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Efficient and Generalizable Ensemble Urban Inundation Forecasting with Diffusion-Based Super-Resolution

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Urban flood risks are characterized by substantial uncertainties, which pose challenges for deterministic inundation predictions in risk-informed applications. Consequently, ensemble-based probabilistic flood forecasting has gained increasing attention for its ability to indicate the likelihood of extreme inundation events and associated damage risks. This study presents an efficient and generalizable diffusion-based super-resolution (SR) framework for rapid, ensemble-based, high-resolution urban flood forecasting. The framework first employs a two-dimensional hydrodynamic model to simulate flood dynamics over extensive urban areas at a coarse spatial resolution (100 m). The resulting simulations are subsequently downscaled to a fine spatial resolution (5 m) using a conditional diffusion model that performs single-step, distillation-free super-resolution. By leveraging the inherent stochasticity of diffusion models, the framework naturally supports ensemble generation, allowing for uncertainty quantification in high-resolution inundation predictions. Applied to the Beijing Sub-Center, the model efficiently simulates the spatiotemporal flood dynamics of a 24-hour rainfall event in less than 10 minutes, producing high-fidelity, fine-scale flood inundation maps at substantially reduced computational cost. The integrated framework provides a scalable and uncertainty-aware pathway for real-time, high-resolution urban flood forecasting and ensemble-based scenario analysis in large metropolitan regions.