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Isotope-based partitioning of streamflow in the oil sands region, northern Alberta: Towards a monitoring strategy for assessing flow sources and water quality controls

J.J. Gibson[a,b,*], Y. Yi[a,b], S.J. Birks[a,c]

[a] Alberta Innovates Technology Futures, 3-4476 Markham Street, Victoria, BC, Canada
[b] Department of Geography, University of Victoria, P.O. Box 3060 STN CSC, Victoria, BC, Canada
[c] Alberta Innovates Technology Futures, 3608 33rd Street NW, Calgary, AB, Canada

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ABSTRACT

Study region: This study is based on the rapidly developing Athabasca Oil Sands region, northeastern Alberta.
Study focus: Hydrograph separation using stable isotopes of water is applied to partition streamflow sources in the Athabasca River and its tributaries. Distinct isotopic labelling of snow, rain, groundwater and surface water are applied to estimate the contribution of these sources to streamflow from analysis of multi-year records of isotopes in streamflow.
New hydrological insights for the region: The results provide new insight into runoff generation mechanisms operating in six tributaries and at four stations along the Athabasca River. Groundwater, found to be an important flow source at all stations, is the dominant component of the hydrograph in three tributaries (Steepbank R., Muskeg R., Firebag R.), accounting for 39–50% of annual streamflow. Surface water, mainly drainage from peatlands, is also found to be widely important, and dominant in three tributaries (Clearwater R., Mackay R., Ells R.), accounting for 45–81% of annual streamflow. Fairly limited contributions from direct precipitation illustrate that most snow and rain events result in indirect displacement of pre-event water by fill and spill mechanisms. Systematic shifts in regional groundwater to surface-water ratios are expected to be an important control on spatial and temporal distribution of water quality parameters and useful for evaluating the susceptibility of rivers to climate and development impacts.

1. Introduction

Hydrograph separation based on streamflow data is one of the most widely used methods for quantifying surface water—groundwater interactions at the reach to catchment scales (Kalbus et al., 2006). Typically, geochemical or isotopic data have been used to trace changes in the proportion of event and pre-event water contributions during storms or snowmelt events. As noted in a recent review by Klaus and McDonnell (2013), these studies have forced a fundamental re-examination of the processes of water delivery to streams. In particular, they have revealed a high proportion of pre-event water in the storm hydrograph, even at peak flow, (Klaus and McDonnell, 2013). Depending on the distinctiveness of solute or isotope

* Corresponding author.
E-mail address: jjgibson@uvic.ca (J.J. Gibson).

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labelling and catchment properties it has been possible in some studies to resolve two or three separate components of the hydrograph, and to infer mechanisms of runoff generation such as groundwater ridging or variable source area contributions.

While a variety of tracer and non-tracer methods have been utilized for hydrograph separation (see Gonzales et al., 2009), stable isotopes of water have the advantage of being incorporated within the water molecule and being mass-conservative during mixing. Stable isotopes of water are especially useful due to natural labelling of flow sources that often arises from selection and fractionation processes that occur in the water cycle (Gat, 1996). Several examples include the distinctly depleted isotopic signatures normally associated with snow (and snowpack) compared to rainfall owing to temperature-dependent isotopic fractionation during condensation of atmospheric moisture (Gat, 1980), temporal isotopic variability in precipitation which serves to distinguish individual events from long-term averages typically reflected in meteoric groundwater (Gat, 1996), selective recharge, which may accentuate the difference between precipitation events and meteoric groundwater, and evaporative enrichment of wetland waters or lakes that have resided in surface storage (Gibson et al., 2015a). Evaporation from soil may also lead to distinctive isotopic labelling of shallow soil water, particularly in the arid zone (Gat, 1981).

Hydrograph separation using stable isotopes of water has been demonstrated mainly for hillslopes or small experimental catchments over event time scales (Tetzlaff et al., 2015) with less emphasis placed on application at larger scales or over seasonal time periods (see Uhlenbrook et al., 2002). This study explores use of isotope hydrograph separation as an integrated component of streamflow monitoring in meso- to macro-scale peatland-rich catchments to better understand the physical processes controlling runoff generation. The main questions that we wish to answer include: 'How do peatland catchments react to snowmelt and precipitation events?', 'What is the timing and proportion of various water sources to streamflow on a seasonal, annual and interannual basis?', 'What flow paths, storage effects, and runoff mechanisms are important?' and 'Are there important regional differences in streamflow response?' One of the primary applications we envision is better understanding and prediction of the temporal distribution of water quality and contaminants in peatland-dominated systems. It is also interesting to explore whether inter-annual time-series monitoring may be useful for assessing potential changes in streamflow drivers due to climate or development-related impacts.

Previous work on stream water chemistry including hydrograph separation studies have been conducted in the oil sands region by Schwartz (1980) and Schwartz and Milne-Home (1982a,b). Based on a three-year record of major ion tracers in five meso-scale catchments, they partitioned the hydrograph into direct precipitation, groundwater and muskeg water, and were successful in showing that muskeg (i.e. peatland) plays a significant role in determining the watershed chemistry, in attenuating runoff during spring melt, and in dilution of water chemistry during summer, particularly between runoff events. In addition, they determined that groundwater plays a dominant role during winter controlling water quantity and quality. Notably, these studies also demonstrated that meaningful partitioning could be achieved in the region over seasonal to inter-annual time periods. However, as these studies used geochemical rather than isotopic labelling for hydrograph separation they did not attempt to partition snowmelt from rainfall.

This paper offers basic confirmation of some of Schwartz's results for the Muskeg, Firebag and Steepbank Rivers, as well as some clarification on the role of different runoff components in each season and inter-annually for these and several additional basins (Mackay, Ells, Clearwater and several stations along the Athabasca River), based on datasets that extend for over a decade in some cases. We present a methodology for partitioning of snowmelt, rainfall, groundwater and surface water using stable isotopes of water and apply it to infer some of the major processes controlling runoff for mesoscale catchments as well as for the Athabasca River both upstream and downstream of the oil sands region. We identify the underlying sources of runoff and runoff generation mechanisms that produce spatial and temporal variations in streamflow in the wetland-muskeg runoff regime. Understanding runoff generation in the region is important as it is an essential control on water quality and aquatic habitat, yet may be changing due to ongoing development for oil sands or due to impact of climatic changes that are known to have affected permafrost thawing and other runoff generation processes in the region (Gibson et al., 2015a,b).

1.1. Study area

The study area lies within the Athabasca River basin, Alberta, Canada. The Athabasca River flows northeast over 1,231 km from its origins in the Rocky Mountains to the Peace-Athabasca Delta and Lake Athabasca, draining 156,000 km^2 of landscape varying from snow-capped and glaciated mountains to agricultural plains, boreal forest and wetlands. No dams are constructed along the river and consumptive divergences of water are small due to minimal agricultural use (Jasechko et al., 2012). The river is part of the Mackenzie River system, and its waters eventually flow to the Arctic Ocean. The lower reaches of the Athabasca River coincide with the Athabasca Oil Sands region (AOSR). Here, approximately 1% of the rivers annual flow is diverted for use as make-up water for oil sands mining and processing operations (Canada, Government of Canada, 2013).

The climate is highly seasonal with monthly mean temperatures that vary from −19 °C in January to 17 °C in July, with a mean annual temperature near 0 °C. Annual precipitation is 450 mm, with 60% falling as rain. Relief is subdued with the exception of large river incisions. Fine-grained soils, in combination with the climate, have resulted in formation of abundant wetlands across the region. Ombrogenous (precipitation-fed) bogs and geogenous (groundwater-fed) fens, which together occupy more than 50% of watershed areas in the AOSR (Gibson et al., 2015a), govern hydrology and infiltration at the surface (Vitt et al., 1994). Mineral soil uplands are also common in the lower, incised portions of river basins. Peatlands and mineral