Hydrometeorology and landscapes control sediment and organic matter mobility across a diverse and changing glacier-sourced river basin

Craig A. Emmerton[1], John F. Orwin[2], Cristina Buendia[1α], Michael Christensen[3], Jennifer A. Graydon[1], Brian Jackson[4], Elynne Murray[4], Stephanie Neufeld[3], Brandi W. Newton[2], Ryan Ozipko[4], Rick Pickering[4], Nadine Taube[2], Chris Ware[4]*

Supporting information

Catchment structural units

Catchment structural units (CSUs) describe an integrated landscape condition code for 400 m^2 landscape areas based on various geospatial datasets (Orwin et al., 2022). Geospatial datasets used to construct CSUs include: land cover (Alberta Biodiversity Monitoring Institute, 2013), human footprint (Alberta Biodiversity Monitoring Institute, 2016), surficial geology (Alberta Geological Survey, 2015), wetland cover (Government of Alberta, 2019), and topography (Altalis, 2017). Each dataset has a listing of codes in a particular position of the typically six-digit code. However, it is possible for entire categories to not be present within a CSU and thus are zeroed in that digit position. For land cover, absence of leading sixth digit may indicate agricultural cover (i.e., cross referenced with land use) or wetland cover. Absence of or zero in the fifth position indicates no specific anthropogenic land uses in the CSU. See Table S1 for details about the coding approach and the dominant codes by area for the North Saskatchewan River basin tributary catchments in the current study.

Mass export models

Quantifying export of suspended and dissolved material of rivers presents challenges and can produce widely different estimate precisions (Aulenbach et al., 2016). *Loadflex* uses four different modelling approaches to help delineate this between-model variability in daily export estimates of a river (Appling et al., 2015). All models use datasets of periodically collected water quality concentration measures and more frequent river flow measurements. The first model uses a rectangular interpolation approach that connects consecutive concentration measurements using a period-weighted average approach. Daily export is quantified using the product of filled concentrations and flow data on a given day. The second model is a simple log regression model between periodically measured concentrations and its paired flow data on the day of collection. This model is then used with the full flow data record to quantify the product of concentration and flow for a daily export estimate. The third model is the United States Geological Survey Loadest model (Runkel et al., 2004). This approach fits several different regressions to periodic concentration data and paired flow to find the best performing regression model to fit the data. This model is then used with flow data to quantify daily export. Finally, the composite model uses a regression model (Loadest as default) and collected concentration data to generate a residual dataset between regression estimates and real data. These residuals are then used systematically to correct regression estimates to provide an improved regression that is

used with flow to quantify daily export. *Loadflex* includes estimates of daily standard error of prediction for each export model and are shown in Tables S9 and S10. To produce annual water year export for each site and each model, we summed all daily export estimates for each water year and associated daily errors via summing propagation of error rules. For errors related to unmonitored flow, we used the mean proportional error of the river(s) used to calculate unmonitored flows via their yields (see Methods). Errors related to the change in storage (ΔS) term were determined by simple error propagation rules.

In most cases, errors surrounding annual export estimates were reasonably low reflecting the close relationships between TSS and river flow, and DOC and river flow. However, at stations where those relationships were poor, error surrounding estimates was much higher. These errors were then propagated to calculated terms like change in storage (ΔS). However, these high errors occurred in the log-log regression model only and did not occur in other models at a given site.

Alberta Biodiversity Monitoring Institute. (2013). Wall-to-wall Landcover Inventory - Year 2010. Retrieved from https://abmi.ca/abmi-home/data-resources/data-portal-main/data-portal/single-data-portal-detail.html?name=63

Alberta Biodiversity Monitoring Institute. (2016). Wall-to-Wall Human Footprint Inventory - Year 2016. Retrieved from https://abmi.ca/abmi-home/data-resources/data-portal-main/data-portal/single-data-portal-detail.html?name=51

Alberta Geological Survey. (2015). Surficial Geology of Alberta, Generalized Digital Mosaic (DIG 2013-0002). Retrieved from https://geology-ags-aer.opendata.arcgis.com/maps/745bb49973194f46b19d5ad2f84afd61/about

Altalis. (2017). Alberta Provincial Digital Elevation Model. Retrieved from https://open.alberta.ca/opendata/gda-c16469a2-5541-455c-bba0-63a24c0ff08a#summary

Appling, A. P., Leon, M. C., & McDowell, W. H. (2015). Reducing bias and quantifying uncertainty in watershed flux estimates: the R package loadflex. Ecosphere, 6(12), 1–25. https://doi.org/10.1890/ES14-00517.1

Aulenbach, B. T., Burns, D. A., Shanley, J. B., Yanai, R. D., Bae, K., Wild, A. D., et al. (2016). Approaches to stream solute load estimation for solutes with varying dynamics from five diverse small watersheds. Ecosphere, 7(6), 1–22. https://doi.org/10.1002/ecs2.1298

Bush, E., & Lemmen, D. . (2019). Canada's Changing Climate Report. Environment and Climate Change Canada, Government of Canada. Retrieved from www.ChangingClimate.ca/CCCR2019

Government of Alberta. (2019). Alberta Merged Wetland Inventory 2015. Retrieved from https://climate.esri.ca/maps/6933a7b62a11440bbc2d69a0d6d047c0/about

Orwin, J. F., Klotz, F., Taube, N., Kerr, J. G., & Laceby, J. P. (2022). Linking catchment structural units (CSUs) with water quality: Implications for ambient monitoring network design and data interpretation. Journal of Environmental Management, 312(October 2021), 114881. https://doi.org/10.1016/j.jenvman.2022.114881

Runkel, R. L., Crawford, C. G., & Cohn, T. a. (2004). Load Estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers. Techniques and Methods. U.S. Geological Survey. U.S. Department of the Interior.

Tables

Table S1 (a.) Catchment structural unit (CSU) coding used in this study (modified after Table 1 of Orwin et al., 2022). (b.) Top five CSU codes by area from each monitored North Saskatchewan River basin tributary and mainstem catchment and associated percent catchment area (%) covered by the CSU within the catchment. See Table 1 in the main manuscript for monitoring station information.

a. Catchment structural unit (CSU) codes									
Land cover[1]	**Code**	**Land use[2]**	**Code**	**Surficial geology[3]**	**Code**	**Wetland[4]**	**Code**	**Slope[5]**	**Code**
Water[D1]	10000	Disturbed	1000	Mixed	100	Wetlands	10	< 10%	1
Snow/Ice[D2]	20000	Agriculture[D3]	2000	Fine Grained	200	Water	D1	≥ 10%	2
Rock/Rubble	30000	Forestry	3000	Coarse	300	Absent	00		
Exposed	40000	Mining	4000	Glaciers	D2				
Developed	50000	Oil & gas	5000	Indeterminate	500				
Shrubland	60000	Linear	6000	Bedrock	600				
Grassland	70000	Reservoir	7000						
Agriculture	D3	Urban	8000						
Forest	90000	Absent	0000						
Ag., wetlands	00000								

[D#]Duplicated code between CSU datasets; code removed.
[1]Alberta Biomonitoring Institute 2010 Wall-to-Wall Land Cover; [2]Alberta Biomonitoring Institute 2016 Wall-to-Wall Human Footprint Inventory; [3]Surficial Geology of Alberta 2013; [4]Government of Alberta Merged Wetland Inventory 2015; [5]Altalis Alberta Digital Elevation Model 2017.

b. North Saskatchewan River basin catchment structural units (CSUs) by catchment													
NSR-WPt.		**Ram**		**Clearwater**		**Brazeau**		**Baptiste**		**Nordegg**		**Rose**	
%	**code**	**%**	**code**	**%**	**code**	**%**	**code**	**%**	**code**	**%**	**code**	**%**	**code**
16.4	30602	38.8	90102	19.7	90102	15.1	90102	26.7	90301	20.6	90301	24.1	90301
13.3	30102	14.9	90302	10.0	90302	13.3	90302	13.5	3301	17.1	3301	19.7	90201
12.8	90302	9.8	30602	8.7	90301	10.6	90301	11.0	311	12.6	90302	12.7	211
11.0	90102	5.4	30102	8.0	30602	9.7	30602	10.6	211	11.6	3302	7.8	2301
10.3	20602	5.2	90301	5.2	90101	9.6	30102	7.1	90201	7.4	311	7.6	311
Tomahawk		**Modeste**		**Sturgeon**		**Strawberry**		**Whitemud**		**Redwater**			
%	**code**	**%**	**code**	**%**	**code**	**%**	**code**	**%**	**code**	**%**	**code**		
24.2	2201	31.9	2301	28.7	2301	48.4	2301	45.6	2301	41.9	2301		
14.7	2301	15.4	90301	23.7	2201	13.5	2201	10.9	311	11.5	2201		
14.0	211	9.9	2201	7.9	90301	10.0	311	10.4	2201	8.7	2101		
12.5	90201	9.6	311	5.8	211	8.9	90301	6.1	1301	4.6	90101		
9.9	90301	5.8	211	5.0	311	2.7	6301	3.7	6301	4.6	90201		
NSR-Saund.		**NSR-Clearwater**		**NSR-Devon**		**NSR-Pakan**							
%	**code**	**%**	**code**	**%**	**code**	**%**	**code**						
18.7	90102	22.6	90102	12.9	90102	16.4	2301						
17.4	30602	13.9	30602	10.7	90301	9.6	90301						
13.0	30102	13.2	90302	8.9	90302	8.8	90102						
12.9	90302	9.9	30102	7.1	30602	7.7	2201						
5.2	90301	6.4	90301	5.5	30102	6.0	90302						

Grey-cordillera catchments; Green-foothills catchments; Blue-mixed agriculture catchments; Red-agricultural catchments; white-NSR mainstem catchments.

Table S2 Water volume and runoff from the North Saskatchewan River (NSR) mainstem (emphasized) and its tributaries from 2019 to 2022 water years. CA-catchment area. Landscape types: C-cordillera; F-foothills; MA-mixed agriculture; A-agriculture. "Other" are calculated remainder values (see Equation 1 in main manuscript) and therefore do not have catchment areas or runoff values.

Station	CA (km^2)		Volume ($km^3\ yr^{-1}$)					Runoff (mm)			
			2019	2020	2021	2022		2019	2020	2021	2022
NSR at Whirlpool Pt. (C)	1,870		1.7	1.9	2.0	1.9		921	1,013	1,064	1,013
unmonitored land	3,219		1.0	1.3	0.6	0.8		297	388	196	248
Other (ΔS_{NSR})	-		0.2	0.2	0.4	0.5		-	-	-	-
NSR at Saunders Camp.	**5,089**		**2.9**	**3.3**	**3.0**	**3.2**		**568**	**651**	**597**	**621**
Ram R. (C)	1,878		0.6	0.7	0.4	0.5		297	388	196	248
unmonitored land	748		0.2	0.3	0.1	0.2		297	388	196	248
Other (ΔS_{NSR})	-		-0.1	-0.2	-0.0	-0.1		-	-	-	-
NSR u/s Clearwater R.	**7,715**		**3.6**	**4.1**	**3.5**	**3.7**		**465**	**535**	**455**	**476**
Clearwater R. (C)	3,190		0.8	1.1	0.6	0.8		245	330	186	235
Baptiste R. (F)	1,350		0.3	0.4	0.1	0.2		199	313	89	144
Nordegg R. (F)	869		0.3	0.3	0.1	0.1		320	339	115	132
Brazeau R. (C)	5,693		2.4	2.3	1.4	1.7		416	402	244	296
Rose Ck. (F)	657		0.1	0.2	<0.1	0.1		152	296	29	109
Modeste Ck. (MA)	1,174		0.1	0.3	<0.1	0.1		107	275	21	91
Tomahawk Ck. (MA)	190		<0.1	<0.1	<0.1	<0.1		121	168	3	30
Strawberry Ck. (A)	591		<0.1	0.1	<0.1	<0.1		74	152	18	61
unmonitored land	4,933		1.4	1.7	0.8	1.1		291	343	165	216
Other (ΔS_{NSR})	-		-1.2	-1.2	-0.8	-1.2		-	-	-	-
NSR at Devon	**26,362**		**7.8**	**9.3**	**5.8**	**6.5**		**296**	**355**	**219**	**245**
Whitemud Ck. (A)	1,095		0.1	0.1	<0.1	<0.1		50	82	8	28
Sturgeon R. (MA)	3,390		0.2	0.3	<0.1	0.1		48	76	6	19
Redwater R. (A)	1,612		0.1	0.1	<0.1	0.04		34	89	3	22
unmonitored land	6,874		0.3	0.6	<0.1	0.1		44	80	6	21
Other (ΔS_{NSR})	-		-0.1	0.01	-0.02	-0.01		-	-	-	-
NSR at Pakan Bridge	**39,333**		**8.3**	**10.4**	**5.8**	**6.7**		**210**	**264**	**148**	**171**

Table S3 Loadest and log-log regression export model concentration-flow relationships for total suspended solids (TSS) and dissolved organic carbon (DOC) from the North Saskatchewan River (NSR) mainstem (emphasized) and its tributaries from 2019 to 2022 water years. C-cordillera; F-foothills; MA-mixed agriculture; A-agriculture. *indicates statistically significant relationship at α=0.05.

	TSS			DOC	
Station	**Loadest r^2**	**Regression r^2**		**Loadest r^2**	**Regression r^2**
NSR at Whirlpool Pt. (C)	0.963*	0.841*		0.954*	0.024
NSR at Saunders Camp.	**0.286***	**<0.001**		**0.650***	**0.090***
Ram R. (C)	0.943*	0.761*		0.947*	0.667*
NSR u/s Clearwater R.	**0.815***	**0.437***		**0.718***	**0.201***
Clearwater R. (C)	0.941*	0.739*		0.915*	0.555*
Baptiste R. (F)	0.942*	0.774*		0.979*	0.616*
Nordegg R. (F)	0.931*	0.695*		0.984*	0.854*
Brazeau R. (C)	0.805*	0.436*		0.942*	0.356*
Rose Ck. (F)	0.949*	0.793*		0.989*	0.248*
Modeste Ck. (MA)	0.965*	0.834*		0.990*	0.452*
Tomahawk Ck. (MA)	0.981*	0.410*		0.991*	0.055
Strawberry Ck. (A)	0.974*	0.319*		0.995*	0.170*
NSR at Devon	**0.908***	**0.774***		**0.891***	**0.489***
Whitemud Ck. (A)	0.956*	0.715*		0.983*	0.189*
Sturgeon R. (MA)	0.961*	0.521*		0.985*	0.166*
Redwater R. (A)	0.979*	0.587*		0.996*	<0.001
NSR at Pakan Bridge	**0.923***	**0.848***		**0.930***	**0.647***

Table S4 Export and yields (median of four *Loadflex* export models) of total suspended solids (TSS) from the North Saskatchewan River (NSR) mainstem (emphasized) and its tributaries from 2019 to 2022 water years. CA-catchment area. Landscape types: C-cordillera; F-foothills; MA-mixed agriculture; A-agriculture. "Other" are calculated remainder values (see Equation 1 in main manuscript) and therefore do not have catchment areas or runoff values.

Station	CA (km^2)		Export (ktonne yr^{-1})					Yield (tonne km^{-2} yr^{-1})			
			2019	2020	2021	2022		2019	2020	2021	2022
NSR at Whirlpool Pt. (C)	1,870		69	116	195	119		36.6	62.0	104.2	63.9
unmonitored land	3,219		146	285	37	772		45.3	88.6	11.4	240.0
Other (ΔS_{NSR})	-		-189	-371	-208	-864		-	-	-	-
NSR at Saunders Camp.	**5,089**		**26**	**30**	**23**	**28**		**5**	**6**	**5**	**6**
Ram R. (C)	1,878		85	166	21	451		45.3	88.6	11.4	240.0
unmonitored land	748		34	66	9	179		45.3	88.6	11.4	240.0
Other (ΔS_{NSR})	-		-30	-44	16	-472		-	-	-	-
NSR u/s Clearwater R.	**7,715**		**115**	**218**	**69**	**186**		**15**	**28**	**9**	**24**
Clearwater R. (C)	3,190		63	178	17	591		19.8	55.9	5.4	185.4
Baptiste R. (F)	1,350		10	96	2	38		7.8	71.5	1.6	28.1
Nordegg R. (F)	869		22	182	1	5		25.2	209.1	0.9	5.5
Brazeau R. (C)	5,693		12	10	2	5		2.0	1.7	0.4	0.9
Rose Ck. (F)	657		21	264	1	44		32.4	401.4	1.4	67.2
Modeste Ck. (MA)	1,174		18	262	2	41		15.1	223.5	1.6	35.0
Tomahawk Ck. (MA)	190		2	4	<1	<1		10.7	19.3	0.0	1.4
Strawberry Ck. (A)	591		16	179	2	51		26.4	302.0	2.6	85.5
unmonitored land	4,933		59	422	10	279		11.9	85.6	2.0	56.5
Other (ΔS_{NSR})	-		589	1,994	48	-487		-	-	-	-
NSR at Devon	**26,362**		**927**	**3,809**	**153**	**753**		**35**	**145**	**6**	**29**
Whitemud Ck. (A)	1,095		16	41	1	9		14.8	37.7	1.2	8.6
Sturgeon R. (MA)	3,390		13	36	1	8		4.0	10.6	0.2	2.3
Redwater R. (A)	1,612		1	7	<1	2		0.9	4.5	0.0	1.1
unmonitored land	6,874		35	96	2	21		5.1	13.9	0.3	3.1
Other (ΔS_{NSR})	-		-53	834	-70	205		-	-	-	-
NSR at Pakan Bridge	**39,333**		**940**	**4,824**	**87**	**998**		**24**	**123**	**2**	**25**

Table S5 Export and yields (median of four *Loadflex* export models) of dissolved organic carbon (DOC) from the North Saskatchewan River (NSR) mainstem (emphasized) and its tributaries from 2019 to 2022 water years. CA-catchment area. Q-flow. Landscape types: C-cordillera; F-foothills; MA-mixed agriculture; A-agriculture. "Other" are calculated remainder values (see Equation 1 in main manuscript) and therefore do not have catchment areas or runoff values.

Station	CA (km2)		Export (ktonne yr-1)					Yield (tonne km-2 yr-1)			
			2019	2020	2021	2022		2019	2020	2021	2022
NSR at Whirlpool Pt. (C)	1,870		1	1	1	1		0.6	0.5	0.5	0.5
unmonitored land	3,219		4	5	2	4		1.4	1.7	0.5	1.2
Other (ΔS_{NSR})	-		-3	-4	~-1	-3		-	-	-	-
NSR at Saunders Camp.	**5,089**		**3**	**3**	**2**	**2**		**0.5**	**0.6**	**0.4**	**0.4**
Ram R. (C)	1,878		3	3	1	2		1.4	1.7	0.5	1.2
unmonitored land	748		1	1	1	1		1.4	1.7	0.5	1.2
Other (ΔS_{NSR})	-		~-1	-2	~-1	~-1		-	-	-	-
NSR u/s Clearwater R.	**7,715**		**5**	**5**	**3**	**5**		**0.7**	**0.7**	**0.4**	**0.6**
Clearwater R. (C)	3,190		2	2	1	2		0.6	0.8	0.3	0.6
Baptiste R. (F)	1,350		3	5	1	2		2.2	3.6	0.7	1.5
Nordegg R. (F)	869		3	3	1	1		3.6	4.0	0.7	1.1
Brazeau R. (C)	5,693		12	9	4	5		2.1	1.6	0.7	0.9
Rose Ck. (F)	657		2	4	<1	2		3.5	5.8	0.4	2.6
Modeste Ck. (MA)	1,174		2	6	<1	2		2.0	5.5	0.3	1.6
Tomahawk Ck. (MA)	190		1	1	<1	<1		6.0	7.0	0.1	1.0
Strawberry Ck. (A)	591		<1	2	<1	1		1.5	3.6	0.3	1.1
unmonitored land	4,933		10	12	2	5		2.0	2.5	0.5	1.1
Other (ΔS_{NSR})	-		-5	4	-1	-5		-	-	-	-
NSR at Devon	**26,362**		**37**	**55**	**12**	**20**		**1.4**	**2.1**	**0.4**	**0.7**
Whitemud Ck. (A)	1,095		1	2	<1	<1		0.8	1.5	0.1	0.3
Sturgeon R. (MA)	3,390		3	5	<1	1		0.9	1.5	0.1	0.3
Redwater R. (A)	1,612		1	5	<1	1		0.9	2.9	0.1	0.5
unmonitored land	6,874		6	13	1	2		0.9	1.8	0.1	0.4
Other (ΔS_{NSR})	-		~-1	3	2	1		-	-	-	-
NSR at Pakan Bridge	**39,333**		**48**	**82**	**15**	**25**		**1.2**	**2.1**	**0.4**	**0.6**

Table S6 Linear mixed model results for total suspended solids (TSS) for tributary stations of the North Saskatchewan River (NSR) basin. Fixed effects are landscape type, water year, and export model (see Methods). C-cordillera; F-foothills; MA-mixed agriculture; A-agriculture. *indicates statistically significant relationship at α=0.05. df-degrees of freedom. F-F statistic. C.I.-confidence interval.

Fixed effects	Numerator df	Denominator df	F	Significance
Intercept	1	5.5	2.81	0.149
Landscape	3	7.8	9.15	0.006*
Water Year	3	75,899	567.87	<0.001*
Model	3	75,899	89.67	<0.001*
Landscape * Water Year	9	75,899	44.42	<0.001*
Landscape * Model	9	75,899	31.39	<0.001*
Water Year * Model	9	75,899	2.56	0.006*
Landscape * Water Year * Model	27	75,899	0.78	0.782

	Estimates	Mean	Standard Error	df	C.I. Lower	C.I. Upper
	Grand mean	-1.205	0.719	5.498	-3.004	0.594
Land-scape	Cordillera	0.206	0.764	6.151	-1.653	2.065
	Foothills	-0.869	0.808	5.783	-2.864	1.127
	Mixed agriculture	-2.217	0.782	6.736	-4.081	-0.353
	Agriculture	-1.940	0.771	7.076	-3.759	-0.121
Water year	2019	-0.884	0.719	5.502	-2.684	.915
	2020	-0.862	0.719	5.502	-2.661	0.937
	2021	-1.648	0.719	5.502	-3.448	0.151
	2022	-1.424	0.719	5.502	-3.224	0.375
Model	Interpolation	-0.978	0.719	5.502	-2.778	0.821
	Loadest	-1.290	0.719	5.502	-3.089	0.509
	Regression	-1.226	0.719	5.502	-3.025	0.574
	Composite	-1.325	0.719	5.502	-3.124	0.474

							2019	2020	2021	2022
Landscape	Cordillera	Foothills			Cordillera	Foothills				
	Cordillera	Mixed Ag.	*		Cordillera	Mixed Ag.	*	*	*	*
	Cordillera	Agriculture	*		Cordillera	Agriculture	*	*	*	*
	Foothills	Mixed Ag.			Foothills	Mixed Ag.				
	Foothills	Agriculture			Foothills	Agriculture				
	Mixed Ag.	Agriculture			Mixed Ag.	Agriculture				
							Int	Load	Reg	Comp
Water year	2019	2020			2019	2020				
	2019	2021	*		2019	2021	*	*	*	*
	2019	2022	*		2019	2022	*	*	*	*
	2020	2021	*		2020	2021	*	*	*	*
	2020	2022	*		2020	2022	*	*	*	*
	2021	2022	*		2021	2022	*	*	*	*
							Int	Load	Reg	Comp
Model	Interpolation	Loadest	*		Cordillera.	Foothills				
	Interpolation	Regression	*		Cordillera	Mixed Ag.	*	*	*	*
	Interpolation	Composite	*		Cordillera	Agriculture	*	*	*	*
	Loadest	Regression	*		Foothills	Mixed Ag.				
	Loadest	Composite			Foothills	Agriculture				
	Regression	Composite	*		Mixed Ag.	Agriculture				

Table S7 Ratios of annual (water years 2019 – 2022) maximum to minimum runoff (from Table S2), total suspended solids (TSS) yield (from Table S4), and dissolved organic carbon (DOC) yield (from Table S5) for all tributaries and North Saskatchewan River (NSR) mainstem (emphasized) sites. C-cordillera; F-foothills; MA-mixed agriculture; A-agriculture.

Station	MAX:MIN Runoff	MAX:MIN TSS Yield	MAX:MIN DOC Yield
NSR at Whirlpool Pt. (C)	1	3	1
NSR at Saunders Camp.	1	1	1
Ram R. (C)	2	21	3
NSR u/s Clearwater R.	1	3	2
Clearwater R. (C)	2	34	3
Baptiste R. (F)	4	45	6
Nordegg R. (F)	3	235	6
Brazeau R. (C)	2	5	3
Rose Ck. (F)	10	280	15
Modeste Ck. (MA)	13	143	17
Tomahawk Ck. (MA)	57	437	94
Strawberry Ck. (A)	8	114	14
NSR at Devon	2	25	5
Whitemud Ck. (A)	10	32	16
Sturgeon R. (MA)	13	66	16
Redwater R. (A)	32	113	48
NSR at Pakan Bridge	2	55	6

Table S8 Linear mixed model results for dissolved organic carbon (DOC) for tributary stations of the North Saskatchewan River (NSR) basin. Fixed effects are landscape type, water year, and export model (see Methods). Comparisons (lower table) shown only for statistically significant models. *indicates statistically significant relationship at α=0.05. df-degrees of freedom. F-F statistic. C.I.-confidence interval.

Fixed effects	Numerator df	Denominator df	F	Significance
Intercept	1	3.316	3.770	0.139
Landscape	3	6.720	6.789	0.019*
Water Year	3	75,899	558.907	<0.001*
Model	3	75,899	31.307	<0.001*
Landscape * Water Year	9	75,899	45.153	<0.001*
Landscape * Model	9	75,899	7.338	<0.001*
Water Year * Model	9	75,899	0.794	0.621
Landscape * Water Year * Model	27	75,899	0.170	1.000

	Estimates	Mean	Standard Error	df	C.I. Lower	C.I. Upper
	Grand mean	-1.191	0.613	3.316	-3.042	0.660
Land-scape	Cordillera (C)	-0.454	0.645	3.820	-2.277	1.369
	Foothills (F)	-0.655	0.681	4.135	-2.523	1.212
	Mixed agriculture (MA)	-1.865	0.653	4.256	-3.636	-0.093
	Agriculture (A)	-1.790	0.642	4.338	-3.519	-0.061
Water year	2019	-0.906	0.613	3.319	-2.756	0.945
	2020	-0.968	0.613	3.319	-2.818	0.883
	2021	-1.553	0.613	3.319	-3.403	0.298
	2022	-1.337	0.613	3.319	-3.188	0.513
Model	Interpolation	-1.117	0.613	3.319	-2.967	0.734
	Loadest	-1.141	0.613	3.319	-2.992	0.709
	Regression	-1.246	0.613	3.319	-3.097	0.604
	Composite	-1.260	0.613	3.319	-3.111	0.590

							2019	2020	2021	2022
Landscape	Cordillera	Foothills			Cordillera.	Foothills				
	Cordillera	Mixed Ag.	*		Cordillera	Mixed Ag.			*	*
	Cordillera	Agriculture	*		Cordillera	Agriculture			*	*
	Foothills	Mixed Ag.			Foothills	Mixed Ag.			*	
	Foothills	Agriculture			Foothills	Agriculture			*	
	Mixed Ag.	Agriculture			Mixed Ag.	Agriculture				
							Int	Load	Reg	Comp
Water year	2019	2020	*		Cordillera.	Foothills				
	2019	2021	*		Cordillera	Mixed Ag.			*	*
	2019	2022	*		Cordillera	Agriculture		*	*	*
	2020	2021	*		Foothills	Mixed Ag.				
	2020	2022	*		Foothills	Agriculture				
	2021	2022	*		Mixed Ag.	Agriculture				
Model										
	Interpolation	Loadest								
	Interpolation	Regression	*							
	Interpolation	Composite	*							
	Loadest	Regression	*							
	Loadest	Composite	*							
	Regression	Composite								

Table S9 Export ± standard error of prediction of total suspended solids (TSS; ktonnes) from the North Saskatchewan River (NSR) mainstem (emphasized), its tributaries, and other mass balance terms (see Equation 1 from main manuscript) from 2019 to 2022 water years for each *Loadflex* export model.

	Station/Model	Interpolation	Regression	Loadest	Composite
Water year: 2019	NSR-W.Pt.	42±10	89±8	79±7	63±7
	Unmonitored	125±290	163±30	161±45	135±27
	Other (ΔS_{NSR})	-139±290	-226±31	-215±45	-174±28
	NSR-Saund.	28±2	26±2	25±2	24±3
	Ram	73±169	95±18	94±26	79±16
	Unmonitored	29±67	38±7	37±10	31±6
	Other (ΔS_{NSR})	-48±182	-48±34	-71±33	46±44
	NSR-Clear.	82±10	111±28	85±17	180±41
	Clearwater	50±169	72±16	65±18	65±15
	Baptiste	4±37	16±4	13±3	9±2
	Nordegg	6±5	43±28	10±3	28±14
	Brazeau	11±1	11±1	13±1	12±1
	Rose	6±33	38±15	21±8	20±10
	Modeste	9±97	20±4	25±5	17±5
	Tomahawk	2±1	2±1	1±0	2±1
	Strawberry	8±11	27±8	14±11	13±5
	Unmonitored	35±143	82±24	59±17	60±19
	Other (ΔS_{NSR})	443±674	650±167	931±252	334±111
	NSR-Devon	656±627	1071±159	1238±250	741±99
	Whitemud	10±3	24±7	18±4	13±3
	Sturgeon	12±3	14±35656	15±2	14±2
	Redwater	1±1	1±0	2±0	1±0
	Unmonitored	25±9	44±38067	38±7	32±7
	Other (ΔS_{NSR})	-89±1073	-67±52159	-230±308	175±216
	NSR-Pak.	614±870	1087±147	1081±180	976±192
Water year: 2020	NSR-W.Pt.	100±10	142±15	102±10	120±14
	Unmonitored	138±290	474±85	353±87	175±31
	Other (ΔS_{NSR})	-208±290	-586±87	-425±88	-265±34
	NSR-Saund.	31±3	30±2	29±2	29±3
	Ram	81±169	277±50	206±51	102±18
	Unmonitored	32±67	110±20	82±20	41±7
	Other (ΔS_{NSR})	-25±182	-55±687	-104±84	8±42
	NSR-Clear.	119±10	363±685	213±64	180±37
	Clearwater	87±169	286±60	155±39	186±36
	Baptiste	15±37	171±80	71±23	129±46
	Nordegg	4±5	397±705	24±11	302±198
	Brazeau	10±1	10±1	11±1	8±1
	Rose	60±33	569±283	149±59	276±140
	Modeste	198±97	394±129	265±74	192±64
	Tomahawk	3±1	6±1	2±0	4±1
	Strawberry	88±11	347±171	38±37	241±160
	Unmonitored	168±149	784±400	257±96	481±181
	Other (ΔS_{NSR})	4959±676	-421±1264	2938±1304	500±550
	NSR-Devon	5711±628	2905±579	4124±1294	2497±420
	Whitemud	11±3	72±34	39±11	43±15
	Sturgeon	25±3	55±12285	27±3	36±3
	Redwater	6±1	11±1	5±1	7±1
	Unmonitored	48±8	155±11515	81±14	97±20
	Other (ΔS_{NSR})	2011±1074	337±16857	1130±1842	-143±740
	NSR-Pak.	7813±871	3536±546	5407±1311	2538±609

Table S9 (continued) Export ± standard error of prediction of total suspended solids (TSS; ktonnes) from the North Saskatchewan River (NSR) mainstem (emphasized), its tributaries, and other mass balance terms (see Equation 1 from main manuscript) from 2019 to 2022 water years for each *Loadflex* export model.

	Stations	Interpolation	Regression	Loadest	Composite
Water year: 2021	NSR-W.Pt.	193±10	142±12	126±14	240±28
	Unmonitored	30±289	679±530	37±9	41±10
	Other (ΔS_{NSR})	-202±290	-792±530	-137±17	-262±30
	NSR-Saund.	21±2	29±2	27±2	19±2
	Ram	18±169	396±309	21±5	24±6
	Unmonitored	7±67	158±123	9±2	9±2
	Other (ΔS_{NSR})	28±182	-370±4242	14±10	15±9
	NSR-Clear.	73±10	212±4228	71±8	68±6
	Clearwater	14±169	1265±1307	20±5	19±3
	Baptiste	3±37	36±16	2±0	2±0
	Nordegg	1±5	4±1	1±0	1±0
	Brazeau	2±1	6±1	3±0	2±0
	Rose	2±33	68±35	1±0	1±0
	Modeste	3±97	42±12	1±0	2±1
	Tomahawk	0±1	0±0	0±0	0±0
	Strawberry	2±11	94±71	2±1	1±1
	Unmonitored	9±279	545±243	11±3	10±3
	Other (ΔS_{NSR})	41±715	-1358±4439	12±14	83±19
	NSR-Devon	150±627	915±221	123±9	188±17
	Whitemud	1±3	10±2	1±1	1±1
	Sturgeon	0±3	7±254292	1±0	0±0
	Redwater	0±1	1±0	0±0	0±0
	Unmonitored	2±13	20±249904	2±1	2±0
	Other (ΔS_{NSR})	-66±1073	-131±356534	-51±11	-94±20
	NSR-Pak.	87±870	821±177	76±5	97±11
Water year: 2022	NSR-W.Pt.	111±10	142±12	106±10	119±10
	Unmonitored	704±290	679±530	423±457	1283±973
	Other (ΔS_{NSR})	-785±290	-792±530	-502±457	-1377±973
	NSR-Saund.	31±2	29±2	28±2	25±4
	Ram	411±169	396±309	247±266	749±568
	Unmonitored	164±67	158±123	98±106	298±226
	Other (ΔS_{NSR})	-486±182	-370±4242	-226±302	-806±622
	NSR-Clear.	120±10	212±4228	146±94	266±118
	Clearwater	357±169	1265±1307	236±194	507±312
	Baptiste	58±37	36±16	20±7	37±15
	Nordegg	8±5	4±1	2±1	5±2
	Brazeau	4±1	6±1	6±1	4±0
	Rose	44±33	68±35	28±13	36±21
	Modeste	32±97	42±12	26±7	65±24
	Tomahawk	0±1	0±0	0±0	0±0
	Strawberry	31±11	94±71	13±15	65±76
	Unmonitored	192±247	545±243	120±53	259±126
	Other (ΔS_{NSR})	-440±703	-1358±4439	494±465	-644±385
	NSR-Devon	406±627	915±221	1092±408	599±120
	Whitemud	12±3	10±2	6±1	9±2
	Sturgeon	12±3	7±254292	4±1	9±1
	Redwater	3±1	1±0	1±0	2±1
	Unmonitored	30±8	20±249904	13±3	23±5
	Other (ΔS_{NSR})	881±1073	-131±356534	-169±516	238±252
	NSR-Pak.	1343±870	821±177	948±315	880±221

Table S10 Export ± standard error of prediction of dissolved organic carbon (DOC; ktonnes) from the North Saskatchewan River (NSR) mainstem (emphasized), its tributaries, and other mass balance terms (see Equation 1 from main manuscript) from 2019 to 2022 water years for each *Loadflex* export model.

	Stations	Interpolation	Regression	Loadest	Composite
Water year: 2019	NSR-W.Pt.	1±0	1±0	1±0	1±0
	Unmonitored	4±1	5±0	4±0	4±0
	Other (ΔS_{NSR})	-3±1	-3±0	-3±0	-3±0
	NSR-Saund.	3±0	2±0	2±0	3±0
	Ram	3±0	3±0	3±0	3±0
	Unmonitored	1±0	1±0	1±0	1±0
	Other (ΔS_{NSR})	-1±0	-1±0	-1±0	0±1
	NSR-Clear.	5±0	6±0	4±0	6±0
	Clearwater	2±0	2±0	2±0	2±0
	Baptiste	3±0	3±0	3±0	3±0
	Nordegg	3±0	3±0	3±0	3±0
	Brazeau	12±0	13±0	10±0	14±0
	Rose	2±0	2±0	2±0	2±0
	Modeste	2±0	2±0	2±0	3±0
	Tomahawk	1±0	1±12735	1±0	1±0
	Strawberry	1±0	1±0	1±0	1±0
	Unmonitored	10±1	10±12039	8±0	11±0
	Other (ΔS_{NSR})	-5±4	-3±17525	-3±2	-8±2
	NSR-Devon	36±4	41±2	32±2	38±2
	Whitemud	1±0	1±0	1±0	1±0
	Sturgeon	3±0	3±0	3±0	3±0
	Redwater	2±0	1±0	1±0	2±0
	Unmonitored	6±0	6±0	6±0	6±0
	Other (ΔS_{NSR})	-1±4	1±3	-2±3	1±3
	NSR-Pak.	46±2	53±2	41±2	51±2
Water year: 2020	NSR-W.Pt.	1±0	1±0	1±0	1±0
	Unmonitored	5±1	6±0	7±0	4±0
	Other (ΔS_{NSR})	-3±1	-4±0	-6±0	-2±0
	NSR-Saund.	3±0	3±0	3±0	3±0
	Ram	3±0	3±0	4±0	3±0
	Unmonitored	1±0	1±0	2±0	1±0
	Other (ΔS_{NSR})	-2±0	-1±1	-3±0	-2±0
	NSR-Clear.	5±0	6±1	6±0	5±0
	Clearwater	2±0	3±0	3±0	2±0
	Baptiste	4±0	5±0	6±0	5±0
	Nordegg	2±0	4±0	4±0	3±0
	Brazeau	10±0	8±0	9±0	9±0
	Rose	4±0	3±0	4±0	4±0
	Modeste	6±0	7±0	7±0	6±0
	Tomahawk	2±0	1±9094	1±0	1±0
	Strawberry	2±0	2±0	2±0	2±0
	Unmonitored	12±1	12±11681	13±1	12±1
	Other (ΔS_{NSR})	18±4	4±14803	-2±4	-3±4
	NSR-Devon	67±4	55±6	52±4	46±4
	Whitemud	2±0	1±0	1±0	2±0
	Sturgeon	5±0	5±0	5±0	5±0
	Redwater	6±0	4±0	4±0	5±0
	Unmonitored	14±0	12±0	11±0	13±0
	Other (ΔS_{NSR})	7±4	-2±6	3±6	3±5
	NSR-Pak.	101±2	76±3	76±4	75±3

Table S10 (continued) Export ± standard error of prediction of dissolved organic carbon (DOC; ktonnes) from the North Saskatchewan River (NSR) mainstem (emphasized), its tributaries, and other mass balance terms (see Equation 1 from main manuscript) from 2019 to 2022 water years for each *Loadflex* export model.

	Stations	Interpolation	Regression	Loadest	Composite
Water year: 2021	NSR-W.Pt.	1±0	1±0	1±0	1±0
	Unmonitored	2±1	2±0	2±0	2±0
	Other (ΔS_{NSR})	0±1	0±0	-1±0	-1±0
	NSR-Saund.	2±0	2±0	2±0	2±0
	Ram	1±0	1±0	1±0	1±0
	Unmonitored	0±0	0±0	0±0	0±0
	Other (ΔS_{NSR})	0±0	0±0	0±0	0±0
	NSR-Clear.	3±0	3±0	4±0	3±0
	Clearwater	1±0	1±0	1±0	1±0
	Baptiste	1±0	1±0	1±0	1±0
	Nordegg	1±0	1±0	1±0	1±0
	Brazeau	3±0	4±0	4±0	4±0
	Rose	0±0	0±0	0±0	0±0
	Modeste	0±0	0±0	0±0	0±0
	Tomahawk	0±0	0±1	0±0	0±0
	Strawberry	0±0	0±0	0±0	0±0
	Unmonitored	2±2	2±14	3±0	2±0
	Other (ΔS_{NSR})	-1±4	-2±14	0±1	-2±0
	NSR-Devon	11±4	11±0	15±1	10±0
	Whitemud	0±0	0±0	0±0	0±0
	Sturgeon	0±0	0±0	0±0	0±0
	Redwater	0±0	0±0	0±0	0±0
	Unmonitored	1±0	1±0	1±0	1±0
	Other (ΔS_{NSR})	2±4	3±0	1±1	1±1
	NSR-Pak.	13±2	15±0	17±0	13±0
Water year: 2022	NSR-W.Pt.	1±0	1±0	1±0	1±0
	Unmonitored	4±1	4±0	4±1	4±1
	Other (ΔS_{NSR})	-3±1	-3±0	-3±1	-2±1
	NSR-Saund.	2±0	2±0	2±0	2±0
	Ram	2±0	2±0	3±0	2±0
	Unmonitored	1±0	1±0	1±0	1±0
	Other (ΔS_{NSR})	-1±0	0±3	-1±1	0±1
	NSR-Clear.	5±0	5±3	5±0	5±1
	Clearwater	2±0	2±0	2±0	2±0
	Baptiste	2±0	2±0	2±0	2±0
	Nordegg	1±0	1±0	1±0	1±0
	Brazeau	5±0	5±0	6±0	5±0
	Rose	2±0	2±0	2±0	2±0
	Modeste	2±0	2±0	2±0	2±0
	Tomahawk	0±0	0±121	0±0	0±0
	Strawberry	1±0	1±0	1±0	1±0
	Unmonitored	5±1	5±428	6±0	5±0
	Other (ΔS_{NSR})	-4±4	-10±445	-1±2	-5±2
	NSR-Devon	20±4	14±1	25±2	20±2
	Whitemud	0±0	0±0	0±0	0±0
	Sturgeon	1±0	1±0	1±0	1±0
	Redwater	1±0	1±0	1±0	1±0
	Unmonitored	2±0	3±0	3±0	2±0
	Other (ΔS_{NSR})	0±4	3±1	0±3	0±2
	NSR-Pak.	25±2	22±1	31±2	25±1

Figures

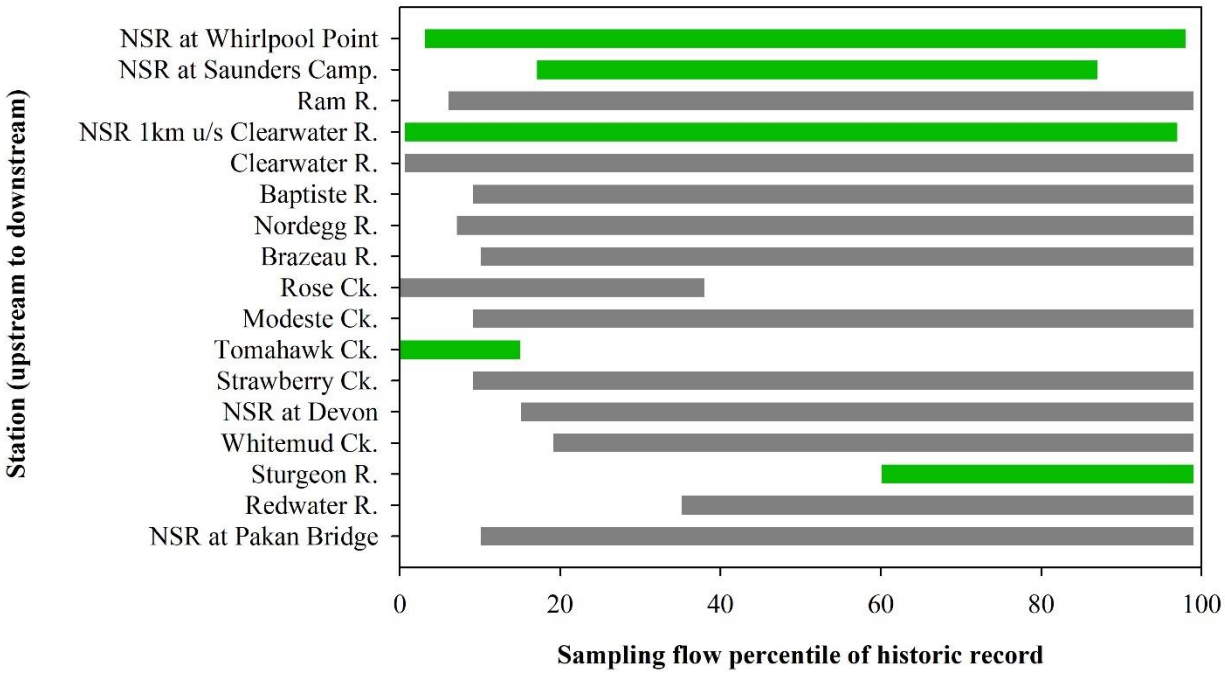

Figure S1 Ranges of flow percentiles for all tributary and major river stations between which water quality sampling occurred between 2019 to 2022 water years.

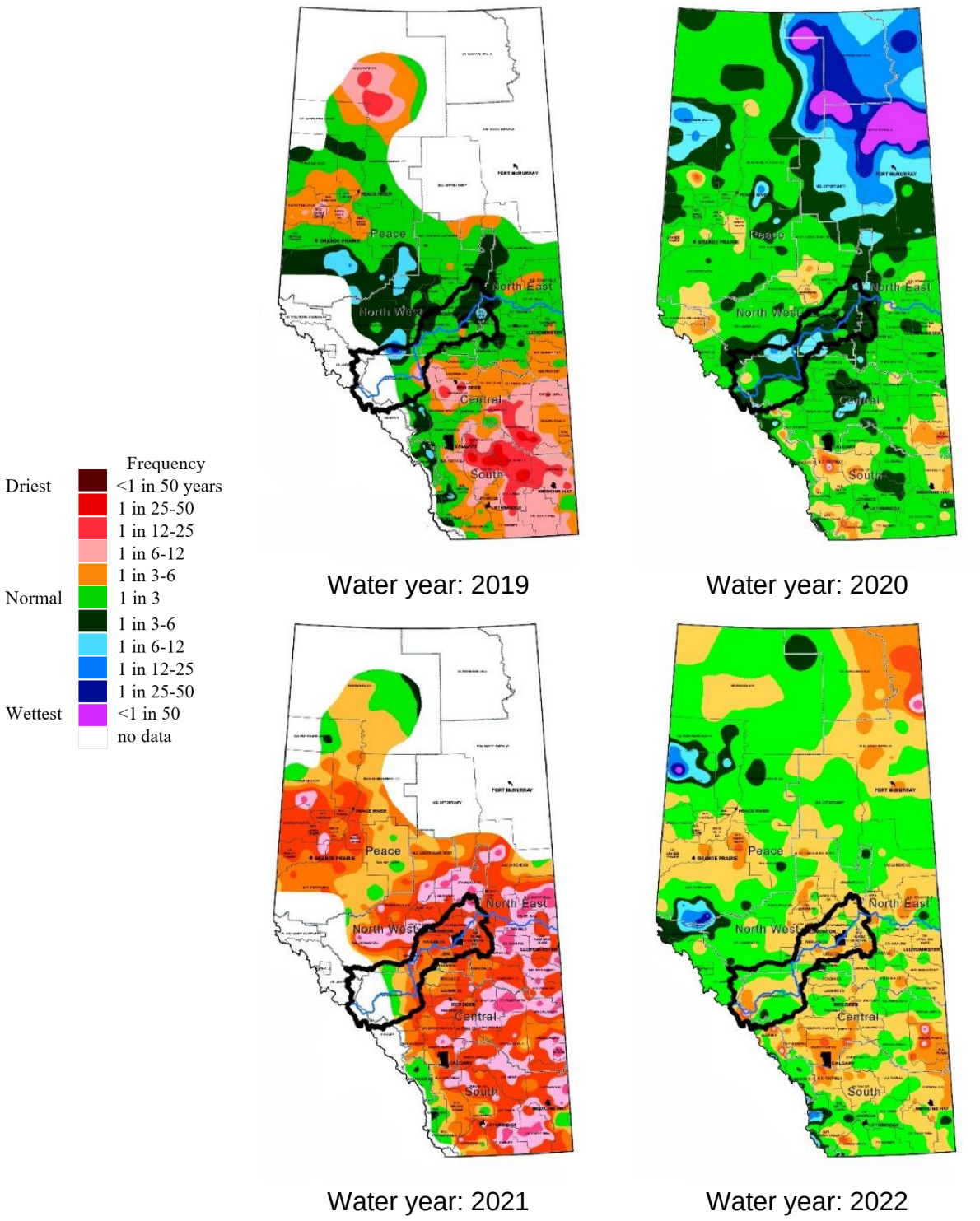

Figure S2 Precipitation accumulation relative to normal for the water years of 2019 to 2022 for Alberta. The North Saskatchewan River basin is outlined. Data provided by Agriculture and Irrigation, Alberta Climate Information Service (ACIS) https://acis.alberta.ca (data retrieved November 13, 2024).

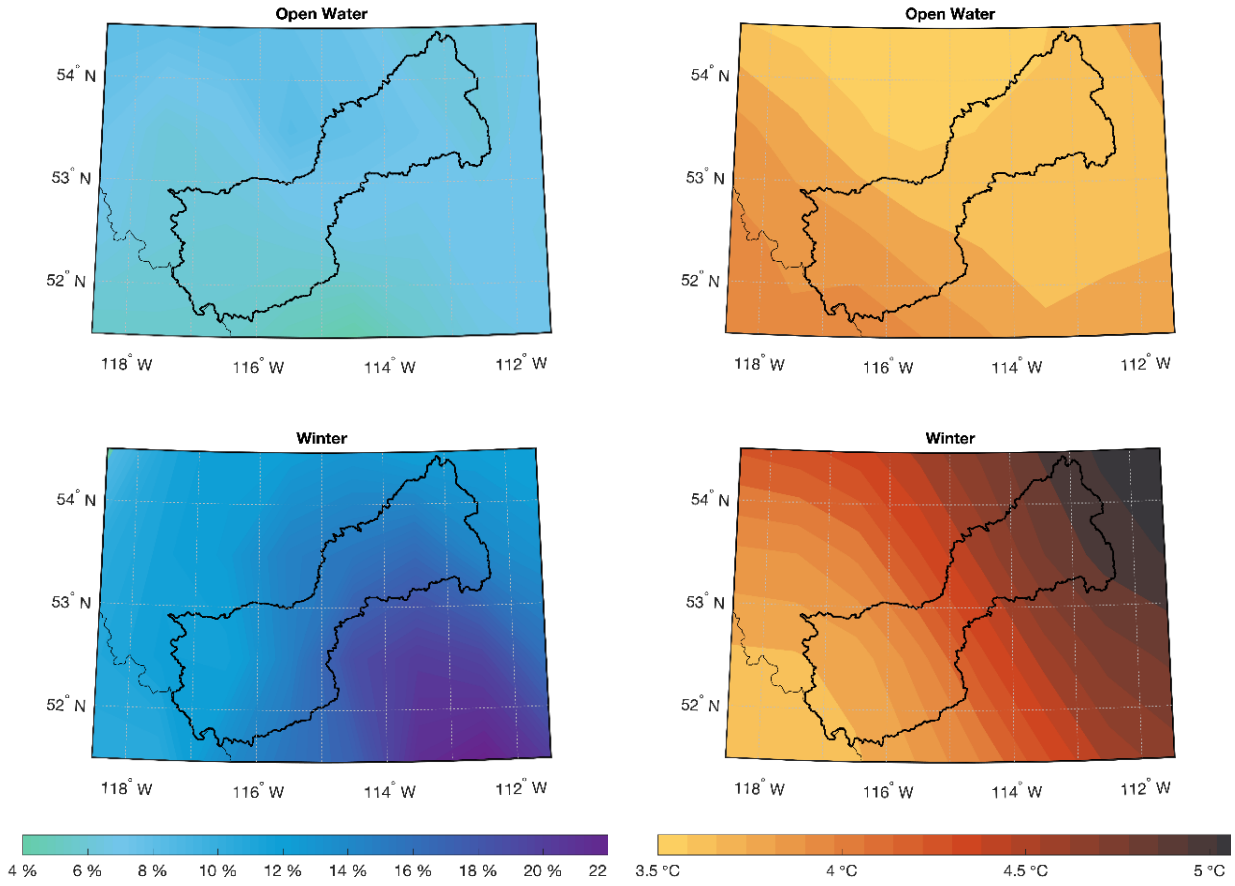

Figure S3 Projected 2061 to 2080 precipitation (as percent increase) and air temperature (as °C increase) relative to reference conditions (1986 to 2005) for the North Saskatchewan River basin from Canada's Changing Climate Report (Bush & Lemmen, 2019). Both open water (May to October) and winter (November to April) projections shown.