通过关联基础设施系统的适应性防灾减灾规划提升气候变化背景下的城市韧性

Adaptation Planning and Hazard Mitigation for Interdependent Infrastructure Systems to Enhance Urban Resilience Under Climate Change

韩煜
HAN Yu

美国得克萨斯农工大学景观设计与城市规划系博士后研究员
Postdoctoral Associate, Department of Landscape Architecture and Urban Planning, Texas A&M University

黄啸
HUANG Xiao

美国阿肯色大学地理科学系助理教授
Assistant Professor, Department of Geosciences, University of Arkansas

叶信岳
YE Xinyue*

美国得克萨斯农工大学景观设计与城市规划系哈罗德·L·亚当斯讲席副教授
Harold L. Adams Endowed Associate Professor, Department of Landscape Architecture and Urban Planning, Texas A&M University

巴哈·达达肖娃
Bahar DADASHOVA

美国得克萨斯农工大学交通研究院副研究员
Associate Research Scientist, Texas A&M Transportation Institute

*Corresponding Author
Address: Texas A&M University, College Station, TX 77840, USA
Email: xinyue.ye@tamu.edu

编辑 | 张晨希、王颖
翻译 | 黄芷仪、韩煜、张晨希、王颖
EDITED BY | ZHANG Chenxi, WANG Ying
TRANSLATED BY | HUANG Zhiyi, HAN Yu, ZHANG Chenxi, WANG Ying

摘要

气候变化和自然灾害对人类社会造成了多方面的影响。城市规划与设计是应对气候变化和防灾减灾的有效手段。然而，由于城市基础设施系统间的关联性，城市系统遭受的由气候变化引发的风险及影响尺度繁多且复杂。规划者需要了解并评估自然灾害对关联基础设施的潜在风险及可能产生的连锁反应，制定应对这些影响的适应性规划策略。本文讨论了将社会和实体基础设施系统纳入适应性防灾减灾规划过程的机遇和挑战。适应性防灾减灾规划过程包括气候灾害评估、适应性规划目标确立、适应性战略制定及适应性政策实施。城市大数据和高性能计算资源的广泛使用可辅助城市规划者和决策者更好地应对气候变化和自然灾害所带来的复杂影响。为成功构建结合关联基础设施系统的适应性防灾减灾规划，需要解决气候预测的不确定性、适应性规划的制度性问题，以及城市大数据的代表性存疑等问题。上述问题可通过多学科专家共同合作，不同层级政府部门相互协调，以及开发更完善的数据保护机制和更健全的数据检测方法解决。

关键词

适应性规划；防灾减灾；关联基础设施系统；气候变化；城市韧性；大数据

ABSTRACT

Climate change and natural hazards have created multiple impacts on human settlements. Urban planning and design are effective tools in dealing with climate adaptation and mitigation issues. However, climate risk and its impacts are multiscale and complex due to interdependence between urban infrastructure systems. Identifying adaptation strategies to cope with these impacts requires planners to understand potential interdependent and interrelated consequences of infrastructure failure under natural hazards, and evaluate cascading and cumulative effects of climate change. This article discussed opportunities and challenges to incorporate interdependent social and physical infrastructure systems in the adaptation planning and hazard mitigation process, including climate hazard assessment, adaptation goal identification, adaptation strategy development, and implementation. The availability of urban big data and high computational resources will enable urban planners and decision-makers to better deal with those complex impacts from climate change and natural hazards. Successful adaptation planning and hazard mitigation for interdependent infrastructure systems also needs to solve issues in uncertainties of climate projection, institutional barriers of adaptation, and challenges of urban big data. Potential solutions to these challenges would include cooperation among multi-disciplinary experts, coordination between different levels of governments, and developing the ethical framework for data protection and robust methodologies to detect and reduce data bias.

KEYWORDS

Adaptation Planning; Hazard Mitigation; Interdependent Infrastructure System; Climate Change; Urban Resilience; Big Data

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1 引言

为维持自身的高速运转，城市通常依靠基础设施系统来提供必要的服务与资源[1]。随着技术革新，这些关键基础设施系统之间的关系越发紧密，但也交错复杂，极易引发城市系统内部的连锁问题——也就是说，一旦其中的某一功能出现问题，就可能导致整个系统的灾难性后果。因此，关联基础设施之间的复杂运行机制令韧性城市规划设计难以施展拳脚[2]。不仅如此，城市规划还面临着受人类活动影响的气候变化的严峻挑战——海平面上升和极端天气事件将极大影响未来的土地利用模式、城市的社会和实体基础设施系统，以及居民的健康、安全和生活等各方面[3]。随着气候变化对人居环境威胁的加剧，在建立韧性城市的过程中，需更好地规划、整合关联基础设施系统[4]。

气候变化给城市规划和管理带来了多层级、多尺度的系统性复杂问题，这些问题很难用传统的线性方法来解决[5]，需要从更多维度来处理各层级的问题。气候变化对城市系统的主要影响之一是日益频发的自然灾害，包括极端降水和沿海洪灾等，它们会影响交通规划、住房与社区发展，以及公共卫生等多方面的政策制定[6][7]。一种由极端潮汐和风暴潮引起的沿海灾害逐渐成为困扰美国沿海社区的严重问题——每年，海水都会漫上陆地，淹没海拔较低的社区，威胁沿海基础设施系统的正常运作。2017年，途经休斯敦城区的哈维飓风给这座城市造成了毁灭性后果，经济损失超过1 800亿美元[8]。若未在城市规划中考虑气候适应性措施和灾害风险管理，建设韧性城市社区将成为空谈。

少数族裔和低收入社区通常位于易受洪水影响或公共交通系统薄弱的不适宜开发地区[9]。《美国气候评估（2014年）》报告指出，沿海灾害会对城市中的“弱势人口”产生更大的影响[10]。为了更好地适应气候变化，地方政府需要将气候适应性规划纳入城市土地利用、住房、经济发展、灾难应对、交通和基础设施规划中[11][12]，均衡城市发展，为受气候变化和自然灾害影响较大的低收入群体和少数族裔谋求更多福祉。

制定强有力的适应性防灾减灾政策和构建有效的风险转移机制是政府适应气候变化、进行灾害风险管理中的两个重要方法。1968年，

1 Introduction

Cities rely on infrastructure systems to provide essential services and resources to support urban prosperity[1]. These essential infrastructure systems are increasingly interdependent over time with the evolution of technology. Nevertheless, the complexity between interdependent infrastructure systems increases the potential risk of cascading failure, where the small-scale loss of function in one system would cause catastrophic consequences in the whole system. Interdependences among infrastructure systems have complex mechanisms that impede the planning and design of urban resilience[2]. Meanwhile, anthropogenic climate change has become one of the key challenges in the field of urban planning. Sea-level rise (SLR) and extreme weather events adversely affect future land use patterns, social and physical infrastructures, as well as the health, safety, and welfare of residents[3]. As the impacts of climate change on human settlements are becoming more apparent, urban planning needs to well integrate and incorporate infrastructure interdependences in building resilient urban communities[4].

Climate change poses a complex problem in the field of urban planning and management in that it is a multi-layered, multi-scaled, and systematic problem that traditional linear approaches cannot resolve[5]. Addressing these problems requires a multi-dimensional approach to deal with the problems experienced in all the layers. One of the major impacts of climate change on urban systems is the increased natural hazards, such as extreme precipitation and coastal flooding that can have implications for policymaking in various levels such as transportation planning, housing and neighborhood development, and public health among others[6][7]. A common type of coastal hazards is from the king tides and storm surges, where seawater spills onto the land annually and inundates low-elevated built environments. This kind of flooding threats well-functioning of coastal infrastructure systems and are increasingly becoming a serious problem in coastal communities of the United States. For example, during the devastating Hurricane Harvey in 2017, more than USD 180 billion dollars of damages came from Hurricane storm surges in the Houston urban area[8]. It will be challenging to build resilient urban communities under climate change without considering climate adaptation and risk management in the planning process.

Minority and low-income communities are consistently built in regions thought unsuitable for urban development, including flood-prone regions and communities with limited access to public transportation facilities[9]. The 2014 report by the National Climate Assessment concludes that coastal hazards will inordinately affect the region's "most disadvantaged populations"[10]. To successfully adapt to climate change, local governments need to incorporate climate adaptation into cities' network of plans, including land use, housing, economic development, disaster, transportation and infrastructure plans[11][12]. These plans are interdependent and play significant roles in guiding a balanced urban development and reducing inequalities among low-income and minority groups that are particularly vulnerable to natural hazards and climate change.

Governments have several ways to influence climate adaptation. Making robust adaptation and hazard mitigation plans and designing effective risk transfer

美国联邦应急管理局（FEMA）在《住房与城市发展法》中增加了《全国洪水保险计划》的条款，以帮助居民和企业尽快从洪水灾害中恢复。同时，FEMA绘制了洪水风险地图，并鼓励地方政府通过土地利用规划和防灾减灾规划，明确并减少洪水风险。然而，这些政策并未有效降低易受洪水影响地区的风险——过去几十年来，由于规划目标不明确及洪水风险信息滞后，地方政府在制定适应性防灾减灾规划的过程中受到了诸多限制。此外，依照《全国洪水保险计划》，私营企业购买具有高额补贴的保险，将洪水风险转嫁给美国联邦政府。这不仅使FEMA债台高筑，还向公众传递了错误的风险信息。因此，在气候变化的大背景下，如何通过城市规划和土地利用等规划决策来提高城市应对自然灾害的能力，是规划者需要承担的一项重要任务。成功的适应性规划离不开私营部门与政府的协作，为了提高洪水灾害下的城市韧性，国家和地方层级的政府在制定适应性防灾减灾规划时，需要在规划、设计和实施等多个方面考量关联基础设施系统的社会、物理和生态功能[13]。鉴于此，本文期望探讨将关联基础设施系统纳入适应性防灾减灾过程的途径及阻碍。

2 城市中的关联基础设施系统

近年来，气候变化引发的一系列连锁反应揭示了基础设施系统的三个简单事实：首先，城市是一个动态的系统——人口、货物和信息在城市中流动交换，同时城市在基础设施投资和自然灾害干扰中不断进行建设或重建；第二，城市由社会和实体基础设施系统组成，它们相互作用并产生复杂的影响和反馈[14]，但全球范围内不断扩张的城市系统及日益严重的气候变化使这些社会和实体系统愈发难以应对自然灾害[15]；第三，城市是由看似独立实则相互关联[13]的基础设施组成的复杂系统，城市的运行离不开这些基础设施[16]。这也意味着基础设施系统所提供的基本服务是相互关联的。基于上述特质，如果城市中资源汇集区域的基础设施系统因气候变化或自然灾害受损，那么整个城市地区居民的日常活动和城市经济都可能遭遇破坏性连锁反应。例如，2021年1月，美国得克萨斯州的冬季风暴潮引发了停电事件，这场风暴潮不仅损坏了得州的电网系统，更影响了饮用水的供应。加之新冠肺炎（COVID—19）疫情的影响，持续的停电对得州居民的影响涉及方方面面，包括企业商户、

mechanisms are two important approaches in natural hazard risk management. For example, the US Federal Emergency Management Agency (FEMA) designed the National Flood Insurance Program in 1968 within the Housing and Urban Development Act to help homeowners and businesses to recover faster from flood disasters. FEMA developed flood risk maps to indicate local flood risk and encourage local governments to implement land use and hazard mitigation plans to reduce flood risk. However, these policies did not effectively mitigate flood risk in flood-prone areas due to ineffective risk communications. Adaptation planning and hazard mitigation activities by local governments have been limited over the past decades due to unclear planning goals and outdated flood risk information. Private sectors purchased high subsidized flood insurance to transfer flood risk to the federal government, which resulted in the high debt of FEMA and delivered false risk messages to the general public. How to support communities to well prepare for and respond to natural disaster impacts through planning decisions, such as urban development and land use regulations, is an essential task that planners need to resolve under climate change. Since successful adaptation efforts require cooperation and coordination between private sectors and government activities, to improve urban resilience to flood hazards, adaptation planning at both federal and local levels needs to integrate social, physical, and ecological components of the interdependent infrastructure systems in the planning, design, and implementation of hazard mitigation policies[13]. To fill these needs, this article aims to discuss opportunities and challenges to incorporate interdependent infrastructure systems in the adaptation planning and hazard mitigation process.

2 Urban Interdependent Infrastructure Systems

A series of interrelated impacts that climate change poses in recent years has revealed three simple facts within infrastructure systems: First, cities are dynamic systems. Population, freight, and information flow in and out of cities without stop. Also, cities are constantly being built and rebuilt under infrastructure investment and external disturbances, such as natural disasters. Second, cities consist of social and physical infrastructure systems, which interact with each other and create complex effects and feedbacks[14]. The growing urbanization worldwide and climate change increase social and physical vulnerability of cities to natural hazards[15]. And third, although city's infrastructure systems are often considered individually, their impacts are interrelated[13]. Cities are complex systems that include extensive interdependent infrastructure systems to support them[16]. In another word, essential services provided by infrastructure systems are interdependent. If infrastructure systems in source areas of a city are disrupted by climate change or natural hazards, then the whole urban area could be affected. Such interdependent impacts from infrastructure systems could lead to cascading disruptions on human activity and urban economy. An example of such cascading effects is the power outage during the winter storm of Texas, US in January 2021. The winter storm caused disruptions on Texas' power grid system and affected water supply in the state. The ongoing power outage amid with COVID-19

交通和经济发展，地方政府不得不为弱势人群提供食物和庇护所。由此可见，在适应性防灾减灾规划中尤须考虑关联基础设施系统。

城市中的保障性资源和基础设施直接影响了城市在多大程度上可以承受和应对自然或人为灾害[17]。近年来，针对城市韧性的研究[18]指出，社会和实体基础设施系统之间的关联会极大影响社会脆弱性和城市系统韧性。“社会脆弱性”（social vulnerability）概念常用作描述人们应对自然灾害影响的能力，作为城市和区域规划中的一项重要内容，在适应性规划中常被广泛讨论；但针对社会基础设施——即保障并维持居民社交活动和联系的基本服务和设施[19]——却讨论不足。在研究中常用居民收入、年龄、性别、种族、民族等社会经济特征来评价社会脆弱性及社会不平等。由于防灾减灾需同时考量社会和环境两方面因素，仅从任意一方面来提升灾害应对能力都可能忽略另一方面的容纳能力和限制。因此，为了更好地实现城市韧性，需要将物理、社会和自然因素的综合影响纳入对适应性规划政策的评估中。随着技术进步，与人类活动相关的结构化与非结构化的实时数据，可帮助规划和研究人员了解个体层面的居民活动特征，从而更好地理解社会和实体基础设施之间的关联[20]。基于数据的分析和建模方法为适应性规划提供了多样信息——通过机器学习和深度学习、自上而下或自下而上的系统建模工具等方法，可以同时分析多个指标并精准描绘城市未来的发展趋势[21]；还可通过城市微观模拟模型阐述社会和实体基础设施系统间的依赖性和关联性，此种方法可以在适应性防灾减灾规划政策的评估中整合多个相互依赖的子系统[22][23]。例如，为在空间层面上解决适应性规划问题并评估洪水风险管理政策的有效性，有学者于2019年开发了一个基于主体的模型以探究居民、地方政府和洪水风险保险公司在沿海地区适应性规划中的相互作用，同时分析个体减灾行为在缓解洪水风险中的重要性[24]。而在此之前，个体行为的作用常被忽视。该模型随后被进一步用于评估应对不确定性洪水灾害和海平面上升的城市适应性规划策略中[23]。

3 气候变化背景下的适应性防灾减灾规划

洪水、风暴潮、海平面上升、干旱和极端高温等气候变化引发的自然灾害将导致并加剧城市应对灾害的脆弱性。联合国政府间气候变化专

pandemic seriously affects almost every aspect of residents’ life in Texas, including businesses, mobility, and economy. Local governments had to provide food and shelters to vulnerable populations. These interrelated impacts indicate the necessity to incorporate interdependences in disaster resilience planning.

Urban vulnerability and resilience to man-made and natural disasters are directly related to clusters of supporting resources and infrastructures in cities[17]. From recent years of urban resilience research[18], interactions between social and physical infrastructure systems could largely affect social vulnerability and system resilience. Social vulnerability has been discussed extensively in adaptation planning to describe population capacity to respond to impacts of natural hazards and disasters. Although it has been an important component in urban and regional planning, the concept of social infrastructure has been less discussed previously. Social infrastructure represents the fundamental services, constructions, and maintenance of facilities that support social activities and connections[19]. Multiple aggregated socioeconomic characteristics, such as income, age, gender, race and ethnicity, are often used to differentiate capacity and social inequality of residents in front of natural hazards. Since the mitigation of risk involves both social and physical factors, a reduction of vulnerability from either side would overlook the capacity and limitation of the other. Therefore, to better achieve the goal of resilient city, the assessment of adaptation plan and policies needs to incorporate the coupled influence of both physical, social, as well as natural components. As information technology evolved, real-time human activities data, in both structured and unstructured formats, allows planners and researchers more easily to get access to individual-level human activities and to better understand interdependences between social and physical infrastructures[20]. Data-driven analysis and modeling provide rich and diverse information in adaptation planning. Data-driven approaches, such as machine learning and deep learning, top-down/bottom-up modeling tools, could accurately depict future direction of urban development and include multiple objectives in the analysis[21]. Another kind of approaches, urban microsimulation modeling, has the advantage to integrate multiple interdependent sub-systems in policy evaluation during the adaptation planning and hazard mitigation process, and could illustrate system dependences and interconnections between social and physical infrastructures[22][23]. For example, to handle adaptation problems within spatial context and evaluate policy effectiveness in flood risk management, scholars have developed and applied an agent-based model to evaluate interactions between the residents, local government, and flood risk insurer in coastal adaptation and indicate the importance of adaptive behaviors of residents in flood risk mitigation[24], which was overlooked in previous research. This model was further developed to evaluate urban adaptation strategies under uncertain flood hazards and SLR[23].

3 Adaptation Planning and Hazard Mitigation for Climate Change

Climate change would cause and amplify the vulnerability of human settlement to multiple natural hazards. These hazards include flooding, storms, SLR, drought,

门委员会认为[25]，城市可以从多方面来应对海平面上升的影响，包括：1）建设生态和社会基础设施；2）优化技术；3）管理自然资源；4）加强制度建设与观念普及、行为变革；5）通过金融手段转移风险；6）建立主动规划和预警信息系统。其中，第一和第四项策略已被广泛应用于适应性规划中[26]。而在适应性防灾减灾规划的整个过程中，相关个人的参与和政府机构的决策同等重要。

为提高社区韧性，国家和地方政府在城市规划中需要协调适应性防灾减灾规划及相应的制度政策。事实表明，地方政府是否具备较强的规划能力和丰富的防灾减灾经验，会极大影响防灾减灾政策和总体规划的制定[27]。荷兰有超过55%的国土位于平均海平面以下，其中就包含大量具有完备基础设施的高度发达城市。所以荷兰有着严格的海防基础设施建设传统，且在法律中规定，无论未来气候条件如何、海平面是否上升，荷兰的海岸线都要维持不变。然而，近年来，荷兰的海岸线（尤其是较深处）正面临一定程度的沙土流失[28]。这意味着，强行维持海岸线的固定形态并不能有效保护沿海社区，于是荷兰政府开始采用“与海共生”的适应性策略，取代了之前与海平面上升相对抗的政策。政策的变化表现出决策者观念的转变：气候变化并非威胁，应视其为变革的机遇[29]。

减灾规划通常以提高沿海社区的适灾韧性为目的，具体过程包括气候灾害评估、适应性规划目标确立、现有风险的适应性战略的制定，以及适应性政策的实施。其中气候灾害评估是适应性防灾减灾规划的核心部分。此评估首先识别在自然灾害中的易受影响的人员、财产和基础设施，后绘制该城市的社会经济地图，并结合大数据分析，为保护政策的制定提供依据[30]。在气候灾害评估完成后，将进一步制定适应性规划的目标及具体指标。进而针对这些目标，提出相应的适应性策略和方案[10]，包括：1）通过防灾知识宣传和风险信息沟通，提高公民的灾害应对能力；2）建立管理系统或配套机制，如土地利用政策与规范或保险机制；3）采取可行的适应性措施，如建造灰色或绿色基础设施等。在这个过程中，为避免采取不当或无效策略，所有方案的有效性都将被讨论并评估，以确定其是否适用于当地情况。近年来已有不少研究

and extreme heat, etc. From the Intergovernmental Panel on Climate Change[25], adaptation to SLR could be taken in a variety of forms, including 1) ecological and social infrastructure development, 2) technological optimization, 3) natural resource management, 4) institutional, educational and behavior change or reinforcement, 5) financial approach to transfer risk, and 6) information system for proactive planning and early-warning. Among these approaches, the social infrastructure development and institutional and educational change or reinforcement are widely recognized and accepted solutions in adaptation planning[26]. The response of adaptation planning and hazard mitigation to natural hazards is influenced by behaviors of both individual stakeholders and the government institutional actions.

Adaptation planning, hazard mitigation actions, and institutional policies need be coordinated into federal and local plans toward greater urban resilience. It has been shown that the planning capacity of local governments, and the experiences of natural hazards play important roles in public risk mitigation policies and comprehensive plan[27]. For example, in the Netherlands, more than 55% of land is below the average sea level, which includes many highly developed cities and infrastructure facilities. Therefore, the Netherlands has a tradition to build rigid sea-defense infrastructure and the law requires that the coastal line needs to be maintained irrespective of the future SLR or other climate conditions. Nevertheless, recent observation shows that the its coast has a net loss of sand, especially for its deeper coast[28]. This means a rigid policy defending the SLR would fail to protect coastal communities in the long run, and therefore, the Netherlands government changes its adaptation strategy from defending the SLR to the “Growing with the sea.” This policy transition implies that climate change should not be interpreted as a threat, but as an opportunity to make a change[29].

Hazard mitigation aims to reduce the vulnerability of coastal communities from natural hazards and climate change impacts. Its general process includes the assessment of climate hazard, identifying adaptation goals, development of the strategies to tackle existing risk, and the implementation of adaptation strategies. The climate hazard assessment is a core part of adaptation planning and hazard mitigation. It provides evidence to adaptation and mitigation approaches in the planning process. It identifies vulnerable population, assets, and infrastructure that need to be effectively protected from natural hazards. This process often involves mapping cities’ socioeconomic profile and performing data-driven analysis to inform policymaking[30]. Specific targets and goals in adaptation need to be carried out as part of the planning process after the climate hazard assessment. Afterwards, corresponding adaptation strategies and options to achieve designed adaptation goals are proposed[10]. These adaptation options include 1) actions that build adaptive capacity, such as risk knowledge creation and sharing, risk communications, 2) established management systems or supportive mechanism, such as land use policy and regulations or insurance mechanisms, and 3) adaptation actions that are implemented on the ground, including grey or green infrastructures. In this process, effectiveness of each adaptation solution is often discussed and assessed to determine their suitability to the local context, which involves adaptation decisions that avoid

广泛探讨了基于自然的解决（NBSs）方案在应对极端高温天气或洪水等自然灾害中的作用，此类方案具有诸多优势——不仅可以降低灾害风险，而且能更好地建设城市自然系统并提高人们的生活质量。

4 在适应性防灾减灾规划中整合关联基础设施系统

如上所述，适应性防灾减灾规划的过程及关联基础设施系统的内部联系均相当复杂，研究者应当探索新的技术与方法，将二者更好地融合。例如，可通过风险暴露评估、脆弱性评估和危害性分析，优化适应性防灾减灾规划中的气候灾害评估[25]。风险暴露评估主要对暴露在自然灾害中的资产和居民受到的直接或间接影响进行评估[31]，其中的资产包括基础设施、人口，以及社会资产（如企业发展和经济水平等）[19]。由于自然灾害会对整个城市系统造成破坏，城市总体规划中的每项规划都应进行风险暴露评估并制定适应性战略。这就要求在判断基础设施系统复杂关联性及连锁反应的过程中，将可能发生的自然灾害考虑在内。可以利用当地的遥感数据建立模拟模型，预测基础设施出现故障时与社会、物理和自然系统产生的复合效应[19][32]。脆弱性评估的具体内容包含社区暴露于自然灾害的程度、敏感性和适灾能力。为得到时间跨度较大、对象较全面且精确的结果，此评估需借助社会、物理和自然系统的耦合。由于自然灾害通常会对基础设施系统造成严重破坏，可以结合危害性分析来确定易受损区域。基于从人口角度出发的危害性分析通过社会经济数据（如家庭收入、贫困程度）和人口普查数据（如年龄、种族）来确定易受灾群体的空间分布[33]。然而，由于基础设施系统对国家安全和经济安全至关重要，且对易发生连锁反应的气候变化越发敏感，危害性分析应结合更具地方针对性的脆弱性评估，探究基础设施系统的破坏可能产生的影响——如交通发生故障导致的行程延误、城市停电造成的经济损失等[6]。基于人类活动和人口流动特征模拟的危害性分析可以将基础设施系统在社会和实体层面的脆弱性同时纳入考量，因而更有利于在气候不确定的情况下制订适应性防灾减灾规划。

尽管成本效益分析常用于适应性规划的决策中[34]，但在分析时需考虑多方面的不确定性因素。首先，由于城市未来发展和经济状况不明确，适应性防灾减灾规划——尤其是作为一项针对整个地区的长期规

undesirable actions or maladaptation. In recent years, Nature-Based Solutions have been widely discussed to tackle natural hazards from extreme heat to floods. The benefits of nature-based adaptation solutions are manifold. These benefits are not only in hazard mitigation, but also offering opportunities to build urban natural systems and boost people's quality of life.

4 Integrating Interdependent Infrastructure Systems in Adaptation Planning and Hazard Mitigation

Given the above processes in adaptation planning and hazard mitigation and the complexity of interdependent infrastructure systems, new techniques and methodologies could be developed and integrated into the adaptation planning and hazard mitigation process. Climate hazard assessment could be improved through the evaluation processes of exposure assessment, vulnerability assessment, and criticality analysis[25]. Assets exposed to natural hazards include physical assets, such as infrastructure, population, as well as social assets, including businesses and economy[19]. In another word, both direct and indirect impacts of natural hazards need to be considered in the assessment. Exposure assessment of natural hazards refers to the economic assets and people that are exposed to natural hazards[31]. Since natural hazard threats the entire city, the exposure assessment and adaptation strategies development should be integrated into each individual component of a master/comprehensive plan. This will inevitably involve measuring complex interdependences of infrastructure systems under natural hazards. Simulation models based on local social sensing data could evaluate these compound effects and interdependent consequences of infrastructure failures in the coupled social, physical, and natural systems[19][32]. Vulnerability assessment deals with exposure, sensitivity, and adaptive capacity of communities to natural hazards. Based on the coupled social, physical, and natural systems, more accurate long-term exposure, sensitivity, and adaptive capacity of all stakeholders in the community could be evaluated. Since natural hazards often cause substantial damages on infrastructure systems, criticality analysis could be applied to identify vulnerable areas. Criticality analysis identifies vulnerable areas based on population-based vulnerability assessment that use socio-economic (e.g., household income, poverty) and demographic (e.g., age, ethnicity) measures[33]. Nevertheless, since critical infrastructures are essential for national and economic security and are increasingly compromised by interrelated climate change impacts, criticality analysis should consider incorporating place-based vulnerability such as disruptions on the infrastructure systems (e.g., travel delays on the transportation network, economic disruptions due to power outage under natural disasters)[6]. Criticality analysis based on human activity and mobility simulation could combine social and physical vulnerability of infrastructure systems in the evaluation, and therefore, will benefit robust adaptation planning and hazard mitigation under climate uncertainties.

Cost–benefit analysis is a commonly used approach to select desirable strategies in adaptation decision-making[34]. Nevertheless, this process involves many uncertainties

划——各方案的成本和收益难以准确预测或量化。其次，由于气候变化的不确定性，未来风险难以量化，所以难以准确预估各适应性策略的当前效益，进而进行决策。例如在交通规划中，何时或如何规划才能改善现有交通基础设施就是一项难度较大的决策。在此过程中，常见的方法是情景分析法，即通过常应用于提升系统思考能力的严肃游戏方法模拟多种情景，来量化气候变化的影响。气候学家通常会构建全球或区域尺度的气候模拟模型来预测未来气候变化，但由于这一方法计算负担过重，很难开发城市尺度的气候预测模型[35]。因此，适应性规划中较少应用气候模拟模型。一个可行的方法是，将能够反映当地情况的不确定参数输入高性能并行计算的计算资源，分析城市尺度规划的成本效益[36]——研究人员及规划师将从当地收集的统计数据等信息输入相关模型中，根据高性能云计算平台得出多个平行的适应性规划情景，再选择能更准确描述未来情景的结果（如具有95%置信区间的结果），进行适应性分析。

5 城市大数据在适应性防灾减灾规划中的应用

结合了关联基础设施系统的适应性防灾减灾规划离不开新的数据来源与技术。当前，城市大数据作为一个新兴的研究领域，可为气候变化背景下的适应性规划研究和实践提供重要数据来源。而大数据来源、分析方法和工具也尤为重要，它们可在地理区域范围广和时间跨度长的研究中解决数据尺度、密度，以及格式不兼容等问题，以快速且全面地识别城市特征。皮尤希米塔·塔库里亚等人将城市大数据分为六类，其中部分数据可能在很大程度上促进韧性城市的建设[37]。这六个类别包括：

1）传感器系统数据（如交通网络、建筑管理传感器系统、互联系统和物联网）；

2）用户生成的内容数据（如社交媒体、线上社交网络和参与式传感系统）；

3）行政数据（如商业交易、税收和盈利数据、公民就业和支付数据）；

4）私营部门数据（如商业记录，以及公共服务和金融机构的使用数据）；

5）艺术和人文科学数据（如文本、图像、语言学数据和其他非结构化数据的存储库）；

from multiple sources. First, the benefit of adaptation is difficult to be quantified. Adaptation planning and hazard mitigation usually aims to protect the city for a long period of time, while the costs and benefits under different planning scenarios would be difficult to accurately project due to unclear urban development and economic conditions. Second, it is difficult to quantify future risk due to uncertainties of climate change, hence making it challenging to accurately estimate the present value of different adaptation strategy (e.g., when and how to implement transportation infrastructure improvement). Therefore, developing robust adaptation decisions are not trivial. A common approach is to apply scenario analysis to quantify these impacts through serious games, which are often used to improve system thinking. Although climate scientists often develop global or regional climate models to describe future climate change, it is difficult to develop climate projections on the fine scale due to high computational burden[35]. Therefore, climate simulation models are seldom used in the planning process. Relying on high performance computational resources, it would be possible to conduct city-scale cost-benefit analysis by incorporating uncertain parameters that reflect local conditions[36]. Researchers and planners could collect model inputs and statistics from the city and derive multiple parallel adaptation scenarios based on simulation results from high performance cloud computing, and select results that could better describe future conditions, such as results with 95% confidence interval, for adaptation analysis.

5 Opportunities of Urban Big Data in Adaptation Planning and Hazard Mitigation

Adaptation planning and hazard mitigation for interdependent infrastructure systems requires new data sources and techniques. Meanwhile, urban big data are rapidly emerging as a new area of research, and presenting important data sources for research and practice under the context of climate change. Of particular importance to adaptation planning and hazard mitigation is that big data sources, analytics, and tools offer the potential to tackle issues of scale, data density, and incompatibility of data formats for data covering large geographical areas and time spans, providing rapid and comprehensive situational awareness of cities. Piyushimita Thakuriah et al. classified urban big data into six categories, which are expected to largely facilitate the establishment of resilient cities[37]. These six categories include:

1) sensor systems (e.g., transportation, building management sensor systems, connected systems, and Internet of Things);

2) user-generated content (e.g., social media, online social networks, and participatory sensing systems);

3) administrative data (e.g., data on transactions, taxes and revenue, individual-level data on employment, and payment);

4) private sector data (e.g., business records as well as usage data from utilities and financial institutions);

5) arts and humanities data (e.g., repositories of text, images, linguistic data, and other unstructured data);

6）混合数据（包括测量传感器和人口普查—行政记录在内的关联数据）。

传感器系统可为城市提供丰富的数据集，涵盖可被识别的城市物质实体（如建筑物和树木）、土地情况（如地表覆盖信息和土地利用方式）和人口流动等多种活动和变化。社会感知数据为测量与基础设施系统相关的社会活动提供了数据来源。比如一些城市中建筑的位置、高度和占地面积会对城市环境中的人口和基础设施分布产生影响，而这些物理实体数据作为建设韧性城市的基础，可以用于识别灾害暴露地区、评估自然灾害造成的损失和评估灾害救援措施。以必应地图为例，这款足迹产品由微软公司于2018年6月发布，共包含1.25亿个通过遥感技术获得的高分辨率图像，涵盖整个美国本土的最新、最全面的建筑足迹数据[38]。此类建筑足迹开放数据库有望提供准确的人口分布和基础设施信息。另一种是街景图像（如谷歌街景、Mapillary和KartaView），它不同于上述遥感系统提供的图像，能够从人类（水平）视角审视实体建筑。这样的新视角在灾害损失评估和基础设施变化检测方面具有较大潜力，可以为减灾规划和韧性社区建设提供策略[39]。

用户生成的内容数据也是适应性防灾减灾规划的重要数据来源。随着推特、Flickr和Instagram等社交媒体平台的兴起，目前几乎可以实时监测人口流动和灾害事件。在这些系统中，由拥有数以百万计用户的巨大传感网络提供的实时地理空间信息，为评估灾害下基础设施系统的关联性提供了可能[40][41]。通过适当的信息检索和分析技术，用户生成的内容数据可在多个方面发挥作用：根据时间和地理空间信息，检查和监测用户关注的事件和模式，识别公众的关注点、情感和偏好；而在应对突发情况时，也可以实时了解城市动态（如城市基本服务中断和政策变化等）[37]。

行政数据包括公民的业务或交易等大量信息，记录了公民和公共／私营部门之间的来往数据。这些数据通常由政府收集，且大部分不会向公众或普通研究者开放，但"公开数据"中不太敏感的数据依然可以用于研究社会和实体基础设施之间的关联，帮助制定更合理的适应性战略。

综上所述，城市大数据可以在研究相互关联的气候变化风险方面有所应用。未来相关研究可以进一步探讨对不同来源数据的利用，以将这些数据更好地应用于韧性城市建设。

and 6) hybrid data (e.g., linked data including survey sensors and census–administrative records).

Sensor systems provide rich datasets that are able to detect activity and changes in a wide variety of urban phenomena that include urban objects (e.g., buildings and trees), physical conditions (e.g., land cover and land use), and human mobility. Social sensing data provides essential data sources for measuring social activities that connecting infrastructure systems. The locations, heights, and sizes of buildings, for example, dictate population and infrastructure distributions in urban settings, which provides essential knowledge for studying urban resilience that include identifying hazard exposure, assessing climate hazard damages, and evaluating humanitarian relief strategies. For example, based on high-resolution imagery obtained via remote sensing platforms, the Microsoft building footprint product, Microsoft Bing Map, released in June 2018, contains over 125 million newest building footprints for the entire conterminous US[38]. Open building footprint databases, like the one released by Microsoft, are expected to play important roles in providing spatially explicit population distribution and infrastructure information. Different from remote sensing systems, street view imagery (e.g., Google Street Views, Mapillary, and KartaView) enables the examination of visual features from the human (horizontal) perspective. Such a new perspective has great potential in damage assessment of natural disasters and infrastructure change detection, allowing for better strategies for hazard mitigation and building resilient communities[39].

User-generated content is another important data source that benefits adaptation planning and hazard mitigation. The rise of social media analytics based on social media platforms, such as Twitter, Flickr, and Instagram, offers another possible means to monitor human activity changes and to provide real-time situational awareness during disaster events. The timely geospatial information from social sensing techniques constituted by millions of users presents new opportunities to evaluate interdependences under disasters[40][41]. Given appropriate information retrieval and analytics techniques, the potential of user-generated content allows detection and monitoring of events and patterns of interest on spatiotemporal scales, provides the capability in identifying concerns, emotions, and preferences among the general public, particularly in response to emergent situations, for real-time understanding of urban dynamics under operation disruptions and policy changes[37].

Administrative data that contain rich information relevant to citizens' business or operational processes are often collected by governments, documenting the interactions between citizens and public/private sectors. Although many administrative data sources are restricted from the public and common researchers, the "Open Data" initiatives have made many less-sensitive records accessible for interdependence research between social and physical infrastructures, which provide opportunities to develop better adaptation strategies.

The above discussion identifies the opportunities that urban big data are able to provide in understanding interdependent climate change risks. We expect more efforts to be made towards better harnessing strategies of these data sources to assist in building resilient societies and cities.

6 成功构建适应性防灾减灾规划的障碍

城市通常将适应性防灾减灾规划直接应用或纳入其他规划，如针对电力系统、交通基础设施网络或沿海地区管理、国民经济等层级的规划。在城市规划和综合管理中建立不同社会和实体部门之间的关联关系，将有利于建设可持续的韧性城市。然而，在现有关联基础设施系统中，仍存在一些影响适应性防灾减灾规划成功实施的障碍。

为更好地应对气候变化，应积极制定可持续的适应性防灾减灾规划，而非被动地实施灾害救援。这就需要及时的气候预估信息和灾害影响分析，但此类信息通常具有不确定性，且小城市的数据通常较难获得[42]。产生于自然气候变化和建模技术的不确定性往往是适应性防灾减灾规划中的障碍[23]。因此，此类规划应当将城市规划的各方面纳入考量，并结合多个领域的专家指导，解决不确定的气候变化对关联基础设施系统的复合影响。

制度性障碍是成功实施适应性防灾减灾规划的另一个挑战。城市决策者和基础设施管理者往往能够认识到社会和实体基础设施系统之间相互关联和相互依赖的重要性。然而，如何从社会、经济和生态等多个视角评估适应性措施的落地效果，仍需更多研究探索[24]。在美国，国家尺度的适应性规划可以从多方面的政策上鼓励城市尺度的各种适应性举措，如建筑法规、功能分区、饮用水供应、土地利用、绿色基础设施建设和减灾方案等。然而短期经济利益目标和长期可持续发展目标之间存在矛盾，加之资金支持有限，适应性规划的制定与实施难以获得地方政府的长期持续关注与扶植。要想解决此类问题，就需要国家和地方政府之间协调合作，促进适应性政策的实施。

尽管城市大数据有助于监测、描述和评估气候危害和社区脆弱性，但城市大数据在适应性防灾减灾规划中仍会面临数据难获取、不可靠和不具代表性等问题[43]。这就要求研究人员基于伦理道德保护数据隐私，建立更加稳定的监测方法，保证数据的可靠性和代表性[44]。

随着自然灾害在全世界许多城市地区日益频发，适应性防灾减灾规划对城市的可持续发展越来越重要。在规划中考虑社会和实体基础设施系统间的复杂性和关联性是成功制定并实施适应性防灾减灾规划策略的关键。LAF

6 Barriers to Successful Adaptation Planning and Hazard Mitigation

Cities usually employ or integrate adaptation planning and hazard mitigation into a network of other plans. For example, plans target certain critical sectors, such as power and transportation infrastructure, and in certain context, such as coastal-zone management or economic growth. Building interdependences among different social and physical sectors in urban planning and management could facilitate planners to develop more sustainable and resilient cities. Nevertheless, some barriers exist to successful adaptation in the interdependent infrastructure systems.

Sustainable adaptation planning and hazard mitigation for climate change requires proactive adaptation actions rather than reactive responses, which requires up-to-date climate projection and impact analysis. This information often involves uncertainties and are not available for small cities[42]. These uncertainties come from natural processes and modeling techniques, which are often viewed as barriers in adaptation[23]. Therefore, adaptation planning and hazard mitigation could be integrated into every aspect of urban planning process, which requires participation of experts from different fields to address compound effects of uncertain climate on interdependent infrastructure systems.

Institutional barrier is another challenge in successful adaptation planning and hazard mitigation. Urban policy makers and infrastructure managers could often recognize the importance of interconnections and interdependences between social and physical infrastructure systems, but how to measure adaptation outcomes from multi-perspective, including social, economic, and ecological aspects, still needs more research efforts[24]. Adaptation policies from the national government could stimulate all kind of adaptation plans in local governments, such as building codes, zoning policy, water supply management, land-use policy, green infrastructure initiative, and hazard mitigation plans, while it is challenging to gain consistent support and commitment from local officials, especially for the case of the United States, in adaptation planning and implementation. This is often due to the conflict between short-term economic goals and long-term sustainable goals under limited financial resources. This requires coordination and cooperation between national, and local government to support adaptation policies.

Urban big data can contribute to monitor, characterize, and assess natural hazards and vulnerabilities of communities. Nevertheless, issues of data accessibility, reliability, and representativeness exist in the application of urban big data in adaptation planning and hazard mitigation[43]. These challenges require researchers to develop the ethical framework to protect data privacy, as well as robust methodologies to detect and reduce data bias[44].

As natural hazards continue growing in most urban areas around the world, the adaptation planning and hazard mitigation would be increasingly important for sustainable urban development. To successful develop and implement adaptation planning strategies, planners need to consider the complexity and interdependences between social and physical infrastructure systems in their decision-making. LAF

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