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Simulation of monthly dissolved organic carbon concentrations in small forested watersheds

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ABSTRACT

Dissolved organic carbon (DOC) plays an important role in both terrestrial and aquatic ecosystems. In-stream DOC concentration is an important indicator of water quality, because high in-stream DOC concentrations naturally lead to reductions in dissolved oxygen. Recent studies indicate that DOC is responsible in transferring toxic metals (e.g., mercury, Hg) from terrestrial sources to aquatic ecosystems. However, assessing DOC or Hg dynamics is fairly challenging as a result of extreme spatiotemporal variation. Typically, process-based models with short-to-medium term temporal resolutions are required to model DOC and Hg dynamics. The objective of this research is to develop a watershed-based monthly DOC production and export model that integrates the treatment of (i) forest-litter decomposition (DOC production), (ii) wetland-to-watershed area ratio (DOC storage), and (iii) relevant hydrological processes (DOC export) in the simulation of in-stream concentrations. Model results are compared against DOC concentrations collected at the stream outlets of two separate forested watersheds in Kejimkujik National Park, Atlantic Canada. Comparisons for the two watersheds show that predicted monthly DOC concentrations are generally in good agreement with field-based concentrations, giving R^2-values of 0.61 and 0.63 for Pine Marten Brook watershed and 0.72 and 0.75 for Moose Pit Brook watershed for model calibration and validation, respectively.

1. Introduction

Dissolved organic carbon (DOC) leached from terrestrial ecosystems is an important source of energy for aquatic ecosystems in small watersheds (Wetzel et al., 1972; Wetzel, 1983; Pace, 1993; Kim et al., 2010). In streams, DOC can be utilised by bacteria and other microorganisms as food substance (Wetzel, 2006). Transport of terrestrial C to streams is an important component of the overall C cycle of ecosystems (Ludwig et al., 1996; Warnken and Santschi, 2004; Battin et al., 2009).

DOC concentration is an important water-quality indicator as high in-stream DOC concentrations and heightened microbial activity naturally lead to depletion of oxygen in streamwater (Yano et al., 2000; Moore et al., 2003). Within-watershed transfer of DOC also facilitates the transfer of toxic metals (e.g., mercury, Hg) from terrestrial to aquatic ecosystems (Driscoll et al., 1995, 2007; Krabbenhoft et al., 1995; Scherbatskoy et al., 1998). As a result, opportunity exists to model in-stream Hg concentrations from predictions of DOC concentrations (Dennis et al., 2005; Meng et al., 2005; Reddy et al., 2007).

In the scientific literature there are three types of DOC-export models: (i) process-based models (Neff and Asner, 2001; Futter et al., 2007), (ii) steady-state models (Currie and Aber, 1997; Canham et al., 2004), and (iii) data-based, statistical models (Meng et al., 2005), all with their own limitations. For instance, process-based models rarely address the impact of topography and vegetation cover on within-watershed DOC production and export processes and steady-state and empirical models are incapable of simulating seasonal dynamics, because of their internal structure and assumptions. Compared with existing process-based models, the integrated model of this study explicitly addresses external factors that directly impact the production of DOC, including vegetation cover, topography, and water flowing through the decomposing litter. This DOC model is the only model of its type in the scientific literature.

For instances when annual average concentrations of Hg and DOC may meet water-quality standards, individual concentrations used in the calculation of the annual average may actually exceed the standard. Therefore, it would be helpful to develop a dynamic model that can predict DOC concentrations, and those of

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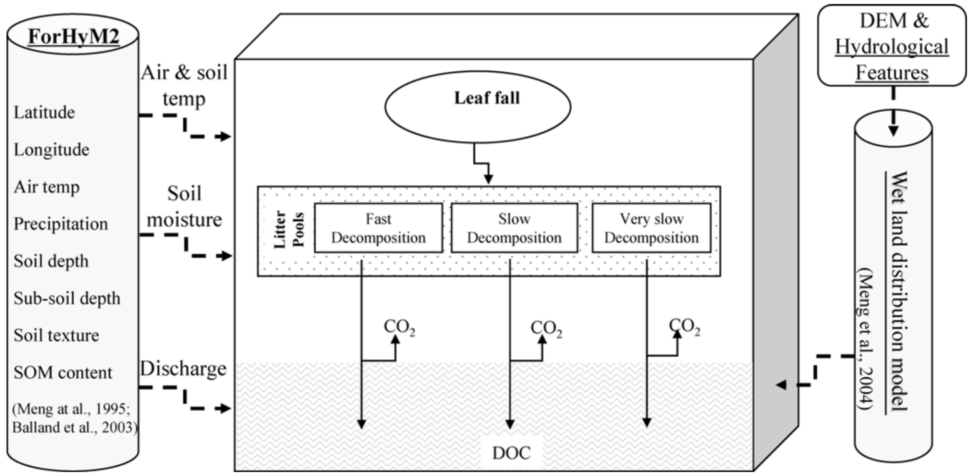

Fig. 1. Structure of the DOC production and export (in-stream concentration) simulation model. ForHyM2 is used to simulate variation in soil temperature and water content and stream discharge. Modified monthly FLDM is used to simulate monthly litter decomposition. Output from the new FLDM-component is used as input to the DOC model in estimating DOC export from decomposing litter. Wetland-to-watershed-area ratio derived from the wetland distribution model is used to calculate within-watershed DOC export from upland and wetland areas of the watersheds. SOM refers to soil organic matter.

associated contaminants (e.g., Hg), over shorter time intervals. The objective of this research is to develop a watershed-based DOC production and export model that integrates the processes of (i) forest-litter decomposition (and DOC production), (ii) wetland-to-watershed area ratio (DOC storage), and (iii) relevant hydrological processes (involved in DOC export) in the calculation of monthly in-stream DOC concentrations. Integration of these three concepts into a single unifying structure provides a first attempt to model seasonal DOC-concentration dynamics in small forested watersheds from a mechanistic, forest-process standpoint. The calibrated model is subsequently validated by comparing model predictions of monthly DOC concentrations at the outlet of two small forested watersheds (containing 1st- to 2nd-ordered streams) with stream-based concentrations.

2. Conceptual model

A series of DOC sources, sinks, and fluxes can be identified as DOC moves from terrestrial to aquatic ecosystems, all of which are mediated by local hydrology (Moore, 1997). In forest ecosystems, DOC production is largely controlled by forest-litter decomposition and to some extent, by forest throughfall and root exudates (McDowell and Likens, 1988; Qualls and Haines, 1991; Currie and Aber, 1997; Moore, 1997; Müller et al., 2009). Rate of litter decomposition and DOC production depends on the chemical composition of the decomposing organic matter (OM) and the internal environment of the substrate, particularly its core temperature and liquid-water content (Godde et al., 1996; Currie and Aber, 1997; Hongve, 1999). When OM decomposes, the partly decomposed material becomes water soluble and is flushed out as water flows through the decomposing litter (Gosz et al., 1973; Yavitt and Fahey, 1985; Thurman, 1985; Stevenson, 1994; David et al., 1995; Zsolnay, 1996).

DOC production and export in this integrated model is controlled by three main factors, i.e., (i) litter decomposition, (ii) wetland-to-watershed-area ratio, and (iii) water movement through the decomposing litter. Fig. 1 gives the overall structure of the integrated DOC production and export model.

Litter decomposition in the integrated DOC model (Fig. 1) is simulated with a modification of the Forest Litter Decomposition Model (FLDM) described in Zhang et al. (2007, 2010). As in the dissolved organic carbon model (DOCMOD), the production of DOC is assumed to be mostly associated with decomposing leaf and root litter and, to a smaller extent, decomposing coarse woody debris (Currie and Aber, 1997).

DOC export is expected to increase with an increase in surface water flow through the decomposing litter layer (Eckhardt and Moore, 1990; Trofymow et al., 2002). Flushing of DOC from the decomposing forest litter to nearby streams is addressed empirically with Eckhardt and Moore's (1990) regression equations (see Section 3.4).

In general, wetlands store a smaller amount of DOC than upland areas, as oxidised upland soils tend to absorb more DOC than reduced, saturated wetland soils (Fiedler and Kalbitz, 2003). In our model, the impact of wetlands on DOC export is simulated according to the relationship between in-stream DOC concentration and a wetland-to-watershed area ratio (Eckhardt and Moore, 1990). The area ratio is calculated from a raster-based wetland-mapping procedure developed by Meng et al. (2004).

DOC absorption by mineral soil is modelled as a fraction of DOC production from litter decomposition based on the fact that over time DOC absorption is in equilibrium with DOC input in both upland and wetland areas (Nodvin et al., 1986).

Input to the integrated DOC production and export model, includes (i) soil temperature and soil water content to simulate forest-litter decomposition with a modified form of FLDM (Fig. 1) and (ii) water discharge, to simulate DOC export. Timeseries of these variables are generated with an existing Forest Hydrology Model (ForHyM2; Meng et al., 1995; Balland, 2003, Fig. 2).

3. Model specifics

3.1. Forest Hydrology Model

ForHyM2 is site-specific and simulates within-forest environmental conditions at a daily timestep. Results from model simulations with ForHyM2 have been previously used as input in ecosystem nutrient cycling (Zhu et al., 2003) and forest-litter decomposition modelling (Zhang et al., 2008, 2010). ForHyM2 is composed of a heat-conduction and water-flow component. The heat-conduction component simulates forward and backward heat transfer between the forest canopy, the forest floor, the upper soil, and lower soil. The water-flow component addresses the processes of (i) precipitation, either in the form of rain or snow, (ii) forest interception, (iii) evapotranspiration, (iv) throughfall, (v)