Calibration and Validation of a Proposed Informal Settlement Growth Model

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SUMMARY

Rapid growth of informal settlements in developing countries constitutes one of the most intriguing forms of urbanization. However, factors and theories underpinning this rapid and prevalent dynamic of informal settlements are often restricted to the descriptive phase. Limited studies have been undertaken to effectively demonstrate how these factors and theories can be incorporated into a framework to simulate and model the dynamic expansion of informal settlements. This paper presents how Geographic Information Systems and Cellular Automata are integrated to propose an Informal Settlement Growth Model (ISGM). The proposed ISGM is a transparent and flexible program written is Visual Basic and which uses Idrisi™ for output display. Specifically, the model framework is discussed, the results of different calibrations of the proposed model on the case study (Yaoundé, Cameroon) are presented, and the model performance is evaluated. The application of the proposed ISGM on Yaoundé indicates that the model has the potential to improve the urban planning and decision-making processes in developing countries cities.

KEYWORDS: *Informal settlement, calibration, dynamic modelling, decision support, developing countries*

INTRODUCTION

Current urbanisation in developing countries (DCs) is mostly characterised by the proliferation of slums and informal settlements. Unfortunately, existing strategies and policies have done little to mitigate their expansion. In the meantime, the discourse on IS dynamics has been dominated by the descriptive approach. However, recent progress in the study of complex urban forms by techniques such as Geographic Information Systems (GIS) and cellular automata (CA) gives a new opportunity to investigate and gain better insight into the behaviour of IS patterns. This paper argues that a dynamic model and simulation tool could be useful for urban planning, and IS policy formulation in cities in developing countries. Firstly, the paper briefly reviews contributing factors to the emergence of IS growth mechanisms, and then the theories that sustain their dynamics. Secondly, the calibration method used in the proposed Informal Settlement Growth Model (ISGM) is presented. Thirdly, the paper demonstrates how the calibration of the ISGM on Yaoundé, Cameroon, predicts IS patterns. Finally, four main criteria (sensitivity, reliability, validity and usability) are used to evaluate the proposed ISGM performance.

INFORMAL SETTLEMENTS: THEORIES AND FACTORS OF GROWTH

The UN-Habitat (2003) reports that 78.2 % of the urban population within developing cities currently live in informal settlements (IS). Moreover, IS are growing at least twice the rate of planned settlements (Choguill, 1996). These IS are mainly characterised by a chronic lack of services, low standard housing, illegal dwelling, insecure tenure, overcrowding, high density, poverty and exclusion. Various factors and theories have been suggested as to why IS occur in both cities developed countries and developing countries.

Informal settlements theories

In developed countries cities, three main theories are frequently discussed. Firstly, the *Chicago School* in the 1930s regarded IS as residential differentiation resulting from the different income levels of different ethnic groups who competed for 'valuable' or desirable urban land (Burgess, 1925 as cited by UN-Habitat, 2003). Secondly, *Alonso's neo-liberal theory* of *slums* suggested that IS are a response to the housing needs of urban dwellers who cannot afford a formal dwelling due to discriminatory urban regulations and public spending (Smith, 1980). Finally, *post-modern theory* of urban landscape or *factorial ecology,* perceive IS as the product of skills segregation within urban spaces - urban dwellers settle according to their profession and social status (Flood, 2000).

In developing countries, however, four major theories of IS are commonly referred to: land management; colonial legacy; inadequate economy; demand and supply disequilibrium. Specifically, one school of thought believes that inefficiency of urban authorities, along with poor land management practices and inadequate urban planning schemes, cause the *informalisation* of urban areas (Fekade, 2000). The second theory links the expansion of IS to political and historical factors, especially colonialism, postcolonial practices and civil and political instabilities (Debusmann & Arnold, 1996; Global Urban Observatory, 2003). A third view suggests that the introduction of a new economic system has played an important role in the development of IS. This theory argues that the introduction of urban trade, income and class differences is spatially translated into residential discrimination and social exclusion (Huchzermeyer, 2002). A fourth theory explains the emergence and growth of IS by the disequilibrium between the demand and supply of urban commodities (land, services and infrastructures). This viewpoint explores the sustainability and persistence of IS and postulates that while effort is deployed to improve slums, new IS is mushrooming in other parts of the city (Jacopsen *et al.*, 2002).

In summary, the plethora of explanations suggests that there is no single theory that can fully explain the emergence and the expansion of IS. However, within developing cities it is usually argued that IS are the result of combination of factors such as poor management, especially failed urban policies, poor governance, corruption, inappropriate regulations, dysfunctional land markets, social insecurity, poor economic performance and lack of political will.

Factors of emergence and growth of IS

This section discusses factors that explain who lives in IS and why. Physical characteristics of IS and socio economic influents are also discussed. Research shows that IS flourishes marginal or less valuable urban land such as riverbanks, steep slopes, dumping grounds, abandoned or unexploited plots, along transportation networks, near industrial areas and market places, and in low lying areas or wetlands (Blight & Mbande, 1998). Other work suggests that IS seem to be driven, at least in part, by spiritual or religious factors (Berg-Schlosser & Kersting, 2003). Research also indicates that IS dweller have similar socio-cultural backgrounds (Malpezzi & Sa-Adu, 1996). Moreover, there is now sufficient evidence to argue that IS dwellers tend to have previously lived in informal settlement (probably nearby) or they are planning to move to a future informal settlement (UN-Habitat, 2003). This suggests that established IS duplicate themselves and serve as a stepping-stone for the emergence of future settlements on the nearest available land. Another important factor is the close correlation between the informal economy and IS (Kengne, 2000). This is because knowledge, skills and experience are not pre-requisites for accessing the job market, as it is the case within the formal or public sectors (Happe & Sperberg, 2003). Migrants to the urban areas have long fuelled the informal economic sector (often represented by popular market places), which employs more than 70% of the labour force, and contributes an average of 40% of the GDP of developing cities (Kengne, 2000). A final factor that helps to explain the proliferation of IS is the rigidity of urban planning regulations associated with poor governance that lead to a severe shortage of land, squatting, and infringements of building regulations (Fekade 2000). The end result of all these factors is rapid, unstructured and unplanned expansion, conflicting land tenure and property rights, poor-quality dwellings, decay of the physical environment, severe social problems, and low socio-economic status for IS occupants.

INFORMAL SETTLEMENTS GROWTH MODEL FRAMEWORK

This section discusses how the theories invoked above, along with the key factors behind IS emergence and growth, are used to develop a dynamic Informal Settlement Growth Model (ISGM).

Conceptual framework of the ISGM

The ISGM is inspired by existing urban dynamics models, based upon the integration of GIS and CA, such as those developed by Clarke and Gaydos (1998), Batty *et al*. (1999), and Yeh and Xie (2001). Following similar principles, the ISGM loosely couples GIS and CA technologies to predict the emergence and growth of IS patterns. That is, the ISGM is conceived on CA principles whereby pixels, or cell-based grid squares change one by one. Their multiple states are synchronously updated in discrete time steps according to generic rules. In other words, the previous states of neighbouring cells determine the state of each cell at any given iteration. The ISGM uses various forms of Moore extended neighbourhood, and it accommodates user-defined rules. It is worth noting that the cellular automata developed within the ISGM is extremely flexible due to its ability to incorporate functions such as thresholds, constraints, probability factors, attraction variables and edge shaping factors. These general assumptions of IS growth can be fine-tuned to suit the local conditions whilst still maintaining the general conditions pertaining to the emergence and growth of IS. Such assumptions are drawn from the theories and factors behind IS emergence and growth (as discussed above) to design the proposed model.

Technical specifications of the ISGM

The technical specifications of the ISGM are as follows: (a) the model's space is made up of a two-dimensional matrix of square, equal size cells; (b) it accommodates an unlimited amount of input data with the same format and properties; (c) each layer consists of at least two states (e.g., road and non-road); (d) each layer is in raster format and each cell has a unique identification number (ID) because changes operates at a cell level; (e) changes operates only on vacant land on the defined matrix; (f) cells change according to predefined and homogeneous rules; (g) changes operates on an array of 4 x 4 extendable Moore neighbourhood; (i) each layer has a unique identification number (ID) (e.g., water: 20, vacant land: 1). This allows the macro program to read and convert the value of each land use category into *ascii* format, as well as set up the spatial neighbourhood filters in a logical way; and (j) the selection of any one cell is random, but any cell across the complete grid can be chosen.

The essence of the ISGM is its defining of CA-like conditions under which any matrix cell should behave at each time step. It can accommodate an unlimited number of rules, but here the following were declared to express the general conditions under which IS are thought to emerge in the test city:

1. Existing, formal land use classes are not changing, and so IS resulting from the decaying of planned developments is beyond the scope of the ISGM. That is, all new IS occur on vacant land. However, using the same ISGM, Wyatt *et al.* (2002) demonstrate that it is quite possible for an ISGM to take into account the conversion of planned developments into IS.
2. No cell 'dies' after emerging. That is, it evolves and maintains its state. This condition suggests that an IS cell cannot return to it previous state or mutate to another land use type once it created.

This rule is in line with the spread and consolidation of IS patterns observed within cities where unplanned developments prevail.

3. If a cell's neighbourhood does not contain at least one IS cell, a new IS cell cannot emerge. This condition prevents IS emerging in an isolated area, and consolidates of IS patterns.
4. Any new IS cell is generated with a user-defined probability. The probability depends on two conditions: the stages of growth the model is in, and the properties of the surrounding cells (land uses). However, if a vacant cell is located on a high slope, then its probability of becoming an IS cell at the next iteration decreases (*bust* factor).
5. If a vacant cell is located close to (e.g., less than four extended neighbours away from) a road, river, market place, worship place or low slope cell, then its probability of becoming an IS cell increases by a user-defined value (*boost* factor). Moreover, if a vacant cell is close to both water and road, its probability of becoming an IS cell becomes even greater.

The probability of IS emerging on vacant land is either *boosted* or *inhibited* by the type of dominant cultural and ethnic group located within its neighbourhood. The model provides possibilities to fine-tune its rules in order to adapt to a specific condition and to improve its accuracy. Accordingly, the model underwent several instances of refinement and modification to increase its simulation capacity and test the validity of its underlying assumptions. This is because the ISGM is written in the *Excel*^{TM} macro language, from the same family as *Microsoft Visual Basic (VB)*. *Visual Basic macro* language was chosen because it is reasonably easy to learn, write and modify. Unlike other GIS programs that have specific languages, *VB macro* is a cross platform language that is appropriate for prototyping and which can be supported by almost any GIS environment. Hence in comparison to other CA models, the ISGM is *transparent* in the sense that one can access and modify its source commands, record new macros, manipulate the model's spreadsheet and so directly check its consistency. The Macro language code calls a GIS interface to display the results of the application, and for this application we have used the *Idrisi*^{TM} GIS because of its ability to preserve the properties of input and output files. Figure 1 shows the sequence of operation of the five main modules of the ISGM, which are setting up, calibration, looping, application of rules, and display.

Firstly, the user states the general condition of the macro and lists all of the files to be used for the calibration. Secondly, in the calibration module the user states the *base_year*, the *final_year*. This automatically generates the number of iterations (annual changes), the *nett_pixel_gain* (which is the amount of space to be converted into informal settlement) and the *annual_target* (which is a constant that divides the expected number of new IS cells by the iterations). The annual target can be mathematically expressed as:

$$\Delta_t(X,Y) = \left| N_{pixel}(Y,t) - N_{pixel}(X,t) \right| \quad (1)$$

where:

$\Delta_t(X,Y)$ = Net gain pixel of land use t from year Y to year X

$N_{pixel}(X, t)$ = Number of pixel characterizing a land use of type t for a year X

Figure 1 summarises a step-by-step procedure to successfully execute the program.

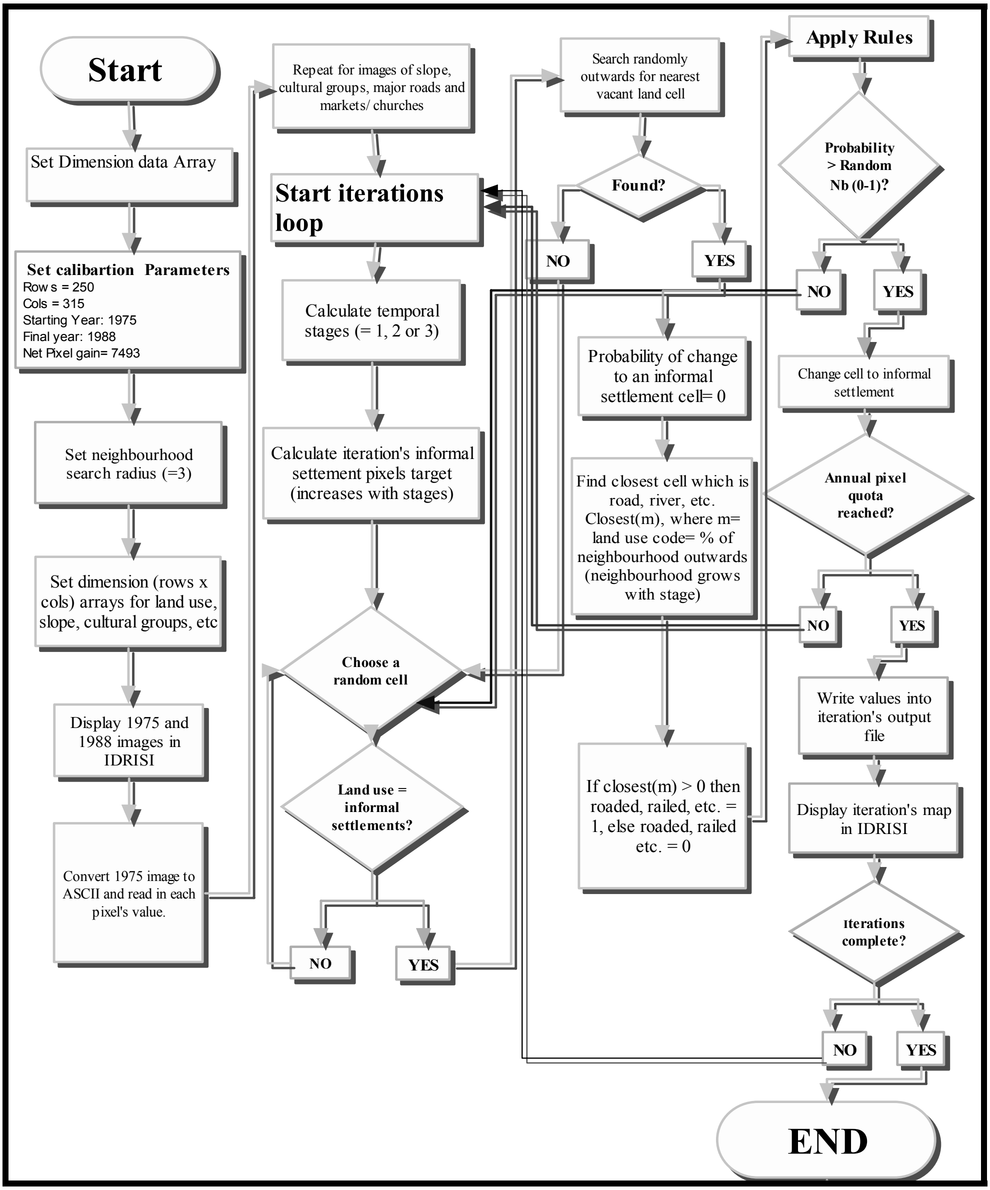


Figure 1. Sequence of operations and flowchart of Informal Settlement Growth Model execution

Thirdly, in the looping module five loops are automatically set: (1) the ***iterations loop*** checks the user-defined number of iterations at different temporal growth stages; (2) the ***annual change loop*** resets the changes to zero; (3) the ***random cell loop*** continuously checks the map to locate a random cell; (4) when a random cell is not found, the ***non-changing cell loop*** sends the operation back to the random cell loop; (5) otherwise, the macro proceeds to ***search for the cells*** at the edge (neighbourhood) of the existing IS cell. Fourthly, the transition rules module executes the conditions (using *If Statements*) and the probabilities (local and general) changes the vacant cell to an IS cell if all the conditions are satisfied, verifies if the quota (*annual_target*) has been reached and records the value into the output file. Finally, the display module sets the parameters for automatic display calibration results based upon the user-defined, GIS environment, image format, size, colour and palette.

CALIBRATION OF THE PROPOSED ISGM TO YAOUNDE

This section briefly introduces urban growth experienced in Yaoundé, Capital city of Cameroon in Central Africa, followed by the presentation of data preparation and use procedure.

An overview of Yaoundé urban informal settlements growth

Yaoundé is the second largest city (after Douala) and also the capital city of Cameroon in Central Africa (figure 2). It has been selected for testing the ISGM because of its rapid urban population growth and the extent of its unplanned development. The urban area of Yaoundé has grown by almost tenfold in less than five decades. With an urban area of about 1,500 ha in 1956, Yaoundé covered 5,300 ha in 1980 and about 14,000 ha in 2000 (Sietchiping, 2003). Studies show that 80% of settlements in Yaoundé are informal (against 30% in 1960s) and accommodate about 85% of city dwellers (Pettang *et al.*, 1995). Similarly, the informal market represents more than 80% of housing stock (Pettang, 1998) and Yaoundé last had a planning document in 1982 (Bopda, 2003).

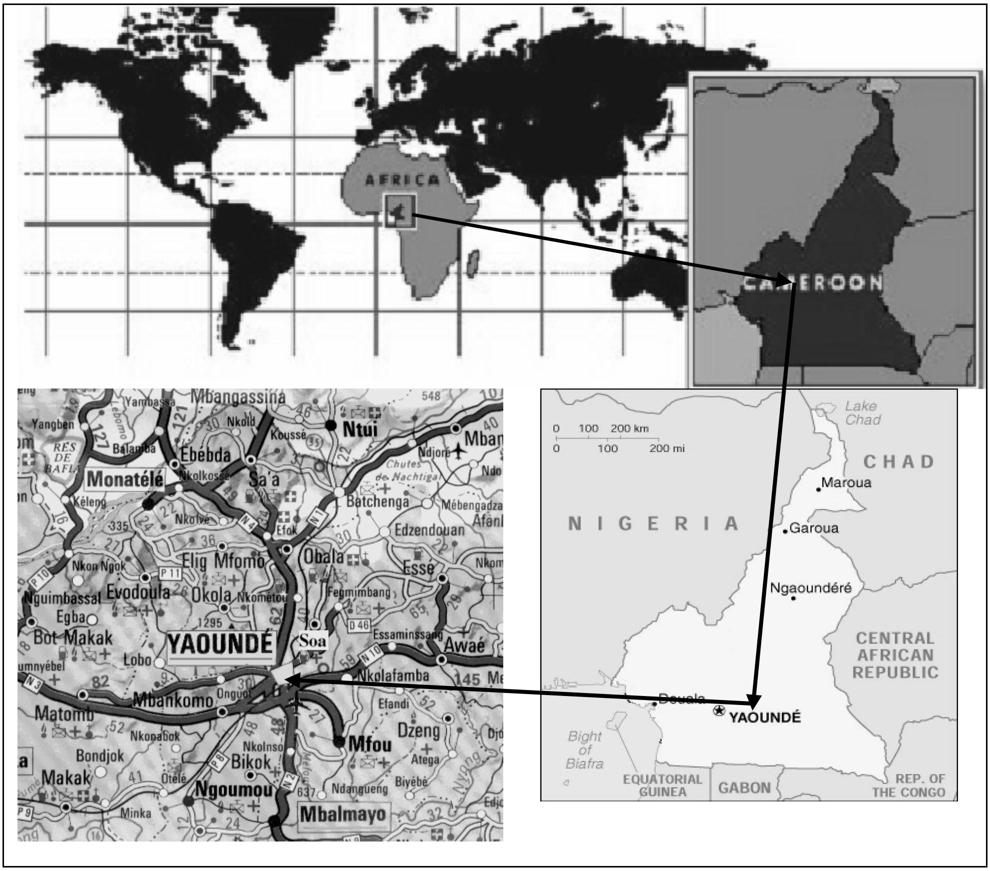
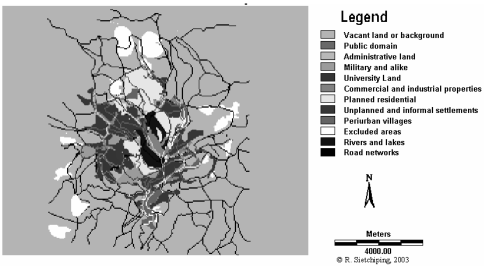


Figure 2: Location of the study area: Yaoundé, Cameroon in Central Africa

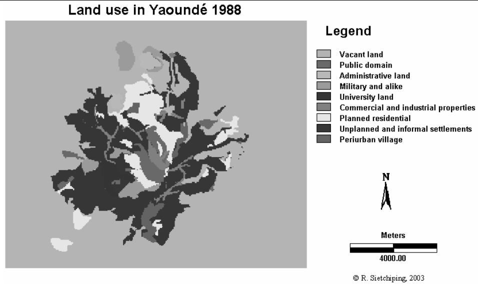
Source: http://www.map.freegk.com/cameroon/cameroon.php

Data preparation and use for the ISGM

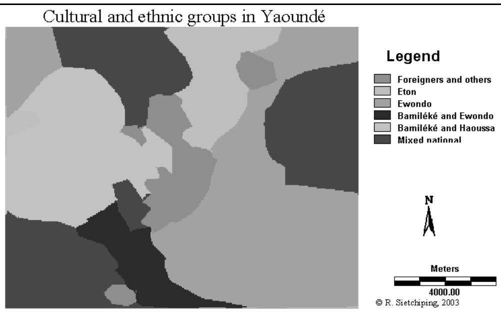
Various Geographic Information Systems (GIS) software (*ArcINFO*^{TM}, *ArcView*^{TM} and *Idrisi32*^{TM}) were used to prepare the data. Maps considered include: transportation network (railway, major roads, other roads and proposed ring road), land use categories (base and final years), river systems, worship places, market places, topography, and ethnic and cultural groups. Some of these layers are used individually and others are merged to improve the model performance. Figure 3 shows the final layers used in the calibration of ISGM on Yaoundé, Cameroon.



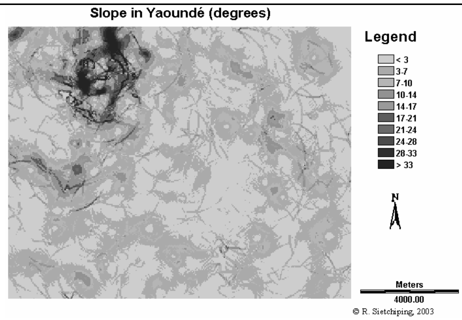
a. Base map used for the calibration where four layers are merged: land use (1975), roads, water and excluded area



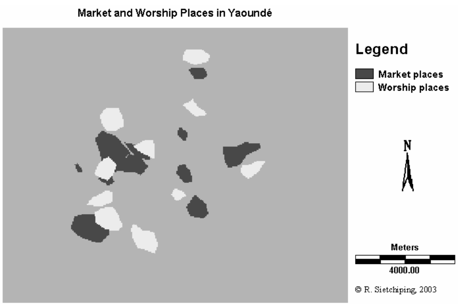
b. Final land use in Yaoundé (1988)



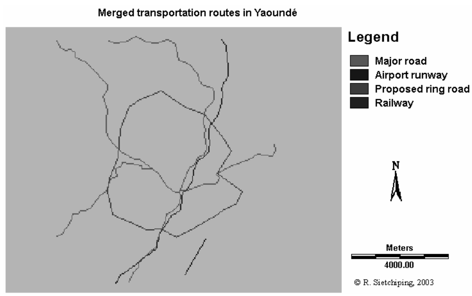
c. Six major cultural and ethnic groups in Yaoundé



d. Slope in Yaoundé (in degrees)



e. Markets and worship places in Yaoundé



f. Transportation map in Yaoundé, with four merged files: major road, airport ring road, proposed ring road and railway

Figure 3: Final maps layers used for the calibration of ISGM on Yaoundé, Cameroon

CALIBRATION RESULTS OF THE ISGM

This section describes some of the modifications introduced into the ISGM and the subsequent results, which indicate how the model is sensitive to different input parameters. Selected samples of calibration results based upon the IS growth criteria and theories are presented in figure 4 (for clarity and space, the map scale and legends for the simulated maps are purposely omitted).

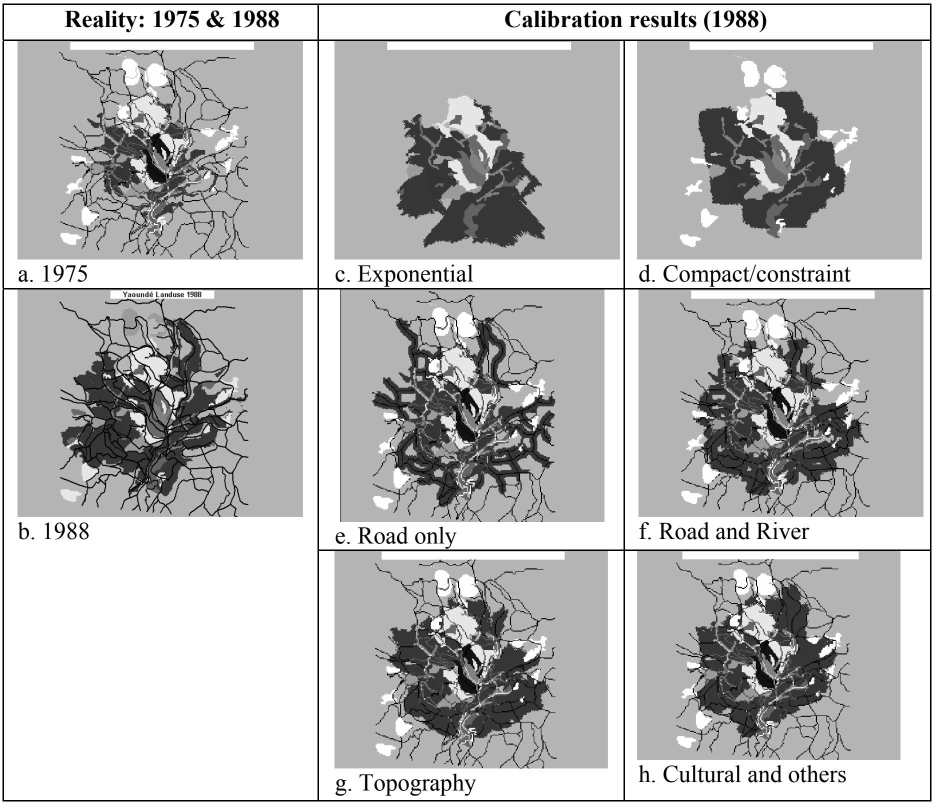


Figure 4. Sample of the calibration of ISGM in Yaoundé

Figure 4 presents six different calibration results that were obtained by changing different input parameters and by fine-tuning the ISGM. Each simulation result would be compared with the pattern in the base year (fig.4.a) and the actual configuration of IS in the target year (fig. 4.b). The exponential growth (fig. 4.c) tests the ISGM when it runs without any constraints. Informal settlement cells emerge at the proximity of existing IS cells with a probability of one. The result shows that this application does not capture the essence of IS growth mechanisms, especially the direction and spread of IS patterns. The next calibration (fig.4.d), however, applies some basic constraints to the model that generates a more compact form of IS pattern. This was achieved by adding the excluded areas and by increasing the probability of new IS cells to emerge in the neighbourhood of existing IS.

The ISGM is then modified to test the sensitivity of the model to road layers (fig. 4.e), with the probability of 0.8 for road and 0.2 for existing IS cells in the neighbourhood. After that, the linearity of the IS growth pattern is further improved by combining the road and river systems with the existing IS patterns (fig. 4.f), with their respective probability of 0.4, 0.3 and 0.3. However, there are still some 'pockets of vacant cells' simulation outputs (Figs. 4.e and 4.f). Slope factor is, therefore, added and major roads are differentiated from other roads along with their respective probabilities: major road (0.3), other road (0.1), gentle slope or lowland (0.2), existing IS cell (0.1), market and worship places (0.2) and river (0.1). This calibration generates the IS patterns shown in figure 4.g. It is worth mentioning that this version of the model also takes into consideration the location of market and worship places. Finally, figure 4.h shows the contribution of cultural and ethnic composition (along with other factors previously tested such as road, river, topography, markets and worship places) in the expansion and spatial distribution of IS patterns in Yaoundé. Compared to previous calibrations, this version defines two factors of proximity: one for all the criteria considered in the model (equation 2) except for river cell (equation 3) as follows:

$$m+ = \frac{(neigh(n)+1)-a}{neigh(n)} \qquad (2) \qquad m_{-} = \frac{(outside(n)+1)-b}{outside(n)} \quad (3)$$

where:

neigh(n) = total number of neighbors of *m* within the radius range of n pixels.

a = closest vacant pixel in the neighborhood

outside (n) = total number of neighbors – *neigh(n)*

b = total number of vacant land in a radius *n – a*

This redefinition is necessary to capture the essence of IS growth towards the river course, whereas in other cases, the growth occurs outwards, and possibly at different stages.

EVALUATION OF THE PROPOSED ISGM

This section evaluates the ISGM based on four main criteria: sensitivity, validity, reliability, and efficiency and utility (Giudici, 2002).

Sensitivity

Sensitivity assesses the behaviour of the model whenever changes are made to its properties, structure and inputs. In the case of Yaoundé, the ISGM has clearly demonstrated that the modification of the configuration of the model reflects on its output. For instance, the output of a road-based ISGM was different from other results. The ISGM tests various hypotheses of IS (see above), especially when the key factors are progressively added to the model. In that respect, factors such as main roads, vacant land, cultural and ethnic groups, topography and markets places play an important role in the emergence and expansion of IS. Similarly, enclosed and protected areas, such as military camps and airport, are a serious deterrent to the exponential growth of IS.

Validity

Validity assesses how the output agrees with the conceptual framework of the model. The calibration results show that it is possible to combine the GIS and CA approaches to simulate and predict IS dynamics. One of the advantages of the loose coupling of a flexible CA (*Visual Basic macro language*) and spatial GIS environment is that it facilitates building and maintaining of models. With such model, one can easily modify probabilities and explore what happens if the model mutates its structure due to new information, or due to spatial and temporal changes. In particular, the proposed model has demonstrated what the main driving forces behind the expansion of IS are, as well as indicates their respective weights at different stages or scenarios of urban development. The capacity to combine physical changes with socio-cultural aspects is significantly important in terms of increasing our understanding of IS behaviour and improving urban planning responses. This knowledge is especially vital for urban planners and governments who use the model to better anticipate the emergence of future IS. However, the results of the ISGM could not be compared with other models' results, only because such similar IS models do not exist.

Reliability

Reliability examines the quality and truth of the results provided by the model. In that regard, the proposed ISGM has performed properly and generated expected outputs based on the data input, the rules and the probabilities. The simulation of IS could allow planners and policy-makers to do a preliminary *What if?* analysis with the purpose of assessing the system's behaviour under different conditions and evaluating which alternative policies should be adopted. The application of the proposed ISGM to Yaoundé has shown that the choice of key IS growth factors, the definition of rules and the application of sound probability estimates, significantly improve the calibration of the predicted output. The model does not, however, take into consideration other important factors of IS emergence and growth, such as urban policies and intrinsic behaviour of urban dwellers, decision makers, which could have improved its performance if suitable data about them had been available.

Efficiency, utility and generality

Efficiency refers to the model's precision given time, equipment and expertise limitations, whereas utility assesses the efficiency, usefulness and generality of the model. Generality is the extent to which a method can be successfully applied, with minor modifications, to a wide range of cities. Compared to other urban dynamics models, the ISGM is a *low cost* model (Wyatt *et al.*, 2002) and can be obtained free of charge from the author. Moreover, the proposed ISGM is fast to run and quite flexible in data input. In terms of equipment, the ISGM is versatile and it can be implemented on a standard computing platform with a *Visual Basic* application, and a nominated raster GIS. Also, the testing of the ISGM within Yaoundé clearly show that, with limited modifications, the model has the potential to be successfully used to explore the expansion of IS in other cities of DCs. Also, the model provides multiple outputs, which can serve to create a *movie* of IS dynamics, thus gaining better insights into the dynamic of IS patterns. As the case study of Yaoundé indicated, ISGM allows the rapid development of different types of growths, which could greatly improve interaction amongst government and urban stakeholders. This is of paramount importance for proactive strategic planning that can anticipate the future location of IS and then act before they become widespread. Nevertheless, the viability of the proposed model would be even greater if the program were converted into menu driven software.

CONCLUSION

This paper has shown that GIS technology can be loosely coupled with the CA approach to simulate the behaviour of IS dynamics. The *Visual Basic* language used for the simulation allows flexibility and provides full control (customisation) over the modelling and simulation processes. The ISGM embodies the logic of IS growth, sheds light on human settlement behaviour in DCs and in doing so, helps urban researchers to better understand processes of unplanned expansion in order to inform planning. I therefore believe that this proposed ISGM represents an important contribution to the state-of-art of informal settlement modelling within DCs. Importantly, the model adds to our capacity to plan because it is able to incorporate a larger range of variables and in particular, socio-cultural characteristics that are important to understanding human settlement behaviours. In doing so, it could be argued that it begins to challenge the assumption that models cannot be used to predict human behaviour because they cannot handle such behaviour. The proposed model shows that within certain boundaries, important human dimensions and characteristics can be incorporated. The evaluation of the proposed model based upon its sensitivity, reliability, validity and usability has indicated that the ISGM can potentially improve the urban planning and decision-making processes that would ultimately lead to the improvement of the quality of life in developing cities. The proposed model is at its early stages and so has room for further improvement, especially in the area of fine-tuning the model, user-friendly, more rigorous calibration algorithm, and menu-driven interface.

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