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

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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.

Flow station pairing on North Saskatchewan River mainstem

Though all tributary monitoring stations have flow and water quality monitoring paired in space, water quality stations on the North Saskatchewan River mainstem may be unpaired in space with flow monitoring stations. To estimate a flow record at these water quality stations, we first identified the closest flow station to each water quality station. If the flow station was upstream of the water quality station, then there would be a shortfall of flow at the water quality station if that record was used. Conversely, if the flow station was downstream of water quality monitoring, there would be too much flow at the water quality station if that record was used. We determined, via GIS, the catchment areas of the water quality and flow stations in both situations and quantified daily runoff yields from a nearby monitored tributary flow station. These yields were then multiplied by the difference in catchment area between the flow and water quality monitoring stations to quantify expected flow running off this land area. This flow was then either added to the flow station record (flow upstream of water quality) or subtracted from the flow station record (flow downstream of water quality) to quantify a paired flow record at the North Saskatchewan River mainstem water quality stations.

Sample quality control / quality assurance

Water quality collections included in this study are integrated within a broader, Alberta-wide quality control/quality assurance (QA/QC) program as summarized by

Laceby et al. (2022). The river QA/QC program includes collections of field blanks and duplicate samples as a proportion of all environmental samples collected (~100 rivers stations sampled 8-12 times per year, totalling nearly 2,000 samples over a five-year period). During that time, we collected nearly 350 field blanks from various trips across the province, including from trips that produced data for this assessment. From all trip field blank data, we found contamination frequency (i.e., field blanks with hits) of 4% for TSS and 13% for DOC. Contamination frequency is an important measure, but it also matters what concentrations these hits amount to relative to environmental data. If field blank hits result in blank concentrations much lower than environmental data, one would expect the environmental data to be little impacted by potential contamination. In our study, our rivers are relatively high in TSS (n=807; mean: 67.2 mg/L) versus the "typical" values of field blanks (B95-90 from Laceby 2022; mean: 1.3 mg/L). That amounts to ~2% potential contamination and a potential reduction down of mean concentrations from 67.2 mg/L to 66.2 mg/L. This error is very small compared to the substantial variability of TSS concentrations within a given year in a river, between years at a given river, and between rivers of a given landscape category (Figure 3 in manuscript). Combine that with the large variability in flow between years and rivers (i.e., influences yield/export), we further expect this field blank contamination to be inconsequential.

For DOC, our rivers are only moderately high in concentration (n=806; mean 8.9 mg/L) versus the "typical" values of field blanks (B95-90 from Laceby 2022; mean: 0.87 mg/L). This amounts to ~10% potential contamination added to samples and a potential reduction down of mean concentrations from 8.9 to 8.0 mg/L. Though we observed less variability between years and rivers for DOC compared to TSS, coefficients of variation for DOC concentrations collected from all stations was 26-94% (mean: 58%) compared to flow, which reported 32-256% coefficient of variability (mean: 143%). Therefore, we expect most of the variability in our loading and yield estimates (i.e., products of concentration and flow) to be driven by the changes in flow between years and between rivers of a given landscape category, rather than changes in DOC concentration. This gives us additional confidence that a potential contamination correction of 13% on a typical sample will not be important relative to flow changes and have even less impact on export and yield estimates.

Mass export models and uncertainty

Quantifying export of suspended and dissolved material of rivers presents challenges and can produce widely different estimate precisions (Aulenbach et al., 2016). The typical sampling strategy to quantify export in rivers is to periodically sample for water quality at the same location where high-frequency flow monitoring is occurring and producing average daily flow rates. Manual water sampling of many rivers across large areas, such is the case in the North Saskatchewan River basin, is a laborious and expensive effort typically leading to monthly or biweekly sampling. This approach means daily or sub-daily changes in flows and water quality, typically during fleeting storm events, can be missed. This leads to less data for models to draw from particularly when flows and water quality concentrations can be high together, with potential impacts on model precision. Aside from fullness of datasets, how one quantifies export can be performed differently (e.g., regression, interpolation, etc.) and can also impact uncertainty as well. *Loadflex* (Appling et al., 2015) uses four different modelling approaches to estimate export from rivers; each having advantages and disadvantages affecting the accuracy and precision of export estimates (Kamrath et al., 2023).

In our study, our typical accumulation of samples for a given river was between 30 and 50 over a four-year period, but with samples from a majority of flow conditions experienced historically in each river (Figure S1) and a sampling bias towards higher flow conditions with enhanced freshet monitoring. From this, we expect improved daily model precisions in *loadflex* but uncertainty around annual export (reported as standard error of prediction) was typically between 10 and 20% for each of our stations (Tables S9, S10). Indeed, there were some TSS or DOC-poor rivers that did not have strong concentration-discharge associations and therefore had much more severe uncertainties. This reduces our confidence in export calculations of individual river stations in any given year. However, we also observed that variability of export measured: 1. between years of a given river; 2. between rivers of a given landscape class; 3. between rivers of different landscape classes; and 4. between export models of a given river was often substantial beyond the uncertainty reported for any given river export value. We also observed the same export patterns between years, rivers, and landscapes regardless of the model used (Tables S9, S10), suggesting that uncertainty at the river station level was not impacting the interannual and inter-river yield and export patterns. Therefore, though there is notable uncertainty around the absolute values of export and yields in our rivers, the larger differences in export and yields driven by interannual changes in hydrometeorology and differences between landscapes appears to override this as demonstrated in Tables S9, S10 and our linear mixed model approach.

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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 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 2013 Wall-to-Wall Land Cover; [2]Alberta Biomonitoring Institute 2016 Wall-to-Wall Human Footprint Inventory; [3]lAlberta Geological Survey surficial geology 2015; [4]Government of Alberta Merged Wetland Inventory 2019; [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 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	0.0	-0.0	-0.0		-	-	-	-
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 sediment (TSS) and dissolved organic carbon (DOC) from the North Saskatchewan River (NSR) mainstem (emphasized) and its tributaries from 2019 to 2022 water years. r^2 is the coefficient of determination of the regression and Loadest models and statistical significance (α=0.05) of the model, as determined by the F-statistic, is denoted by an asterisk. C-cordillera; F-foothills; MA-mixed agriculture; A-agriculture.

	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± standard error of prediction of four *Loadflex* export models) of total suspended sediment (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 manuscript) and do not have catchment areas or yield 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		71±8	111±12	206±21	115±10		38±4	59±6	110±11	61±5
unmonitored land	3,219		148±37	264±86	38±10	692±493		46±12	82±27	12±3	215±153
Other (ΔS_{NSR})	-		-194±38	-345±87	-217±29	-788±494		-	-	-	-
NSR at Saunders Camp.	**5,089**		**25±2**	**30±2**	**24±2**	**28±2**		**5±0**	**6±0**	**5±0**	**6±0**
Ram R. (C)	1,878		86±22	154±50	22±6	403±288		46±12	82±17	12±3	215±153
unmonitored land	748		34±9	61±20	9±2	161±115		46±12	82±17	12±3	215±153
Other (ΔS_{NSR})	-		-48±39	-40±133	15±10	-428±462		-	-	-	-
NSR u/s Clearwater R.	**7,715**		**98±23**	**196±50**	**69±7**	**179±106**		**13±3**	**25±7**	**9±1**	**23±14**
Clearwater R. (C)	3,190		65±17	170±49	18±4	432±253		20±5	53±15	6±1	135±79
Baptiste R. (F)	1,350		11±4	100±42	2±0	37±16		8±3	74±31	1±0	27±12
Nordegg R. (F)	869		19±10	163±105	<1±0	5±2		22±11	187±120	1±0	5±2
Brazeau R. (C)	5,693		12±1	10±1	2±0	5±1		2±0	2±0	<1±0	1±0
Rose Ck. (F)	657		21±13	213±99	<1±0	40±27		31±19	324±151	1±0	61±41
Modeste Ck. (MA)	1,174		18±5	232±86	2±1	37±18		16±4	197±73	1±0	31±15
Tomahawk Ck. (MA)	190		2±1	3±1	<1±0	<1±0		12±3	18±4	<1±0	1±0
Strawberry Ck. (A)	591		14±9	165±98	2±1	48±43		23±16	279±166	3±2	81±73
unmonitored land	4,933		59±22	369±165	10±3	225±185		12±4	75±33	2±1	46±37
Other (ΔS_{NSR})	-		546±210	1,719±970	48±16	-542±584		-	-	-	-
NSR at Devon	**26,362**		**906±204**	**3,515±603**	**151±14**	**757±315**		**34±8**	**133±23**	**6±1**	**29±12**
Whitemud Ck. (A)	1,095		16±4	41±13	1±1	10±2		14±3	38±12	1±1	9±2
Sturgeon R. (MA)	3,390		14±3	32±3	1±1	8±2		4±1	9±1	<1±0	2±1
Redwater R. (A)	1,612		1±0	7±1	<1±0	2±0		1±0	4±1	<1±0	1±0
unmonitored land	6,874		35±8	89±17	2±7	21±6		5±1	13±2	<1±1	3±1
Other (ΔS_{NSR})	-		-78±691	734±1,458	-68±547	53±794		-	-	-	-
NSR at Pakan Bridge	**39,333**		**1,028±186**	**4,472±740**	**88±9**	**914±268**		**26±5**	**114±19**	**2±0**	**23±7**

Table S5 Export and yields (median± standard error of prediction 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 manuscript) and do not have catchment areas or yield 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	1±0	1±0	1±0	1±0	0.6±0.0	0.5±0.0	0.5±0.0	0.5±0.0
unmonitored land	3,219	4±0	5±0	2±0	4±1	1.4±0.1	1.6±0.1	0.5±0.0	1.2±0.2
Other (ΔS_{NSR})	-	-3±0	-3±0	-1±0	-3±1	-	-	-	-
NSR at Saunders Camp.	**5,089**	**3±0**	**3±0**	**2±0**	**2±0**	**0.5±0.0**	**0.6±0.0**	**0.4±0.0**	**0.4±0.0**
Ram R. (C)	1,878	3±0	3±0	1±0	2±0	1.4±0.1	1.6±0.1	0.5±0.0	1.2±0.2
unmonitored land	748	1±0	1±0	<1±0	1±0	1.4±0.1	1.6±0.1	0.5±0.0	1.2±0.2
Other (ΔS_{NSR})	-	-1±0	-2±0	~1±0	-1±1	-	-	-	-
NSR u/s Clearwater R.	**7,715**	**6±0**	**5±0**	**3±0**	**5±0**	**0.7±0.0**	**0.7±0.0**	**0.4±0.0**	**0.6±0.1**
Clearwater R. (C)	3,190	2±0	3±0	1±0	2±0	0.6±0.0	0.8±0.0	0.3±0.0	0.6±0.1
Baptiste R. (F)	1,350	3±0	5±0	1±0	2±0	2.2±0.1	3.5±0.2	0.6±0.0	1.4±0.1
Nordegg R. (F)	869	3±0	4±0	1±0	1±0	3.6±0.1	4.3±0.2	0.7±0.0	1.1±0.0
Brazeau R. (C)	5,693	13±0	9±0	4±0	5±0	2.0±0.1	1.6±0.0	0.6±0.0	0.9±0.0
Rose Ck. (F)	657	2±0	4±0	<1±0	2±0	3.6±0.1	5.6±0.2	0.4±0.0	2.7±0.1
Modeste Ck. (MA)	1,174	2±0	6±0	<1±0	2±0	2.0±0.1	5.5±0.2	0.3±0.0	1.6±0.1
Tomahawk Ck. (MA)	190	1±0	1±0	<1±0	<1±0	6.2±0.5	6.8±0.6	0.1±0.2	1.0±0.2
Strawberry Ck. (A)	591	1±0	2±0	<1±0	1±0	1.6±0.1	3.8±0.2	0.3±0.0	1.1±0.1
unmonitored land	4,933	10±1	12±1	2±1	5±0	2.0±0.1	2.4±0.1	0.5±0.2	1.0±0.1
Other (ΔS_{NSR})	-	-4±3	1±4	-1±2	-5±3	-	-	-	-
NSR at Devon	**26,362**	**37±2**	**54±4**	**11±0**	**20±2**	**1.4±0.1**	**2.0±0.2**	**0.4±0.0**	**0.8±0.1**
Whitemud Ck. (A)	1,095	1±0	2±0	<1±0	<1±0	0.9±0.0	1.5±0.1	0.1±0.0	0.3±0.0
Sturgeon R. (MA)	3,390	3±0	5±0	<1±0	1±0	0.9±0.0	1.4±0.0	0.1±0.0	0.3±0.0
Redwater R. (A)	1,612	1±0	5±0	<1±0	1±0	0.9±0.0	2.9±0.1	0.1±0.0	0.4±0.0
unmonitored land	6,874	6±0	13±0	1±0	2±0	0.9±0.0	1.8±0.1	0.1±0.0	0.4±0.0
Other (ΔS_{NSR})	-	~-1±3	3±5	2±1	<1±2	-	-	-	-
NSR at Pakan Bridge	**39,333**	**49±2**	**76±3**	**14±0**	**25±1**	**1.2±0.0**	**1.9±0.1**	**0.4±0.0**	**0.6±0.0**

Table S6 Linear mixed model results for total suspended sediment (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 or difference 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				
Water year							Int	Load	Reg	Comp
	2019	2020			2019	2020				
	2019	2021	*		2019	2021	*	*	*	*
	2019	2022	*		2019	2022	*	*	*	*
	2020	2021	*		2020	2021	*	*	*	*
	2020	2022	*		2020	2022	*	*	*	*
	2021	2022	*		2021	2022	*	*	*	*
Model							Int	Load	Reg	Comp
	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 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 or difference 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

Landscape							2019	2020	2021	2022
	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				
Water year							Int	Load	Reg	Comp
	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 S8 Export ± standard error of prediction of total suspended sediment (TSS; ktonnes) from the North Saskatchewan River (NSR) mainstem (emphasized), its tributaries, and other mass balance terms (see Equation 1 from 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 S8 (continued) Export ± standard error of prediction of total suspended sediment (TSS; ktonnes) from the North Saskatchewan River (NSR) mainstem (emphasized), its tributaries, and other mass balance terms (see Equation 1 from 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	220±28	126±14	240±28
	Unmonitored	30±289	39±7	37±9	41±10
	Other (ΔS_{NSR})	-202±290	-232±29	-137±17	-262±30
	NSR-Saund.	21±2	27±2	27±2	19±2
	Ram	18±169	23±4	21±5	24±6
	Unmonitored	7±67	9±2	9±2	9±2
	Other (ΔS_{NSR})	28±182	5±7	14±10	15±9
	NSR-Clear.	73±10	64±5	71±8	68±6
	Clearwater	14±169	16±3	20±5	19±3
	Baptiste	3±37	2±0	2±0	2±0
	Nordegg	1±5	1±0	1±0	1±0
	Brazeau	2±1	3±0	3±0	2±0
	Rose	2±33	0±0	1±0	1±0
	Modeste	3±97	1±0	1±0	2±1
	Tomahawk	0±1	0±0	0±0	0±0
	Strawberry	2±11	1±0	2±1	1±1
	Unmonitored	9±279	9±2	11±3	10±3
	Other (ΔS_{NSR})	41±715	55±12	12±14	83±19
	NSR-Devon	150±627	153±11	123±9	188±17
	Whitemud	1±3	2±1	1±1	1±1
	Sturgeon	0±3	1±19133	1±0	0±0
	Redwater	0±1	0±0	0±0	0±0
	Unmonitored	2±13	3±24679	2±1	2±0
	Other (ΔS_{NSR})	-66±1073	-69±31227	-51±11	-94±20
	NSR-Pak.	87±870	88±6	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 S9 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 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 S9 (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 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

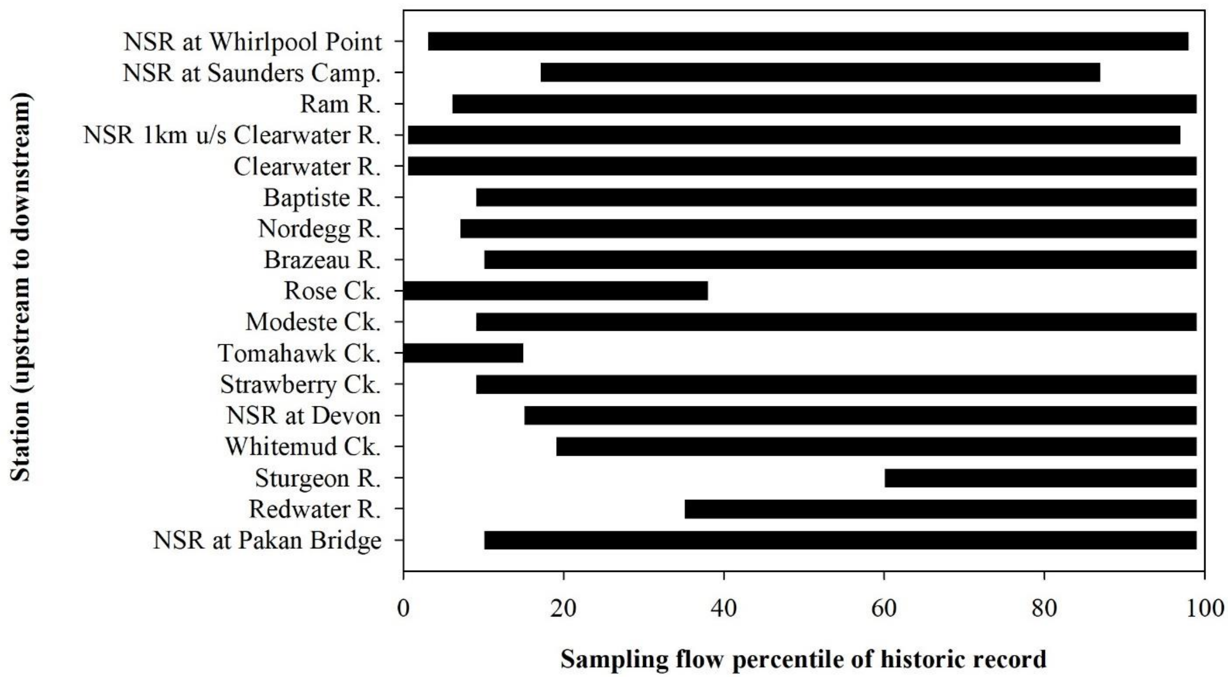

Figure S1 Range of flow conditions, as percentiles of the historic record, experienced during sample collection at each station between 2019 and 2022 water years.

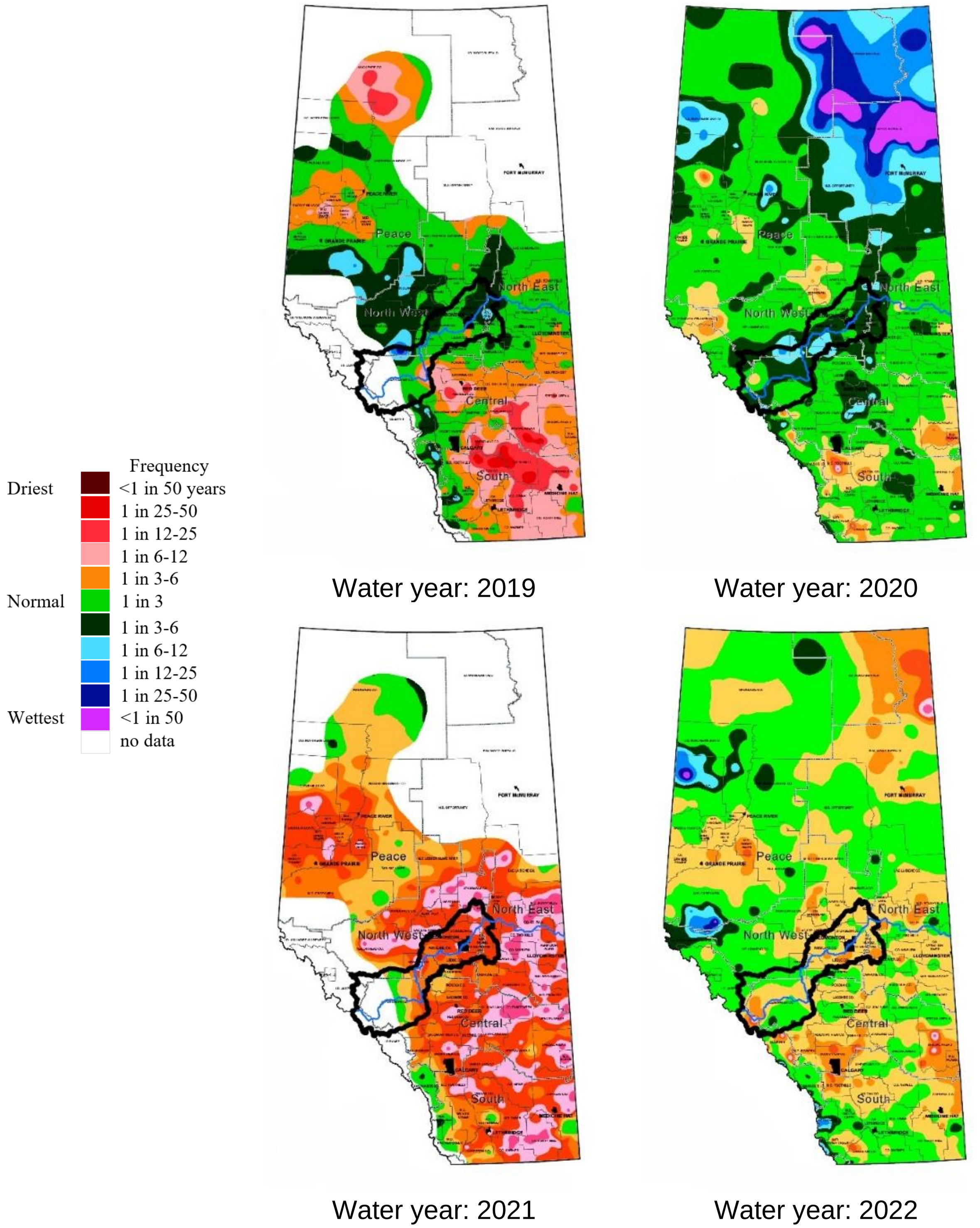

Figure S2 Precipitation accumulation relative to normal for the water years of 2019 to 2022 for Alberta. The North Saskatchewan River basin is outlined. Data provided by Agriculture and Irrigation, Alberta Climate Information Service (ACIS) https://acis.alberta.ca (data retrieved November 13, 2024).

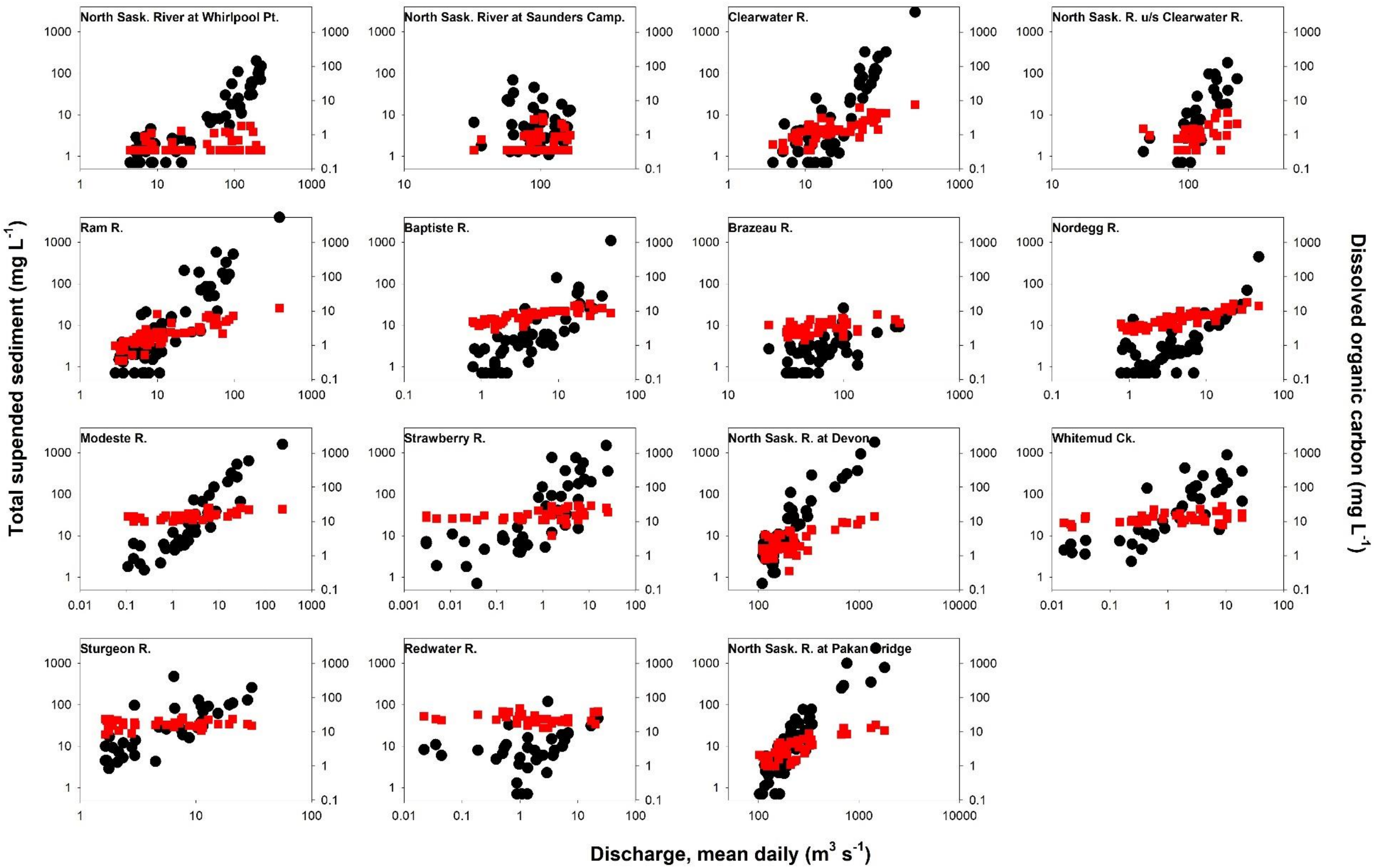

Figure S3 Concentration – discharge associations for total suspended sediment (black dots) and dissolved organic carbon (red squares) of monitored river stations from water years 2019 to 2022. Stations ordered upstream to downstream.

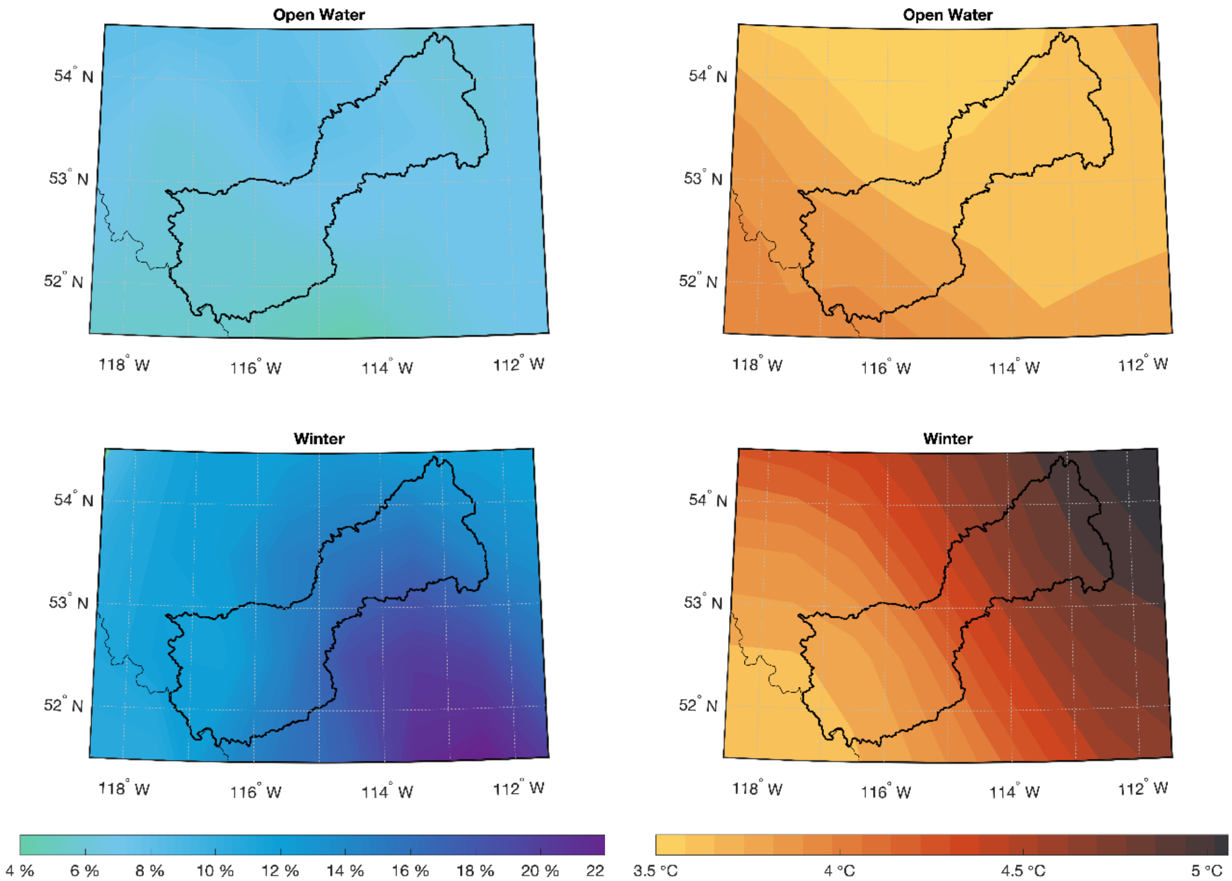

Figure S4 Projected 2061 to 2080 precipitation (as percent increase) and air temperature (as °C increase) relative to reference conditions (1986 to 2005) for the North Saskatchewan River basin from Canada's Changing Climate Report (Bush & Lemmen, 2019). Both open water (May to October) and winter (November to April) projections shown.