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Exploring the potential climate change impact on urban growth in London by a cellular automata-based Markov chain model

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ABSTRACT

Urbanization has become a global trend under the combined influence of population growth, socioeconomic development, and globalization. Even though recent urban planning in London has been more deliberate, the relationships between climate change and urban growth in the context of economic geography are still somewhat unclear. This study relies on rainfall prediction with the aid of the Statistical DownScaling Model (SDSM), which provides the statistical foundation for future flooding potential within the urban space of London while considering major socioeconomic policies related to land use management. These SDSM findings, along with current land use policies, were included as other factors or constraints in a cellular automata-based Markov Chain model to simulate and predict land use changes in London for 2030 and 2050. Two scenarios with the inclusion and exclusion of flood impact factor, respectively, were applied to evaluate the impact of climate change on urban growth. Findings indicated: (1) mean monthly projected precipitation derived by SDSM is expected to increase for the year 2030 in London, which will affect the flooding potential and hence the area of open space; (2) urban and open space are expected to increase > 16 and 20 km^2 (in percentage of 1.51 and 1.92 compared to 2012) in 2030 and 2050, respectively, while agriculture is expected to decrease significantly due to urbanization and climate change; (3) the inclusion of potential flood impact induced from the future precipitation variability drives the development toward more open space and less urban area.

1. Introduction

As one of the megacities in Europe with the highest population density, London's unique geographic location has led to an interactive relationship between its networked cities and corridors, which achieve synchronous growth. Land use changes are directly impacted by most economic, social, and environmental activities, reflecting on urban development and growth (Litman, 1995). However, in parallel with London's population increase and its economic development as the financial center of Europe, the area of forest and agriculture decreased significantly between 2000 and 2006 in exchange of the growth of urban and open space (Corine Land Cover, 2017). As floods have been threatening the economic development of the city since the 1700s (Greater London Authority, 2002), the impacts of climate change need to be addressed in order to shape urban planning strategies for land use changes in future scenarios. Even though recent urban planning in London has been more deliberate, the relationships between climate change and urban growth in the context of economic geography remain unclear to a certain extent.

Economic geography refers to location, distribution, and spatial organization involving economic activities worldwide (Clark, Gertler, & Feldman, 2003). The combination of the fundamental network structure and the large size of systems consists of complex networks that could be a striking approach for growth dynamics modeling (Andersson, Frenken, & Hellervik, 2006). Yet incomputable networks and connections are extremely difficult to count or identify within the systems. Analyzing schematic structures or simple systems to represent a dynamic growth on a large-scale region remains difficult to achieve. Therefore, a comprehensive and systematic approach based on different levels of factors and networks is required in order to study the complex and evolving system (Barabási & Albert, 1999).

Macro-level modeling analysis involves significant portions of the internal dynamics of objects, relatives, and implications (Andersson et al., 2006). Such dynamic models can predict potential changes with global parameters, which differs from conceptual models designed simply to address one fundamental question. As one of the

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representative models in the urban planning regime, grid-based cellular automata (CA) models can simulate the multiplicative growth at micro level from more detailed local activities of simple systems. Furthermore, CA models can be agglomerated in varying scales to analyze the spatial variation of a network as well as to predict potential urban evolutionary changes over a long period of time. The history of CA dates back to the 1940s (Von Neumann & Burks, 1966) and it was further developed by numerous studies (Batty, 2007; Clarke, Hoppen, & Gaydos, 1997; Takeyama & Couclelis, 1997; Torrens, 2000; Xie, 1996). As extensions of CA, some approaches such as artificial neural networks (Hopfield, 1988; Yegnanarayana, 2009), logistic regression (Hu & Lo, 2007; Peduzzi, Concato, Kemper, Holford, & Feinstein, 1996), and Markov chain models (MC) (Guan et al., 2011; Kamusoko, Aniya, Adi, & Manjoro, 2009) are more related to time-series prediction; these are general methodologies rather than only applications for simulating urban evolutionary processes.

This study depends on the rainfall predictions from the Statistical DownScaling Model (SDSM) (Wilby, Dawson, & Barrow, 2002), which provides the statistical foundation for future flooding potential within the urban space of London while considering major socioeconomic policies related to land use management. In this context, a CA-based MC model was applied for a spatiotemporal assessment that took advantage of the spatial values of CA models and temporal coverage of MC models simultaneously (Memarian et al., 2012). In other words, CA models can spatially simulate land use and land cover (LULC) changes on a large scale based on the grid-based principle, whereas MC models are able to quantify the actual amount of changes over time periods dynamically (Moghadam & Helbich, 2013). This can be achieved due to the fact that MC models use mathematical theory to calculate the probability of changes during two specific time periods (Arsanjani, Helbich, Kainz, & Boloorani, 2013). Therefore, CA-based MC models are ideally integrated into a modeling system to simulate LULC changes spatially based on the calculated likelihood of LULC changes over specified temporal scales mathematically. By implementing the CA-based MC model, the study can address spatiotemporal complexity specifically using long-term precipitation variability and climate change impact as the driving force to search for better urban planning strategies.

The objective of this study is therefore to simulate and predict LULC changes for 2030 and 2050 in London by using an integrated CA-based MC model regarding the interactions between climate change and urban growth from local networks and large-scale dynamics to increase the insight for future scenarios of LULC changes. Rainfall forecasting conducted by SDSM provides the statistical foundation of climate change and flood impact in 2030 and 2050. Two scenarios are developed to explore the difference between the inclusion and exclusion of climate and flood impacts. The applied software, including geographic information system (GIS) and IDRISI integrated in TerrSet, can collaborate and realize the goal of simulation and prediction of land use changes. With such model settings, the study seeks to analyze and answer the following three scientific questions: (1) How will rainfall change by 2030 and 2050 and what are its potential impacts on flooding within the urban space of London? (2) How will the LULC patterns of London change under the impact of climate change (i.e., rainfall variability) in 2030 and 2050 as a whole? and (3) What are the differences between the inclusion and exclusion of flood impact regarding LULC changes in 2030 and 2050?

2. Study area

London, the capital of the UK, is located in southeast England and is the largest metropolitan area in the country, as well as one of the largest urban zones in Europe. The city covers about 1572 km^2 (607 mile^2) with a population of > 8.67 million in 2015. London is vulnerable to flooding from various sources, including storm surge and fluvial flood from the Thames River and surrounding tributaries as a result of heavy rainfall and overwhelmed drainage systems (Greater London Authority, 2002). Flooding can also be exacerbated by the increase in urbanized regions and the lack of green space to retain runoff.

Following World War I, green space was seen as an alternative for shifting rapid urban densification in the city's center toward suburbanization. However, the need for suburbanization threatened available green space, as policymakers sought to develop these areas in the mid-20th century (Rotenberg, 2008). Toward the late 20th century, policymakers were seeking new solutions to balance urban growth while protecting green space surrounding London as much as possible (Urban Task Force, 2002). Recent practices on the policy level for the 21st century have sought to not only protect green space surrounding the center of London but also to incorporate more green space within the city as part of sustainable drainage systems (SuDS), which can be utilized to address concerns over flood risk in London (Greater London Authority, 2015).

3. Data and software

3.1. Data collection and pre-processing

The data required in this study involve land use, land cover, road, Green Belt land, Central Activities zone boundary, areas for intensification points, opportunity area points, strategic industrial location points, London brownfield sites, digital elevation data, parks and gardens, and buildings (Table 1). The Greater London Authority established a new center of commercial and residential community in the

Table 1
Applied dataset and source.

Data	Description	Date	Source
Land use land cover	100x100m resolution	2000,2006,2012	Corine Land Cover
Road	Existing road	2016	Ordinance Survey Open Data
Green Belt land	–	2011	London Datastore
Central Activities Zone Boundary	For strategic finance, specialist retail, tourist and cultural uses and activities, residential, and other local functions	2009	London Datastore
Areas for intensification points	For residential, employment and other uses	2009	London Datastore
Opportunity area points	For new employment and housing	2009	London Datastore
Strategic industrial location points	For general business, industrial, warehousing, waste management, and transport sectors	2009	London Datastore
OPDC	New center and community for development	2016	London Datastore
London brownfield sites	For redevelopment and reuse	2010	London Datastore
Digital elevation data	90x90m resolution	2010	USGS SRTM 1 Arc-Second Global
Parks and gardens	Historic parks and gardens	2016	Historic England
Buildings	Existing buildings	2016	Historic England
Recorded flood area	Records from 1706 to 2015	1706–2015	UK Environment Agency