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Modeling of urban growth dynamics and its impact on surface runoff characteristics

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ABSTRACT

Modeling urban growth and generating scenarios are essential for studying the impact and sustainability of an urban hydrologic system. Urban systems are regarded as complex self-organizing systems, where the dynamic transitions from one form of landuse to another occur over a period of time. Therefore, a modeling framework that captures and simulates this complex behavior is essential for generating urban growth scenarios. Cellular Automata (CA)-based models have the potential to model such discrete dynamic systems. In this study, a constraint-based binary CA model was used to predict the future urban growth scenario of the city of Roorkee (India). A hydrologic model was applied on the simulated urban catchment to study its hydrologic response. The Natural Resources Conservation Service Curve Number (NRCS-CN) method, which is suitable for ungauged urban watersheds, was adopted to determine the impact of urban growth on the quantity of storm water runoff over a period of time. The results indicate that urban growth has a linear relationship with peak discharge and time to peak for the catchment under investigation.

1. Introduction

Rapid urbanization combined with a spiraling population growth in the cities of developing nations creates land resource demands which leads to serious environmental issues. In 1901 in India, the number of urban agglomerations was 1,827. By year 2001, it has increased to 5,161. Similarly, the urban population has increased from 25.8 million to 285.3 million over the same period of time (Datta, 2006). This steep increase of the urban population has exerted heavy pressure on the land resources surrounding the cities. It has depleted the available open spaces and agricultural lands and has destroyed the natural vegetation. At the beginning of the urbanization process, removal of the vegetation cover may decrease evapotranspiration and increase stream sedimentation. When urban construction begins, the impacts may include decreased infiltration, increased storm flows and decreased base flows during dry periods. After development, the imperviousness of the ground increases and therefore, it reduces the time of concentration of storm discharge and increases the peak discharge (Weng, 2009). Construction of storm water drains accelerates the runoff process. Consequently, the natural hydrologic cycle is affected and the chance of urban flooding increases. Therefore, a better understanding of the urban growth process and its effect on the environment is essential for efficient urban management.

Urban modeling has emerged as part of the effort to quantify the growth process based on scientific principles. Mathematical models transform the ideas encapsulated in conceptual models into mathematical symbology, although the conceptualization varies substantially between them. Large Scale Urban Models (LSUMs) which were developed before the 1970s were largely based on gravity-type formulations. These models attracted severe criticism for their complexity, data hungriness, and their inability to assist in micro-level planning (Lee, 1973). These models were based on traditional macroeconomic theories and failed to address the key issues of social and environmental problems (Itami, 1994). Due to these criticisms, spatial choice models were developed in which the decisions are made based on the available discrete choices. Apart from these, other concepts like bid-rent theory were also incorporated in LSUMs (Torrens, 2000). However, all these models were macroscopic in nature and followed a top-down approach. The top-down approach was slowly replaced by a bottom-up approach in the late 1980s. This change was due to the advancement of computer applications in the field of urban planning (Leao, Bishop, & Evans, 2004) and created a paradigm shift in conceptualizing urban growth phenomena (Batty & Densham, 1996). The new concepts with this type of modeling include fractals and cellular automata (CA).

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Cellular automata are described as a discrete dynamic system whose behavior is completely specified in terms of its local relation (Leao et al., 2004). The temporal processes of change are represented through interactions between various objects in the immediate proximity within the system (Batty, Xie, & Sun, 1999). These models were used for testing hypotheses, simulating urban forms and exploring the mechanisms of urban growth (Li & Yeh, 2002). Many researchers have demonstrated the application of CA-based models in simulating the urbanization process (Batty & Xie, 1994, 1997; Couclelis, 1997; Deadman et al., 1993; Leao et al., 2004; Li & Yeh, 2000, 2001; White & Engelen, 1997; Wu, 1998a; Wu & Webster, 1998; Yeh & Li, 2002).

CA models are preferred for land cover change modeling over other contemporary models because of their flexibility in defining the neighborhood configuration and transition rules. The transition rules and neighborhood configurations are based on the individual's choice and their perception of urban growth process. In traditional CA models, the number of cells in a particular state is determined internally by cellular dynamics. In reality, the number of cells in a particular state is based on the level of demand that is carried out in the cells. Therefore, in order to achieve a realistic representation of the system, it is necessary to implement external constraints on CA by specifying the demand for the number of target cells in each state. The cells are updated from one state to another in discrete time steps. Normally, the cells are updated simultaneously after the application of rules. However, in a constrained CA, sequential updating simplifies the problem by attaining the appropriate amount of cells in various states (White & Engelen, 2000).

In general, predictive models are not free from uncertainties. There are several reasons, such as errors associated with data input, propagation of the errors in the model, and the implicit errors in the model due to a lack of complete knowledge of the processes involved. It all depends on the data sets used, the algorithm applied, and the person's level of expertise. The transition rules and the neighborhood are defined by the analyst on an ad hoc basis, based on his own understanding of the process. Therefore, the simulated outputs of the CA models are not free from uncertainties (Yeh & Li, 2006). These land cover scenarios generated by the CA model serve as the input for hydrologic models. Therefore, it is essential to choose a hydrologic model that is less sensitive to spatial uncertainties, in order to minimize the propagation of errors.

Hydrologic models can be broadly classified into two categories: lumped and distributed. Lumped-parameter models treat an entire watershed as one unit and take no account of the spatial variability of input and processes within the spatial unit. On the other hand, distributed models explicitly consider all spatial variability (Chow, Maidment, & Mays, 1988). The spatial uncertainties associated with the CA model limits the application of using fully distributed models. Therefore, the NRCS (Natural Resources Conservation Service) Curve Number (CN) method, a lumped hydrologic model, is applied on the simulated watershed.

Hydrologic models present the relationship between the rainfall distributed over the watershed and the runoff measured at the outlet in the form of hydrographs. The geomorphological factors of a watershed and the storm characteristics are critical for the computation of a runoff hydrograph (Subramanya, 1984). A unit hydrograph (UH) is the characteristic hydrograph of the watershed resulting from the unit excess rainfall over the watershed at a uniform rate during a given period of time (Sherman, 1932). The temporal changes of the land use pattern play a major role in changing the shape of this characteristic hydrograph of a particular watershed. As a result, the timing parameters of the storm hydrograph changes along with the runoff volume and peak runoff rate for a particular storm event.

NRCS runoff computation is based on spatially distributed morphological characteristics and its associated resources like soil, vegetation and land cover (Sharma & Singh, 1992; Weng, 2001). The main objective of using this method is to calculate the runoff of an un-gauged catchment by using easily obtainable and quantifiable parameters. It is also used to estimate other significant parameters like time of concentration and time to peak (NRCS, 2004b, chap. 10). Several studies carried out on Indian catchments reported that the model output has good correlation with observed values (Patil, Sarangi, Singh, Singh, & Ahmad, 2008a; Patil, Sarangi, Singh, & Ahmad, 2008b; Sharma & Singh, 1992). NRCS CN method is also integrated with GIS to derive flood hydrographs for ungauged catchments (Merkel, Kaushika, & Gorman, 2008; Muzik, 1992; Schultz, 1996; Sui, 2005; Tsihrintzis & Hamid, 1997).

The advancement in remote sensing and GIS has satisfied the data requirements and provided an excellent modeling environment for CA simulations (Li & Yeh, 2000) and hydrologic modeling. Temporal images obtained from remote sensing satellites serve as input data for the model, after processing it in the GIS environment. GIS serves as a preprocessor by generating input data derived from a variety of sources; as a data management tool at each stage of analysis; and finally as a postprocessor for data visualization and planning. In the late 1990s, GIS-integrated CA models, like SLEUTH (Clarke, Hoppen, & Gaydos, 1997), and Sim Land (Wu, 1998b), were developed for urban growth simulations. The integration of urban growth models with climatic and simplified hydrologic models were carried out by researchers to study the impact of future urban growth on the environment. Arthur-Hartranft, Carlson, and Clarke (2003) coupled a microclimatic model with the SLEUTH model (Clarke et al., 1997) for studying the impact of urban growth on hydrology. Rainfall–runoff ratios were computed using a regression analysis using the available stream flow data. Tang, Engel, Pijanowski, and Lim (2005) studied the effects of urbanization on runoff volume and pollutant loads in the Muskegon watershed using simplified techniques.

In the present study, a tightly coupled CA model has been developed by customizing the raster-based GIS software using built-in macro languages. Macros were written in ERDAS Macro Language (EML) and Spatial Modeler Language (SML) scripts to run the model in the ERDAS Imagine software environment. This paper presents a conceptual framework essential for the integrated modeling of urban growth and to determine its impact on surface hydrology. The mathematical basis and the methodologies adopted for the development of the models are presented. The developed model is then applied on an urbanizing catchment to demonstrate the impact of urbanization on the surface runoff process.

2. Description of the study area

The city of Roorkee is located between 29°51′00″–29°54′00″N latitudes and 77°51′30″–77°55′00″ E longitudes in the district of Haridwar, in the state of Uttarakhand. It is situated 172 km north of New Delhi. The strategic location of Roorkee makes it the fourth highest populated city of the state. The plain terrain of Roorkee and the presence of small industries make it a viable option for migration. By nature, cities tend to grow in the direction where no physical boundaries exist. In the present case, the right bank of the river Solani which flows in the east–west direction serves as the northern boundary for the city. An army cantonment in the southern part along the left bank of the upper Ganges canal limits the growth in that direction. The construction of Upper Ganges canal has altered the natural drainage pattern of the city. The banks of the canal were artificially raised, leaving some portions of the city below its high flow level. The natural drainage patterns are aligned