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ASSESSING REHABILITATION STRATEGIES OF URBAN DRAINAGE SYSTEMS BASED ON FUTURE SCENARIOS OF URBANIZATION

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The growth of the population and the rapid urbanisation are creating a big need to improve the planning processes and management of urban infrastructures. Urban drainage networks are one of the vital services needed for any urban area, modelling its growth and expansion is a challenge because of the dynamics of the system. This work describes the integration of a cellular automata model, to simulate urban land use changes, with algorithms to deduct the future layout of the drainage network and with SWMM 5.0 as the hydraulic engine to assess the performance of the drainage systems in the current condition and in the future. The model was built using Dinamica EGO to simulate the land use changes in the future. The model was setup using a set of two land use maps for the municipality of Birmingham in the UK, for the year 2000 and 2006. The model was connected with the NSGAII algorithm to handle the calibration process. Once the model is calibrated three scenarios of future population growth and urbanization are run for the year 2040. The future generated map is then used to classified and cluster the areas of new developments that are suitable to expand the drainage network. Once the new layout of the network is defined, the system can be connected to the existing urban drainage network and the performance of the expanded network can be assessed. To upgrade the system several rehabilitation strategies can be tested to improve the capacity of the system. The integration of these models allows the exploration of several planning scenarios, in this way is possible to help the decision makers with tools and methods to anticipate bottlenecks and solutions in the urban drainage system.

INTRODUCTION

Cities can be considered as complex systems considering their characteristics of emergence, self-similarity, self-organization and non-linear behavior of land use changes with time [Batty and Langley 1994]. The use of computer modeling tools can help in the understanding of the above–mentioned characteristics and to gain knowledge about the patterns and mechanisms behind urban dynamics. Cellular automata (CA) models have been used increasingly in many applications and tested on several case studies.

Several authors have used CA models to predict land-use changes at the catchment scale. Their results have shown that the application of CA for land-use change modelling is feasible and that the outcome of the models is close to reality. The Moland framework, [Barredo et al. 2003] an example of such a model that has been successfully applied and calibrated in case studies in Europe. Several examples using cellular automata models like Dinamica EGO and SLEUTH among others have been applied in different cities around the world [see for example, Barredo et al. 2003, Engelen et al. 2007, Soares et al. 2011].

This paper presents the results from an ongoing research work that aims to develop a framework to assess the impact of scenarios of future growth the existing urban drainage network. This framework can be used to determine the optimal distribution of urban drainage network in new developed areas and the effects of the new developments in the existing drainage system. This frame work was applied in the city of Birmingham in UK as a case study. The frame work can be used to assess rehabilitation strategies in the existing drainage network depending on the future land use changes

METHODOLOGY

The framework for the evolution of urban drainage networks consists of doing a spatial analysis to find characteristics that connects the land use pattern distribution of an urban area with the properties of the urban drainage system. In this way, the output of the cellular automata model can be used together with the agent-based algorithm to explore scenarios of future growth and urban dynamics were water is at the center

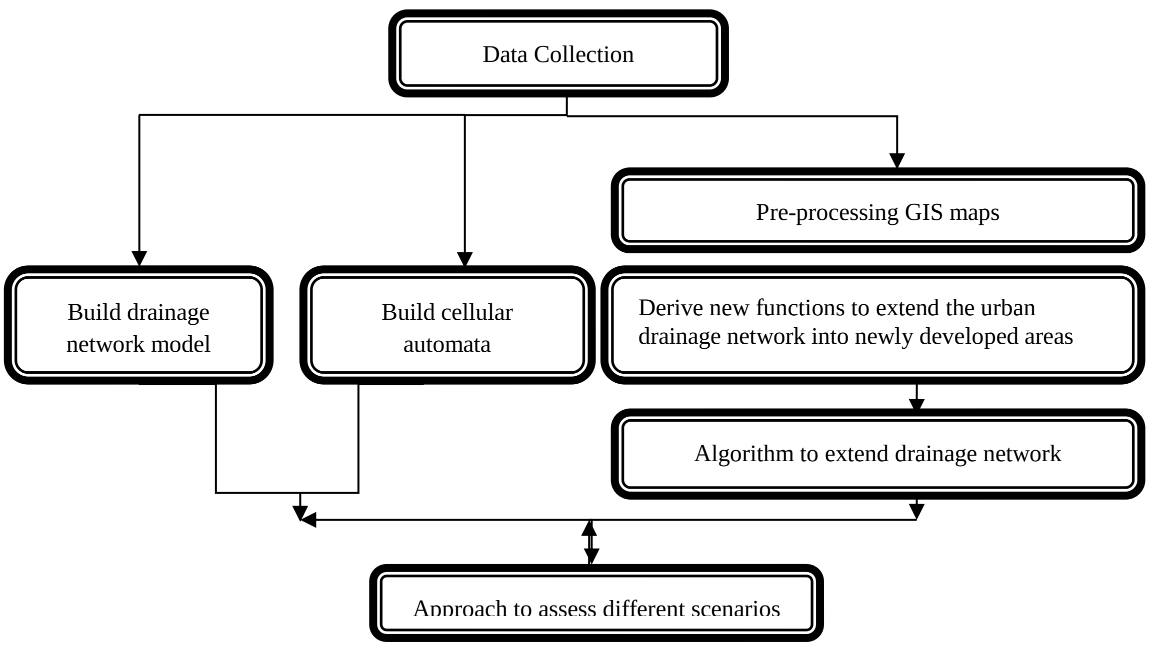

Figure 1. Overall Approach

Modelling Land use Changes with CA

In this study, DINAMICA EGO software is used as a simulation platform for our urban dynamics model [Soares et al. 2011]. DINAMICA employs, as input, a set of maps. This includes the initial and final map of land use, also known as landscape maps. The model considers that a landscape could be viewed as a bi-dimensional array of land use types. The other inputs are two sets of ancillary maps: the static and dynamic variables, the latter named so because they are iteratively updated by the model. These two sets of variables control the spatial allocation of changes, since they are used to calculate the weights of evidence. The weights of evidence represents each variables influence on the spatial probability of transition a to b. The variables are combined by summing their weights of evidences [Goodacre et al. 1993, Bonham-Carter 1994, Soares-Filho et al. 2011] to produce a transition probability map, which shows the most favourable areas for change [Soares-Filho et al. 2002, 2004, 2011].

DINAMICA EGO uses as a local CA rule, a transition engine composed of two complementary transition functions, the Expander and the Patcher [Soares-Filho et al. 2002]. DINAMICA splits the cell selection mechanism into these two processes. The first process is dedicated only to the expansion or contraction of previous patches of a certain class, and it is called Expander. The second process is designed to generate or form new patches through a seeding mechanism, and it is called Patcher. For each transition of land use to another, the percentage of cell changes executed by the Expander function in relation to the Patcher must be defined. Within the software this process is handled by the Modulate Change matrix function. This matrix specifies the percentage of changes (number of cells per transition) that will be executed by the expander and the Patcher. These values need to be fine tune in the calibration process.

$$Transition(ij) = X * Expander + Y * Patcher$$

Where X + Y =1.

The validation of the outcome of the cellular automata model consists of a comparison between the model results and a reference map, in this case, the land use map at the simulation final time. There are several map comparison techniques to assess the spatial match between two maps. Nonetheless, there is no consensus about which technique yields the most appropriate validation. The fuzzy comparison method described by [Hagen 2003] was adapted to be used in Dinamica and in this study.

Calibration of the CA

Several applications were coded in Borland Delphi to read and update the specific components of the model. Following the recommendations given by the developers of Dinamica Ego (Soares et al., 2011), the initial weights of evidence matrix computed by the model was optimized within certain constraints. The best set was then used to optimise the parameters of the functions that account for the processes of urban dynamics, namely the expansion or contraction of the land use clusters, described above. The names of these functions in Dinamica EGO are the expander and the patcher. The change matrix is a type of communication function that calculates the number of cells to be changed between the expander and the patcher.

To handle the optimization process the NSGA-II algorithm developed by [Deb 2002] was used. The NSGA-II has been tested and probed to develop good Pareto fronts and can manage several objective functions and constraints [i.e. Barreto et al. 2006, Muschalla 2006]. The DINAMICA

EGO 1.6 developed by [Soares et al. 2011] is used as computational engine to simulate the land use changes. Figure 1 shows the optimization loop.

The optimization loop to calibrate the parameters was run for 144 generation and 12 populations (for a total of 1728 evaluations). The objective function consisted of the fuzzy similarity fitness indicator

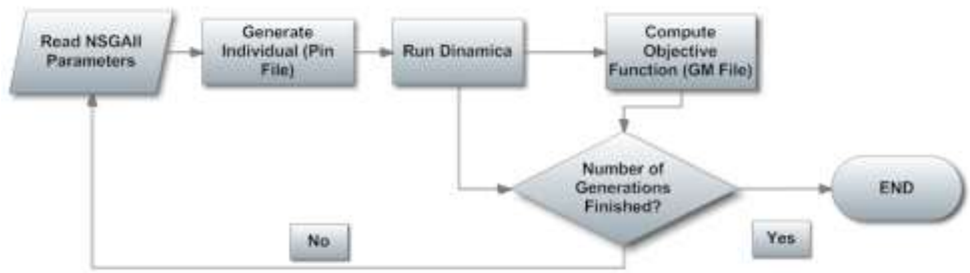

Figure 2. Optimization loop used for calibration.

Case Study

The city of Birmingham is located in the West Midlands of England. The city has an area of 267.77 km^2. It has a population of 1,028,700 inhabitants according to the City Council estimate made in 2008 (Birmingham City Council, 2012). The West Midlands is the United Kingdom's second most populous urban area with a population of 2,284,093 according to the census of 2001 (Birmingham City Council, 2012). Industrial activity in the city has declined over the past fifty years. The economic crises in the 1980s caused a decrease in population that lasted until the year 2000. Since 2001 the city has experienced a rise in population as the rate of increase in population has been 4.2% between 2000 and 2010 (Birmingham City Council, 2012).

Birmingham relies on a centrally managed water supply and wastewater/sewage collection service. Much of this infrastructure dates back to Birmingham's industrial development during the 19th century, yet remains largely operational today (Darthe et al., 2008). Population growth is leading to an increased demand for potable water and there is a corresponding increase in the flows and loads in the sewerage network and wastewater treatment plants. It is anticipated that the West Midlands population will increase by 6.6% between 2003 and 2023. This potentially poses a major problem for Birmingham because much of the area is drained by combined (stormwater and wastewater) collector systems and as such there will be an increased need to control runoff from rainfall events and attenuate localised flood risk (Last et al., 2011).

Results

The cellular automata model was setup in DINAMICA EGO to estimate the land use changes between the years 2000 and 2006.For these two years the land use is known, according with the CORINE classification of land uses. For this dataset, the model was setup using a spatial dataset collected for the study area. The dataset consisted of the following maps: digital terrain model (DTM), derived slope map, main highways and motorways, primary and secondary roads, rail network, main rivers and canals, and the overland flow paths. The terrain data corresponded to the Shuttle Radar Topography Mission (SRTM) data with 100 meter resolution. The resolution of all the data was converted to 100 meter cell size following the land use data resolution.

After the calibration –validation process for the growth and land use changes model. The performance of the cellular automata model seems to be good for the known information on this test case study, the fuzzy similarity test shows a 49% match between the real and simulated land use maps. Figure 3 shows the results of the best set after optimization.

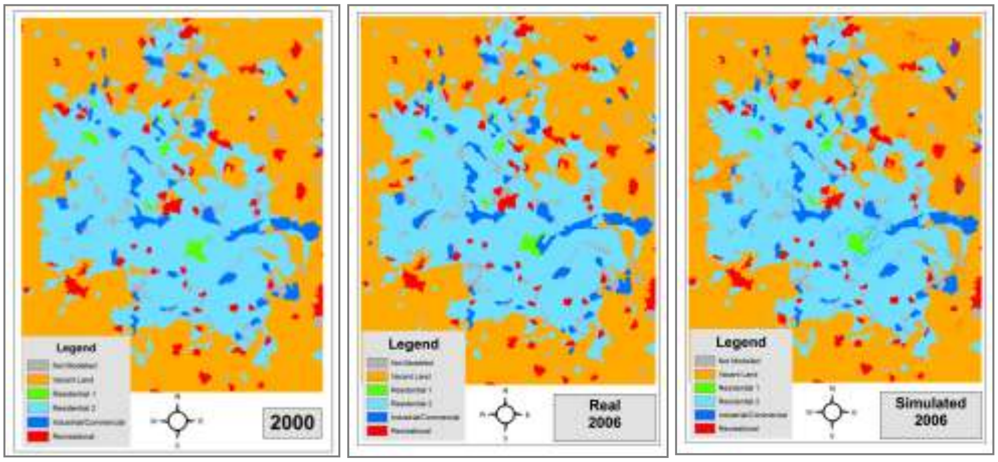

Figure 3. Corine Land use maps for the years 2000, 2006 and simulated 2006.

These values suggest that even though this research work in a complex scenario in terms of cell resolution and number of classes than traditional uses of the software, the values of similarity or fitness obtained are good. This also suggests that the model can be used for the simulation of future scenarios of change with some confidence.

Scenarios of urban growth

Using the best parameters of the calibration, the model was set up to run the future land use simulation, corresponding to the year 2040. The simulations are done by manipulating the parameters of the expander and patcher to reflect land use policies. The following scenarios are simulated and presented in figure 4:

- BUA: Business as usual, this scenario keeps all the parameters found during the calibration and the transition rates found for the period 2000-2006 are used incrementally until the year 2040.

- Sprawl: This scenario the transitions are assigned to the patcher mainly, the transitions rates are kept similar as for scenario BUA. The simulation shows a development that is more fragmented and covers more space.

- Expansion: This scenario the transitions are assigned to the expander mainly, the transitions rates are kept similar as for scenario BUA. The simulation shows a development that corresponds to a more organic growth, basically expanding the current clusters of land use classes. The development looks more organized and continuous.

- Densification: This scenario the transition rates are changed. The idea is that all the transitions occurring to residential classes are assigned to residential class high density. This can be the result of a land use policy to reduce sprawl. In other words the growth of the urban area occurs internally. As can be observed in figure 4 the area of the urban conglomeration does not growth significantly.

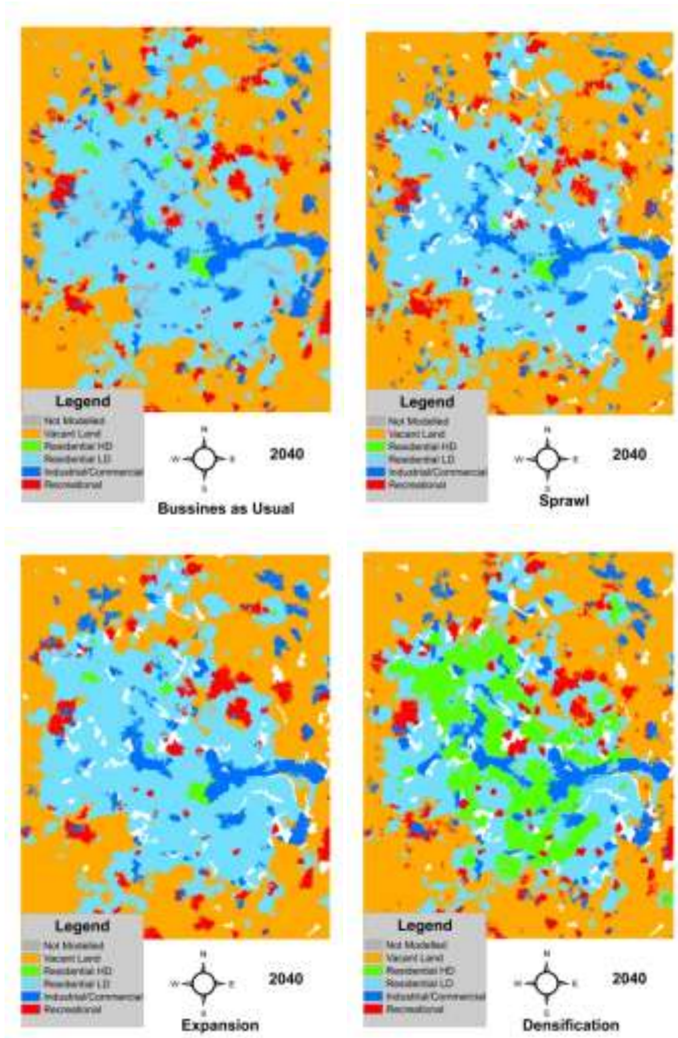

Figure 4. Scenarios of Urban Growth

After assessing the different scenarios of land use change for year 2040, the following question is how the new developments or changes can be incorporated into the existing infrastructure of urban drainage and what will be the impact of such a connection to the existing system performance. For this case study the mathematical model of one part of the drainage network was available, this allowing the assessment of the future land use scenario.

Integration with the drainage network model

The information regarding the urban drainage network was obtained through the SWITCH Learning Alliance established in Birmingham (www.switchurban.eu). The hydraulic model of urban drainage network used in this study was obtained from Severn Trent and it covers the Upper Rae Main catchment. Previous research done with this dataset has been reported by Thuy (2009) and Last (2011).

The approach and methods to expand the drainage network based on the future land use map has been developed and presented in Sanchez et al, 2013. For the scenario business as usual the possible expansion of the drainage network to the new developments is presented in figure 5.

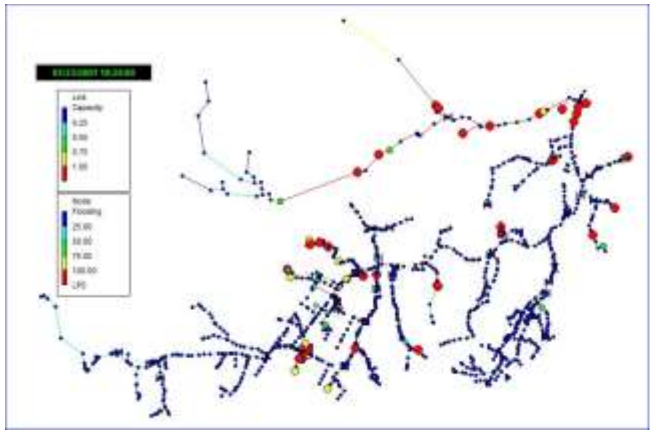

Figure 5. Expanded Drainage network for the year 2040, scenario BUA. Surcharged nodes.

The expansion of the drainage network will increase the total number of locations with flooding to 50 nodes or manholes. Part of the new developments is likely to occur in the area where the system is already in a critical condition (i.e., does not have sufficient capacity) which is highlighted by the total volume of flooding increasing to almost double its original value while the total duration of the flooding does not change significantly. Out of all the surcharged pipes, those elements with the largest change (i.e., pipes for which the increase in surcharge capacity is greater than 0.5) can be identified.

The identification of these critical conduits is useful information that can be used to evaluate potential rehabilitation strategies for the system. This again can be undertaken as a dynamic optimisation problem (see for example, Sanchez, 2007 and Vojinovic et al., 2006).

Conclusion

To visualize the impacts of future urbanization growth on the existing drainage infrastructure, a cellular automata model of land use changes was used in the study area in Birminham, UK. After calibration of the CA model, several scenarios were created and assessed. to demonstrate the potential of this approach, the output map of the cellular automata model for the year 2040 and the scenario business as usual was used to derive a possible expansion of the drainage network. The catchment parameters needed for the rainfall-runoff process can be estimated based on the future land uses. The pipes were sized using the NSGA II algorithm coupled with SWWM within an optimization loop. The new pieces of the drainage network were then interconnected to the existing model of the drainage system to assess its new performance and to evaluate the consequences of the future land use changes for the existing infrastructure.

The interconnected model for the future urban growth scenario of Birmingham shows that the future developments will contribute further to the flooding problem if not rehabilitation measures are implemented in the existing drainage system. The total number of flooded manholes will increase by 50 and most of the runoff volume that will be generated by the new developments will exacerbate the flood-related problems due to the lack of hydraulic capacity of the existing system. The approach presented in this paper can also be used to identify the critical pipes that require immediate attention for rehabilitation purposes. The same approach can be used to evaluate rehabilitation strategies to improve the performance of the system now and in the future.

REFERENCES

[1] Barredo J., Kasanko M., McCormick N., Lavalle C. Modeling dynamic spatial processes: simulation of urban future scenarios through cellular automata. Journal of Landscape and urban planning. Vol 64. pp 145-160. Elsevier Science. 2003.

[2] Barreto W. J., Vojinovic Z., Price R.K., Solomatine D.P. Approaches to multi-objective multi-tier optimization in urban drainage planning. 7th international conference on hydro-informatics. Nice, France. 2006.

[3] Birmingham's City Council. http://www.birmingham.gov.uk. Accessed via Web. 2012

[4] Bonham-Carter, G Geographic information systems for geoscientists: modeling with GIS. Pergamon, New York, 1994.

[5] Engelen G., C. Lavalle , J.I. Barredo, M. van der Meulen and R. White. The Moland modeling framework for urban and regional land-use dynamics. In: Modeling Land Use change: Progress and applications. Edited by Koomen Eric, Stillwell John, Bakema Aldrik, Scholten Henk J. Springer. The Netherlands. 2007.

[6] Goodacre CM., Bonham-Carter GF., Agterberg FP., Wright DF. A statistical analysis of spatial association of seismicity with drainage patterns and magnetic anomalies in western Quebec. Tectonophysics, v. 217, 205-305, 1993.

[7] Hagen A. Fuzzy set approach to assessing similarity of categorical maps. International Journal of Geographical Information Science, v. 17, 235–249, 2003.

[8] Last Ewan M. (2011). City water balance: a new scoping tool for integrated urban water management options. Ph. D. Thesis. University of Birmingham.

[9] Muschalla D. Optimization of water resources systems using multi-objective evolution strategies. 7th international conference on hydro-informatics. Nice, France. 2006.

[10] Sanchez Arlex. (2007). Towards a demonstrator of an urban drainage decision support system. MSc Thesis. UNESCO-IHE, Delft, NL.

[11] Soares Filho BS., Pennachin CL., Cerqueira G. DINAMICA – a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecological Modelling, v. 154, 217-235, 2002.

[12] Soares-Filho B., Alencar A., Nepstad D., Cerqueira G., Vera Diaz M., Rivero S., Solórzano L., Voll E. Simulating the Response of Land-Cover Changes to Road Paving and Governance Along a Major Amazon Highway: The Santarém-Cuiabá Corridor. Global Change Biology, v. 10, 745-764, 2004.

[13] Soares-Filho BS., Cerqueira G., Araujo W., Voll E. DINAMICA project. http://www.csr.ufmg.br/dinamica visited February, 2011.

[14] Vojinovic Z., Solomatine D.P., and Price, R.K., (2006). Dynamic Least-Cost Optimisation of Wastewater System Remedial Works Requirements, Water Science and Technology, Vol. 54, No 6-7, pp. 467-475, IWA Publishing.

[15] Vojinovic Z., Sánchez Torres A. and Barreto W. (2008). Optimising Sewer System Rehabilitation Strategies between Flooding, Overflow Emissions and Investment Costs. Paper presented at 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

[16] Thuy T. P. MAI. (2009). Integrated sustainability assessment of stormwater management strategies – a case study of The Catchment Upper Rea Main, Birmingham City, the United Kingdom. MSc Thesis. UNESCO-IHE, Delft, NL.