Advanced Automation of HEC-RAS for Predictive Floodplain Mapping and Early Warning through Probabilistic Deep Learning

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Overview

Introduction	Challenge & technology gap
Methods	Modelling architecture
Solution Framework	Automation engine
Applications	Expected outcomes
Conclusion	Key take-aways & next steps

Transformer-Powered Probabilistic Hydrological Modeling

with

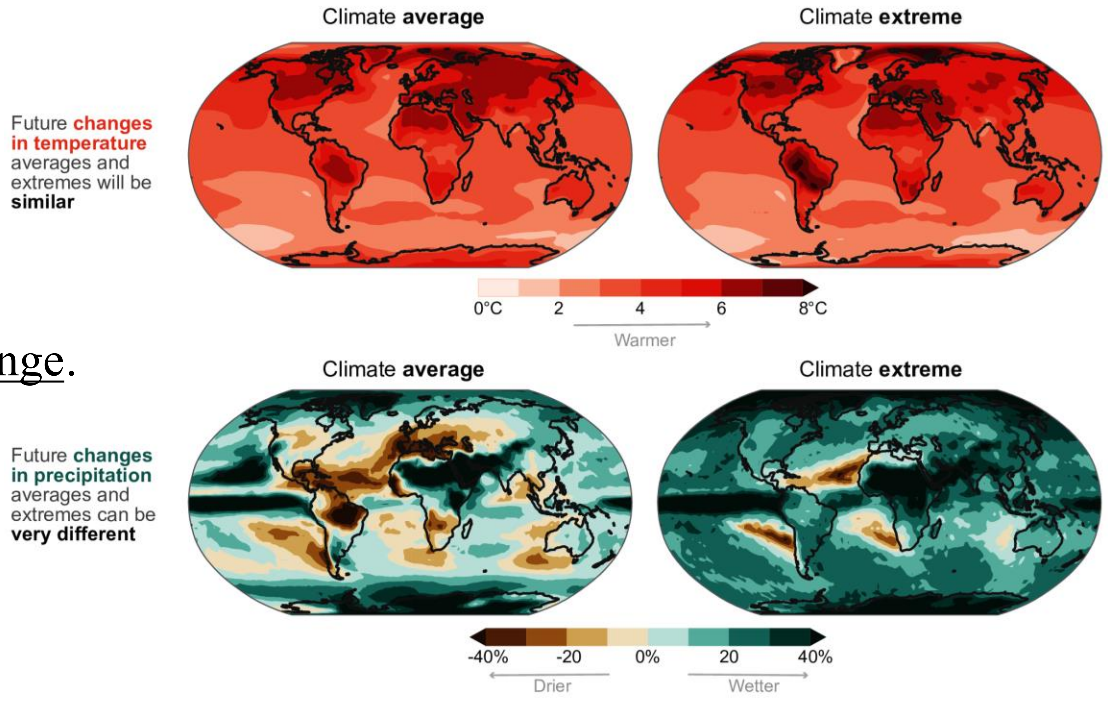
Automated 2D HEC-RAS

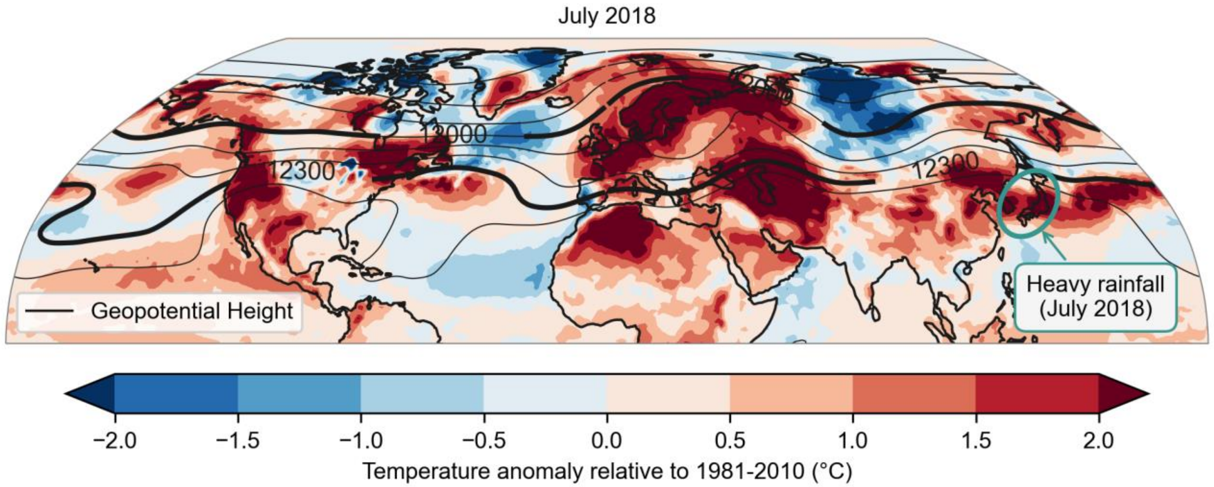
for

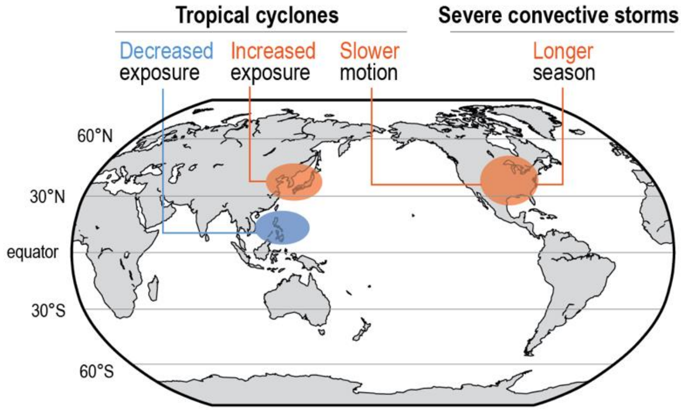
Digital-Twin-Ready Flood Intelligence

Climate Change and Flood Risks

- Floods impact **1.81 billion** people globally (**23%** of population).
- 2023 global insured flood loss: **USD 82 Bn**.
- **+35 %** rise in Asian fluvial losses since 2000.
- Flood risks projected to rise **30–50%** by 2035 due to climate change.
- South Korea: **$1.2B** in damages from the 2020 Seoul floods.
- Accounted for **~93%** of Korea's total natural disaster damages.





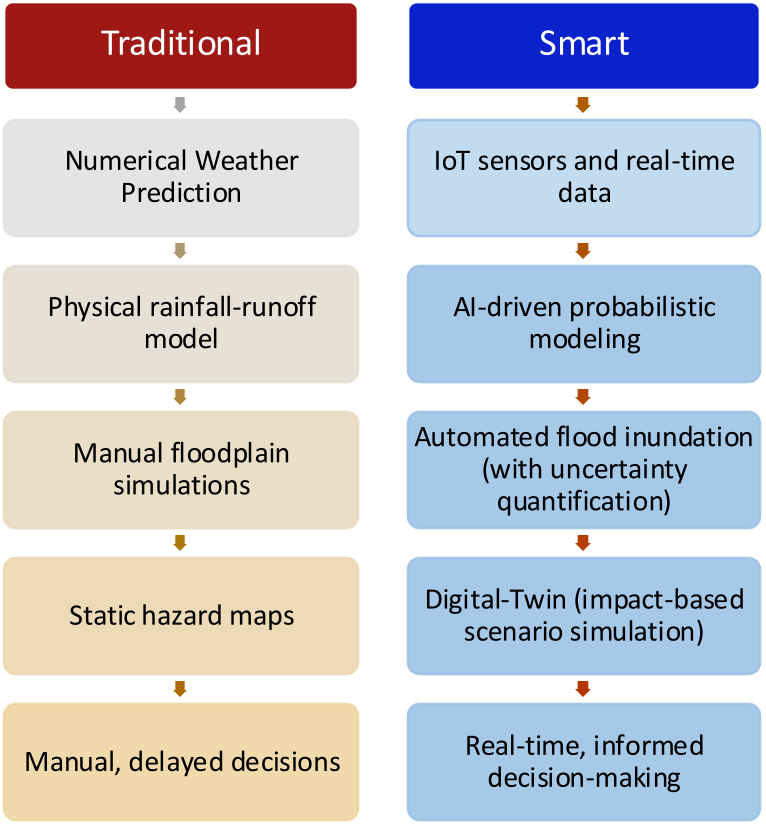


Current Practice ≠ Future Needs

- **Case:** "2023 Seoul Flood, Delayed response due to poor impact data."

Pain-Point	Status-Quo	Impact
Hydro forecast	Deterministic lumped	Under-predict extremes
HEC-RAS workflow	Manual GUI, single run	Days of lead-time lost
Uncertainty	Single design event	No risk envelope

- **Call-out:** Regulations require HEC-RAS (or equivalent), yet manual workflows slow crucial decisions. An automated, probabilistic solutions is required for **smart cities**.
  - ✓ **Smart Cities:** Leverage IoT for real-time flood response.
  - ✓ **Probabilistic Framework:** Automates flood inundation forecasts with uncertainty bounds.
  - ✓ **Digital Twins:** Simulate urban flood scenarios for better-informed decision-making.
  - ✓ **Impact:** Enables targeted, impact-based actions (e.g., precise evacuations).



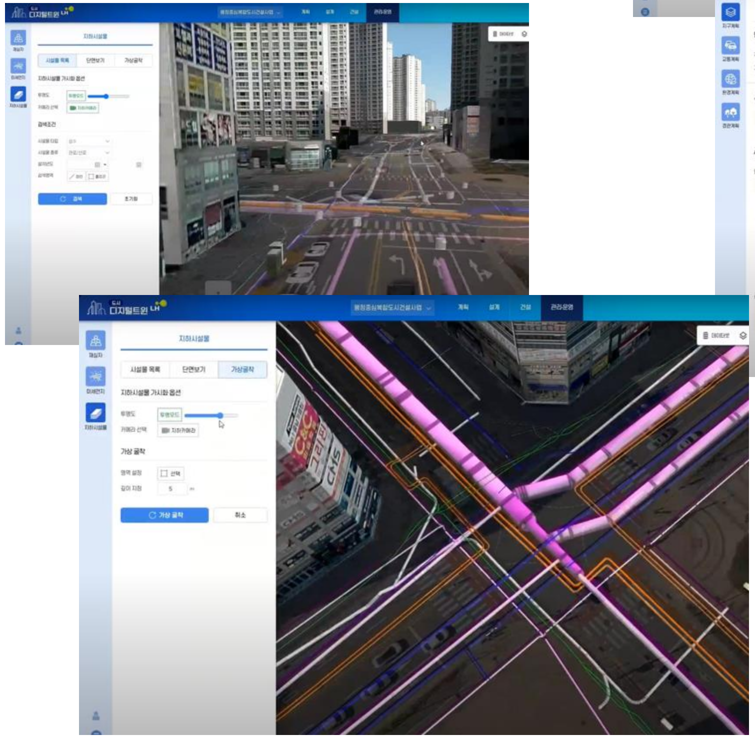
A vision for Flood Intelligence

- **Objective:** Deliver automated, uncertainty-aware HEC-RAS modeling to empower smart cities with predictive flood intelligence for proactive urban planning and dynamic flood response.

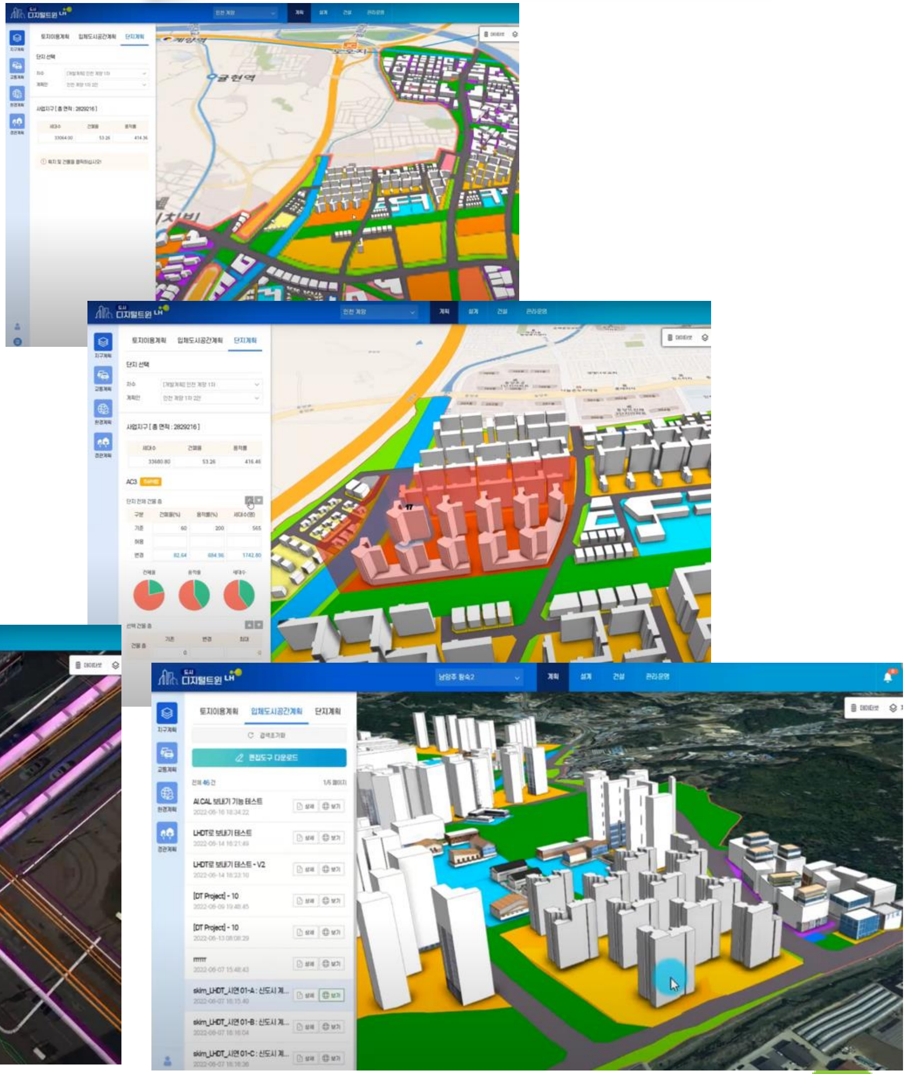
- **Flood Intelligence for Smart Cities:**

  ➢**Strategic Horizon:**
  Long-term flood forecasting and climate change analysis to inform <u>smart urban planning, infrastructure investment, and land-use decisions</u>.

  ➢**Operational Horizon:**
  Short-term probabilistic flood forecasting with dynamic impact prediction to enable <u>real-time, risk-informed emergency response and infrastructure protection</u>.



Operational Horizon



Strategic Horizon

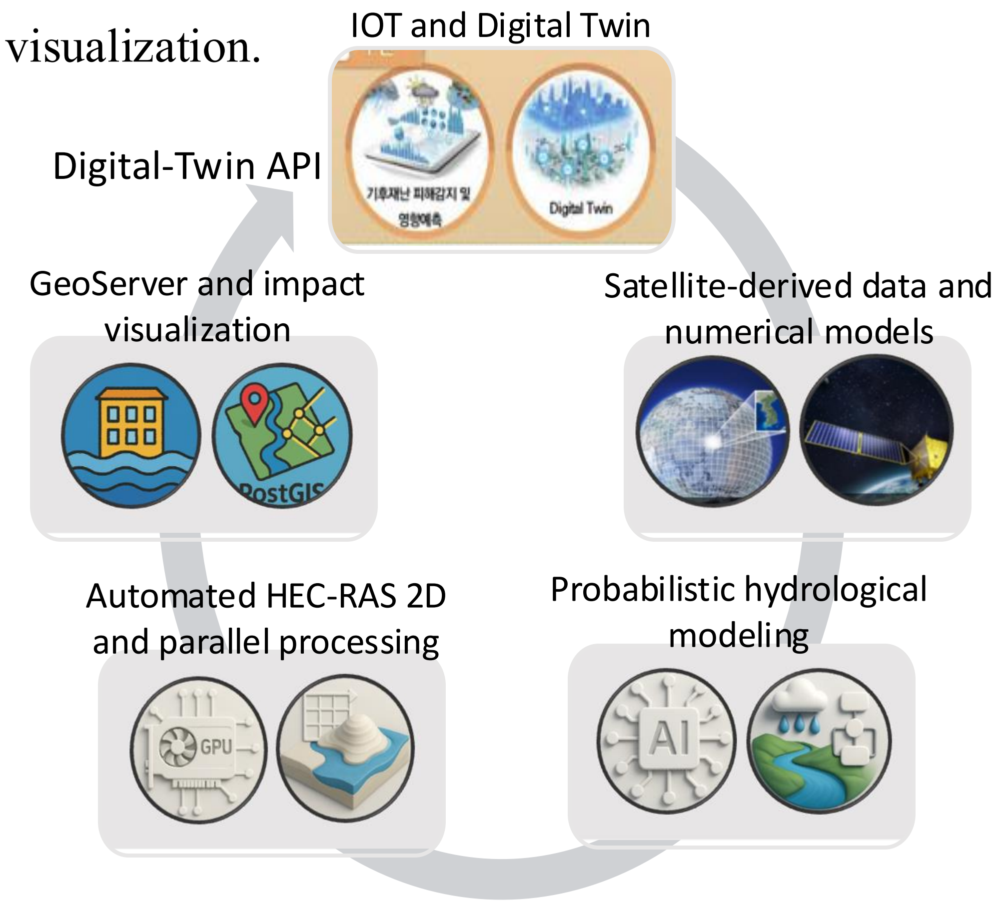
<Acknowledgment: This project was supported by LH Corp.>

A Novel Framework for Flood Forecasting

- **Objective:** Enable nationwide, autonomous floodplain mapping through integrated short- and long-term probabilistic flood forecasting and derived impact visualization.

- **Strategic Horizon:**
  Leverage long-term streamflow forecasting based on historical observations to produce multi-step ahead daily to monthly flood predictions, supporting climate resilience and urban planning.

- **Operational Horizon:**
  Utilize short-term streamflow forecasting based on near real-time observations and current hydrological states to produce multi-step ahead hourly flood predictions, enabling real-time emergency response and dynamic risk management.



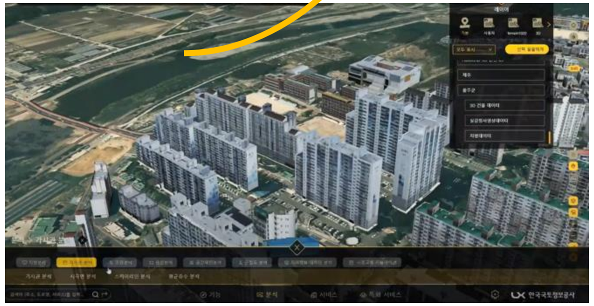
Digital-Twin server↦ hydroclimate data↦**DL-QPF→Q (X-Transformer + Mixture Density Head)** ↦ **HEC-RAS 2-D GPU farm** ↦ PostGIS/GeoServer ↦ Digital-Twin API.

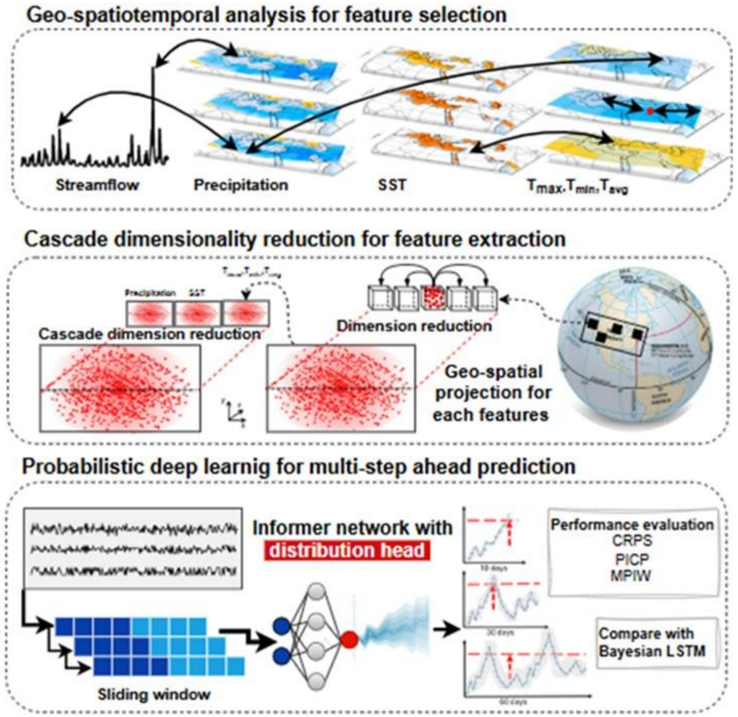
Probabilistic Deep Learning Engine

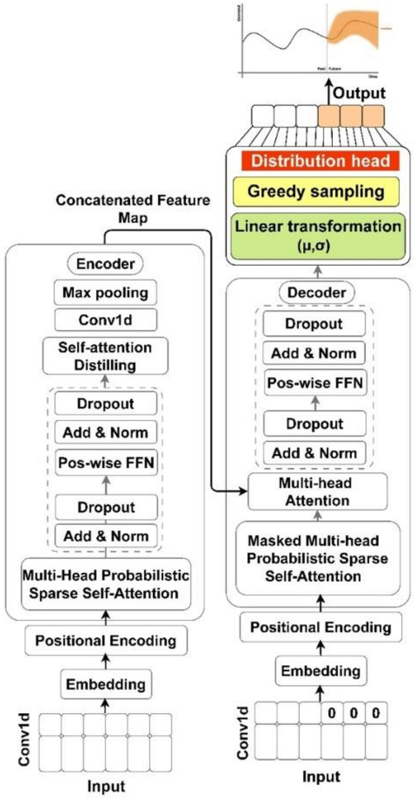
- **Model:** X-Transformer with distribution head for uncertainty.
- **Output:** Probabilistic streamflow predictions.
- **Advantage:** Adapts to South Korea's hydrology.

Without significant automation or HPC infrastructure, **large-scale modeling becomes a bottleneck** for timely flood risk assessment and decision-making.

Online Digital Twin



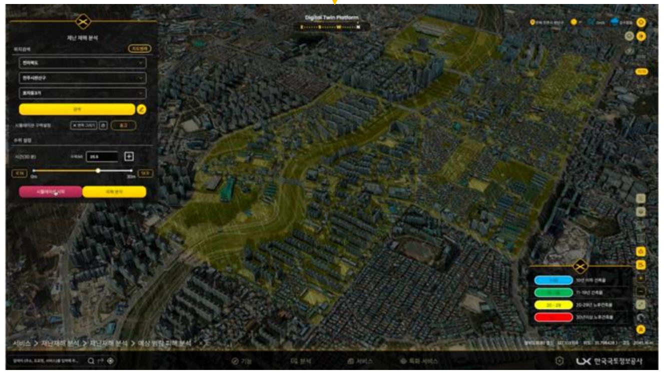




X-Transformer (L=8, d=256) + MDN (K=5 Gaussians)

Solution framework for HEC-RAS 2D automation

Digital-Twin API



Flood impact forecasting

Compute: 1x4090, <15 min for 500 realizations.

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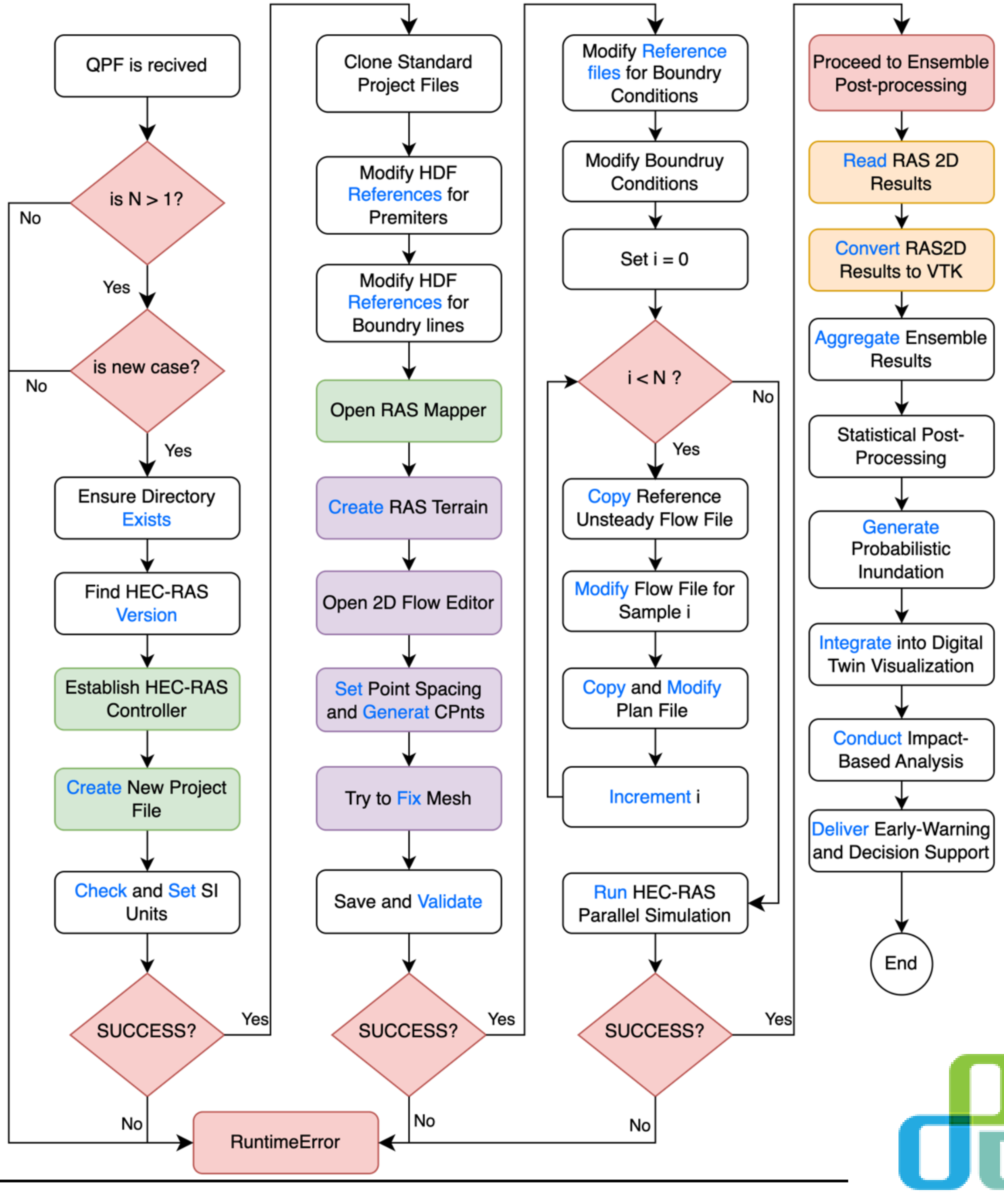
Automated HEC-RAS 2-D

- **Production:** Generate p5–p95 water-surface rasters → define upper/lower flood boundaries.
- **Acceleration:** ~30× faster than GUI workflows; 500 simulations completed in <15 min.
- **Post-Processing:** Intersect probabilistic flood layers with 3D maps and cadastral datasets for asset-level impact assessment.

Handling Methods and Color Codes

Color	Handling Method	Title for Legend Box
Black	Programmatic Automation (Python scripts, file manipulation)	**Programmatic Automation**
Green	HEC-RAS Controller (official COM API for HEC-RAS operations)	**HEC-RAS COM Controller**
Purple	GUI Automation (AutoMouse for RAS Mapper)	**GUI Automation (AutoMouse)**
Orange	pyHMT2D toolkit (for post-processing, flood mapping, VTK export)	**Post-Processing with pyHMT2D**
Red	Error Handling / Conditional Checks (inside Python)	**Error Handling and Quality Control**



Business & Research Value

For Industry

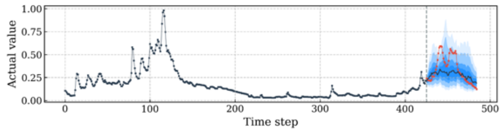
- 24-h actionable lead-time; ~16 h faster than manual pipelines.
- Enhances smart urban planning, infrastructure investment, and land-use decisions.
- Enable real-time, risk-informed emergency response and infrastructure protection.
- Enables tiered asset screening and insurance pricing.

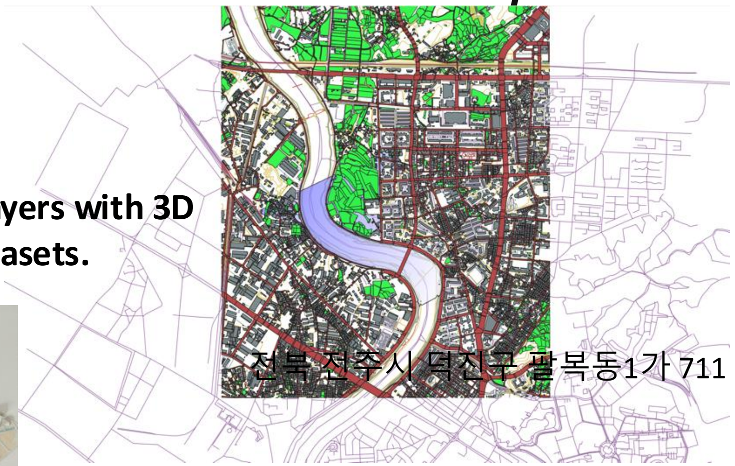
For Academia

- Open-source code & data (MIT licence).
- Reproducible benchmark for probabilistic hydro-hydrodynamic modeling.
- Automated integration of DL inflow predictions with HEC-RAS 2D flood modeling.
- Scalable and adaptable across basins with minimal reconfiguration.

Key Performance Indicators (Targeted)

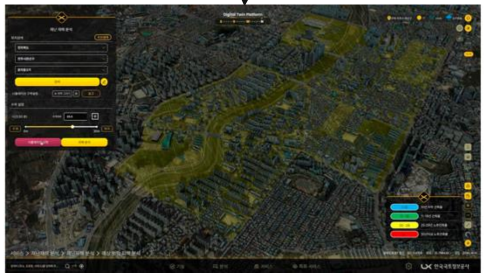
- RMSE water-level ↓ **35 %** compared to deterministic baselines.
- Ensemble spread calibrated ($\alpha = 0.05$, K-S test).





Intersect probabilistic flood layers with 3D maps and cadastral datasets.

Near-real-time readiness for integration into Digital Twin platforms.



Conclusion

Novelty: A fully automated and GPU-ready pipeline linking probabilistic DL streamflow forecasts to high-resolution 2D hydraulic simulations.

Contribution: Enable uncertainty-aware flood predictions critical for smart early warning and urban flood resilience.

Future Directions:

- Integration into digital twin ecosystems for dynamic flood risk visualization and management.
- Expand validation across diverse hydro-climatic regions (South Korea pilot ongoing).
- Incorporate real-time sensor assimilation and SAR flood extent data.
- Explore reinforcement learning (RL) for dynamic floodgate operations.

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