Simulating flood impacts in Kampala, Uganda: when do land patterns matter

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Abstract

The use of urban growth modeling has been found useful in searching for strategies to improve flood risk management in Kampala, Uganda. However, to generalize the approach in the context of Sub-Saharan Africa, a deeper understanding of the modeling's implications is required. Building on a simple cellular automata model calibrated for Upper Lubigi catchment, Kampala, a set of scenarios is defined to explore their impacts on flood outcomes. These scenarios include variations on the spatial determinants of urban growth as well as on the level of built up land demand. Land demand is found to affect total hydrological measures but not the flooding patterns. Spatial patterns can introduce important differences in exposure of built up land cover to flood, especially when development is assumed to avoid recurrently flooded locations. Finally, it is not sufficient to consider only built up land cover; variations on the proportions of vegetation and bare soil are found to have large impacts on flood hazard and exposure.

Keywords: Scenario planning, urban growth, flood hazard, exposure, Kampala.

1. Introduction

Recent research efforts on flooding and urban growth at ITC were articulated under the Integrated Flood Management Kampala (IFMK) project, which had the aim of "[demonstrating] how flood risk can be addressed in an integrated, multi-dimensional and participatory manner" (Sliuzas et al., 2013b).

The IFMK project organized integrated modeling of urban dynamics and flooding, with the drivers of development accounted for through urban growth models to simulate future, spatially explicit landscape outcomes of the Upper Lubigi catchment in Kampala, Uganda. These were inputted into the openLISEM rainfall-runoff-flood model, to generate flood maps. Simulated flood and land patterns were overlaid to assess the exposure of new development to flood. This strategy was used in a scenario-based approach to simulate possible policy interventions, such as infrastructure (e.g. drainage improvements) and land (e.g. land covers with higher drainage, relocation of urban development in flooded areas) policies (Sliuzas et al, 2013a).

Looking forward into extending the methods of the IFMK project in the context of Sub-Saharan Africa, how should land dynamics modeling be improved? This paper explores the issue by specifying a variety of scenarios of land dynamics and tracing their flood impacts, in terms of hazard and exposure of built up land cover.

2. Research design

Land cover scenarios were simulated according to three population growth rates (trend, low and high) and eight allocation rules: trend cellular automata (CA) (wetland), pure CA, pure randomness, upstream growth, downstream growth, elevation, base year flood, and trend CA (base year flood). Flood maps for each scenario were estimated and overlaid with new urban development. Two propositions were tested:

- *Flood hazard* responds more to the amount of land cover change, determined by population increase, than to its distribution.
- Spatial patterns are crucial in evaluating *exposure* to flood hazard.

3. Methods and data

3.1 Land cover and population data models

Land cover maps were created by revising existing building footprints maps (generated by the Kampala City Council Authority) of 2004 and 2010, through visual inspection and unsupervised classification of high spatial resolution imagery for those years. The resulting maps were aggregated into $400m^2$ square cells, as percentages of: built up, vegetation, off road bare soil, on road bare soil, tarmac, and water.

Population estimates were taken from Pérez-Molina (2014), calculated for the entire city from UN data. The estimated 2010 population was projected to 2020. This figure was converted to land demand using the 2010 estimated gross density; the population in Upper Lubigi was apportioned assuming it equal to the population share of the Kawempe division, according to the 2002 census.

3.2 Urban growth model

The urban growth models used was calibrated with data from 2004-2010. Documented in Pérez-Molina et al. (2015), it identifies cells undergoing urban growth under a global constraint (the total amount of change in the simulated period is fixed).

Space is conceived as a set of square cells, each cell being an automaton *A* characterized by a set of states (**G**) –the land cover percentages of the land cover data model–, a set of transition rules (**T**) governing changes to these states and a set of states of neighbouring cells (**R**). The transition rules **T** define the state of the automaton ($\mathbf{G_{t+1}}$) in time step t + 1, based on the automaton's state ($\mathbf{G_t}$) in the preceding time step, and on an input, I_t.

I_t measures the development potential of each cell for building. It is defined as a weighed summation of spatial factors. For spatial trend, these are: percentage of built up land cover in adjacent cells (neighbourhood factor), percentage of base year vegetation, location within wetlands and travel time to CBD. The pure CA scenario uses only the neighbourhood factor; the random scenario, a random number. Upstream and downstream scenarios are based on the amount of cells contributing inflow into the downslope cell (with cells of equal value being randomly selected). For the elevation scenario, the highest elevations are developed before the lowest. Unsuitability due to flood is assumed inversely related to flood depth, with non-flooded cells randomly allocated. A modified trend scenario introduces flood depth in lieu of wetlands.

Development is assigned to each cell with the highest I_{it} value at each time step until the exogenous land demand for that time step has been satisfied.

3.3 Flood model

Flood modeling was performed with the openLISEM model (De Roo et al, 1996). openLISEM was calibrated for the Upper Lubigi basin, Kampala (Sliuzas et al, 2013a) using discharge figures from drainage projects of 2002 and 2010. This calibration included measuring rainfall data, developing a soil hydrological and infiltration map, and generating a data for drainage channel layout and its geometry. Land cover effects are introduced by: interception for areas where vegetation and built up (roof interception) exist and lower infiltration rates for compacted soil, roads and built up land covers (Jetten, 2014).

4. Results and discussion

For the same spatial scenario, an increase in land demand results in greater total flood measures (total discharge, flooded area) but instantaneous measures, such as peak discharge at the outpour point, remain constant (figure 1).

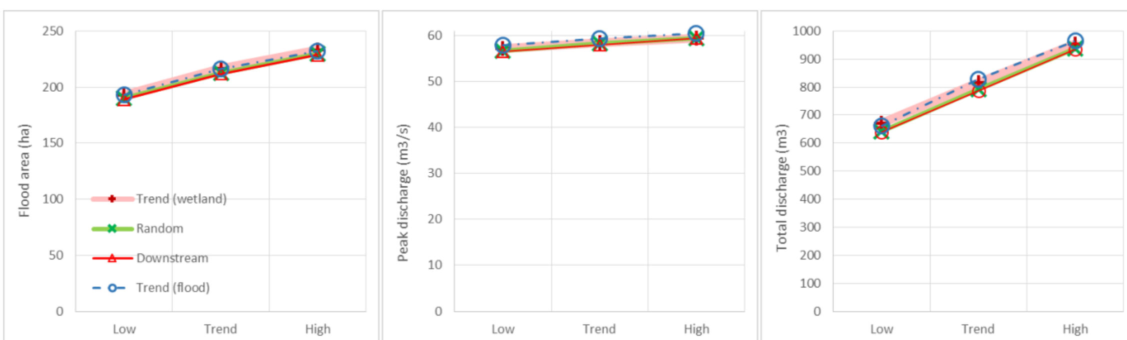

Figure 1. Variation of flood hazard with land demand for selected scenarios.

Given the same land demand, e.g. trend population growth (figure 2), there is virtually no difference in the hydrological outcomes (flooded area, peak discharge at outpour point, total discharge) between scenarios. This is remarkable, since it has been argued (Mejía and Mogle, 2009) that urban development patterns can be generated to minimize flood impacts. These results could be explained by large amounts of built up land cover in the base year of the simulation, limiting the possibilities of urban growth to alter urban patterns. Further, population growth in the region is fast –and hence land demand is large–, leading to near saturation of available land for development.

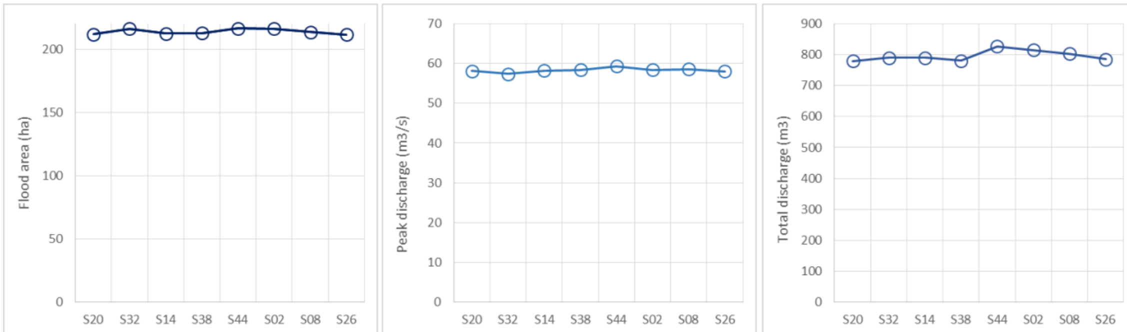

Figure 2. Variation of flood hazard with spatial patterns for trend population growth[1].

Despite evident differences in input land cover pattern (cells predicted to change by the model and built up percentages), the flood patterns are essentially unchanged (figure 3). The clusters identified based on flood depth are nearly identical for all three land demand conditions. This result is unsurprising, given peak discharge was found to be constant across land demand conditions. Small differences in patterns could be explained by the assumption that the ratio of vegetation to off road bare soil is constant (see table 1 and associated discussion) or to the near level of saturation of urban development in the study area.

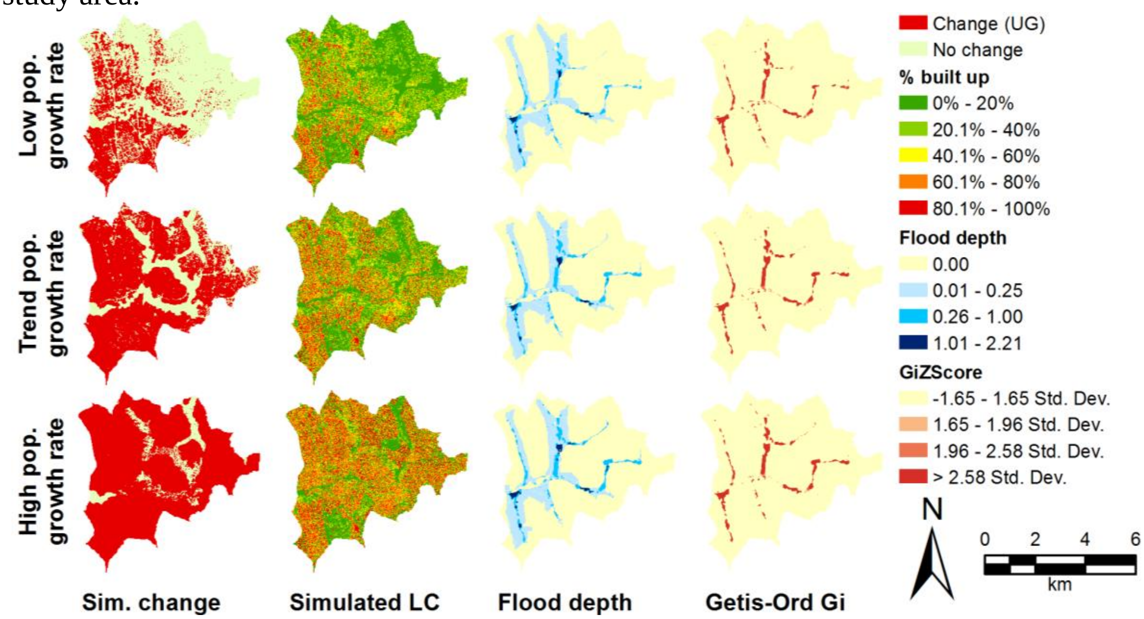

Figure 3. Spatial trend (wetland) land cover scenarios and flood maps for low, trend and high population growth.

When considering exposure of built up land to flood, some spatial scenarios do introduce clearer differences (figure 4); specifically, when development is assumed to avoid areas flooded in the base year –a reasonable rule, since most urban actors would like to shun these locations– or when it is assumed to occur from higher to lower elevations (scenarios S32, S38, and S44 trend), exposure of built up land to flood depths

[1] S02: Trend (wetland) | S08: CA | S14: Random | S20: Upstream | S26: Downstream | S32: Elevation | S38: Flood | S44: Trend (flood)

greater than 25cm decreases substantially. It is also interesting to note that upstream and downstream scenarios (S20 and S26) are not much different from trend (wetland), clustered (pure CA) or random development (scenarios S02, S08, S14). Because the catchment is small and irregular, most downslope cells accumulate flow from few other cells; thus, these scenarios are mostly controlled by randomness.

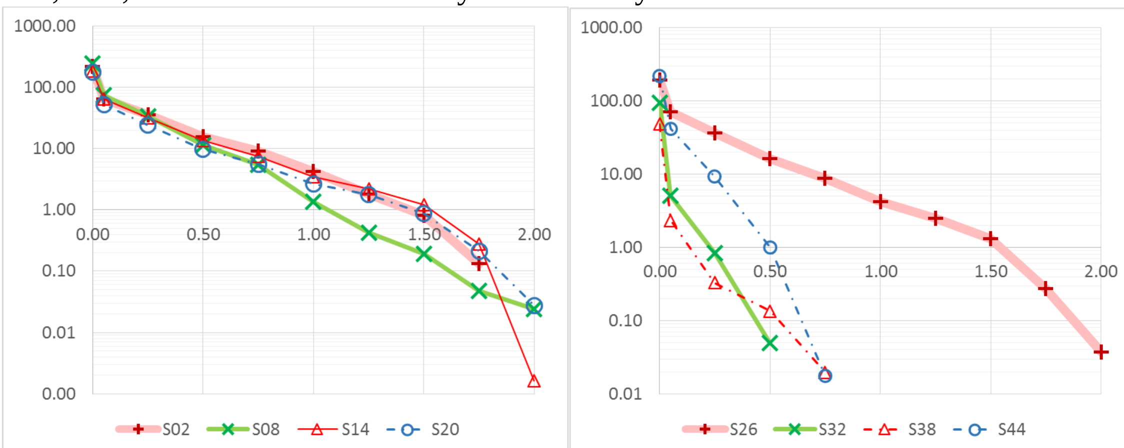

Figure 4. Percentage of flooded urban growth (new built up) vs. flood depth for trend population growth scenarios[2].

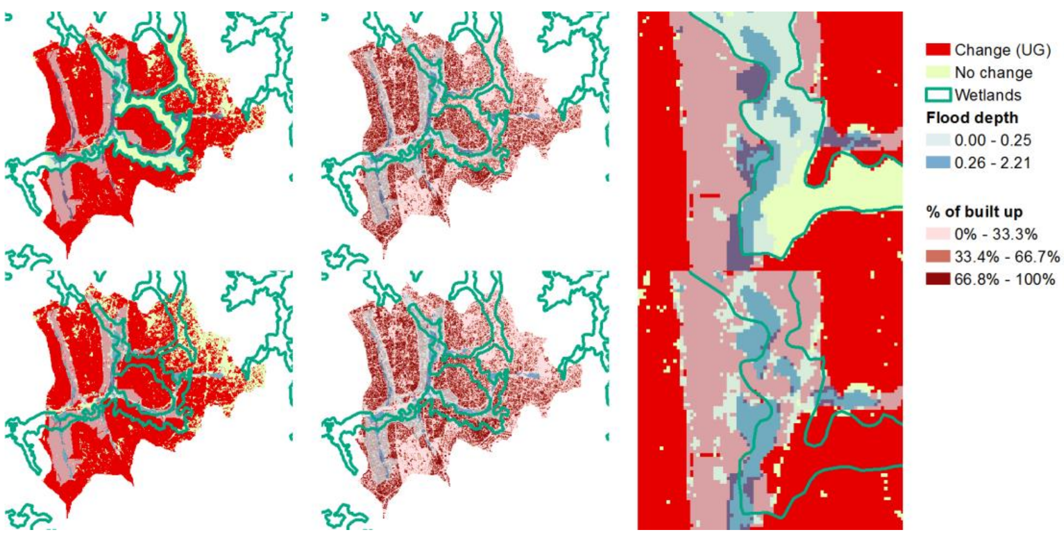

Figure 5. Trend (wetland) vs. trend (flood) scenarios for trend growth population.

For the calibration data (2004-2010), Pérez-Molina (2014) concluded wetland and flood in the base year caused similar effects. However, when 2010 is used as the base year and since saturation is nearly reached by 2020 for trend or high population growth, the consequences of these factors diverge when simulating into the future (see figure 5). The crucial fact is, there is not enough free space outside of the wetland areas to accommodate all expected urban development, leading to the restriction posed by this factor to loose effectiveness into the future. As a corollary for future work, it is important

[2] S02: Trend (wetland) | S08: CA | S14: Random | S20: Upstream | S26: Downstream | S32: Elevation | S38: Flood | S44: Trend (flood)

to determine the extent to which people are avoiding all wetlands vs specifically the part of the wetlands suffering from recurrent flooding.

	(A)	(B)	(C)
HYDROLOGICAL OUTCOMES			
Total flooded area (ha)	216.2	178.6	264.9
Peak discharge (m^3/s)	58.4	53.2	66.1
Total discharge (m^3)	815.3	545.8	1347.9
EXPOSURE OF URBAN GROWTH (NEW BUILT UP AREA)			
Total UG area flooded (ha)	219.91	210.26	254.11
UG area flooded +25cm (ha)	35.74	24.32	50.13
Total urban growth (ha)	422.8	422.8	422.8

Table 1. Hydrological and exposure measures for auxiliary scenarios: spatial trend (wetland) with variations on the vegetation to off road bare soil ratio[3]

Two additional scenarios were developed: for spatial trend (wetland) conditions and trend population growth, the sum of vegetation and off road bare soil for the 2020 simulated pattern was distributed following three rules: the original model assumption of proportionality with the base year (A), an assumption that all of this land is vegetation (B), and that all of it is bare soil (C). The differences, both in hydrological outcomes and exposure (reported in table 1) are striking, particularly for absence of vegetation. Even factors such as peak discharge show differences. Since vegetation and bare soil are linked to different forms of urban development (e.g. high income areas likely have more vegetated gardens, informal development results in trampling of the ground leading to more bare soil), it is not sufficient to model built up as an aggregate category and rules linking urban development to its neighbourhood context should be examined.

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[3] (A) vegetation and off road bare soil proportional to 2010, (B) off road bare soil set to 0% (all area covered by vegetation) and (C) vegetation set to 0% (all area assumed bare soil).