UNIVERSITÀ DEGLI STUDI FIRENZE | DINFO DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE | DISIT DISTRIBUTED SYSTEMS AND INTERNET TECHNOLOGIES LAB | SNAP4CITY

Assess Flooding Impacts in Urban Environment: Integrating Fluid-Dynamic Simulations in Smart City Digital Twin

Enrico Collini[1], Marco Fanfani[1], Federico Galli[1], Paolo Nesi[1], Paola Zamperlin[1]

[1] DISIT Lab, DINFO, University of Florence, Florence, Italy
https://www.disit.org, https://www.snap4city.org, https://digitaltwin.snap4city.org

Flooding Events

Drivers

Climate Change
→ More frequent extreme rainfall events 6.5% for every degree Celsius of global warming

Urbanization
→ Increased exposure of people and assets

Soil Sealing
→ Reduced infiltration capacity

→

Flooding Events

Drivers

Impacts

Climate Change
→ More frequent extreme rainfall events 6.5% for every degree Celsius of global warming

Urbanization
→ Increased exposure of people and assets

Soil Sealing
→ Reduced infiltration capacity

Human Losses
→ 335 deaths*

Economic Damage
→ Infrastructure and property losses >18B€*

Environmental Impact
→ Water contamination and damage
→ 30% EU river network experienced flooding*

* In Europe in 2024

Flooding Events

Drivers → Impacts → Need For Action

Drivers

Climate Change
→ More frequent extreme rainfall events 6.5% for every degree Celsius of global warming

Urbanization
→ Increased exposure of people and assets

Soil Sealing
→ Reduced infiltration capacity

Impacts

Human Losses
→ 335 deaths*

Economic Damage
→ Infrastructure and property losses >18B€*

Environmental Impact
→ Water contamination and damage 30% EU river network experienced flooding *

Need For Action

Flood Forecasting
→ Early warning systems

Risk Assessment
→ Hazard and vulnerability mapping

Digital Twin Simulation
→ Sensors, IoT, Smart City Digital Twins SCDTs

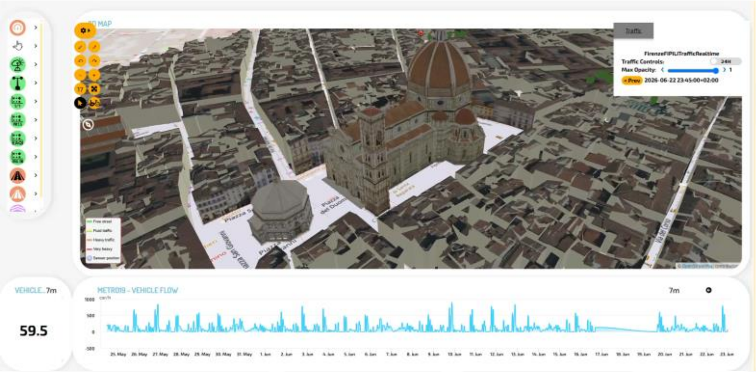
* In Europe in 2024

Unifying SCDTs and Flood Risk Mapping

Smart City Digital Twins unify GIS information about a city with IoT and data integration.

The Gap

Most SCDT environments **lack physics simulation** engines capable of representing **Flooding** events



Proposed system: An open-source fluid-dynamic simulator coupled with Snap4City SCDT to manage dynamic visual analytics for decision makers to identify critical flooding areas.

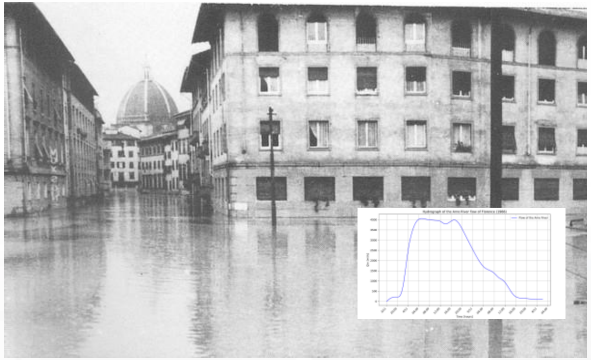
Unifying SCDTs and Flood Risk Mapping

Smart City Digital Twins unify GIS information about a city with IoT and data integration.

The Gap

Most SCDT environments lack physics simulation engines capable of representing Flooding events

⬇



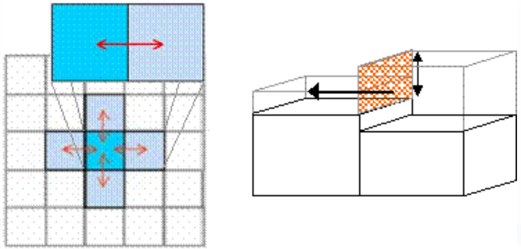
Firenze Nov 1966 – system validation

Discharges ranging up to 4000 m^3/s

Proposed system: An open-source fluid-dynamic simulator coupled with Snap4City SCDT to manage dynamic visual analytics for decision makers to identify critical flooding areas.

LISFLOOD-FP

- 2D hydrodynamic simulation model for Flooding
- Raster grids from 1x1m up to 100x100m cells
- The model solves a simplified version of the 2D shallow water Saint-Venant equations



The continuity equation of the Saint-Venant system is:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = r - f$$

Water level variation

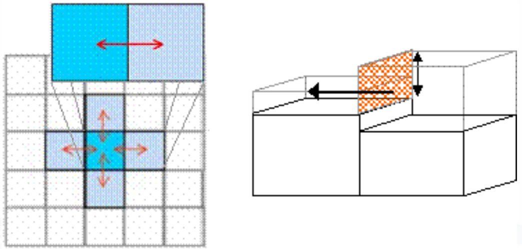
Water Flow nord-sud

Water Flow est-ovest

h is the water depth, u,v the components of the mean velocity on x and y direction respectively, r the possible rain, and f the infiltration (both expressed in mm/h).

LISFLOOD-FP

- 2D hydrodynamic simulation model for Flooding
- Raster grids from 1x1m up to 100x100m cells
- The model solves a simplified version of the 2D shallow water Saint-Venant equations



The continuity equation of the Saint-Venant system is:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = r - f$$

h is the water depth, u,v the components of the mean velocity on x and y direction respectively, r the possible rain, and f the infiltration (both expressed in mm/h).

Solver

1 determine u,v solving Saint-Venant diff equations (simplified)
2 compute unit discharge
3 use continuity to update h

$$h(t + \Delta t)$$

Local Inertia Solver

$$\begin{cases} \frac{\partial q_x}{\partial t} + gh\frac{\partial H}{\partial x} + g\,\frac{n^2 q_x |q_x|}{h^{\frac{7}{3}}} = 0 \\ \frac{\partial q_y}{\partial t} + gh\frac{\partial H}{\partial y} + g\,\frac{n^2 q_y |q_y|}{h^{\frac{7}{3}}} = 0 \end{cases}$$

Water moves from gravity effect. → The steeper the terrain, the faster it accelerates.

Terrain friction slow the water movement → **Manning's n (Roughness Coefficient):** An empirical parameter representing the **friction/resistance** applied to the flow by the surface material (e.g., concrete vs. grass).

Smooth pavement → Water flows easily
Grass → Water encounter greater resistance

The mass has inertia →

Dynamic Modelling: Accounts for the time water needs to accelerate, contrasting gravity/slope against friction (*n*).

Urban Complexity → Effectively captures building barrier effects and street channelling. Buildings are modelled by locally increasing terrain elevation and applying specific roughness values.

$$\frac{\partial q_x}{\partial t} + gh\frac{\partial H}{\partial x}$$

LISFLOOD-FP Integration in Snap4City

INPUT FILES

- **Terrain elevation (.asc)**
  Digital Elevation Model in ASCII raster format
- **Surface roughness (.asc)**
  Manning's coefficient per land-use class
- **Boundary conditions (.bci/.bdy)**
  Inlet/outlet flow rates; time-varying hydrographs
- **Initial conditions (.asc)**
  Starting water levels (set to 0 then filled)
- **Simulation parameters (.par)**
  Solver, CFL coefficient, timestep, duration

OUTPUT

Temporal raster water levels (.wd)
One file per timestep — matrix of **water height (m)** added to terrain elevation.
Cells written at each sampling interval.

Post-processing & Heatmap Generation

→ Parse .wp files into .con
→ Coordinate projection
→ Binary Serialization
→ GeoTIFF Generation, GeoServer publish

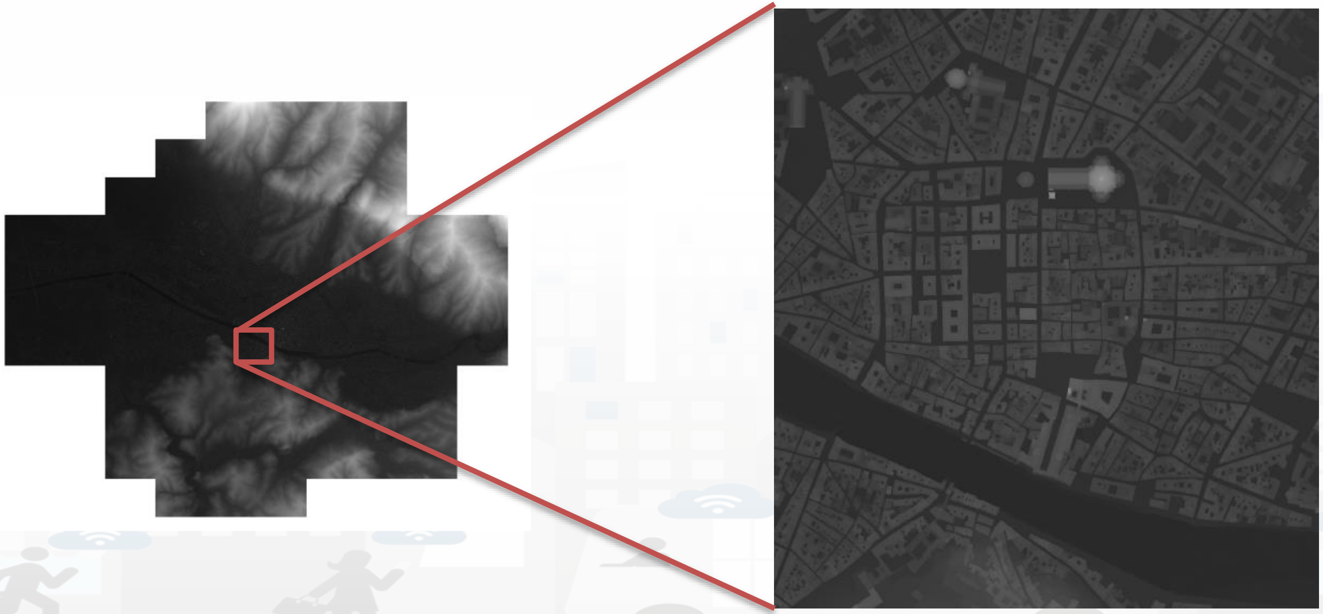
Data Enrichment

→ ColorMap config.
→ Metadata upload
→ .con Upload

← (Heatmap Manager Snap4City DT)

Experimental results

Digital Terrain Model (DTM) of the urban area has been used to model the terrain elevation and identify the bed of the Arno River, Florence.

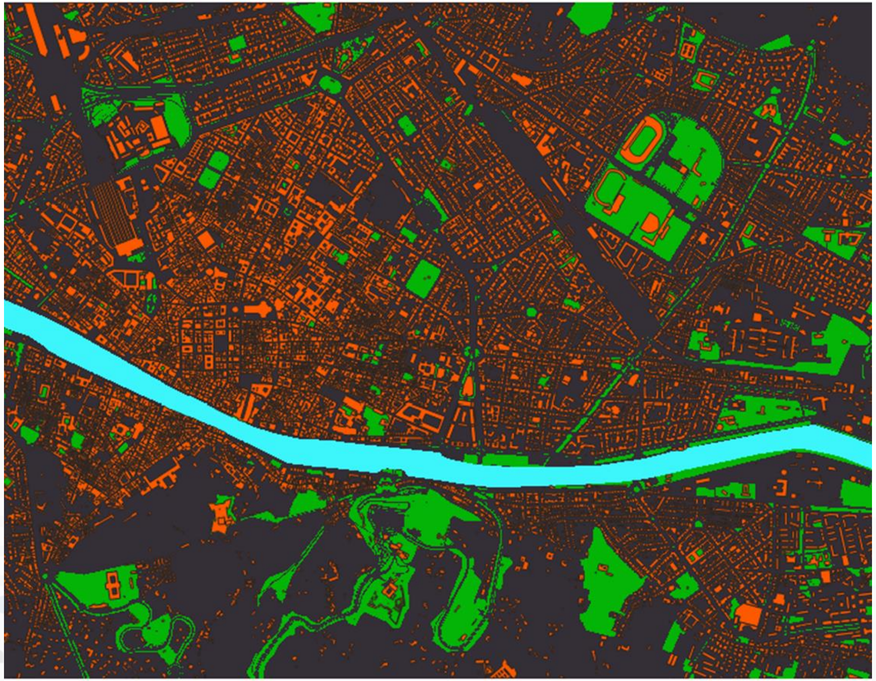


Experimental results

To model the surface roughness, i.e., the Manning's coefficient, a spatial differentiation according to land use has been used.

- urban surfaces (e.g., asphalt, concrete) 0.025;
- green areas with a value of 0.05;
- and water bodies to which a value of 0.04

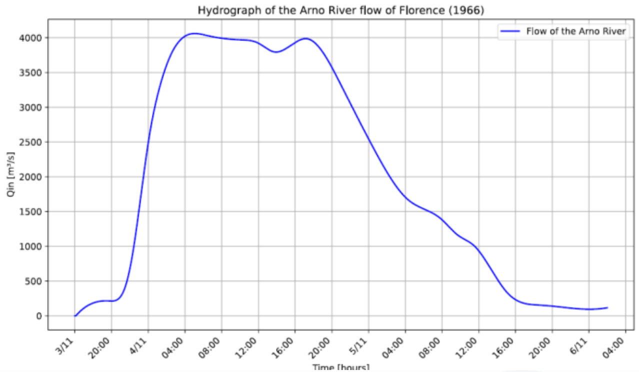
In red the buildings of the city →



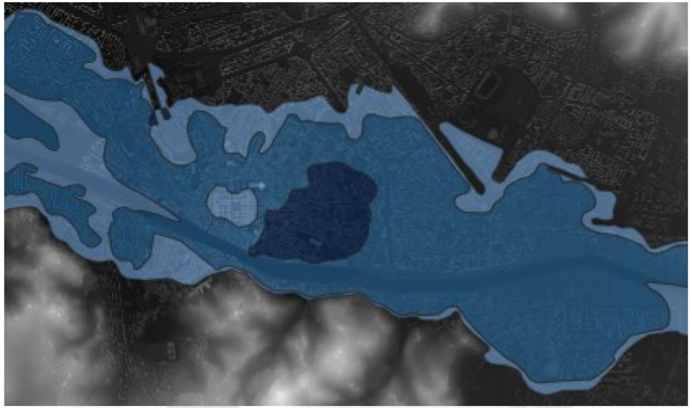
UNIVERSITÀ DEGLI STUDI FIRENZE | DINFO DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE | DISIT DISTRIBUTED SYSTEMS AND INTERNET TECHNOLOGIES LAB | SNAP4CITY

Experimental results

The simulation timespan has been specified at 48 hours (from 4:00 PM on November 3rd to 02:00 AM on November 6th) with a sampling time of 20 minutes.



Historic Arno's discharge measured during the 1966 flooding. From late hours of November 3rd to the afternoon of November 5th, 1966.



Flooding reference map for the event of 1966 in Florence, highlighting the three zones: light-blue for water depth values between 0 and 2 meters; mid-blue for values from 2 to 4 meters; dark-blue for values from 4 to 5 meters.

Experimental results

To evaluate the balance between simulation precision and computational efficiency, two spatial cell resolutions—1 m² and 4 m²—have been tested.

Experimental results on the simulations performed on 1 m² cells and 4 1 m² cells.

Parameter	1 m² simulation	4 m² simulation
Number of cells	22.5 million	5.5 million
Computational time	2 weeks	4 days
MAE	1.11m	1.10m
RMSE	1.27m	1.26m

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |h_{\text{sim},i} - h_{\text{obs},i}|$$

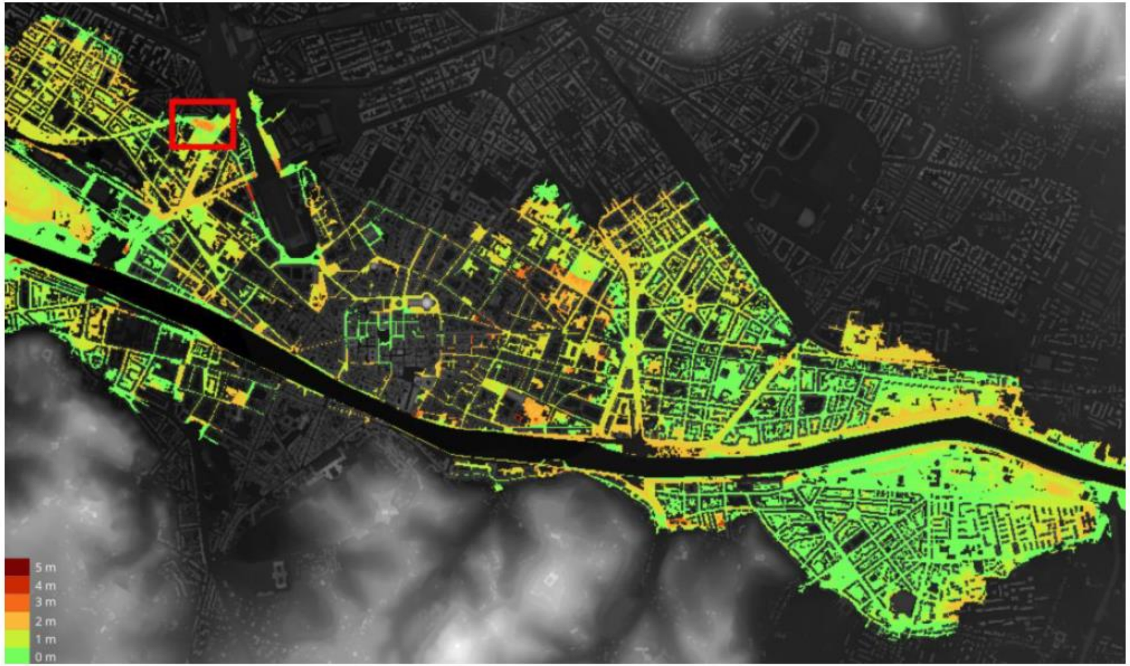
$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_{\text{sim},i} - h_{\text{obs},i})^2}$$

Experimental results

To evaluate the balance between simulation precision and computational efficiency, two spatial cell resolutions—1 m² and 4 m²—have been tested.

Optimization Insight: *Transitioning to a 4m² resolution saves 71% of computational time with absolutely negligible changes to accuracy (MAE differs by less than 1 cm).*

1966 Flooding Comparison with Simulation Results



Flooding absolute error map from the simulations using 4 m² cell compared to the data from the 1966 flooding (at 6AM of 4th of November, near the discharge peak).

In the red box in the top left corner an area obtaining large errors due to changes in the urban landscape between the 1966 (year of the Florence flooding) and the year of DTM acquisition.

UNIVERSITÀ DEGLI STUDI FIRENZE | DINFO DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE | DISIT DISTRIBUTED SYSTEMS AND INTERNET TECHNOLOGIES LAB

Snap4City DT Flooding Sim Visualization

Conclusions

Integrated Framework

Successful integration of the hydrodynamic simulation engine (Local Inertial Formulation) with the Smart City Digital Twin platform.

3D

Interactive navigation across both spatial and temporal dimensions through web-based 3D dashboards.

Mesh Resolution

Datasets with 1 m^2 and 4 m^2 grid cells were tested and compared.

Data Ingestion

Automated management of simulation outputs, encoded as time-series heatmaps.

Experimental Validation

Model reliability demonstrated through the accurate reconstruction of the catastrophic 1966 Florence flood.

Impact On Decision Support

Rapid identification of the most critical and vulnerable urban areas

Thank you for your attention

Enrico Collini| DISIT Lab, University of Florence
https://www.snap4city.org | https://www.disit.org

Appendix

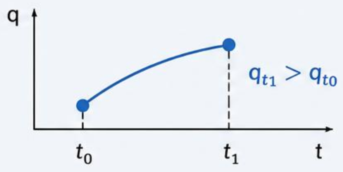
Components of the Local Inertia Solver Equations

$$\begin{cases} \dfrac{\partial q_x}{\partial t} + gh\dfrac{\partial H}{\partial x} + g\dfrac{n^2 q_x |q_x|}{h^{7/3}} = 0 \\ \dfrac{\partial q_y}{\partial t} + gh\dfrac{\partial H}{\partial y} + g\dfrac{n^2 q_y |q_y|}{h^{7/3}} = 0 \end{cases}$$

T1 – Inertia (Local Acceleration)

How quickly the flow is changing.
This is the inertia term.

If q increases from t_0 to t_1 ($q_{t_1} > q_{t0}$), the flow is accelerating.

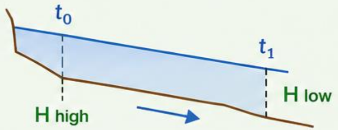


T2 – Gravity (Driving Force)

The gravitational force that accelerates the water.

$H = h + z$ (water surface elevation)

- H is high at t_0
- H is low at t_1
- The surface is sloped
- Water wants to flow downhill



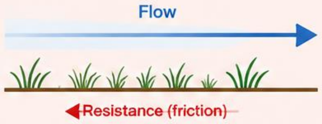
T3 – Friction (Resistance)

The friction that opposes the flow.

It depends on:

- Manning's *n* (roughness)
- Flow depth *h*
- Flow velocity *q*

Friction slows down the flow.



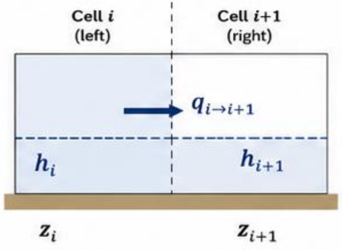
The equation balances these three effects:
Inertia (T1) + Gravity (T2) + Friction (T3) = 0

Local Inertia Solver – buildings

Why water accumulates upstream of a building?

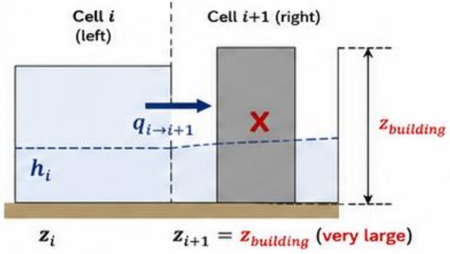
The building increases the terrain elevation z in the cell on the right.

1 Initial situation



- Same terrain elevation: $z_i \approx z_{i+1}$
- Water surface: $H = h + z$
- Moderate slope: $\frac{\partial H}{\partial x}$ is small
- Flow q from left to right

2 Right cell has a building



Effect on the gravity term

$$T2 = gh\frac{\partial H}{\partial x}$$

- z_{i+1} (right) becomes very large
- $H_{i+1} = h_{i+1} + z_{i+1}$ becomes large
- The gradient $\frac{\partial H}{\partial x} = \frac{H_{i+1} - H_i}{\Delta x}$ becomes large
- ⇒ The gravity term $gh\frac{\partial H}{\partial x}$ becomes large
- **⇒ The discharge $q_{i \to i+1}$ decreases** (the building opposes the flow)

Continuity equation (per cell)

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \qquad (1)$$

During the simulation, Δq keeps arriving from the left.

In each cell, **the only variable that can change** to satisfy (1) is $\boldsymbol{h}$.

3 What happens? (Continuity)

Δq continues to arrive from the left (**inflow > outflow**).

Since the building strongly reduces the flow to the right, $\frac{\partial q_x}{\partial x} < 0.$

From the continuity equation (1):

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0$$

- $\frac{\partial h}{\partial t}$ ↑ This term must increase
- $\frac{\partial q_x}{\partial x}$ ↓ Negative (inflow > outflow)
- $\frac{\partial q_y}{\partial y}$ ↓ Often small (simplified 1D view in x)

Therefore:

$$\frac{\partial h}{\partial t} > 0$$

⇒ h increases

⇒ Water depth rises in the cell upstream of the building.

The model raises h (water depth) in the upstream cell until the flow that can pass around the building balances the inflow.

In summary

Building appears
The terrain elevation z in the right cell becomes very large.

↓

$H = h + z$ increases
The water surface elevation on the right becomes high.

↓

$\partial H / \partial x$ becomes large
The slope of the water surface increases.

↓

Gravity term (T2) becomes large
The driving force toward the building is strongly opposed.

↓

Flow q across the face decreases
Less water can leave to the right.

↓

Inflow > Outflow
$\frac{\partial q_x}{\partial x} < 0$

↓

h increases
Water accumulates upstream of the building.

Key point: In the Local Inertia Solver, buildings are represented by a high elevation z and a high roughness n.
This modifies $H = h + z$, increases the gravity term, reduces the flow, and—through continuity—causes $\boldsymbol{h}$ to increase.