Quantifying the Water Balance of Coles Lake in Northeastern British Columbia Using In Situ Measurements and Comparisons with Other Regional Sources of Water Information

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Introduction

Northeastern British Columbia (BC) is undergoing rapid development for oil and gas extraction, largely depending on subsurface hydraulic fracturing (fracking), which relies on 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 socioeconomic sectors dependent on the resource, including ecological systems. This, in turn, demands a comprehensive understanding of how water in all its forms interacts within the watershed and an identification 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 balance in the Coles Lake watershed, northeastern BC, through a combination of fieldwork and observational data analysis. Baseline information generated from this study will support the assessment of the sustainability of current and future plans for freshwater extraction in the region by the oil and gas industry. The initial results of fieldwork and a partial observational analysis were already published by Abadzadesahraei et al. (2016). This paper provides a complete observational analysis for the hydrological year 2013–2014, providing a better understanding of boreal wetland dynamics by identifying the water balance of Coles Lake. In addition, the outcomes of this study are compared with other available regional sources of water in northeastern BC.

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. For instance, Johnson (2010) developed a conceptual water balance model for the Horn River Basin near Fort Nelson and identified knowledge gaps including the identification of wetlands, delineation of fens and bogs, location and distribution of permafrost, identification of the 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 (BC Oil and Gas Commission and BC Ministry of Forests, Lands and Natural Resource Operations, 2016). Additionally, the BC Water Portal (WP), which is an online map-based water information tool, was designed in 2014 to provide a wide range of water-related data and information for northeastern BC (BC Ministry of Forests, Lands and Natural Resource Operations and BC Oil and Gas Commission, 2016). The WP contains water quantity and quality data wherever the data are available for both surface water and groundwater. Furthermore, it links climate information and historical hydrographs of mean monthly water depth of provincial observation wells (Holding et al., 2015).

Recent studies indicate that the combination of climate change, shale gas development activities and the physical characteristics of northeastern BC watersheds make hydrological studies in this region particularly challenging (Johnson, 2010). These challenges are exacerbated by the combination of gentle topography, relatively fine-textured surficial materials, extensive wetlands, discontinuous permafrost and seasonally frozen ground (Golder Associates, 2010; Johnson, 2010). Although several studies have explored these concerns, there are still many knowledge gaps (e.g., role of vegetation canopies in the water balance) that need to be addressed.

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

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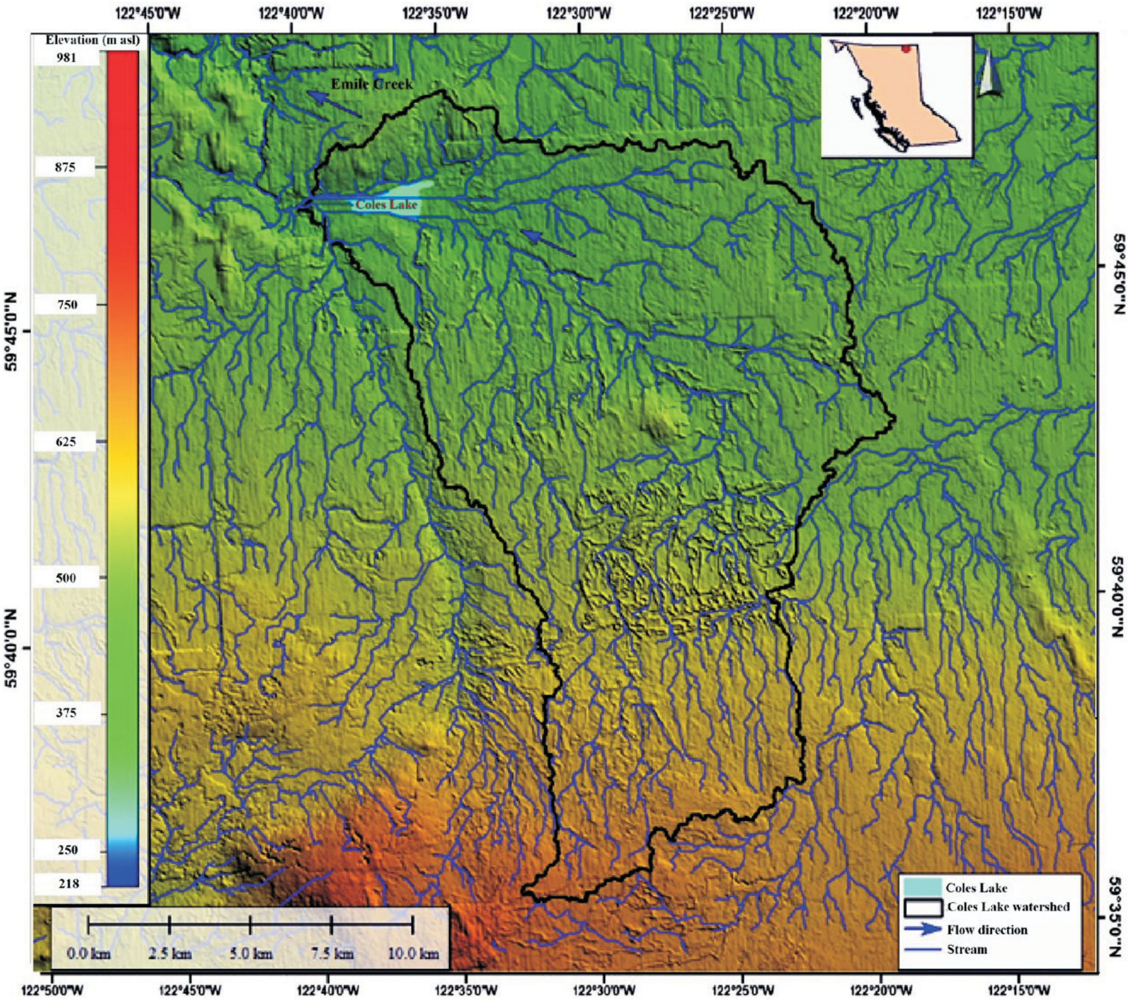

Figure 1. Location of Coles Lake and its topography, northeastern British Columbia. Data from HydroSHEDS (World Wildlife Fund, 2009).

Study Area Characteristics

The Coles Lake watershed is in northeastern BC, between Fort Nelson and the Northwest Territories border. The watershed is about 140 km northeast of Fort Nelson and has a drainage area of approximately 227 km^2 (Figure 1). Its elevation ranges from 311 to 550 m above sea level (asl) with an average elevation of 524 m asl and contains an elevated central highland, which acts as a drainage divide. According to the BC biogeoclimatic ecosystem classification (BEC) system, the Coles Lake watershed is located in the moist cool boreal white and black spruce zone (Delong et al., 2011). This zone contains 10% of BC's total land area, which makes it the province's largest biogeoclimatic zone (DeLong et al., 1991). This zone 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). Based on a 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 is used to identify open, mixed and closed vegetation canopies (≤25% open, >25–61% mixed, >61% closed).

Coles Lake is a small and shallow water body, with a maximum depth of 2.2 m, situated in the northwestern corner of the Coles Lake watershed. 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 1.72 km^2 (Figure 1). The southern and western side of the study area drains to the west and north through Emile Creek and flows into the Petitot River, whereas the northern and eastern side of the study area drains to the east and north through Fortune Creek and also flows into the Petitot River. Based on data from an automated weather station installed near Coles Lake (latitude 59°47'22.2"N, longitude 122°36'42.8"W, elevation 480 m asl), the mean annual air temperature was 1.7°C with a total annual precipitation of 429.5 mm for the 2013–2014 hydrological year. Permanent snow cover typically lasts from early November until early to mid-May.

Methodology

Estimating the Water Balance

Determination of Coles Lake's water balance requires an estimation of stored water and fluxes. Precipitation (rain and snow), stream inflow and groundwater to the lake are considered the main inputs; evaporation, stream outflow and water extraction from the lake are considered outputs as follows:

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

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; 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 only 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 adverse weather conditions. The results of this work will support the quantification and understanding of the Coles Lake water balance. A general description of each field procedure used and its purpose is available in Abadzadesahraei et al. (2016).

Water Balance Components

Wetlands are an essential part of the hydrological cycle within this region, with water balance components including precipitation, evaporation, surface water and groundwater flows (Ingram, 1983). Each of these components and results from the 2013–2014 hydrological year are discussed below.

Rainfall (R)

Local rainfall data were collected every 15 min at the automated weather station and then summed for a daily total to calculate the total contribution of rainfall on Coles Lake. Rainfall from November 1, 2013 to May 15, 2014 is taken as zero because temperatures are continuously subfreezing during this period and reported data during this period is from snowfall rather than rainfall. In total, 262.1 mm of rainfall is reported, with maximum rainfall occurring in June (73.9 mm) and July (61.9 mm).

Snowfall (S)

Based on Environment and Climate Change Canada standard equivalences, 1 cm of snow is assumed to correspond to 1 mm of water. Therefore, snowfall for the Coles Lake weather station totals 167.4 mm (water equivalent) based on the ultrasonic ranging sensor.

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 (open-water) period. Landsat images were downloaded and reviewed to determine the start and end time of freezing and melting of the ice cover at Coles Lake. Based on the Landsat images, Coles Lake began freezing around November 1, 2013, and the melting period began near to May 15, 2014. Once the ice-free period was identified, the Food and Agriculture Organization (FAO) of the United Nations' Penman-Monteith method was selected to estimate evaporation from the lake surface (Hendriks, 2010). To use the FAO Penman-Monteith method, the net radiation at the earth's surface, air temperature, wind speed, relative humidity and air pressure were collected for the duration of the open-water period. The results suggested that maximum evaporation occurred in July (97.7 mm) and minimum evaporation occurred in December (2.6 mm). This demonstrates a correlation with temperature, with a total loss of 368.5 mm during the ice-free months. In addition, the potential contribution of blowing snow sublimation to the water balance of Coles Lake was assessed using the Piektuk blowing snow model (Déry et al., 1998). This model indicates that blowing snow sublimation does not contribute significantly to the water balance 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. Unfortunately, it was not possible to use the stage–discharge relationship to measure the streamflow because beaver dams altered flow during the field campaign. Since these structures blocked water, the water level recorded by transducers in July, August and September stayed mostly 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 of obtaining representative streamflow data was employed. To compute the amount of discharge, the streamflow data from Emile Creek and two Coles Lake stations were 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 midpoint method were correlated with data for the same days 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 at each site for each day of the study period with total inflow of 106.6 mm and total outflow of 198.5 mm for the hydrological year.

Groundwater (G)

To estimate the contribution of groundwater fluxes to the lake, nine piezometers in three transects were installed on February 5, 2014 (Abadzadesahraei et al., 2016). Groundwater fluxes were only estimated from February 5, 2014 to September 30, 2014, and only during the ice-free period. In fact, there are no data available prior to this study. In addition, it is assumed that the water fluxes are zero during the freezing period. Although this logical inference is based on sound assumptions, there may be an underestimation of the flux. To compute the net average annual flow of water at Coles Lake, Darcy's equation was employed (Lohman, 1972):

$$Q = q \times A \tag{2}$$

where Q is water flow ($m^3 \cdot s^{-1}$), q is the net flux (has a dimension of velocity in $m \cdot s^{-1}$) and A (m^2) is the cross-sectional area of the shoreline segment, representing a vertical plane at the shoreline through which water passes to either enter or leave the surface-water body. This method assumes that the aquifer is homogeneous and isotropic within the segment; however, its assumption of a constant aquifer thickness is violated where the water table slopes in the vicinity of a surface water body.

According to the analysis, a total of 4.1 mm of groundwater contributed to the water balance of the lake each month from the three transects (flow = Q × number of seconds for the specific months / the area that each transect covers in m^2). Flows to and from the surface-water body were summed to calculate the net groundwater contribution to the entire lake. Based on these assumptions, 22.6 mm (4.1 mm × 5.5 months) of groundwater had flowed into the lake during the ice-free period.

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

Water Withdrawal (W)

The BC Oil and Gas Commission (BCOGC) gave Quicksilver Resources Canada Inc. (Quicksilver) a maximum water withdrawal allocation of 38.5 mm for the 2013–2104 hydrological year from Coles Lake. However, actual water withdrawal was zero because the plant was closed in response to low natural gas prices (Quicksilver Resources Canada Inc., pers. comm., 2013).

Water Balance Results

After computing the hydrological components, it was possible to determine the final water balance components, listed in Table 2.

Evaluation of the Coles Lake Hydrological Components

This section evaluates the hydrological components of Coles Lake using comparisons with other available sources of water information in northeastern BC. The sources employed were the NEWT and WP, as well as hydrometeorological data from the Fort Nelson climate normals (FNCN) station (Environment and Climate Change Canada, 2016a) and Fisheries and Environment Canada (FEC) lake evaporation data (Fisheries and Environment Canada, 1978). The precipitation data reported by the NEWT are from ClimateWNA (Centre for Forest Conservation Genetics, 2015) and hydrometric data originate from Water Survey of Canada (Environment and Climate Change Canada, 2016b) gauging stations with various periods of record. The WP is based on observational data for the 2013–2014 water year. The FNCN are the average climatic data from 1981 to 2010 recorded at Fort Nelson, whereas the FEC data represents the mean value of the annual evaporation of open water bodies, based on the 10-year period 1957–1966.

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

Component	Total (mm)
Rainfall (R)	262.1
Snowfall (S)	167.4
Inflow (I)	106.6
Outflow (Q)	198.5
Evaporation (E)	368.5
Groundwater (G)	22.6
Water withdrawal (W)	0*
Change in stored water (ΔS)	-8.3

*Although, the potential maximum water allocation is 38.5 mm, the total amount of water withdrawal is zero since there was no water extracted during this study period.

For the 2013–2014 water year, observed precipitation totals 429.5 mm over Coles Lake. The estimated observed precipitation for Coles Lake is within an appropriate range compared to results from the NEWT (435.3 mm; BC Oil and Gas Commission and BC Ministry of Forests, Lands and Natural Resource Operations, 2013), WP (430.3 mm) and FNCN (451.7 mm). In addition, the estimated rainfall during the ice-free period at Coles Lake (262.1 mm) varied only by 27.5 mm compared to FNCN (289.6 mm). Additionally, the total amount of computed snowfall at Coles Lake (167.4 mm) matches well the reported data by FNCN (169.8 mm).

A total amount of 106.6 mm as inflow and 198.5 mm as outflow was estimated for Coles Lake. To evaluate these estimated results, an attempt was made to compare these findings with the NEWT and WP. It was concluded that the results of Coles Lake are not consistent with the results of NEWT for two main reasons. Firstly, NEWT does not separate the total amount of runoff into and out of Coles Lake. Secondly, NEWT does not consider the effect of beaver dams in the area. Thus, only WP values are used for the evaluation, however, the WP values are only representative of the flow in Emile Creek (located downstream of Coles Lake) and not for Coles Lake itself. It was still possible to employ values from WP because Coles Lake streamflow was constructed based on recorded data from Emile Creek. After comparison, the recorded data from Emile Creek highly correlated with the WP data. Furthermore, the WP reported that the streamflow in 2014 approached zero in October, confirming this study's assumption regarding the ice-free period.

The total amount of evaporation estimated for Coles Lake during the ice-free period was 368.5 mm. According to FEC data, the mean annual lake evaporation at Coles Lake varies from 300 to 500 mm. It can be concluded that the estimated results are located within this range reported by FEC.

Although the groundwater data are currently unavailable for comparison, previous studies by Quicksilver indicated a low hydraulic conductivity and consequently low permeability at the Coles Lake watershed. This fact may explain a low computed value of groundwater contribution to Coles Lake.

Summary and Future Approach

In this paper, the water balance of Coles Lake, including its inputs, outputs and storage terms, is quantified, and the obtained results were compared with other available sources of water information in northeastern BC. In the next phase of this work, historical water balance of Coles Lake and its associated hydrological processes will be quantified using a hydrological model—MIKE SHE (DHI Water & Environment, 2007). The MIKE SHE hydrological model is selected to identify the interactions among the atmosphere, surface and subsurface in this region. In addition, the water balance tool within MIKE SHE is used to estimate the historical water balance of northeastern BC watersheds over 35 years. Simulated results will be compared to other watersheds to investigate the differences/similarities of the Coles Lake watershed with others in the region. Therefore, the main goal of this research is to advance and improve the knowledge of hydrological processes and water resources in northeastern BC. Outcomes of this study may assist regulators in balancing multiple priorities in a way that will not compromise the long-term sustainability of water resources. More specifically, this study can help determine how much freshwater can be extracted by oil and gas operations by forecasting balance thresholds to avoid the over-allocation of local water resources.

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