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# Landscape-scale control of carbon budget of Lake Simcoe: A process-based modelling approach

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ABSTRACT

We present an application of the Integrated Catchments model for Carbon (INCA-C) to simulate dissolved organic carbon (DOC) dynamics in two main tributaries of Lake Simcoe. This is the first application of the INCA-C model to a large watershed with mixed agricultural, urban and forest land use. Understanding DOC dynamics in the Lake Simcoe watershed will aid in understanding the spatial and temporal patterns of organic and metal contaminant transport in the watershed which should, in turn, lead to improved watershed management. We were able to successfully simulate flows in the Beaver River and to capture the seasonal and inter-annual patterns in DOC concentration in the Beaver and White Creeks, two of Lake Simcoe's major tributaries. Sensitivity analysis showed the importance of hydrology and land use in controlling surface water DOC. The success of the model application presented here suggests that some of the same processes which control DOC in headwater watersheds are also operating in larger river basins.



## Introduction

Concentrations of dissolved organic carbon (DOC) in surface waters have exhibited different trends in regions of the world due to differences in the landscape processes that control organic matter production and transformation in the environment. Widespread increases in DOC have been reported in European watersheds but show mixed trends in North American surface waters (Monteith et al. 2007). This has made it difficult to extrapolate temporal patterns in DOC dynamics from one region to another.

Several mechanisms have been proposed to explain the observed temporal trends in DOC. These include increasing frequency of summer drought (Schindler et al., 1997), changes in acid deposition (Evans et al., 2006), incident solar radiation (Hudson et al. 2003) and altered hydrological cycles due to land use change (Tranvik and Jansson, 2002).

Changing surface water DOC is a concern for several reasons. In addition to being a potential source of greenhouse gases to the atmosphere, DOC provides a terrestrial subsidy for the aquatic food web (Farjalla et al, 2006) and transports organic contaminants (Balakrishna et al., 2006; Schindler et al., 1997). Furthermore, DOC protects aquatic organisms from the harmful effects of UV-B radiation (Molot et al., 2004). Changes in surface water DOC can alter nutrient dynamics and increase algal blooms (Goodale et al., 2005), although very high DOC can impair primary production (Drakare et al., 2002; Górniak et al., 2003).

Increased DOC can enhance bacterial production and reduce the availability of dissolved oxygen (de Wit et al., 2007). The toxicity and bioavailability of trace metals such as copper (Ashworth and Alloway, 2007), lead (Klaminder et al., 2006) and mercury (Ravichandran, 2004) are affected by DOC. It controls water acidity (Aherne et al., 2008) by buffering acid-base equilibria of soft-water systems. It can also form a potential carcinogenic precursor with halogenated compounds both in nature and during water treatment practices (Chow et al., 2003; Katsoyiannis and Samara, 2007). For these reasons, DOC is an important regulator of ecosystem function and possibly human health. Understanding the controls on DOC will help watershed managers design effective mitigation strategies to protect water resources as our environment changes.

Lake Simcoe is the largest lake in southern Ontario, Canada (excluding the Great Lakes). The lake and its watershed are subject to pressures from both agriculture and increasing urbanization. The watershed is home to approximately 350,000 people. The lake supports an important recreational fishery, provides drinking water for eight communities and receives discharges from 15 sewage treatment works. Changing organic carbon inputs from the surrounding rivers may be affecting the Lake Simcoe ecosystem. A process-based biogeochemical model operating at a basin scale that incorporates potential effects of landscape regulation and climate change is required to model riverine organic carbon inputs to Lake Simcoe.

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Here, we evaluate the Integrated Catchments model for Carbon (INCA-C) as a means of simulating riverine DOC dynamics in the Lake Simcoe watershed. The INCA-C model applications presented here represent the first time that the model has been used to simulate DOC dynamics in a large basin in which forests are not the dominant land cover type. The main objective of this paper is therefore to test the effectiveness of INCA-C in simulating DOC seasonality in two sub-watersheds of the Lake Simcoe (Beaver and White Creeks) before applying the model to other, contrasting tributaries within the watershed.

## Study site

Lake Simcoe (44° 25′ N, 79° 20′ W) is a dimictic, hard water lake with a watershed area of approximately 3621 km$^2$. The terrestrial area of the watershed is approximately 2899 km$^2$ (80%). The lake itself has a surface area of 722 km$^2$ (20%) (Winter et al., 2007). The Beaver and White Creeks are located in the eastern part of Lake Simcoe watershed (MOE and LSCRA, 2009). Both rivers have dendritic drainage structure and similar patterns of land use (Table 1). However, there may be considerable heterogeneity within land cover types. In the model applications presented here, intensive and non-intensive agriculture are lumped as agriculture. Coniferous, deciduous, mixed forest and woodlands are lumped as forest. The lumped wetland land use type contains about 35 different wetland-like categories.

The Beaver River drains an area of 282 km$^2$ while the White Creek drains an area of 90 km$^2$. Beaver River flows have been monitored by Environment Canada (EC, site 02EC011, Environment Canada, 2009). Flows in the White Creek are not gauged but were simulated from calibration functions from Beaver River. The EC weather station at Woodville supplied air temperature and precipitation data for both sites. The Woodville station (44° 24′ N, 78° 58′ W) is situated at the boundary of both subwatersheds. This suggests that it might be representative of the climatic conditions in both subwatersheds.

Data on DOC from January 1994 to July 1997 were available for both the Beaver and White Creeks. DOC was analyzed by oxidizing the acidified supernatant of samples collected in acid-persulfate medium in UV digester. This was then dialyzed and measured by an AutoAnalyzer II (AAII) Colorimeter using loss of absorbance in buffered alkaline phenolphthalein. All DOC analyses were performed by the MOE laboratories at Dorset and Toronto.

## Model description

INCA-C is a dynamic, semi-distributed mass balance model that can be used to investigate the biogeochemical dynamics of carbon cycling within a watershed. It is part of a larger family of water quality models developed for simulating the behavior of nitrogen (Whitehead et al. 1998), phosphorus (Wade et al. 2002) and sediment (Jarritt and Lawrence, 2007) in rivers. All members of the INCA family operate on a daily time step and simulate both aquatic and terrestrial processes.

INCA-C can be described as a “white box” model that links the effect of different landscape elements, in-soil biogeochemistry, and aquatic processes with hydrologic flow paths to simulate watershed-wide DOC dynamics. Thus, INCA-C explicitly simulates the retention and transport of DOC in aquatic systems as well as changes in the solid organic carbon (SOC) pools in organic and mineral soils (Futter et al., 2007).

**Table 1**
Sub-watershed area and land use for Beaver River and White Creek.

| Subwatershed | Area (km$^2$) | Land use proportions used for calibration | | | |
|---|---|---|---|---|---|
| | | Forest (%) | Agric (%) | Urban (%) | Wetland (%) |
| Beaver | 282 | 9 | 56 | 17 | 18 |
| White | 90 | 7 | 59 | 14 | 20 |

With a calibrated parameter set derived from current conditions, INCA-C can be used to project the possible impacts of environmental stressors such as climate and land use change as well as point source inputs from waste water treatment plants on riverine carbon biogeochemistry of surface water DOC. The entire INCA-C model chain is composed of the spatial and terrestrial hydrologic components, and in-soil and in-stream carbon processes. INCA-C is driven by several data inputs to each of these model components. Sub-watershed boundaries, stream length and area and land cover proportions are derived using geographic information system (GIS) and are used as spatial inputs to the model.

Application of any version of INCA requires estimates of soil moisture deficits (SMD) and hydrologically effective rainfall (HER). These are obtained from an external rainfall-runoff model. Typically, the Hydrologiska Byråns Vattenbalansavdelningen (HBV) rainfall-runoff model (e.g. Lindström et al., 1997) is used to simulate these time series. The HBV version used here was developed in the STELLA modelling software (ISEE, 2008). HBV is calibrated first using observed stream flow, temperature and precipitation. Outputs of HER and SMD from HBV are then used as inputs to INCA-C (Fig. 1).

The HBV-simulated SMD is an estimate of the difference of maximum soil water content and net soil moisture balance or water required by the soil to return to field capacity. This has been described by Finkele et al. (2006) as capillary water in the soil that cannot be acted upon by force of gravity. This is particularly important in this modelling process, as it determines the infiltration capacity of the soil that, in turn, determines microbial turnover of carbon in the soil. HER represents the net precipitation, either as rainfall or snowmelt, that can infiltrate after the effect of soil water withdrawal caused by evapotranspiration. Evapotranspiration was simulated within the HBV soil moisture routine from mean monthly air temperature using the Thornthwaite method (Kumar et al., 1987).

Within INCA-C, in-soil and in-stream carbon stocks of DOC, dissolved inorganic carbon (DIC) and solid organic carbon (SOC) are simulated (Futter et al., 2007). Terrestrial and aquatic carbon stocks and processes are simulated. In the terrestrial component, carbon processes and exchanges are represented within litter layer (if forest), organic and mineral soil layers. The aquatic component has open water and sediment compartments. Both photolytic and microbial

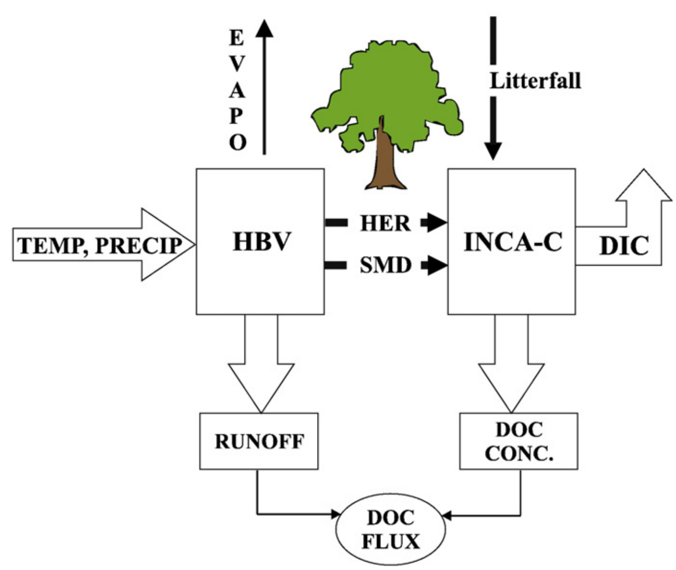


**Fig. 1.** Conceptual structure of models used. Evapo means evapotranspiration. HER means hydrologically effective rainfall. Net precipitation that infiltrates into the soil for biogeochemical processes excluding snow and evapotranspiration. SMD means soil moisture deficit. An estimate of soil dryness for soil microbial mediated processes.