Accessible Multi-scale Flood Modeling via the 3D Lattice Approach

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MIT CONCRETE SUSTAINABILITY HUB

Flooding: A Mounting Threat to Urban Communities

Flooding is both one of the most frequent and one of the most devastating natural disasters. It poses a particular threat to urban areas, which house 55% of the world's population and are responsible for 80% of global GDP [1].

A majority of cities analyzed in a UN Department of Economic and Social Affairs report were found to be highly vulnerable to flood-related mortality (76%) and/or economic losses (72%). Even cities with low levels of flood exposure must take the hazard seriously: 26.5% of cities studied had low flood exposure but high flood-related mortality risk, 24.0% of cities studied had low flood exposure yet high flood-related economic risk [2].

In addition to its risk to economics and life for city inhabitants, surface flooding is estimated to be the most serious risk to infrastructure due to **extreme climate events** (ECEs), potentially impacting 39% of the world's land area [2] For more information on pavement-related risks, see Figure 1. As ECEs like flooding are projected to increase in frequency and severity, it is imperative that urban buildings and infrastructure be built to withstand this hazard [3].

Great strides have been made toward understanding flooding risks for urban areas. State-of-the art flood modeling tools allow for a degree of hazard risk assessment on the community scale, making it possible for decision makers to evaluate and act on certain flood projections. It is important to note that community-scale risk assessments are available for **fluvial or coastal flooding** (which occurs when bodies of water overflow) but not **pluvial flooding** (which occurs when rain overwhelms drainage systems, as occurs in a flash flood). This is in part because simplified modeling tools rely on **one-dimensional drainage modeling**, which tracks the movement of water particles from where they fall to a large body of water such as an ocean. This causes them to struggle with modeling the impact of **neighborhood texture** (the arrangement of buildings, infrastructure, and other features with respect to one another) during flood events, which is essential for understanding pluvial flood propagation.

Key Takeaways:

- Floods present a mounting risk to communities and infrastructure, particularly in urban areas.
- Many flooding modeling approaches are computationally, logistically, and financially expensive, relying on proprietary resources and significant processing power.
- The MIT CSHub has developed a computationally inexpensive way to forecast floods in urban spaces.
- The approach can capture flooding at multiple scales, from the local scale to the state scale and beyond.

Figure 1. Flooding is among the most serious weather-related risks to infrastructure, particularly in urban areas. It can cause lasting damage to pavements and make road travel hazardous or impossible (a problem which compounds when emergency service vehicles cannot transverse certain areas). Investment in infrastructure that can better withstand flood events (like concrete pavements in some cases) is needed as extreme climate events become more frequent and more severe. More rapid, accessible flood modeling approaches (such as 3DLA) that can account for the arrangement of elements in the urban environment could help decisionmakers better understand where infrastructure investment and changes are needed.

Our scalable and efficient approach to flood modeling

A new approach is needed to make flood modeling more accessible and less expensive. At the MIT Concrete Sustainability Hub, we have developed a novel approach to flood modeling: **The 3-Dimensional Lattice Approach (3DLA)**. It estimates the flooding risk of urban areas based on their neighborhood textures. The texture of neighborhoods can have degrees of “porosity” which relate to the risk and impacts of flooding [Figure 2]. Our model is designed to be computationally inexpensive and use widely available data from sources like OpenStreetMap and digital elevation models. In addition, it is highly scalable and can be run at the local, state, or even larger scale levels.

In contrast to the models that rely on one-dimensional drainage modeling, our approach models neighborhood texture and flooding via a **lattice approach**. Our **lattice** is a three-dimensional space in which city features like buildings, roads, and sidewalks are represented by **lattice points**. These are points which can have different heights or consist of different materials.

Due to this lattice-driven approach, our model can perform simulations quickly with limited resources. For instance, the case study that follows this section was simulated on a consumer-grade desktop computer with 64 gigabytes of random access memory (RAM).

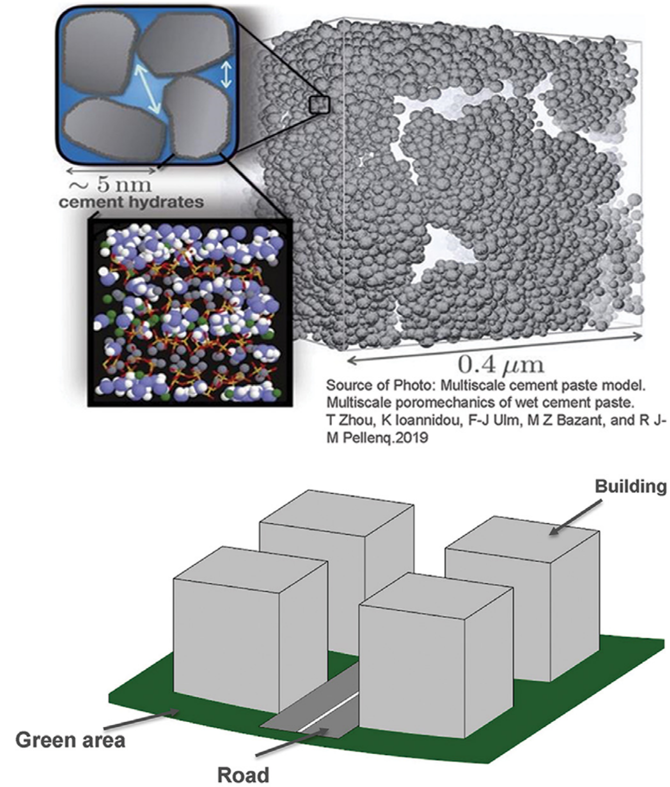

Figure 2. Here, we make an analogy between the neighborhood texture of a city and the porous structure of concrete. 3DLA relies on a lattice density functional theory that surfaces in the built environment influence the adhesive potential of its nearest neighboring lattice-point(s). For further reading see [4, 5].

Case study: MIT Campus

To demonstrate the efficacy of 3DLA, we opted to model the flooding of a 20 square-kilometer area of Cambridge, Massachusetts, particularly an area of MIT campus around Massachusetts Avenue. We simulated a **10-year flood**: A flood of a severity such that it has a 10% probability of occurring in a given year (essentially, a flood that happens, on average, once every 10 years) [Figure 3].

For our lattice, we used a horizontal resolution of 5 meters and a vertical resolution of 0.3 meters. We then divided the area of study into 11 subdivisions or **subcatchments**, which we designed such that, during a flooding event, the average height of the water for each of them would be the same. For these subcatchments, we used a horizontal resolution of 0.46 meters.

We then compared the performance of our approach [Figure 4c] to an integrated catchment model created by fellow Hub researcher Katerina Boukin [Figure 4b]. We obtained an R-squared value of 0.994, indicating a good fit between the average water height for each sub-catchment predicted by our approach and the benchmark heights.

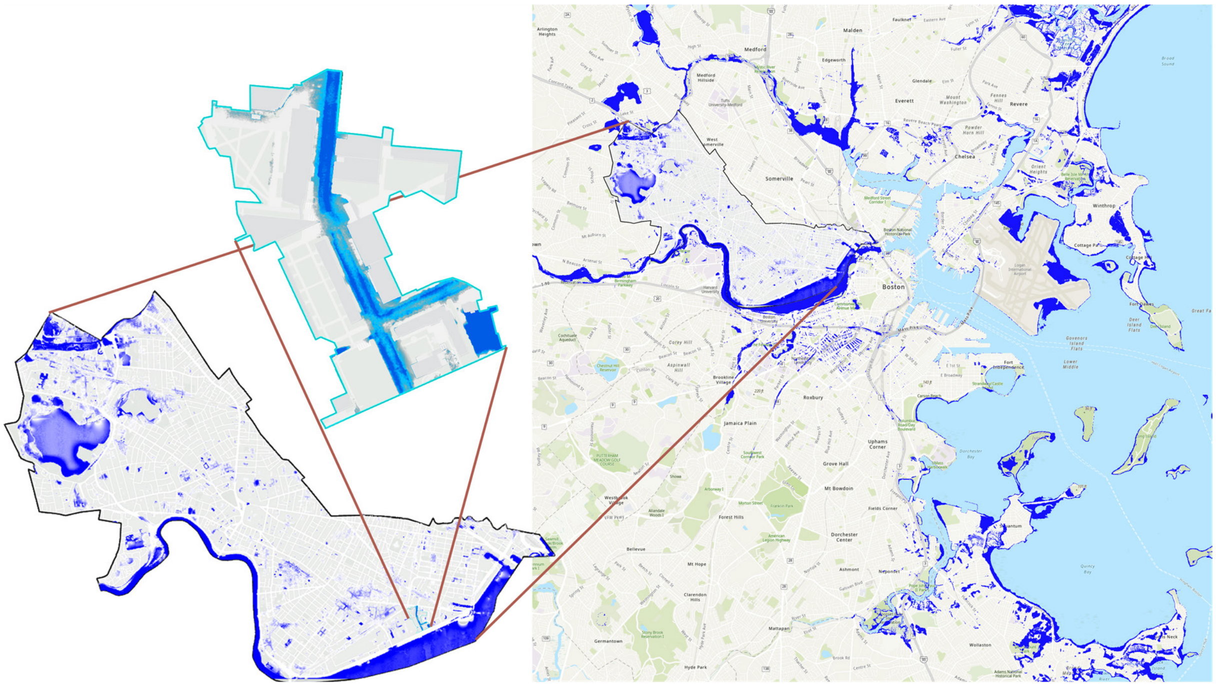

Figure 3. The areas of Cambridge, Massachusetts projected to be flooded by 3DLA during a 10-year flood event. The smallest cutout with cyan-tinted flooding is a subsection of the MIT campus around Massachusetts Avenue.

Applications of 3DLA for Multi-scale Flood Modeling

It is evident that our buildings and infrastructure should be built to withstand increasingly frequent and severe ECEs. For flooding, it is essential that decision makers look to sources like meta-models to inform their design of flood protection systems.

We believe that our modeling approach offers a new avenue into flood risk assessment because it is computationally inexpensive and draws from widely available resources. In addition, it is capable of capturing flooding at multiple scales, including local, state, and larger scales.

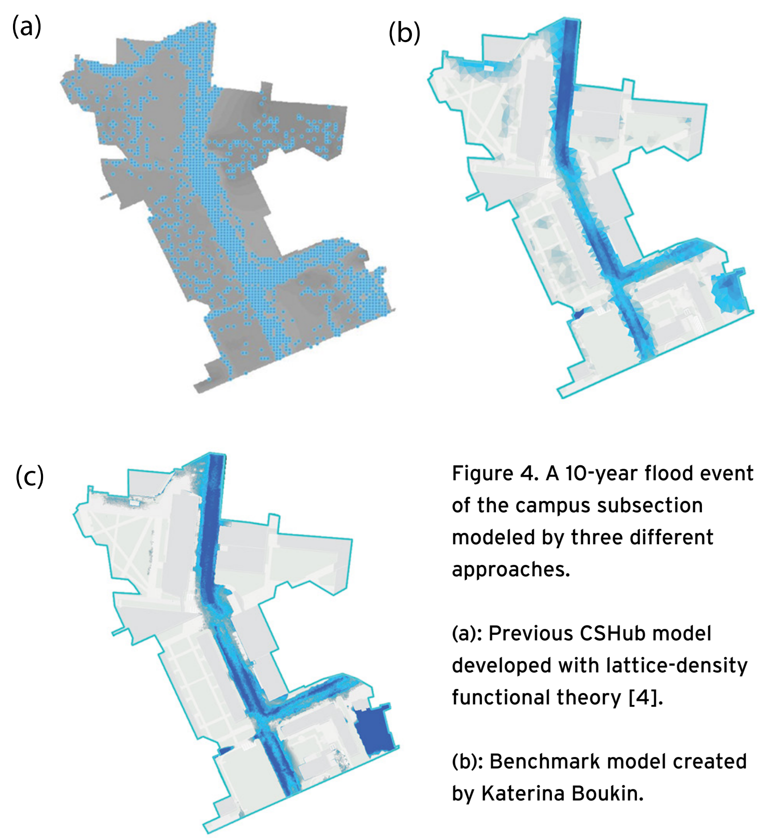

Figure 4. A 10-year flood event of the campus subsection modeled by three different approaches.

(a): Previous CSHub model developed with lattice-density functional theory [4].

(b): Benchmark model created by Katerina Boukin.

(c): Current 3DLA iteration.

References

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Related Links:

- MIT CSHub Research Brief, "Assessing Urban Flood Risks: The Critical Role of Dynamic Modeling"
- Computational Modeling of Concrete and Concrete Structures, "Modeling inundation flooding in urban environments using density functional theory"

Citation:

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