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Effects of projected climate on the hydrodynamic and sediment transport regime of the lower Athabasca River in Alberta, Canada

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Abstract

The potential effects of climate change on the hydrodynamic and sediment transport regime of the lower Athabasca River (LAR) in Alberta, Canada, is investigated. Future climate projections for the region suggest a potential increase in mean air temperature and precipitation by about 2.8–7.1 °C and 8–25%, respectively, by the end of this century. Implications of these climatic changes on the hydrologic regime of the LAR are found to be significant with spring flows expected to increase by about 11–62% and 26–71% by the end of the century for a moderate and high emissions scenarios respectively with corresponding decreases in summer flows. The effects of such changes are examined using the MIKE-11 hydrodynamic and sediment transport modelling system with inflow boundary conditions corresponding to the changing hydro-climatic regime. The results suggest that there will be an overall increase in flow velocity, water level, and suspended sediment concentration and transport for most seasons except in the summer months when there may be some decreases. The projected changes in suspended sediment concentration will result in an overall increase in mean annual sediment load in the LAR and to the Peace Athabasca Delta by over 50% towards the latter part of this century (2080s) compared with the 1980s base-line period. Implications of such potential changes in the transport characteristics of the river system to the mobilization and transport of various chemical constituents and their effects on the region's aquatic ecosystems are subjects of other ongoing investigations.

KEYWORDS

climate change, hydrodynamic modelling, lower Athabasca River, sediment transport

1 | INTRODUCTION

The sediment load transported by rivers has important implications for the functioning of aquatic ecosystems through its influence on material fluxes, geochemical cycling, and water quality. In addition to its important role in river morphodynamics and delta development, sediment transport is responsible for transporting a significant fraction of nutrients and other constituent chemicals with implications on different ecosystems and habitats such as fish and benthic communities (Walling, 2009). The hydrodynamic and sediment transport regime in river systems is determined by the prevailing morphological and hydro-climatic condition in the region through linkages via the hydrology of the river basins. Consequently, the future state and variation of

flow as well as sediment and constituent chemical transport in river systems will most likely be affected by a changing climate. Some of the effects could be through changes in the magnitude and timing of seasonal mean as well as extreme river discharges, sediment inflow, flow velocity, and depth, which would in turn affect the available environmental flow, shear stress, erodibility, and transport capacity of rivers (Thodsen, Hasholt, & Kjærsgaard, 2008).

There is a growing body of evidence that climate change is having a significant impact on the sediment loads and transport in rivers. Comparing data collected in the 1970s with those from the 1990s, Amsler and Drago (2009) showed that recent increases in precipitation and run-off across parts of the Parana–Paraguay system in South America have caused increased erosion and sediment mobilization and indicated that climate change has been strongly affecting the hydro-sedimentological regime of the river network. Using a GIS-based model under a climate-change scenario, Asselman, Middelkoop, and Van Dijk (2003) investigated the potential effects of changes in climate and land use on the mobilization of fine sediment and the net transport of wash load from the upstream basin to the lower Rhine delta. Their research indicated that erosion rates will increase in the Alps and decrease in the German part of the basin as a result of the changing climate and land use. Modelling climate induced changes in suspended sediment transport for two Danish river catchments, Thodsen et al. (2008) also found that suspended sediment transport increases during winter months as a result of the increase in river discharge caused by enhanced precipitation, and decreases during summer and early autumn months when precipitation also decreases. Similarly, Praskievicz (2016) investigated the potential impacts of climate change on streamflow and suspended-sediment transport for snowmelt-dominated rivers in the interior Pacific Northwest and indicate that climate change is likely to amplify the annual cycle of river discharge and simulated changes in suspended-sediment transport that generally follow the changes in streamflow.

The current and projected future states of flow in the Athabasca watershed has been actively investigated by a number of recent studies. Some of the studies that were based on analysis of observed streamflow data in the region have shown statistically significant decreasing trends in streamflow, particularly in recent decades (Bawden, Linton, Burn, & Prowse, 2014; Sauchyn, Luckman, & St-Jacques, 2015). However, using a correlation model between river flow and climate variables to reconstruct long-term (>100 years) natural modes of river discharge, Chen and Grasby (2014) did not find true long-term declines of the annual flow in the Athabasca River basin (ARB). The findings of Rood, Stupple, and Gill (2015) from century-long records also contrast with interpretations from the above short-term studies and emphasize the need for sufficiently long time series for hydrologic trend analysis. Peters, Atkinson, Monk, Tenenbaum, and Baird (2013) demonstrated that potentially inconsistent and/or divergent trend results can be obtained when using different time periods and/or regions of the watershed. A number of hydrologic modelling studies have also been used for projecting streamflow in the ARB under multiple climate scenarios derived from various Global Climate Models (GCMs; Eum, Dibike, & Prowse, 2017; Leong & Donner, 2015).

With respect to sediment transport, Conly, Crosley, and Headley (2002) determined the contribution of the upstream boundary and tributaries in the annual load of sediments in the lower Athabasca River (LAR) and found that suspended sediment derived from main stem and tributary sources between Fort McMurray and Embarras account for 18% of the mean annual load of the Athabasca River with the remaining originating upstream of Fort McMurray. A recent study by Shrestha and Wang (2018) used the Soil and Water Assessment Tool with future climate projections over the ARB and show a potential increase in soil erosion rate due to climate change is greater than reported soil formation rates in the region. Studies that have attempted numerical modelling of flow and sediment transport in the LAR found it to be challenging due to the complex morphology and seasonality of the flow regime. Andrishak, Abarca, Wojtowicz, and Hicks (2008) and Pietroniro et al. (2011) made early attempts to numerically model the flow in LAR using one-dimensional (1D) models that incorporated simplified rectangular sections to represent channel geometry. More recently, Shakibaeinia et al. (2016; 2017) and Kashyap, Dibike, Shakibaeinia, Prowse, and Droppo (2016) developed an integrated numerical modelling framework (1D and two-dimensional) for simulation of flow and sediment transport covering larger portions of the LAR using detailed surveyed bathymetric data.

Although there are a number of studies that have investigated the potential impacts of climate change on the hydrologic (discharge) regimes of the LAR, none have examined the implications of the altered flow regimes on the hydrodynamic and sediment transport characteristics of the river. Therefore, this study investigates the potential impacts of future climate on hydrodynamic and sediment transport regime of the LAR by employing the MIKE-11 1D flow and sediment transport model. While the hydrodynamic and sediment transport model used for this study was calibrated/validated using historical observed discharge and sediment inflow data (Shakibaeinia, Dibike, Kashyap, Prowse, & Droppo, 2017), the corresponding future scenario data are derived from a recent study by Eum et al. (2017). Eum et al. (2017) and Dibike, Eum, and Prowse (2018) investigated the potential hydrologic response of the ARB to projected changes in future climate using the Variable Infiltration Capacity (VIC) process-based and distributed hydrologic model (Liang, Lettenmaier, Wood, & Burges, 1994). The climatic forcings for the VIC hydrologic model were derived from a selected set of GCMs from the latest Coupled Model Intercomparison Project (CMIP5) and statistically downscaled to a higher (10 km) spatial resolution. A subset of the VIC simulated river discharge scenario data corresponding to the baseline period of 1970–1999 (1980s), and the two future periods of 2040–2069 (2050s) and 2070–2099 (2080s) are used as upstream and tributary inflow boundary conditions for the 1D hydrodynamic and sediment transport model of the LAR. Outputs of the hydrodynamic and sediment transport model simulations for the baseline and future periods are then analysed to quantify the potential changes in the mean annual and monthly values of water levels and flow velocities as well as suspended sediment concentrations (SSC) and sediment load in the LAR. The results are also presented in terms of projected changes in the exceedance probabilities of those variables at a location along the LAR.

2 | STUDY AREA AND DATA SETS

2.1 | Site description

The Athabasca River, with a 156,000 km^2 drainage area, originates from the Columbia glacier in Jasper National Park and flows approximately 1,500 km north-eastward to Peace Athabasca Delta (PAD) and Lake Athabasca. The hydrodynamic and sediment transport scenario simulation is conducted over the ~200 km reach of the LAR starting from below the city of Fort McMurray and extending to Old Fort which is located few kilometres upstream of the river discharging into the PAD (Figure 1). This river reach is characterized as meandering and braided with vegetated islands and alternating sand bars as the river and many of its tributaries cuts through the McMurray formations where bitumen can be found close to the earth surface. Major tributaries within the LAR reach include the Steepbank, Ells, MacKay, Muskeg, and Firebag Rivers. Mean daily temperatures in the LAR range between approximately −20 °C in January and around 15 °C in July while the mean annual precipitation in the region is <500 mm with over 60% occurring as rainfall and the remainder as snowfall (Conly et al., 2002). The mean annual streamflow at the station below Fort McMurray over the period of 1958 to 2011 is around 615 m3/s, ranging between mean monthly values of 158 m3/s in February and 1,368 m3/s in July (HYDAT, 2012). Sediment transport plays an important role in the Oil-Sands region of the LAR and the PAD ecosystem as the bitumen-related chemical constituents (such as metals and polycyclic aromatic hydrocarbons) are mainly transported by fine sediments (Garcia-Aragon, Droppo, Krishnappan, Trapp, & Jaskot, 2011; Ghosh, Gillette, Luthy, & Zare, 2000).

2.2 | River bathymetry data

The river bathymetry data for the LAR are obtained by combining different legacy data sets with a high-resolution (0.5 m) bed elevation data between Fort McMurray and Old Fort surveyed by Environment Canada using a Geoswath sonar sensor (Shakibaeinia et al., 2016; Shakibaeinia et al., 2017). The topography of floodplains and islands are reproduce using high resolution (5 m) light detection and ranging (LiDAR) data along the LAR banks from Alberta Environment and Parks that was further processed into Digital Elevation Model (DEM) by Environment and Climate Change Canada, and Digital Elevation Model data of the region from Geobase (2012). The data from all these sources were combined to construct a continuous bathymetry for the LAR main channel and adjacent flood plains with a resolution ranging from 10 to 25 m. The data were then interpolated on the 1D cross-sections along the LAR (200 cross-sections with ~1 km intervals) to construct the required model geometry.

2.3 | Historical hydrometric and sediment data

The historical hydrometric (flow rates and water levels) and sediment data used as boundary conditions as well as for the purpose of model calibration and validation were obtained mainly from three different sources including (a) The Water Survey of Canada, 2013 hydrometric stations, (b) Regional Aquatics Monitoring Program, 2013 hydrology stations, and (c) The VIC hydrologic model of the ARB (Eum et al., 2017) that provides flow data for the smaller tributaries where there are no hydrometric stations. Table 1 lists the hydrometric stations used in this study along with the responsible agencies that collect the data. Climate data required for the study, such as air temperature (daily and hourly), wind speed, cloud coverage and precipitation, were obtained from Environment Canada climate database (Environment Canada climate data, 2011). The measurements for SSC in the LAR and its tributaries are usually taken at various frequencies covering different time periods; hence, continuous time-series data that can be used directly as upstream and lateral boundary conditions are not available. Instead, the available observed data are used here to develop sediment-discharge rating curves that can then be used to
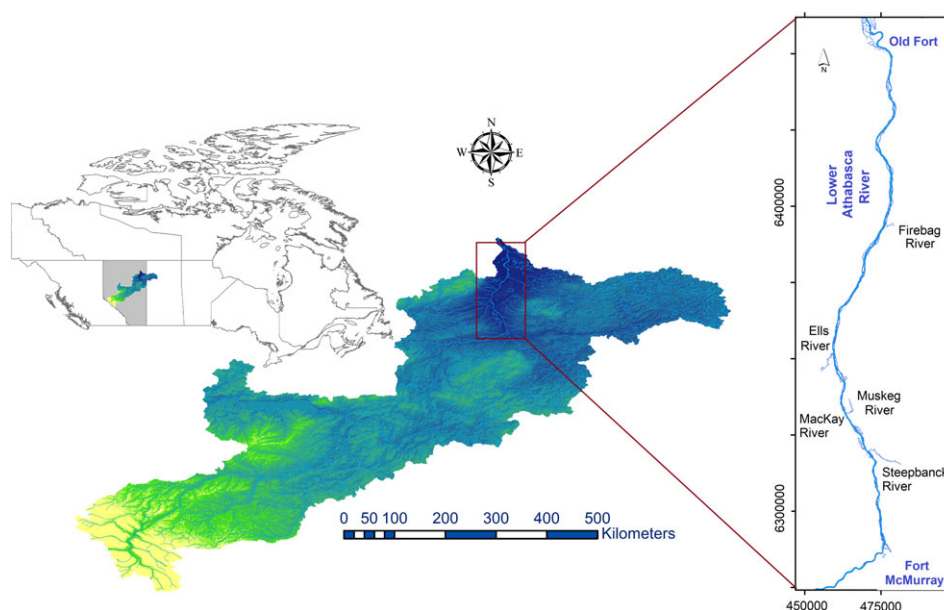

FIGURE 1 Study area: the Athabasca River basin (ARB) and the lower reaches of the Athabasca River (LAR) below Fort McMurray, in Alberta, Canada [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Name and locations of the hydrometric stations in the LAR and tributaries used in this study along with the responsible agencies that collect the data

| | Station ID | Station name | Operator | Data type | | | Coordinates | |
				Flow	W.L.	SSC	Easting	Northing
Mainstem	07DD011	Athabasca River near Old Ft.	WSC		✓		469,487	6,470,518
	07DA001	Athabasca River Below Ft. McMurray	WSC	✓	✓	✓	475,439	6,293,000
	07DD001	Athabasca River at Embarras Airport	WSC	✓		✓	477,079	6,451,600
	S24	Athabasca River below Eymundson Creek	RAMP	✓	✓		466,313	6,372,760
	S46	Athabasca River near Embarras airport	RAMP	✓	✓		470,241	6,463,206
	ATR-DC	Athabasca River at Donald Creek	RAMP			✓	475,020	6,298,154
	ATR-SR	Athabasca downstream of Steepbank River	RAMP			✓	470,937	6,319,625
	ATR-MR	Athabasca upstream Muskeg River	RAMP			✓	463,504	6,332,230
	ATR-DD	Athabasca downstream of developments	RAMP			✓	463,856	6,367,949
Tributaries	07DA006	Steepbank River near Ft. McMurray	WSC	✓		✓	475,285	6,317,398
	07DA008	Muskeg River near Ft. Mackay	WSC	✓		✓	465,543	6,338,813
	07DC001	Firebag River near the mouth	WSC	✓		✓	487,908	6,389,883
	07DA017	Ells River near the mouth	WSC	✓		✓	456,928	6,347,420
	07DB001	Mackay River near Ft. Mackay	WSC	✓		✓	458,014	6,341,017
	07DA014	Calumet River	WSC	✓		✓	458,990	6,362,490
	07DA011	Unamed River near Ft. Mckay	WSC	✓		✓	468,990	6,391,131

Note. LAR = lower Athabasca River; RAMP = Regional Aquatics Monitoring Program; WSC = Water Survey of Canada.

generate continuous time series of SSC. Some examples of such rating curves are shown in Figure 2.

2.4 | Hydro-climatic data for the future period

2.4.1 | Climate scenario projections

The climate scenario is based on the latest GCM projections conducted within the framework of the CMIP5 (Taylor, Stouffer, & Meehl, 2012). However, because of the higher computational demand of running the hydrodynamic and sediment transport model of a 200 km reach for over a hundred years with multiple emission scenarios, only two out of the six GCMs selected by Eum et al. (2017) to drive the VIC

hydrologic model of the Athabasca watershed are considered in the present study. The two GCMs, namely, the Canadian CanESM (Arora et al., 2011) and the French CNRM (Voldoire et al., 2013) models are selected based on the ranking of the CMIP5 models, which differs by region, that is carried out by the Pacific Climate Impact Consortium to provide the widest spread (range) in projected future climate for smaller subsets of the full ensemble (Cannon, 2015). CNRM represents the closest scenario to CMIP5 multimodel ensemble mean whereas CanESM is the farthest from the first selected GCM (i.e., CNRM) corresponding to higher projected increases in precipitation and temperature. Moreover, as the GCMs data are at coarser resolution (200–300 km) and as they are also known to have seasonal biases compared with the observed climate for the historical period, a widely
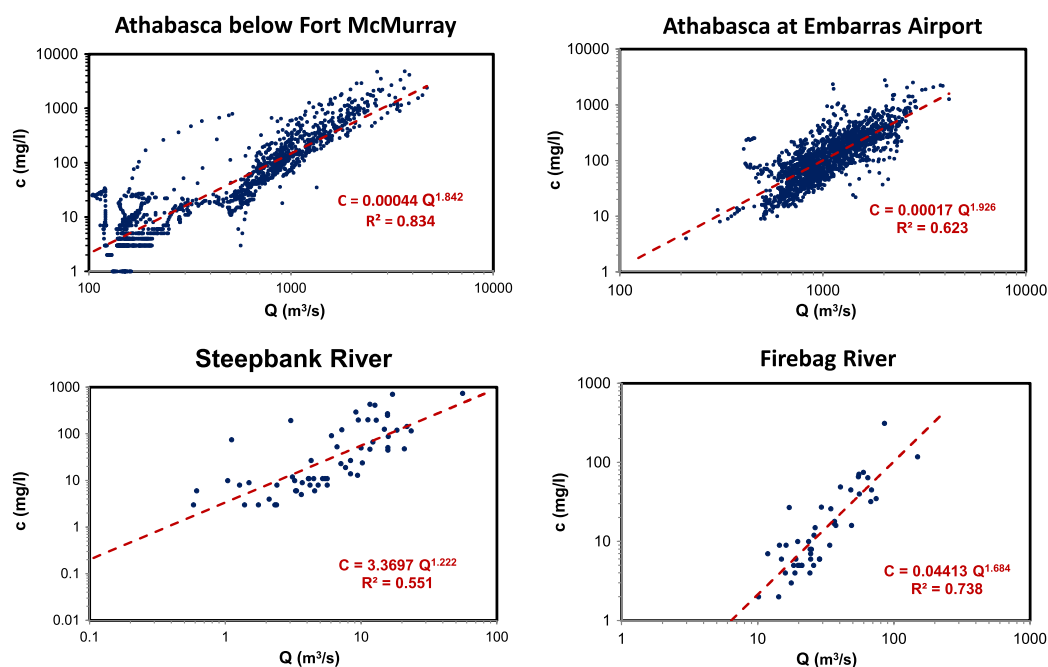

FIGURE 2 Example sediment-discharge rating curves (in log scale) for the LAR below Fort McMurray (St. ID: 07DA001), Athabasca River at Embarras Airport (St. ID: 07DD001), Steepbank River near Ft. McMurray (St. ID: 07DA006), and Firebag River near the mouth (St. ID: 07 DC001) [Colour figure can be viewed at wileyonlinelibrary.com]

used statistical technique, namely, Bias-Correction/Spatial Disaggregation (Wood, Leung, Sridhar, & Lettenmaier, 2004), was applied to spatially downscale the GCMs' outputs based on the 10-km resolution Australian National University thin plate spline (ANUSPLIN) algorithm based gridded observed data (Hopkinson et al., 2011). Also, only two of the emission scenarios, namely, the RCP4.5, which is a stabilization scenario that achieves the goal of limiting emission and radiative forcings, and the RCP8.5, which is an emission scenario that greenhouse gas increases as usual until 2100, were considered for the hydrologic simulation (Eum et al., 2017). Therefore, a total of four sets of the ARB VIC hydrologic model projections corresponding to two GCMs (CNRM and CanESM), and two emission scenarios (RCP4.5 and RCP8.5) are employed in this study. Table 2 shows the projected changes in mean annual temperature and precipitation over the ARB corresponding to each of the four scenarios considered with respect to the baseline period. While the projected warming over the ARB range between 2.8 and 7.1 °C, the corresponding projected increase in precipitation ranges between 7.9% and 25% by the 2080s with respect to the 1980s baseline period. In general, CanESM model project wetter and warmer future scenarios compared with that of CNRM.

2.4.2 | Hydrologic model simulations for the baseline and future periods

Eum et al. (2014; 2017) developed the ARB VIC hydrologic model using gridded high resolution (10 km × 10 km) ANUSPLIN daily

TABLE 2 Projected changes in mean annual temperature (T) and precipitation (P) over the ARB compared with the baseline period of 1980s for each of the four scenarios considered in this study

Scenarios	GCMs	RCPs	ΔT (°C)		ΔP (%)	
			2050s	2080s	2050s	2080s
1	CanESM	RCP4.5	3.73	4.15	12.3	22.3
2	CanESM	RCP8.5	4.37	7.05	20.5	25
3	CNRM	RCP4.5	2.17	2.83	4.3	7.9
4	CNRM	RCP8.5	2.82	4.64	7.5	13

Note. CanESM = Canadian Earth System Model; CNRM = Centre National de Recherches Meteorologiques; GCMs = Global Climate Models; RCP = Representative Concentration Pathway.

precipitation and air temperature data over the 1985 to 2010 historical period. The model generally performs well in replicating most of the observed streamflow data with a Nash–Sutcliffe coefficient of efficiency for the Fort McMurray station of 0.79 and 0.74 for the calibration (1985–1997) and validation (1998–2010) periods, respectively. Hydrologic model simulations were also conducted for the baseline period of 1970–1999 (1980s) as well as for the two future periods of 2040–2069 (2050s) and 2070–2099 (2080s) using the select set of climate scenario data. While the baseline climate scenario corresponds to the historical emission level, the projected climate for the two future periods corresponds to each of the two emission scenarios (RCP4.5 and RCP8.5).

Figure 3 shows box-plots of observed and simulated monthly mean discharges and their distribution at the Fort McMurray hydrometric station for the baseline period. The three sets of simulated flows correspond to the ANUSPLIN gridded observed climate data and the statistically downscaled GCM climate scenarios from the CanESM and CNRM during the 1980s baseline period. While the simulated flows slightly overestimate the winter low flows and underestimate the summer high flows, the results presented in Figure 3 indicate that the VIC hydrologic model of the ARB driven by the statistically downscaled GCM climate data was able to reproduce the main features of the observed hydrologic regime at the Fort McMurray station very well. Moreover, Figure 4 presents comparison of the VIC model simulated mean monthly discharges between the baseline and the two future periods at the Fort McMurray station corresponding to each climate model and emissions scenario combinations considered for this study. All those projections agree in the overall future increase in the annual mean river flows despite their seasonal difference in both magnitudes and signs of change. For example, the mean projected increases in spring flows by the 2080s (compared with the baseline period of the 1980s) for the RCP4.5/RCP8.5 emissions scenarios are +11/+26% and + 62/+71% when the VIC model is forced with the CNRM and CanEMS climate projections, respectively. The corresponding decreases in summer flows are also −2/−3.5% and 0/−12% for the two emissions scenarios and the two GCMs, respectively. Over all, the VIC hydrologic model driven by the CanEMS climate projection is found to be more sensitive to increased emission
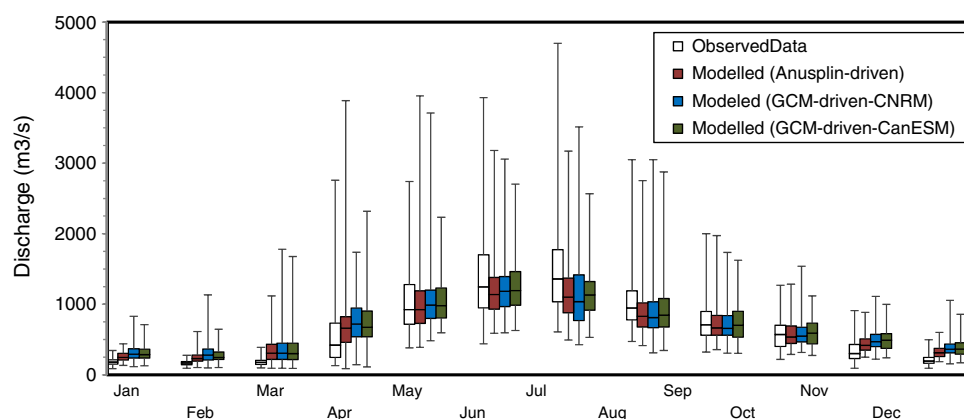

FIGURE 3 Comparison of observed and Variable Infiltration Capacity model simulated monthly mean discharges at the Athabasca River downstream of Ft. McMurray averaged over the baseline period of 1970–1999. Flows are simulated by the Variable Infiltration Capacity model driven by the ANUSPLIN gridded observed data and statistically downscaled GCMs' data from CNRM and CanESM. GCM = Global Climate Model [Colour figure can be viewed at wileyonlinelibrary.com]
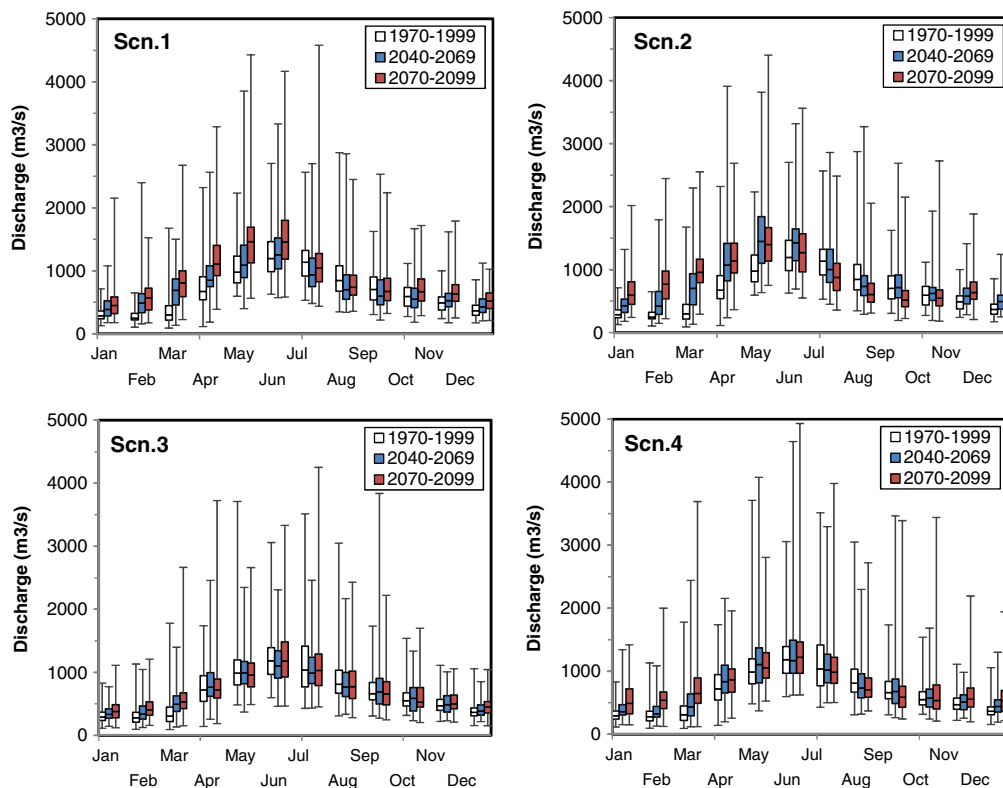
FIGURE 4 Comparison of the baseline (1980s) and future (2050s and 2080s) monthly mean discharges at the Athabasca River below Fort McMurray as simulated by the Variable Infiltration Capacity hydrologic model of the Athabasca River basin driven by spatially downscaled precipitation and temperature data corresponding to the two GCMs forced with the two emissions scenarios (Scn. 1: CanESM & RCP4.5, Scn. 2: CanESM & RCP8.5, Scn. 3: CNRM & RCP4.5, Scn. 4: CNRM & RCP8.5) [Colour figure can be viewed at wileyonlinelibrary.com]

scenario and resulted in higher increases/decreases that those driven by the CNRM climate projections. The changes in streamflow are also generally higher for RCP8.5 compared with the RCP4.5 and the 2080s compared with the 2050s, although that may not be always the case because of possible nonlinear hydrologic response of the watershed to the projected increases in precipitation and temperature. The following section presents the implication of these projected changes in the hydrologic regime of the ARB on the hydrodynamic and sediment transport regime of the LAR.

3 | HYDRODYNAMIC AND SEDIMENT TRANSPORT MODEL OF THE LAR

3.1 | Hydrodynamics

Although a two-dimensional model could have provided a more detailed results on potential changes in sediment erosion and deposition along the river and its floodplains, the application of such model in the context of a climate change impact study that requires long-term (~100 years) simulation with multiple climate models and emissions scenarios over a large (200 km) river reach is computationally prohibitive. Consequently, this study employs the MIKE-11 (Danish Hydraulics Institute, 2012) 1D numerical modelling system for the long term hydrodynamic and sediment transport simulation along the LAR. The 1D (area averaged) equations for conservation

of mass and momentum are given by the Saint Venant's formulation:

$$\begin{cases} \dfrac{\partial A}{\partial t} + \dfrac{\partial Q}{\partial x} = q \\ \dfrac{\partial Q}{\partial t} + \dfrac{\partial}{\partial x}\left(\dfrac{\alpha Q^2}{A}\right) + gA\dfrac{\partial h}{\partial x} + gA(S_0 - S_f) = 0 \end{cases}, \tag{1}$$

where t is the time, x is the streamwise distance, $h(x, t)$ is the water height, $Q(x, t)$ is the discharge, $A(x, t)$ is the flow area, q lateral inflow (per unit length), α is momentum distribution coefficient, $S_0(x)$ is the bed slope, $S_f(x, h, Q)$ is the friction slope, here given by Manning equation as:

$$S_f = \dfrac{gn^2 Q|Q|}{A^2 R^{4/3}}, \tag{2}$$

where n is Manning's coefficient and R is the hydraulic radius calculated from a parallel channel analysis in which the total conveyance of the section at a given elevation is equal to the sum of the conveyances of the parallel channels. The MIKE-11 hydrodynamic module (HD) uses an implicit finite difference method to solve the above Saint Venant's equation (Danish Hydraulics Institute, 2012).

3.2 | Sediment transport

To model the transport of fine sediments, the Advection–Dispersion (AD) and Cohesive Sediment Transport modules of MIKE-11 are used. The AD module is based on the 1D conservation of mass (of dissolved

or suspended materials). The Cohesive Sediment Transport module is coupled with AD module and is used to describe transport of suspended fine sediments. The erosion/deposition is considered as a sink/source term of the AD equations. The areal averaged 1D AD equation used in MIKE-11 is given by:

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} - \frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) = AKC + Sq, \tag{3}$$

in which C is the concentration, D is dispersion coefficient, K is linear decay coefficient, S is source/sink concentration, and q is lateral inflow. The two primary source/sink terms are sediment deposition (S_d) and erosion (S_e). When the bed shear stress, τ_b, is less than the critical shear stress for deposition, $\tau_{cd,}$ the particles and flocs in suspension begin to deposit onto the bed. By contrast, the river bed begins to erode when the bed shear stress, τ_b, exceeds the critical shear stress for erosion, τ_{ce}. The deposition and erosion rates S_d, S_e are described by the Van Rijn equations (1984):

$$S_d = W_s c\left(\frac{\tau_{cd}-\tau_b}{\tau_{cd}}\right) \text{ if } \tau_b \leq \tau_{cd}; \ \& \ S_d = 0 \text{ if } \tau_b > \tau_{cd} \tag{4}$$

$$S_e = E_0\left(\frac{\tau_b-\tau_{ce}}{\tau_{ce}}\right)^n \text{ if } \tau_b \geq \tau_{ce}; \ \& S_e = 0 \text{ if } \tau_b < \tau_{ce} \tag{5}$$

where W_s is the sediments settling velocity, and E_0 and n are the erosion coefficient and exponent, respectively. The erosion rate and critical shear stress values used in this study are based on physical laboratory experiments conducted by Droppo et al. (2014) in a circular flume on sampled bed materials collected from the lower Athabasca region.

3.3 | Model setup

As a first step in setting up the 1D MIKE-11 river model, 200 evenly divided cross sections of the LAR (with an average interval of ~1 km) were generated from the combined bathymetry data of the ~200 km river reach. The flow and sediment transport boundary conditions for

the model include time series of flow rates and the corresponding sediment concentration at the mainstem upstream inflow boundary below Fort MacMurray as well as at the confluences of each of the tributaries with the main channel. The time series of water level near Old Fort and a zero-gradient sediment concentration were used as downstream boundary conditions. The important effects of river-ice cover on the hydrodynamics and sediment transport characteristics of the LAR during the cold season have also been taken into account by introducing a synthetic shear stress value at the water surface, equivalent to the under-ice shear stress computed by an off-line river-ice model. This permits modelling of the increase in water level and decrease in bed-shear stress, caused by the winter ice cover. The procedure for including the effect of winter ice cover on the river flow (by externally coupling a river-ice model) is presented in detail in Shakibaeinia et al. (2016). The MIKE-11 model of the LAR was set up for the following three sets of model simulations corresponding to the historical and future periods: (a) the calibration/validation period, (b) baseline or reference period, and (c) future scenario period.

The historical period between 2001 and 2011 was selected for calibration/validation of the hydrodynamics and sediment transport model on the basis of available observed discharge and SSC data at various locations along the study reach. The first 3 years of data are used to adjust model parameters, and the model is subsequently validated by comparing observed and simulated data over the entire 11-year period. The key hydrodynamic model parameter for calibration is the bed-roughness that was adjusted to achieve a best match between modelled and observed water levels. The sediment transport parameters used for model calibration are critical shear stresses for erosion and deposition, erosion rate, and fall velocity. The detailed calibration/validations process of the LAR hydrodynamic and sediment transport model is explained in Shakibaeinia et al. (2017). Figure 5a shows the daily time series of simulated and measured river discharge and water level near Bitumount (x = 80 km from the upstream boundary below Ft. McMurray). The simulated and measured values over the validation period of 2001–2011 compare very well with Nash–
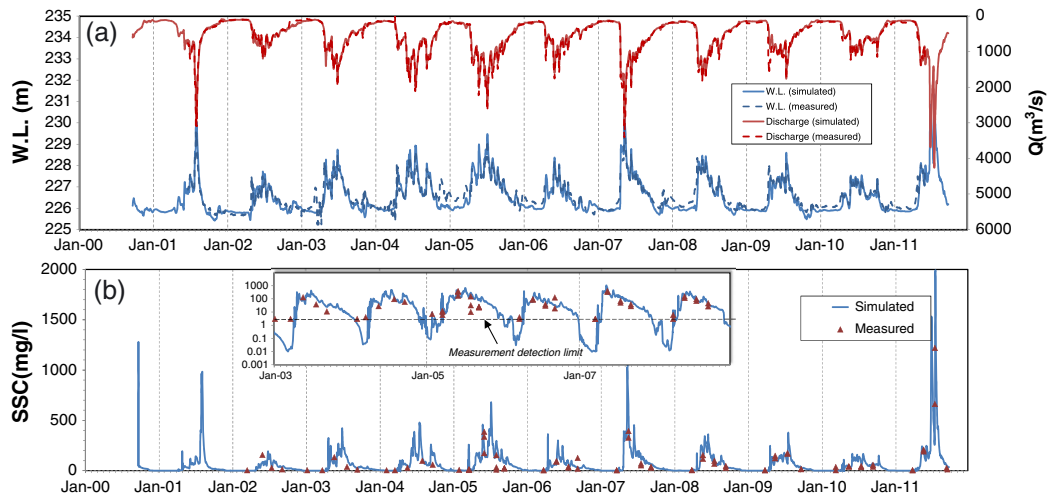

FIGURE 5 Comparison of measured and MIKE-11 simulated results for (a) water level (W.L.) and river discharge (Q) at x = 80 km (Stn.: S46), and (b) suspended sediment concentration (SSC) at x = 82 km (Stn.: ATR DC), for the model validation period of 2001–2011 [Colour figure can be viewed at wileyonlinelibrary.com]

Sutcliffe efficiency values of 0.96 and 0.89 for daily discharge and water level, respectively. The corresponding time series of the simulated and measured SSC in the LAR near Bitumount (x = 82 km from the upstream boundary) are also shown in Figure 5b. A secondary graph with a logarithmic SSC scale is also plotted on the same Figure 5b for a better visual comparison of the order-of-magnitude in seasonal variations. The simulated and measured SSC values generally show good agreement (with Nash–Sutcliffe efficiency = 0.67), and the plots also exhibit the variability of SSC throughout the year with several orders of magnitude difference between the high and low flow seasons. The maximum SSC occur during the summer months of June and July, when the flow rates are higher, whereas it gets very small (near zero) during the winter low-flow season, which also corresponds to low bed shear stress and river-ice cover.

4 | EFFECTS OF PROJECTED CLIMATE ON THE HYDRODYNAMIC AND SEDIMENT TRANSPORT REGIMES

The potential effects of climate change on the hydrodynamic and sediment transport regimes in the LAR are investigated using the streamflow scenario data simulated with the VIC hydrologic model of the ARB for the baseline (1980s) and the two future periods (of 2050s and 2080s) as presented in Eum et al. (2017). The hydrologic model outputs corresponding to each combination of GCM and RCP pairs are used as upstream and lateral boundary conditions to the MIKE-11 hydrodynamic and sediment transport model of the LAR. The time series for the upstream and tributary sediment inflows corresponding to each scenario are also generated by applying
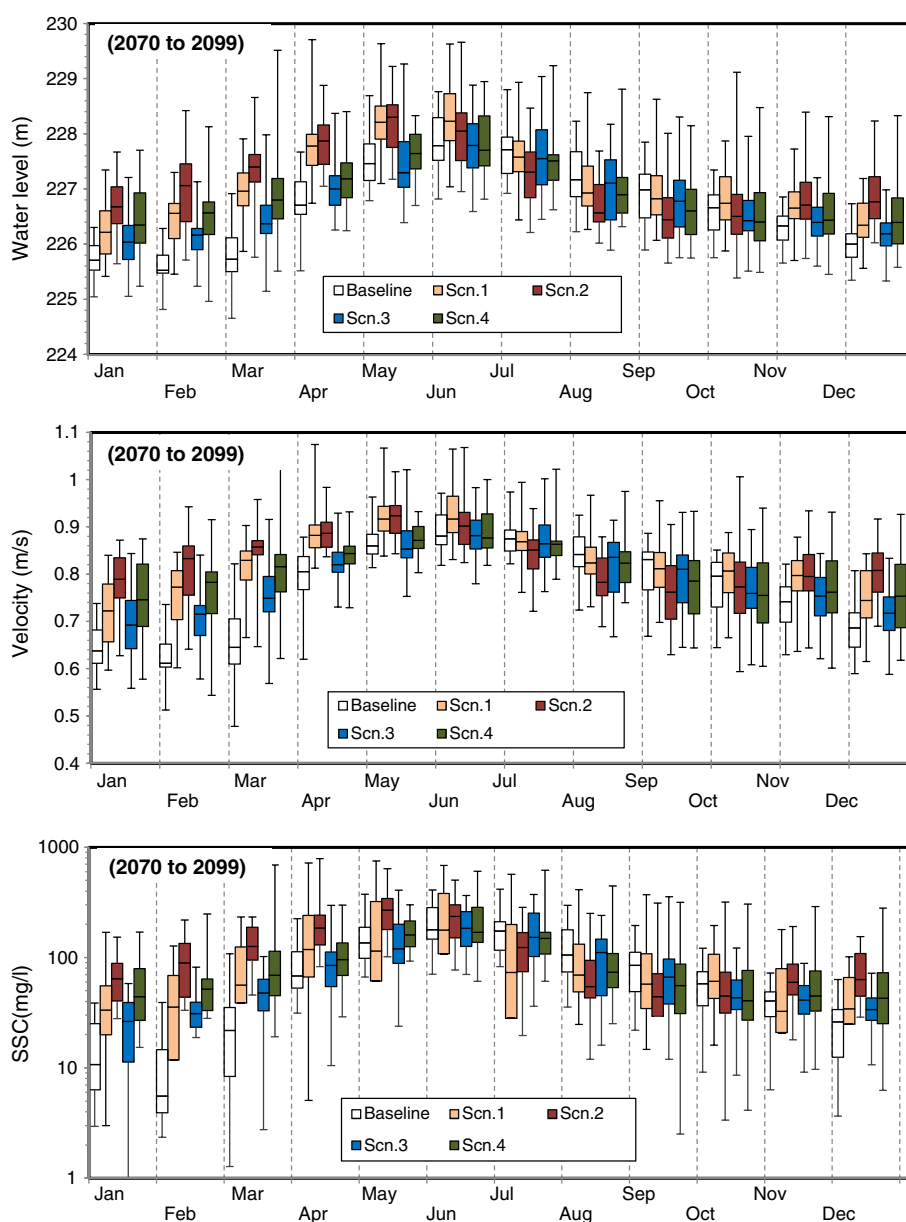

FIGURE 6 Comparison of simulated monthly mean water level, flow velocity, and suspended sediment concentration (SSC) for the 1980s baseline and the 2080s future periods in the lower Athabasca River at a location near Bitumount corresponding to the four hydro-climatic scenarios (Scn. 1: CanESM & RCP4.5, Scn. 2: CanESM & RCP8.5, Scn. 3: CNRM & RCP4.5, Scn. 4: CNRM & RCP8.5) [Colour figure can be viewed at wileyonlinelibrary.com]

the sediment-discharge rating curves developed using the historical observed data. The assumption here is that the current sediment-discharge rating curves at each inflow location will still be applicable under future hydro-climatic conditions. This assumption is justifiable since the morphology of Athabasca River immediately upstream of the main sediment inflow boundary (near Fort McMurray) is characterized by steep slope and deep and narrow valley with coarse riverbed; and sediment-rating curves in such morphology are less sensitive to potential changes in the flow magnitude as it is less likely to overtop the river or to pose a significant change in the river morphology. With all the driving boundary conditions provided, the MIKE-11 model simulates the flow velocity, water level, and SSC along the LAR corresponding to the two GCMs (CanESM and CNRM) under two emissions scenarios (RCP4.5 and RCP8.5). The potential effects of the projected climate on the hydrodynamic and transport regime in the LAR are then identified by computing the changes in flow and sediment transport variables between the baseline and the two future periods.

4.1 | Projected changes in average monthly values

Changes in mean monthly values in simulated flow velocity, water level, and SSC between the baseline (1980s) and each of the two
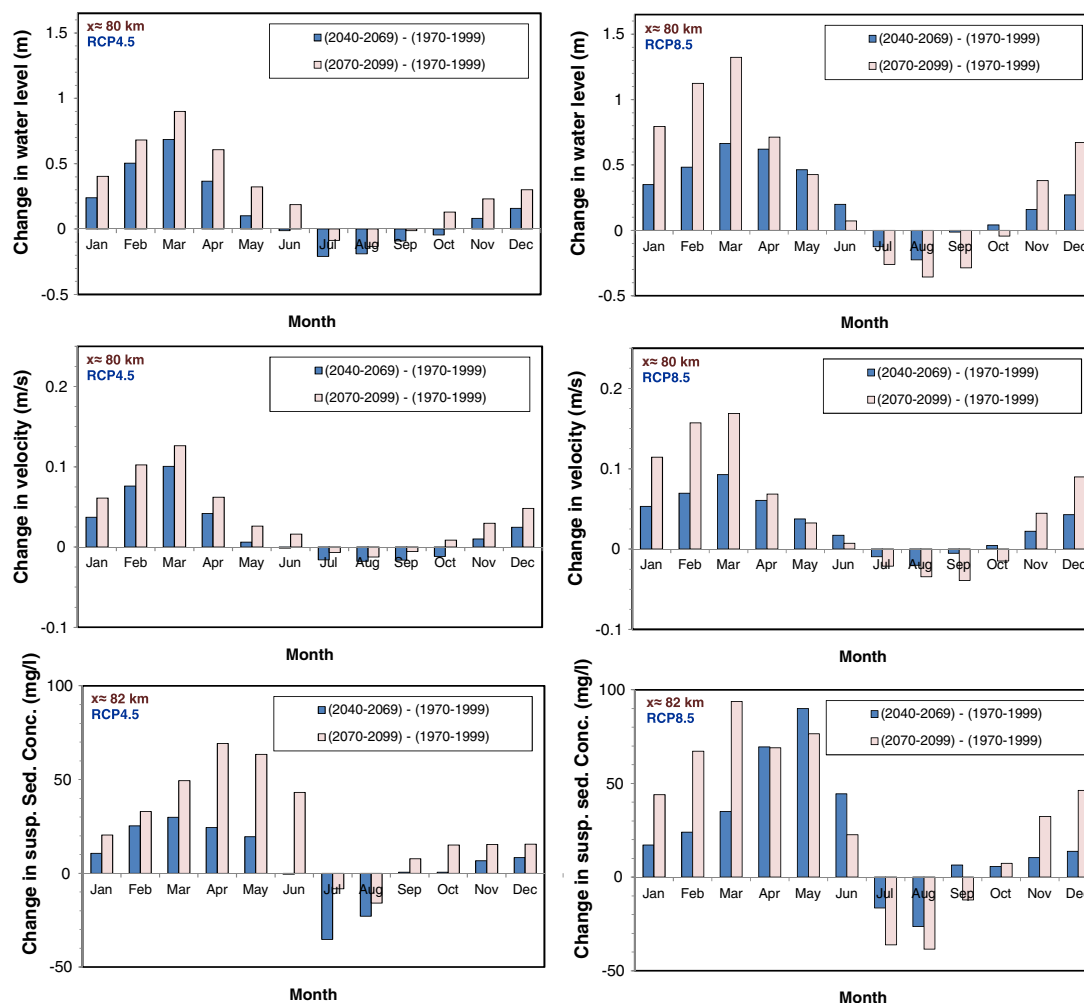

FIGURE 7 Mean projected changes in monthly averaged water level (top), flow velocity (middle), and suspended sediment concentration (SSC; bottom) between the 1980s baseline and each of the two future periods (2050s and 2080s) corresponding to the RCP4.5 (left column) and RCP8.5 (right column) emissions scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Average sediment loads in the LAR (at Stn.: ATR DC; x = 82 km) for the different scenarios and future periods and the corresponding percent change with respect to the baseline period

Period	Sediment load	Scn.1	Scn.2	Scn.3	Scn.4	RCP4.5	RCP8.5
1970–1999	Mass (ton/day)	8,774.0	8,660.8	8,392.4	8,854.9	8,583.2	8,757.9
2040–2069	Mass (ton/day) Change (%)	10,929.8 24.6	15,853.080 83.0	7,834.181 −6.7	9,986.3 12.8	9,382.0 9.3	12,919.6 47.5
2070–2099	Mass (ton/day) Change (%)	16,640.9 89.7	15,168.4 75.1	10,151.1 21.0	11,725.8 32.4	13,396.0 56.1	13,447.1 53.5

Note. (Scn. 1: CanESM & RCP4.5, Scn. 2: CanESM & RCP8.5, Scn. 3: CNRM & RCP4.5, Scn. 4: CNRM & RCP8.5). LAR = lower Athabasca River.

future periods (2050s and 2080s) are presented in Figure 6 for a location near Bitumount. The results show an overall projected increase in each of these flow variables over most seasons except in the summer and early fall months of July, August, and September when they all show potential decreases. For example, the monthly median values of water-level/flow-velocity/SSC in March are projected to increase from their baseline values of 225.7 m/0.65 m/s/22 mg/L to their corresponding values by the 2080s ranging from 226.6 m/0.75 m/s/ 49 mg/L to 227.4 m/0.86 m/s/120 mg/L depending on the climate models and emission scenarios considered. These results are also consistent with the projected changes in the hydrologic regime as simulated by the VIC model of the ARB. However, there are also clear differences in the magnitudes of the projected changes resulting from each of the two GCMs. The projected changes in the mean monthly values of water level and flow velocity corresponding to the CanESM are consistently higher than those of the CNRM. For instance, the maximum water level change by the 2080s is 37% higher for CanESM projection comparing with that of CNRM. The differences are even more pronounced in the case of changes in SSC, where those corresponding to CanESM projection exhibit up to 5 times higher concentration than those of CNRM possibly because of the exponential relationship between flow velocity and SSC. Such differences are exhibited for both RCPs, and the magnitude of the climate change effect is generally higher for the RCP8.5 emissions scenario compared with that of the RCP4.5.

While the variation in the results corresponding to each GCM show the sensitivity of the potential impacts to the particular climate scenarios used to drive the hydrologic model, a more robust interpretation of the results can be made by computing the mean values of the projected changes corresponding to the two GCMs considered in this study. Figure 7 shows the ensemble projected changes in mean monthly values of the three flow parameters between the

baseline and the two future periods. The results once again indicate the seasonal variations in the magnitude of changes with the higher projected increases in mean monthly values (of up to 1.3 m for water level and 0.17 m/s for flow velocity) occurring in the winter and spring months and a decrease (of up to 0.4 m for water level and 0.05 m/s for flow velocity) occurring in the late summer and early fall months of July, August, and September. The projected changes are generally higher for the 2080s period compared with the 2050s, and they are also larger for the RCP8.5 emissions scenario compared with that of the RCP4.5, especially during the latter period.

Projected changes in the concentration of suspended sediments shows a pattern similar to that of the water level and flow velocity. SSC is projected to increase for most of the year except the summer months of July and August when it is expected to decrease. The highest increase in SSC (of 93 mg/L) occurs in March, and the highest decrease (of about 38 mg/L) occurs in August for RCP8.5 emission scenario during the 2080s. The results also show some lags between the months of highest increases in water level and flow velocity (in February and March) and the months of highest increases in SSC (mostly in April and May). This seems to be because of the lag time between the increased sediment inflows at the upstream and lateral (tributary) boundaries and their subsequent effect on SSC along the study reach. All these results are consistent with the corresponding patterns of projected changes in streamflow presented in Figure 3. Table 3 also shows the combined effect of the overall projected increases in discharge and SSC on the total sediment load transported through the LAR and the corresponding changes with respect to the 1980s baseline period. The results show that the increases corresponding to the different scenarios ranging from 21% for CNRM with RCP4.5 to 89.7% for CanESM with RCP4.5 scenarios. The multimodel mean projected increases in the sediment load transported by the LAR
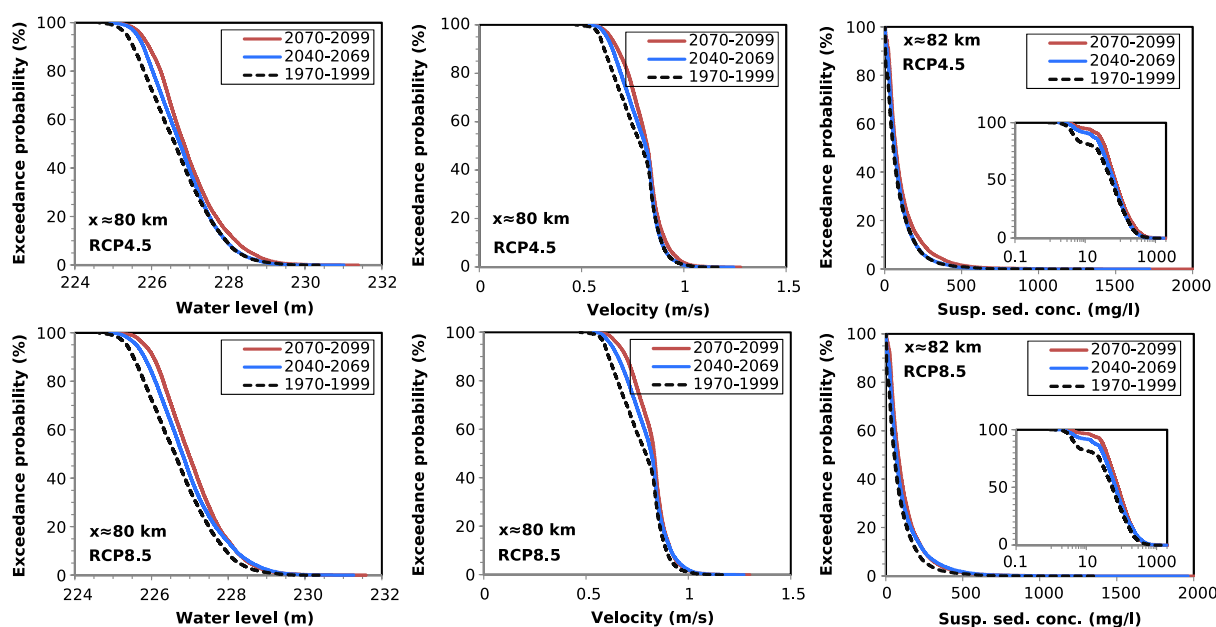

FIGURE 8 Exceedance probabilities for daily mean values of water level (left column), flow velocity (middle column), and suspended sediment concentration (right column) at a location near Bitumount for the 1980s baseline and two future periods (2050s and 2080s) corresponding to RCP4.5 (top row) and RCP8.5 (bottom row) emissions scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

by the 2080s corresponding to the RCP4.5 and RCP8.5 emissions scenarios are 56.1% and 53.5%, respectively. These projected increases in sediment load are attributable to the potential increases in the sediment generating capacity of a wetter climate along with the higher sediment carrying capacity of a higher discharge.

4.2 | Projected changes in exceedance probability

The scenario simulation results are also presented in terms of probability of exceedance describing the likelihood of the daily mean value of a specified flow variable being exceeded in a given time period. Figure 8 presents the exceedance probabilities of daily mean water level, flow velocity, and SSC for the baseline and future periods for a location near Bitumount by combining simulation results corresponding to the CanEMS and CNRM projections. The results show an overall increase in the exceedance probabilities of each of the three flow parameters for all future scenarios. For the RCP4.5 case, the exceedance probabilities of lower flow and SSC values exhibit substantial increases by the 2050s while the corresponding increases for higher values do not occur until the 2080s. For example, the probability of exceedance for a flow velocity of 0.7 m/s increases by ~10% (from 75% to 85%) by the 2050s and 15% (to 90%) by the 2080s. On the other hand, for the RCP8.5 case, the exceedance probabilities for both high- and low-flow parameters show noticeable increases by the 2050s, and only the low flows show further increases in their exceedance probabilities by the 2080s. This is because channel overflow to adjacent floodplains during periods of high flow prevents the water level and mean flow velocity from increasing any further. Figure 8 also shows that projected increases in exceedance probabilities of the SSC (plotted in both logarithmic and non-logarithmic scales) are mainly for lower concentrations (SSC < ~10 mg/L) following similar patterns of changes to that of flow velocity (and therefore bed shear stress). Plots of exceedance probabilities at other locations along the river have also shown similar patterns of projected changes (not shown).

5 | SUMMARY AND CONCLUSIONS

The potential effect of climate change on the hydrodynamic and sediment transport regime of the LAR is investigated. The main sources of uncertainty in the study are the range of climate projections and the corresponding hydrologic simulations. An attempt is made to capture the variations in the hydrologic response to a range of potential climate projections by applying the VIC hydrologic model outputs corresponding to two of the CMIP5 GCMs (CNRM and CanEMS) representing moderate and higher rates of changes in precipitation and temperature over the study region, respectively, under each of the two emission scenarios (RCP8.5 and RCP4.5). Statistical downscaling of the GCM climate scenarios is also important in that, in addition to removing possible biases, it disaggregates the climate data (daily precipitation and temperature) to a higher spatial resolution that is most appropriate to drive the process based and distributed VIC hydrologic model. The projected increases in both precipitation (+8% to +25%) and temperature (+2.8 to +7 °C) over the Athabasca watershed are expected to alter the hydrologic regime in the river

by increasing the winter and spring flows and reducing the summer flows as a result of increasing rain on snow events and earlier timing of the freshet initiation because of the warming climate.

The transport model simulation study showed that the projected changes in the hydrologic regime will have serious consequences on the hydrodynamic and sediment transport regimes of the LAR. An overall increase in mean water level (by up to 1.3 m), mean flow velocity (by up to 0.17 m/s), and suspended sediment consecration (SSC by up to 93 mg/L) is projected for most seasons except in the summer when they all show potential (but smaller) decreases consistent with the hydrologic projections. The projected changes in these variables are larger for the RCP8.5 emissions scenario compared with that of the RCP4.5, especially during the latter period (2080s) when the changes are generally higher. There is also an indication that there will be some lag between the months of highest increases in water level and flow velocity on the one hand and the months of highest increases in SSC on the other because of the response time between the increased sediment inflows at the upstream and lateral (tributary) boundaries and their subsequent effect on SSC along the study reach. The scenario simulation results also show an overall increase in the exceedance probabilities of all the three flow parameters for all future scenarios. For the case of RCP4.5, the exceedance probabilities of lower flow and SSC values exhibit substantial increases by the 2050s whereas the corresponding increases for higher values occurred only by the 2080s. On the other hand, for the case of RCP8.5, the exceedance probabilities for both high and low flow parameters have shown noticeable increases by the 2050s, and only the low flows show further increases in their exceedance probabilities by the 2080s. In all the above cases, there is an inherent uncertainty in the magnitude of changes projected by the cascade of models arising from a number of factors such as emission scenarios, observed or estimated inputs to the models, sediment inflow rating curves, and model parameters. However, the hydrodynamic and sediment transport modelling approach applied in this study using hydrologic projection corresponding to the two climate models (CNRM and CanEMS) and the two emissions scenarios (RCP4.5 and RCP8.5) depict the general direction of potential changes in the flow and sediment transport regime of the LAR.

In general, climate change is projected to cause increasing precipitation and temperature in the Athabasca watershed that will, in turn, alter the hydrologic regime in the LAR system. Through hydrodynamic and sediment transport simulation in the LAR, this study found that, by the end of this century, there will be a corresponding potential increase in flow velocity and water level leading to an overall increase in sediment load and transport in the LAR and to the PAD compared with the contemporary baseline period. Implications of such potential changes in the transport characteristics of the river system to the mobilization and transport of various chemical constituents and their effects on the region's aquatic ecosystems are subjects of other ongoing investigations.

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