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Framework for Modeling Urban Flood Depth Dynamics and Their Impact on Emergency Medical Response: Integrating System Dynamics and SINDy Algorithm

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Urban flooding, driven by the dual forces of climate change and rapid urbanization, presents significant challenges to modern cities, particularly in the context of emergency medical response systems. The dynamic and nonlinear nature of flood events disrupts urban systems, influencing ambulance dispatch, hospital capacity, and resource allocation, thus exacerbating the vulnerability of urban populations during extreme weather events. This study develops a comprehensive framework to investigate the interplay between urban flood depth dynamics and emergency medical response (EMS) using a combination of advanced modeling techniques, including system dynamics (SD) and the Sparse Identification of Nonlinear Dynamics (SINDy) algorithm.

The research framework aims to address two key objectives: (1) to model the nonlinear dynamics of urban flood depth changes and identify the primary factors driving flood behaviors, and (2) to evaluate the systemic impacts of these flood dynamics on EMS performance, with a particular focus on ambulance dispatch time and patient waiting time during urban flooding events. To achieve these objectives, the study integrates extensive datasets and innovative methodologies.

Data collection focuses on two complementary dimensions. For urban flood modeling, the study utilizes time-series data on flood depth changes, rainfall intensity, drainage system flow rates, and urban heat island effects, combined with spatial data such as digital elevation models (DEM) and land use information. For EMS impact analysis, the study collects data on road accessibility under varying flood conditions, ambulance availability, and emergency case classifications, along with in-hospital metrics such as emergency room patient load, bed capacity, and medical staff availability. These datasets provide the foundation for developing an integrated modeling framework.

The methodological framework is divided into two stages. First, the SINDy algorithm is applied to discover simplified nonlinear equations that describe urban flood depth dynamics over time. This involves preprocessing time-series and spatial data, performing feature selection, and integrating key urban features such as rainfall, drainage, and surface permeability into the equations. The resulting models are validated by comparing SINDy outcomes with hydraulic models and machine learning predictions to evaluate their accuracy and interpretability. Second, a system dynamics (SD) model is developed to simulate the cascading effects of flood dynamics on EMS operations. This model incorporates causal relationships among flood depth, road accessibility, ambulance dispatch time, and in-hospital resource availability. The SD model outputs are then combined with SINDy-derived equations to quantify the complex interactions between flood depth changes and EMS performance.

Urban flooding presents unique challenges to emergency medical systems, as it disrupts road accessibility and delays ambulance dispatch while simultaneously overwhelming hospital capacity. This study focuses on two critical stages in the EMS workflow during floods: (1) ambulance dispatch time, which depends on road conditions, vehicle availability, and emergency classification, and (2) patient waiting time, determined by hospital capacity and resource availability. Moreover, extreme flood events can directly impact hospital infrastructure, reducing operational capacity by damaging facilities, disrupting power and water supplies, and limiting the availability of critical medical resources. These compounded effects exacerbate the strain on already overburdened healthcare systems, leaving urban populations more vulnerable during disasters. By using SD modeling, the study captures the feedback loops and cascading effects of flood-induced disruptions, enabling a detailed analysis of resource allocation and system bottlenecks. Furthermore, the integration of SINDy enables the identification of key variables driving EMS performance, offering insights into optimizing dispatch strategies and enhancing hospital readiness under adverse conditions. This dual approach highlights the fragility of EMS during floods while providing actionable strategies to improve system resilience.

The integration of SINDy and SD approaches in this study provides a unique opportunity to bridge predictive modeling and system-level analysis, enabling researchers and decision-makers to better understand the temporal and systemic impacts of urban flooding on critical infrastructure. By offering interpretable equations and dynamic simulations, the proposed framework supports the identification of vulnerabilities in EMS, optimization of resource allocation, and strategic planning for urban resilience.

Beyond its methodological innovations, this research has substantial real-world implications. Policymakers can leverage the findings to implement targeted interventions, such as improving urban drainage systems, developing flood-adaptive EMS protocols, and enhancing hospital surge capacities. Additionally, the insights gained from this study can be extended to other urban systems, such as transportation and power grids, highlighting the broader relevance of integrating nonlinear modeling and system dynamics in urban disaster management. Ultimately, this study contributes to the growing body of knowledge on climate-adaptive urban planning, offering a scalable and transferable framework to address the escalating challenges posed by climate change in rapidly urbanizing regions.