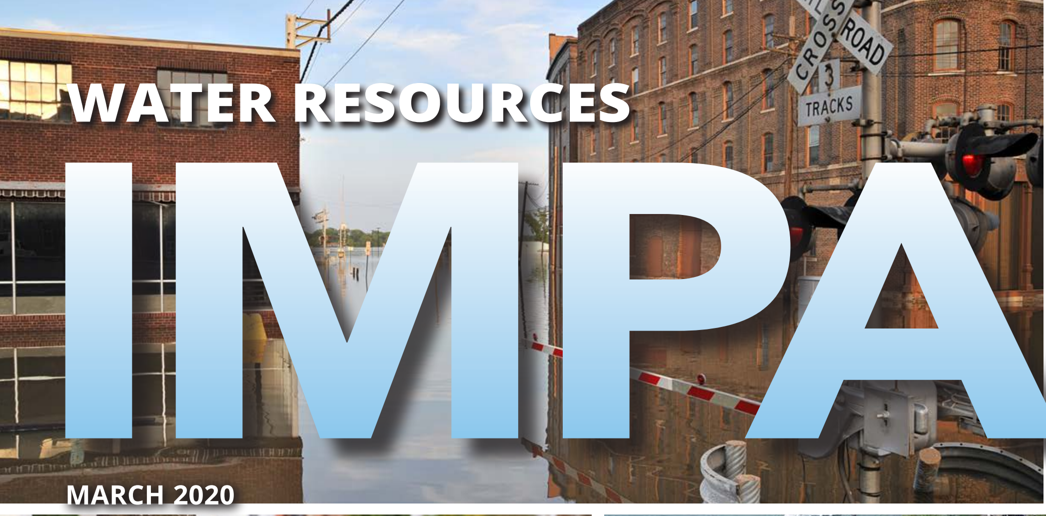

GEOSPATIAL WATER TECHNOLOGY: COMPLEX SYSTEMS

AMERICAN
WATER RESOURCES
ASSOCIATION

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ABOUT THIS ISSUE

Geospatial Water Technology: Complex Systems
Guest Editors: Venkatesh Merwade and Lilit Yeghiazarian

This issue of *Water Resources IMPACT* covers the 2020 *Geospatial Water Technology Conference: Complex Systems.* Centuries of experience in water resources management have taught us that water resources systems are complex, multi-layered systems that involve flows in the natural environment and built infrastructure which include surface water and groundwater, sewerage and drinking water systems, stormwater flows and green infrastructure. We must embrace this complexity to manage water sustainably. Specifically, this issue looks at the use of emerging geospatial and Internet technologies for managing floods and water resources. Stephen Bourne and Caroline Resor discuss the application of City Simulator for Surfside, FL, to assess the flood resiliency in response to future natural and human changes. David Blodgett and Emily Read present the U.S. Geological Survey's work in developing the "Internet of Water" for integration and dissemination of water information. Siddharth Saksena makes a case for data-driven, integrated and bottom-up approach towards simulation of complex urban flooding systems. Alvan Karlin describes how high density Lidar can be effectively used for simulating surface water within urban environments. Finally, Mike Johnson and his team describe a semantic network approach for organizing and delivering information related to complex urban systems.

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PRESIDENT'S MESSAGE

Betsy A. Cody, AWRA 2020 President

IT'S MARCH AND MY MIND AUTOMATICALLY turns to "March Madness." Not just the NCAA basketball tournaments, but the time of year when everything seems to be popping. For AWRA staff and conference planning volunteers it's a mad-dash to ensure our members and other attendees have the best experience possible at our upcoming 2020 Geospatial Water Technology Conference in Austin, Texas (March 23-26, 2020). I do hope you'll join us. It promises to be a fantastic opportunity to hear from our colleagues around the country about cutting-edge technology devoted to understanding, analyzing, and sharing information about complex systems critical to water resources management. Please check out the in-depth program assembled by our terrific planning committee and register for the conference if you haven't already done so. We'll also be paying tribute to David Maidment for his outstanding technological contributions to the water resources community. A full day Maidment Symposium sponsored by CUAHSI (Consortium of Universities for the Advancement of Hydrologic Science, Inc.) will immediately follow the AWRA specialty conference.

Meanwhile, our conference volunteers from the Florida AWRA state section are hard at work generating interest and coordinating details for the AWRA annual conference Nov. 9-12 in Kissimmee Florida. The location offers terrific opportunities for field trips, special sessions, and of course family vacations for those able to stay a little longer or arrive early. Keep your eyes open for the Call for Abstracts coming out soon!

As always, I hope you'll reach out to your AWRA state sections and student chapters and become engaged with them as well as AWRA national. We've reinstituted regular check-in calls with both and hope that we can build an even stronger network to share information and ideas in these critical times. Some of our sections have fantastic events planned. Please contact us for more information on how to reach or start a state section or student chapter. These are great ways to share your work and get new input from the work of others. Our publications, JAWRA and Water Resources IMPACT, of course are another great way to share your research, as are our webinars.

We are also working hard on some association basics, including updating and improving our website, our membership notification and renewal processes, and smoothing out technological and organizational glitches as we evolve as an organization. All hopefully will contribute to better experiences for you, our members.

I hope everyone will enjoy this edition of IMPACT. A special thank you to our guest editors, Venkatesh Merwade and Lilit Yeghiazarian, for gathering articles and working closely with our technical editor Michael Campana to put together another great edition. I want to thank all those involved in IMPACT's production for your hard work behind the scenes, including our top-notch AWRA staff. A shout-out also goes to our terrific 2020 Geospatial Water Technology Conference planners. They have done a wonderful job putting together the conference program and getting ready for the conference in Austin, TX March 23-26, 2020.

I hope to see everyone in Austin later this month. I hope I can count on your continued support as we lay the foundation for a great year. And good luck to all with the madness that is March. (I myself have my eyes on the UofO women's bball team). ■

2020 AWRA OFFICERS AND BOARD OF DIRECTORS

HIGHLIGHTS - JAWRA FEBRUARY 2020

[access full table of contents here: https://onlinelibrary.wiley.com/toc/17521688/0/0]

CELEBRATING 56 YEARS OF JAWRA – SUSTAINED CONTRIBUTIONS TO IMPROVE WATER RESOURCES

CELEBRATING 56 YEARS OF JAWRA –
This issue marks the beginning of the 56th year of the publication of the journal and true to its tradition, the issue continues to publish papers on a range of water resources topics.

In their water commentary, **Richer et al.,** discuss the potential for purchasing river water rights to maintain healthy aquatic habitats. They point to the need for much greater public/private funding and that transactional expertise is needed.

Driscoll et al., highlight the importance of correlation between simulated runoff and surface depression storage using continental extent models in order to improve our understanding and representation of surface depression storage processes.

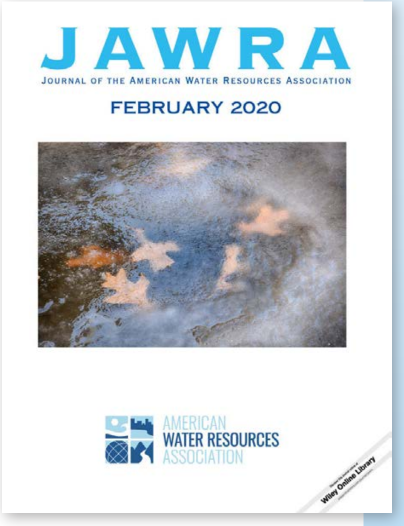
Shafequee et al., study the altitudinal distribution of meltwater in Glaciated catchments of central Asia. They conclude that Critical zone controls a larger portion of variability in meltwater and runoff, whereas temperature change is identified as a dominant driver for total runoff changes in most of the glacierized catchments.

Ercan et al., study the potential effects of climate change on the water balance of the Upper Neuse Watershed. The results of this study can aid planning for the RTP's future hydrologic and water supply conditions and expanding the knowledge of local impacts of climate change on critical watersheds.

Oplanski et al., using data from 229 cities across the US show that monthly maximum temperature strongly affects municipal water use, especially in cold, dry cities during summer.

The study by **Hoard et al.** demonstrates the importance of water cycle monitoring in urban settings toward the understanding of how stormwater control measures may reduce or otherwise influence flows to receiving waters.

Using the SPARROW model, **Miller et al.**, show that targeted management of a small number of catchments in the Chesapeake Bay watershed may be effective for reducing watershed-scale loading of total nitrogen to the Bay.



Terragosa et al.'s study shows that Coastal fog and recharge strongly influence late summer instream hydroclimate conditions critical to coho salmon and help to identify watersheds least vulnerable to future warming.

Antolini et al., evaluate various Agricultural best management practices (BMPs) and conclude that they can also reduce flood risk in addition to their primary intended purpose of nutrient reduction.

Discussions and Replies are integral parts of sustaining scientific debate of publication of scientific articles. In the February issue **Nash et al.,** discuss the paper by **Hunt et al.,** Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California title (published in vol. 54 (5) 2018). Which is followed by a reply. I urge the readers to read the original paper, the discussion and the reply.

A full table of contents for the February issue can be found at Wiley Online There are several other articles tackling various water resources issues on the Early View section of JAWRA's website.

FEATURE

Using Simulation to Forecast Resilience in Surfside, Florida

Stephen Bourne and Caroline Resor

COLLINS AND HARDING AVENUES in Surfside, FL, north-south arterial roads bringing commuting workers up and down the Miami-area Atlantic coast, pulse with activity each morning. Residents of the 5,800-person community join in the fray, turning north onto Collins Avenue or south onto Harding and driving past single-family homes to the west and condominiums and hotels to the east.

The Atlantic-facing condos sit atop a limestone coastal ridge that is part natural, part imported sand from Central Florida. The original intent of the imported sand was to protect the coastal development from hurricane storm surge, but with projections of potentially six feet of sea level rise by 2100, the Town of Surfside is wondering if elevation could be an eventual answer. Would a Surfside 4-6 feet higher than its current elevation be prepared for the 22nd century? This is one of the many questions the Town intends to assess as it plans for a resilient future.

To investigate different adaptation scenarios, Surfside applied to participate in a pilot organized by the American Flood Coalition (AFC) in which the awardee would receive an application of City Simulator, a new tool developed by global engineering consultancy, Atkins. City Simulator uses simulation to measure the likely costs and benefits of adaptation and mitigation measures. The tool will help Surfside weigh the pros and cons of many different potential adaptation actions including designing and installing green infrastructure, adding stormwater retention capacity, and elevating the entire Town.

A joint AFC/Atkins team is working with Surfside to explore these and other scenarios. Their first step is to use City Simulator to create a detailed digital twin of 2020 Surfside, a geospatial database that describes the interdependent systems of systems the town comprises. Transportation infrastructure, building stock, land parcels, rivers, canals, stormwater controls, water distribution, power, telecommunications, and seawalls are all depicted. The digital twin also includes agents, a population of avatars of each town inhabitant that collectively match the US-Census based statistics of Surfside. These avatars are assigned homes, workplaces, job descriptions, gender, age, educational level, and other properties that help increase the realism of the simulation. Each avatar is also given a decision tree, which is used within the simulation to determine the mode of transportation they might use to go to work, the grocery stores they might prefer, the recreational activities they might partake in, and so on.

With the digital twin loaded, City Simulator then runs a simulation forecast as a nested loop (see Figure 1). The outer loop runs once per year. It begins with future changes to the natural system. For example, if the sea level is forecasted to rise 3mm in the coming year, the sea level in the digital twin is elevated by this much. The outer loop then forecasts economic growth in the coming year, which is translated to a number of new commercial buildings. The buildings are placed in vacant or underdeveloped lots across the town in a process that seeks to emulate potential land development, where desirable parcels are developed first. The new buildings are then stocked with new businesses, which are populated with new agents,

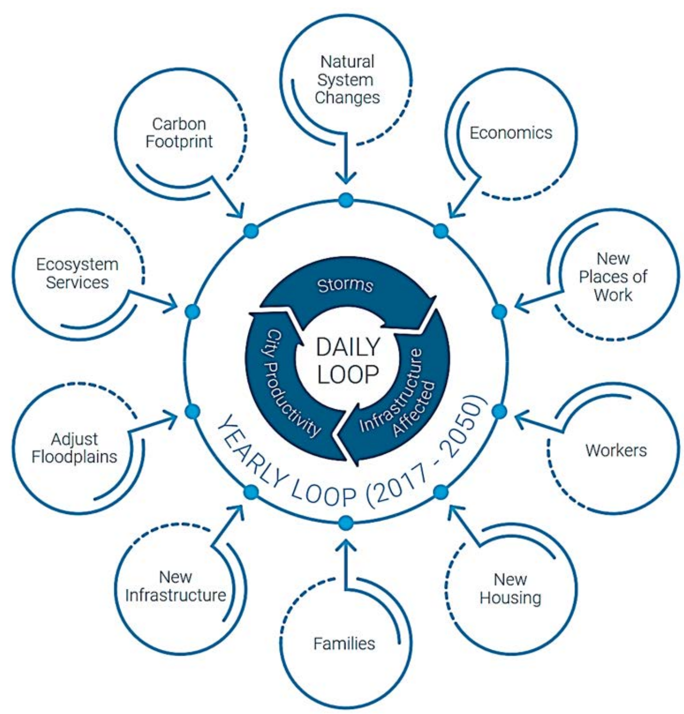


Figure 1: City Simulator Nested Loop Simulation Algorithm

resulting in population change in the town. The new agents are then given homes, which are also placed in the town as new residential construction. New infrastructure is then created such as roads and utilities to connect new building stock and provide capacity for the new population. Finally, the outer loop calculates impacts to natural system components as a result of the new urbanization. Elements like floodplains, shifts in ecosystem services as a result of lost natural habitats, and shifts in town-wide carbon footprint are evaluated.

The inner loop of the simulation algorithm focuses on natural disasters and daily activities like commuting, working, commerce, and recreation. The loop is driven by a daily weather forecast created by spatially and temporally downscaling global climate projections using an algorithm within City Simulator. These projections are used to ensure that the climate change signal is present in the simulation. A 500-1,000 member ensemble forecast of rain and temperature is created to reflect the uncertainty in future climate and its impact on weather. The simulation is run with all members of the forecast as independent simulations; the results are used to estimate the distribution of the various forecast metrics.

Each day of the forecast, the inner loop first determines if a disaster occurs; for example, a large rainstorm. If it does, the response to the storm is evaluated for each building and road segment in the town. To estimate the response, existing models such as FEMA flood insurance study HEC-RAS or NOAA SLOSH models are used to create rain-to-flood and wind-to-flood response curves for each piece of building stock and infrastructure. Leveraging existing models means that the development of the digital twin and subsequent simulation analysis can be done very quickly and within the context of a planning exercise, which typically has a time frame of months.

The response curves take the size of the rainstorm (e.g., 9 inches in 24 hours) as input and give the level of flooding in the building or the depth of overtopping of the road segment as output. Based on insurance studies, advice from flood response experts, and recommendations from Town staff, each building and road is also given a recovery curve, which estimates the amount of time the building or road will take to return to regular usability based on the severity of the initial damage. Costs of damage are also calculated as damage occurs, to estimate the financial impacts of repair.

When a building or road is flooded, the agents that use these elements either as their home, workplace, or as part of their commute path are delayed in their daily activities, and possibly even prevented from doing them at all until the building or road has recovered. This drop in productivity - measured as number of commute trips prevented or salary unearned - is tracked by City Simulator as key metrics of vulnerability in the town to climate change.

Because of the level of detail in the model, the locations of highest vulnerability and highest level of disruption to daily activity in the wake of disasters can be pinpointed down to the building and bridge. This information can be used to drive new approaches to making the town more resilient. For example, elevating particularly at-risk homes, enlarging existing stormwater retention basins, or adding green infrastructure in areas most prone to causing future runoff. More indirect and systemic approaches can also be attempted, such as adding economic development zones that incentivize development in less vulnerable areas, or conversely require more robust building standards to reduce vulnerability. These approaches are represented as town-wide adaptation scenarios in City Simulator, where a portfolio of mitigation and adaptation actions are specified and then the simulation is run again, to evaluate the system-wide impact of the proposed scenario.

The Atkins team is assessing a spectrum of scenarios in Surfside that range from simple enhancement of the stormwater control system to elevating the town. The variables for each scenario include geographic scope, hypothetical implementation date, and projected cost. Using the resulting detailed estimates of loss avoided, costs incurred, and resilience gained, the Town of Surfside and its residents and businesses will be better equipped to respond to the future reality of stronger storms, higher seas, and more frequent flooding. ■

Stephen Bourne, P.E., is a project director and Atkins Fellow at Atkins and lead developer of City Simulator. Over his twenty-year career, he has worked as a researcher, climate scientist, engineer, and decision support system developer. Steve is most interested in creating a more direct bridge between research and practice; he does so by building collaborative teams from academia and industry to solve shared vision problems, most recently increasing resilience of communities in a future with changing climate.

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FEATURE

U.S. Geological Survey Water Resources Mission Area: Progress Toward an Internet of Water

David L. Blodgett and Emily Read

Water information is fundamental to national and local economic well-being, protection of life and property, and effective management of the Nation's water resources. The U.S. Geological Survey (USGS) Water Resources Mission Area (WMA) works with partners to monitor, assess, conduct targeted research and deliver information on a wide range of water resources and conditions including streamflow, groundwater, water quality, and water use and availability.

The 2017 Aspen Institute report on *The Internet of Water* recognized the WMA and Core Science Systems, the mission area that oversees the National Hydrography Datasets, as the leading federal water information hub in the Internet of Water. The WMA is responding to this Aspen Institute charge and filling the role of an Internet of Water hub by providing access to water data from USGS and other providers; maintaining an extensive collection of web-based water science information; and developing innovative and forward-looking water data applications with partners.

Recently, the WMA modernized its Web content (see outcome here: https://usgs.gov/wma), which are now standardized and mobile compatible by default. This transition has required all WMA web content to be inventoried, evaluated, and updated. An example of this modernization is the USGS Water Science School (https://usgs.gov/wss), which provides a wide variety of water science information accessible to K-12 audiences, and draws about ten million users per year. Teachers, students, and curious citizens can now easily access water information Water Science School pictures, maps, and interactive content on mobile devices.

The WMA takes part in numerous activities to increase public access to water information and is committed to open-source software development practices. To encourage transparency and re-use of government-developed code, the USGS WMA recently expanded the use of a public-facing dashboard for all the open-source water applications WMA develops and contributes to: (labs.waterdata.usgs.gov/repositories/).

One of these open-source repositories contains software that is a modern, mobile-friendly take on the classic USGS site-based monitoring pages on NWISWeb (Figure 1; https://go.usa.gov/xdkkj). These new monitoring location pages were launched in 2019, and recent feature additions include:

- integration of cameras from selected sites, e.g., monitoring location number 05428500, Yahara River at East Main Street at Madison, WI, (https://go.usa.gov/xdkkB)
- custom time range for the interactive hydrograph,
- the ability to see upstream and downstream monitoring locations on a map,

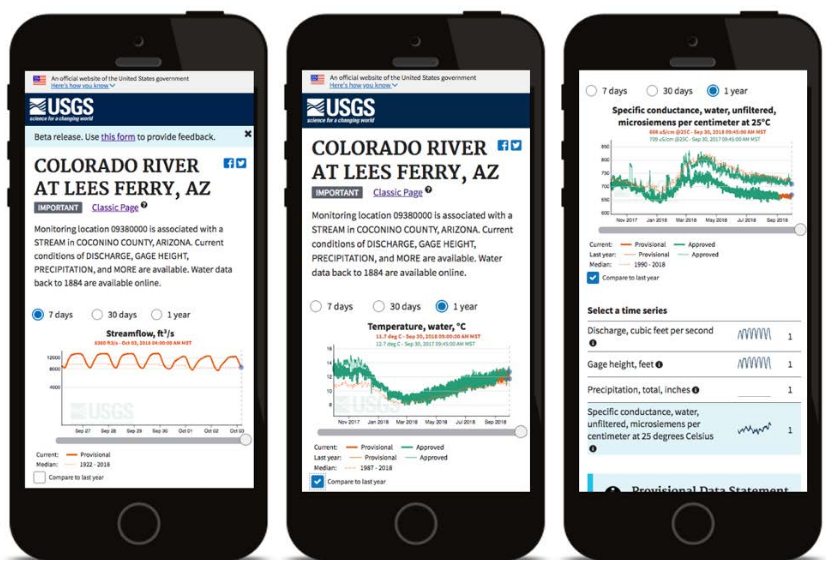

Figure 1. New site pages are responsive to different screen sizes like mobile devices.

- improved display of groundwater levels that are measured as feet below the land surface, and
- a graph image application programing interface (API) for web developers: https://go.usa.gov/xdkkk.

While development of new web pages and data delivery activities are primarily focused on providing data to the public, others involve focus on building a cross-organizational "Internet of Water" through engineering and interoperability experiments with U.S. and international partners.

The modern Web is made possible by focused yet powerful programming interfaces and information models. Advances in data science and machine learning, while incredibly powerful and revolutionary, require large amounts of accessible and machine-readable information. The WMA is increasing access to machine-readable data through projects such as the Network Linked Data Index (NLDI) (https://go.usa.gov/xdkkX), a search engine for data that can index data to the river network. A public, cloud-based version of the Hydro-Network Linked Data Index API was recently released by USGS WMA; see here for API documentation (https://go.usa.gov/xdkkR). Another innovative technology project, the Environmental Linked Features Interoperability Experiment (opengeospatial.github.io/ELFIE/), is developing best practices for publishing machine-readable water data, like rivers linked to monitoring sites, in ways that are more compatible with search engines, like Google.

Published in 2019, the WMA was involved in developing a new Open Geospatial Consortium (OGC) Web standard for geospatial feature data that is being used to help improve access to information about the sites at which water data is collected. A first implementation of this standard for all USGS monitoring locations was recently released by the WMA: (https://go.usa.gov/xdkkm). Tools like the NLDI, interoperability experiments like ELFIE, and numerous Web standards are the laying groundwork for easy display and linking of water information in web browsers and other software – imagine searching for your local water conditions as easily as you can search for your local weather. Find out how water data is being linked across international boundaries and explore more experimental technology on the USGS Water Data Labs (labs.waterdata.usgs.gov).

A major project that will use these standards is National Hydrography Infrastructure (NHI), which the WMA is developing with Core Science Systems and other partners. It combines the National Hydrography Dataset Plus High Resolution framework, with tools for linking, or addressing, water information to that framework, and makes that information searchable and discoverable through the NLDI. The NHI will also be the backbone for WMA geospatial information architecture, called the National Hydrologic Geospatial Fabric, going forward.

A newly formed National Integrated Water Availability Assessments (IWAAs) (https://go.usa.gov/xdkkV) program is the WMA activity delivering the National Water Census, as mandated by the SECURE Water Act of 2009. The first public product of the National IWAAs is a daily-updating prototype concept map of one National water availability indicator (Figure 2; https://go.usa.gov/xdkkp). The model that underlies the map is a daily time-step Precipitation Runoff Modeling System implementation of the WMA's National Hydrologic Modeling infrastructure. Nightly model runs are executed on cloud computing resources, and the mapping application is implemented with the high-performance and modern web-mapping technologies. This USGS demonstration is a first-of-its kind regularly updating water availability indicator information product that will be improved and expanded as the IWAAs program moves forward.

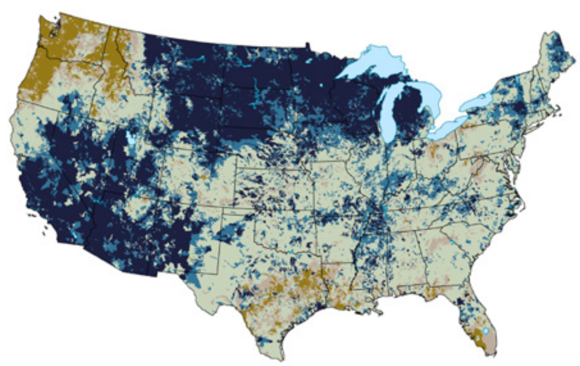

Figure 2. The IWAAs water availability concept map shows how wet or dry the landscape is relative to historical norms.

To learn more about Internet of Water and other activities of the WMA, find us at https://usgs.gov/wma and follow us on twitter @USGS_Water! ■

Davld L. 'Dave' Blodgett is a hydro informatics specialist with the USGS Integrated Modeling and Prediction Division Geo-Intelligence Branch. He holds a B.S. in civil and environmental engineering and an M.S. in water resources engineering form the UW-Madison. He is currently working as a hydro-informatics lead across the USGS Water Mission Area and the hydroscience community.
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FEATURE

Flood Prediction in a Changing World: Time to Break Traditions

Siddharth Saksena

SEVERAL STUDIES HAVE HIGHLIGHTED that human-induced climate change may have been an important factor in increasing the frequency of hurricanes in the past few years. Further, the reduction of hurricane translation speed and increase in moisture content carrying capacity due to increasing surface temperatures may result in more intense storms in the future. In addition to increased flood risk, rapid urbanization is causing significant shifts in land use patterns in coastal cities which will in an increase flood exposure.

In recent years, there has been a big push towards building flood resilient communities that are not only designed to reduce potential flood impacts but also contain safeguards in place to sustain the damage from more frequent and intense flooding. Basically, we have learned to live with the reality that a changing climate will test us with unprecedented events and how we react to this would determine our sustainability as a society.

In this regard, our ability to understand how intense storms translate into flood inundation is still a work in progress. The answer to the most frustrating yet increasingly relevant question of when and where will it flood remains as difficult as finding gold in the sand. This is in part because there is no one-size-fits-all solution for flood prediction, but also because newer and better techniques need to be implemented dynamically at a systems level.

In urban areas, riverine flooding impacts several urban systems simultaneously, but the existence of these features also determines how floodwaters propagate through them. Therefore, capturing the spatiotemporal variability and complex behavior of physical processes interacting with these complex urban systems is not possible using the conventional techniques for flood prediction. An example of floodwaters propagating though the urban infrastructure during Hurricane Harvey (2017) is provided in Figure 1. Further, urban areas are not just affected by large riverine floods and coastal storm surge but also smaller but more frequent precipitation that can give rise to nuisance flooding. This problem is especially prevalent in flat coastal regions where even a small amount of rainfall can result in flooded streets.

To better predict floods, we not only need better hydrologic and hydraulic (H&H) modeling, but also better representation of urban systems inside flood models. An integrated hydrosystems approach, therefore, has the potential to enhance our flood prediction capabilities for a range of storm forcing. Some of the new approaches for integrated urban flood modeling and recommendations for future directions are discussed below.

Potential Avenues and New Directions

With increasing resolution and quality of data, it is now possible to develop data-driven integrated models

Figure 1. Example of extreme flood inundation in Houston, Texas, during Hurricane Harvey (source – Google Earth and NOAA)

that can estimate urban flood inundation following a bottom-up approach. For example, Wade Barnes and his team at Parkhill, Smith & Cooper have built an integrated model for the City of Midland, TX, to propose better infrastructures and detention ponds for flood reduction with zero downstream impact. Such local-scale applications are steps in the right direction in addressing flood prediction using a systems approach.

Recently, our team has been working on multi-scale flood prediction which is aimed at building models that can not only simulate the hydrology and hydraulics across large regional scales, but also remain accurate and relevant at local neighborhood scales. In the past, the application of such models has been difficult without compromising the spatiotemporal scale and resolution, computational efficiency and local-scale hydrodynamics. We are trying to develop an integrated modeling framework using a combination of automated tools for ingesting geospatial descriptors and a computationally efficient hybrid design for large scale flood modeling and forecasting.

In addition, leveraging nationally available datasets for driving local flood models could be very advantageous for both immediate flood response and long-term urban planning. For example, the National Water Model (NWM https://water.noaa.gov/about/nwm) from NOAA can forecast both the rainfall and streamflow nationally. A step towards integration of national and local datasets and models is the automated flood forecasting system developed by Peter Singhofen and his team at Streamline Technologies (Orlando, Florida). This system uses the near-real time rainfall, streamflow and ET data from the NWM and runs preexisting Interconnected Channel and Pond Routing (ICPR) models to produce street-level flood forecasts.

Finally, communicating flood forecast information to the stakeholders and the general public is very crucial. As rightly said by Robert Kiyosaki, "There is gold everywhere, most people are not trained to see it.". Providing simple yet effective answers to flooding-related queries remains challenging even though there are several resources available. The good news is that some cities like Roanoke, VA, have already recognized this as an issue and are investing in tools that can provide the probability of flooding from rainfall-induced events. The PUFFIN app developed by Conrad Brendel (Virginia Tech) for Roanoke is designed to not only import and simulate a slew of precipitation forecast into flood models, but also quantify the uncertainty associated with forecasted precipitation. Similarly, developing a framework for sharing flood information at a national scale has the been the focus of the Urban Flooding Open Knowledge Network (UFOKN) team that I am fortunate to be a part of (see article by J. Michael Johnson et al. in this issue).

By implementing an integrated urban flood modeling framework and a system to communicate this information to the public, our 'reactionary' flood response can be changed into 'real-time' action and our long-term planning efforts can be driven towards building flood resilient communities. The key takeaway from this article is that we should start investing more resources towards integrating urban hydrosystems in H&H models and build large-scale forecast tools to be better prepared for whatever is to come in the future. ■

Siddharth Saksena is a Research Assistant Professor in the Charles E. Via Jr. Department of Civil and Environmental Engineering at Virginia Tech. His research is focused on developing tools for improving flood prediction in response to land use and climate change involving watershed-scale flood modeling and forecasting using an integrated hydro-systems analysis.
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FEATURE

Why Use High-Density Lidar for Surface Modeling in Urban Environments?

Alvan Karlin

DURING THE PAST 20 YEARS, THE SURFACE WATER modeling community has experienced a paradigm shift from using photogrammetrically derived contours for their topographic base maps to using lidar (light detection and ranging) for mapping. In contrast to contours that would be hand drawn, or maybe computer-constructed using a CAD or GIS program after a surveyor goes out into the field and measures a few hundred "topo-shots" in a square mile, even the earliest aerial lidar sensors would measure a tens of thousands of "shots" in that same square mile. The drawback, of course, is that lidar produces a "point cloud" of shots, with only some of those lidar shots falling to the ground, some shots fall in the trees, some on ponds and streams, some on cars and trucks, some were on rooftops and other surface objects (Figure 1).

As the lidar technology has advanced since the early 2000s, so has the point density in the point cloud and the processor's ability to apply filters to identify ground and other features. The newer sensors - topobathymetric lidar sensors - not only can "see through water" but can also produce several million points per square mile. With greater number of points in the point cloud, the greater the number of points that fall onto the ground to better define the ground surface for water modeling, but also the greater the number of points falling onto structures and rooftops to better define those features, too.

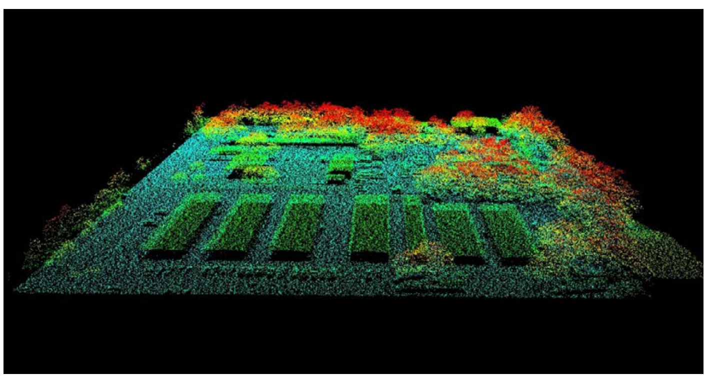

Figure 1. Dense Lidar point cloud in Hillsborough County (FY2017). Lidar points colored by elevation (blue= low ground to red = high tree canopy). Note cars lined up in parking area in foreground.

The question becomes how to use all of those points, both the ones on the ground and those not on the ground, to improve the surface water models.

A Case For High-Density Lidar

In 2017, Hillsborough County, the City of Tampa, and the Southwest Florida Water Management District (SWFWMD), through the Cooperative Funding Initiative Program, contracted for a county-wide high-density lidar data collection to update Federal Emergency Management Agency (FEMA) floodplain models and Digital Flood Insurance Rate Maps (FDIRMs). The project specified an average lidar point density of 24 points/m2 (approx. 93,000,000 points/mile2); however the achieved point density was a bit higher, in the 30 – 35 points/m2 range (over 100,000,000 points/mile2), with some open areas reporting over 50 points/m2. The combination of the high point density and high vertical accuracy (<10 centimeters (cm) Root Mean Square error (RMSE) from North American Vertical Datum of 1988 (NAVD88)), resulted in point cloud that could easily map tree crowns and branches, shrubby vegetation and other natural surface features, as well as ground and man-made features, such as rooftops.

In early lidar surveys, where only one or a few points would fall on rooftops, it was difficult, if at all possible, to delineate the edges of a roof. However, with several hundreds of points on the rooftop in open areas, and even with only hundreds of points on the roofs in obscured areas, the roof edges, and hence the shape of the roof could be discerned easily. In the American Society of Photogrammetry and Remote Sensing (ASPRS) standard lidar classification system, Class 6, is reserved for lidar points on rooftops while Class 2 is reserved for bare earth/ground.

Prior to the paradigm shift, non-directly connected impervious area (nDCIA) - that portion of the impervious area (IA) not directly connected to the storm water collection system through pipes and drains (rooftops, etc.) that contributes to storm water runoff - was measured as an estimate from aerial imagery, or from property appraiser's records and generally for an entire watershed. Lidar survey, point cloud classification, and subsequent Geographic Information System (GIS) computer processing can then be used to construct polygons around clusters of Class 6 points defining rooftops and edges (driplines). This not only produces a much finer-grained, parcel-level estimate of the nDCIA, but also provides an avenue to estimate finished floor elevations (see below), as well as fixing a long-standing problem with lidar- derived digital elevation models (DEMs) that are used for storm water and floodplain hydraulic and hydrologic (H&H) modeling.

Prior to the widespread use of lidar-derived DEMs, the DEMs used for H&H modeling were constructed from contour surveys. The contours were generally constructed at 1 foot (30cm) intervals with an accuracy of +/- 0.5 (15cm) feet and a 10'x10' (3 meter (m) x 3 meter or larger cell-size) DEM was extracted from the contours. The lidar-derived DEMs are generally constructed based on a much smaller cell size (generally 1m x 1m or 0.5m x 0.5m) and have an accuracy of under 10cm. Given the millions of lidar points in a square mile, smaller elevation differences may occur in a lidar-derived DEM that would be smoothed-over in a contour-derived DEM.

Among those elevation differences that get smoothed over in contour-derived DEMs are the small differences around building foundations. While the differences may not be large, when the Triangular Irregular Network (TIN) from which the DEM is derived, is constructed from the lidar, multiple, irregular triangles form over building foundations. These large triangles result in "basement sinks" or divots in each structure in a bare-earth DEM (Figure 2). The sinks add to water storage and result in

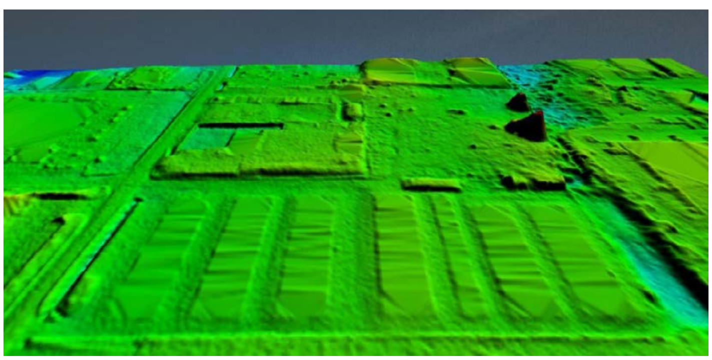

Figure 2. Lidar-derived DEM constructed from Class 2 (bare ground) without building driplines. Notice the triangles cutting through the buildings in the foreground.

non-normal water flow in the vicinity of the structure. Instead of water flowing around a house, it flows into the basement sink.

Early on at the SWFWMD, we tried a few different approaches to force H&H modeling units (catchments, sub-basins) to flow around, rather than through buildings. We discovered that by incorporating the highest Class 6 points per building into the DEM, catchments would be delineated along the roof ridgeline; better than water running through the building, but still not correct, and the approach was very laborious especially in areas of high density residential housing. We found a better approach to the problem.

By using the GIS-constructed rooftop polygon (actually the building dripline because of the roof overhang) we could not only force water to flow around each building, but also estimate the finished floor elevation for on-grade buildings. Using a GIS-process called "conflation", we now identify the highest Class 2 (=ground) point within 1m of the building and assign that elevation to the polygon. Then to be safe, we add 10cm (the error in the lidar) to the highest Class 2 elevation and use the now 3-dimensional polygon to make a building pad and enforce the elevation and dripline shape the DEM (Figure 3). The

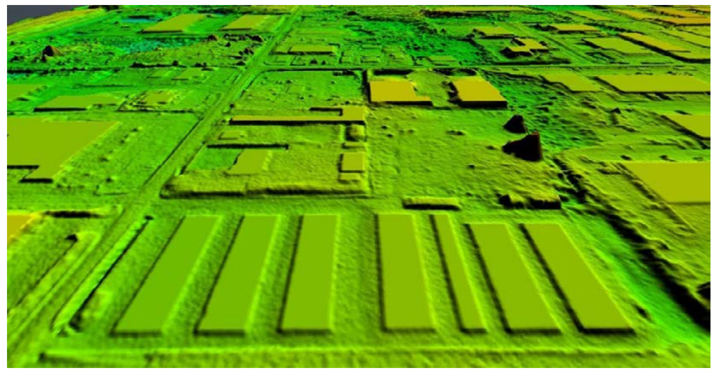

Figure 3. Lidar-derived DEM constructed from Class 2 (bare ground) with 3-dimension building driplines built into the DEM. The building pads force water to flow between, rather than through, the buildings.

raised building pad fills the basement sink and forces water to flow around the building, into the street and/or Florida drain, solving the basement sink issue.

As an additional bonus, we discovered that the building pad closely approximates the finished floor elevation of a building constructed on-grade. The conflated elevation of the lidar-derived building pad was within a few centimeters of the surveyed finished floor elevations in buildings that were built on- slab and on-grade; the common practice throughout Hillsborough County. We could not estimate the finished floor elevations for buildings that were elevated off-grade. ■

"I really like how the footprints of the structures are more extruded in the DEM which helps us evaluate structural flooding more accurately for floodplain mapping purposes. I also really, really like how you can very clearly see the edge of pavement on the streets, the high points in the road, and where the curbing is located." – Ben Allushuski, Hillsborough County, Stormwater Engineering Division

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FEATURE

Moving from Information to Insight by Linking Urban and Hydrologic Systems through the Urban Flooding Open Knowledge Network

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Floods are the costliest type of disaster in the United States. While evaluating flood risk remains a critical issue for the scientific community, assessing the total impact across complex urban systems is an even greater challenge. During flood events, interconnected urban infrastructure like the power grid, transportation network, drinking water and sewerage systems are all impacted, and experience cascading failures. We call this interconnected system of systems the Urban Multiplex. Even though we have data about individual components of the Urban Multiplex and an abundance of hydrologic forecasts, this information is not yet connected in a way that promotes clear, immediate insight about existing and potential problems.

OVER THE LAST THREE DECADES, three prominent ideas have fundamentally changed the way we store, manage and interact with data and documents. We believe they can help elevate our representation of flood impacts. These include:

WWW and Semantic Web 3: The World Wide Web was designed by Tim Berners-Lee in 1989 to connect documents on the internet through navigable hyperlinks. The vision for the Web 3.0, or the semantic web, is that the network of hyperlinked human-readable web pages will include machine-readable metadata that describes the fundamental content and relationships of the data. Through these links, connections to other related resources can be derived providing a "linked" or collective view of the world's knowledge (*e.g.* knowledge graph). This transition from linear connections (user clicks through links) to semantic relationships (metadata is used to connect diverse documents) marks a large step toward the Internet's ability to provide not just information, but also insight.

Digital Earth: In 1998, US Vice President Al Gore proposed the idea of a Digital Earth in which information about a collective cultural and scientific understanding of the world (imagery, text, geospatial objects) could be stored in an interactive 3D globe. At the same time, significant investments were made in creating geospatial datasets that represent our spatial understanding of where things are in the world and what attributes are associated with them. In 2008, a working group published a paper on the *Next Generation of Digital Earth* emphasizing that a truly Digital Earth must not be a single system, but a collection of integrated infrastructures built on open data.

National Water Model: In 2016, the National Ocenic and Atmosperice Administration (NOAA) implemented version 1.0 of the National Water Model (NWM; https://water.noaa.gov/about/nwm) which provides current and forecasted streamflow simulations for the entire Continental United States (CONUS). Such a system is built on a rich collection of national scale geospatial products, which fundamentally changes the landscape of federated hydrologic forecasting.

Combined, these developments offer a new and exciting opportunity to better connect our understanding of the built and natural environments through the way we document, structure, store and share knowledge about the human-environment interface.

No Clear Semantic Understanding of Flooding

The Google search bar provides a unique lens into the way human knowledge about any topic is modeled, and how well relevant data can be connected in the semantic web. In a familiar example, a search for 'coffee shop near me' is able to link our understanding of 'coffee shop', and 'near me', to provide not only locations but also relevant information such as hours, reviews, and menus. Today, a similar search for "flooding near me" (Figure 1 left panel; made in Santa Barbara on February 21st, 2020) produces less informative results. Instead of a rich set of information, the first entry is a link to a general question of *"where can I get flood maps"* while the second and third entries advertise an Australian service called "*Floods Near Me*". Moreover, the videos are from 2017 and 2018 events in the Midwest and Texas. The limitations in connecting the idea of flooding to the time and place of the query, and to other compatible information (like weather) highlights an opportunity to transform the way flood information is communicated.

To illustrate, if a clear semantic understanding of flooding and its relationship to space and time were contained in a knowledge graph, the quality of these results could be improved to resemble something like Figure 1 (right panel) where the connections between geospatial products are defined, the connections to hydrologic models and observation systems are explicit, and the contextualization of flooding as a weather-driven phenomenon is concrete. In this way, flooding would not give us reviews, hours and menus like a 'coffee shop', but maps (Digital Earth), warnings (NWM), and weather reports.

When these links and relationships are defined, knowledge can be traversed in such a way that we immediately connect streamflow values to the structures at risk, and to the entities those structures serve. That is, we can identify if a streamflow is large enough to impact a power station; the address points and infrastructure served by that power station; and the role those entities play in the Urban Multiplex. Such connections not only help homeowners prepare for imminent flooding risks but also anticipate other problems such as possible power outages, sewage backflows, and service closures. More importantly, such connections enable the analysis and optimization of the interactions among various urban infrastructures such that damages can be minimized, and recovery expedited. In this way a forecast becomes more than just information, but insight that can inform context-based decisions at all scales.

The Urban Flooding Open Knowledge Network (UFOKN)

In 2019, as part of the National Science Foundation's (NSF) push to harness the Big Data revolution through the Convergence Accelerator pilot, a team of researchers set out to model our understanding of flooding by developing the semantic connections between the Urban Multiplex and hydrologic predictions.

In the first phase of this project, two stakeholder workshops were organized to bring together industry, academic, and government participants to better understand their day-to-day challenges. From these, a robust list of user personas was identified to guide the initial content and relationships needed in a urban flooding-focused knowledge graph. To date, we have successfully linked OpenStreetMap infrastructure and OpenAddress points with the NWM to provide real-time assessments and historic synopses of impacted infrastructure allowing users to search for flooded roads or at-risk homes. As this graph grows, additional infrastructure types like power grids, bridges, and Superfund sites are being added along with their high-level relationships to one another (e.g. power grids serve homes).

Like Digital Earth, a truly successful open knowledge network will be a constantly evolving entity, able to integrate a wide array of resources from other architectures and users. To achieve this, we are developing an extendable conceptual model that allows others to introduce their own model output, observation networks, and urban information to what we hope will be a community resource. In this vein our team involves a host of modelers, engineers, geographers, social scientists, data and computer scientists, seeking to generalize the type of information that can be ingested and extracted from the graph. More broadly, we hope that through this work our semantic understanding of flooding will become rich enough so that finding

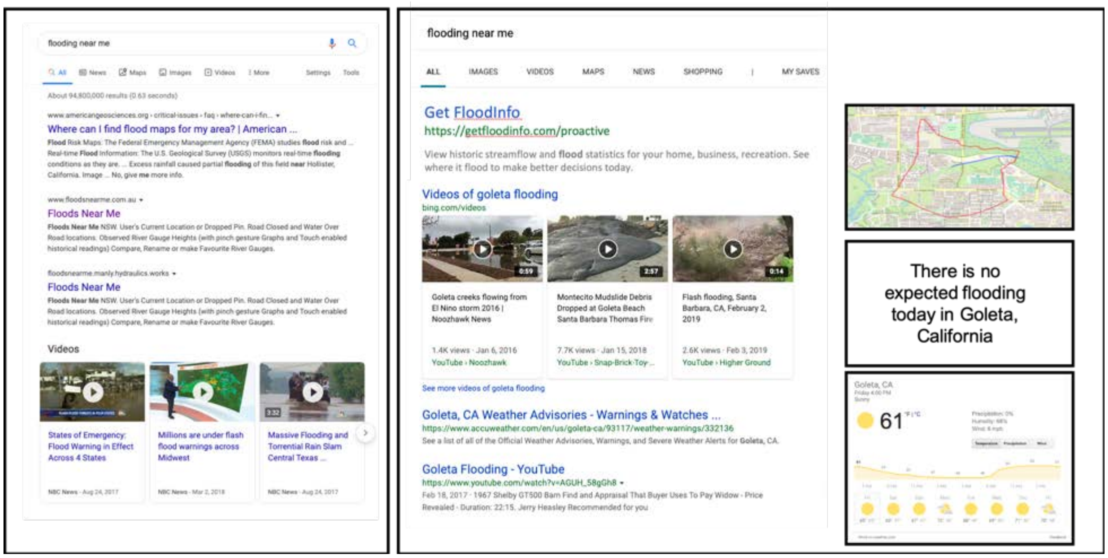

Figure 1. Searching for "flooding near me": current results (left panel);
and expected results enabled by the Urban Flooding Open Knowledge Network (right panel).

relevant flood information will be as simple as finding a good coffee shop. ■

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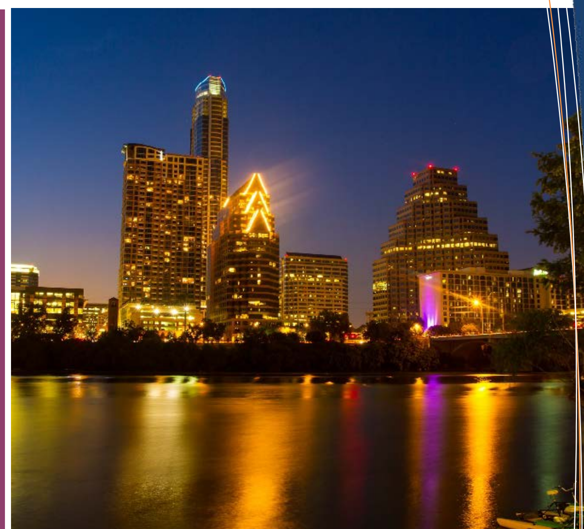

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