Measuring and Modeling Urban Dynamics: Impact on Quality of Life and Hydrology

Objectives and methodology

Frank Canters and Tim Van de Voorde
Department of Geography
Vrije Universiteit Brussel
Brussels, Belgium
fcanters@vub.ac.be

Rudi Goossens, Dennis Devriendt and Frederik Tack
Geography Department
Ghent University
Ghent, Belgium
rudi.goossens@ugent.be

Okke Batelaan and Jef Dams
Department of Hydrology and Hydraulic Engineering
Vrije Universiteit Brussel
Brussels, Belgium
batelaan@vub.ac.be

Guy Engelen
Centre for Integrated Environmental Studies (IMS)
Vlaamse Instelling voor Technologisch Onderzoek (VITO)
Mol, Belgium
guy.engelen@vito.be

Yves Cornet and Marc Binard
Unité de Géomatique
Université de Liège
Liège, Belgium
ycornet@ulg.ac.be

Carlo Lavalle and José Barredo
Land Management and Natural Hazards Unit
Joint Research Centre
Ispra, Italy
carlo.lavalle@jrc.it

Abstract— **The objectives and methodology of the MAMUD research project are presented in this paper. MAMUD is an acronym for Measuring and Modeling Urban Dynamics: Impact on Quality of Live and Hydrology. The research will be conducted over a four year period (2007-2011). The major goal is to investigate how earth observation can contribute to a better monitoring, modeling and understanding of urban dynamics, and its impacts on the urban and suburban environment.**

Spatial metrics; Urban growth; Land-use change; Urban runoff; Multi-resolution remote sensing

I. Introduction

Urban change processes that have taken place over the last decades are affecting the human and natural environment in many ways and have stressed the need for new and more effective urban management approaches based on the notion of sustainable development. However, the problem analysis, planning and monitoring phases of a sustainable urban management policy requires reliable and sufficiently detailed information on the urban environment and its dynamics [1], as well as knowledge about the causes, chronology and effects of urban change processes [2]. Remote sensing imagery is an important data source for monitoring and modeling urban change and its environmental impact. With the recent launch of high-resolution sensors like Ikonos and Quickbird, which allows more detailed mapping of complex urban areas, the potential of satellite remote sensing for urban change analysis has substantially increased. At the same time, interpretation of medium-resolution data from sensors like Landsat TM/ETM+, SPOT-HRV, etc. at the sub-pixel scale, based on spectral unmixing approaches, offers interesting perspectives for an improved use of historic time series of medium-resolution imagery in the monitoring and modeling of urban dynamics [3] [4] [5] [6] [7].

A key element in the study of urban dynamics is the analysis of changes in urban land use. In contrast to land cover, which refers to the physical properties of the earth's surface, land use is linked to socio-economic activities and, as such, cannot be directly inferred from spectral information only. Previous studies, however, have demonstrated a strong relationship between the spatial structure of the built-up environment and its functional characteristics [8]. The link between land use and urban form is a key element in visual interpretation of remotely sensed imagery of urban areas. A rather novel approach in this research area is to describe urban form and structure by means of spatial metrics. Spatial metrics describe various properties of the spatial heterogeneity and configuration of land cover in a given area. Originally developed for landscape ecological research, spatial metrics have recently been shown to have considerable potential for the analysis of urban environments [9] [10] [2].

In order to understand changes in urban form, and how these changes relate to urban development processes that drive these changes (or are affected by it), increasing use is made of computer based urban growth models. The performance of

Project sponsored by the Belgian Federal Science Policy Office

these models strongly depends on the availability of different types of data, needed for calibration and validation. One of the aims of this project is to examine how spatial metrics, derived from satellite imagery may complement existing land-use maps in calibration and validation of these land-use change models.

On its turn spatio-temporal change in land-cover gradients and land use, obtained through analysis of time series of remotely sensed imagery, as well as future land-use patterns predicted by urban growth modeling, may be used to study demographic as well as environmental impacts of urban dynamics. Previous studies have indeed shown strong relationships between population distribution as obtained from census data and satellite-derived land-use information [11] [12] [13]. One of the environmental impacts of urban dynamics is the change in hydrological characteristics of the area, for example growth of urban runoff. It has been proven by many authors that land-use changes influence the catchment hydrology [14]. In studying the effects of land-use change, hydrologists increasingly discover the possibilities of implementing remote sensing derived information [15].

II. Objectives

The objectives of the proposed research can be divided into four categories.

The first category involves improvement of the extraction of urban land-use and land-cover (LULC) information and elevation data from high- and medium-resolution imagery. Work on high-resolution data will focus on exploiting the potential of multi-angle image acquisition for reducing the impact of shadow and occluded areas, and for improving the labelling of urban objects. Medium-resolution data will be used to produce accurate time series of gradient information (sub-pixel proportion of impervious surfaces and vegetation). Historic information on the 3D-structure of urban areas will be extracted from HR stereoscopic archive imagery, and will be used to complement the land-cover gradient information with information on the vertical dimension of urban structures.

The second research objective relates to the development and implementation of spatial metrics and constitutes the link between remote sensing, and the inference of information on urban form and function, which will be used for monitoring and modeling of urban dynamics. The main aim is to define a set of spatially explicit urban metrics capable of describing urban morphological and structural dynamics in a coherent and systematic way, and readily obtainable from RS-derived information (LULC-distribution, density gradients) at high- and/or medium-resolution. So far, most spatial metrics used to describe urban form are adopted from landscape ecological research and are applied to categorical land-use maps. In this research we intent to examine the potential of field-based (magnitudes, densities) instead of object-based representations of urban areas for deriving useful indicators (metrics) of urban structure.

A third objective is to examine the potential of the, from remote sensing derived, spatial metrics for urban growth monitoring and modeling. The proposed metrics will be used to complement detailed land-use maps in the historic calibration of a spatially-dynamic land-use model. The general analysis framework aimed in this project is shown in Fig. 1. The focus will be on the link between remote sensing and spatial metrics, and the link between spatial metrics and urban modeling. After the model has been build up, future land-use and urban growth patterns will be estimated under alternative spatial planning and policy scenarios.

Finally the study aims to measure the impact of urban dynamics on population distribution and environmental conditions in the urban/rural interface. A major focus will be on the implementation of the obtained information in hydrological modeling.

Research will focus on two urban areas in Europe (Dublin and Istanbul). Both are part of a European study called MOLAND [16] of which output will be used in the project.

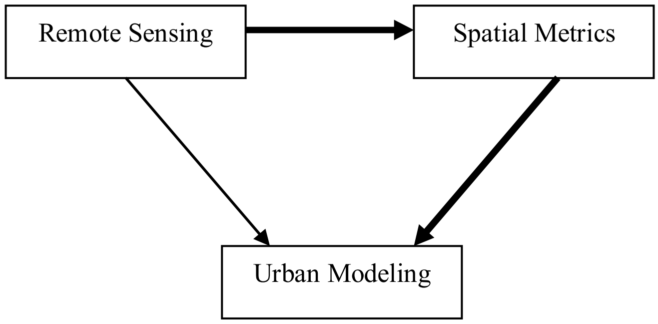

Figure 1. General framework for analysis and modeling of spatial urban dynamics (adapted from [2])

III. Proposal working strategy

The research plan, which is to be carried out over a period of four years (2007-2011), consists of four main modules which are closely linked to the objectives of the project. The working strategies adopted in each module are described below.

A. Extraction of land-use/land-cover information and elevation data from high- and medium-resolution imagery

In order to extract LULC information from RS imagery a 3D-model will be developed for one of the study areas using an Ikonos image triplet, each image corresponding to a different view angle. After photogrammetric processing of the HR imagery various approaches will be tested to reduce the impact of remaining zones of occlusion and to improve the quality of the obtained 3D-model.

Apart from the multi-scopic imaging, also the potential of extracting 3D information from archive imagery, not explicitly recorded for stereoscopic purposes but acquired under viewing angles that approach a difference of 180°, will be evaluated. The procedure will be tested for images from the same sensor (Ikonos), as well as for imagery acquired by two different sensors (Ikonos/Quickbird). Accuracy statistics of the 3D-models obtained will be compared to the quality and the accuracy of the models produced from the Ikonos image triplet.

Afterwards a supervised LULC-classification approach, making optimal use of the produced digital surface model and multi-angle information, and separately dealing with shaded and non-shaded areas, will be developed and validated, based on HR-reference data.

Next to information extraction from HR imagery, the first research module will also focus on extracting sub-pixel information on urban land cover from time series of MR data. Spectral mixture analysis (SMA) will be applied to estimate sub-pixel proportions of different types of LC from the MR-data. A strategy will be developed to calibrate and validate the SMA-models for different periods in time, based on recently acquired HR-data. Important considerations that will be taken into account in developing the models are: a) that the acquisition dates of the MR- and the recent HR-data are different, b) that classes like vegetation and impervious surfaces, for which gradient information will be derived, may be spectrally very heterogeneous, c) that no one-to-one relationship exists between LC classes and physical end members, observed in feature space, and d) that small shifts in the co-registration of HR- and MR-imagery should not have a negative effect on model calibration and validation.

Finally historic information on the three-dimensional structure of urban areas will be extracted from HR stereoscopic archive imagery (SPOT-5, KFA-1000), and will be used to complement the land-cover gradient information with information on the vertical dimension of urban structures.

B. *Describing urban form and structure based on spatial metrics*

From a literature review, a set of spatially explicit metrics will be selected which qualify for further analysis. Also new metrics will be defined to describe spatial characteristics of the urban environment that are not captured well by existing metrics. The metrics will be implemented and tested on the land-cover and elevation data that was previously derived from RS. MR- and HR-imagery for which the dates of acquisition are close will be used to analyse the impact of spatial resolution and of thematic information content on the type of structural information that can be derived from the imagery. Also the sensitivity of the metrics to uncertainty in the land-cover gradient information used to derive the metrics will be analysed. Based on the proposed metrics, alternative typologies for describing urban structure and form will be defined, specifically adapted to the type of information that can be derived from remotely sensed data.

Special attention in this research also goes to the monitoring of change in urban structure and form, based on the metrics that will be defined. An important consideration in the monitoring of change in urban form is the impact of uncertainty in the land-cover gradient images obtained from the time series of MR-data on the trajectory of change that is observed.

Following recent work by [17], [18] and [7], a rule-based approach will be developed to detect irrational changes and improve the quality of the spatio-temporal information produced. Based on the spatial metrics proposed, alternative typologies for describing urban form will be defined. Relationships between RS-derived typologies and LU classification schemes, like the one used in the MOLAND project, will be investigated by confronting the detailed LU maps that are produced in the MOLAND project with the metric-based descriptions of urban form derived from RS imagery.

C. *Spatial dynamic modeling of urban growth*

The selection of a proper set of urban metrics, discussed above, will be closely linked to the work on land-use change modeling in MOLAND. The metrics developed will be used to complement existing, detailed land-use maps in the historic calibration of a spatially-dynamic land-use model of the type cellular automata (CA) similar to, and based on, the MOLAND model. Based on simulation runs with the CA model, it will be tested whether the spatial patterns generated by the model as emergent properties of scenarios or policies tried out can also be discerned and differentiated by means of the selected metrics in remote sensing images of the same time period.

To test the performance of the developed RS metrics for calibration purposes, relationships will have to be established between these metrics and metrics that will be selected to describe the spatial patterns observed in the LU maps, produced by the MOLAND model. This will involve the development of methods enabling a translation of LU patterns into descriptions of urban form similar to those derived from RS imagery.

Calibrated models will be used to forecast future land-use and urban growth patterns under alternative spatial planning and policy scenarios.

D. *Impact of urban dynamics*

Remote sensing derived gradients and metrics, as well as the output of the land-use change modeling, will be used to study the consequences of urban dynamics in terms of population density and distribution, quality of life and environment.

Correlation analysis will be applied to explore the relationships between population, obtained from census data, and various LC and elevation metrics derived from the MR and HR-imagery. Multivariate regression models will be developed to estimate population from selected combinations of metrics. The statistical modelling will be linked to a dasymmetric mapping approach, to produce estimates of population distribution at the level of grid cells smaller than the census unit level.

Concerning the impact of urban dynamics on the quality of life and environment, the aim is to select and develop indicators that are able to measure the potential effects of urban development and organization on the environment and the quality of life of inhabitants of cities and of rural areas affected by urbanization. The most promising of these indicators will be incorporated in the MOLAND model for direct computation, or executed on LU maps generated by MOLAND.

A substantial part of the research will focus on the impact of urban growth on runoff. To this end, detailed information on urban land cover, obtained from time series of remotely sensed data, as well as future land-use patterns, linked to alternative planning scenarios, will be used as input for spatially distributed runoff modeling.

The fully distributed, grid based, rainfall-runoff model WetSpa [19] will be used in this project. The model will be adapted for flexible input from RS derived model parameters, such as NDVI, LAI, SAVI, etc. A case study will be developed for the River Tolka (Ireland, Dublin). The catchment of the River Tolka is situated in the study area for which the spatial metrics analysis and the land-use change modeling will be performed.

Calibration of the runoff model will be based on a data assimilation approach, making optimal use of information with respect to land cover and evapotranspiration, obtained from the available time series of remotely sensed data, including the in this project established time-series of maps of sub-pixel imperviousness.

Based on the outcome of the by the MOLAND model produced land-use simulations, the future risk of flooding under extreme rainfall conditions, for different development scenarios, will be assessed using an adapted version of the WetSpa model.

IV. Conclusions

Because of the increasing pressure of urban change processes on human and natural environments, research on urban dynamics is gaining interest. The MAMUD project aims to develop new methods for deriving detailed information on the urban environment and its dynamics based on RS imagery. An important element in the research is the, thus far little explored, potential of the combined use of remote sensing and spatial metrics in land-use change modeling [2]. Furthermore the project aims to improve the extraction of urban LULC information from RS imagery based on multi-angle remote sensing and on sub-pixel classification of MR images, using HR data for training and validation. Results of the RS information extraction (including spatial metrics) and land-use change modeling will be used in this project to study the impact of urban dynamics on population distribution, quality of life and hydrology. Developments and research results will be published on www.MAMUD.be.

Acknowledgement

The research presented in this paper is funded by the Belgian Science Policy Office in the frame of the STEREO II programme – project SR/00/105.

References

[1] European Commission – Environment DG, 2004. Towards a thematic strategy on the urban environment. Communication from the Commission to the Council, the European Parliament, the Euroean Social and Economic Committee and the Committee of the Regions, European Publication Office, Luxemburg, 56p.

[2] Herold, M., H. Couclelis and K.C. Clarke, 2005. The role of spatial metrics in the analysis and modeling of urban land use change. Computers, Environment and Urban Systems, 29, pp. 369-399.

[3] Ridd, M.K., 1995. Exploring a V-I-S (vegetation-impervious surface-soil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities. International Journal of Remote Sensing, 16(12), pp. 2165-2185.

[4] Civco, D.L., J.D. Hurd, E.H. Wilson, C.L. Arnold and M.P. Prisloe, 2002. Quantifying and describing urbanizing landscapes in the northeast United States. Photogrammetric Engineering and Remote Sensing, 68(10), pp. 1083-1090.

[5] Yang, L., G. Xian, L.M. Klaver and B. Deal, 2003. Urban land-cover change detection through sub-pixel imperviousness mapping using remotely sensed data. Photogrammetric Engineering and Remote Sensing, 69(9), pp. 1003-1010.

[6] Yang, X. and Z. Liu, 2005. Use of satellite-derived landscape imperviousness index to characterize urban spatial growth. Computers, Environment and Urban Systems, 29, pp. 524-540.

[7] Xian, G. and M. Crane, 2005. Assessments of urban growth in the Tampa Bay watershed using remote sensing data, Remote Sensing of Environment, 97, pp. 203-215.

[8] Barr, S. and M. Barnsley, 1997. A region-based. graph-oriented data model for the inference of second order information from remotely-sensed images. International Journal of Geographical Information Science, 11(6), pp. 555-576.

[9] Parker, D.C., T.P. Evans and V. Meretski, 2001. Measuring emergent properties of agent-based landuse/landcover models using spatial metrics. Seventh Annual Conference of the International Society for Computational Economics. URL: http://php.indiana.edu/~dawparke/parker.pdf

[10] Alberti, M. and P. Waddell, 2000. An integrated urban development and ecological simulation model. Integrated Assessment, 1, pp. 215-227.

[11] Yuan, Y., R.M. Smith and W.F. Limp, 1997. Remodeling census population with spatial information from Landsat TM imagery. Computers, Environment and Urban Systems, 21(3/4), pp. 245-258.

[12] Li, G. and Q. Weng, 2005. Using Landsat ETM+ imagery to measure population density in Indianapolis, Indiana, USA. Photogrammetric Engineering and Remote Sensing, 71(8), pp. 947-958.

[13] Wu, S., X. Qiu and L. Wang, 2005. Population estimation methods in GIS and remote sensing: a review, GIScience and Remote Sensing,

[14] Calder I.R., 1993. Hydrologic effects of land-use change. Chapter 13 in Maidment, D.R., Handbook of hydrology. McGraw-Hill, New York. pp. 50.

[15] Schmugge et al., 2002. T.J. Schmugge, W.P. Kustas, J.C. Ritchie, T.J. Jackson and A. Rango, Remote sensing in hydrology. *Advances in Water Resources* **25** (2002), pp. 1367–1385.

[16] European Environment Agency, 2002. Towards an urban atlas. Assessment of spatial data on 25 European cities and urban areas. European Commission — Directorate General Joint Research Centre Institute for Environment and Sustainability — Land Management Unit Urban and Regional Development Sector, Ispra, Italy. CESUR, Centre for Urban and Regional Studies, IST, Technical University of Lisbon, Portugal. CNIG, National Centre for Geographical Information, Portugal. EEA, Copenhagen, Denmark. Environmental issue report, No 30.

[17] Liu, H. and Q. Zhou, 2004. Accuracy analysis of remote sensing change detection by rule-based rationality evaluation with post-classification comparison. International Journal of Remote Sensing, 25(5), pp. 1037-1050.

[18] Zhou, Q., B. Li and C. Zhou, 2004. Detecting and modelling dynamic land-use change using multi-temporal and multi-sensor imagery, International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol.34, Part XXX, Vol. XXXV, Part B2, XXth ISPRS Congress (Commission 2), 12-23 July 2004, Istanbul, Turkey, pp. 697-702.

[19] Liu, Y.B., S. Gebremeskel, F. De Smedt, L. Hoffmann, L. Pfister. A diffuse transport approach for flow routing in GIS-based flood modeling. Journal of Hydrology, 283, pp. 91-106