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Mosaic Model Map (M^3): Hong Kong's Cutting-edge Solution for Real-time City-wide Flood Risk Visualisation

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ABSTRACT

Hong Kong's steep topography, rapid urbanisation, and exposure to both extreme rainfall and storm surges create one of the most challenging environments for real-time flood forecasting. Traditional hydrodynamic modelling, while physically robust, is too computationally intensive for operational use during fast-evolving events. The Drainage Services Department (DSD) of the Hong Kong Special Administrative Region Government of the People's Republic of China, has therefore developed the Mosaic Model Map (M^3), an innovative system that achieves territory-wide, street-level flood visualisation in near real time by pre-running thousands of high-resolution 1D/2D scenarios and dynamically selecting and mosaicking the most relevant results. This paper presents the system architecture, its three-stage methodology (pre-run, scenario mapping, mosaic compilation), implementation details, and its proven operational value as exemplified during Super Typhoon Ragasa in September 2025.

KEYWORDS: Flood Risk Mapping, GIS, Hydrodynamic Modelling, Drainage Master Plan, Hydrometric Information System, Real-time Visualisation, Flood Forecasting

1 INTRODUCTION

Hong Kong receives an average annual rainfall of approximately 2,400 mm, concentrated mainly in the wet season from May to September. The combination of steep catchments, limited natural storage, and extensive impervious cover results in extremely short times of concentration—often less than one hour. When heavy rain coincides with high astronomical tides or tropical-cyclone-induced storm surges, compound flooding develops rapidly, leaving little margin for conventional forecasting approaches.

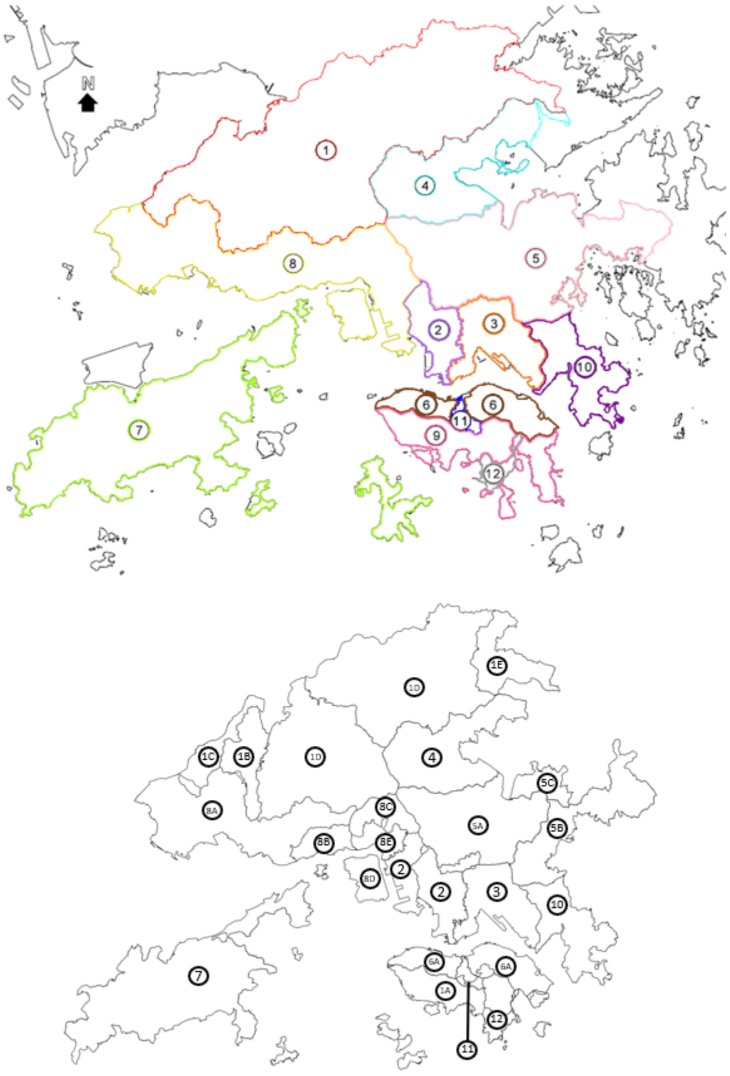
Despite substantial drainage upgrades since the establishment of the DSD in 1989 and the progressive implementation of Drainage Master Plan Review (DMPR) recommendations, the intensification of extreme weather under climate change continues to test the city's resilience. Effective real-time forecasting has remained challenging because detailed 1D/2D hydrodynamic simulations of the entire territory typically require several hours—far exceeding the available decision window.

2 CHALLENGES OF REAL-TIME FLOOD FORECASTING IN HONG KONG

In Hong Kong, real-time flood forecasting has historically been constrained by four principal factors. First, the city's extremely rapid catchment response means that even moderate rainfall can lead to flash flooding with minimal warning time. Second, rainfall patterns are highly localised due to convective storms influenced by complex topography, making uniform predictions unreliable. Third, as a coastal city, Hong Kong frequently experiences coupled flooding from simultaneous rainstorms and elevated sea levels, requiring models that integrate hydrological and oceanographic dynamics. Fourth, the computational demands of territory-wide coupled 1D/2D hydrodynamic modelling prohibit on-the-fly simulations during storms, as runtimes often exceed the critical response window. Flood forecasting is one crucial topic where different methodologies were proposed and discussed as it enables timely predictions to mitigate flood impacts and may allow timely and appropriate follow up measures (Byaruhanga et al. 2024). The above-mentioned challenges render traditional approaches impractical for operational use.

3 LEVERAGING AVAILABLE ASSETS FOR ENHANCED FLOOD FORECASTING

The M³ system capitalises on decades of prior investment in stormwater planning and monitoring infrastructure since the 1990s. In particular, the detailed 1D/2D hydrodynamic models from twelve comprehensive DMPR studies provide a consistently calibrated, high-resolution representation of Hong Kong's territory-wide drainage networks and overland flow paths.



Drainage Master Plan Review (DMPR) Studies	
1	Yuen Long & North District
2	West Kowloon
3	East Kowloon
4	Tai Po
5	Shatin & Sai Kung
6	Northern Hong Kong Island
7	Lantau & Outlying Islands
8	Tuen Mun, Tsuen Wan & Kwai Tsing
9	Southern Hong Kong Island
10	Tseung Kwan O
11	Happy Valley

M³ Catchments	
1A	Yuen Long Town & Kam Tin
1B	Tin Shui Wai
1C	Lau Fau Shan
1D	North District
1E	Sha Tau Kok
2	West Kowloon
3	East Kowloon
4	Tai Po
5A	Shatin
5B	Sai Kung
5C	Ma On Shan
6A	Northern Hong Kong Island - East
6B	Northern Hong Kong Island - West
7	Lantau & Outlying Islands
8A	Tuen Mun
8B	Sam Tseng
8C	Tsuen Wan
8D	Tsing Yi
8E	Kwai Chung
9	Southern Hong Kong Island
10	Tseung Kwan O
11	Happy Valley
12	Repulse Bay & Tai Tam

Figure 1 –23 M³ catchments evolved from the existing models developed under 12 drainage planning studies

These models, built with InfoWorks ICM, utilises 1D and 2D finite volume models based on well-established hydraulic principles, such as the St. Venant equations, and Navier-Stokes equations (Autodesk, 2025). These models provide detailed hydrodynamic analysis with a holistic consideration of various factors, including rainfall, downstream sea-water levels, and specific catchment characteristics such as topography and land use. These models incorporated the latest infrastructure upgrades and climate-change allowances. Complementing these are the real-time observations from the Hydrometric Information System (HIS), a dense telemetric network established in the 1990s that comprises more than 300 gauging with sensors including rain gauges, river level stations, and tide gauges delivering data every minute. Additionally, high-resolution radar-based rainfall nowcasts (updated every 6 minutes) and combined astronomical tide plus storm-surge predictions are sourced from the Hong Kong Observatory, ensuring that M^3 operates with reliable meteorological inputs.

4 METHODOLOGY

The system is built by a three-step mythology with model pre-run, scenario mapping and mosaic compilation as detailed in following sub-sections and as illustrated in Figure 2.

4.1 Model Pre-run

Hong Kong is divided into 23 hydrological catchments following DMPR boundaries (Figure 1). For each catchment, a matrix of 12 rainfall intensities (30–160 mm/h) × 20 boundary water levels (2.0–6.2 mPD) was simulated offline, yielding more than 5,000 scenarios territory-wide. Flood extents and depths from each simulation were exported as GIS shapefiles and stored as “mosaic tiles” in a relational database.

4.2 Scenario Mapping

Every six minutes, the system automatically evaluates current and forecasted hydrometeorological conditions across all 23 catchments to produce four standard outputs: one real-time map and three short-range forecast maps at 60, 90, and 120 minutes ahead. Real-time rainfall intensity is derived from surrounding HIS rain gauges, whereas forecast intensities for the forward horizons are based on the statistical distribution of the Hong Kong Observatory’s high-resolution gridded nowcast data, thereby accounting for the highly localised nature of the upcoming rainstorm. Tide and storm-surge levels are similarly derived from real-time HIS tide gauges and Observatory astronomical-plus-surge predictions. For each catchment and each time horizon, the mosaic tile whose rainfall intensity class and tide/surge class most closely matches — or deliberately exceeds to prioritise safety — the observed or forecasted values is selected.

In addition to this fully autonomous mode, M^3 offers a manual “what-if” capability that is particularly valuable for medium- to longer-range planning. Authorised users may specify any custom rainfall hyetograph (uniform, spatially varying, or a full design storm) and any tide/surge boundary condition, including multi-day ensemble surge forecasts issued several days in advance. The system then identifies and retrieves the corresponding pre-computed tiles for all 23 catchments according to the same conservative matching logic used in the autonomous mode.

4.3 Mosaic Compilation

Once the appropriate tiles have been selected — whether through the automatic six-minute cycle or through a user-defined manual “what-if” scenario — the 23 individual catchment tiles are automatically merged in QGIS to create a seamless territory-wide flood risk map. The resulting GIS layers (flood extent and depth) are instantly published on the internal web portal, together with supporting layers such as forecasted rainfall contours and tide graphs (Figure 5 and Figure 3).

4.4 Implementation

Its continuous operation is driven by a Python-based module known as the “M³ Integrated Data Keeper”, which continuously harvests and harmonises inputs from the HIS and the Hong Kong Observatory. The core processing engine, running within QGIS on standard office workstations, handles scenario selection and mosaic compilation, completing each full cycle well within the six-minute update interval. Since its full deployment in early 2025, M³ has been providing 24/7 real-time flood risk visualisation, integrated directly into DSD’s Emergency Control Centre workflows.

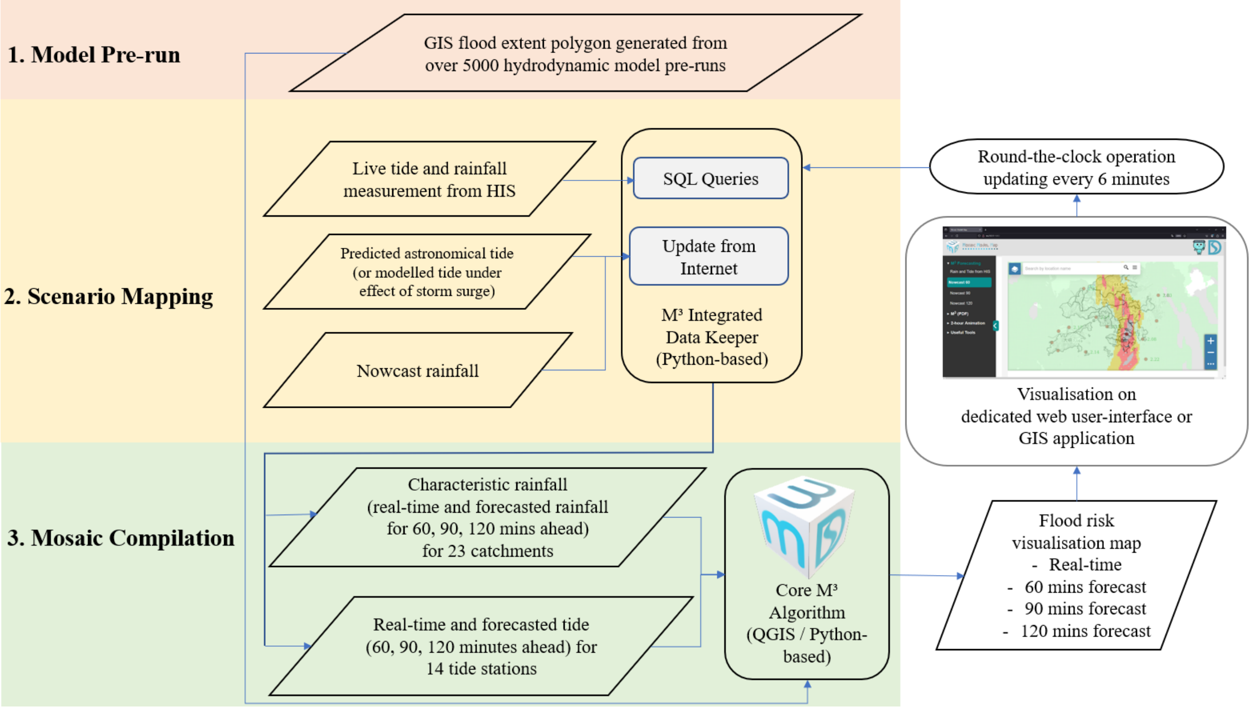


Figure 4 - Schematic workflow of the M³ system under the autonomous mode

Figure 5 – Screenshot of M³'s user interface accessed through web browser, showing the city-wide layers of modelled flood extent, forecasted rainfall contour, predicted tide levels and flood extent at one glance

Figure 6 – When hiding layers on gridded rainfall forecast and tide levels, modelled flood extent at different levels of modelled flood depth may be more clearly displayed

5 OPERATIONAL APPLICATION: SUPER TYPHOON RAGASA (SEPTEMBER 2025)

Since its official deployment in early 2025, M³ has been continuously supporting DSD emergency operations throughout an exceptionally severe wet season. Hong Kong experienced multiple black rainstorm warnings, with August 2025 recording the highest monthly rainfall since records began in 1884 (>500 mm) and a daily peak of 355.7 mm on 5 August 2025. During these intense rainstorm events, M³'s six-minute autonomous updates provided real-time flood extent forecasts, enabling rapid deployment of up to 180 emergency teams and pumping robots to more than 240 flood-prone and reported locations.

The system's most widely publicised application occurred during Super Typhoon Ragasa, which passed ~120 km south of Hong Kong on the morning of 24 September 2025, triggering Hurricane Signal No. 10 — only the second such signal of the year. The typhoon brought over 200 mm of rainfall and a storm surge peaking at 3.4 m above Chart Datum at Quarry Bay, comparable to Super Typhoon Hato (2017). The manual "what-if" mode was intensively used with ensemble surge forecasts to generate worst-case inundation scenarios days in advance. In view of Super Typhoon Ragasa edging closer to the coast of Guangdong, the Authorities held an inter-departmental joint press conference on 22 September 2025 to inform the public of areas with heightened risk for major flooding with the use of the M³ flood risk maps. The maps clearly highlighted low-lying areas or windy residential areas with higher risks including Tai O, Lei Yue Mun, Tai Po and Yuen Long etc., prompting pre-emptive measures that included increased emergency crews, pre-positioned pumping robots, additional sandbag distribution, temporary shelter arrangements, and early closure of vulnerable underpasses. These actions, taken more than 24 hours before peak surge, significantly reduced flooding impacts across the territory.

6 COMPARISON WITH OTHER FORECASTING APPROACHES

Real-time flood forecasting globally has evolved through several paradigms, each addressing the tension between computational speed and physical accuracy. Data-driven models, particularly artificial neural networks (ANN) and other machine-learning techniques, have gained significant traction in recent years due to their ability to deliver rapid predictions from historical data patterns (Byaruhanga et al., 2024). These approaches excel in environments with abundant training datasets and can achieve sub-minute runtimes, making them suitable for large-scale applications. However, they often require extensive calibration, specialised data-science expertise, and substantial computational resources for training.

Moreover, ANN models can exhibit reduced transparency and reliability during extreme events that fall outside the training envelope, potentially leading to opaque decision-making in high-stakes scenarios.

In contrast, physically-based hydrodynamic models grounded in equations like Saint-Venant equations provide interpretable, robust simulations but at the cost of lengthy runtimes. A notable hybrid solution is the pre-computed inundation library approach demonstrated by Bhola et al. (2018) for the 11.5 km^2 catchment in Kulmbach, Germany. Their framework refreshed flood forecasts every three hours by matching observed discharge rates to a pre-run library of MIKE-11/MIKE-21 simulations, achieving operational efficiency without sacrificing physical fidelity. This method proved effective for a single, relatively small catchment but highlighted scalability challenges for larger, heterogeneous urban areas.

The M^3 system builds directly on this pre-run philosophy while addressing its limitations through several key advancements. It extends coverage from a single catchment to an entire megacity encompassing 23 diverse hydrological units, enabling true territory-wide analysis. Unlike the discharge-focused matching in Kulmbach, M^3 uses direct rainfall and tide levels as indices, which are more readily available and responsive in real time, particularly for compound flooding scenarios. Furthermore, by leveraging high-resolution gridded nowcasts and a conservative percentile-based selection, M^3 captures spatial rainfall variability more effectively. Most critically, its six-minute refresh rate aligns with Hong Kong's ultra-rapid catchment dynamics, providing actionable insights during the narrow warning windows of flash floods. The combination of physically-based modelling, territory-wide coverage, compound tide-rainfall effects, and a six-minute update cycle appears unique among currently operational systems, marking M^3 as an important contribution to real-time flood risk visualisation.

7 LIMITATIONS AND ONGOING DEVELOPMENTS

Despite its strengths, the M^3 system incorporates a deliberately conservative scenario-selection logic that rounds up to the nearest higher rainfall or tide class, which may occasionally result in slight overestimation of flood risks to prioritise safety. The underlying DMPR models, while regularly updated for major infrastructure changes, are primarily planning-grade and may not immediately reflect minor site alterations, such as temporary construction or natural sediment shifts. Additionally, the system focuses on capacity-based flooding and does not yet account for localised incidents like drainage blockages from debris, which are common triggers in urban Hong Kong. Forecast accuracy remains contingent on the inherent uncertainties in short-range rainfall nowcasts and storm-surge predictions, particularly during tropical cyclones. To address these, ongoing developments include the integration of IoT-based blockage detection sensors, incorporation of higher-resolution digital twins for dynamic model updates, and hybrid enhancements using machine learning to refine tile selection without compromising physical interpretability.

8 CONCLUSION

The Mosaic Model Map (M^3) demonstrates that real-time, physically-based, territory-wide flood visualisation is achievable without requiring supercomputing infrastructure or entirely new data ecosystems. By reorganising existing high-quality hydrodynamic models into a pre-run mosaic framework matched against live observations and forecasts, M^3 overcomes the four fundamental barriers—rapid response times, rainfall localisation, compound effects, and computational delays—that have long hindered operational flood forecasting in Hong Kong. Its proven performance during Super Typhoon Ragasa illustrates tangible benefits for emergency preparedness, resource deployment, and public communication, ultimately contributing to reduced flood impacts on communities and infrastructure. The methodology is inherently scalable and offers a cost-effective blueprint for other steep, densely developed coastal cities worldwide grappling with intensifying climate-driven flood risks.

9 ACKNOWLEDGEMENTS

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