Understanding the Water Balance Paradox in the Athabasca River Basin, Canada

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Abstract

This study demonstrates the importance of the including and appropriately parameterizing peatlands and forestlands for basin-scale integrated surface-subsurface models in the northern boreal forest, with particular emphasis on the Athabasca River Basin (ARB). With a long-term water balance approach to the ARB, we investigate reasons why downstream mean annual stream flow rates are consistently higher than upstream, despite the sub-humid water deficit conditions in the downstream regimes. A high-resolution 3D variably-saturated subsurface and surface water flow and evapotranspiration model of the ARB is constructed based on the bedrock and surficial geology and the spatial distribution of peatlands and their corresponding eco-regions. Historical climate data were used to drive the model for calibration against 40-year long-term average surface flow and groundwater observations during the historic instrumental period. The simulation results demonstrate that at the basin-scale peatlands and forestlands can have a strong influence on the surface-subsurface hydrologic systems. In particular, peatlands in the middle and downstream regimes of the ARB increase the water availability to the surface-subsurface water systems by reducing water loss through evapotranspiration. Based on the comparison of forestland evapotranspiration between observation and simulation, the overall spatial average evapotranspiration in downstream forestlands is larger than that in peatlands and thus the water contribution to the stream flow in downstream areas is relatively minor. Therefore, appropriate representation of peatlands and forestlands within the basin-scale hydrologic model is critical to reproduce the water balance of the ARB.
1 Introduction

The Athabasca River Basin (ARB), covering approximately 160,000 km² of northern Alberta, Canada, has its headwaters in the Columbia Icefield (> 3000 m, a.s.l.) and flows approximately 1200 km to Lake Athabasca (~ 200 m, a.s.l.). Average annual streamflow increases along its length. Major inputs to the river are from snowmelts in the Rocky Mountains and water inputs from its major tributaries such as the McLeod, Pembina, Lesser Slave, Clearwater, and Firebag Rivers. The Athabasca River contributes more than 50 % of the total input to Lake Athabasca (Rasouli et al., 2013). Climate in the ARB is classified as sub-humid, with annual potential evapotranspiration (PET) exceeding total precipitation, resulting in a net water deficit most years (Marshall et al., 1999; Smerdon et al., 2005; Devito et al., 2012).

Peatlands in the Western Boreal Plains (WBP) including the ARB are ecologically important features that provide habitats for plant and animal communities and sequester carbon dioxide (Gorham, 1991; Tuittila et al., 2004). Price et al. (2005) conducted a thorough literature review of hydrologic responses and water-quality in Canadian wetlands and identified the important role of wetlands with respect to land surface-atmosphere, and surface-groundwater fluxes. The review also indicated that generalizing site-specific studies and upscaling to regional-studies could be a major research challenge for wetland hydrology in Canada. Rezanezhad et al. (2016) indicated that the upscaling of hydrological flow and chemical transport from pore-scale peat soils is of particular interest as future research. Previous studies, mostly at scales less than 100 km², used water balance and/or numerical modelling approaches to improve the understanding of the peatland water
exchange mechanisms in the WBP, (Ferone and Devito, 2004; Smerdon et al., 2005; Devito et al., 2005b; Smerdon et al., 2007; Brown et al., 2010; Wells and Price, 2015). For example, Smerdon et al. (2005, 2007) investigated lake-groundwater interactions to provide an understanding of the near-surface hydrologic processes in northern Alberta, using a water budget analysis and integrated surface water and groundwater simulations. Smerdon et al. (2007) indicated that the inclusion of the riparian peatlands is one of the major control factors for the lake-groundwater interaction to maintain surface water on permeable northern landscapes.

It is worth noting that most of the ecohydrologic studies for the WBP suggest roughly balanced or water deficit conditions in this area. Specifically, Wells and Price (2015) characterized a saline-spring fen in a Athabasca oil sands region using geochemical and hydrological (or water budget) approaches to conclude that estimated site-scale seasonal evapotranspiration exceeded precipitation during the study periods (June to September in 2011 and April to September in 2012). In the vicinity of the ARB, a similar water deficit condition was reported in the Utikuma region (Devito et al., 2012). Along with the site-scale studies, many peatland reclamation studies have attempted to incorporate water deficit conditions as long-term climate scenarios (Elshorbagy and Barbour, 2007; Carrera-Hernández et al., 2011; Carrera-Hernández et al., 2012). However, Rasouli et al. (2013) investigated the contributions of surface water input to Lake Athabasca during a 51-year period and found that average stream flows in the downstream areas (i.e., Athabasca and McMurray gauge stations) of the Athabasca River Basin are about two times higher than those in upstream areas (i.e., Jasper and Hinton gauge stations), suggesting a water surplus

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within the basin. Recently, Rood et al. (2015) reported a similar trend that the mean annual stream flow at the Below McMurray gauging station was about 3.3 times higher than that at the upstream Hinton gauging station, and found that there is a strong correlation between mean annual and mean warm season stream flow rates along the Athabasca River. While many studies have attempted to quantify the hydrological and ecological responses of the ARB to changing climate, far less attention has been given to the role of peatland and forestland interaction with the atmosphere, surface and subsurface flow systems at the basin scale.

The water balance in each sub-basin of the ARB can be simply estimated by substracting downstream flow from upstream flow, which is physically the same as the net precipitation (= precipitation – actual evapotranspiration) unless there is artificial water mass input and output (Hwang et al., 2015). Table 1 lists a long-term (1971 ~ 2010) annual average stream flow and water balance at the sub-basins in the ARB. The normalized flow for each sub-basin can also be the same as the spatially-averaged net precipitation. The water balance in each sub-basin and normalized flow at each sub-basin are all positive (>80 m³/s), the change of the normalized flow rate decreases in the downstream sub-basins, indicating the spatial average net precipitation in the downstream areas is lower than that in upstream (Table 1). The long-term water balance of the ARB is somewhat of a paradox, with the sub-basin-wise water balance consistently positive, despite the sub-humid, potentially water deficit conditions, in the downstream regimes.

We develop and calibrate a 3D fully-integrated physically-based surface-subsurface flow and evapotranspiration model of the ARB for long-term average steady-state flow
conditions to analyze the role of the physical flow and evapotranspiration characteristics of the ARB as they relate to this water balance paradox. Rennermalm et al. (2010) investigated the impact of mean climate conditions on long-term peat accumulation/depletion using a steady-state approach. The study suggested that climate variability including precipitation, evapotranspiration and temperature is an important factor affecting peat accumulation and decomposition. Based on the climate analysis in the ARB, annual mean precipitation and potential evapotranspiration for the simulation period from 1971 to 2010 are approximately 505 mm/yr with a standard deviation ($\sigma$) of 46 mm/yr and 571 mm/yr ($\sigma = 27$ mm/yr), respectively. The climate variation during the 40-year simulation period is approximately 9% of the mean precipitation and 5% of the mean PET. According to Rennermalm et al. (2010), the net peat accumulation/depletion is almost zero over large spatial and temporal scales. Therefore, the steady-state approach with average climate conditions over 40 years used in this work can represent general spatial trends of actual evapotranspiration in the peatlands.

Using a calibrated long-term steady-state model, we analyze peatlands and forestlands interactions with the atmosphere-surface-subsurface water resources systems of the ARB.

2 Methods

2.1 Ecology, hydrology, and hydrogeology of the Athabasca River Basin

The ecological unit classification system of Alberta (Natural Regions Committee, 2006) identifies three major ecologic units (or Natural Regions) in the ARB: Rocky Mountains, Foothills, and Boreal Forest Natural Regions. Specifically, the Rocky Mountains Natural Region in the ARB consists of three Natural Subregions including Alpine, Subalpine,
and montane. The Foothills Natural Region within the ARB, a transition region between Rocky Mountain and Boreal Forest Natural Regions, consists of Upper and Lower Foothills.

The Boreal Forest Natural Region, covering the central and downstream regimes of the Athabasca River, is dominated by the Central Mixedwood Natural Subregion (Natural Regions Committee, 2006).

Within the ARB, Environment Canada maintained six streamflow gauging stations along the Athabasca River (HYDAT, 2010), which are located at Jasper, Hinton, Windfall, Athabasca, Fort McMurray, and Embarras Airport, and the Government of Alberta Groundwater Observation Well Network (GOWN) maintained groundwater monitoring wells operated by the Government of Alberta (Figure 1). Details describing the GOWN and its well installation can be found in Government of Alberta (2012) and Humez et al. (2016), respectively. Using the locations of the stream flow gauging stations, the basin is divided into six sub-basins (i.e., Jasper (JA), Hinton (HT), Windfall (WF), Athabasca (AT), Fort McMurray (FM), and Embarras Airport (EA) sub-basins). The stream flow rate at each gauging station can then be used to approximate net precipitation (precipitation minus evapotranspiration) for each sub-basin (Hwang et al., 2015). The sub-basin-wise approach was employed in this study as it can be useful to illustrate and evaluate the relationships of the water balance between the sub-basins as well as within each sub-basin (Hwang et al., 2015).

The hydrological conditions of the ARB are schematically described in Figure 2. The six hydrometric stations are placed based on their geographical locations along the Athabasca River (Figure 2a). The topographic change in the upstream area from the Jasper to Windfall
stations is relatively large because of the Rocky Mountains. In the midstream from Windfall before the Below Fort McMurray stations, the elevation change is relatively mild compared to the upstream area. In the downstream area from the Below Fort McMurray and Embarras Airport, the change is even milder, but there is drastic elevation change at the upstream of the Below Fort McMurray station. The historical stream flow rates measured at the stations along the Athabasca River were statistically analyzed over 40 years (1971 ~ 2010) (Figure 2b).

Note that, during the period, the historic stream flows at all the gauging stations were commonly available only in three years (1972, 1973 and 1975). In Figure 2b, the orange solid lines represent annual streamflow rates measured in 1972, 1973 and 1975 at the six stations along the Athabasca River. The green solid lines represent those measured from 1971 to 2010 at the Jasper, Hinton, Athabasca and Below Fort McMurray stations. The mean and standard deviations of the annual stream flows over all available years between 1913 and 2010 show a clear trend that the stream flow consistently increases along the river with the distance from the origin. This trend implies the water surplus conditions between any pair of hydrometric stations in an annually averaged sense.

Based on the Alberta GOWN, the monitoring wells were installed at various depths from 10 to 300 m. In the up- and midstream areas including JA, HT, WF, and AT, the groundwater well depths are less than 50 m, while being mostly deeper than 100 m in the Athabasca oil sand regions such as FM and EA. Given the wells completed less than 50 m, the water table averaged over all available years from 1960 to 2013 show that the water table elevation is strongly correlated with the ground surface elevation within the ARB: the mean depth to groundwater table ranges from 2 to 29 m (Figure 2c). Although there are not many
groundwater datasets from the shallow groundwater wells in the downstream areas, the
general trends in the basin follows the shallow groundwater system reported by Devito et al.
(2005a). In the Fort McMurray area, water levels at the deep wells (>100 m) are often deeper
than 100 m from the ground surface, which are likely to be affected by groundwater pumping
or oil sands mining operations because the temporal changes of water table is higher than 20
m during the observation period. Except for the area where water table is deep, the standard
deivation of the measured water table depth is less than 5 m.

2.2 Climate and peatlands of the Athabasca River Basin

Using climate data from the Climate Research Unit (CRU) (Harris et al., 2014), mean
annual total precipitation between 1971 and 2010 varies from 390 to 930 mm/yr in the ARB.
The values tend to decrease toward the downstream of the ARB: the annual total precipitation
ranges from 720 to 930 mm/yr in the Jasper (JA) and Hinton (HT) sub-basins, from 580 to
620 mm/yr in the Windfall (WF) and the upstream area of Athabasca (AT) sub-basins, and
from 390 to 530 mm/yr in the downstream of AT, Fort McMurray (FM), and Embarras
Airport (EA) sub-basins. The magnitudes and patterns of the annual total precipitation
applied in this study are similar to those reported by Natural Resources Canada (2009). A 40-
year trend of potential evapotranspiration (PET) in the ARB was also analyzed based on CRU
datasets. PET in CRU is calculated using the Penman-Montieth method with gridded climate
datasets (i.e. mean, minimum, and maximum temperatures, vapor pressure, wind, and cloud
cover) (Harris et al., 2014). The 40-year mean annual PET in the ARB ranges from 460 to
580 mm/yr in the JA, HT, WF, and the midstream area of AT sub-basins, from 610 to 650
mm/yr in the downstream of AT and the upstream of FM sub-basins, and from 530 to 610 mm/yr in the downstream area of the FM and EA sub-basins.

According to Turchenk and Pigot (1988), climate plays an important role in the formation of peatlands, with preference shown for cool, wet, and anaerobic conditions. Figure 3 shows the spatial distribution of peatlands in the ARB based on Tarnocai et al. (2002). The extent of peatland coverage in the ARB ranges from 0 to 68 % and in each sub-basin, there is a trend that upstream basins have relatively less peatland, and downstream have more. The upstream and midstream sub-basins are dominated by a peatland coverage of less than 20 % (i.e., JA, HT, WF, AT), while higher peatland coverage (> 20 %) is dominant in the downstream sub-basins such as FM and EA. Regarding the vegetation of the peatland areas in the ARB, the region upstream of the Athabasca River is dominated by boreal forest, while peat-forming and some woody vegetation are relatively dominant in the mid and downstream. Specifically, in the oil sands mining region, fens and bogs cover a significant portion of the area (64 % of the land cover class), and marshes and swamps cover less than 4 % (Harris, 2007; Rooney et al., 2012). Peat bogs in the region are dominated by sphagnum mosses, which is a type of hummock-forming moss (Shotyk et al., 2014). According to Gabrielli (2016), there are two types of fens in the Fort McMurray area: poor and rich fens. The poor fen is dominated by low-density black spruce (Picea marina) and Sphagnum mosses, while the rich fen is dominated by densely-canopied tamarack (Larix laricina) and various types of mosses including Tomentypnum nitens (Hedw.) Loeske (Bryophyta). Because the peat-forming mosses are non-vascular plants, they depend highly on the capillary pressure to uptake water from soils (Raddatz et al., 2009; Goetz and Price, 2016).
2.3 Integrated surface-subsurface model

In this study, an integrated surface water and variably-saturated subsurface flow and evapotranspiration simulator, HydroGeoSphere (HGS), was used to quantify the influence of peatlands and forestlands on the surface water and groundwater system over the ARB. HGS is a three-dimensional control-volume finite element model, which is designed to simulate fully-integrated surface-subsurface water flow and solute transport in a parallelized manner (Hwang et al., 2014; Aquanty Inc., 2015). Regarding the boundary conditions assigned for the integrated surface-subsurface ARB model, three types of boundary conditions were applied to the ARB model: critical depth (or free-fall), rain fall (or source), and evapotranspiration (or sink) boundary conditions. The critical depth conditions were implemented along the outer boundary of the surface domain and the rainfall and evapotranspiration boundary conditions were assigned on top of the integrated surface-subsurface domain. Limitations on representing the peatland distributions of the ARB model are discussed further in the results and discussion section.

2.3.1 Model calibration approach

To calibrate the steady-state model, a total of 55 calibration targets were considered, which include 45 groundwater levels and 10 surface water gauging datasets. Table 2 lists the calibration processes applied for this study. The model calibration takes two main steps: 1) estimating spatially-averaged actual evapotranspiration (AET) at each sub-basin using an iterative method (Hwang et al., 2015) and 2) calibrating the ARB model based on the measured surface flow rates and the groundwater table elevations. During the first step, a sub-basin-wise AET rate is estimated based on the water balance between net precipitation and
surface flow. The estimated areal average AET can provide AET value ranges to be matched at the sub-basins in the next calibration step. During the second step, the model is calibrated by manually changing the ET parameters as well as hydraulic parameters of the soil materials to fit with calibration targets such as the surface flow rates and total head. In this step, estimated parameters are primarily related to the peatlands: friction factors of peatland, hydraulic conductivities for the near surface, ET parameters including transpiration partitioning factors and evaporation limiting saturation and peatland coverages that can represent the peatlands in the ARB.

Regarding the peatland distributions of the ARB model, the peatland coverage is classified into six subgroups with a 10 % interval (<20 %, 20~29 %, 30~39 %, 40~49 %, 50~59 %, and > 60 %) and then a total of five peatland distribution cases are accounted for the model calibration (Figure 3). In each case, a peatland zone is assigned if peatland coverage is higher than a certain percentage such as 20, 30, 40, 50, and 60 %, and the rest of the domain is assigned as forestlands (or mineral soil zones). With the five peatland distribution models, the transpiration fitting parameters and the transpiration limiting saturation values are manually adjusted by narrowing the value ranges until the simulated groundwater levels and surface flow rates fall within one standard deviation of the mean observed datasets. Most parameter value ranges are based on previous studies that performed measurements or simulations to estimate the parameter values (see Table 2). Specifically, the transpiration limiting saturation parameters includes wilting point, field capacity, oxic limit, and anoxic limit factors. Among them, the wilting point and the oxic limit factors are considered in the calibrations because they represent the lower (or dry conditions) and upper
(or wet conditions) limits of transpiration. For dry conditions, the wilting point controls the minimum saturation that vegetation can transpire and thus the calibration range of the wilting point is from residual saturation to field capacity. For wet conditions, the calibration range for the oxic limit factor ranges from field capacity to 1.0 because transpiration (i.e., growth and photosynthesis) of peat mosses (i.e., Sphagnum) are limited under highly saturated conditions (Clymo, 1970; Rice and Giles, 1996; Belyea and Clymo, 2001; Smolders et al., 2002).

If the hydraulic properties and ET parameters for a peatland model lie outside of their acceptable fitting ranges, the peatland model is considered as failing to achieve the model calibration cutoff. Among the five peatland cases, a peatland distribution model is selected based on the calibration results. Since the convergence criteria applied in the calibration process comprise one standard deviation about the mean observation, the calibrated parameter values are listed as ranges in the following model description sections. The simulations were conducted on the General Purpose Cluster operated by the SciNet Consortium at the University of Toronto (Chris et al., 2010). The total computing time taken with eight cores (2.53 GHz Intel Xeon with 16 GB RAM) was approximately 48 hours.

2.3.2 Overland flow

The top surface of the simulation domain (ground surface) was defined using the USGS Hydro1K digital elevation model (DEM) of 1 km resolution (U.S. Geological Survey, 2000). Based on the University of Maryland land cover classification dataset (Hansen et al., 2000), land cover in the ARB is dominated by three main classes: boreal forest including evergreen needle-leaf forest, mixed forest, woodland covers about 129,100 km$^2$ (about 81 % of total area); 14,500 km$^2$ (8.7 %) for wooded grassland, and 10,700 km$^2$ (6.5 %) for water.
bodies. The boreal forest and wooded grassland cover almost 90% of the area and peatlands in the Canadian boreal forest are present in a discontinuous mosaic, which consists of peatlands and forestlands (Metcalf and Buttle, 2001; Petrone et al., 2007). Therefore, the land cover of the ARB are simplified into five groups based on the peatland distributions and their corresponding eco-regions reported by Turchenek and Pigot (1988): Boreal Uplands, Boreal Foothills, Boreal Mixedwood, peatlands and water (Figure 4).

The 2D surface domain of the ARB was discretized using various sizes of triangular elements, consisting of 44,592 nodes and 87,568 elements. The average horizontal resolution of the 2D mesh is about 3 km in the upland and it was refined along the major surface drainage features at a resolution of 0.5 km (Figure 4). Table 3 summarizes the surface flow parameter values assigned to the ARB model. The friction values for the land cover classes are assigned based on Engman (1986) and McCuen (1989) – the friction coefficients for the Boreal Uplands and Boreal Foothills (0.6 and 0.1 m$^{-1/3}$s, respectively) are relatively high compared to that used for the Boreal Mixedwood (0.05 m$^{-1/3}$s). The lowest friction is assigned to the Water (0.01 m$^{-1/3}$s). The friction factors of Boreal Uplands, Foothills, and Mixedwood correspond to dense conifer forest, row crop fields, and wetlands and sparse forest in McCuen (1989), respectively. For the peatlands, the friction coefficient ranges from 0.1 to 2.0 m$^{-1/3}$s, which was estimated from the model calibrations.

2.3.3 Subsurface flow

The conceptual geologic model for the Athabasca River Basin (ARB) is constructed based on studies by Adams et al. (2004), Bachu et al. (1993), and the Geological Atlas of the Western Canada Sedimentary Basin from the Alberta Geological Survey (AGS). The model
included 13 geologic units as follows (Figure 5): (1) Topsoil units (mineral soils/peatlands/riverbeds), (2) unconsolidated sediment, (3) Paskapoo Formation, (4) Tertiary Upper Cretaceous, (5) Cretaceous Colorado, (6) Cretaceous Viking Formation, (7) Cretaceous Mannville, (8) Jurassic, (9) Devonian Wabamun, (10) Devonian Winterburn, (11) Devonian Beaverhill, (12) Devonian Elk Point, and (13) and the Canadian Rocky Mountains.

Regarding the numerical discretization of the ARB domain, the subsurface domain consists of 19 layers and is discretized with 3D prism elements (Figure 5). The model consists of approximately 1.0 million nodes and 1.9 million elements. The lower bound of the geological domain is defined by the Precambrian structure (Burwash et al., 2008), which the elevation ranges approximately from -6000 m in the Rocky Mountain unit on the left side of the domain, to 350 m in the Devonian elk Point Group on the right side of the domain (see an inset of Figure 5).

Regarding the topsoil units, it is difficult to represent the peatland coverages as a zone because the hydrologic responses of the peatlands and forestlands are significantly different ( Metcalfe and Buttle, 2001; Petrone et al., 2007). Additionally, riverbed materials play an important role for quantifying the flux exchange flux between surface water and groundwater as well as groundwater interactions in riparian zones (Chen, 2000; Landon et al., 2001; Sawyer and Cardenas, 2009; Strasser et al., 2015). Therefore, we divided the topsoil layer into three types such as mineral soils, peats and riverbeds. The peat layer is up to 3.5 m thick and vertically refined using four layers of varying thicknesses (less than 0.5 m for the top two; less than 1.5 and 1.0 m for the bottom two), as they can be important for the surface water and groundwater interaction. Additionally, many studies reported that macropores in peats
play an important role in moisture, nutrient, and energy distribution in peatlands (Holden, 2009; Dettmann et al., 2014; Dettmann and Bechtold, 2016; Mezbahuddin et al., 2016; Rezanezhad et al., 2016). Similar to the approach used by Burow et al. (2005), a highly conductive layer was applied to the top 0.5 m of the peatlands to reflect the preferential flow through macropore layers. Table 4 lists hydraulic parameter values for the mineral soils, peats, highly conductive zones and riverbeds. The mineral and peat soils were assigned based on studies from Huang et al. (2011) and Rezanezhad et al. (2012), respectively. The hydraulic conductivities for the riverbeds and highly conductive zones, obtained from the calibration processes, are in ranges of $1.42 \times 10^{-4} \sim 9.6 \times 10^{-3}$ m/s and $1.8 \times 10^{-3} \sim 6.1 \times 10^{-3}$ m/s, respectively.

The bedrock geology for the ARB was defined using the geologic contact surfaces from the AGS, specifically the surfaces provided in the Shetsen grid format. The layers of the Cretaceous Mannville and the Devonian Elk Point groups are identified to play an important role for groundwater flow in this region and thus they are also further refined vertically. The bottom of the ARB model was defined using the top of the Precambrian formation (Burwash et al., 2008). The Canadian Rocky Mountains unit located in the southwestern upstream of the ARB consists of various types of geological units from Cambrian to Cretaceous and therefore the unit consists of highly disturbed consolidated materials (Pana and Elgr, 2013). Table 5 lists the hydraulic parameters pertaining to subsurface flow below the peat layer. The horizontal hydraulic conductivity values are $5.0 \times 10^{-5}$ m/s for the unconsolidated sediment, and $10^{-7}$ m/s for the Paskapoo formation. Hydraulic conductivity for the Cretaceous Mannville and the Devonian Elk Point Groups are assigned based on the work by Adams et.
For each of the geologic units, the vertical hydraulic conductivity ($K_z$) is assumed to be one tenth of the horizontal hydraulic conductivity ($K_x$ and $K_y$).

### 2.3.4 Evapotranspiration model

In this study, the actual evapotranspiration (AET) is estimated following the approach suggested by Kristensen and Jensen (1975). The ET model has been widely used for various types of vegetation and also applied to peatland areas to estimate hydrologic interactions between surface water and groundwater flow regimes (Price et al., 2010; Ala-aho et al., 2015; Thompson et al., 2015; Ala-aho et al., 2017; Thompson et al., 2017). Detailed information on the approach can be found in the HGS documentation (Aquanty Inc., 2015). However, it is noted that the evapotranspiration (ET) model was simplified for the ARB model calibrations to reduce the number of parameters related to transpiration. Specifically, the evaporation ($Ev$) and transpiration rate ($Tr$) are computed using the following equations:

$$AET = Tr + Ev$$  \hfill (1a) \\
$$Tr = f_1 \cdot f_2(S_w) \cdot RDF(z) \cdot E_P$$  \hfill (2b) \\
$$Ev = (1 - f_1) \cdot f_3(S_w) \cdot EDF(z) \cdot E_P$$  \hfill (3c)

where $f_1$ is a transpiration and evaporation partitioning factor, $f_2(S_w)$ and $f_3(S_w)$ are the water stress functions for transpiration and evaporation respectively, $S_w$ is the water saturation, $RDF(z)$ and $EDF(z)$ are the root distribution function and evaporation distribution function over the soil profile from ground surface to the maximum transpiration and evaporation depths, respectively, and $E_P$ is the potential evapotranspiration. The water stress function for transpiration ($f_2$) follows Feddes et al. (1978): it is zero below wilting saturation; linearly increases from 0 to 1 when saturation changes from wilting point to field capacity;
remains to be unity between field capacity to oxic limit; linearly decreases from 1 to 0 between oxic and anoxic limits; and zero when the saturation is larger than the anoxic limit. For evaporation, $f_3$ is zero when the saturation is below the minimum evaporation limiting saturation; linearly increases from 0 to 1 when the saturation changes from the minimum to maximum limiting saturations; and remains unity when the saturation is larger than the maximum limiting saturation.

The ET properties applied in the integrated simulations are listed in Table 6. The ET zones in the ARB consist of forestlands (mineral soils), peatlands (peat soils), and water. The soil types in the bracket correspond to the topsoil zones connected to the ET zones. The ET parameters for the forestlands and peatlands are assigned based on the studies from Huang et al. (2011) and Ala-aho et al. (2015), respectively. The transpiration partitioning factors for the forestlands and peatlands controls the ratio of transpiration to evaporation. Based on the simulation results, the transpiration partitioning factors of the forestlands in shallow groundwater areas are inversely proportional to the actual evapotranspiration under the same hydrologic conditions because the transpiration is limited at full saturation (i.e., $S_{ox} = 0.93 \sim 0.95$). Instead, evaporation, with a maximum limiting saturation of 1.0, in the areas increases with decreasing the transpiration partitioning factors and thus resulting in increasing actual evapotranspiration. For the role of the transpiration partitioning factor in peatlands, if the transpiration limiting saturation ($S_{ox}$) is 1.0, the transpiration partitioning factor is proportional to actual evapotranspiration because the transpiration in peatlands is maximized under full saturations. It is noted that the transpiration fitting parameters and the transpiration...
limiting saturation values are adjusted during the calibration of the ARB model to best match the measured stream flow and groundwater table and depths.

3 Results and discussion

3.1 Surface-subsurface flow model calibration results

Steady-state long-term (1971 ~ 2010) average surface water and groundwater characteristics were simulated using the integrated surface-subsurface model. Since all the surface flow measurements along the Athabasca River are only available for the period of 1972, 1973 and 1975, a 3-year short-term steady-state calibration was also performed to estimate the net precipitation ratios for the Windfall and Embarras sub-basins. Although the short-term steady-state climate conditions were relatively wet compared to the long-term climate conditions based on the stream flow rates as illustrated in Figure 2b, the calibration results of the long- and short-term surface-subsurface characteristics such as actual evapotranspiration (AET) and net precipitation ratios can provide calibration target ranges for each sub-basin of the integrated hydrologic model. Based on the results of the first calibration step using the iterative method, the net precipitation ratios for all the five peatland distribution models are 0.54±0.08 in JA, 0.52±0.08 in HT, 0.29±0.21 in WF, 0.26±0.13 in AT, 0.21±0.16 in FM, and 0.23±0.14 in EM sub-basins. AET rates estimated from the first calibration step are in the ranges of 79 ~ 90 m$^3$/s in JA, 48 ~ 106 m$^3$/s in HT, 90 ~ 203 m$^3$/s in WF, 554 ~ 877 m$^3$/s in AT, 576 ~ 862 m$^3$/s in FM, and 300 ~ 386 m$^3$/s in EM.
After calibration step 2 based on the calibration guidelines estimated from step 1, simulated stream flow rates for the short- and long-term periods are compared to the measured values at six and four gauging stations, respectively (Figure 6a). The annual average flow rates measured at the upstream gauging stations (i.e., Jasper and Hinton) are 87 (85) and 168 (169) m$^3$/s and the simulated mean flow rates at the same locations are 90 (82) and 168 (153) m$^3$/s, respectively (numbers in parentheses correspond to the long-term steady-state conditions). For both the short-term and long-term calibrations results, the difference between measured and simulated mean surface flow rate at the Jasper gauging station is approximately 4 % of the observed flow rate. The difference between measured and simulated mean stream flow at Hinton is approximately 9 %. For the mid and downstream stations (i.e., Windfall, Athabasca, Below Fort McMurray, and Embarras Airport), the measured mean flow rates for the short-term periods range from 233 to 782 m$^3$/s, and the simulated mean flow rates range from 259 to 865 m$^3$/s. The simulated stream flow rates at the mid and downstream gauging stations are overestimated approximately 8 to 19 % of the observations, but they are within one standard deviation. Similarly, for the long-term calibration results, the measured mean flow rates at the Athabasca and Below Fort McMurray stations are 420 and 613 m$^3$/s, respectively and the mean flow rates simulated at these stations are 429 and 540 m$^3$/s, respectively. The simulated flow rates at the downstream stations also agree well with the measured with less than 12 % of difference, which is less than the standard deviation of the observations. Overall, a high level of agreement between the simulated and measured stream flow was achieved with an $R^2$ value of 0.96 (Figure 6a).
For subsurface flow, both the simulated short-term and long-term steady-state potentiometric heads are compared to the measured mean groundwater table elevations (Figure 6b). Because the groundwater level measurements were not temporally continuous and the measurement period is different for each observation well, it is noted that the measured head values for each of the observation wells were averaged over all available years from 1960 to 2013. Therefore, the same mean observed groundwater table datasets were applied for both the short- and long-term groundwater level calibrations. The results in Figure 6b show that simulated heads agree reasonably well with the observed with an $R^2$ of about 0.95 for the long- and short-term cases. However, there are some mismatches where the groundwater table is about 100 m and deeper in oil sands mining areas of the Fort McMurray sub-basin. The deep groundwater tables might be caused by mining-related activities such as groundwater pumping and excavations. Overall, considering only for the shallow groundwater tables less than 20 m below surface, the differences between simulated and measured groundwater tables ranges from -7 % to 13 % of the measured datasets (red circles in Figure 6b).

Using the parameters estimated from the model calibrations, the steady-state integrated flow simulation results for the long-term climate conditions are illustrated in Figure 7. Figures 7a, 7b and 7c show the average spatial distributions of the depths to the groundwater table, AET and exchange flux in the ARB, respectively. The groundwater table depths are greater than 20 m in the upstream areas including the Rocky Mountains and Foothills because of topographic fluctuation in the areas, but there is shallow groundwater near the Athabasca River (Figure 7a). With response of the groundwater system in this area,
the simulated mean AET in the areas ranges from 290 to 390 mm/yr, and the spatial variation is less than 100 mm/yr (Figure 7b). For the exchange flux distributions shown in Figure 7c, the positive exchange flux represents the exfiltration (or groundwater seepage) to the surface, while the negative exchange flux represents the water infiltration from the surface to subsurface. In most of the streams and lakes, groundwater flows from the subsurface to surface, while infiltration and groundwater recharge is dominant in the rest of the area. Specifically, in the Rocky Mountains and Foothills, infiltration occurs dominantly in mountains with a range of -700 ~ -400 mm/yr and exfiltration is dominant in the streams and valleys, which is higher than 500 mm/yr. On the mountain hillsides, both the magnitudes of the mean infiltration and exfiltration fluxes are relatively low, which ranges from -200 to 200 mm/yr.

In the mid and downstream areas such as AT, FM and EA sub-basins, shallow groundwater systems with mean groundwater table depths less than 10 m are dominant because of relatively small topographic changes as well as low elevations compared to the upstream sub-basins. In the peatland areas, the water table is approximately 0.5 m from the ground surface mainly because of the highly conductive layer, or macropore, assigned to the top of the peat soils (Figure 7a). Additionally, the groundwater table on hilly terrains remains near the land surface, less than 0.5 m, due mainly to groundwater seepage (or exfiltration) (Figure 7c). Because of the shallow groundwater systems in the mid and downstream sub-basins, the mean AET in the peatlands ranges from 200 to 560 mm/yr with a spatially-averaged AET of 369 mm/yr, which is approximately 36 % lower than a spatially-averaged PET (= 575 mm/yr) in the sub-basin areas. Similarly, a spatially-averaged AET and PET in
the forestlands is approximately 403 and 592 mm/yr, respectively. In the riparian areas along the rivers, the mean AET ranges from 50 to 400 mm/yr because of relatively deeper groundwater tables, which decreases AET by lowering the water saturation in the vadose zone. Therefore, the results indicate that the stream flow in the mid and downstream areas of the ARB can be supported by the reduced AET (or increased net precipitation) in the peatland areas. The water balance of the ARB is discussed further in the next section.

3.2 Comparison to measurements from previous studies

Regarding the validity of the simulation results, the simulated groundwater depths and AET are compared to literature data reported from field studies in peatlands and forestlands (Table 7). The locations of the field study sites are shown in Figures 7a and 7b. The numbers in Figures 7a and 7b correspond to 1) Carey (2008) and Gabrielli (2016), 2) Scarlett et al. (2017), 3) Wells and Price (2015), 4) Gabrielli (2016), 5) Devito et al. (2005a), 6) Syed et al. (2006), Mezbahuddin et al. (2016) and 7) ~ 12) catchment studies based on Devito et al. (2017). In the South Bison Hill (SBH), located approximately 35 km northwest of Fort McMurray and shown as literature #1 in Figures 7a and 7b, Carey (2008) analyzed energy and water exchange fluxes for the reclamation site constructed with overburden from oil sands mining during the growing seasons from 2003 to 2005. According to Carey (2008), the depth to the groundwater table in this area was less than 0.1 m for the entire summer (Table 7). The simulated mean depth to groundwater table ranges from 0.4 to 0.9 m, which is similar to the measurements (Figures 7a). Average ET measured using the eddy covariance method was 251 mm/yr with a standard deviation ($\sigma$) of 30 mm/yr (Table 7). In Poplar Fen, located approximately 8 km apart from SBH, Gabrielli (2016) quantified total ET based on the
ecosystem-scale energy balance using the eddy covariance technique. Average ET estimated from the fen was 270 mm, with a range of 225 to 315 mm, for the 2013 growing season (Table 7). Compared to the observations, the simulated mean ET in the areas ranges from 372 to 460 mm/yr, which is approximately 60 % higher than the measurements (Figures 7b). The areas are located within the peatland areal coverage of 30 ~ 39 %, which is assigned as the forestlands in the ARB simulation and resulted in overestimations. In the eastern side of the oil sand mining area (literature #2 in Figures 7a and 7b), Scarlett et al. (2017) measured AET at various plot types such as control, moss, moss-mulch, ponds and seedlings in the Nikanotee Fen located in approximately 20 km north from Fort McMurray. The measured groundwater depth was less than 0.1 m (Table 7) and the simulated groundwater depth at this location is 0.2 m and is less than 0.85 m within a 3 km range (Figure 7a). Cumulative AET fluxes during the growing season in 2014 ranged from 179 mm in moss-mulch to 331 mm in ponds with an average of 256 mm (Table 7). The mean AET simulated in this location was 286 mm/yr ($\sigma=7.7$). Within a 3 km range, the mean simulated AET varies from 207 to 450 mm/yr (Figure 7b).

Below Fort McMurray (literature #3 in Figures 7a and 7b), Wells and Price (2015) analyzed hydrological responses of a saline-spring fen in the Athabasca oil sand region by measuring climate data and hydraulic parameters during the growing seasons in 2011 and 2012. Wells and Price (2015) reported that the measured groundwater table depth ranged from 0 to 0.65 m (Table 7), which is similar to the simulated mean groundwater table depth of 0.26 m with $\sigma$ of 0.58 m (Figure 7a). The seasonal AET measured in the site was 236 mm in 2011 and 421 mm in 2012, which is a mean AET of 329 mm (Table 7). The mean AET

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simulated in this study was 406 mm/yr ($\sigma = 84$) (Figure 7b). Additionally, the simulated
mean AET in the surrounding area ranges from 260 to 480 mm/yr, which falls into the
observations in various areas in the site such as inter-ridge depressions, ridge/lawn and
ponds. In Pauciflora fen located approximately 40 km south of Fort McMurray (Gabrielli,
2016; literature #4 in Figures 7a and 7b), measured mean AET was 173 mm during the
growing season in 2013, with a range from 83 to 263 mm (Table 7). Simulated mean AET in
this area 232 mm/yr ($\sigma =130$), which is approximately 34 % higher than the observation, but
the observed value falls within the range of the simulated AET, which is from 102 to 362
mm/yr.

In the midstream areas, Devito et al. (2005b) performed a water balance study in an
upstream catchment of Moose Lake, approximately 170 km south west from Fort McMurray
(literature #5 in Figures 7a and 7b). The catchment consists of wetland, forested and
harvested areas, and AET was calculated based on the energy-water balance equation.

Measured depths to the groundwater table ranges from 0.5 to 3.5 m in the uplands near the
wetland in the catchment and from 0 to 1.5 m in the valley-bottom wetland and ephemeral
draws in downstream sub-catchments (Table 7). Compared to the observed groundwater table
depth, the simulated mean depth to groundwater table in this area ranges from 0 to 0.4 with a
$\sigma$ of 0.2 m, which is relatively shallower than observed, but falls within the seasonal changes
in the downstream sub-catchment areas (Figure 7a). The estimated AET ranges from 192 to
492 mm with an average AET of 366 mm for growing seasons from 1997 to 2001 (Table 7),
and the simulated AET in this area ranges from 378 to 467 mm/yr with a spatially-averaged
value of 400 mm/yr ($\sigma =34$) (Figure 7b). Mezbahuddin et al. (2016) analyzed the hydrology
and energy responses in a fen peatland located approximately 80 km northeast of Athabasca, Alberta (literature #6 in Figures 7a and 7b). According to Syed et al. (2006), the study site was classified as a moderately-rich treed fen and net energy fluxes and meteorological data as well as groundwater levels were measured for ecosystem CO₂ exchange analysis. Regarding the groundwater table depth, the measured seasonal groundwater table depth ranges from 0 to 0.72 m (Table 7) and the simulated mean groundwater table depth ranges from 0.1 to 1.5 m, which is similar to the measured data at this site, but the simulated groundwater table is somewhat deeper than the measured data (Figure 7a). The cumulative ET based on the energy balance between precipitation and eddy covariance ET ranges from 174 to 258 mm with an average AET of 224 mm during the growing seasons for 5 years (2004 ~ 2009) (Table 7). The simulated mean AET at this location is 280 mm/year with a (σ =7) (Figure 7b), which is slightly higher than the measurement range.

Overall, the difference of groundwater table depths between the observation and simulation ranges from -0.14 to 1.8 m (negative and positive signs represent overestimation and underestimation, respectively). The maximum difference occurs at the Moose Lake where the groundwater depth is relatively deeper in the upstream catchment. Although groundwater table depths were underestimated, the simulated groundwater system in the peatlands was similar to the measurements reported from various peatland studies in the ARB (R²=0.71). For the AET comparison, except for literature #1, the comparison results show that the mean simulated AET at the peatland areas (literature #2 ~ #6) is approximately 321 mm, which is 19 % higher than the estimated AET (270 mm) from the five literatures.
In order to evaluate the reasonableness of the simulation results in the forestlands, the simulated mean AET in the downstream areas of the ARB were compared to five catchment studies based on the long-term water balance (Devito et al., 2017). The catchments for mean AET comparisons were selected with forest areas larger than \(2 \times 10^2 \text{ km}^2\) (polyongs in Figure 7b) and their corresponding CIDs (catchment identification numbers) and estimated long-term AETs were listed in Table 7. In the FA and EA sub-basins, the estimated and simulated annual mean AETs are 381 and 419 (\(\sigma =26\)) for literature #7, 362 and 399 (\(\sigma =25\)) for literature #8, 388 and 356 (\(\sigma =40\)) for literature #9, 408 and 407 (\(\sigma =41\)) for literature #10, 459 and 411 (\(\sigma =22\)) for literature #11, 353 and 403 (\(\sigma =29\)) for literature #12, respectively. The difference between the estimated and simulated AET ranges from -48 to 50 mm, and the relative difference between them is less than 15 % of the estimated AETs. Additionally, the simulated spatial average AET for all the catchments is 404 mm, which is similar to the estimated value of 396 mm and approximately 84 mm higher than the simulated mean AET in the peatlands.

Based on the comparison to the field studies conducted in the peatlands, the simulation results tend to slightly underestimate the groundwater table depths, with a maximum difference of 3.1 m, in the Moose Lake study site (Devito et al., 2005b) and overestimate the AET in the oil sands mining region. However, the overall simulation results are in reasonable agreement with the observations. The shallow groundwater system resulted in reduced AET and thus increased its contribution to stream flow in the basin. The comparison of the estimated and simulated AET in the forestlands shows relative differences in a range up to 15 % of the catchment AET estimated by Devito et al. (2017) and the overall
areal average AET matches well. Therefore, the basin-scale peatlands and forestlands model can reasonably reproduce the AET in the middle and downstream of the ARB. In the next section, the water availability and contributions to water resources systems of the ARB are analyzed based on the aridity index and actual aridity index across the ARB.

3.3 Assessment of peatland contributions to the water balance

An actual aridity index (AAI), defined in this study as the ratio of total precipitation to actual evapotranspiration (AET), is analyzed to quantify the spatial contribution to the water balance of the ARB. For comparison, the aridity index (AI), a ratio of total precipitation to potential evapotranspiration (PET) (UNEP, 1997), is computed to evaluate the potential water availability in the ARB.

Figure 8a shows the spatial distribution of the AI in the ARB based on the mean annual total precipitation and PET from 1971 to 2010. Overall, the AI in the ARB is higher than 0.61, which can be classified as a dry sub-humid to humid condition. Specifically, the AI in the Jasper (JA), Hinton (HT), and Windfall (WF) sub-basins is greater than 1.0, which indicates a humid condition, while the sub-basins downstream of the ARB including Fort McMurray (FM) and Embarras Airport (EA) are close to a dry sub-humid condition, similar to the results from other studies (Marshall et al., 1999; Thompson et al., 2015). The spatial distribution of AAI based on the calibration results for the long-term climatic conditions is shown in Figure 8b. The AAI values in the upstream sub-basins such as JA, HT, WF are higher than 1.3, indicating that positive net precipitation (or water surplus) conditions are dominant. This is comparable to the water balance in WF and the upstream of the AT sub-basin where the AI is approximately 1.0, indicating the water balance is neither a surplus nor
deficit condition (Figure 8a). In the mid and downstream areas, the spatial distributions of AAI and AI are significantly different from each other: a water deficit condition is dominant for AI, while the AAI distribution shows that water surplus conditions occur strongly in the surrounding areas of the Athabasca River because of relatively deep groundwater tables. AAI in the peatlands of the FM and EA sub-basins is higher than 0.9, which implies that water surplus condition is dominant (Figure 8b). In the forestlands of the FM and EA sub-basins, the AAI ranges from 0.7 to 2.5, which corresponds to various water balance conditions ranging from water deficit to surplus (Figure 8b). Overall, although the magnitudes of AAI in the FM and EA sub-basins for the peatlands and forestlands are different, the contribution patterns for both zones are similar. This result indicates that peatlands in the middle and downstream of the ARB increase the water availability to the surface-subsurface water systems by reducing water loss through evapotranspiration. The overall spatial average evapotranspiration in downstream forestlands is larger than that in peatlands and thus the water contribution to the stream flow in downstream areas is relatively minor compared to that from peatlands.

4 Summary and conclusions

Upscaling to regional-scale hydrologic analysis is one of the major challenges for wetland hydrology in Canada. The main objectives of this study are to analyze basin-scale hydrologic responses of peatlands and forestlands and to investigate why long-term annual downstream flow rates are consistently higher than upstream under the sub-humid water deficit conditions in the Athabasca River Basin (ARB). In this study, a high resolution, three-dimensional integrated surface-subsurface flow and evapotranspiration model was used to
analyze the influence of the distributions and hydrologic characteristics of peatlands and forestlands on the water balance in the ARB. The integrated numerical model was constructed by incorporating the available geologic, land use, and ecohydrologic data, including the peatland distribution. The conceptual subsurface model consists of 22 layers; a peatland layer comprised of four sublayers was assigned at the top of the model and the bottom of the model was bounded by the Devonian Elk Point Group. The topsoil layer was constructed using the extents of the peatland coverage that were classified based on the spatial density of the peatlands and then simplified into three groups: mineral soils, riverbeds and peatlands having more than 40% of peatland coverage. The land cover of the ARB was simplified to five classes: Boreal Uplands, Boreal Foothills, Boreal Mixedwood, peatlands, and Water Bodies. The ET model consisting of forestlands, peatlands and water was constructed based on the material zones assigned for the topsoil layers of the subsurface domain. The ET parameters for short- and long-term climatic conditions were assigned based on previous studies as well as model calibrations.

The model calibrations were performed with a systematic approach consisting of two steps: estimating sub-basin-wise actual evapotranspiration (AET) based on the water balance and fitting manually the ARB model parameters with 83 observations and the spatially-averaged AET estimated in the previous step. Additionally, groundwater table depths and AET were compared to measurements from six field sites. The simulated surface flows and groundwater table elevations for both the short- and long-term cases show high levels of agreement with the measured datasets. Although groundwater table depths were underestimated, the simulated groundwater system in the peatlands was similar to the
measurements reported from various peatland studies in the ARB. Additionally, the simulated AET values are in similar range to those reported at most of the field sites considered in this study. The calibration results indicated that groundwater exfiltration is dominant in the streams, while groundwater infiltration is dominant in other areas including the peatlands and forestlands. Groundwater infiltration is significantly less in lakes and water bodies compared to the upstream and midstream sub-basins.

The water balance and contributing areas of the ARB were analyzed using actual aridity index (AAI) and the spatial distribution of AAI was compared to aridity index (AI), which is known to be a dryness indicator. Based on the AI distributions of the ARB, the upstream sub-basins is classified as the humid condition, while the downstream areas are close to the dry sub-humid condition. The AAI in upstream sub-basins is similar to the AI, but the middle and downstream sub-basins such as Athabasca, Fort McMurray and Embarrass Airport sub-basins are found to be under either water-balanced or surplus conditions. Although several areas in the peatlands are in the water deficit conditions, the peatlands are dominated by water surplus, which implies that peatlands tend to contribute significantly to the overall water resources system in the ARB. Compared to the AET in the peatlands, the spatially-averaged AET in forestlands is larger and thus the water contribution to the stream flow in the areas is relatively minor. The main mechanisms for stream water contribution over the ARB may include groundwater inputs as well as surface runoff by reducing actual evapotranspiration in the downstream sub-basins. The mechanisms can be generalizable to other peatland studies for analyzing interactions between atmosphere-surface-subsurface hydrologic systems. Additionally, the AAI introduced in this study is more practical to
understand whether a hydrologic system in an area is a water surplus or deficit condition. Based on this approach, it is found that the peatland coverage rate of higher than 40% could be representative for long-term water balance studies in a basin. Although it is highly dependent on a case by case, the modelling approach applied in this study can be applied to other peatland systems with mosaics of peat and mineral zones with a single parameter set.

5 Acknowledgments

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Table 1. Long-term (1971~2010) water balance based on stream flow in the sub-basins of the Athabasca River Basin.

<table>
<thead>
<tr>
<th>Sub-basin</th>
<th>Cumulative area (km²)</th>
<th>Mean flow rate (m³/s)</th>
<th>Water balance in sub-basin (m³/s)</th>
<th>Normalized flow (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jasper</td>
<td>3.9×10^3</td>
<td>85.3</td>
<td>85.3</td>
<td>2.2×10⁻⁸</td>
</tr>
<tr>
<td>Hinton</td>
<td>9.8×10^3</td>
<td>169.3</td>
<td>84.0</td>
<td>1.7×10⁻⁸</td>
</tr>
<tr>
<td>Athabasca</td>
<td>7.5×10^4</td>
<td>420.0</td>
<td>250.7</td>
<td>5.6×10⁻⁹</td>
</tr>
<tr>
<td>Fort McMurray</td>
<td>1.3×10^5</td>
<td>613.1</td>
<td>193.1</td>
<td>4.6×10⁻⁹</td>
</tr>
</tbody>
</table>
### Table 2. Model calibration steps and estimated parameters.

<table>
<thead>
<tr>
<th>Step</th>
<th>Parameter to be estimated</th>
<th>Range</th>
<th>Calibration Target</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sub-basin AET</td>
<td></td>
<td>Long- and short-term surface flow rates</td>
<td>Iterative Newton method</td>
</tr>
<tr>
<td></td>
<td>Peatland coverage rate (%)</td>
<td>0 ~ 68 (^{1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Macropore layer K (m/s)</td>
<td>$10^{-3} \sim 10^{-1} (^{2})$</td>
<td>Groundwater level, depth to groundwater table and surface flow rates</td>
<td>Manual calibration based on step 1 results</td>
</tr>
<tr>
<td></td>
<td>River bed K (m/s)</td>
<td>$10^{-5} \sim 10^{-2} (^{3})$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Transpiration partitioning factor (-)</td>
<td>0 ~ 1 (^{4})</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transpiration limiting saturation (-)</td>
<td>0 ~ 1 (^{4})</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Evaporation partitioning factor (-)</td>
<td>0 ~ 1 (^{4})</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peatland friction factor (m(^{-1/3})sec)</td>
<td>0.1 ~ 6 (^{5})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{1}\) Peatland coverage was simplified with five cases, which peatland was assigned if the peatland coverage is higher than 20, 30, 40, 50, and 60 %.

\(^{2}\) Range was selected based on references (Dimitrov et al., 2010; Scarlett and Price, 2013; Wells and Price, 2015; Mezbahuddin et al., 2016).

\(^{3}\) Range was selected based on references (Chen, 2000; Landon et al., 2001; Strasser et al., 2015).

\(^{4}\) Range was selected based on references (Huang et al., 2011; Ala-aho et al., 2015).

\(^{5}\) Range was selected based on references (Ala-aho et al., 2017)

\(^{6}\) 40-year period from 1971 to 2010

\(^{7}\) 3-year period: 1972, 1973 and 1975

\(^{8}\) Hwang et al. (2015)
Table 3. Surface flow parameter values with land cover types.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Water</th>
<th>Boreal Uplands</th>
<th>Boreal Foothils</th>
<th>Boreal Mixedwood</th>
<th>Peatland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction factor (m $^{1/3}$ sec)</td>
<td>0.01 $^{1)}$</td>
<td>0.6 $^{2)}$</td>
<td>0.1 $^{3)}$</td>
<td>0.05 $^{4)}$</td>
<td>0.1 ~2.0 $^{5)}$</td>
</tr>
<tr>
<td>Rill/obstruction storage height (m $^{1/3}$ sec)</td>
<td>$5 \times 10^{-4}$</td>
<td>$5 \times 10^{-4}$</td>
<td>$5 \times 10^{-4}$</td>
<td>$5 \times 10^{-4}$</td>
<td>$5 \times 10^{-2}$</td>
</tr>
<tr>
<td>Coupling length (m)</td>
<td>$10^{-3}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
</tbody>
</table>

1) selected based on references (Engman, 1986; McCuen, 1989)
2) corresponding to dense conifer forest in McCuen (1989).
3) corresponding to row crop fields and plantation in McCuen (1989).
4) corresponding to wetlands and sparse forest in (McCuen, 1989).
Table 4. Parameter values for variably-saturated flow in peat layers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mineral soils</th>
<th>Riverbeds</th>
<th>Peats: top 0.5 m (Highly conductive layer)</th>
<th>Peats: below 0.5 m (Peat layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\text{sat}}$ (m/s)</td>
<td>$1.42 \times 10^{-4}$ 5)</td>
<td>$1.42 \times 10^{-4}$~$9.6 \times 10^{-3}$</td>
<td>$1.8 \times 10^{-3}$~$6.1 \times 10^{-3}$</td>
<td>$1.98 \times 10^{-6}$ 6)</td>
</tr>
<tr>
<td>$S_r$ 1)</td>
<td>0.004</td>
<td>0.004</td>
<td>0.4</td>
<td>0.4 6)</td>
</tr>
<tr>
<td>$\phi$ 2)</td>
<td>0.41</td>
<td>0.41</td>
<td>0.86</td>
<td>0.86 6)</td>
</tr>
<tr>
<td>$\alpha$ 3)</td>
<td>4.93</td>
<td>4.93</td>
<td></td>
<td>dual-porosity model 6)</td>
</tr>
<tr>
<td>$n$ 4)</td>
<td>2.767</td>
<td>2.767</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) residual saturation; 2) porosity; 3) van Genuchten parameter; 4) van Genuchten parameter
5) averaged value from Huang et al. (2011); 6) Rezanezhad et al. (2012)
Table 5. Parameter values for subsurface groundwater flow.

<table>
<thead>
<tr>
<th>Layer in ARB geologic model</th>
<th>$K_z = 0.1 K_x \text{ (m/s)}$</th>
<th>Porosity (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoil layer</td>
<td>See Table 3</td>
<td></td>
</tr>
<tr>
<td>Unconsolidated sediment</td>
<td>$10^{-7}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Paskapoo formation</td>
<td>$10^{-5}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Tertiary and Upper most Cretaceous</td>
<td>$10^{10}$</td>
<td>0.15</td>
</tr>
<tr>
<td>Cretaceous Colorado Group</td>
<td>$10^{-8}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Cretaceous Viking Formation</td>
<td>$10^{-7}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Cretaceous Mannville Group A</td>
<td>$1.26 \times 10^{-7}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Cretaceous Mannville Group B</td>
<td>$3.98 \times 10^{-8}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Cretaceous Mannville Group C</td>
<td>$3.98 \times 10^{-7}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Jurassic</td>
<td>$1.58 \times 10^{-9}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Devonian Wabamun Group</td>
<td>$10^{-7}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Devonian Winterburn Group</td>
<td>$10^{-7}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Devonian Beaverhill Lake Group</td>
<td>$2.0 \times 10^{-8}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Devonian Elk Point Group A</td>
<td>$2.0 \times 10^{-8}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Devonian Elk Point Group B</td>
<td>$2.51 \times 10^{-13}$</td>
<td>0.05</td>
</tr>
<tr>
<td>Devonian Elk Point Group C</td>
<td>$1.26 \times 10^{-7}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Canadian Rocky Mountains</td>
<td>$10^{-9}$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 6. Evapotranspiration parameter values assigned for evapotranspiration simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Forestlands (Mineral soils)</th>
<th>Peatlands (Peats)</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root depth (m)</td>
<td>1.0 (^7)</td>
<td>1.0 (^8)</td>
<td>0.1</td>
</tr>
<tr>
<td>Transpiration partitioning factor ((f_1))</td>
<td>0.60±0.10</td>
<td>0.50±0.05</td>
<td>0.0</td>
</tr>
<tr>
<td>Transpiration limiting saturation (-)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(S_{wp} (^3))</td>
<td>0.0097</td>
<td>0.35 (^9)</td>
<td>0.0097</td>
</tr>
<tr>
<td>(S_{fc} (^4))</td>
<td>0.017 (^7)</td>
<td>0.41 (^9)</td>
<td>0.017</td>
</tr>
<tr>
<td>(S_{ox} (^5))</td>
<td>0.93 ~ 0.95</td>
<td>0.95 ~ 1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(S_{ao} (^6))</td>
<td>1.0 (^7)</td>
<td>1.0 (^8)</td>
<td>1.0</td>
</tr>
<tr>
<td>Evaporation depth (m)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Evaporation limiting saturation (-)</td>
<td>min</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>0.18</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\(^1\)average climate between 1972, 1973 and 1975; \(^2\)average climate from 1971 to 2010
\(^3\)Wilting point; \(^4\)Field capacity; \(^5\)Oxic limit; \(^6\)Anoxic limit; \(^7\)Huang et al. (2011); \(^8\)Aalasaho et al. (2015)
## Table 7. Field studies and observed depth to groundwater table (DGWT) and evapotranspiration (ET)

<table>
<thead>
<tr>
<th>No.</th>
<th>Literature</th>
<th>Study site</th>
<th>DGWT (m)</th>
<th>ET&lt;sup&gt;1&lt;/sup&gt; (mm)</th>
<th>Spatially-averaged ET (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Measured</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Range&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Simulated</td>
</tr>
<tr>
<td>1</td>
<td>Carey (2008), Gabrielli (2016)</td>
<td>South Bison Hill, Poplar Fen</td>
<td>251</td>
<td>224 ~ 283</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Scarlett et al. (2017)</td>
<td>Nikanotee Fen</td>
<td>&lt; 0.1</td>
<td>256</td>
<td>179 ~ 331</td>
</tr>
<tr>
<td>3</td>
<td>Wells and Price (2015)</td>
<td>Saline-spring Fen</td>
<td>&lt; 0.65</td>
<td>329</td>
<td>236 ~ 421</td>
</tr>
<tr>
<td>4</td>
<td>Gabrielli (2016)</td>
<td>Pauciflora Fen</td>
<td></td>
<td>173</td>
<td>83 ~ 263</td>
</tr>
<tr>
<td>5</td>
<td>Devito et al. (2005b)</td>
<td>Moose Lake (upstream catchment)</td>
<td>0.5 ~ 3.5&lt;sup&gt;4&lt;/sup&gt;</td>
<td>366</td>
<td>192 ~ 492</td>
</tr>
<tr>
<td></td>
<td>Syed et al. (2006); Mezbahuddin et al. (2016)</td>
<td>Fen peatland</td>
<td>&lt; 0.72</td>
<td>224</td>
<td>174 ~ 258</td>
</tr>
<tr>
<td>7</td>
<td>Devito et al. (2017)</td>
<td>CID 2</td>
<td>381</td>
<td>419&lt;sup&gt;6&lt;/sup&gt; (26&lt;sup&gt;7&lt;/sup&gt;)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>CID 3</td>
<td>362</td>
<td>399&lt;sup&gt;6&lt;/sup&gt; (25&lt;sup&gt;7&lt;/sup&gt;)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>CID 4</td>
<td>388</td>
<td>356&lt;sup&gt;6&lt;/sup&gt; (40&lt;sup&gt;7&lt;/sup&gt;)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>CID 9</td>
<td>408</td>
<td>407&lt;sup&gt;6&lt;/sup&gt; (41&lt;sup&gt;7&lt;/sup&gt;)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>CID 10</td>
<td>459</td>
<td>411&lt;sup&gt;6&lt;/sup&gt; (22&lt;sup&gt;7&lt;/sup&gt;)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>CID 14</td>
<td>353</td>
<td>403&lt;sup&gt;6&lt;/sup&gt; (29&lt;sup&gt;7&lt;/sup&gt;)</td>
<td></td>
</tr>
</tbody>
</table>

<sup>1</sup>Cumulative ET measured during the growing seasons; <sup>2</sup>Mean ET during the growing seasons; <sup>3</sup>Minimum and maximum ET reported from field studies; <sup>4</sup>Uplands; <sup>5</sup>Wetlands; <sup>6</sup>mean; <sup>7</sup>standard deviation
Figure 1 Sub-basins and locations of surface water gauging stations and groundwater observation wells in the ARB: JA=Jasper; HT=Hinton; WF=Windfall; AT=Athabasca; FM=Fort McMurray; and EA=Embarras Airport sub-basin.
Figure 2 Surface and subsurface hydrologic conditions in the Athabasca River Basin: a) Athabasca River elevation and gauge station locations, b) long-term trends of surface flow measured at gauge stations, c) mean groundwater levels measured in three sub-basins.
Figure 3 Spatial distribution of peatlands in the Athabasca River Basin: JA=Jasper; HT=Hinton; WF=Windfall; AT=Athabasca; FM=Fort McMurray; and EA=Embarras Airport sub-basin.
Figure 4 Land cover type distributions in the Athabasca River Basin and mesh.
Figure 5 3-D subsurface model for the Athabasca River Basin.
Figure 6 Comparison between simulated and measured datasets for short-term (1972, 1973, and 1975) and long-term (1971 ~ 2010) cases: a) surface flow rates at gauging stations and b) groundwater table (GWT) elevations at monitoring wells.
Figure 7 Results of steady-state surface-subsurface flow and evapotranspiration simulation: a) mean groundwater table (GWT) depth b) mean actual evapotranspiration (AET), and c) mean exchange flux.
Figure 8 a) spatial distribution of aridity index (AI) and b) spatial distribution of actual aridity index (AAI) based on long-term steady state simulation results: JA=Jasper; HT=Hinton; WF=Windfall; AT=Athabasca; FM=Fort McMurray; and EA=Embarras Airport sub-basin.