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Utilizing a cellular automaton model to explore the influence of coastal flood adaptation strategies on Helsinki's urbanization patterns

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ABSTRACT

A cellular automaton model (SLEUTH-3r) is utilized to explore the impacts of coastal flood risk management strategies on the urbanization parameters of Helsinki's metropolitan area, at a 50-m spatial resolution by 2040. The current urbanization trend is characterized by the consolidation of existing built-up land and loss of interspersed green spaces, whereas the most intense growth is forecast inside the coastal flood risk areas. This baseline is compared to strategies that test various responses of the planning system to real estate market forces and the spatial distribution of flood risks. A set of scenarios translates property price effects of flood risk information into various attraction-repulsion areas in and adjacent to the floodplain, while a second set explores varying degrees of restricting new growth in the flood risk zones without reference to the housing market.

The simulations indicate that growth under all scenarios is distributed in a more fragmented manner relative to the baseline, which can be interpreted favorably regarding house prices and increased access to ecosystem services, although the indirect effects should also be considered. Demand for coastal flood-safe properties does not appear to automatically translate to refocusing of development toward those areas, unless planning interventions encourage this redistribution. The character of the planning system with respect to market drivers and the spatial distribution of risks and amenities is thus important. A mixture of market-based measures and moderate zoning interventions may be preferable for flood risk management and provide the necessary precision for adaptation strategies.

1. Introduction

Coastal urbanization is typically characterized by intense concentrations of population, infrastructure, and activities. Proximity to the sea and coastal ecosystems entails risks, notably flooding; however, it also drives growth in coastal urban agglomerations. The question is, therefore, how to steer coastal development toward sustainable configurations: risk management and adaptation to changing risks require not only flood-related restrictions, but also understanding how spatial interventions affect fundamental mechanisms behind urban growth and development.

However, it is often assumed that risks and interventions interact in the absence of urban dynamics. One reason is the uncertainty surrounding urbanization. Evidence-based modelling frameworks are rare and the absence of quantified scenarios prevents urban evolution from being grasped or accounted for during decision-making. Moreover, it is often neglected that decision-makers seek clear signals from markets, which, however, react to immediate changes rather than to gradual phenomena such as urban evolution. Loose connection of urban dynamics with flood-related interventions may entail conflicts between environmental and economic objectives that hinder urban sustainability; for instance, municipalities often reconcile strict land use policies with pragmatic growth targets. Consequently, there is substantial need to implement assessment frameworks that quantify the link between urban dynamics, climate-sensitive risks, and interventions. The use of cellular automata is motivated by their ability to model the evolution of the adapting city concurrently with the impacts of spatial interventions and to reproduce the distribution of growth in a spatially explicit manner, allowing to understand the implications of alternative spatial policies and refine them.

This study aims to explore the influence of flood-related policy instruments on urbanization dynamics, by calibrating the SLEUTH cellular automaton model for Helsinki's metropolitan area and simulating three scenarios. The first scenario forecasts the evolution of Helsinki's current urbanization trends as identified in calibration. The second (with two variations) simulates a market-led adaptation process that relies on flood risk information and subsequent price and demand adjustments in the housing market. The third (with three variations) simulates an adaptation process that relies on regulating coastal growth without

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reference to market behavior. The simulations offer insights into how planning systems can respond to flood risks and to markets adapting to those risks.

2. Flood risk management and urban dynamics

Coastal and river-line areas are the most vulnerable to climate-related impacts (Wilbanks et al., 2007). Flooding is a major risk in urban areas (Revi et al., 2014) and the economic losses of coastal flooding are expected to rise, owing to unsound urban development and exacerbated by changing hydrological patterns and sea levels (Nicholls & Cazenave, 2010; Neumann et al., 2015; Vousdoukas, Mentaschi, Voukouvalas, Verlaan, & Feyen, 2017; for Helsinki, Venäläinen et al., 2010; Parjanne & Huokuna, 2014; for Finland, Perrels et al., 2010). It has been recognized that resilience to flooding requires a comprehensive understanding of the functioning of urban areas and of indirect effects mechanisms, beyond direct short-term damage costs (Aerts et al., 2014; Hallegatte, 2008; Li, Crawford-Brown, Syddall, & Guan, 2013; Meyer et al., 2013; Ruth & Coelho, 2007). Urbanization parameters affect all risk components (exposure, vulnerability, hazard severity; IPCC, 2014), whereas adaptation and sustainability objectives overlap through their interactions in society, industry, and the built environment (Wilbanks et al., 2007).

In practice, flooding participates in urban growth and development mechanisms in a number of ways. Flood risk is a locational disamenity that, if transparent, reduces house prices (Bin, Crawford, Kruse, & Landry, 2008; Daniel, Florax, & Rietveld, 2009), whereas disclosure of previously non-transparent flood risks adjusts prices according to risk (Votsis & Perrels, 2016) and income level (Rajapaksaa, Wilson, Hoang, Lee, & Managi, 2017). These effects can be bounded-rational (Daniel et al., 2009; Votsis & Perrels, 2016) and fade with time (Atreya, Ferreira, & Kriesel, 2013), but show that the spatial distribution of risks influences, via residential location and property price dynamics, aspects of a city's spatial equilibrium, notably land use and where new growth is demanded. Systematic non-marginal shifts have also been documented (Bin & Landry, 2013; Hallegatte, 2008), including when attitudes adapt to changing risks (Filatova, 2015; Filatova & Bin, 2013). For urban planning and management, policies representing different spatial configurations of risks, resources, and interventions entail different impacts from catastrophic flooding (Perrels et al., 2015), whereas well-functioning urban agglomerations have capital stock structures with long-term lower sensitivity to impacts (Perrels et al., 2010; Virta et al., 2011). Similarly, (over)production capacity in construction (Hallegatte, 2008), policies supporting accessibility and network flows (Li et al., 2013), and green infrastructure (Davies et al., 2011; De Groot, Wilson, & Boumans, 2002; Renaud, Sudmeier-Rieux, & Estrella, 2013) influence impacts and recovery, all posing their own implications for urbanization. Flood risks therefore both influence and are influenced by urban spatial dynamics, and the role of spatial planning interventions in steering urbanization to safer configurations is recognized (Neuvel & van den Brink, 2009; Schanze, Zeman, & Marsalek, 2006; Wilson, 2007). Spatially explicit modelling with cellular automata can explore the relation between natural and imposed land constraints, the transport network, and urban growth, and is increasingly used to forecast the future location and form of growth in flood-prone urbanities (Nigussie & Altunkaynak, 2017; Sekovski, Mancini, & Stecchi, 2015; Song, Fu, Gu, Deng, & Peng, 2017).

The shift of interest from flood protection to risk management and adaptation underlies Finnish strategies, bar spatial dynamical modelling. The metropolitan adaptation strategy, based on regional climate change scenarios, stipulates the consideration of extreme events and climate variation/change in land use planning (HSY, 2012) and a fine-grid assessment of social vulnerability to climate change has been produced (Kazmierczak, 2015). Detailed flood probability maps (environment.fi/floodmaps) are available in compliance with Finland's national climate adaptation strategy (Marttila et al., 2005) and EU's Water Directive (European Communities, 2000). These maps improved resilience in the real estate sector as prices/m^2 and demand adjusted to reflect more accurately the spatial distribution of coastal flood risks (Votsis & Perrels, 2016). More precise considerations of the effects of flood-related strategies on urban dynamics remain, however, unknown, both in international literature and in Finland. This study moves a step further by simulating the effects of information-led price adjustments and of alternative growth restrictions on urban evolution.

3. Methodology and scenario assumptions

3.1. Models

SLEUTH (**s**lope-**l**and-use-**e**xclusion-**u**rban-**t**ransportation-**h**illshade) is a cellular automaton model of urban growth and land use transitions (Clarke & Gaydos, 1998; Clarke, Gaydos, & Hoppen, 1997). This study implements SLEUTH-3r (Jantz, Goetz, Donato, & Claggett, 2010), a modification that maintains SLEUTH's functionality and theoretical underpinnings, but improves computational performance and introduces additional calibration metrics. Cellular automata (von Neumann, 1951; von Neumann & Burks, 1966; Batty, 1997, 2007) are computational frameworks that model in discrete time bottom-up interactions between elementary spatial entities (cells). They can both generate forms consistent with known urban processes and optimize those forms by simulating how different development strategies result in actual urbanization patterns (Batty, 1997). They consist of cells in an $n \times k$ lattice, initial and possible states of cells, and transition or cellular interaction rules that govern the state transitions of cells.

SLEUTH simulates four types of urban growth: diffusive, new spreading center, edge, and road-influenced. Diffusive (spontaneous) growth simulates urbanization non-contingent to preexisting infrastructure, while its expansion is simulated by new spreading center growth. Edge growth simulates urbanization contingent to existing urban areas, while road influenced growth simulates urbanization along major transport corridors. These growth types are controlled by five growth coefficients: diffusion, breed, spread, slope resistance, and road gravity. Diffusion (dispersion) controls a cell's random selection frequency for possible spontaneous growth. Breed controls the probability that a spontaneous urban cell will also become a new spreading center. Spread controls the probability that a new spreading center will generate additional urban areas. Slope resistance affects all growth types, controlling the extent to which urbanization overcomes steep topographies. Road gravity controls road influenced growth through the area of influence of transport infrastructure. Candau (2002) provides a full exposition. Gazulis and Clarke (2006) approach the growth coefficients as a region's DNA and illustrate how different combinations reproduce known urban morphologies. A calibrated model produces a scenario, if the calibrated parameters are used to forecast the future trajectory of observed growth.

SLEUTH is widely utilized (Chaudhuri & Clarke, 2013; Gazulis & Clarke, 2006) due to its transferability, straightforward implementation, computational efficiency, interpretability, and universalizability (Clarke, 2008; Jantz, Goetz, & Shelley, 2004; Silva & Clarke, 2002). The limitations of modelling urban dynamics via non-customizable transition rules rather than implementation of urban economic theory are a concern (Kim & Batty, 2011). However, the model's value is its high spatial resolution, standardized and accessible inputs (cf. the data needed by CGE or LUTI models), and first-principles approach that adapts a transparent set of spatial interaction assumptions into empirical settings. SLEUTH does not impose strong assumptions, accommodating diverse policy viewpoints.

3.2. Data

SLEUTH-3r is calibrated to capture Helsinki's growth dynamics at a 50-m spatial resolution. The full extent of Helsinki's metropolitan area