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Impact of land-use changes on the hydrological processes in the Elbow river watershed in southern Alberta

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Abstract: Due to the rapid population growth and urbanization in the City of Calgary, the Elbow River watershed in southern Alberta covering 1238 km^2 has been subjected to considerable land-use changes over the last decade. The objective of this study is to assess the impact of land-use intensification simulated with a cellular automata (CA) model on the hydrological processes of the watershed using MIKE-SHE, a physically-based and distributed hydrological model. MIKE-SHE was calibrated for the period 1985-1990 and validated for the period 2000-2005. The calibration was achieved by comparing observed and simulated flow data. The CA model was calibrated using four land-use maps covering the period 1985-2001 and validated against the map of 2006. It was then used to forecast land-use changes over the period 2006-2031 at a five-year interval. Land-use based watershed characteristics were extracted from these simulated maps and transferred to MIKE-SHE to assess the impact on the hydrological processes in the watershed. Results of calibration and validation showed sufficient model performance. The total water balance error for all MIKE-SHE model runs was less than 1% of the total precipitation. Simulations carried out between 2001 and 2031 showed a 25% increase in urbanization (corresponding to 5% of the watershed area) in the watershed which resulted in a 2.6% increase in overland flow (OL), 2.3% reduction in evapotranspiration (ET), and a 11% increase of combined overland and base flow into the river flow.

***Keywords**:* Cellular automata, hydrological modelling, integrated modelling, MIKE-SHE, land-use change modelling

1. INTRODUCTION

Water is an essential component in our environment that humans often take for granted, and forecasting its availability for the next generation has become an essential task in planning and resource management for rapidly growing cities. Forecasting the spatial distribution of water availability requires hydrologic modeling of ground water and surface water. In growing cities, one of the primary factors that cause changes in water resources is the constant evolution in land use. Recent studies demonstrated the potential of an integrated modelling approach to evaluate the impact of land-use changes on water resources (Lin *et al.* 2006; Bithell and Brasington 2009). Lin *et al.* [2006] combined a land-use change model (CLUE-s) and a distributed/lumped hydrological model developed by Haith and Shoemaker [1987] to evaluate the impacts of land-use change scenarios on the hydrology and land-use patterns in the Wu-Tu watershed in Northern Taiwan. These authors found that the impact on hydrological processes was very significant and cumulatively influenced by land-use changes. Bithell and Brasington [2009] coupled three models representing society, ecology, and hydrology to investigate how demographic changes influence deforestation, which in turn affects the forest ecology, along with the stream hydrology and water availability. The authors found that as the number of households increased from 3 to 337 in 200 years of simulation, the predicted storm response becomes progressively flashier. The expansion of agriculture and the loss of forest contributed to a 4% increase in total evaporative losses, a 22% decrease in annual discharge and an 18% increase in the internal storage of water and loss to deep ground water.

The Elbow River watershed (Figure 1), which covers 1238 km^2 is located in southern Alberta, Canada. 65% of the watershed is located in the Kananaskis improvement district; the remaining area is divided among the municipal district of Rocky View (20%), the Tsuu T'ina Nation (10%) and the City of Calgary (5%) (ERWP: Elbow River Watershed Partnership website 2007). It is the source of the Glenmore reservoir which provides drinking water to the City of Calgary and to one in six Albertans. Due to the rapid population growth of the City of Calgary, this watershed has been subjected to considerable changes in the last decade (City of Calgary 2005). This area belongs to the Canada's Western Prairie Provinces, which lie in the rain shadow of the Rocky Mountains, and as a result, are the driest areas of southern Canada. It is predicted that in the near future, climate warming, through its effect on glaciers, snow packs and evaporation, will combine with cyclic droughts and rapidly increasing human activity in the Western Prairie Provinces to cause a crisis in water availability in this area (Schindler and Donahue 2006). Therefore, investigating the rapid changes in land-use in the Elbow River watershed and their impact on the land phase of the hydrological life cycle and on water availability is becoming a crucial issue.

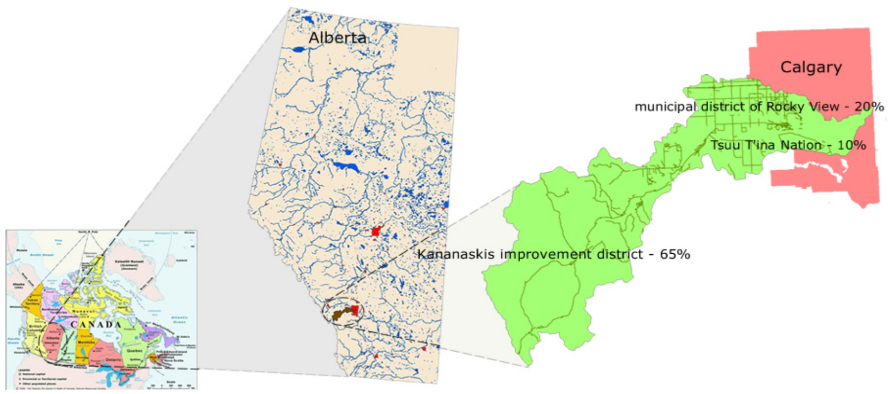

Figure 1. The study area – Elbow River watershed

To fulfill this goal, two dynamic models were chosen: 1) a land-use cellular automata (CA) applied to simulate land-use changes, and 2) a hydrological model, MIKE-SHE (combined with the MIKE-11 river model) to simulate the hydrologic cycle within the study area. CA models are remarkably effective at simulating spatial patterns and structures of the landscape. Unlike conventional land-use modeling techniques, they are spatially explicit, compatible with many spatial data formats, able to represent dynamic spatial processes, highly adaptable, able to simulate a wide variety of spatial behaviors, and simple while demonstrating a rich behavior (White and Engelen 2000). The MIKE-SHE flow model along with the MIKE-11 river 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 compared to other hydrological models (Sahoo *et al.* 2006). To forecast water availability accurately, it is important to simulate localized land-use changes and their impact on the water/hydrologic cycle at a spatially distributed level. It is expected that a hydrological model that operates at that level using physical properties that are both land-use based (e.g. surface roughness) and non land-use based (e.g. soil characteristics) will produce more detailed and potentially more accurate results compared to a model that operates at an aggregated (lumped) level (Refsgaard 1996, Yang *et al.* 2000). For these reasons, MIKE-SHE/MIKE-11 and a land-use CA model were chosen for this study.

2. OBJECTIVE

The overall goal of this project is to assess the impact of land-use changes on the hydrological processes and water resources in the Elbow River watershed by coupling a land-use CA model and the MIKE-SHE/MIKE-11 model. It is undertaken in collaboration with Alberta Environment and the Danish Hydraulic Institute in Cambridge Ontario, developer of MIKE-SHE/MIKE-11. This paper describes the approach used to calibrate and validate both models and the preliminary results achieved when linking them to forecast the impact of land-use changes on the hydrology of the watershed. When fully tested, it is expected that this integrated modelling system can be used as a regional spatial decision support tool by policy makers, water resource managers, and other stakeholders (e.g. watershed advisory councils) to guide land-use planning and water resource management in the context of urban growth, land-use intensification, and climate change.

3. METHODOLOGY

3.1 Datasets

Table 1 provides a description of the datasets used for the setup of both the land-use CA model and MIKE-SHE/MIKE-11. The data were collected from field surveys, scientific literature, and various online sources.

Table 1. Dataset collection and preparation

Data	Description on data gathering and processing
LAI – leaf area index	LAI values were calculated for each land-use class for each month of the year based on satellite derived spatially distributed LAI for the year 2000 and on scientific literature (in comparison to standard LAI values for different types of vegetation).
Root depth (RD)	Average RD values for commonly harvested crops (e.g. wheat, barley, canola, and tame hay) in southern Alberta were obtained from the literature. The temporal changes in root depth for the agricultural and other vegetation classes were also obtained from the literature.
Manning number M	Each land-use class was assigned a Manning's M roughness coefficient value based on the literature (Wanielista *et al.* 1997; Vieux 2004).
Ground water	The spatially distributed static ground water table was derived using the groundwater information system database prepared by the Groundwater Information Centre (GIC), Government of Alberta.
Climate data	Grided township climate data (temperature, precipitation, reference evapotranspiration) obtained from Alberta Agriculture. This data set was derived by applying interpolation procedures on measured climate data from weather stations across the province.
Topography	25 meter resolution, hydrologically corrected digital elevation model (DEM) was obtained from Alberta Sustainable Resource Development.
River cross sections	Approximately 50 cross sections surveyed in 2008 were combined with derived cross sections using DEM.
Water flow/level	Data from two selected hydrometric stations were used for the calibration of MIKE-SHE based on spatial location and data availability.
Land-use maps	Historical land-use maps were created from Landsat-TM satellite imagery acquired in the years 1985, 1992, 1996, 2001, and 2006.

3.2 Calibration and validation of the land-use CA model

A cellular automata (CA) is a dynamic simulation model that represents space as a matrix of regularly arranged cells. Each cell has its own state defined by a numerical value. The model incorporates transition rules that evaluate the next state of the current cell considering the values of the adjacent cells composing its neighborhood and some additional constraints that can be incorporated in the model. This neighborhood can either include four, eight adjacent cells or can be extended in which case additional adjacent cells within a predefined zone are considered. The state of each cell evolves through discrete time steps with transition rules applied to all cells iteratively (White and Engelen 2000).

The CA model used to simulate the land-use changes in the Elbow watershed consists of two interrelated modules: the first one is designed for the extraction of the transition rules and the model calibration, while the second one is used to run simulations and generate land-use maps at each time step (Hasbani and Marceau 2007). The model is raster based and was implemented at a resolution of 60 m to capture the required land-use details in the study area. The neighborhood was designed to approximate a disc of 900 m around a central cell and several circular rings of size 180, 300 and 800 m were used to evaluate the influence on the central cell.

The model was calibrated using historical land-use maps generated from Landsat Thematic Mapper satellite images acquired during the summer of 1985, 1992, 1996, 2001, and 2006. These maps contain nine land-use classes, namely: water, road, rock, evergreen forest, deciduous forest, agriculture, rangeland/parkland, built-up, and clear-cut areas (Figure 2). A detailed analysis of these maps revealed that four factors were driving the historical land-use changes: the distance to a main river, the distance to downtown Calgary, the distance to a main road, and ground slope. The calibration procedure implemented by Hasbani and Marceau [2007] involved the following steps. First, the historical land-use maps and the maps corresponding to the driving factors were read and the number of cells of a particular state in the neighborhood of each central cell was computed. For each type of land-use change, all the cells that have changed state in the historical land-use maps were identified. Frequency histograms were built to display the value of the driving factors and the number of cells of each land use located within the neighborhood of these cells that have changed state. These histograms were displayed and interpreted to identify the range of values of each parameter to be included in the conditional transition rules. This information was then automatically translated into mathematical transition rules, allowing the model to identify the most likely transition and transition rule to be applied on any neighborhood configuration. Eight cell state transitions (evergreen to agriculture, deciduous to agriculture, evergreen to built-up, deciduous to built-up, agriculture to built-up, rangeland/parkland to built-up, rangeland/parkland to agriculture, agriculture to rangeland/parkland) were simulated using this model.

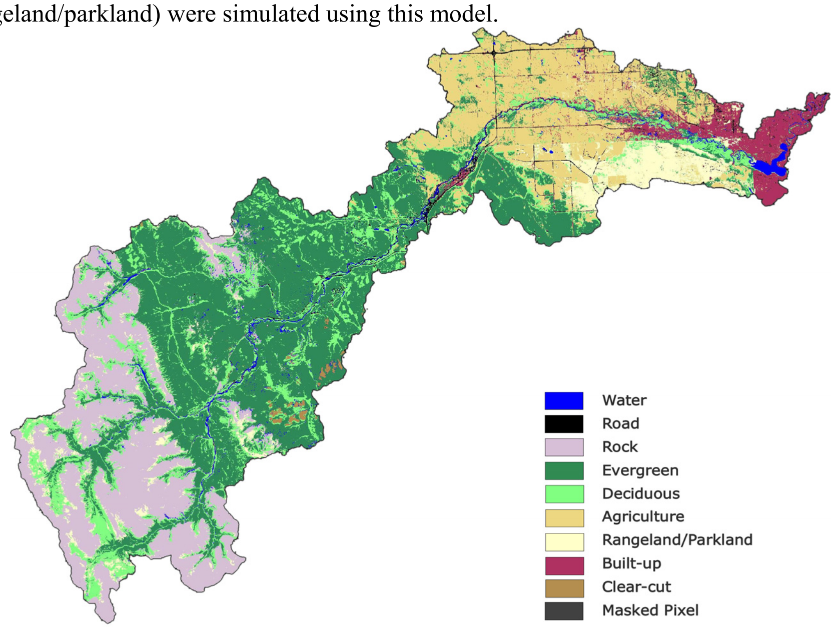

Figure 2. Land-use map of 2001

Since Hasbani and Marceau [2010] found that the land-use CA model wass sensitive to the neighborhood configuration, a sensitivity analysis was carried out by selecting various neighborhood configurations using the nine land-use classes, the eight state transitions, and the four driving factors. For each tested neighborhood configuration, the quality of the calibration was verified by running the CA model calibration from the year 1985 to the year 2001 and comparing the simulated map of 2006 (produced from running simulation from the year 2001 to the year 2006 using the 2001 land-use map as the initial map) with the land-use reference map of the same year. A percentage of spatial correspondence was calculated using the state of the cells within a neighborhood of five cells, dismissing their spatial location, for the comparison. The best neighborhood configuration for the land-use CA model was identified as three neighborhood rings with a number of 5, 9, and 16 cells of radius for each ring. The quality assessment based on this neighborhood configuration showed a 87% level of spatial correspondence. Using the same neighborhood configuration, the land-use CA model was calibrated using the historical land-use maps of 1985, 1992, 1996, 2001, and 2006. In order to improve the simulation results, constraints were applied. Using historical and forecasted population data within the Calgary economic region from the year 1996 to 2019 (Calgary economic development 2006), global constraints of urban growth within the Elbow River watershed were set. Urban growth within the Tsuu-T'ina nation region was forbidden using a local constraint due to the fact that this region operates on its own administrative policies and that new urban development is not part of their planning.

3.3 Calibration and validation of the MIKE-SHE/MIKE-11 model

In MIKE-SHE, all the processes are physically based, distributed and equally weighted (methods can be selected to simulate each hydrological process at equal complexity) (DHI 2007). Within MIKE-SHE, the canopy interception module along with the evapotranspiration module and the snowmelt module simulate the vegetation-based evapotranspiration and infiltration. The root zone module along with the one-dimensional unsaturated zone module simulates the unsaturated groundwater flow, while the 3-dimensional saturated flow module simulates the saturated groundwater flow. The overland and channel flow module simulates the overland surface flow and flooding while MIKE-11 simulates the channel flow in rivers and lakes. MIKE-11 operates as a separate model integrated with MIKE-SHE.

Considering the complexity of the methods within MIKE-SHE/MIKE-11, the simulation requirements, and the data availability, a conceptual model was constructed to carry out the hydrological modeling. It was decided to use the two-layer water balance method to simulate the evapotranspiration and the unsaturated zone (UZ) flow, the 2-D diffusive wave approximation of the St. Venant equation to simulate overland flow, the linear reservoir method to simulate the saturated zone (SZ) flow, and the fully dynamic 1-D St. Venant equation to simulate the river flow. The spatially distributed data used to configure MIKE-SHE/MIKE-11 include: topography, daily precipitation, reference evapotranspiration (ET), max/min temperature, Manning's roughness coefficient, leaf area index (LAI), root depth (RD), soil distribution with soil characteristics, groundwater table, and river cross sections. The non-spatially distributed data were the ET surface depth and the linear reservoir method parameters for interflow and base flow reservoirs.

Sensitivity analysis was conducted for the following parameters: saturated hydraulic conductivity, degree day coefficient, detention storage, surface roughness for the river, and time constants for interflow and base flow of the linear reservoir model used for SZ flow. The model calibration was then carried out using observed discharge data measured at two hydrometric stations along the main river channel and using the total water balance as an indicator. The performance of the model was evaluated using the Nash and Sutcliffe efficiency (NSE) calculated between simulated and observed flow hydrographs over a one year period. The calibration years of 1990, 1991, and 1987 involved using the simulation of five years of data prior to each corresponding year (i.e.: 1985-1990, 1986-1991, 1982-1986) to stabilize the river conditions. These time periods were selected based on different climate conditions representing average (1991), wet (1990), and dry (1987) conditions and the land-use change map of 1985. The model was validated using the land-use map of 2001 and the NSE was calculated for the year 2005 (simulation period: 2000-2005). The NSE was also calculated for the period 2000-2005.

In addition to the surface runoff, interflow, and base flow, the main Elbow River also receives water from the Elbow Lake at the head of the Elbow River, which is not included in the current MIKE-SHE model setup due to data unavailability. Furthermore, recent studies done in the Elbow River watershed showed that in the upstream part of the river, the bank storage accounts for about 73% of the actual groundwater discharge during a normal base flow recession (Manwell 2005). The linear reservoir model selected to simulate groundwater has a simple method to produce interflow and base flow based on time constants, and sub-catchment reservoirs configured for the watershed. Therefore it does not have the capacity to account for complex groundwater surface flow interactions and does not simulate the bank storage effect for the Elbow River (DHI 2008). Due to the above reasons, the MIKE-SHE/MIKE-11 model setup underestimated the flow hydrograph during the calibration. To compensate for this, a two constant value head water inflow boundary condition was added to MIKE-11 channel model as boundary inflow. The most fitting values of inflow for an improved model NSE were derived during the calibration.

3.4 Simulations

The calibrated land-use CA model was used to simulate future land-use maps for the years 2011, 2016, 2026, and 2031. Hydrological simulations were then carried out to investigate the impact of land-use changes on hydrological processes using the land-use maps of 2001, 2006, 2011, 2016, 2021, 2026, and 2031. The spatial resolution used for the hydrological simulations was 100 m. For each simulation of MIKE-SHE, the spatial distribution of the land-use classes was changed according to the simulated land-use maps produced by the land-use change model. The temporal vegetation properties (LAI and RD) for each land-use class (including the changes of LAI, and RD over time), and climate data (daily precipitation, reference evapotranspiration, daily temperature) that were used for the simulations were the data corresponding to the time period 2000-2005. For each simulated land-use map, maps of surface roughness (Manning's M) were re-created for each land-use class and the spatial distribution of LAI and RD values was changed.

4. RESULTS

A high level of spatial correspondence (87%) was obtained between the simulated land-use map and the reference map of 2006 when applying constraints to urban growth in the CA model. While further testing is needed to assess and potentially improve the quality of the simulation results, the calibration of the CA model was considered sufficient at this point to extract the land-use parameters needed for MIKE-SHE from the simulated maps.

The sensitivity analysis conducted with MIKE-SHE showed that the distributed surface roughness highly affects both the total water balance error and the goodness-of-fit (NSE). Saturated hydraulic conductivity, degree day coefficient, detention storage, surface roughness of the river bed, and time constants for interflow and base flow affected the goodness-of-fit to varying degrees. The two main parameters that were adjusted during the calibration were the saturated hydraulic conductivity (1e-012 m/s for urban, 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 total water balance error during all model runs was less than 1%. The MIKE-SHE/MIKE-11 model setup did not provide the expected level of goodness-of-fit based on hydrometric station measurements of water flow for the period 1985-1990. However, the goodness-of-fit for the calibration and validation was greatly improved with the introduction of two constant level water inflow at the head of the Elbow River. For the year 1990, based on a comparison of simulated and observed flow data at two hydrometric stations, NSE values of 0.53 and 0.50 were obtained. For the year 1991 (the average climate condition year), and 1987 (dry), the obtained NSE values were less than 0.5. Within the calibration period, the model performed well for wet climate conditions. This was confirmed with the validation carried out for the year 2005 with annual precipitation being above average. The NSE obtained for the year 2005 and the period 2000-2005 was 0.63 and 0.27, respectively, at one hydrometric station. The time step used for simulated streamflow in all simulations was 24 hours. The reported NSE values using a daily time step from the literature range from -0.23 to 0.89. After calculating monthly averages from daily observed and simulated data to derive NSE value using 30-day time step (monthly), the NSE calculated for the validation for the period 2000-2005 was 0.79. NSE values for all MIKE-SHE simulations were higher using the monthly interval than the daily interval. General performance ratings for recommended statistics for a monthly time step in hydrological modeling reveal that NSE above 0.5 is satisfactory (Moriasi *et al.* 2007).

The land-use maps (historical and simulated) for the years 2001 to 2031 (Figure 3) reveal an increase of 25% in urban areas (5% of the total area), an increase of 41% in rangeland/parkland areas (8% of the total area), an increase of 33% in agricultural areas (20% of the total area), a 42% reduction in deciduous vegetation/forest areas (19% of the total area), and a 13.5% reduction in evergreen vegetation/forest areas (47% of the total area). When using these maps to extract the land-use parameters required to carry out the simulations with MIKE-SHE, the results indicate a 2.6% increase in overland flow (OL), a 2.3% reduction in evapotranspiration (ET), and a 11% increase of combined overland and base flow (OL+BF) into the river flow (Table 2).

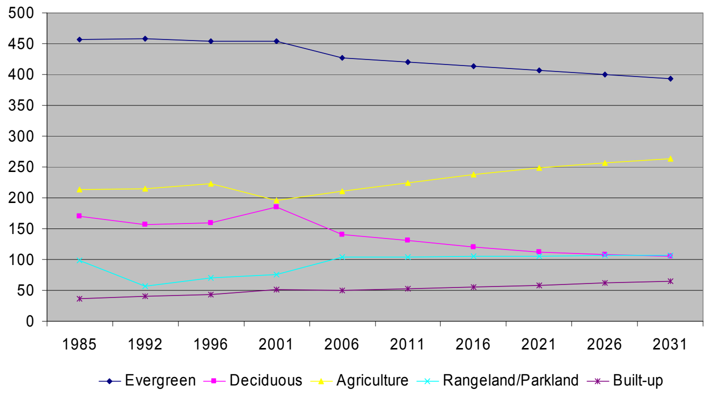

Figure 3. Changes in the total area of different land uses within the Elbow River watershed during the period 1985-2031

Table 2. The amount of evapotranspiration (ET), overland flow (OL), and combined overland and base flow (BF) into the river in storage depth (mm) from 2001 to 2031

Year	ET (mm)	OL (mm)	BF (mm)	OL+BF (mm)
2001	1697	340	433	773
2006	1685	342	493	835
2011	1678	343	498	841
2016	1671	344	502	846
2021	1666	344	505	849
2026	1661	348	507	855
2031	1657	349	509	858

5. CONCLUSION AND FUTURE WORK

The validation method used to evaluate the quality of the calibration provides a general assessment of the simulated results, but it does not distinguish between agreement due to land-use persistence and agreement due to land-use change. Therefore, the land-use CA model needs to be further tested to ensure that the accuracy of the calibration is sufficient and to improve the confidence in the simulation results. The performance of MIKE-SHE/MIKE-11 in simulating river flow hydrographs improved after compensating for the head water and bank storage effect. Despite the limitations with the current model implementation, adequate performance was achieved for both the land-use CA and MIKE-SHE/MIKE-11 models. The simulations ran for forecasting up to 2031 demonstrated that land-use changes progressively increase the impact on the hydrological processes in the watershed. The reduction of evapotranspiration into the atmosphere creates less atmospheric vapor and possibly have a long-term impact on the annual precipitation. Increased surface runoff and groundwater discharge into the river reveals a rising flow in the river streams and possible long term rise of the water level. Reduced infiltration creates less groundwater recharge and will have a negative impact on ground water storages in the study area. The study also demonstrates that the above changes are mainly caused by the increased urbanization, agricultural activities, and decreased evergreen and deciduous forest areas.

Additional work is in progress to improve the simulation of land-use changes using an object-based CA model that is not sensitive to cell size and neighborhood configurations (Moreno *et al.* 2009). An interface will be built to automatically extract and input the land-use parameters required for MIKE-SHE. Furthermore, a more detailed and comprehensive groundwater component will be combined with the MIKE-SHE surface water component. With this, three-dimensional Darcy equations will be used to simulate the groundwater flow in order to better represent complex surface-ground water interactions.

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