Linking a land-use cellular automata and a hydrological model to investigate the impact of land-use changes on the hydrological processes in the Elbow River watershed in southern Alberta, Canada

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Abstract

This paper describes the linkage of a land-use cellular automata (CA) model with a spatially explicit, physically-based hydrological model (MIKE SHE/MIKE 11) to simulate the impact of land-use changes on the hydrological processes in the Elbow River watershed in southern Alberta. Prior to the linkage, the two models were tested for the sensitivity of different parameters and configurations. They were then calibrated and validated for the Elbow River watershed, after which simulations were carried out up to the year 2031 with an interval of five years. The results of the overall study demonstrated that land-use changes affect the hydrological processes significantly in the watershed which are caused mainly by the increased urbanization and decreased forested areas.

Background and Relevance

The Elbow River is the source of the Glenmore reservoir, which provides drinking water to the City of Calgary. Due to the rapid population growth and urbanization in the City of Calgary, the Elbow River watershed is under considerable pressure for development (City of Calgary 2005). The watershed lies in the rain shadow of the Rocky Mountains, and as a result, is among the driest regions of southern Canada. It is predicted that along with the effects of climate change and the rapidly increasing human activities, water availability will become a critical issue in the near future (Schindler and Donahue 2006). Therefore, investigating the future possible land-use changes in the Elbow River watershed and their impact on the hydrological processes and water availability is becoming a crucial issue. To simulate land-use changes and the land phase of the hydrological cycle in the Elbow River watershed, two dynamic models were chosen: 1) a cellular automata (CA) to simulate land-use changes (Hasbani *et al.*, 2010), and 2) a hydrological model, MIKE-SHE/MIKE-11, to simulate the hydrologic cycle within the study area.

Cellular automata (CA) are dynamic, spatially explicit models composed of a regular discrete lattice of cells having a finite set of possible states. Each cell state is updated at regular temporal steps through a set of transition rules that take into account the value of the cells in its local or extended neighborhood. Despite their simplicity, they are remarkably effective at generating realistic simulations of land-use patterns and other spatial structures and are increasingly used to test what-if scenarios in spatial planning (White and Engelen 2000). The MIKE-SHE/MIKE-11 model is a comprehensive, deterministic, distributed, and physically-based modeling system capable of simulating all major processes in the land phase of the hydrologic cycle (Sahoo *et al.*, 2006). This study was initiated in collaboration with Alberta Environment and the Hydrological Danish Institute (DHI) to investigate the possible impact of land-use changes on the hydrology of the watershed and the availability of water resources.

Methods and Data

Historical land-use maps of 1985, 1992, 1996, 2001, 2006, and 2010 were classified into nine land uses (water, road, rock, evergreen forest, deciduous forest, agriculture, rangeland/parkland, built-up, and clear-cut areas) using Landsat TM imagery at the spatial resolution of 30 m. Maps showing the distance to a main river, the distance to downtown Calgary, the distance to a main road, and ground slope were prepared and used to represent the influence of external driving factors on land use. Analyses were first conducted to assess the sensitivity of the CA model to different parameters, including the cell size, neighborhood configuration, and selection of external driving factors (Hasbani et *al.*, 2010). The land-use CA model was then calibrated at the scale of 60 m using a semi-interactive calibration procedure using historical land-use maps of the years 1985, 1992, 1996, 2001, and validated against the reference land-use maps of 2006 and 2010. Simulations of land-use changes were then performed from 2006 to 2031 at a five year interval.

A suitable conceptual model was prepared using the MIKE-SHE/MIKE-11 modeling environment to carry out hydrological modeling based on the data availability and the focus of the study. A sensitivity analysis was conducted for the parameters: saturated hydraulic conductivity, evapotranspiration (ET) surface depth, degree day coefficient, detention storage, surface roughness, and time constants for interflow and baseflow. The model calibration was then carried out based on the goodness-of-fit calculated between observed and simulated flow data measured at three hydro-metric stations (using Nash-Sutcliffe coefficient of efficiency criteria). MIKE-SHE/MIKE-11 was calibrated using data for the period 1985-1990 and validated for the period 2000-2005. Land-use based watershed characteristics such as spatial vegetation properties (leaf area index, root depth), spatially-distributed hydraulic conductivity, and spatially-distributed surface roughness, were extracted from the simulated land-use maps and transferred to MIKE-SHE/MIKE-11 to assess the impact of land-use changes on the hydrological processes in the watershed. Simulations with

MIKE-SHE/MIKE-11 were carried out for five years using different values of land-use based characteristics based on each land-use change in 2001, 2006, 2011, 2016, 2021, 2026, and 2031. After each simulation, the total water balance error, total overland flow, baseflow, infiltration, and evapotranspiration were calculated and tabulated. The simulated river hydrograph at the end of the Elbow River after each simulation was also obtained.

Results

Based on the sensitivity analysis of MIKE-SHE/MIKE-11, the two main parameters that were adjusted during the calibration were the saturated hydraulic conductivity (1e-012 m/s for urban and clear-cut, 8e-008 m/s for the remaining area) and the surface roughness for the river bed (Manning's M: 15). The remaining parameters were assigned the default values and physical values appropriate to the Elbow River watershed. The Nash and Sutcliffe coefficient of efficiency values calculated for the calibration period (1985-1990) and for the validation period (2000-2005) were 0.56, 0.52, 0.79, and 0.75 using monthly data based on different hydrometric stations. The total water balance error during all model runs of MIKE-SHE was less than 1%. These values indicate an adequate performance of MIKE-SHE/MIKE-11.

Simulations carried out between 2001 and 2031 based on a 'business as usual' scenario showed a 65% increase in urbanization and 36% decrease in total forest areas in the watershed, which resulted in a reduction of 1%, 13%, 2% in total evapotranspiration, baseflow and infiltration respectively, 7% increase in total overland flow, and 4% reduction of total annual river flow.

Conclusions

This study demonstrates that land-use changes affect the hydrological processes significantly in the watershed and that these effects are mainly caused by the increase of urban development and the diminution of forested areas. The model shows a decreased water retention capacity in the watershed which increases the total overland flow to the main river. This can increase the occurrences of flash flood in the area in a rainfall event of high magnitude. With the reduced infiltration, the ground water storage can decrease. The results also show that due to the reduced baseflow to the main river as a consequence of the above, the total annual river flow is reduced in the Elbow River. This might have a negative impact on the total water supply to the Glenmore reservoir with the reduction of total supply of drinking water to the city of Calgary from the reservoir. The reduction of total annual flow of the river and reduced ground water will further affect the existing and new surface water and groundwater extractions, respectively.

Further work is in progress to improve the setup of the two models. Additional constraints and transition rules could be implemented in the CA model to better capture certain aspects of the dynamics of the watershed, such as the deforestation. Work is being carried out to integrate a physically-based comprehensive groundwater model and improve the calibration of the MIKE-SHE/MIKE-11 model. It is expected that this will lead to a better representation of the surface-groundwater interactions in the watershed.

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