Assessing Urban Flood Risks: The Critical Role of Dynamic Modeling

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MIT CONCRETE SUSTAINABILITY HUB

Current and Future Risks

Extreme Climate Events (ECEs) resulting in flooding are among the world's gravest natural hazards, [1] with surface flooding estimated to be the most serious ECE infrastructure damage risk for 39% of the world's land area [2]. Climate simulation models suggest a future in which extreme climate events will only become more frequent [3,a].

While flooding from ECEs presents a crucial threat to states and provinces, this risk is amplified in cities. As 55% of the world's population lives in urban areas, and 80% of global GDP is generated in cities, proper design of infrastructure is needed to protect these economic engines and contribute to their sustainable growth [4]. As this brief will show, urban communities have a higher risk of flooding than current models suggest, making it more vital than ever to ensure that our pavements, buildings, and infrastructure are built to withstand the stresses of future flooding events.

The world faces two mounting flood threats: overflowing bodies of water referred to as **fluvial or coastal flooding** and rain storms overwhelming drainage referred to as **pluvial flooding**. Even though fluvial flood events tend to capture media coverage, pluvial flooding from rain storms actually causes greater cumulative damage due to its **greater frequency** [5]. Despite

Key Takeaways:

- Extreme climate events resulting in flooding are a growing hazard.
- Common tools for flood risk assessment often struggle to model pluvial flooding, influenced by landscape texture and other factors.
- MIT CSHub has identified the critical role of the two-dimensional hydrodynamic rain-on-mesh approach in forecasting pluvial flooding.
- Seven times more Cambridge land area was estimated to be flooded by our approach than one relying on a catchment (C) model.
- Urban communities have a higher risk of flooding than current models suggest, making it more vital than ever to ensure that our pavements, buildings, and infrastructure are built to withstand the stresses of future flooding events.

As opposed to fluvial flooding, pluvial flooding can happen even in places nowhere near a body of water. Pluvial flooding is affected by terrain, urban infrastructure, and the dynamic nature of storm loads.

the gravity of pluvial flooding, prevalent flood simulation tools – referred to as catchment models – underestimate urban flood risk because they focus on the capacity of a city's **underground** drainage system. Recently, more sophisticated tools have been introduced that integrate surface flow simulation with models of the underground drainage network – these tools are referred to as one- and two-dimensional hydrodynamic simulations (1&2DH sims).

Unfortunately, deployment of 1&2DH simulations is severely limited by two important factors – most areas do not have detailed digital representations of their underground drainage networks and developing such data is costly. We all take for granted the availability of detailed digital data on above-ground buildings and infrastructure. These are freely available thanks to satellite image processing and the aggregation of data collected for mapping and routing services. However, there are no analogs for underground systems. So, **the cost burden of developing them falls on local governments.**

The CSHub is exploring the potential of using 1&2DH sims to characterize flooding risk using *only* freely available surface data. If this proves effective, as this brief suggests it may be, **it would be possible to rapidly apply this new toolkit to all areas without the need to wait for costly and time-consuming underground surveying efforts.** This will provide new information on the vulnerability of infrastructure, allowing agencies to more effectively assess the value of climate adaptation strategies.

Overcoming Current Modeling Limitations

Current flood risk assessment methods use what is referred to as a **catchment approach**, which is often combined with one dimensional flow models of a city's drainage network. The catchment modeling approach assumes that precipitation falls in predefined areas (i.e., catchments) and the runoff is transported directly to the

Data about underground drainage networks is scarce and costly to obtain. The CSHub is exploring the use of simulations to characterize flood risk with only surface data.

underground drainage networks. In such a model, flooding occurs after the drainage network fills and water backs up into the city. Because of this, catchment models depend on detailed data about a city's underground systems.

Catchment models were not developed to simulate the surface flow of water. When simulating a massive quantity of water overflowing a river or coast, the omission of surface effects is not significant. But when flooding depends on the balance between inflow (from precipitation) and outflow (water flowing around a city and through its drainage network), **current tools underestimate the extent and severity of surface flooding**, particularly in complex urban areas. Several solutions have been proposed to address the approximations within catchment models, including representing the city with a large number of finely divided areas. However, what appears to be the most promising solution is to incorporate models that explicitly simulate the flow of water across and through the urban setting. These 1&2DH sims are made possible by the decreased cost of computational power.

Although 1&2D sims provide valuable insights, to date they have been applied in cases where detailed information

The terms "10-year design storm" and "thousand-year design storm" refer to storms that statistically have a specific chance of occuring in a given year. The former is modeled on a storm with a 10% chance of occuring in a given year, while the latter is modeled on a storm with a 0.1% chance of occuring in a given year [6].

was available about both above ground buildings and terrain and below ground drainage systems. As mentioned earlier, the lack of digital data on underground systems and the cost and time required to create such data creates a real barrier to applying these tools.

To overcome this barrier, the MIT Concrete Sustainability Hub is developing a method leveraging an integrated **one-and-two-dimensional rain-on-mesh** simulation (**1&2D-ROM)** [b,c]. In this simulation, surface flow is modeled in two-dimensions considering the topography of the city including the arrangement of buildings and roads and accounting for pervious and impervious surfaces. Flow within the drainage network is modeled using conventional one-dimensional methods. Finally, the rain-on-mesh label describes how rain is modeled as entering the system – uniformly across the analysis area. With the approach, we capture the dynamic and time-sensitive nature of surface flooding in urban areas. In this brief, we compare the results this approach when both above-ground and below-ground information is available and when only above-ground information is available. We also look at the same case using a more conventional catchment model.

Case Study: Pavement Flooding Risks in Cambridge, Massachusetts

To better understand the implications of the integrated 1&2DH-ROM modeling approach (and to examine flood risks for the MIT campus), we applied it to a case study of the city of Cambridge, Massachusetts [d]. We simulated the impact of nine different storms, ranging from a 10-year design storm experienced today to a thousand-year design storm modelled on expected future climate scenarios. The effects of each storm were simulated using both a baseline 1&2DH catchment and an integrated 1&2DH-ROM approach. The 1&2DH catchment model (referred to as CATCH) serves as a proxy for a 1DH catchment model that might be found in current flood risk assessment tools. As the CATCH model accounts for more complex water flow compared to a more common 1DH catchment model, we expect it to detect more precipitation-induced surface flooding and, as such, the differences in conventional 1DH catchment and 1&2DH-ROM results may be even larger than our observations suggest. Finally, the 1&2DH-ROM model was used in two conditions: one that included full details about both above- and below-ground buildings and city infrastructure (referred to as ROM-DRAIN) and one that only included above-ground city details (i.e., ignoring below ground drainage and water systems – referred to as ROM-SURF).

Figure 1 shows the predicted flooding (dark blue areas) for the three model runs for one specific storm – the “hundred-year” storm based on 2070’s climate.

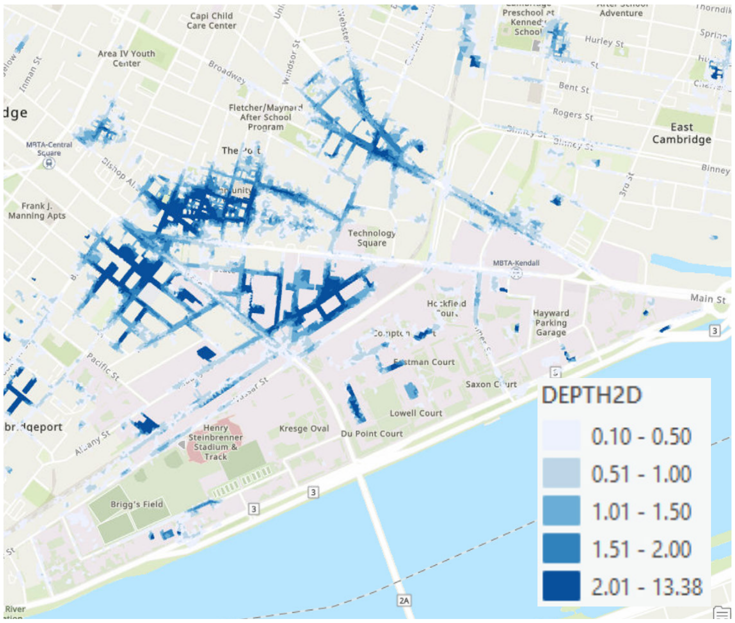

Figure 1a: CATCH model simulation of maximum flood depths during 2070’s hundred-year storm around MIT campus. Flooding shown has a minimum depth of 0.10 ft.

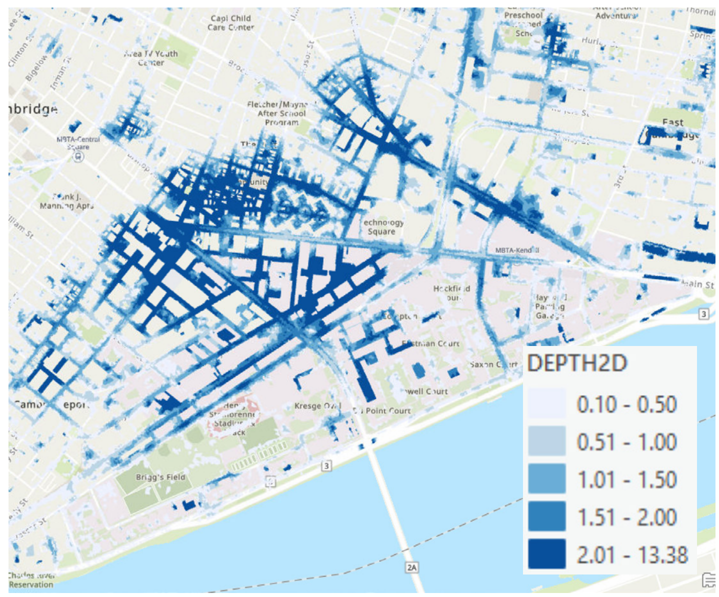

Figure 1b: ROM-DRAIN simulation of maximum flood depths during 2070’s hundred-year storm around MIT campus. Flooding shown has a minimum depth of 0.10 ft.

Figure 1c: ROM-SURF simulation of maximum flood depths during 2070’s hundred-year storm around MIT campus. Flooding shown has a minimum depth of 0.10 ft.

These maps make it clear that different modeling approaches lead to different flood risk forecasts. Notably, the 1&2DH-ROM model that considers both above and below-ground city details (ROM-DRAIN, shown in Figure 1b) forecasts **seven times more land area to be flooded than the CATCH model simulates.** The third model, ROM-SURF, without below ground morphology, forecasts a flooded area about 30% larger at peak than the more comprehensive ROM-DRAIN model considering the subsurface pipe systems.

Although the results produced by ROM-SURF may be an overestimate, its lower computational and labor demand compared to ROM-DRAIN may justify its use in some cases, such as in rural applications where details on subsurface systems may be sparse.

Figure 2 plots the development of modeled flooded area in Cambridge over the course of the 24-hour storm for the same three modeling approaches. All three approaches forecast a rapid increase in flooded area around hour 11 of the storm, but, just as with the mapped result, the ultimate peak extent of flooding differs dramatically between the CATCH result and the two ROM results. This figure supports the idea that ROM models not only identify larger areas at flood risk, but also reveal that large areas within a city may stay flooded for more than twelve hours, even for a 24-hour storm. This information about flood behavior is critical for planning evacuation routes and for identifying infrastructure that needs to be hardened to a given level of flood exposure.

These results imply that **1&2DH-ROM modeling can identify more parts of the urban environment at risk of flooding than the catchment approach**. It is clear that the manner in which precipitation is modeled—in terms of how it is introduced into a system and how it moves within it—has an impact on the ability of a given model to forecast surface flooding. It is essential that more advanced flood simulation tools like 1&2DH-ROM be implemented to help key actors better understand which parts of cities are most vulnerable to both fluvial and pluvial flooding. This research makes it clear that **urban communities are more at risk of flooding than current flood maps suggest**. This makes it more vital than ever to ensure that our pavements, buildings, and infrastructure are built to withstand the stresses of future flooding events.

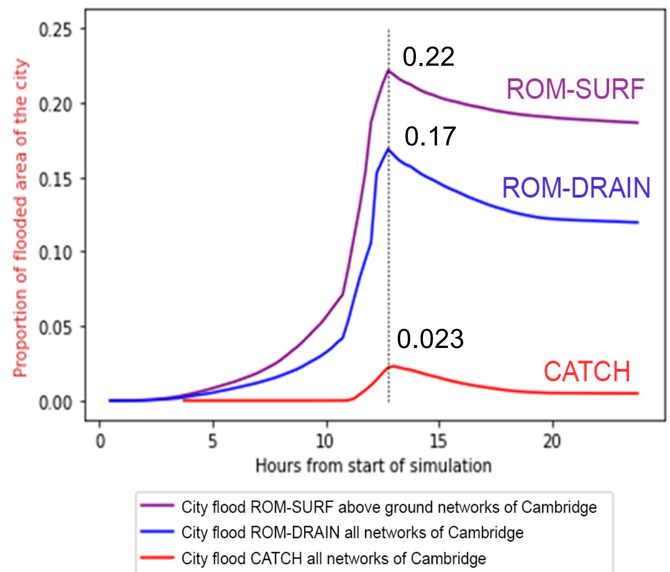

Figure represents the same rainstorm event, 100yr 24hr 2070 with total accumulated rain of 11.2 inches.

Figure 2: A comparison of the proportion of flooded land area estimated by CATCH and 1&2DH-ROM modeling of 2070's hundred-year storm. At peak flooding time, 1&2DH-ROM estimates 17% of Cambridge land area to be flooded, while CATCH estimates 2.3% to be flooded.

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References

[1] Gu, D. (2019). Population Division Exposure and vulnerability to natural disasters for world's cities*. [online] Available at: https://www.un.org/en/development/desa/population/publications/pdf/technical/TP2019-4.pdf.

[2] Koks, E.E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S.A., Hall, J.W. and Hallegatte, S. (2019). A global multi-hazard risk analysis of road and railway infrastructure assets. Nature Communications, 10(1). doi:10.1038/s41467-019-10442-3.

[3] Goodess, C., Kossin, J., Luo, Y., Paul, M. and Della-Marta (2012). Asgeir Sorteberg, Carolina Vera. [online] Boris Orlowsky. Declan Conway. Available at: https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap3_FINAL-1.pdf.

[4] World Bank (2020). Urban Development. [online] Available at: https://www.worldbank.org/en/topic/urbandevelopment/overview.

[5] Mobini, S., Nilsson, E., Persson, A., Becker, P. and Larsson, R. (2021). Analysis of pluvial flood damage costs in residential buildings – A case study in Malmö. International Journal of Disaster Risk Reduction, 62, p.102407. doi:10.1016/j.ijdrr.2021.102407.

[6] USGS. The 100-Year Flood. [online] https://www.usgs.gov/special-topics/water-science-school/science/100-year-flood#:~:text=The%20term%20%22100%2Dyear%20flood%22%20is%20used%20in%20an,1%2Dpercent%20chance%20of%20occurring.

Endnotes

[a] The Intergovernmental Panel on Climate Change (IPCC) noted that "climate change is intensifying the water cycle. This brings more intense rainfall and associated flooding" (2021). With the growing hazard of flooding, current infrastructure may not be able to address this risk. There will be an estimated $15 trillion infrastructure investment gap globally by 2040. See https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/. Also see https://www.weforum.org/agenda/2019/04/infrastructure-gap-heres-how-to-solve-it/.

[b] The approach allows for the simulation of rain as falling on surfaces with an equal spatial distribution, with intensity varying with time. The water spreads around the urban environment based on a city's topography, morphology, subsurface features such as pipes or subways, and the characteristics of local soils.

[c] The approach was implemented in INNOVYZE's Integrated Catchment Modeling software.

[d] Details on Cambridge elevations, structures, pavements, underground systems, and soil characteristics were provided by the consultancy Dewberry through funding from the MIT Office for Sustainability and through the City of Cambridge GIS.

Related Links:

- MIT News, "Studying floods to better predict their dangers"
- MIT CSHub, "Precipitation Flooding in Urban Environments"

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