Quantifying the Water Budget for a Northern Boreal Watershed: The Coles Lake Study, Northeastern British Columbia

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Introduction

Northeastern British Columbia is undergoing rapid development for oil and gas extraction and this depends largely on subsurface hydraulic fracturing (fracking), which depends on the available freshwater. Even though this industrial activity has made substantial contributions to regional and provincial economies, it is important to ensure that sufficient and sustainable water supplies are available for all those dependent on the resource, including ecological systems. This in turn demands comprehensive understanding of how water in all its forms interacts within the watershed, and of the potential impacts of changing climatic conditions on these processes. The aim of this study is to characterize and quantify all components of the water budget in the small watershed of Coles Lake, northeastern BC through a combination of fieldwork, observational data analysis and numerical modelling. Baseline information generated from this project will support the assessment of the sustainability of current and future plans for freshwater extraction in the region by the oil and gas industry.

This research will not only quantify the short-term water budget (hydrological year 2013–2014) for Coles Lake but will also examine its historical and regional context, research which aims to benefit the larger northeastern region. Historical water balance quantification can help to identify and assess climatic and biophysical features that contribute to uncertainties in water balance components, such as climate change. Specifically, historical estimates of the water balance can assist in identifying climate change signals on air temperature, precipitation patterns and evapotranspiration. This paper will only provide the latest results of fieldwork and observational analysis for the short-term (hydrological year 2013–2014) water budget. The outcomes of a modelling study will be published separately.

Keywords: *water resources, northeastern British Columbia, Coles Lake watershed, oil and gas extraction*

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Water and Natural Gas in Northeastern British Columbia

Natural gas development has increased globally, but particularly in North America. Natural gas is considered by many to be a reliable, secure and environmentally acceptable fuel. According to the Canadian Association of Petroleum Producers, Canada is the world's third largest producer of natural gas and has access to extensive reserves that are concentrated in the largest producing regions of the western provinces (BC, Alberta and Saskatchewan; Canadian Association of Petroleum Producers, 2015). Within northeastern BC, the Montney shale gas play and Horn River Basin are two regions that have come into prominence in the past few years because of their unconventional natural gas resources. Intensive unconventional development of these shale- and tight-gas reservoirs requires large quantities of freshwater (Chapman et al., 2012).

Overview of Past Research

Shale-gas exploration and development near Fort Nelson has increased demand for surface water in these wetland-dominated landscapes, prompting several studies to assess the sustainable function of such natural ecosystems. Recently, Johnson (2010) developed a conceptual water-balance model for the Horn River Basin near Fort Nelson and identified knowledge gaps. To fill these gaps would require the identification of wetlands, delineation of fens and bogs, location and distribution of permafrost, spatial distribution of evapotranspiration and increased monitoring of discharge. Further contributions to water allocation planning efforts have also been made by Chapman et al. (2012) with the development of the northeast water tool (NEWT)—a web-based hydrological model and planning tool for prediction of water availability based on modelled annual, seasonal and monthly runoff. Recent studies indicate that the combination of gentle topography, relatively fine-textured surficial materials, extensive wetlands, discontinuous permafrost and seasonally frozen ground make hydrological studies in the Fort Nelson area particularly challenging (Golder Associates, 2010; Johnson, 2010). Several studies have explored these concerns, but there are many gaps that still need to be addressed. The current research will consist of short-term monitoring to identify if there is ecosystem change associated with water use and to obtain more knowledge about boreal wetland dynamics by identifying the water balance of the Coles Lake watershed.

Study Area Characteristics

Coles Lake is part of the Peace River Land District and it is situated at 59°46′57″N latitude and 122°36′27″W longitude with an area of 1.715 km^2 (Figure 1). The watershed is about 140 km northeast of Fort Nelson and has a drainage area of approximately 227 km^2. Its elevation ranges from 311 to 550 m asl with an average elevation of 523.9 m asl and contains an elevated central highland, which acts as a drainage divide. Coles Lake is a small and shallow water body with a maximum depth of 2.2 m. The southern and western side of the project area drains to the west and north through Emile Creek and flows into the Petitot River, whereas the northern and eastern side of the project area drains to the east and north through Fortune Creek and flows into the Petitot River.

The Coles Lake watershed is located in the moist and cool boreal white and black spruce subzone (Delong et al., 2011). This subzone is characterized by black and white spruce forests and wetland complexes of discontinuous permafrost, fens, bogs, swamps and marshes on a glaciolacustrine plain, with extensive organic deposits and a lesser component of streamlined tills (Golder Associates, 2010; Johnson, 2010; Huntley et al., 2011; Kabzems et al., 2012).

The banks of Coles Lake are covered by fen-type vegetation, which transitions to mixed wood forest up moderately steep slopes away from the banks. Based on the most recent vegetation resource inventory (VRI) and the BC Land Cover Classification Scheme, approximately 43.3% of this watershed is open, 51.4% has a mixed vegetation canopy and 5.3% has a closed vegetation canopy. Only crown closure (%) of VRI is used to identify open, mixed and closed vegetation canopies (≤25% open, >25–61% mixed, >61% closed). Based on data from the automated weather station (UF) installed near Coles Lake for this study (latitude 59°47′22.2″N, longitude 122°36′42.8″W, elevation 480.0 m asl), the mean annual air temperature was –1.2°C, ranging from –4.0 to 1.0°C, with a total annual precipitation of 372.0 mm in the 2013–2014 hydrological year. Permanent snow cover lasts from early November until early to mid-May, depending on the year, and maximum snow accumulation occurs either in December, January or February.

Methodology

Estimating the Water Balance

The water cycle of Coles Lake is composed of several water fluxes and stocks that need to be quantified. Precipitation (rain and snow) and stream inflow to the lake are considered the two main inputs; evaporation, stream outflow and water extraction from the lake are considered outputs. In addition to surface water flows, the potential role of shallow groundwater flow to the lake is investigated. As a first step, an appropriate water budget equation must be defined

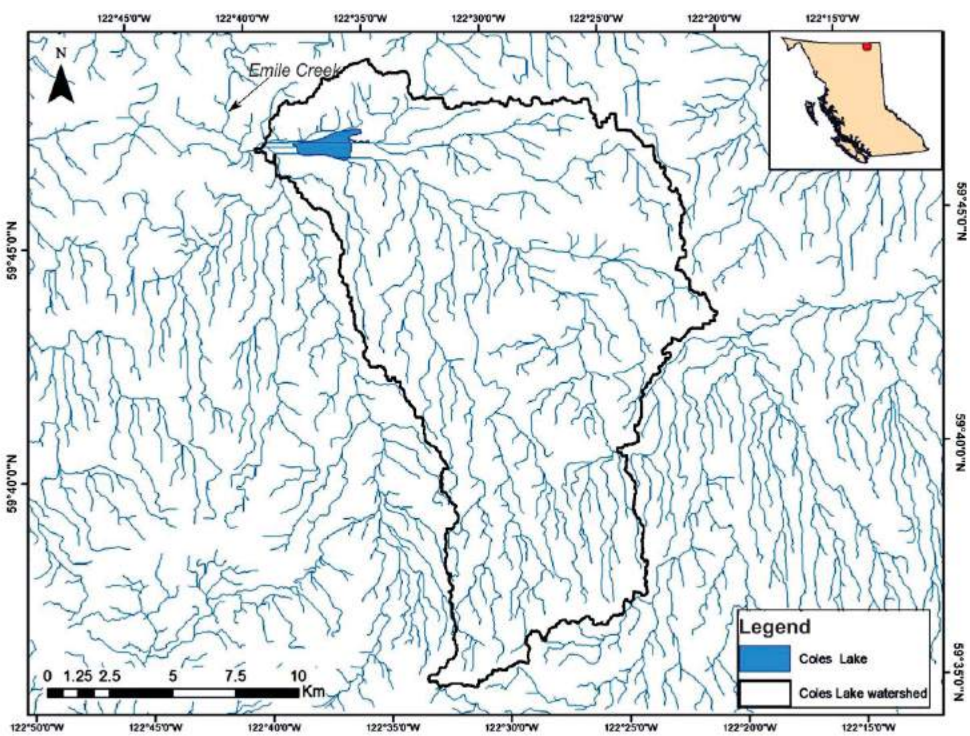

Figure 1. Location of Coles Lake and its watershed boundary, northeastern British Columbia.

to represent these components. Hence, the Coles Lake water balance is defined as follows:

$$\Delta S = P + I \pm G - E - Q - W \quad (1)$$

Where, ΔS is the change in stored water, P is precipitation (P = R + S, where R denotes rainfall and S represents snowfall), I is the mean annual stream inflow to Coles Lake, G is the groundwater exchange, E is evaporation (maximum evaporation), Q is discharge (outflow) and W is the licensed withdrawal of water. Although the water balance has been computed for the entire Coles Lake watershed, results presented here are for the lake itself. All terms are expressed in units of millimetres. A water-year from October 1, 2013 to September 30, 2014 was used as the temporal framework within which to estimate the balance, as this period begins and ends when both discharge and storage are at their minimum levels (Winkler et al., 2010).

Data Collection

Fieldwork was conducted from May 2012 to September 2014 to examine the hydrological components of this watershed in detail. Challenges to the field efforts included the remoteness of the basin and difficult access to the area, as well as frequent severe weather conditions. The results of this work will support the quantification and understanding of the Coles Lake water budget. A general description of each field procedure used and its purpose is outlined below:

- A Campbell Scientific, Inc. weather station (CR1000 data logger) was installed in a large clearing area approximately 400 m from Coles Lake (Figure 2). The purpose was to record the meteorological information used to compute the hydrological components that contribute to Coles Lake and its watershed.
- In addition to the rain gauge at the weather station, three Davis Instruments tipping-bucket rain gauges were deployed under the three different vegetation canopies. The purpose was to identify how different amounts of rainfall contribute to the watershed for the different vegetation canopies (R parameter).
- Three snow survey sites were established at the rain gauge locations. The purpose was to capture the contribution of snowfall to the watershed for the different vegetation canopies (S parameter).
- Nine piezometers equipped with the Odyssey™ capacitance water level recorders (Dataflow Systems Limited) were installed at three transects around the shore of Coles Lake. The purpose was to examine the variability of seasonal shallow groundwater flows and to quantify the contribution of shallow groundwater to Coles Lake (G parameter).
- Two Onset Computer Corporation hydrometric stations (HOBO® data logger) were established, one at the inflow and another at the outflow of the lake (Figure 2). The purpose was to measure the streamflow discharge at the inflow and the outflow stations (I and Q parameters).
- Quicksilver Resources Canada Inc. (Quicksilver) established a hydrometric station on Emile Creek, 4 km downstream of the lake outflow (Figure 2). The purpose was to measure the runoff from the Coles Lake watershed.
- A skin sensor temperature probe (Eclo's iBCod 22L) was installed in the middle of Coles Lake. The purpose was to monitor the water skin temperature and the data was used to compute the amount of evaporation from Coles Lake (E parameter).
- Amounts of water extracted for Quicksilver Resources Canada Inc.'s (Quicksilver) exploration operations were collected. The purpose was to quantify the total amount of water withdrawal from the lake (W parameter).
- Staff gauges were installed in Coles Lake by Quicksilver. The purpose was to record lake water levels.
- A Coles Lake bathymetric map (0.25 m interval) was produced by Quicksilver. The purpose was to provide morphometry information for Coles Lake including surface area, maximum length and width, shoreline length and volume—all crucial to understanding how a lake system functions.

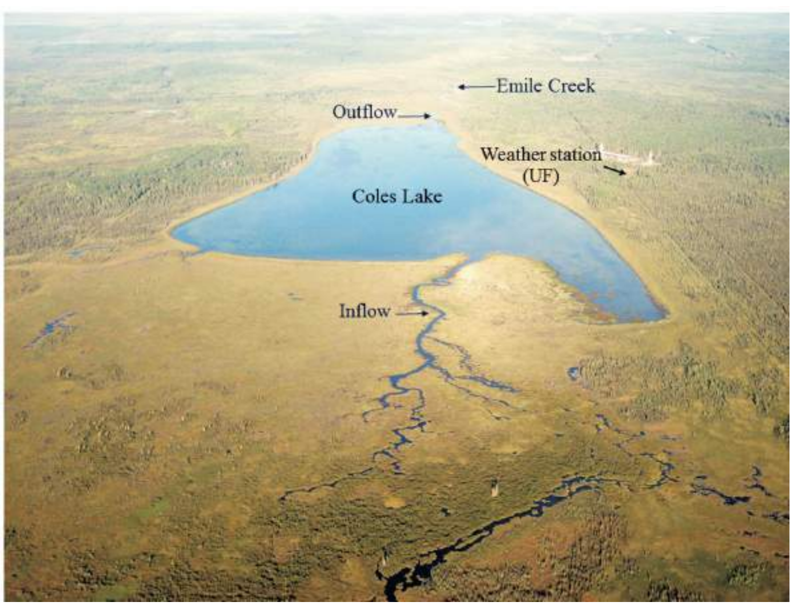

Figure 2. Western view of Coles Lake with location of automated weather and hydrometric stations, northeastern British Columbia.

Results

Rainfall (R)

Local rainfall data were collected every 15 min at the UF weather station and then summed for a daily total. At the three rainfall gauges, which were installed in open, mixed and closed vegetation canopies, every rainfall event was recorded and daily totals were obtained. Although all four gauges were used to compute total rainfall for the whole watershed using the Thiessen method, only recorded data from the UF station were used to calculate the total contribution of mean rainfall on Coles Lake itself. Rainfall data from November to May are considered to be zero, since most of the precipitation reported during this period is from snow and ice melt rather than rainfall. In total 243.9 mm of rainfall is reported, with maximum rainfall occurring in June (73.9 mm) and July (61.9 mm).

Snowfall (S)

Based on Environment Canada standard equivalences, 1 cm of snow is assumed to correspond to 1 mm of water. Therefore, total snow water equivalent (SWE) for the Coles Lake station equals 167.4 mm. In addition, a manual snow sampling procedure was performed at the three canopy sites to measure the SWE and snow depth and will later be used as input to a hydrological model.

Evaporation (E)

Multiple steps were required to compute the total evaporation over the Coles Lake area. The first step was to identify the ice-free period. Landsat images were downloaded and reviewed to determine the start and end time of freezing and melting at Coles Lake. Based on the Landsat images, Coles Lake began freezing on November 1, 2013, and the melting period began by May 15, 2014. The profile method, which was shown by Granger (1991) to provide reliable estimates of latent heat fluxes, was selected to estimate evaporation from the lake surface. To use the profile method, air and water temperature, wind speed, relative humidity and air pressure were collected for the duration of the open-water period. In addition to employing the profile method, several assumptions were made, such as fluxes are constant with height and stability is neutral. The results suggested that maximum evaporation occurred in July and minimum in September, with a total loss of 148.6 mm during the ice-free months. Finally, the potential contribution of blowing snow sublimation to the water budget of Coles Lake was assessed using the Piektuk blowing snow model (Déry et al., 1998). The model indicates that blowing snow sublimation does not contribute significantly to the water budget of Coles Lake and can be safely neglected in this study.

Inflow and Outflow (I, Q)

Discharge measurements were made at both the inflow and the outflow stations. The plot between the discharge and the stage of the river is referred to as the stage–discharge relation or rating curve. The plot helps to obtain the discharge by simply reading the stage and finding out the corresponding discharge. That is, measurement of discharge involves a two-step procedure. First, the development of the stage–discharge relationship, and, second, obtaining the corresponding discharge for each stage. Unfortunately, it was not possible to use the stage–discharge relationship to measure the streamflow because of beaver dams. Since these structures blocked water, the water level recorded by transducers in July, August and September mostly stayed the same. As a result of this natural phenomenon, water levels were raised in the upstream stage, and therefore rendered the rating curve invalid. In light of this challenge, an alternative method to obtaining representative streamflow data was employed. To compute the amount of discharge, the streamflow data from the Emile Creek and two Coles Lake stations was compared. The Emile Creek hydrometric station is located about 4 km downstream from Coles Lake. Four days of onsite discharge measurements of inflow and outflow using the mid-point method were correlated with data for the same day from the Emile Creek station. A high degree of correspondence is demonstrated between the Emile Creek station and each of the inflow and outflow stations. The high correlation coefficients show that discharge measurements are consistent (Table 1).

The obtained regression allowed extrapolation of the daily discharges (I = 106.6 mm and Q = –198.5 mm) at each site for each day of the study period. The total amount of water withdrawal is zero because there was no water extracted during this study period due to low natural gas prices (Quicksilver Resources Canada Inc., pers. comm., 2013). The final result of the Coles Lake water balance compo-

Table 1. The t- and p-values between Coles Lake and Emile Creek stations with the computed Pearson's product-moment correlation coefficients. The t-value reflects the value of the 't' test statistic for the test, and the p-value reflects whether the significance of the correlation (<0.05) is significant.

	t-value	p-value	Correlation
Between inflow station and Emile Creek station	9.39	0.011	0.99
Between outflow station and Emile Creek station	9.78	0.010	0.99

Table 2. Summary of water balance components, hydrological year 2013–2014, Coles Lake, northeastern British Columbia.

Component	Total (mm)
Rainfall (R)	243.9
Snowfall (S)	167.4
Inflow (I)	106.6
Outflow (Q)	-198.5
Evaporation (E)	-148.6
Groundwater (G)	In progress
Water withdrawal (W)	0
Change in stored water (ΔS)	In progress

nents are listed in Table 2. Assessment of the interactions between lake and shallow groundwater is in progress.

Summarys

The main goal of this project is to advance and improve the knowledge of the hydrological cycle in northeastern BC and to estimate the water balance for Coles Lake. In this paper, the water budget for Coles Lake is quantified including its inputs, outputs and storage terms. However, the contribution of shallow groundwater as the last remaining hydrological component of the water budget is yet to be quantified. Once the 2013–2014 water budget for Coles Lake is completed, it will be placed into its historical context using a hydrological model—MIKE SHE (DHI Water & Environment, 2007). These historical results will be compared to other watersheds to investigate the differences/similarities of the Coles Lake watershed with the other watersheds in the northeastern region.

The results of this research can be considered a good source of knowledge for decision-makers to better understand water fluxes of Coles Lake (and similar water bodies in northeastern BC). The aim is to determine how much freshwater can be extracted by oil and gas operations by forecasting balance thresholds and avoiding the over-allocation of local water resources.

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