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City-scale urban dual-drainage modeling increases the accuracy and detail of flood predictions under extreme rainstorms

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Introduction

Climate change is expected to significantly increase heavy precipitation globally, with high to medium confidence (IPCC, 2016). This shift in rainfall intensity is likely to lead to secondary hazards, such as flooding. Hong Kong, characterized by a subtropical climate, has already experienced severe rainfall, exemplified by the record hourly rainfall of 158 mm during the black rainstorm of 2023 (Hong Kong Observatory, 2024). As extreme weather events become more frequent, innovative approaches to flood modeling and impact assessment are essential.

City-scale dual-drainage modeling is crucial for deriving flood depths from rainfall data. The dual-drainage model, which integrates a 2D surface hydrodynamic model with a 1D underground stormwater network model, is particularly suitable for urban areas as it allows for bidirectional flow between surface and subsurface systems (Knight et al., 2021). However, developing a physics-based dual-drainage model that includes thousands of pipes and inlets poses significant challenges. These challenges stem from the extensive data collection required for drainage pipe characteristics and the fine grid resolution needed for densely distributed inlets (Qiang et al., 2021).

Alternative methods have been proposed to account for underground drainage capacity, such as subtracting the water volume in pipes from surface runoff (Chen et al., 2009) and using an equivalent infiltration rate to represent drainage capacity (Qiang et al., 2021). However, these approaches do not accurately capture the physical flow of water underground.

Existing dual-drainage models in the literature

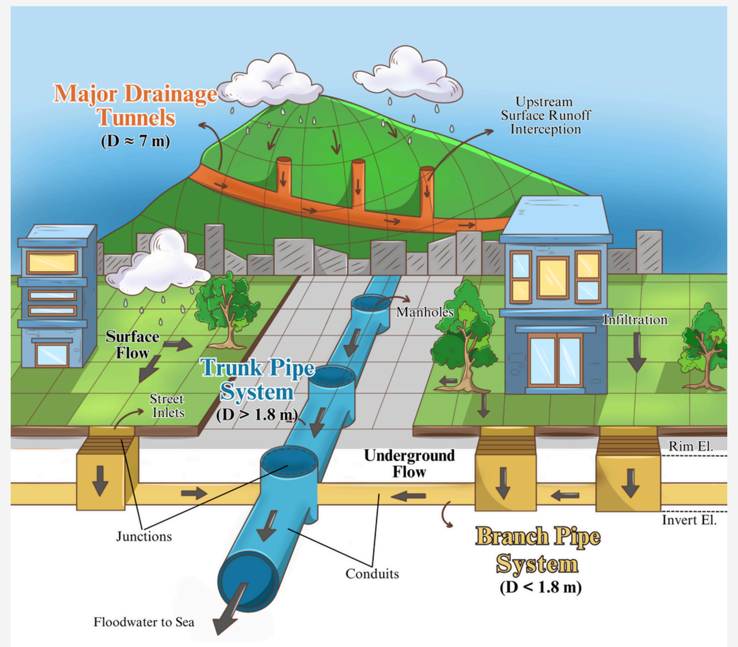
Authors	Modeling Approach and Size
Montalvo et al. (2024)	Used a physics-based approach using virtual sewer network; Size of study area: approximately 0.6 km²; Total length of conduit considered: 11 km (real), 8.57 km (virtual); Total junctions: 444 manholes (real), 149 manholes (virtual)
Qiang et al. (2021)	Used equivalent drainage method for simulating drainage capacity; Size of study area: 47 km²; Conduit considered: Simplified
Wang et al. (2024)	Coupled one-and two-dimensional hydrodynamic model for generating training datasets; Size of study area: approximately 18.34 km²; Total length of conduit considered: 357 pipes; Total junctions: 358 manholes
Zhang et al. (2024)	Developed a surrogate model using graph neural networks (GNNs) for real-time hydraulic prediction; Total manholes: 105
He et al. (2020)	Used a pipe-surface coupled hydraulic model for detailed flood simulation; Size of study area: 47 km²
Oberauer et al. (2024)	Enhanced 2D surface models to achieve comparable outcomes to dual-drainage models with less data; Size of study area: 98 km²; Total length of conduit considered: West - 28 km, East - 53 km

Research Objectives

- Develop a dual-drainage flood model for Hong Kong Island (99.5 km²) that incorporates 31,279 conduits and 34,364 junctions
- Consider three drainage pipe classifications which have not been included yet in existing urban flood models
- Generate detailed flood results by stress testing the model against an extreme event (September 2023 Black Rainstorm)

Hong Kong's Drainage Pipe Classifications

1. Major drainage tunnels
   a. D ≥ 7 m
   b. Intakes: adits and vertical dropshafts
   c. Interception approach
2. Trunk pipe system
   a. D > 1.8 m
   b. Design RP: 200 years
3. Branch pipe system
   a. D < 1.8 m
   b. Design RP: 50 years



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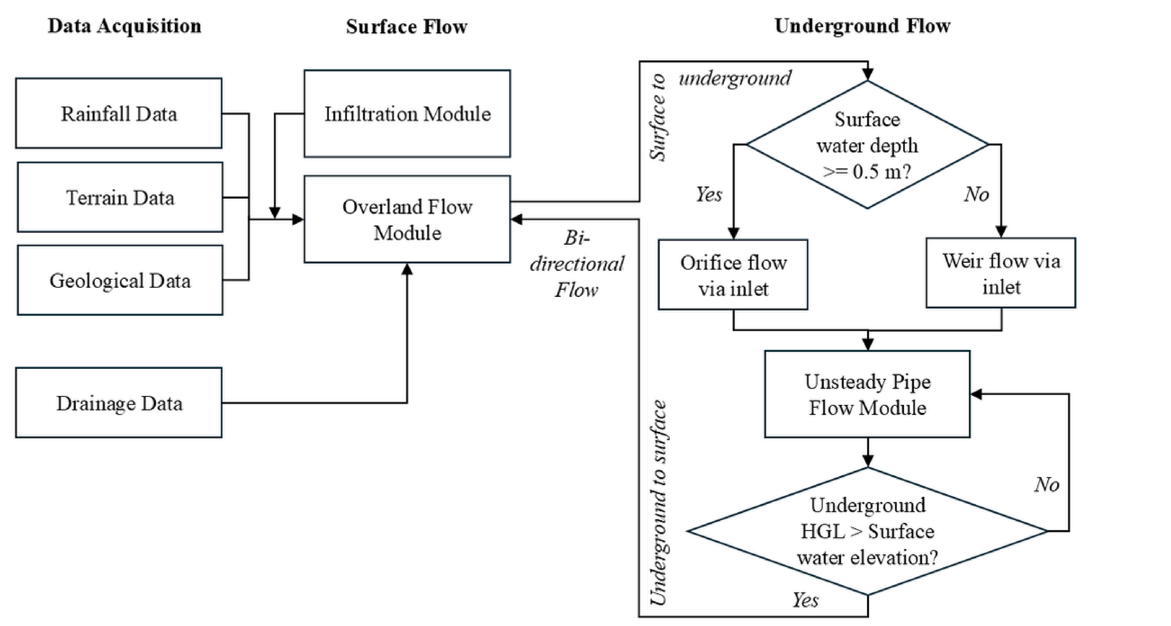
Methods

Dual-drainage Modeling Framework

Model used: Erosion-Deposition Debris Flow Analysis (EDDA 3.0) (Chen & Zhang, 2015)



Surface Flow Equations

Depth-integrated mass conservation equations (Eqs. 1, 2)
Momentum conservation equations (Eqs. 3, 4)

$$\frac{\partial h}{\partial t}+\frac{\partial (hv_x)}{\partial x}+\frac{\partial (hv_y)}{\partial y}=i[C_{v^*}+(1-C_{v^*})s_b]+A[C_{vA}+(1-C_{vA})s_A] \quad (1)$$

$$\frac{\partial (C_v h)}{\partial t}+\frac{\partial (C_v h v_x)}{\partial x}+\frac{\partial (C_v h v_y)}{\partial y}=iC_{v^*}+AC_{vA} \quad (2)$$

$$\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}=g\left[-\mathrm{sgn}(v_x)S_{fx}-\frac{\partial (z_b+h)}{\partial x}\right]-\frac{v_x\{i[C_{v^*}+(1-C_{v^*})s_b]+A[C_{vA}+(1-C_{vA})s_A]\}}{h} \quad (3)$$

$$\frac{\partial v_y}{\partial t}+v_y\frac{\partial v_y}{\partial y}=g\left[-\mathrm{sgn}(v_y)S_{fy}-\frac{\partial (z_b+h)}{\partial y}\right]-\frac{v_y\{i[C_{v^*}+(1-C_{v^*})s_b]+A[C_{vA}+(1-C_{vA})s_A]\}}{h} \quad (4)$$

Underground Flow Equations

St. Venant's equation (Eq. 5)

$$\frac{\partial Q}{\partial t}+gAS_f-2V\frac{\partial A}{\partial t}-V^2\frac{\partial A}{\partial x}+gA\frac{\partial H}{\partial x}=0 \quad (5)$$

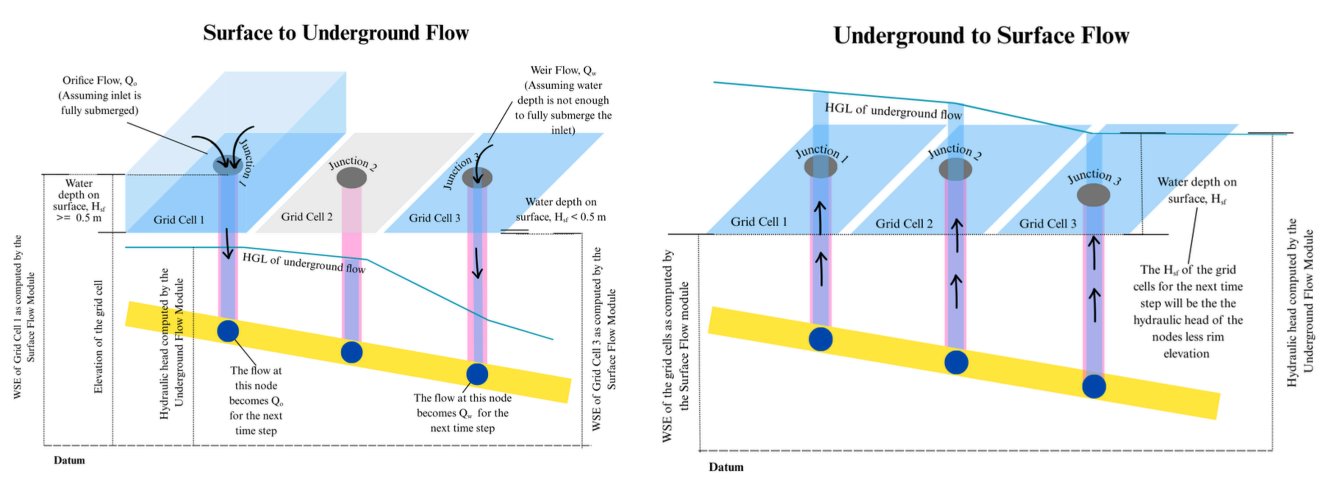
Infiltration Equation

Richard's (Eq. 6) and Gardner's (Eq. 7) equations

$$\frac{\partial}{\partial z^*}\left(k\frac{\partial \psi}{\partial z^*}\right)+\frac{\partial k}{\partial z^*}\cos\beta=\frac{\partial \theta}{\partial t} \quad (6)$$

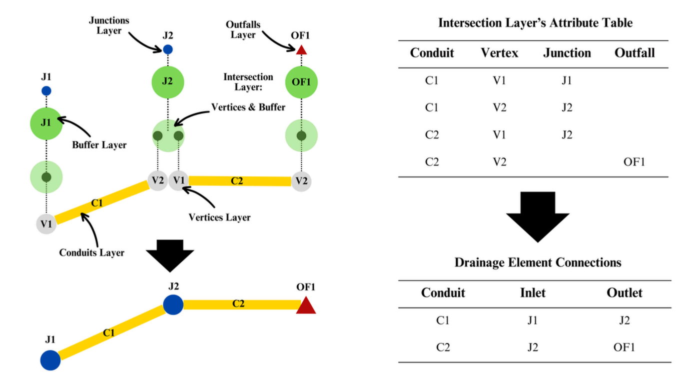
$$k=k_s e^{\alpha\psi} \quad (7)$$

Bi-directional flow between surface and underground

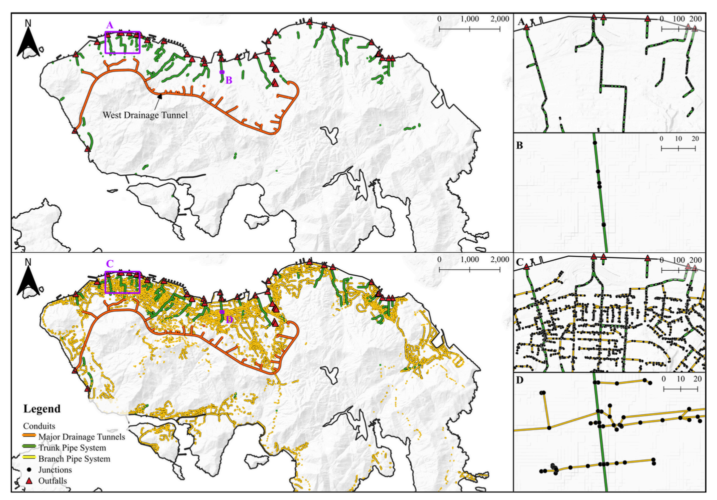


Model Setup

Underground Model Setup



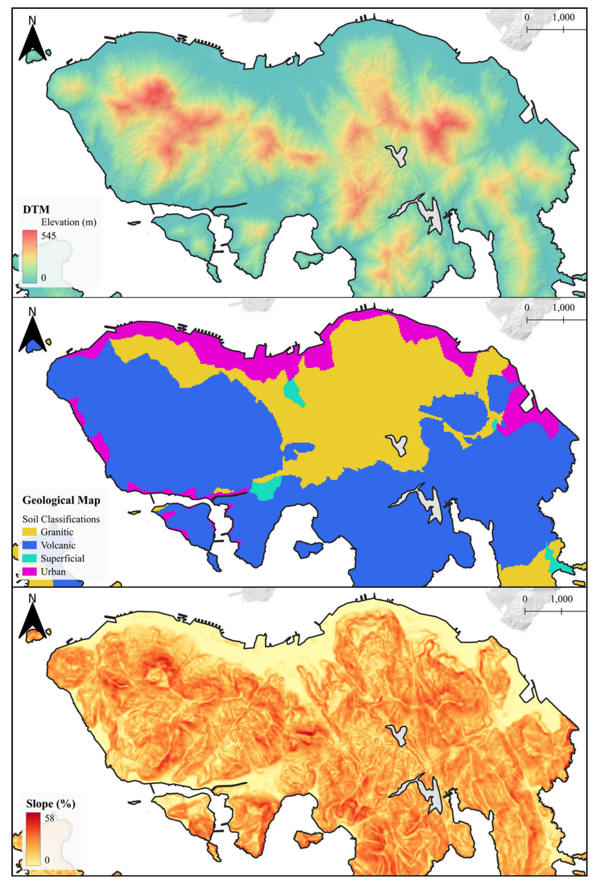
Batch processing in GIS allows instant connection of multiple drainage elements.



Models with different level of network detail were setup accordingly for comparative analysis.

- Simplified: major tunnels and trunk pipe system only (96.439 km)
- Actual: all three pipe classificaations (454.285 km)

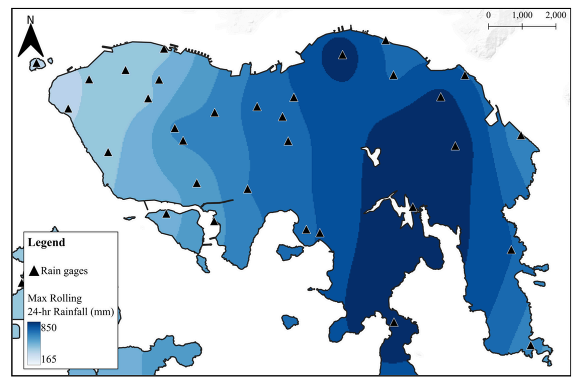
Surface Model Setup



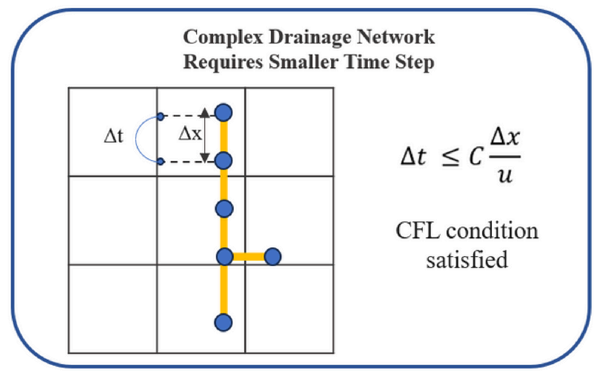
- The Digital Elevation Model of the study area is first discretized into 30 m x 30 m raster grid cells.
- The geological information and the terrain slope layer are also processed using the same resolution.
- The infiltration capacities and roughness coefficients of soil groups were assigned based on the simplified geological map of the study area.

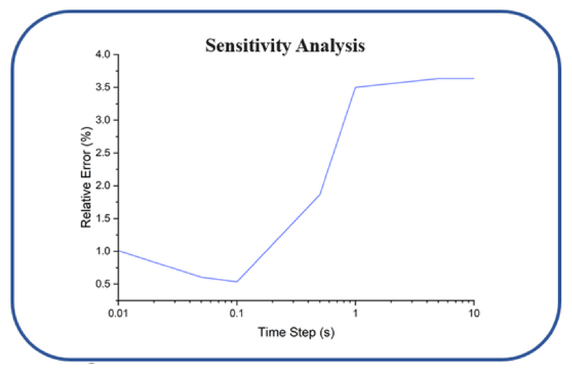
Rainfall distribution

The rainfall timeseries of the 34 stations in the study area were obtained and then interpolated spatially into hourly raster grids of the same resolution, accordingly.



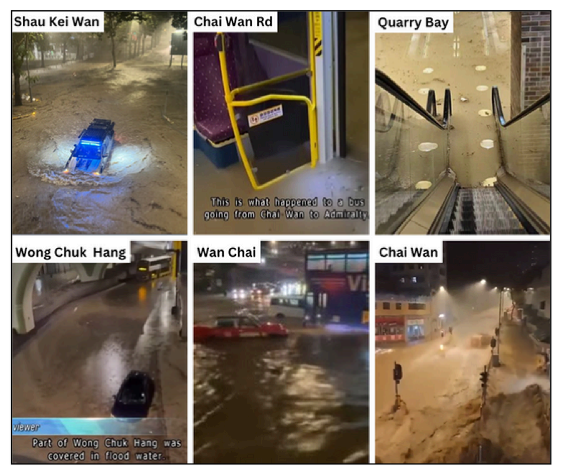
Time Sensitivity Analysis

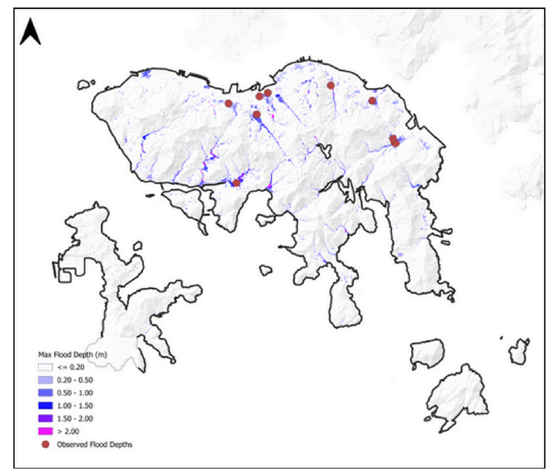




Validation

Event: Black Rainstorm (7-8 September 2023)

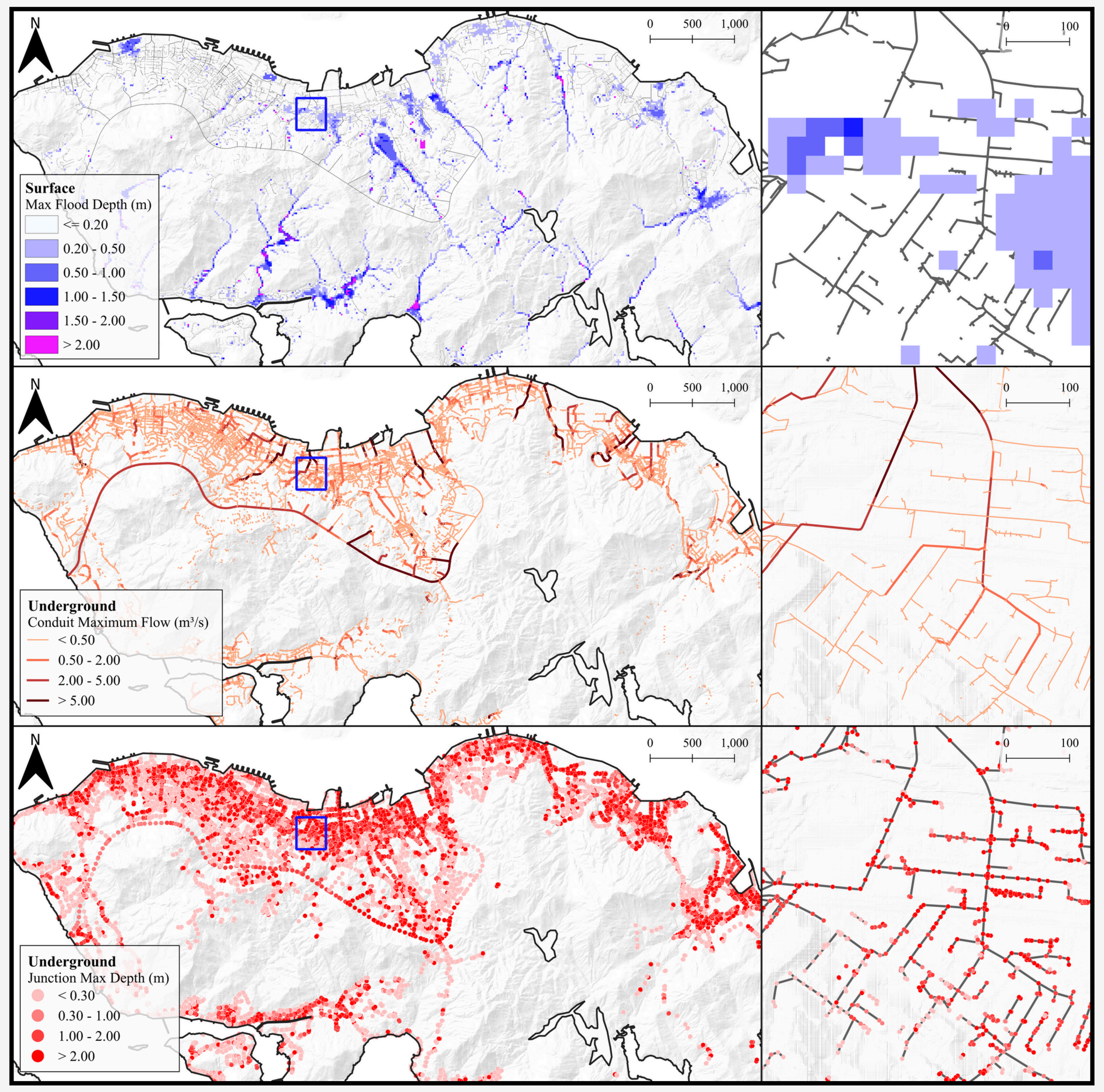




Location	Observed Flood Depths	Simulated Flood Depths
Wan Chai	0.7	0.36
Happy Valley	0.7	0.99
Causeway Bay	0.3	0.38
Victoria Park	0.5	0.33
Wong Chuk Hang	0.6	0.68
Quarry Bay	0.6	0.81
Chai Wan Rd (Bus)	0.3	0.84
Chai Wan	0.4	0.28
Shau Kei Wan	0.7	0.64

Results

A 24-hr simulation of the black rainstorm is conducted from 7 September 2023 15:00 to 8 September 2023 15:00 and the results are shown as follows.

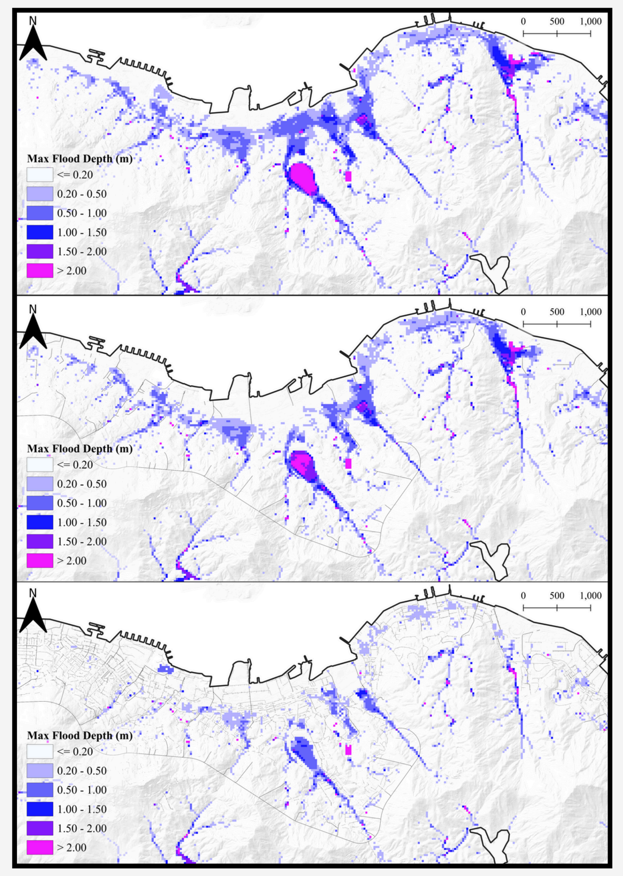


Level of detail

The reduction of flood inundation extent due to the incorporation of more detailed drainage network is illustrated in this section.

The flood extent is defined to be the areal sum of grid cells with maximum depth equal or greater than 0.2 m.

- Flood extent of model without drainage network: **7.482 km²**
- Flood extent of model with simplified drainage network: **6.508 km²**
- Flood extent of model with actual drainage network: **4.146 km².**



Summary

An actual city-scale urban drainage network of Hong Kong Island is successfully integrated in EDDA 3.0. The model follows a dual-drainage setup which integrates a 2D surface hydrodynamic model with a 1D underground stormwater network, enabling two-way flow between them. The total drainage network processed consists of 31,279 conduits and 34,364 junctions. This amounts to a total conduit length of 454.285 km which covers all three pipe classifications in the study area. Flood results were obtained by simulating the September 2023 Black Rainstorm. The level of detail in pipe network considerations has significant effect in the reduction of surface runoff.

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