Evaluation Of A Self-Modifying Cellular Automata In Modelling Urban Growth In Nyeri (Kenya)

Kenneth Mubea, Gunter Menz

Abstract: Urban growth modelling cellular automata has blossomed due to the advancement in geographic information systems (GIS), remote sensing and computer technology. Among such urban growth models, our urban growth model (UGM), was modified from SLEUTH (**S**lope **L**and-use **T**ransport **H**ill-shade) model. UGM has been integrated in the XULU modeling frame-work (e**X**tendable **U**nified **L**and **U**se Modelling Platform). In this research we evaluated a modified UGM whose transition rules were modified. In order to arrive at urban growth modelling, we used multi-temporal Landsat satellite image sets for 1987 and 2010 to map urban land-use in Nyeri. We compared our results with a normal UGM simulation. Thus, we arrived at two urban growth simulations for Nyeri in order to get a better glimpse of land-use system dynamics. Both models were calibrated and urban growth simulated until the year 2030 when Kenya plans to attain Vision 2030. Observed land-use changes in urban areas were compared to the results of both UGM models for the year 2010. The results indicate that the two models resulted in urban growth in different directions and magnitudes. This approach is useful to planners as it gives the scenarios of using different transition rules of a cellular automata model in urban growth modelling.

Keywords: GIS, Urban Growth Model, Cellular automata, XULU, Simulation

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1 INTRODUCTION

Models based on cellular automata (CA) have been applied intensively in urban growth modelling [1].CAs are dynamical systems in which space and time are discrete and consists of an array of cells, each of which can be in one of a finite number of possible states, updated synchronously in discrete time steps, according to a local, identical interaction rule [2].Tobler [3] was the first pioneer who explored urban CA simulation and came up with a geographic model. The model was dynamic with several land-uses namely residential, commercial, industrial, public and agriculture, as cell states and enforced neighborhood rules in the model. Wolfram [4] did a systematic research on CA and their relationships with dynamic systems, and came up with classes of CA behavior. White and Engelen developed a constrained CA and this was a big step into urban modelling using CA [5]. They integrated the CA models in 1960s and Tobler's geographic model [3]. Models based on CA have evolved over the last decades in simulating urban development growth and patterns including SLEUTH [6]. SLEUTH is an acronym for Slope, Land-cover, Exclusion, Urban, Transportation and Hill shade. SLEUTH explores complexities of urban cells and incorporates biophysical factors namely: urban, road, transportation, slope and exclusion layer. The development of the GIS as well as the integration of a GIS and transportation with urban modelling has facilitated urban modelling with rich data sources and new techniques [7].

Our Urban growth model (UGM) was modified from SLEUTH and applied for the German federal state of North-Rhine Westphalia [8]. Simulation of urban land-use change in North Rhine- Westphalia (Germany) with the Java-based modelling plat- form XULU. UGM was later applied in two cities in Kenya, namely; Nakuru [9] and Nairobi [10]. UGM runs in the user friendly modeling frame-work XULU (eXtendable Unified Land Use Modelling Platform) which was developed by Schmitz, Bode, Thamm, & Cremers [11]. XULU takes over the most important functions concerning model control and visualization. Cities in Africa have experienced high growth rates due to high rural to urban migration [12]. Thus this presents a good case to apply our UGM in Nyeri. In this study, we evaluated a self-modifying UGM for Nyeri based on XULU modelling platform. Urban land-use data for Nyeri was derived from annual Landsat image data acquired in 1987 and 2010. This was for the first time a self-modifying UGM has been applied in Kenya. We came up two models, our normal UGM and a modified UGM which were calibrated and validated in XULU using 2010 as the reference year. We compared the two models based on the simulated urban growth and model coefficient values. The models were used to predict future urban land-use development in the year 2030. This offers a worthwhile approach for the study of future urban land-use trends in Nyeri as Kenya plans to achieve Vision 2030, the nation's ambitious economic and social development program [13]

2 THE STUDY AREA

Nyeri municipality lies between latitudes 0° 21′ and 0° 29′ South and longitude 36° 52′ and 36° 57′ East in Kenya. The city covers an area of 136 km² and lies at an average altitude of 1,750 meters above sea level (Figure 1). Nyeri is located about 150 kilometers north of Kenya's capital Nairobi, in the country's densely populated and fertile Central Highlands, lying between the eastern base of the Aberdare Range, which forms part of the eastern end of the Great Rift Valley, and the western slopes of Mount Kenya. Within its administrative borders the city includes urban, agriculture, and rangeland land-uses as well as open/transitional areas, and remnants of evergreen tropical forests. The population was 98,908 in Kenya's census of 1999 (Republic of Kenya, 2000) and 125,357 in 2009 (Republic of Kenya, 2010).

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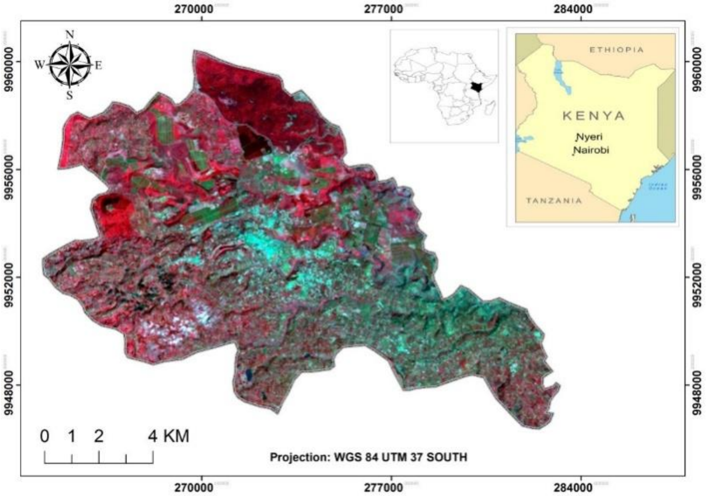


Figure 1: *Administrative boundary of Nyeri municipality (Source: False color composite using bands 4, 3, 2, Landsat 2010)*

3 MODELLING NYERI'S URBAN GROWTH

Our approach to urban growth modelling of Nyeri utilized information derived from multi-temporal Landsat satellite data in combination with additional datasets of slope, roads and an exclusion layer. Figure 2 illustrates the data processing flow applied for urban growth modelling using our normal UGM and our modified UGM. Schmitz et al. [11] developed XULU as a modelling framework that enables model integration and implementation using requisite functions of data storage, input/output methods, model runs, editing and visualization. XULU was initialed applied in Benin inorder to explore scenarios of future land-uses in a watershed based on specific boundary conditions [14]

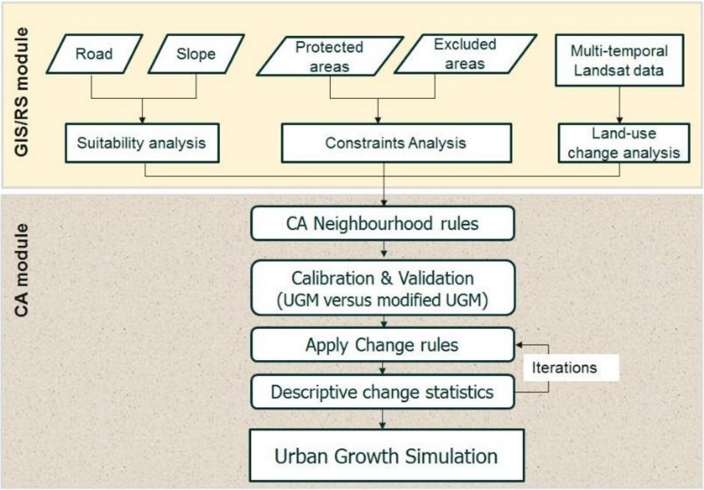
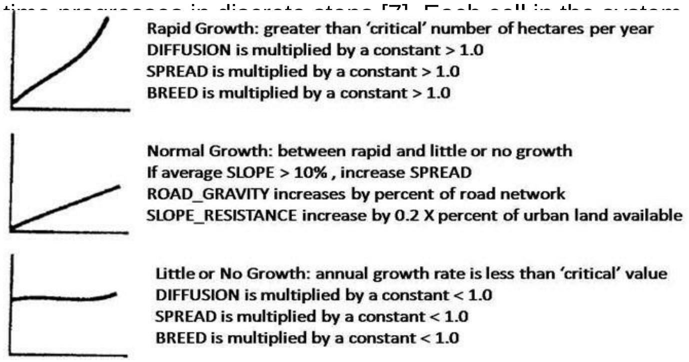


Figure 2: *Flowchart for urban growth modelling*

UGM has been implemented in the XULU modelling platform as a modification of the SLEUTH approach [8], [9]. UGM requires four spatial input parameters: urban land-use, transportation, slope and exclusion. The exclusion layer identifies those areas within the study site that cannot be changed (e.g. water bodies or protected areas) or areas which, if not excluded, are to a certain degree resistant to urbanization. The transportation layer represents the road network in a research area. UGM only needs a map for the starting year of the calibration phase and a reference map at the end year. The simulated urban area of the end year is compared to the reference map using a Multiple Resolution Validation (MRV) procedure as described in Pontius, Jr. et al. [15]. UGM calibration involves a "brute-force" method which is used to determine five calibration parameters. These parameters control the transition rules that are implemented in the model and include: *Dispersion, Breed, Spread, Slope Resistance,* and *Road Gravity*. *Dispersion* controls the number of image pixels that are randomly selected for possible urbanization and determines the extent of their outward distribution. *Breed* refers to the probability that a newly generated settlement initiates its own growth. *Spread* controls the extent to which existing settlements radiate. *Slope resistance* characterizes the likelihood of growth on steep slopes. *Road gravity* influences the creation of new centers along roads. Urban growth can be classified in UGM as: 1) spontaneous new growth; 2) new urban center establishment or spreading urban center growth; 3) edge growth; and, 4) road influenced growth [16]. UGM simulates urban growth based on Cellular Automata (CA). CA is a discrete dynamic system in which space is divided into regular spatial cells, and time progresses in discrete steps [7]. Each cell in the system is


Rapid Growth: greater than 'critical' number of hectares per year
DIFFUSION is multiplied by a constant > 1.0
SPREAD is multiplied by a constant > 1.0
BREED is multiplied by a constant > 1.0

Normal Growth: between rapid and little or no growth
If average SLOPE > 10% , increase SPREAD
ROAD_GRAVITY increases by percent of road network
SLOPE_RESISTANCE increase by 0.2 X percent of urban land available

Little or No Growth: annual growth rate is less than 'critical' value
DIFFUSION is multiplied by a constant < 1.0
SPREAD is multiplied by a constant < 1.0
BREED is multiplied by a constant < 1.0

Figure 3 using a set of additional rules.


Rapid Growth: greater than 'critical' number of hectares per year
DIFFUSION is multiplied by a constant > 1.0
SPREAD is multiplied by a constant > 1.0
BREED is multiplied by a constant > 1.0

Normal Growth: between rapid and little or no growth
If average SLOPE > 10% , increase SPREAD
ROAD_GRAVITY increases by percent of road network
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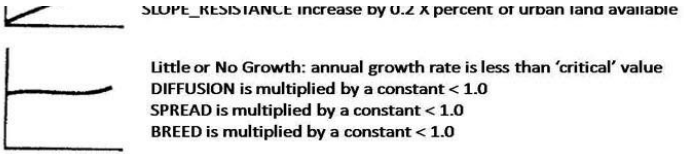
Little or No Growth: annual growth rate is less than 'critical' value
DIFFUSION is multiplied by a constant < 1.0
SPREAD is multiplied by a constant < 1.0
BREED is multiplied by a constant < 1.0

Figure 3: *Self-modification adjustments to the control parameters (Source: Clarke, Hoppen, & Gaydos [6])*


SLOPE_RESISTANCE increase by 0.2 X percent of urban land available

Little or No Growth: annual growth rate is less than 'critical' value
DIFFUSION is multiplied by a constant < 1.0
SPREAD is multiplied by a constant < 1.0
BREED is multiplied by a constant < 1.0

Figure 3 we can see three urban growth scenarios namely: rapid growth, normal growth and little or normal growth. In the rapid growth scenario urban growth exceeds a critical value and thus the model coefficients *diffusion*, *spread*, and *breed* are increased by a multiplier greater than one. However, the critcal value is decreased so to avert uncontrolled exponential growth. In the normal growth scenario urban growth falls below the critical value and thus the model coefficients *diffusion*, *spread*, and *breed* are decreased by a multiplier less than one. This leads to decrease in urban growth which is almost linear or equilibrium. However, the value of road can be increased as roads are expanded and thus simulates road influenced urban growth. Nevertheless, the slope value can be increased to cater for urban growth onto steeper slopes when all suitable land is scarce for expansion. Thus the self modifying UGM presents a dynamic system for urban growth simulation. Initially, our modified UGM (denoted as UGM 2) had the following additional rules: road sensitivity = 0.01, slope sensitivity = 0.1, critical low value = 0.97, critical high = 1.03, boom = 1.1, bust = 0.9. Boom represents the value in which model coefficients are increased. Bust represents the value in which model coefficients are decreased. In this research we performed model calibration of two models, namely our normal UGM (denoted as UGM 1) and a modified UGM (denoted as UGM 2). We compared the two models based on the simulated urban growth and model coefficient values.

4. ANALYSIS

4.1 Data

The land-use data for our UGM was derived from Landsat satellite imagery for 1987 and 2010. Nyeri is entirely enclosed within Landsat TM path 168, row 60. The Landsat data sets used included TM, and ETM+ images in WGS-84 Universal Transverse Mercator (UTM), 37-South projection. Reference data were developed for each of the separate years and then randomly partitioned for classifier training and accuracy assessment. Ground truth data included a topographic map which was used as locational reference data for the 1986 while GPS points served as reference data for the 2010 classification. Road network data for Nyeri was obtained from Survey of Kenya and included all of the roads within the city. An exclusion layer was obtained from Survey of Kenya and included government buildings and property as well as other land areas designated as reserved.

4.2 Land-use Change Analysis

TABLE 1
Land-use summary for Nyeri

Year	**1987**		**2010**	
Land-use class	**Area (Km^2)**	**%**	**Area (Km^2)**	**%**
Urban	1.41	1.03	6.77	4.97
Forest	20.10	14.75	20.14	14.78
Water	3.37	2.47	2.40	1.76
Agriculture	77.76	57.05	83.33	61.14
Open/transition areas	33.66	24.70	23.66	17.36
Total	**136**	100	**136**	100

TABLE 2
Error estimates for Nyeri in 1987

	Reference Data						
Classified Data	Urban	Forest	Water	Agriculture	Open/Transitional areas	Total	User's accuracy (%)
Urban	110	0	0	0	0	110	100.00
Forest	0	325	23	1	0	349	93.12
Water	0	6	86	0	0	92	93.48
Agriculture	0	1	2	212	4	219	96.80
Open/Transitional areas	13	0	0	0	135	148	91.22
Total	123	332	111	213	139		
Producer's accuracy (%)	89.43	97.89	77.48	99.53	97.12		
Overall accuracy (%)	94.55						
Kappa Coefficient	0.9278						

TABLE 3
Error estimates for Nyeri in 2010

	Reference Data						User's accuracy (%)
Classified Data	Urban	Forest	Water	Agriculture	Open/Transitional areas	Total	
Urban	188	0	0	1	0	189	99.47
Forest	0	383	1	12	0	396	96.72
Water	0	0	79	0	0	79	100.00
Agriculture	14	1	3	163	21	202	80.69
Open/Transitional areas	4	0	0	12	87	103	84.47
Total	206	384	83	188	108	969	
Producer's accuracy (%)	91.26	99.74	95.18	86.70	80.56		
Overall accuracy (%)	92.88%						
Kappa Coefficient	0.9034						

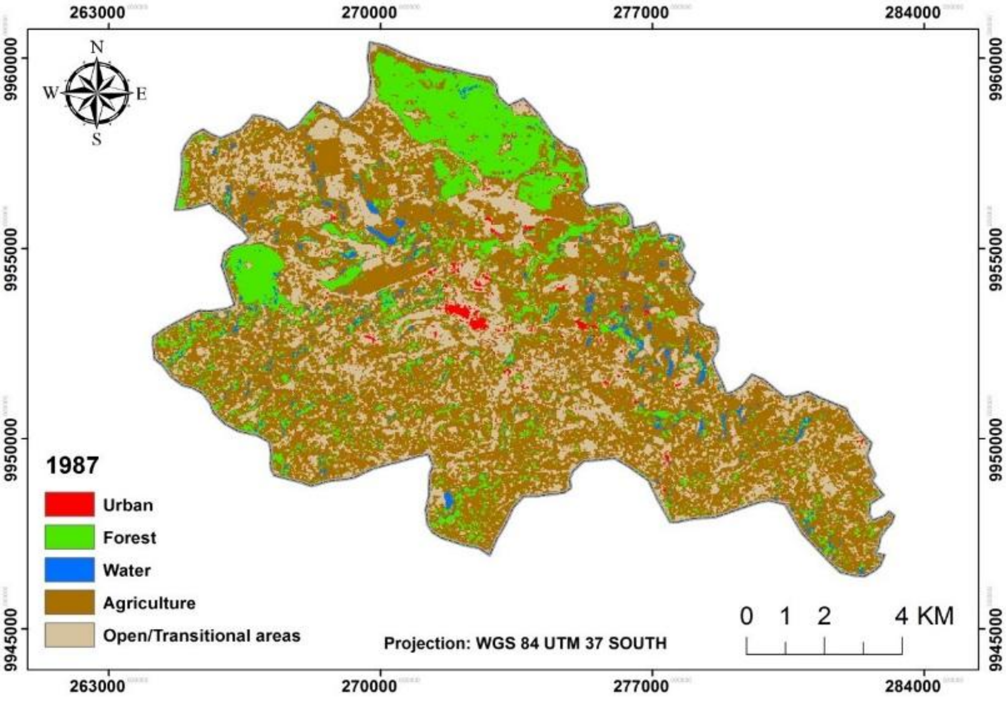


Figure 4: *Land-use map of Nyeri derived from Landsat TM 1987*

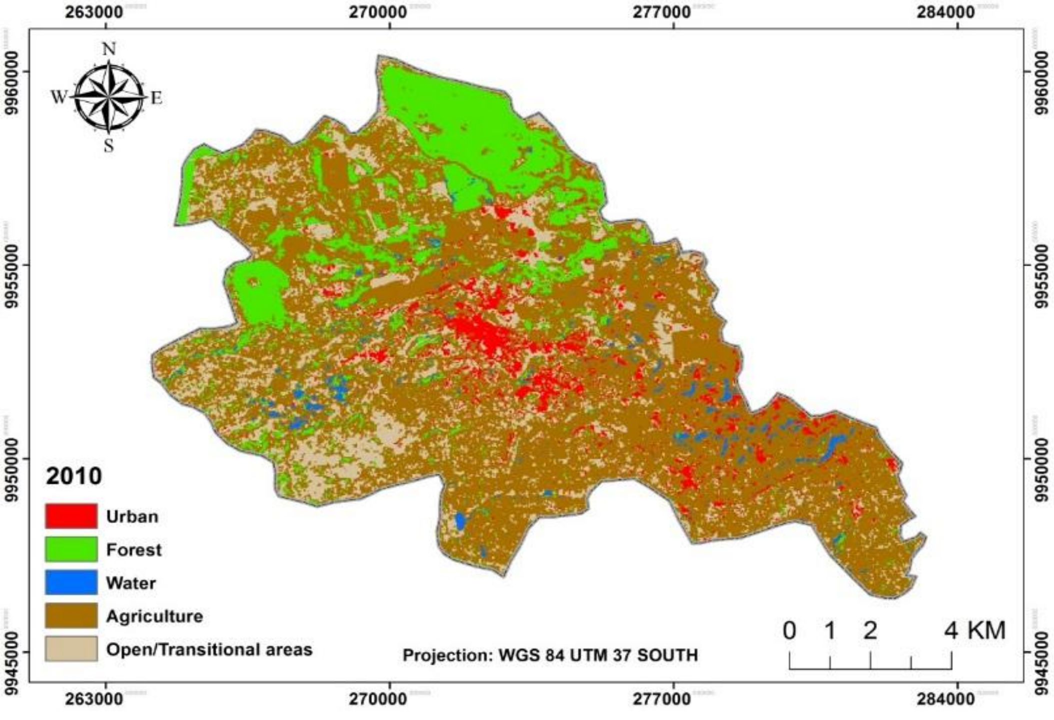


***Figure 5:** Land-use map of Nyeri derived from Landsat ETM + 2010*

Modeling of Nyeri utilized as inputs urban extents extracted from classified land-use maps for 1987 and 2010. Other layers used included slope, areas excluded from development and the Nyeri road network. Calibration was performed using the 2010 land-use map as a reference grid. The best model parameters for UGM were also evaluated based on the weighted average calculated with the MRV using 2010 land-use as a reference grid. We denoted our normal UGM as UGM 1 and our modified UGM as UGM 2.

Figure *6* shows the best model coefficients obtained following successful calibration of UGM 1 and UGM 2. These coefficient values are for UGM 1: slope = 1, spread = 3, dispersion = 1, breed = 89, road = 44, and UGM 2: slope = 5, spread = 5, dispersion = 1, breed = 90, road = 10. These coefficients were obtained at a weighted value of 0.961350 and 0.961625 respectively for UGM 1 and UGM 2.

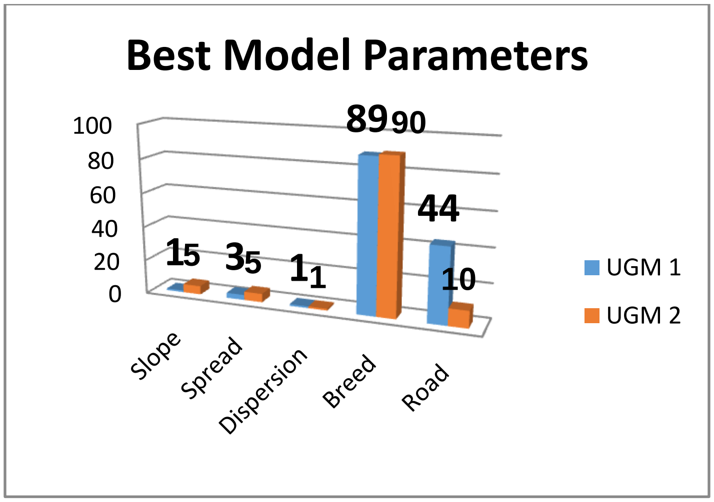


***Figure 6:** Best Model Parameters for Nyeri UGM*

Hence the calibration of UGM 1 and UGM 2 resulted in an agreement of approximately 96 % for the built-up / non-built-up categories between the 2010 reference map and the 2010 map fitted with the model. Thus in order for an urban growth model to be of use to policy makers and urban planners, simulation of urban growth must be performed after calibration. We used both our UGM 1 and UGM 2 to predict Nyeri land-use for the year 2030. We started by using 2010 land-use as reference data during the UGM calibration, and proceeded under the assumption that current urban planning policies would remain constant. Urban growth (built-up areas) was modelled using the UGM 1 and UGM 2 best model parameters in

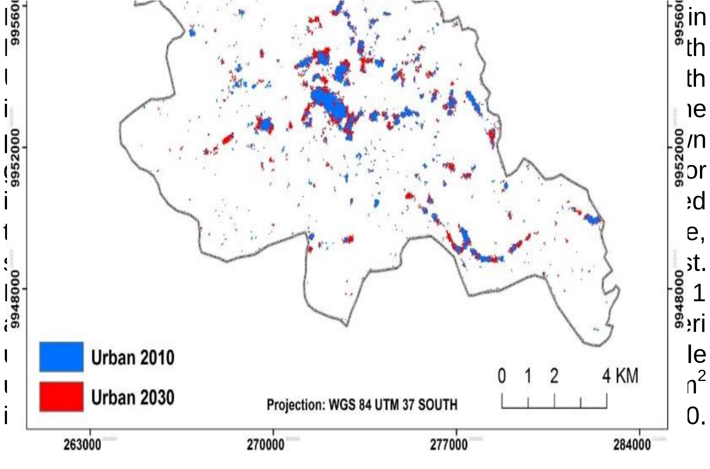


Figure 7, we can see that UGM 1 yielded moderate urban growth was over the research areas compared to the explosive growth using UGM 1 in Figure 8.

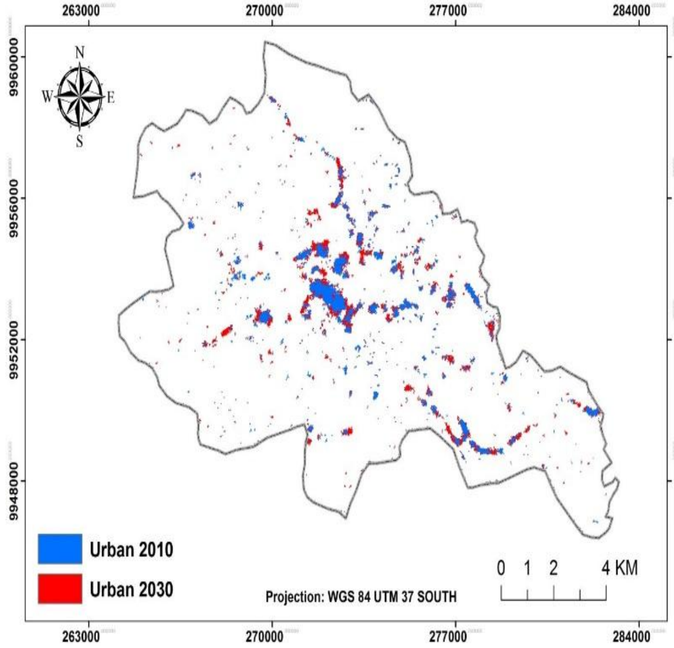


Figure 7: *Simulated urban growth for Nyeri in 2010 – 2030 using UGM 1*

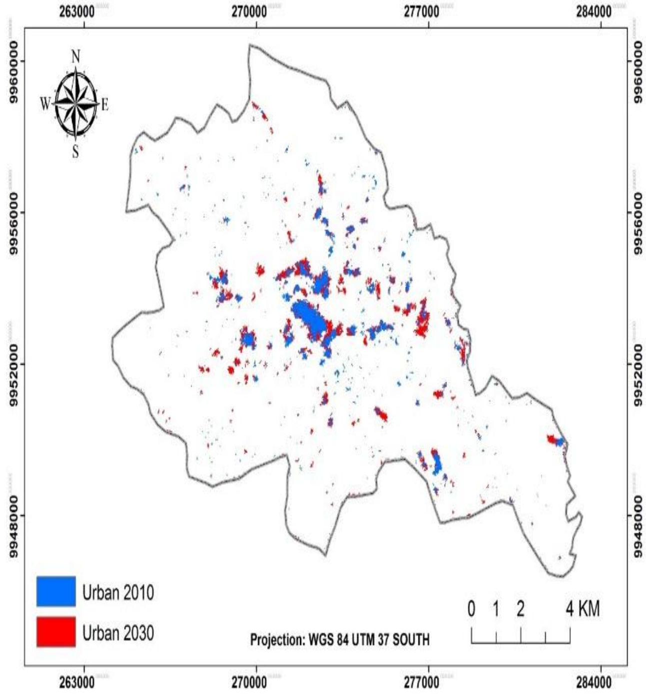


Figure 8: *Simulated urban growth for Nyeri in 2010 – 2030 using UGM 2*

Since breed was the major factor influencing urban growth in Nyeri, we can conclude that urban growth in Nyeri is random. This indicates that urban growth occurs in a haphazard manner without regard for proper land-use policies. Possibilities for such urban growth can be viewed as new built-up areas replace agricultural areas due to failure of some cash crops and raising demand for housing in the city. There has been high rural urban migration attributed to search for employment, education, and social amenities. There has been a growth in education facilities with new universities opening branches in Nyeri such as University of Nairobi, Kenyatta University, Kenya Methodist University (KEMU), Moi University and Dedan Kimathi University of Technology. These results can help regional and urban planners to understand the implications of using different urban growth models. This can allow planners to simulate differing future urban growth scenarios using different models.

6 CONCLUSION

We modelled urban growth in Nyeri using two UGM models. UGM uses cellular automata in urban growth modelling and simulation. Calibration and validation of both models ended up in similar model parameter values. However, each model simulated urban growth in different directions and magnitude. By the year 2030, the nation of Kenya plans to achieve Vision 2030, an ambitious economic and social development program. Effective urban and regional planning is a critical component of the Vision 2030 program. By simulating various urban growth scenarios, policy makers can analyze the effects of establishing new housing and road infrastructure in undeveloped areas rather than in existing settlements. The UGM can provide an accurate and useful guide to the growth of Nyeri, as well as identify and illustrate areas in which expansion can best take place. The UGM can even serve as a master planning tool. Cellular automata modelling is an effective approach for regional modelling of African cities such as Nyeri, and can be adapted to provide effective opportunities to study other African cities using UGM.

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