Science of the Total Environment 473–474 (2014) 326–337

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Uncertainty assessments and hydrological implications of climate change in two adjacent agricultural catchments of a rapidly urbanizing watershed

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HIGHLIGHTS

- Predictive uncertainty in runoff is often larger in managed than pristine catchments.
- CGCM3 projected warmer (4 °C) and longer growing season (26%) in the future.
- Behavioral, not optimum parameter sets should be considered in impacted watersheds.
- Model results show adjacent catchments differ in their snow and groundwater dynamics.
- Human activities exacerbate the differences in integrated hydrological responses.

ARTICLE INFO

Article history:
Received 20 October 2013
Received in revised form 6 December 2013
Accepted 7 December 2013
Available online 27 December 2013

Keywords:
Statistical downscaling
Phenology
Climate change
Lake Simcoe
Hydrological change
Uncertainty analysis

ABSTRACT

Lake Simcoe is the most important inland lake in Southern Ontario. The watershed is predominantly agricultural and under increasing pressure from urbanization, leading to changing runoff patterns in rivers draining to the lake. Uncertainties in rainfall–runoff modeling in tributary catchments of the Lake Simcoe Watershed (LSW) can be an order of magnitude larger than pristine watersheds, hampering water quality predictions and export calculations. Here we conduct a robust assessment to constrain the uncertainty in hydrological simulations and projections in the LSW using two representative adjacent agricultural catchments. Downscaled CGCM 3 projections using A1B and A2 emission scenarios projected increases of 4 °C in air temperature and a 26% longer growing season. The fraction of precipitation falling as snow will decrease. Spring runoff is an important event in LSW but individual HBV best calibrated parameter sets under-predicted peak flows by up to 32%. Using an ensemble of behavioral parameter sets achieved credible representations of present day hydrology and constrained uncertainties in future projections. Parameter uncertainty analysis showed that the catchments differ in terms of their snow accumulation/melt and groundwater dynamics. Human activities exacerbate the differences in hydrological response. Model parameterization in one catchment could not generate credible hydrological simulations in the other. We cautioned against extrapolating results from monitored to ungauged catchments in managed watersheds like the LSW.

1. Introduction

Long term monitoring and observations provide increasing evidence of climate change signals on ecosystem functioning (Campbell et al., 2005; Euskirchen et al., 2007; Menzel and Fabian, 1999; Tetzlaff et al., 2013; Oni et al., 2013a; Vincent and Mekis, 2006; Zhang et al., 2000). These trends are likely to continue as global climate models (GCM) project a warmer future with intensification of hydroclimatic cycles (Huntington, 2006). While there are uncertainties surrounding quantification of the magnitude of these changes, the evidence for climate-related changes is robust enough to devise mitigation and adaptation plans for the future.

Climate drives the hydrological cycle; it is a first order control which drives other biogeochemical processes (Laudon et al., 2013; Oni et al., 2013a). Climate change has led to greater warming of the earth and could impact hydrological processes at both spatial and temporal scales. Possible impacts include changes in runoff duration and distributions, as well as magnitude and frequency of extreme events (Arnell, 2004; Barnett et al., 2005; Cunderlik and Simonovic, 2005). The impact of

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http://dx.doi.org/10.1016/j.scitotenv.2013.12.032

climate change would not be uniform throughout the world. For example, Canada has experienced a greater warming of approximately 0.3 °C (Vincent and Mekis, 2006; Zhang et al., 2000) above the global average of 0.7 °C reported by the International Panel on Climate Change (IPCC) by the end of the 20th century (IPCC, 2007). One possible explanation that has been offered is the high latitude location of Canada (e.g. Tetzlaff et al., 2013; Laudon et al., 2013).

While efforts to better understand the potential impact of climate change on local watershed hydrology are ongoing, significant gaps in knowledge still exist as responses vary from region to region. This is due to several factors including differences in local runoff generation processes and landscape forms as well as varying degrees of landscape disturbances by human activities within watersheds (Franczyk and Chang, 2009; LSRCA, 2008; O'Connor et al., 2011). While scenario-neutral probabilistic ensembles are becoming more common in climate impact studies (e.g. Harris et al., 2010), the use of scenario-driven GCMs are still the most widely used approach to assess the plausible impacts of future climate on watershed hydrology and ecosystem functioning (Arnell, 2004; Oni et al., 2012a,b; Wilby and Dawson, 2013). However, there are a number of uncertainties associated with the GCM projections and downscaling to local conditions under IPCC emission scenarios (Wilby et al., 2002).

Our preparation for future hydrological changes appears to be insufficient due to the larger uncertainty in our present hydrological model structures and forecasting capabilities (Allen and Ingram, 2002; Juston et al., 2013). This is more pronounced in snow-dominated catchments (Barnett et al., 2005; Lawrence and Haddeland, 2011; Oni et al., 2012b) and can be amplified by changing land uses. For example, urbanizing watersheds are characterized by rapid land use changes (Franczyk and Chang, 2009; Furusho et al., 2013) and associated landscape disturbances can shift the rainfall–runoff relationships away from natural processes upon which the conceptualization of most hydrological models are based (e.g. Seibert and McDonnell, 2010). As a result, the uncertainty in rainfall–runoff modeling in managed watersheds can be an order of magnitude larger than pristine watersheds or those propagated by GCMs. A continuous assessment of watershed hydrological responses is therefore necessary to constrain all sources of uncertainty in hydrological simulations before any credible future projections can be made in managed, rapidly urbanizing, and snow-dominated watersheds such as Lake Simcoe.

The Lake Simcoe watershed (LSW) is the most important inland lake watershed in Southern Ontario for socioeconomic reasons (agriculture, recreation and tourism, drinking water supply and angling activities etc.). However, the LSW has been under pressure from urban developments and intensive agriculture in the recent decades. This has led to changes in land use and changing rainfall–runoff relationships across the watershed (Oni et al., 2013b). Here we conducted a robust assessment to constrain the uncertainty in hydrological simulations and climate projections in two adjacent river catchments of LSW (Beaver and Pefferlaw Rivers) where impacts of urbanization are limited but where there have been large impacts from agriculture. It is often assumed in hydrological modeling that adjacent catchments with similar characteristics could have similar runoff generation processes and thus parameterization in one should generate credible runoff conditions in the other (Patil and Stieglitz, 2013; Oni et al., 2012a). We tested this hypothesis and the suitability of this approach of using calibrated parameter sets from one catchment to simulate hydrological processes in adjacent river catchments.

2. Material and method

2.1. Study site description

Lake Simcoe (722 km^2) is a dimictic lake located in south-central Ontario (44° 25′ N, 79° 20′ W). The lake drains a large terrestrial system (~2899 km^2) via its headwater tributaries, which originate mainly at the southern end of the catchment (Fig. 1). There have been increasing pressures from urbanizations in some parts of the LSW (LSRCA, 2008; Oni, 2011), leading to a changing runoff ratio (Oni et al., 2013b). The Beaver and Pefferlaw River catchments were used in this study. They are adjacent catchments with characteristic branched headwater structures where streams of lower order drained into higher order streams and rivers that flow northward into the lake (Fig. 1). Both catchments have limited urban development and are largely impacted by mixed agricultural activities that include both intensive and non-intensive agriculture (Jin et al., 2013).

The Beaver River drains ~282 km^2 while the Pefferlaw River drains ~332 km^2. The Pefferlaw River in this study is the combination of Pefferlaw Brook and Uxbridge Brook (Fig. 1). Both catchments have similar weather and land use patterns (Oni et al., 2013b) and share some similar physiographic features (LSRCA, 2012a,b). The headwaters of the Pefferlaw River (and some part of Beaver River) originate in the Oak Ridges Moraines (ORM) located at the southern part of the LSW (Fig. 1). The ORM was formed at the end of the last glaciation and the high infiltration capacity and total lack of surficial drainage are common to moraine features (Johnson, 1997). The moraine consists of an aquifer complex (confined and unconfined aquifers) that makes it an important recharge zone that contributes baseflow to the headwaters and provides a reliable supply of drinking water (LSRCA, 2012a,b). The peak of the moraine (Uxbridge wedge) is located in the Pefferlaw River catchment, making a steep elevation gradient of 397–220 m above sea level (masl) from ORM to the Lake Simcoe shoreline. In contrast, the Beaver River watershed has a low elevational gradient (LSRCA, 2012b). There are scattered rural communities in the central to downstream regions of the Beaver River watershed. Rural/urban developments in the Pefferlaw River watershed are concentrated around the headwater areas in close proximity to ORM.

Both catchments have similar bedrock geology (soft limestone and shale bedrock) that are covered by thick fertile soils (Jin et al., 2013). However, soils in the Beaver River catchment are Brunisols (formed under imperfectly drained conditions) with some clay loam, sandy loam and organic muck in the headwaters (Johnson, 1997). Soils in the Pefferlaw River catchment are Gray Brown Luvisols that thin out toward the north, thereby limiting groundwater recharge in the central part of the catchment (LSRCA, 2012a). Downstream reaches of the Beaver River drain an extensive wetland complex (19% of the total catchment area) that is concentrated in the center of the catchment and forms a large, well defined recharge zone. In contrast, wetlands in Pefferlaw cover 16–18% of the total catchment area but the wetland system is more patchy and scattered (Jin et al., 2013). This makes the influence of wetland hydrology larger in the Beaver than Pefferlaw River. In addition to the wetlands, a large area of the Beaver River channel is underlain by organic sediment (Baulch et al., 2013).

Both catchments have flow and weather monitoring stations within their catchment boundaries. Flow and weather monitoring stations at Udora in the Pefferlaw River catchment and Woodville in the Beaver River catchment were used in the hydrologic modeling and impact analysis presented herein (Fig. 1). Both the Udora (44° 15′ 45″ N, 79° 09′41″ W) and Woodville (44°24′ N, 78°58 W) stations are monitored by Environment Canada (EC). Available data included runoff (m^3 s^{-1}), precipitation (mm d^{-1}) as well as minimum, average and maximum daily air temperature (°C).

2.2. Climate downscaling

The Statistical Downscaling Model (SDSM) was used to downscale Canadian Global Climate Model 3 (CGCM3) predictors to LSW conditions. Downscaling is important in order to bridge the void between global predictors and local predictands at a watershed scale (Oni, 2011). Using forty years of baseline predictand variables (precipitation and air temperature) from local weather stations (1961–2000) and the equivalent predictor variables from National Center for Environmental