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Developing a cellular automata model of urban growth to inform spatial policy for flood mitigation: A case study in Kampala, Uganda

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ABSTRACT

Urban growth may intensify local flooding problems. Understanding the spatially explicit flood consequences of possible future land cover patterns contributes to inform policy for mitigating these impacts. A cellular automata model has been coupled with the openLISEM integrated flood modeling tool to simulate scenarios of urban growth and their consequent flood; the urban growth model makes use of a continuous response variable (the percentage of built-up area) and a spatially explicit simulation of supply for urban development. The models were calibrated for Upper Lubigi (Kampala, Uganda), a sub-catchment that experienced rapid urban growth during 2004–2010; this data scarce environment was chosen in part to test the model's performance with data inputs that introduced important uncertainty. The cellular automata model was validated in Nalukolongo (Kampala, Uganda). The calibrated modeling ensemble was then used to simulate urban growth scenarios of Upper Lubigi for 2020. Two scenarios, trend conditions and a policy of strict protection of existing wetlands, were simulated. The results of simulated scenarios for Upper Lubigi show how a policy of only protecting wetlands is ineffective; further, a substantial increase of flood impacts, attributable to urban growth, should be expected by 2020. The coupled models are operational with regard to the simulation of dynamic feedbacks between flood and suitability for urban growth. The tool proved useful in generating meaningful scenarios of land cover change and comparing their policy drivers as flood mitigation measures in a data scarce environment.

1. Introduction

The city of Kampala is growing rapidly, as exemplified by the accelerated increase of its urban footprint (Vermeiren, van Rompaey, Loopmans, Serwajja, & Mukwaya, 2012). Because of a weak institutional setting (Goodfellow, 2013) but also due to a complex physical context, this expansion has generated a number of negative impacts – among them, increased urban development has lead to greater runoff, a consequence of more impervious areas. As Kampala's drainage systems are inadequately developed and maintained – despite recent major investments in the system which have mitigated existing problems – this, in turn, has contributed to aggravating local flooding (Lwasa, 2010).

The goal of this paper is to create a generalized instrument to explore the flooding consequences of urban development. This problem is tackled by designing a coupled urban growth-flood model. Emphasis is placed on the potential to create a diversity of meaningful land cover and flooding scenarios. These scenarios should respond both to policy and to social and physical factors which influence land cover patterns and their ensuing flood impacts. Further, the modeling approach must be tractable; given the complexity of emergent behavior in a city, this is achieved by adopting a simple, and therefore understandable, approach to geographic inputs. The urban growth model includes a strong component of randomness to account for seemingly irrational behavior by urban actors, such as poor enforcement of regulations or higher willingness, notably of the urban poor, to occupy and develop hazardous, flood-prone land.

1.1. Conceptual framework

The analysis approaches urban flooding in Kampala as a coupled human and natural system (Alberti et al., 2011). In the specific research context of flooding and landscape patterns of Kampala, urban growth is the mediating phenomenon between human behavior and its physical consequences in terms of flooding. Fig. 1 features both subsystems and the hypothesized relationships between them.

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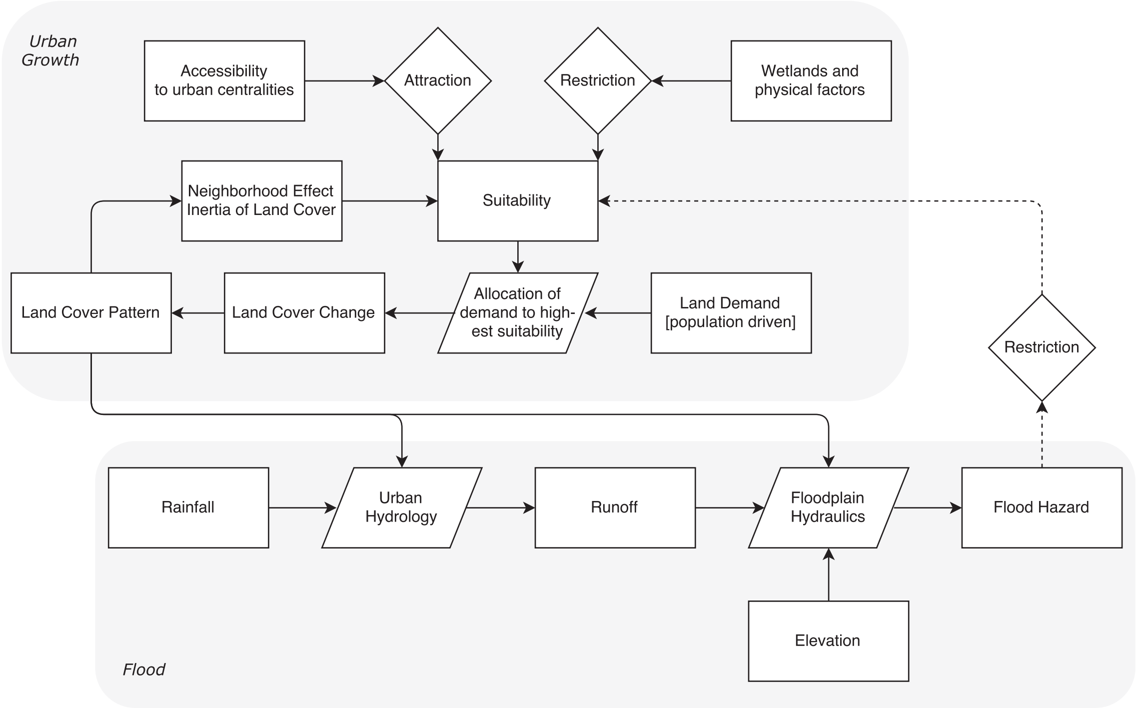

Fig. 1. Conceptual framework: interaction between land cover and flood dynamics.

Urban development is conceived as driven by an external demand for land (due to increased urban population); the location of urban development materializes based on three core principles: suitability of land, continuation of historical development, and neighborhood interactions (van Schrojenstein Lantman, Verburg, Bregt, & Geertman, 2011).

Suitability is determined by accessibility to urban centralities, following the approach originally developed by Alonso (Brueckner, 1987), which implies urban agents will choose to live as close as possible to these central locations. Further, physical characteristics of the land are also included as potential determinants – specifically, flooded areas (wetlands, permanently flooded, or flood zones, flooded as a consequence of an extreme event) – assumed to negatively impact the prospect of urban development (*e.g.*, see Bathrellos, Skilodimou, Chousianitis, Youssef, & Pradhan, 2017). These physical factors follow from McHarg's original concept of suitability as an intrinsic and spatially specific characteristics of the land (McHarg, 1969).

The neighborhood effect assumes "transition[s] from one use of land to another is dependent on the land use of its surrounding cells" (van Schrojenstein Lantman et al., 2011, p. 38), a model originally proposed by Tobler (1979). It can be substantively interpreted to reproduce the Core-Periphery model of Krugman and Fujita and biophysical relationships (van Schrojenstein Lantman et al., 2011).

The hydrological analysis of rainfall-runoff results in estimates of how much rainfall becomes water flowing over the landscape. Sene (2010, p. 110) describes the physical processes: rainfall is either infiltrated into the soil, intercepted (mainly by vegetation), or flows over the landscape; the hydraulic analysis routes the water flowing over the surface, using elevation and other terrain characteristics. Changes in land cover patterns are known to affect the flood patterns: as more areas are urbanized, imperviousness increases (and so does the fraction of rainfall flowing over the landscape), resulting in more and faster flooding (Smith & Ward, 1998). This added flooding could change the suitability patterns; in particular, recurrently flooded locations should be less desirable for development (Bathrellos et al., 2017). However, the importance of this process – relative to other spatial factors determining suitability for urban land – is uncertain and may depend on the specifics of different sites.

1.2. Literature review

Previous studies of the city of Kampala (Abebe, 2013; Fura, 2013; Mohnda, 2013; Vermeiren et al., 2012) have already quantified the impact of the most important determinants of its urban morphology, at mid and detailed scales. These approaches were all statistical, making use of Logit econometrics, without spatial autocorrelation but including neighborhood effects as proxy variables of it. All show broadly consistent results: strong influence of the neighborhood in explaining transformation into built-up land cover, rapid growth rates of the urban footprint. The openLISEM integrated flood model, coupling surface hydrology (*e.g.*, see Baartman, Jetten, Ritsema, & Vente, 2012; Hessel, Jetten, Liu, Zhang, & Stolte, 2003 and Sánchez-Moreno, Jetten, Mannaerts, & Pina Tavares, 2014) to a 2D flood model (Delestre et al., 2014), was used by Mohnda (2013) to assess various runoff reduction strategies in the Lubigi catchment, north of the Kampala central business district (CBD). Habonimana (2014) examined the flood model's sensitivity to input parameters and to spatially explicit representations of rainfall. More generally, the results of spatial-statistical urban growth models developed by Fura (2013) were used as inputs for the openLISEM flood modeling tool to estimate a diversity of scenarios, which included both future plausible land cover as well as interventions on the drainage system and alternative infiltration actions (Sliuzas, Flacke, & Jetten, 2013).

While straightforward, tight coupling of urban growth and flood models has been rare. Most case studies have analyzed the impact of land patterns on hydrological or hydraulic outcomes, among which the work of Ciavola, Jantz, Reilly, and Moglen (2012), Huong and Pathirana (2013), Kumar, Arya, and Vojinovic (2013), and Poelmans, Rompaey, Ntegeka, and Willems (2011) are typical recent examples.