

Addressing the Spatiotemporal Concentration of Rainfall and Runoff: Urban Flood Risk Identification and Resilience Enhancement Under Climate Change

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Since the 1980s, East Asian cities, particularly those in China, have gradually become the regions with the highest proportion of new built-up areas exposed to high flood risk worldwide during rapid urbanization^[1-2]. In recent years, many parts of China have experienced frequent large-scale heavy rainfall and flooding events, and the persistent pattern of disasters underscores the severe challenges that rapidly urbanizing regions are facing under climate change.

The vulnerabilities exposed by flooding manifest across multiple dimensions. For instance, floodwaters rapidly inundate underground spaces, disrupting transportation and municipal services; rescue, debris removal, loss assessment, and infrastructure repair operations are placed under sustained pressure; agricultural production suffers severe setbacks due to inundated farmland and damaged cropland; and older adults as well as people with limited mobility are particularly at risk. These phenomena not only reveal the fragility of urban infrastructure under extreme events but also highlight the differentiated risks and inequalities experienced by various social groups during disasters.

From the perspective of disaster causation, the spatiotemporal concentration of rainfall and runoff constitutes the core mechanism of flood. Similar to the systematic risks triggered by the excessive concentrations of pedestrian, vehicular, or energy flows, the

clustering of rainfall and runoff may also make urban drainage systems overloaded or fail. The consequences extend beyond traffic disruption to significant economic losses and threats to human safety. Under the dual pressures of rapid urbanization and climate change, flood risk has become increasingly severe. In the process of urban expansion, large tracts of land are covered by impervious surfaces, reducing infiltration and natural retention capacity, thereby accelerating runoff accumulation. At the same time, climate change increases the uncertainty of precipitation patterns, and the growing frequency of extreme weather events exposes the limitations of existing flood-control measures. In this context, practitioners engaged in sustainable spatial development must urgently explore and implement more resilient hydrological management strategies to enhance the full-cycle resilience of urban and rural areas against storm events and to advance integrated flood governance.

Against this backdrop, “risk identification” has become a critical component of flood research, emphasizing a holistic understanding of potential hazards, exposed areas or populations, and their vulnerabilities, as well as the quantitative assessment of potential impacts^[3-4]. Key questions include: to what extent will the extremity of rainfall and runoff intensify under climate change, which areas will face greater risks, and what losses might occur? Although

flood risk assessment frameworks differ across domestic and international scholarship, their common goal is to understand the probability of disasters and the magnitude of potential losses. Quantifying the functional disruption of urban systems, along with identifying and evaluating key risk nodes and evacuation routes, facilitates further analysis of the spatial and temporal distribution of flood risks and their implications for social equity^[5].

At the same time, “resilience enhancement” represents a more dynamic and systemic approach to flood governance^[6-7]. Effectively addressing the intense spatiotemporal clustering of flows requires more than traditional drainage and storage measures; it calls for strategies analogous to traffic diversion and peak-shifting, implemented through multiscale, integrated system-level regulation. This includes the coordinated urban-rural and upstream-downstream allocation of water resources across scales, the optimal use of core and peripheral urban zones, and the temporal and spatial regulation of runoff within cities. From a strategic perspective, adopting multi-objective intelligent optimization or dual-use systems that support both routine operation and emergency response, enabling the efficient allocation of limited resources, constitutes a critical direction for further exploration^[8-9].

In summary, urban flood risk identification and resilience enhancement have become key topics among interdisciplinary research. From the perspectives of landscape architecture, hydrology and water resources, public policy, and emergency management, further efforts are needed to develop planning and design methods and technological paths centered on disaster prevention and mitigation. Such approaches can not only deepen the application of resilient urban construction theories in stormwater management but also provide systematic theoretical support for urban disaster prevention planning and emergency decision-making.

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应对降雨与径流的时空高度聚集： 气候变化背景下的城市洪涝风险识别与韧性提升

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自20世纪80年代以来, 以中国城市为代表的东亚城市在快速扩张和建设的进程中, 逐渐成为全球新增高洪涝风险建成区占比最高的地区^[1-2]。近年来, 中国多个地区频繁发生大范围强降雨和洪涝事件, 持续的灾害态势凸显了快速城市化地区在气候变化背景下所面临的严峻挑战。

洪涝灾害所暴露出的脆弱性体现在多个层面: 洪水迅速涌入地下空间, 导致交通与市政设施功能受阻; 救援、清淤、损失评估与设施修复工作承受持续压力; 农业生产因农田受淹和耕地损毁遭受重创; 老年人和行动不便者在洪水中的暴露风险尤为突出……这些现象不仅揭示了城市基础设施在极端事件中的脆弱性, 也反映了不同社会群体在灾害中面临的差异化风险与不平等处境。

从灾害成因来看, 降雨与径流在时间和空间上的高度聚集是洪涝形成的核心机制。类似于人流、车流和能源流在过度集中时引发的系统性风险, 降雨与径流的时空聚集同样可能使城市排涝系统超负荷运行甚至失效, 其后果不仅包括交通中断, 还可能带来严重的经济损失和人身安全隐患。在快速城市化和气候变化的双重压力下, 洪涝风险日益严峻。在城市扩张过程中, 大量土地被不透水表面覆盖, 雨水渗透与自然调蓄功能削弱, 径流迅速汇集。同时, 气候变化增加了降水模式的不确定性, 极端天气事件频繁发生, 使既有防洪措施明显暴露出局限。鉴于此, 城乡空间可持续利用的实践者亟需探索并落实更具韧性的水文管理策略, 以提升城乡在突发暴雨下的全周期应对能力, 推动洪涝灾害

的综合治理。

基于这一背景, “风险识别”已成为洪涝研究的重要环节, 其强调对潜在危害、受暴露区域和人群及其脆弱性的综合认知, 并突出对潜在威胁的量化评估^[3-4]。核心议题包括: 在气候变化的驱动下, 降雨与径流的极端性将达到何种程度? 哪些区域将面临更高风险, 可能造成怎样的损失? 尽管国内外学者提出的洪涝风险评估框架有所差异, 但其共同目标是理解灾害发生的概率及潜在损失。通过量化城市系统的功能损失, 识别与评估关键风险节点及疏散路径, 将有助于进一步分析洪涝风险的时空分布差异及其在社会公平方面的影响^[5]。

与此同时, “韧性提升”体现了更为动态和系统的治理思路^[6-7]。在应对“流”的高度时空聚集时, 不能仅依赖传统的排水与调蓄, 而需要引入类似交通疏导和错峰出行的策略, 在系统层面实施多尺度的整体性调控。这包括城乡与上下游之间的水资源合理分配、城市核心与边缘地区的协调利用, 以及城市内部不同区域的径流错峰调节。在战略层面引入多目标智能优化或“平急两用”等策略, 以合理配置有限资源, 也是亟需深入探讨的重要方向^[8-9]。

综上所述, 城市洪涝风险识别与韧性提升已成为跨学科研究的重要议题。在景观设计、水文水资源、公共政策与应急管理等多领域的交叉视角下, 应进一步探索以防灾减灾为核心的景观规划设计方法和技术路径。这不仅有助于推动韧性城市建设理论在雨洪管理中的实践深化, 也将为城市防灾规划与应急决策提供系统性的理论支撑。