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A WATER ALLOCATION DECISION-SUPPORT MODEL AND TOOL FOR PREDICTIONS IN UNGAUGED BASINS IN NORTHEAST BRITISH COLUMBIA, CANADA[1]

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ABSTRACT: Pressures on water resources due to changing climate, increasing demands, and enhanced recognition of environmental flow needs result in the need for hydrology information to support informed water allocation decisions. However, the absence of hydrometric measurements and limited access to hydrology information in many areas impairs water allocation decision-making. This paper describes a water balance-based modeling approach and an innovative web-based decision-support hydrology tool developed to address this need. Using high-resolution climate, vegetation, and watershed data, a simple gridded water balance model, adjusted to account for locational variability, was developed and calibrated against gauged watersheds, to model mean annual runoff. Mean monthly runoff was modeled empirically, using multivariate regression. The modeled annual runoff results are within 20% of the observed mean annual discharge for 78% of the calibration watersheds, with a mean absolute error of 16%. Modeled monthly runoff corresponds well to observed monthly runoff, with a median Nash–Sutcliffe statistic of 0.92 and a median Spearman rank correlation statistic of 0.98. Monthly and annual flow estimates produced from the model are incorporated into a map- and watershed-based decision-support system referred to as the Northeast Water Tool, to provide critical information to decision makers and others on natural water supply, existing allocations, and the needs of the environment.

(KEY TERMS: surface water hydrology; computational methods; decision-support systems; Northeast Water Tool.)

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INTRODUCTION

As pressures on water resources rise due to changing climate, increasing industrial, agricultural, and domestic demands, and enhanced recognition of environmental flow needs (EFN), there is a concurrent rise in the need for hydrology information to make informed water allocation decisions. However, the absence of hydrometric measurements and limited access to hydrology information in many areas impairs informed water allocation decision-making. Hydrology knowledge gaps have been well documented for many decades, and have been expressed well by Sivapalan et al. (2003), leading to focused research

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efforts under the umbrella of Predictions in Ungauged Basins (PUB) initiative, the 10-year strategy of the International Association of Hydrological Sciences (Hrachowitz et al. 2013). In many areas of the world, adequate data do not exist to drive spatially explicit and complex deterministic hydrology models, suggesting a need for simpler models that incorporate a mix of empirical and deterministic approaches. Simple, regional-scale hydrology models can provide reasonable, use-appropriate water resource information (Caldwell et al. 2015). Also, despite the gains in hydrology process knowledge resulting from the PUB initiative, that knowledge has remained largely within the academic community and has not commonly been operationalized to inform and assist with water allocation and management decision-making, with some exceptions (Hamilton and Seelbach 2011). Advances in operational hydrology are being made, such as with the Watershed Flow and Allocation Model, of Eddy et al. (2017), developed to generate the hydrologic foundation for a variety of water resources management applications in Southeastern United States.

These issues are relevant to northeastern British Columbia, Canada, where order of magnitude increases in industrial water demand over the last several years to support the burgeoning unconventional natural gas industry have resulted in stress on water resources, and a high level of public concern and scrutiny of water allocation decisions. Decision-making for water allocation requires hydrology knowledge, to assess water supply in relation to water demand. For much of northeastern British Columbia, however, there is a dearth of hydrometric measurements to directly support water allocation decision-making. As a result, there is a strong need for hydrological modeling to provide quantified estimates of natural runoff, to understand basic aspects of natural water supply. In addition, the hydrology information that exists is largely in the form of digital data files produced by the Water Survey of Canada (WSC) that are generally incomprehensible to a nontechnical audience, and that provide no direct information on critical issues such as the maintenance of environmental flows, or the likely direction and magnitude of hydrological change associated with future climates. Improvement in the conversion of hydrology data into water management information is important.

This paper describes and summarizes the Northeast Water Tool (NEWT) project for northeastern British Columbia, an approach to operationalize the PUB concepts for applied water management. There are two primary objectives for the study:

1. To produce and evaluate a simple, spatially explicit water balance model providing estimates of mean monthly, seasonal, and annual runoff for rivers and streams in northeastern British Columbia, using available gridded and spatial climate data, land cover/vegetation data, catchment topographic information, and a limited gauge record as primary driving data; and
2. To develop a sophisticated map- and watershed-based application delivered via the web that provides public access to the modeled hydrology data in combination with other critical information relevant to water allocation decision-making (Chapman et al. 2012).

STUDY AREA

This study within northeastern British Columbia includes the area east of the continental divide, draining through the Peace and Liard Rivers into the Mackenzie River and Arctic Ocean (Figure 1). The extent of analysis extends significantly into Alberta, and the Yukon and Northwest Territories to include gauged basins deemed representative of conditions in British Columbia or areas contributing runoff to rivers in British Columbia. The total area within British Columbia under study is approximately 175,500 km^2.

The climate varies from cold continental in the south to cold subarctic in the north, characterized by sustained cold winters and warm summers. Average monthly temperatures for November to March are below freezing. There are few climate stations with long-term records; however, Fort Nelson has a measured 30-year (1981–2010) normal precipitation of 452 mm and a mean temperature of −0.4°C, while Fort St. John has a normal precipitation of 445 mm and a mean temperature of 2.3°C (Table 1) (Canada 2016). Annual precipitation increases to the west of the study area, in the higher elevation terrain of the Rocky Mountain foothills. The streamflow regime is typically nival (snowmelt dominated), with a sustained cold winter period characterized by low rates of streamflow and competent river ice. This is followed by a spring freshet from approximately mid-April to late June, characterized by high rates of streamflow as the winter's accumulated snow melts. After the spring freshet period, river levels generally recede quickly through the summer and autumn until the winter freeze-up. Frontal or convective storm systems bring varying amounts of rain from late spring to autumn, often resulting in increases in river levels and discharge, and occasionally producing flooding. The timing of the annual peak flow usually coincides with the timing of the annual freshet snowmelt runoff, except for small- and mid-sized

FIGURE 1. Study area in British Columbia (BC), Canada, showing the Water Survey of Canada hydrometric gauges used for the hydrology modeling.

river basins, which, on occasion, can experience their largest peak flows from summer frontal or convective rain storms.

The study area lies along the western edge of the physiographic Alberta Plateau within the Interior Plains (Bostock 1970; Mathews 1986). The northern extension of the Rocky Mountains forms the western border of the region. Across the plateau, terrain is gently rolling and relief is generally <200 m. The foothills of the Rocky Mountains have stronger relief, commonly of 600–800 m. Surficial geology is largely the result of the extensive Quaternary glacial history, when multiple periods of glacial advance and retreat scoured the landscape and deposited a range of landforms (Catto 1991). Much of the plateau area is dominated by thin deposits of glacial till overlying bedrock. In the northern half of the study area, the constrained drainage has resulted in extensive wetland development, predominantly subarctic fen and bog (Zoltai and Tarnocai 1975). The most northern extent of the study area contains discontinuous permafrost, further constraining subsurface drainage. Major river valleys typically possess glaciofluvial and glaciolacustrine deposits of varying thickness, but commonly 10–50 m thick. Silty glaciolacustrine deposits associated with Glacial Lake Peace are common proximal to the Peace River (Catto 1991).

TABLE 1. Climate “Normal” (1981–2010) data for stations located in northeastern British Columbia.

	Temperature, mean annual, °C	Temperature, January, °C	Temperature, July, °C	Precipitation, mean annual, mm	Precipitation, November–April, mm	Precipitation, May–October, mm	Snowfall, mean annual, cm
Fort Nelson Airport Lat: 58°50′11′ Long: 122°35′50′ Elev: 382 m WMO ID: 71945	–0.4	–20.3	17.1	452.1	117.7	334.5	190.8
Fort St. John Airport Lat: 56°14′17′ Long: 120°44′25′ Elev: 695 m WMO ID: 71943	2.3	–12.8	16.2	444.7	139.3	305.4	189.6

Note: WMO, World Meteorological Organization.

HYDROLOGY MODELING

The water balance model is based on the available gridded data — monthly and annual precipitation, temperature and evapotranspiration grids, land cover and vegetation, and a digital elevation model (DEM). Input raster data vary in scale from 100 to 1,000 m cells. Measured hydrometric data are used for calibration and validation.

Annual Water Balance, Step 1

The annual water balance model takes a conservation of mass approach and follows on a concept originally applied by other researchers (Solomon et al. 1968; Hock 2003; McCabe and Markstron 2007; Moore et al. 2011). The model simulates the water balance at each grid cell, using the simple continuity equation:

$$\mathrm{RO}_{\mathrm{pred}} = P - \mathrm{ET}, \tag{1}$$

where $\mathrm{RO}_{\mathrm{pred}}$ is the predicted annual runoff (mm), P is the annual precipitation (mm), and ET is the annual evapotranspiration (mm). Since much of the study area is underlain by flat-bedded shales covered with thin glacial and postglacial deposits, infiltration to groundwater is believed to be a minor component of the water balance (Golder 2008; Abadzadesahraei et al. 2017). Over the multidecadal period which this analysis represents, natural additions to and withdrawal from groundwater storage are assumed to result in a net zero balance. Data compilation and spatial analysis for the model development were performed using the SEXTANTE spatial data analysis library and gvSIG software (gvSIG 2009), respectively. The modeled annual runoff for each grid cell was then integrated across the watersheds for each of the hydrometric stations used for calibration, to produce a modeled annual runoff for each watershed.

Residual or unpredicted runoff was calculated as:

$$\mathrm{RO}_{i,\mathrm{resid}} = \mathrm{RO}_{i,\mathrm{pred}} - \mathrm{RO}_{i,\mathrm{obs}}, \tag{2}$$

where $\mathrm{RO}_{i,\mathrm{resid}}$ is the residual or unpredicted annual runoff for watershed i, $\mathrm{RO}_{i,\mathrm{pred}}$ is the predicted annual runoff for watershed i, and $\mathrm{RO}_{i,\mathrm{obs}}$ is the observed runoff for watershed i.

Annual Water Balance, Step 2

Variability, uncertainty, and error exist in the measurements of all the natural processes represented by components of the model, including the hydrometric data to which model results are compared (Coxon et al. 2015). We hypothesize that there is uncertainty in the precipitation and temperature field from the gridded climate data (Wang et al. 2012), due to the paucity of long-term climate observations in boreal northern British Columbia used to calculate the grids. Wang et al. (2006) observed the difficulties in improving the performance of climate surfaces beyond the accuracy of the original PRISM (Daly et al. 2008) surfaces and were only able to apply bilinear interpolation rather than the elevation adjustments also incorporated in the temperature predictions. To explore for patterns in the error, they were mapped, plotted against watershed characteristics, and evaluated using correlation analysis against mean elevation (m), drainage area (km^2), mean annual temperature (°C), mean annual precipitation (mm), latitude (Universal Transverse Mercator

TABLE 2. Correlation matrices for variables used in annual runoff adjustment.

	Residual runoff	UTM_E	UTM_N	Elevation	Mean annual precipitation	Mean annual temperature
Southern Interior Plains (Peace River), n = 18						
Residual runoff	1.000					
UTM_E	0.575	1.000				
UTM_N	−0.229	−0.432	1.000			
Elevation	−0.408	−0.589	−0.368	1.000		
Mean annual precipitation	−0.173	−0.012	−0.802	0.667	1.000	
Mean annual temperature	0.589	−0.640	−0.887	0.031	0.559	1.000
Northern Interior Plains (Liard River), n = 27						
Residual runoff	1.000					
UTM_E	0.400	1.000				
UTM_N	−0.515	−0.219	1.000			
Elevation	0.102	−0.573	−0.520	1.000		
Mean annual precipitation	0.251	−0.606	−0.577	0.908	1.000	
Mean annual temperature	0.499	0.206	−0.922	0.309	0.468	1.000

Note: UTM, Universal Transverse Mercator; E, easting; N, northing.

[UTM] northing), and longitude (UTM easting) (Table 2).

To account for some of this systematic error in RO_{resid}, multivariate regression analysis was completed, regressing residual or unpredicted runoff (mm) against various watershed characteristics, using Systat version 13 (Systat 2011), and testing for statistical significance at the $p \leq 0.05$ level, to adjust the modeled runoff from Equation (1). The data were tested for normality using a Kolmogorov–Smirnov test, and the regression residuals were examined visually for homoscedasticity.

The regression analysis was completed separately for the Southern Interior Plains (predominantly the Peace River drainage) and the Northern Interior Plains (predominantly the Liard River drainage), following the hydrological zonation of Obedkoff (2000). For the Southern Interior Plains, a regression equation using longitude (UTM easting) and mean annual precipitation was statistically significant ($p \leq 0.05$, adjusted R^2 = 0.72, Standard Error of the Estimate (SEE) = 39 mm). For the Northern Interior Plains, a regression equation using latitude (UTM northing) and mean annual precipitation was statistically significant ($p \leq 0.05$, adjusted R^2 = 0.51, SEE = 32 mm). The coefficients from the regression were then applied to gridded datasets of annual precipitation, latitude, and longitude, to create an adjustment to the residual runoff from the annual runoff modeling.

Annual Water Balance, Step 3

Following the development of the residual runoff adjustment factor, the predicted annual runoff and the regressed residual runoff layer were combined to create an adjusted grid of annual modeled runoff incorporating topographic, geographic, and climatic factors.

$$RO_{i,\mathrm{adj}} = RO_{i,\mathrm{pred}} + RO_{i,\mathrm{resid\_regress}}, \tag{3}$$

where $RO_{i,\mathrm{adj}}$ is the adjusted annual runoff for watershed i (mm), $RO_{i,\mathrm{pred}}$ is the predicted annual runoff (mm), and $RO_{i,\mathrm{resid\_regress}}$ is the runoff adjustment (mm) derived from residual analysis. This calculation of adjusted annual runoff in Equation (3) is the final determination of modeled annual water balance in this study.

The percentage error in annual runoff was calculated as:

$$E_i = 100 \times (RO_{i,\mathrm{pred}} - RO_{i,\mathrm{obs}})/RO_{i,\mathrm{obs}}, \tag{4}$$

where E_i is the percent error for watershed i, $RO_{i,\mathrm{pred}}$ is the predicted annual runoff for watershed i, and $RO_{i,\mathrm{obs}}$ is the observed runoff for watershed i. The mean, median, and mean of the absolute values of E_i were calculated and denoted as median error (ME), mean error (MBE), and mean of the absolute values of error (MAE). In addition, the percentage of watersheds with errors of ±20% was calculated.

Monthly Runoff

Monthly runoff in northeast British Columbia is strongly related to the seasonality of temperature and precipitation. Daily average temperature falls below 0°C typically by mid-October, remaining below freezing until April. Thick, competent ice forms on rivers and lakes, and discharge levels fall to low levels by early December, remaining very low until the spring freshet begins, typically by mid-April. With the onset of spring snowmelt, river levels rise during May and June, with mid-sized rivers typically reaching their freshet peak flows by early- to mid-June. Following the snowmelt freshet peak, river levels recede steadily through summer and fall, until the onset of winter freeze-up. In some years, large convective and frontal storm systems produce heavy rainfall in summer and fall, resulting in secondary flood peaks. The timing of runoff from the snowmelt-dominated nival regime is affected by the geographic location of the watershed in northeast British Columbia, with northerly watersheds experiencing snowmelt later in the spring than southerly watersheds, and watersheds at higher elevation in the Rocky Mountain foothills experiencing snowmelt later than watersheds in the lower elevation plateau area.

The monthly runoff model was based on statistical analysis of the monthly distribution of runoff for the WSC hydrometric stations used for model calibration. Monthly runoff was calculated for each station as a percentage of the mean annual runoff.

$$\text{RO-MONTH}_{i,j} = 100 \times (\text{RO-MONTH}_{i,j,\text{obs}}/\text{RO}_{i,\text{obs}}), \tag{5}$$

where RO-MONTH is the monthly runoff for watershed i and month j, % of annual runoff; $\text{RO-MONTH}_{i,j,\text{obs}}$ is the observed monthly runoff for watershed i and month j (mm); and $\text{RO}_{i,\text{obs}}$ is the observed annual runoff for watershed i (mm).

To model monthly runoff across the study area, a multivariate regression approach was used to estimate monthly runoff for each month using the following as possible independent variables: mean watershed elevation (m), drainage area (km^2), mean monthly temperature (°C), mean monthly precipitation, latitude (UTM northing), and longitude (UTM easting). The regression analysis was completed using Systat version 13 (Systat 2011), and tested for statistical significance at the $p \leq 0.05$ level. Individual regression equations were produced for each month. Not all of the independent variables were significant in explaining monthly runoff in all months. The statistical results were good, with adjusted R^2 values varying from a low of 0.46 (SEE = 2.6 mm) for August to a high of 0.82 (SEE = 0.3 mm) for January and February.

The coefficients of the monthly regression models were then applied to the gridded data of adjusted annual runoff (RO_{adj}) to produce estimates of unit runoff across the study area for individual months.

Model Evaluation

The annual water balance model and the monthly runoff model were evaluated to determine their ability to predict mean annual runoff and mean monthly runoff. As described in Equation (4), the percentage error of the annual water balance and adjusted annual water balance were calculated, and various statistics of the error were determined (median error; mean error; mean of the absolute values of error; the percentage of watersheds with errors within ±20% of observed). A leave-one-out cross-validation approach was used to test the results of the adjusted annual runoff modeling and the monthly runoff modeling, following Moore et al. (2011), using the R programming language (R Core Team 2013). As well, patterns in error related to watershed characteristics were evaluated visually.

Modeled monthly runoff was evaluated using a Nash–Sutcliffe efficiency test and a Spearman's rank correlation test, where the Spearman's rank correlation coefficient (r_s) was calculated between the predicted and observed series of mean monthly runoff. Synthetic hydrographs of the adjusted annual runoff and monthly runoff models in relation to observed runoff were evaluated visually (Figure 2). Because monthly and annual runoff can vary considerably within the 30-year climate normal period, the modeled adjusted annual and monthly discharge is presented in relation to the full record of observed runoff in Figure 3, for two study watersheds.

DATA

The water balance model is based on monthly and annual precipitation, temperature and evapotranspiration grids, land cover and vegetation polygons, a DEM, and measured hydrometric data. Input raster data vary in scale from 100 m to 1,000 m cells. A nominal resolution of 600 m was chosen for analysis.

Precipitation and temperature data were extracted from the ClimateWNA program (Wang et al. 2012), which was developed using the PRISM approach (Daly et al. 2008). The ClimateWNA program is provided "scale-free," and allows the user to generate a gridded product at a scale of their choice, in practice typically the same as the scale of available DEM data.

Gridded evapotranspiration data were acquired from the Consultative Group on International Agricultural Research (CGIAR) (Trabucco and Zomer 2010). This product estimates potential evapotranspiration (PET) using a modified Hargreaves approach (Droogers and Allen 2002) taking climate inputs from the WorldClim database, with a 1 km gridded climate surface representing the time period 1950–2000 (Hijmans et al. 2005). A monthly soil reduction factor and vegetation coefficient is applied to the PET estimate to produce a value for actual evapotranspiration (AET).

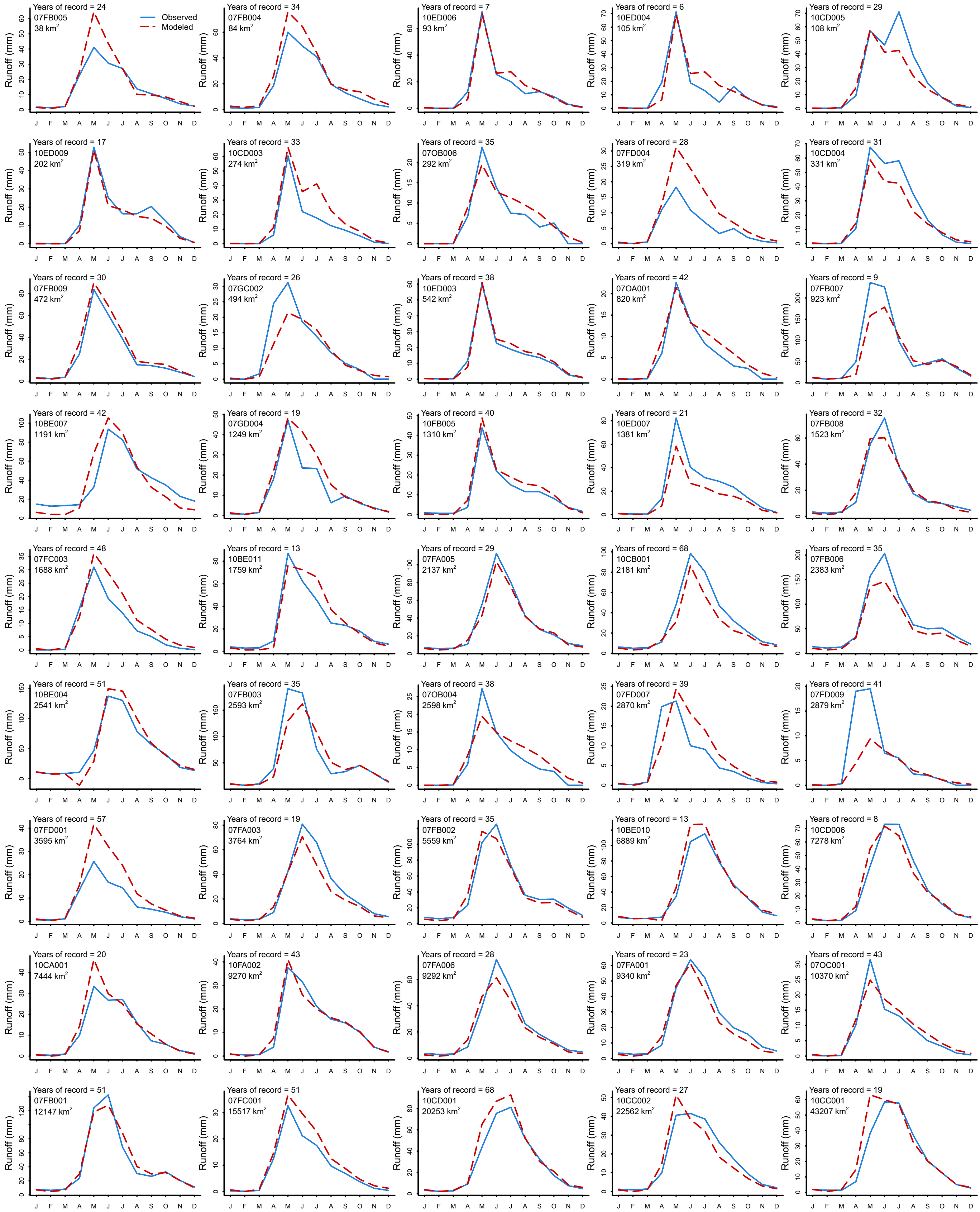


FIGURE 2. Annual hydrographs for watersheds in the study area, showing observed and modeled discharge.

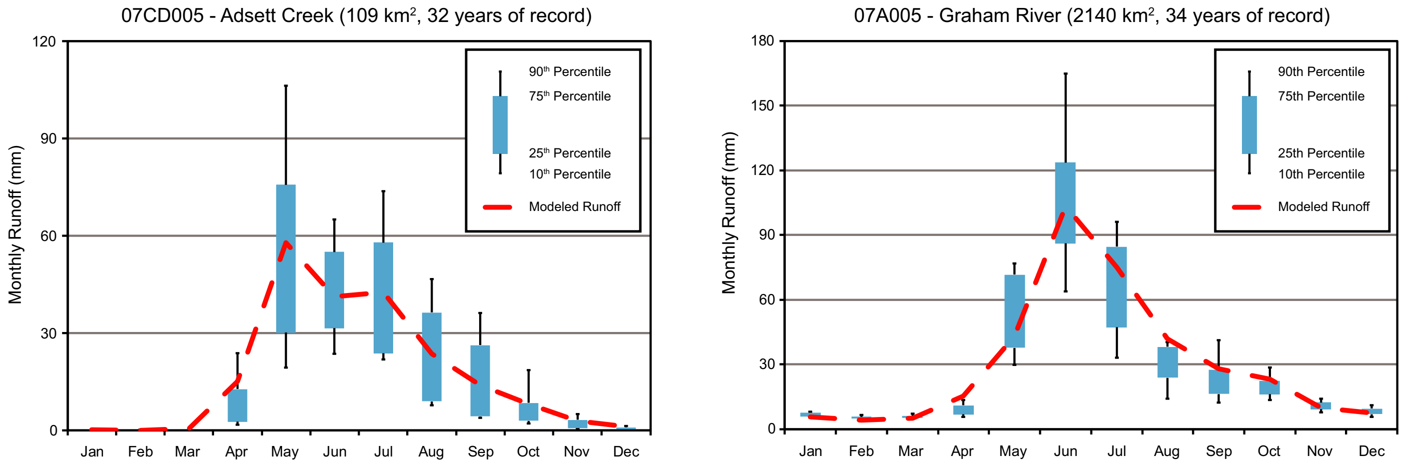


FIGURE 3. Annual and monthly runoff for two watersheds, showing modeled monthly runoff in relation to various percentiles of observed runoff.

The soil reduction factor uses a linear stress function relating monthly soil water content to a uniform maximum soil water content. In the CGIAR product, maximum soil water content is fixed at 350 mm and the vegetation coefficient is held constant at 1, representing a uniform agronomic crop.

The CGIAR-modeled AET was adjusted to better represent the land cover and vegetation in northeast British Columbia, where AET is expected to be different from that of an agronomic crop. Measured AET rates from land cover and vegetation types analogous to those in northeast British Columbia were collated and used to adjust the CGIAR-modeled AET (Table 3).

The primary data source for land cover and vegetation mapping was the Land Cover Circa 2000, derived from vectorized and classified Landsat 5 and 7TM ortho-images from projects coordinated by the

TABLE 3. Measured values actual evapotranspiration (AET) used to adjust gridded ET.

Setting	**Location**	**AET (mm)**	**Reference**
Barren	Canada	126 ± 32	Liu et al. (2003)
Boreal aspen	North Saskatchewan	400–420	Blanken et al. (2001)
Boreal aspen	Central Saskatchewan	403	Black et al. (1996)
Burnt	Canada	184 ± 30	Liu et al. (2003)
Canola	Southern Alberta	400–450	Thomas (1994)
Coniferous forest	Canada	276 ± 71	Liu et al. (2003)
Crop	Canada	341 ± 63	Liu et al. (2003)
Deciduous forest	Canada	492 ± 86	Liu et al. (2003)
Forest	50–70 N	300–400	Budyko (1974)
Grass	Canada	275 ± 42	Liu et al. (2003)
Jack pine	SE Manitoba	240	Amiro and Wuschke (1987)
Jack pine	Central Saskatchewan	218	Nijssen et al. (1997)
Mixed forest	Canada	405 ± 78	Liu et al. (2003)
Old aspen	Central Saskatchewan	270–375	Kljun et al. (2006)
Old aspen	Central Saskatchewan	300–450	Krishnan et al. (2006)
Old black spruce	Central Saskatchewan	345, 366	Arain et al. (2003)
Old black spruce	Central Saskatchewan	225	Jarvis et al. (1997)
Old black spruce	Central Saskatchewan	280–330	Kljun et al. (2006)
Old jack pine	Central Saskatchewan	222–254	Kljun et al. (2006)
Pine	Sweden	399	Grelle et al. (1997)
Shrub	Canada	195 ± 51	Liu et al. (2003)
Snow/ice	Canada	51 ± 7	Liu et al. (2003)
Subarctic boreal fen	North Manitoba	313–341	Chapman (1988)
Urban	Canada	195 ± 32	Liu et al. (2003)
Water	NW Alberta	601–643	Alberta (2013)
Water	NE British Columbia	350–500	Canada (1978)

Note: NW, northwest; NE, northeast; SE, southeast.

Canadian Forest Service, Canadian Space Agency, Agriculture and Agri-Food Canada, and the Canadian Centre of Remote Sensing (Canada 2009). Areas classified as cloud covered or where there were no data were filled in within British Columbia using the B.C. Vegetation Resource Inventory (British Columbia 2014) or the Baseline Thematic Mapping coverage (British Columbia 2011).

The DEM used for the project was compiled from data made available through the Geobase program of Natural Resources Canada (Canada 2000).

Data from 45 WSC hydrometric stations located in British Columbia, western Alberta, and the southern Northwest Territories were used in the modeling (Table 4). Stations were selected if they had unregulated flows and at least five years of record. Not included were gauges on very large main stem rivers that arise from outside the study area (e.g., Peace River, Liard River), lake outlet stations, or stations on drainages with man-made controls. Catchment areas ranged from 38 to 43,200 km^2. Monthly streamflow data for the periods of record for the gauges were converted to an equivalent unit runoff (mm).

The watershed drainage areas for each WSC hydrometric station were defined using the British Columbia Freshwater Atlas (FWA) spatial layer, based on 1:20,000 topographic mapping (British Columbia 2008).

Data pertaining to soils or surficial geology were not available for the study area, a common limitation in remote areas, thus making it not possible to incorporate flux to groundwater into the modeling.

RESULTS

Mean Annual Runoff

The model produces a strong relationship between observed annual discharge and modeled annual discharge (Figure 4) ($r^2 = 0.96$). The error metrics for the annual water balance and the adjusted annual water balance are presented in Table 5. For the unadjusted annual water balance (Equation 1), ME was 1.2%, with about 63% of the watersheds having errors within ±20% of the observed annual runoff. Mean absolute error was 25%. The statistical adjustment to modeled annual runoff to account for the apparent systematic pattern of error results in notable improvement in the model. Adjusted annual runoff (Equation 3) has a ME of 3.7% and a mean absolute error of 16%, with 78% of the watersheds being modeled within ±20% of their observed mean annual runoff. The relations between percent error and watershed characteristics are displayed in Figure 5. The relationship with median watershed elevation indicates a tendency toward underprediction in high-elevation basins, while the relationship with mean annual precipitation indicates a tendency toward underprediction in basins with high precipitation. As basin elevation and precipitation covary, this underprediction is possibly suggestive of the ClimateWNA data underestimating precipitation across the high elevation, mountainous portions of the study area.

Mean Monthly Runoff

The regression-based approach to distribute annual runoff to individual months based on regional characteristics produces good fits (refer to Figure 2). The empirical multivariate regression models for monthly runoff have a reasonable level of confidence. The worst fit was for August, with an adjusted R^2 of 0.46. Most other months had R^2 values of 0.60–0.82. The larger uncertainty for the August regression is possibly due to the effect of localized convective rainfall, which produces high runoff in some watersheds at different times, depending on the pattern and magnitude of the storm precipitation.

The median Nash–Sutcliffe statistic for the monthly runoff model is 0.92, with about 85% of the watersheds having a Nash–Sutcliffe statistic of 0.8 or greater (refer to Table 4). The median Spearman's rank correlation statistic is 0.98, with 91% of the watersheds having a Spearman's rank correlation coefficient of 0.9 or greater. In general, modeled runoff corresponds well to observed runoff.

DISCUSSION

The hydrology model is designed to provide estimates of mean annual and mean monthly runoff for ungauged watersheds across northeast British Columbia, an area of sparse hydrometric data and rapidly expanding demand of water for industrial oil and gas development. The model uses publicly available datasets, and is based on a simple water balance continuity equation. It is our hypothesis that this approach is valid for this geographic area, due to the impervious nature of the dominant bedrock geology, and a glacial history which resulted in thin deposits of surficial materials overlying the bedrock across much of the study area, such that natural additions to and withdrawal from groundwater storage over the multi-decadal "climate normal" period are assumed to result

TABLE 4. Summary of results for modeled basins, with % error in annual runoff, and Spearman correlation coefficient (r_s) and Nash–Sutcliffe statistic for monthly runoff.

Hydrometric station	Name	Basin size (km^2)	Year from	Year to	Mean runoff (measured) mm	P–ET (raw)		P–ET (adjusted)		P–ET (final)		Monthly flow analysis	
						mm	% Error	mm	% Error	mm	% Error	Nash–Sutcliffe	r_s
07FA001	Halfway River near Farrell Creek (lower station)	9,351	1961	1983	256	213	−16.7	241	−5.8	252	−1.4	0.96	0.98
07FA003	Halfway River above Graham River	3,764	1977	1995	298	236	−20.9	266	−10.7	298	0.0	0.93	1.00
07FA005	Graham River above Colt Creek	2,139	1981	2008	388	312	−19.6	374	−3.7	388	0.1	0.98	0.98
07FA006	Halfway River near Farrell Creek	9,296	1981	2008	253	214	−15.4	242	−4.4	253	0.1	0.93	0.98
07FB001	Pine River at East Pine	11,906	1961	2008	503	543	8.0	528	5.1	503	0.0	0.97	0.99
07FB002	Murray River near the mouth	5,558	1977	2008	474	516	8.9	458	−3.3	473	−0.2	0.96	0.93
07FB003	Sukunka River near the mouth	2,591	1977	2008	667	645	−3.3	648	−2.8	666	−0.2	0.88	0.89
07FB004	Dickebusch Creek near the mouth	85	1978	2008	220	339	54.5	283	28.9	220	0.0	0.86	0.99
07FB005	Quality Creek near the mouth	38	1978	2001	165	309	87.2	201	21.8	162	−1.8	0.61	0.98
07FB006	Murray River above Wolverine River	2,383	1977	2008	756	661	−12.5	615	−18.6	751	−0.6	0.90	0.99
07FB007	Sukunka River above Chamberlain Creek	928	1977	1985	832	747	−10.2	722	−13.2	826	−0.7	0.90	0.95
07FB008	Moberly River near Fort St. John	1,522	1980	2008	239	213	−10.9	246	3.0	239	0.1	0.94	0.98
07FB009	Flatbed Creek at kilometre 110 Heritage Highway	479	1982	2008	270	411	52.1	308	14.1	271	0.2	0.96	1.00
07FC001	Beatton River near Fort St. John	16,059	1961	2008	106	143	34.7	135	26.7	107	0.6	0.88	1.00
07FC003	Blueberry River below Aitken Creek	1,775	1964	2008	95	134	39.9	129	34.7	96	0.2	0.82	0.98
07FD001	Kiskatinaw River near Farmington	3,601	1944	2008	91	158	73.7	143	57.2	92	0.7	0.09	1.00
07FD004	Alces River at 22nd Base Line	313	1963	2008	59	113	91.0	109	83.4	63	6.0	-0.42	0.96
07FD007	Pouce Coupe River below Henderson Creek	2,856	1971	2008	73	74	1.8	83	14.3	73	0.2	0.65	0.95
07FD009	Clear River near Bear Canyon	2,876	1971	2009	56	52	−7.1	32	−42.5	55	−2.9	0.25	0.92
07GC002	Pinto Creek near Grande Prairie	494	1986	2009	106	141	33.0	86	−18.8	106	−0.6	0.62	0.92
07GD004	Redwillow River near Rio Grande	1,240	1993	2009	142	242	69.7	179	25.5	143	0.1	0.77	0.99
07OA001	Sousa Creek near High Level	820	1970	2009	62	56	−9.8	71	15.3	62	0.5	0.87	0.97
07OB004	Steen River near Steen River	2,598	1974	2009	73	76	3.5	80	9.6	73	0.2	0.72	0.97
07OB006	Lutose Creek near Steen River	292	1977	2009	68	80	17.1	73	6.6	68	0.0	0.78	0.98
07OC001	Chinchaga River near High Level	10,370	1969	2009	89	84	−5.8	91	2.0	89	−0.1	0.90	0.98
10BE004	Toad River above Nonda Creek	2,549	1961	2008	560	540	−3.6	568	1.5	561	0.1	0.93	0.96
10BE007	Trout River at kilometre 783.7 Alaska Highway	1,191	1970	2008	464	384	−17.2	400	−13.8	462	−0.4	0.75	0.94
10BE010	Toad River near the mouth	6,890	1983	1995	490	476	−2.9	496	1.3	490	0.0	0.96	0.95
10BE011	Grayling River near the mouth	1,760	1983	1995	297	301	1.3	308	3.8	297	0.1	0.93	0.98
10CA001	Fontas River near the mouth	7,439	1988	2008	132	111	−15.6	152	15.5	132	0.2	0.85	0.99
10CB001	Sikanni Chief River near Fort Nelson	2,181	1944	2008	374	281	−24.8	300	−19.7	372	−0.6	0.90	0.98
10CC001	Fort Nelson River at Fort Nelson	43,200	1960	1978	244	233	−4.6	272	11.6	257	5.6	0.86	0.96
10CC002	Fort Nelson River above Muskwa River	22,560	1978	2004	193	146	−24.3	184	−4.6	193	0.0	0.89	0.98
10CD001	Muskwa River near Fort Nelson	20,250	1944	2008	332	333	0.3	373	12.3	332	0.1	0.92	0.99
10CD003	Raspberry Creek near the mouth	275	1979	2008	135	149	10.8	194	44.4	137	2.0	0.75	0.98
10CD004	Bougie Creek at kilometre 368 Alaska Highway	334	1981	2008	251	179	−28.6	208	−17.2	250	−0.5	0.90	0.98

(continued)

TABLE 4. (continued)

Hydrometric station	Name	Basin size (km²)	Year from	Year to	Mean runoff (measured) mm	*P*–ET (raw) mm	*P*–ET (raw) % Error	*P*–ET (adjusted) mm	*P*–ET (adjusted) % Error	*P*–ET (final) mm	*P*–ET (final) % Error	Monthly flow analysis Nash–Sutcliffe	Monthly flow analysis r_s
10CD005	Adsett Creek at kilometre 386.0 Alaska Highway	109	1983	2008	252	186	−26.1	202	−19.7	249	−1.1	0.82	0.96
10CD006	Prophet River above Cheves Creek	7,277	1988	1995	298	262	−12.2	298	−0.1	298	−0.2	0.97	1.00
10ED003	Birch River at Highway no. 7	563	1974	2009	156	118	−24.5	169	7.9	157	0.3	0.99	0.99
10ED004	Rabbit Creek below Highway no. 7	122	1978	1983	155	89	−42.3	171	10.6	165	6.2	0.84	0.92
10ED006	Rabbit Creek at Highway no. 7	110	1984	1990	168	94	−44.3	176	5.0	169	0.4	0.96	0.98
10ED007	Blackstone River at Highway no. 7	1,381	1991	2009	243	111	−54.4	170	−30.2	241	−0.9	0.83	1.00
10ED009	Scotty Creek at Highway no. 7	137	1995	2009	159	103	−35.2	143	−10.2	156	−1.6	0.97	0.98
10FA002	Trout River at Highway no. 1	9,111	1969	2009	141	99	−30.1	147	3.7	141	0.0	0.97	0.98
10FB005	Jean-Marie River at Highway no. 1	1,351	1972	2009	122	108	−12.0	146	19.5	123	0.7	0.95	0.99
	Mean				256	245	1.2	254	5.5	256	0.2	0.81	0.97
	Median				220	186	−7.1	201	3.7	220	0.0	0.90	0.98

Notes: *P*, annual precipitation (mm); ET, annual evapotranspiration.
Results are shown for two iterations of the modeling: raw *P*–ET and *P*–ET with statistical adjustment; and then a final dataset after adjustment to measured flows.

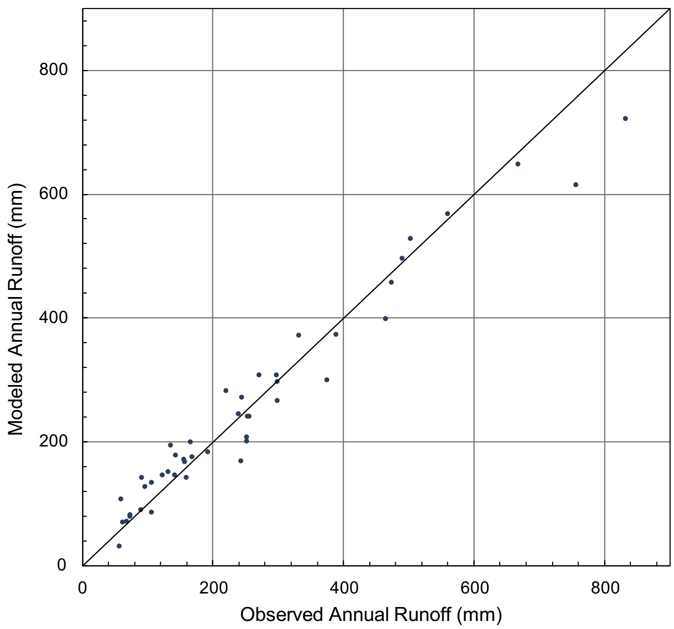


FIGURE 4. Comparison of observed annual runoff and modeled annual runoff. The solid line depicts perfect agreement.

TABLE 5. Error metrics for predictions of annual runoff.

	MBE (%)	MAE (%)	ME (%)	% of Watersheds within ±20% error
Annual water balance	1.2	24.9	−7.1	62.5
Adjusted annual water balance	5.5	16.1	3.7	77.8

Notes: MBE, mean error; MAE, mean of the absolute value of the errors; ME, median error.

in a net zero balance. Water balance research within the study area by Abadzadesahraei et al. (2017) noted that infiltration to groundwater accounted for about 5% of annual precipitation. Most precipitation is retained within the surface water environment subject to surface runoff (Metcalfe and Buttle 1999), producing a seasonally consistent nival runoff dominated by high flows in spring from snowmelt and low flows in winter due to deep and sustained freezing.

Evapotranspiration is the most significant loss of water from the surface environment of northeast British Columbia, accounting for about two-thirds of the precipitation in the gauged watersheds. Surface runoff through rivers and streams is the portion of water remaining after the evapotranspirative demands have been met. Incorporating a vegetation-based evapotranspiration adjustment, consistent with measurements of evapotranspiration across northern boreal environments, was beneficial in adjusting the global CGIAR model grid to reflect the vegetative conditions

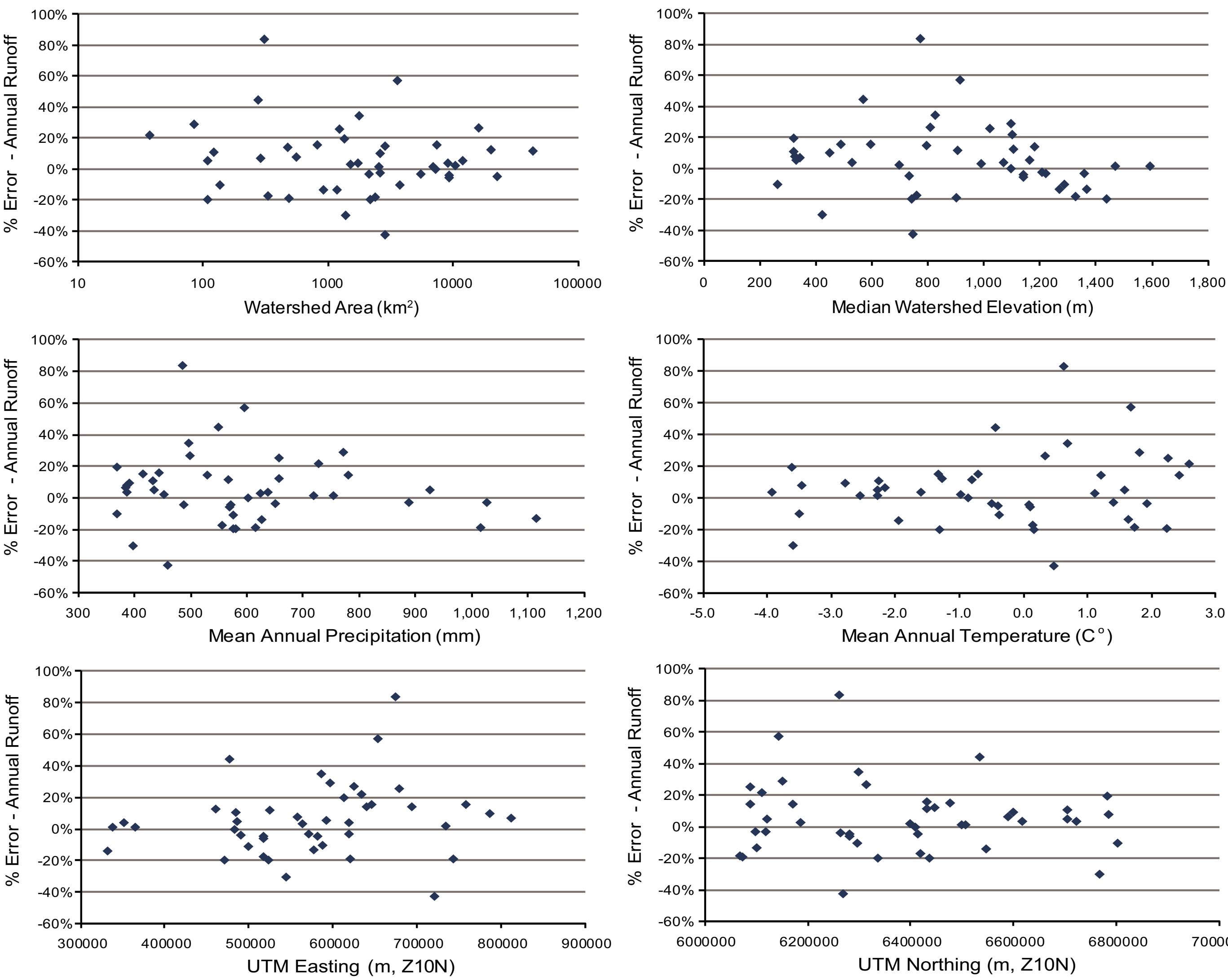


FIGURE 5. Percent error in modeled annual runoff in relation to watershed characteristics.

of northeast British Columbia. Following the ET adjustment, the analysis of the residuals from the basic water balance model indicated the presence of systematic patterns in the unexplained annual runoff. These patterns might be considered a proxy for the error associated with the various datasets used in the model. Much of the error is possibly associated with the precipitation input, as the measured data used in the PRISM model are sparse in much of the study area and completely absent at highest elevations which provide significant volumes of runoff water. Error may also result from variability in water storage in soil and water infiltration to local groundwater among the study watersheds. However, given the glacial history of the study area (Catto 1991), resulting commonly in thin layers of glacial and postglacial deposits resting overtop bedrock, input to groundwater is believed to be small (Golder 2008; Abadzadesahraei et al. 2017), and generally in zero balance over the climate normal study period. We cannot discount, though, that locally extensive aquifers might be found in some of the study watersheds, influencing the quantified water balance. Unfortunately, the absence of soil and surficial geology mapping encompassing the study area does not allow this to be explored. As well, errors in the underlying hydrometric data cannot be discounted (Hamilton and Moore 2012; Coxon et al. 2015). The multivariate regression adjustment in annual runoff, to account for some of the error or uncertainty in the residuals, significantly improved the accuracy of the annual runoff model.

The distribution of annual runoff to monthly time steps is entirely empirical, derived from the observations of the timing of monthly runoff from the 45 WSC hydrometric stations. The approach is dependent on the network of stream gauges used for the analysis, and may result in some error due to limitations in the underlying data. As example, the WSC network generally underrepresents watersheds of small drainage areas. Of the 45 gauges analyzed in this study, only 2 (4.4%) have watershed areas <100 km^2, and 16 (35.5%) have watershed areas <500 km^2. Also, although spring snowmelt dominates the hydrology of the study area, summer convective and frontal rain storms occur, occasionally producing high rates of rainfall for short periods of time, covering limited geographic extent. The magnitude of these summer storms may not be well reflected in the sparse climate data used to generate the PRISM gridded product, but may nevertheless be reflected in the flow record for some small streams. WSC gauge 10CD005 (109 km^2, n = 27 years) reflects this, with 32.2% of years having the highest peak flow of the year in either August or September, associated with summer rain. As a result, the hydrology model presented in this paper underestimates average summer runoff for 10CD005, and may similarly underestimate summer runoff for other small catchments. The model results, however, are well suited to the purpose, to provide robust and defensible information on surface water supply across the large 175,500 km^2 study area in northeastern British Columbia, using a simple, regional-scale hydrology model.

The incorporation of hydrometric data and hydrologic modeling as described in this paper can aid the calibration and validation of climate models, and could improve accuracy of these models in mountainous terrain or areas of sparse climate data. Solomon et al. (1968) effectively utilized such a strategy in their work in Newfoundland. Such cross-disciplinary work using modern datasets and analytics would likely benefit research in both climatology and hydrology.

THE NEWT

Upon completion of the hydrology modeling, a sophisticated map-based decision-support application was developed, to provide public access to the modeled hydrology data along with other types of critical water management information for surface water sources in northeast British Columbia. The application is referred to as the Northeast Water Tool, or NEWT.

Underlying Technology

NEWT is based on an underlying hierarchical watershed map coverage referred to as the Freshwater Atlas (FWA) (Gray 2009). The FWA is derived from 1:20,000 mapping of surface water drainage, providing a unique 144-digit numeric identifier for each first-order stream and catchment, and explicitly defining the upstream and downstream drainage hierarchy from the smallest first-order catchment in British Columbia to either the ocean or to the point where the rivers leave British Columbia and flow into another jurisdiction. The coding system bases this unique identifier on proportional distances along the stream network. As a result, the code is not only unique but it also allows spatial features to be related to one another and distances upstream and downstream to be determined. Every tributary of a stream is associated with a unique watershed area, referred to as a fundamental watershed, allowing the streams to be related to their associated land base. In the northeast British Columbia study area, 600,000 unique first-order fundamental watersheds polygons were mapped and incorporated into NEWT.

Information to be queried through NEWT was attached to the unique Fundamental Watersheds. This information includes:

1. Mean monthly and annual precipitation, derived from Climate WNA (Wang et al. 2012);
2. Catchment drainage area, and maximum, minimum, and mean watershed elevation, derived from DEM (Canada 2000);
3. Mean monthly and annual discharge (m^3/s) and runoff (mm), derived from modeling described in this paper;
4. Projections of temperature and precipitations (2041–2070) for three global climate model scenarios (Murdock and Spittlehouse 2011);
5. Vegetative land cover;
6. Model performance (% ME; % mean absolute error).

Other information queried through NEWT is contained in various databases and is calculated “on the fly” each time a NEWT query is executed. This information includes:

1. Tabulation, listing, and description of all active water allocation licenses or approvals for the query watershed, as well as for the watershed downstream of the next major confluence;
2. Calculation of remaining potential water allocation, derived from modeled hydrology, existing water allocations, and EFN, consistent with the British Columbia Ministry of Environment’s EFN policy (British Columbia 2016a);
3. Calculation of remaining water allocation potential for lakes during winter (ice cover) conditions;

4. Flow sensitivity, based on the British Columbia EFN Policy (British Columbia 2016a).

Output

A user selects a query location on a river or lake by selecting the location on NEWT's map interface, or by inputting the location's geographic coordinates. When selected, NEWT defines the watershed upstream of the query location, and in a few seconds produces an output report of 7+ pages that presents the information described above. An example of the monthly hydrology output page for Coal Creek is depicted in Figure 6.

Application

NEWT is used primarily as information support to assist statutory decision makers employed by the British Columbia Oil and Gas Commission and the Ministry of Forests, Lands, Natural Resource Operations and Rural Development in review and determination for water allocation applications. Under the British Columbia Water Sustainability Act (British Columbia 2016b), water allocation is authorized on either a long-term water license (typically for 5–30 years) or a short-term approval (less than two years). Most water licenses require actual streamflow data to enable a decision on long-term water allocation. NEWT is used to provide screening-level information, indicating where there is likely or not likely to be sufficient water available for allocation, and it is used as a primary source of information for short-term approvals in ungauged basins. The short-term approvals typically contain numerous conditions, often including conditions enforceable under law for the user to monitor and report stream discharge at times of water withdrawal and to maintain specified EFN thresholds. NEWT is also used extensively by various parties (landowners, farmers, industrial water users, etc.) who may be considering applying for an authorization to divert and use water from a surface water body. In this case, NEWT helps the user understand some fundamental aspects of the hydrology of water sources they may be interested in, to help make an informed application decision. Additionally, NEWT is widely used by First Nations, communities and local governments, environmental organizations, and members of the public with legal or personal interest in water management.

Limitations

NEWT is not without limitations. Primary limitations are:

1. **Scale**. With only 2 (4.4%) of the calibration watersheds having watershed areas <100 km^2, the modeled hydrology has higher uncertainty for small basins outside the scope of the calibration dataset.
2. **Hydrology Modeling**. The hydrology information is derived from a hydrology model, and so has inherent uncertainties. The ME in the modeling was 3.7% and mean absolute error was 16.1%; 78% of the watersheds used for model calibration were modeled within ±20% of their observed flow (Chapman et al. 2012).
3. **Monthly Time Step**. The hydrology information in NEWT is modeled on a monthly time step, and can be insufficient to quantify the runoff accurately within an individual month if the mean discharge rate changes quickly during the month. This limitation is particular to small watersheds and periods of time such as following the snowmelt peak, or following short-duration summer convective rain storms.
4. **Water Allocation Data**. The data available within the British Columbia government digital database for existing water licenses can be limited, often not providing seasonal limits (such as for irrigation licenses), or showing maximum diversion volumes rather than actual rates. Generally, existing licensed water demand is overestimated in NEWT.
5. **Modeled Runoff vs. Actual Runoff**. NEWT presents mean monthly and annual runoff, based on a 30-year "normal" period. Actual runoff at any point in time will almost always be different from mean runoff. In some years, such as in periods of drought or periods of flood, actual runoff can be substantially lower or higher than modeled runoff. Operational water management rules and approaches vary among jurisdictions but, in British Columbia, these usually include the requirement for a water user to monitor and report on actual river discharge at the time of water withdrawal and to apply EFN and "zero withdrawal" thresholds. As well, water managers are required to be alert to actual conditions when making water allocation decisions, and to occasionally intervene to suspend all water withdrawals from some water sources during times of drought (BCOGC 2014).
6. **Watershed Mapping**. NEWT is constructed using the 1:20,000 FWA. In some locations, particularly locations of low relief, the basin delineation may have some uncertainty.

Hydrology - Monthly Coal Creek

The chart and table show information on modeled hydrology and existing allocations in the **query watershed**. This location is shown with an orange marker and watershed outline in the map on page 2.

Potential Maximum Allocations

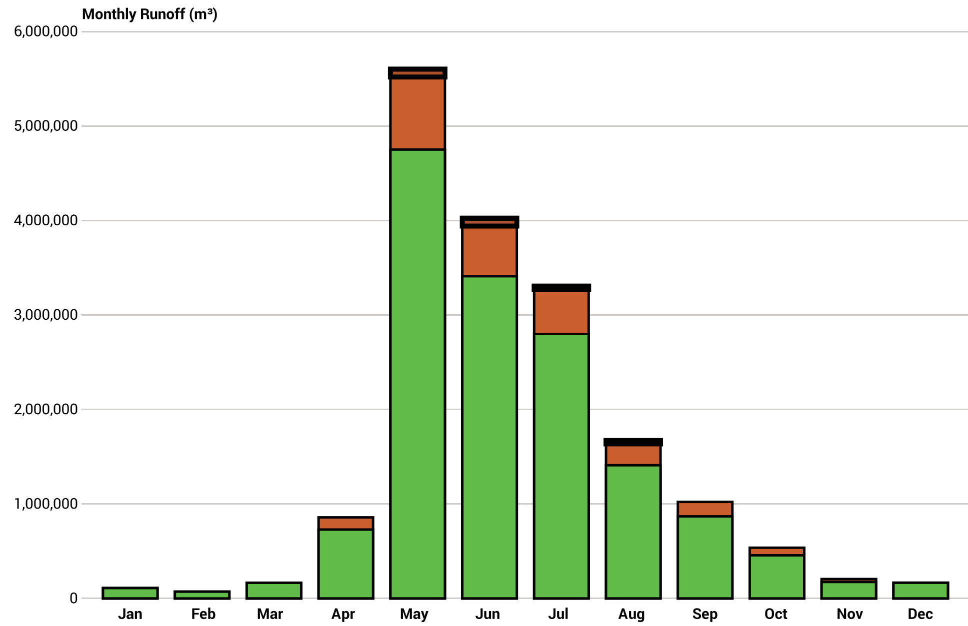
Environmental Flow Needs

Existing Allocations

Mean Annual Discharge (MAD)

0.56 m³/s

20% MAD = 0.11 m³/s
10% MAD = 0.06 m³/s



Month	Mean Runoff (mm)	Mean Discharge (m³/s)	Mean Runoff (m³)	% of MAD	Flow Sensitivity	Environmental Flow Needs (m³)	Potential Max Allocation (m³)	Existing Allocations (m³)	Remaining Potential Allocation (m³)	Notes
Jan	0.5	0.04	110,454	7.4%	High	110,454	0	0	0	W
Feb	0.4	0.03	72,293	5.3%	High	72,293	0	0	0	W
Mar	0.8	0.06	166,204	11.1%	Mod	166,204	0	0	0	W
Apr	4.2	0.33	857,939	59.0%	Low	729,248	128,691	0	128,691	
May	27.5	2.09	5,589,003	372.2%	Low	4,750,653	838,350	84,000	754,350	
Jun	19.8	1.55	4,011,643	276.1%	Low	3,409,897	601,746	84,000	517,746	
Jul	16.2	1.23	3,292,714	219.3%	Low	2,798,807	493,907	36,000	457,907	
Aug	8.2	0.62	1,658,801	110.5%	Low	1,409,981	248,820	36,000	212,820	
Sep	5.0	0.39	1,021,997	70.3%	Low	868,697	153,300	0	153,300	
Oct	2.6	0.20	537,024	35.8%	Low	456,470	80,554	0	80,554	
Nov	1.0	0.08	205,533	14.1%	Mod	174,703	30,830	0	30,830	
Dec	0.8	0.06	166,676	11.1%	Mod	166,676	0	0	0	W
Annual	**87.1**	**0.56**	**17,690,282**	-	-	**15,114,082**	**2,576,198**	**240,000**	**2,336,198**	

Notes

W - Winter flows may be limited.

L - Winter lake withdrawal limits apply. Water withdrawal limits are based on lake surface area and cumulative maximum drawdown of 10 cm for December 1 - March 31.

Environmental Flow Needs Determination

The Commission manages oil- and gas-related water use authorizations to protect fisheries or aquatic resources, and to protect drinking water supply, consistent with the requirements of the **Water Sustainability Act (http://www.bclaws.ca/civix/document/id/complete/statreg/14015)**. The calculations of water availability in the North East Water Tool (NEWT) reflect the Commission's approach to maintaining environmental flows. Please refer to the NEWT application for details.

Model Performance

Mean error: 5.5%, Median error: 3.7%, Mean absolute error: 16.1%, Within ±20%: 77.8%
The hydrology estimates are produced from a hydrology model which included 45 long term hydrometric stations in northeast BC, NWT, and AB.

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FIGURE 6. Monthly hydrology output from the Northeast Water Tool for Coal Creek, UTM location: 661746E, 6204912N, Zone 10. NWT, Northwest Territories.

CONCLUSIONS

Knowledge of stream runoff across a range of scales is of vital importance to many, including the current users of the water resource; potential future users who require water for a variety of beneficial purposes; regulators, who need water resource information to aid in decision-making; First Nations, who have historic rights to water; and the general public, who have an expectation that water resources will be well managed and protected. Hydrology modeling is key to translate information from discrete locations to a broader geographic context. This hydrologic need has been well known for a long time, and has been framed recently in the context of PUB (Sivapalan et al. 2003). Advances in process-based knowledge are occurring (McDonnell 2003; Hrachowitz et al. 2013), but are not yet sufficiently advanced in many areas to contribute to operational, decision-support knowledge (Moore et al. 2011). The hydrology modeling described in this paper uses simple empirical models utilizing existing climate, vegetation, and topographic data, calibrated to available hydrometric data in and adjacent to the study area. The mean annual and monthly runoff results are robust with well-understood uncertainty, and, when applied appropriately and with understanding of the limitations, are well suited to provide information to support water allocation decision-making. Simple, regional-scale hydrology models such as that used in NEWT are effective at providing accurate hydrology information at a monthly time scale, to assist resource managers (Caldwell et al. 2015). Following the completion of the hydrology modeling, the information was incorporated in the NEWT, an innovative GIS-based hydrology decision-support tool developed by the British Columbia Oil and Gas Commission, the Ministry of Forests, Lands, Natural Resource Operations and Rural Development and partners (Chapman et al. 2012; Chapman and Kerr 2016), to provide basic but fundamental water supply information for locations where there is no measured runoff data, i.e., the PUB conundrum (Sivapalan et al. 2003).

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