

Water quality response to river flow regime at three major rivers in Alberta

Sajjad Rostami, Jianxun He and Quazi K. Hassan

ABSTRACT

Both anthropogenic activities and natural factors affect river water in quantity and quality, while anthropogenic activities have been often blamed to cause water quality temporal degradation. In addition, riverine water quality displays intra-annual/seasonal variations, which are often more prominent than inter-annual variations. The intra-annual variations in water quality, which are attracting the attention of managers and policy-makers, beg the question of how to better manage riverine water quality at a finer time resolution. The natural factors, in particular, the hydro-meteorological variables, could be the primary drivers of the intra-annual variations of riverine water quality. Therefore, this paper examined the association between riverine water quality and one hydro-meteorological variable (flow) with the focus on their relationship at the intra-annual timescale on three selected rivers in Alberta, Canada. The results demonstrated that flow drives intra-annual variation of riverine water quality in general. Moreover, some water quality parameters responded to flow distinctively at three flow regimes (low, medium, and high flows). Water quality parameters were categorized into eight groups according to their responses to flow at the flow regimes. These implied the challenges in water quality management while providing insight into how to formulate more effective water management strategies.

Key words | cluster analysis, flow regimes, intra-annual variation, water quality management

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INTRODUCTION

Rivers, as important surface water resources, are susceptible to influences from anthropogenic activities in both quantity and quality. In the context of riverine water quality, anthropogenic activities alter non-point pollution sources (e.g., pollutants deposited on the land surface and washed off by stormwater runoff) and point pollution sources (e.g., treated municipal wastewater effluent) and, consequently, result in the variation of riverine water quality (Bowes *et al.* 2008). Conversely, natural factors including geographical and hydro-meteorological exposure of a river basin are also keys to riverine water quality variation temporally and spatially; however, their effects are commonly different from those of anthropogenic activities in many ways (Singh *et al.* 2004; Pejman *et al.* 2009) and even at different timescales. For instance, although anthropogenic pollution

(e.g., treated wastewater effluent released at a more or less constant rate during a year) often results in major river pollution problems, it does not primarily drive the intra-annual variation of riverine water quality (Singh *et al.* 2004). In contrast, water quality of surface runoff from urban and rural settings often shows intra-annual variations. Furthermore, the effects of anthropogenic activities could be controlled in many ways such as through reducing pollutant loading by improving treatment efficiency of wastewater treatment plants; whereas the natural variation of hydro-meteorological conditions are beyond human control (Malan *et al.* 2003; Nilsson & Renöfält 2008).

The anthropogenic and many natural factors affect river flow, which is linked with riverine water quality directly and/or indirectly (Nilsson & Renöfält 2008). At the

inter-annual timescale, urbanization and deforestation alter quantity as well as quality of stormwater runoff draining into water bodies (Chen & Chang 2014). Climate change largely alters watershed hydrologic cycle and, in turn, affects the transport of pollutants and surface water quality (Whitehead *et al.* 2009). Especially, increasing precipitation could potentially increase the loading of some pollutants into rivers; whereas lesser precipitation results in lower flow and, consequently, decreases the dilution capability of rivers (Prathumratana *et al.* 2008). At the intra-annual timescale, pollutants discharged into rivers from different sources vary with the variations in precipitation, snowmelt, and temperature change sequence in a year (Ouyang *et al.* 2006; Bu *et al.* 2010; Garizi *et al.* 2011), all of which are associated with river flow. Therefore, flow would primarily affect the contribution of various pollutant sources as well as the behavior of pollutants in watercourses (Nilsson & Renöfält 2008; Ocampo-Duque *et al.* 2013) at both timescales.

In water quality management, apparently, attention has been paid to attenuate or mitigate the degradation of riverine water quality over years. In practice, the threshold values for various water quality parameters of interest have been applied when managing water quality. The determination of such values often ignores the fact of varying water quality level due to the variations in pollutant sources and their relative contributions, and governing physical processes under varying hydro-meteorological conditions (Poole *et al.* 2004). As a result, water quality management based upon the thresholds, which are often formulated on the ground of ignoring the intra-annual variations of water quality, might fail (He *et al.* 2011; Hrdinka *et al.* 2012). To the present, several studies have explored feasible ways to attenuate pollution in water bodies considering flow dynamics. Nilsson & Renöfält (2008) and Yang *et al.* (2012) demonstrated that the enhancement of water quality can be achieved by controlling and modifying flow. In addition, Ng *et al.* (2006) proposed a program called the 'seasonal effluent discharge program' (SEDP), in which river dilution capacity is considered when releasing treated wastewater, to improve river water quality and lower the cost of wastewater treatment. All these advocate the importance of flow and call for the need to consider flow regimes when managing riverine water quality. Furthermore, it is not sufficient to consider the flow magnitude only to divide flow regimes,

as the governing mechanisms and thus water quality response to flow can be functions of flow regimes (He *et al.* 2011; He 2016). Therefore, an approach, in which water quality response to flow is taken into consideration, for flow regime division is necessary to promote the water quality management considering flow regimes.

Recently, there has been a trend that governments have started/attempted to consider the intra-annual variation nature of water quality when formulating water quality management guidelines. In the initiative, different management targets/thresholds are determined based on stratified water quality data according to the seasons and/or flow conditions (CCME 2003; Government of Alberta 2012). However, the water quality data grouping for the purpose appears to be quite arbitrary and lack statistical justification. Therefore, the objectives of this paper were to: (1) further understand the intra-annual variations of riverine water quality and its association with flow and (2) explore a simple but practically useful flow division approach and justify it through statistically analyzing the responses of various water quality parameters to flow. To fulfill the objectives, three rivers (Athabasca, Bow, and Oldman Rivers) in Alberta, Canada, were selected to conduct the study.

DESCRIPTION OF THE STUDY AREA

The province of Alberta is situated in western Canada. The west of Alberta is mountainous benefiting from warm chinook winds during winter time, while the eastern part is mostly flat, containing dry prairies. The north of Alberta has less frost-free days than the southern area with desert weather in summer and lack of rainfall. The central area is well known due to its oil sand industry while the majority of the land in the southern part is used for agriculture, especially grain and dairy farming. Alberta's climate varies considerably from south to north. Overall, Alberta has cold winters with the average daytime temperature of -10°C in the south and -24°C in the north, while average summer temperature is 13°C in the Rocky Mountains and 18°C from the dry prairie to the southeast. The average annual precipitation in Alberta varies from a low of below 350 mm in the southeast to more than 600 mm in the mountains.

Considering the availability of flow and water quality data, three rivers (the Athabasca, Bow, and Oldman Rivers), on which there are two or three long-term water quality monitoring stations, were selected from Alberta. Both the Athabasca and Bow Rivers originate from the Rocky Mountains while the Oldman River starts from a small lake near the mountains. The Athabasca River basin is situated mainly in central Alberta, approximately 95,300 km² in area, and 1,538 km in length; while the Bow and Oldman River basins, which are 26,200 and 28,000 km² in area, and 587 and 363 km in length, respectively, are situated in the south of Alberta. These three river basins are subject to anthropogenic activities including agriculture, industry, and/or urbanization to different degrees. The Athabasca River flows through the oil sands' region where the extraction of natural resources is extremely important for Canada as it supports the Canadian economy to a great extent; and such activities may potentially impact the water quality. The Bow River flows through the most populated community center, the city of Calgary, in Alberta; while in the Oldman River basin, forested and agriculture lands are dominant.

METHODS

Water quality and quantity data

Surface water quality has been monitored by both governmental and private sectors since the 1940s, while regular monitoring schemes were established during the 1950s and 1960s. The water quality data, which were measured once a month over the time period of 1988–2014 at the long-term water quality monitoring stations shown in Figure 1 on the three rivers, were used in this paper. The three water quality stations, AB05BH0010, AB05BM0010, and AB05BN0010, on the Bow River, and three water quality stations, AB05AB0070, AB05AD0010, and AB05AG0010, on the Oldman River, are located in the upstream, midstream, and downstream of the rivers, respectively. The two water quality stations, AB07BE0010 and AB07CC0030, are situated in the midstream and downstream of the Athabasca River. Note that this paper did not target any specific water quality parameters but rather investigated the water quality parameters

whose data are available. Eleven water quality parameters including chlorophyll-*a* (Chl-*a*), water temperature (WT), DO, turbidity (TURB), dissolved organic carbon (DOC), total phosphorus (TP), total nitrogen (TN), pH, chloride (Cl⁻), sulfate (SO₄²⁻), and specific conductance (SC) were included. The data sizes range from 178 to 323 and the non-detected data, which are no more than 20% for each parameter, were replaced by half of the detection limits (Field 2011).

Daily flow data were collected from the Water Survey of Canada, which monitors river flow across Canada. The flow gauge stations used are in close proximity to the water quality stations on the rivers. Two flow gauge stations (07BE001 and 07DA001) on the Athabasca River, three gauge stations (05BH008, 05BM002, and 05BN012) on the Bow River, and three gauge stations (05AA024, 05AD007, and 05AG006) on the Oldman River are also shown in Figure 1. Note that flows on water quality sampling dates were extracted from the daily flow datasets and used in this paper.

Statistical analysis

Since water quality data are often not normally distributed because of intra-annual variation as well as the existence of outliers and non-detected data (Rravichandran 2003; Singh et al. 2004; Tabari et al. 2011; Li et al. 2014), non-parametric statistical analyses were adopted. To investigate the intra-annual variations of both flow and water quality, the Kruskal-Wallis (KW) test was applied to identify if a significant difference exists among the medians of each dataset grouped by months. As river flow often varies greatly in magnitude, flow was divided into three regimes, namely, low, medium, and high flow regimes, based upon its magnitude, to investigate the water quality response to flow. The approach of the flow division is provided in the following section. To identify the dependence of water quality on flow, the Spearman correlation coefficient between water quality concentration and flow was calculated in different flow regimes.

In addition, cluster analysis (CA) was employed to categorize the water quality parameters according to their response to flow in different flow regimes. CA is a statistical technique to classify datasets based on their similarities without any prior assumptions and supervision. Among various clustering algorithms, hierarchical clustering has been commonly employed to analyze water quality data

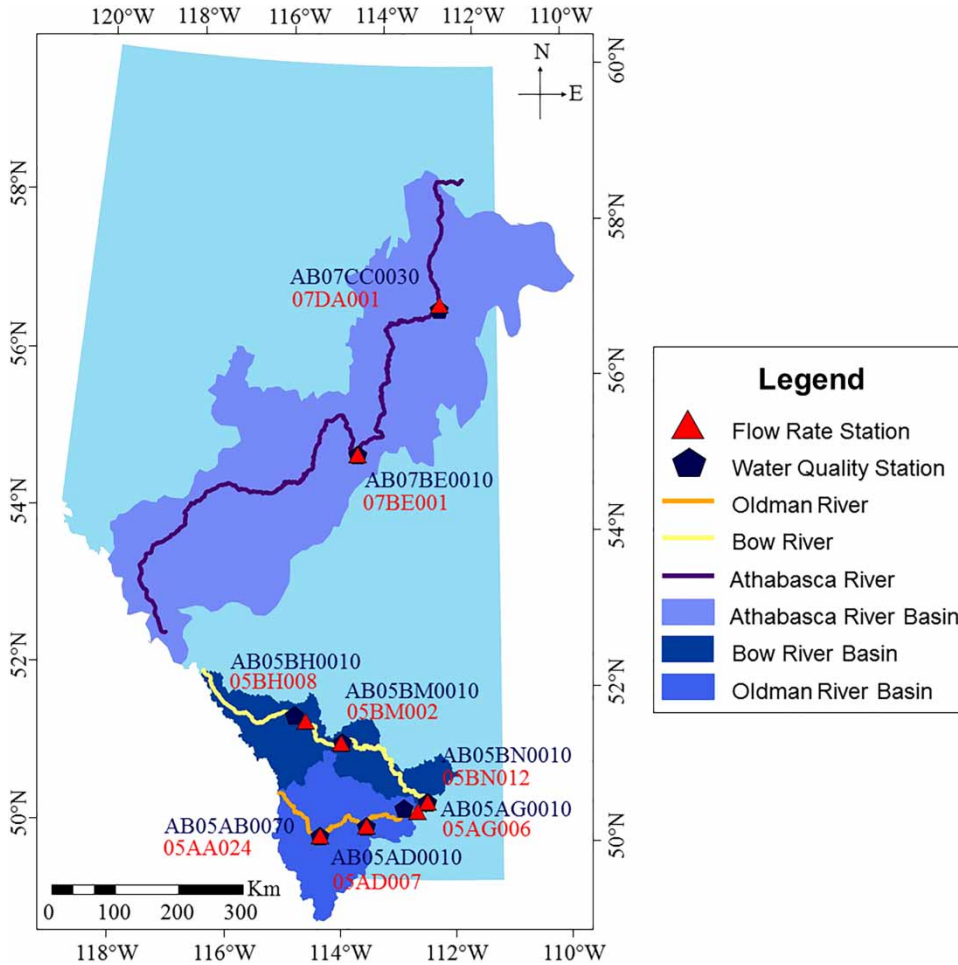


Figure 1 | The study area, water quality, and flow monitoring stations on the three studied rivers in Alberta.

(Bu *et al.* 2010; Juahir *et al.* 2011; Jung *et al.* 2016). In the analysis, the inputs to CA, which are the calculated Spearman correlation coefficients of flow and water quality in the three flow regimes, were grouped using the Euclidean distance. All the analyses in the paper were conducted using MATLAB, and the KW test and the correlation analysis were performed at a significance level of 5%.

RESULTS AND DISCUSSION

Intra-annual variations of flow and water quality

As expected, a significant intra-annual variation of flow was detected at all flow gauge stations (except the midstream

gauge station on the Bow River) on these three rivers in the KW test. Figure 2 displays the intra-annual variation of daily flow at the most downstream flow gauge stations, 07DA001, 05BN012, and 05AG006 of the Athabasca, Bow, and Oldman Rivers, respectively, as examples. A similar intra-annual variation pattern of flow was observed on these rivers. In general, flow in the rivers remains low in winter months, especially from November to March, and then starts increasing until peaking in June or July during the rainy season. Flow then gradually decreases after its peak until November. The average daily flows from upstream to downstream stations are 396 and 574 m³/s on the Athabasca River, 88, 136, and 93 m³/s on the Bow River, and 38, 71, and 76 m³/s on the Oldman River. The decrease of the average flow from midstream to downstream

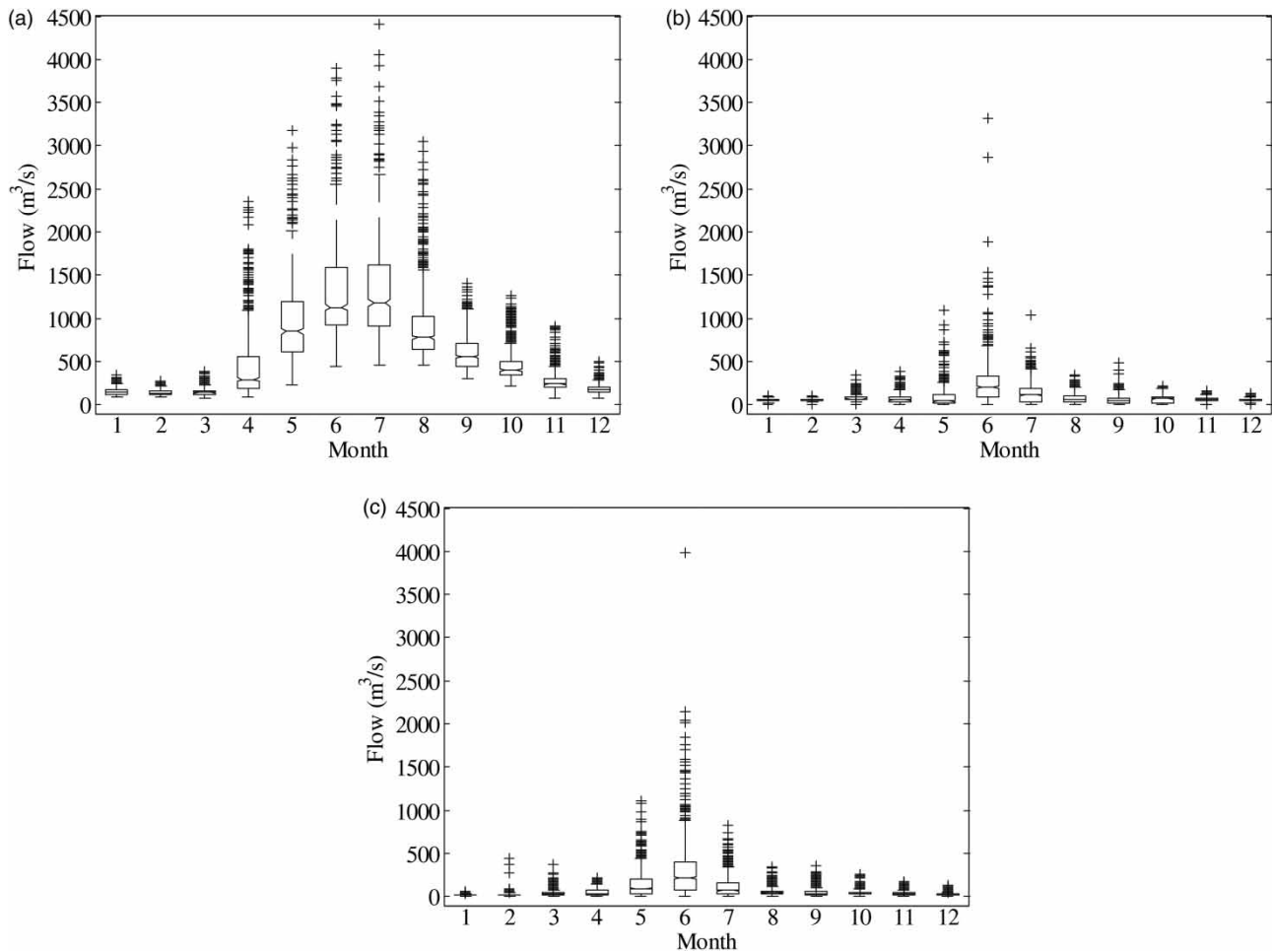


Figure 2 | Box and whisker plots of flow at (a) 07DA001 on the Athabasca River, (b) 05BN012 on the Bow River, and (c) 05AG006 on the Oldman River.

stations on the Bow River could be ascribed to the water withdrawal from the downstream river reach for agricultural irrigation.

Similar to flow, statistically significant intra-annual variations were detected in all water quality parameters at all water quality stations except Chl-*a* and pH at the upstream water quality station on the Oldman River. The box and whisker plots in Figure 3 display the intra-annual variations of three selected water quality parameters including TP, Cl^- , and TN at the selected stations (corresponding to the selected flow gauge stations in Figure 2) on the rivers as examples. Although these water quality parameters demonstrate different intra-annual variation patterns, they appear to be associated with the intra-annual variation of flow in different ways.

Concentrations of some water quality parameters such as TP (Figure 3(a)) and TURB, which are associated with sediments and particulate matters, have a similar intra-annual variation as flow. In many surface water bodies, most TP was often found to attach to sediments (Neal *et al.* 2000; Brett *et al.* 2005). Concentrations of these water quality parameters are high when flow is high, especially from May to July, and vice versa. This suggests that high flow mobilizes sediments deposited in waterway and surface runoff also mobilizes and transports pollutants accumulated on land surface into water bodies. In contrast, the intra-annual variation pattern of dissolved water quality parameters including Cl^- (Figure 3(b)), SO_4^{2-} , and SC (a surrogate measure of dissolved solids), in general, appears to be opposite to that of flow. Namely, their low concentrations

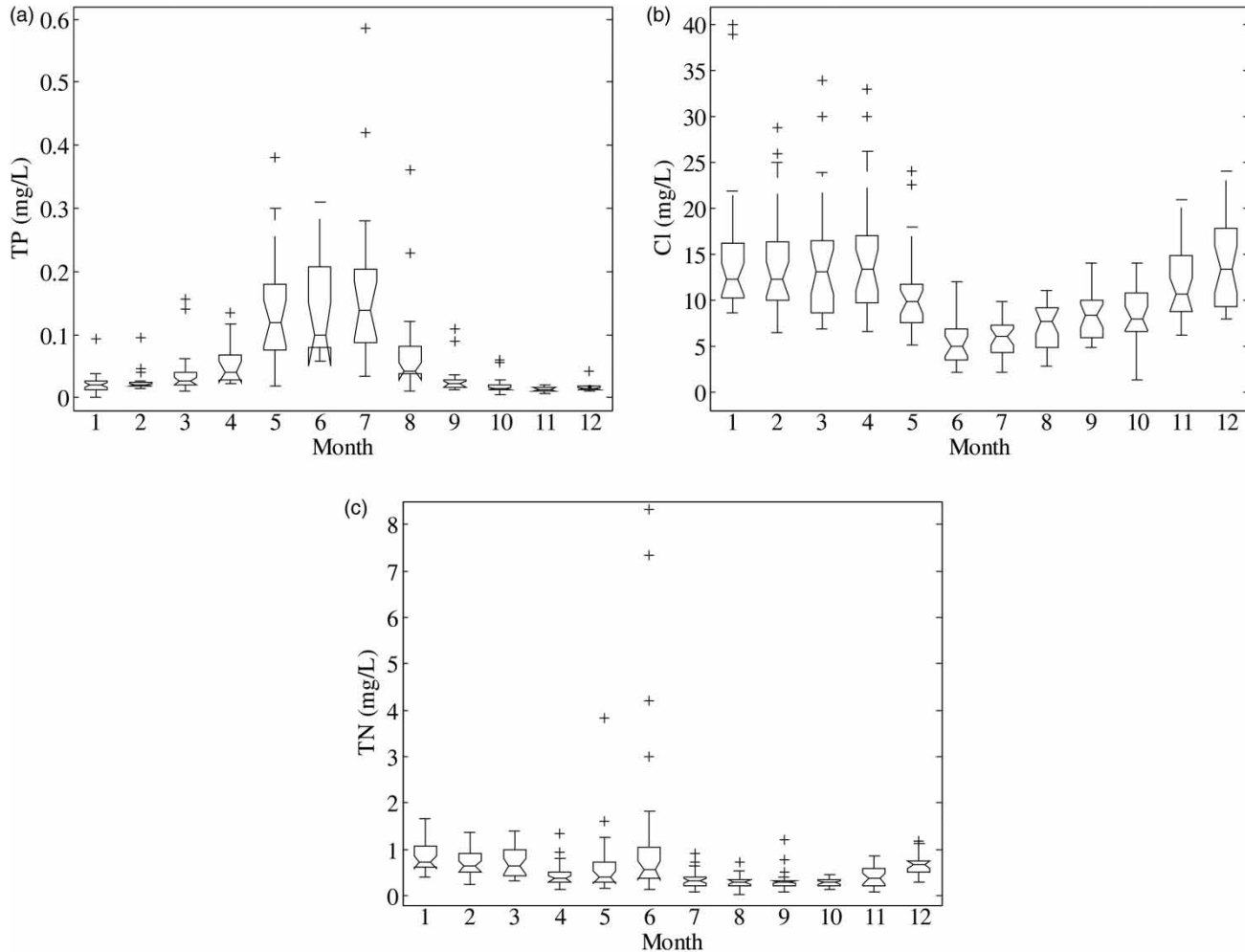


Figure 3 | Box and whisker plots of (a) TP at AB07CC0030 on the Athabasca River, (b) Cl⁻ at AB05BN0010 on the Bow River, and (c) TN at AB05AG0010 on the Oldman River.

are often observed in late spring and summer when flows are relatively high; whereas their high concentrations are often measured during late fall and winter when flows are low. This suggests that high flow might dilute these pollutants while low flow leads to their elevated concentrations.

The intra-annual variation of TN as shown in Figure 3(c) appears to be more complex compared to those aforementioned water quality parameters. Furthermore, obvious differences in the intra-annual variation of TN were observed among the rivers, and high TN concentrations were observed in both low and high flow conditions on the rivers (data not shown). In general, relatively high TN concentrations were observed in May while low

concentrations were measured in October on the Athabasca River. On the Bow and Oldman Rivers, TN concentration peaked during June except at the midstream and downstream stations of the Bow River, where the peak of TN concentration occurred in late fall and early winter, respectively, and low TN levels were measured in July/August. All the observations indicate that the role of flow on TN is not as apparent as its roles on the other water quality parameters. TN measures the sum of various species of nitrogen existing in both dissolved and particulate forms in water bodies. As flow affects the concentrations of dissolved and particulate pollutants differently, the intra-annual variation of such pollutants (like TN) would be a function of composition and sources of TN besides flow. Therefore, a

further study on the intra-annual variation of different nitrogen species is recommended.

The intra-annual variation of other water quality parameters such as Chl-*a*, DOC, and DO (data not shown) appears to be independent from flow. The results are consistent with the concept that these water quality parameters are more associated with aquatic plants in water bodies directly or indirectly, although their masses might be affected by flow (He *et al.* 2011) and many other factors (e.g., nutrient contents) (Shrestha & Kazama 2007; Nilsson & Renöfält 2008). WT (data not shown) has a similar intra-annual variation pattern as flow, but its peak is observed between July and September after the flow peak. It is well acknowledged that meteorological conditions primarily drive WT variation. Similarly, pH (data not shown) can be affected by many factors, e.g., biological activities and chemical composition of point and non-point pollution sources, which makes its variation complex. Therefore, the links between these water quality parameters and flow are not very apparent.

Dependence of riverine water quality on flow in different flow regimes

On these rivers, groundwater recharge is the primary water source to sustain the constant low flow (base-flow), during winters in the absence of surface runoff, and snow and ice melting. During the snow-melt and rainy seasons which correspond to relatively high flows observed on the rivers, surface runoff is believed to drive the increase of flow in a year. Different water sources fed into the rivers imply that different pollution sources and physical mechanisms could govern/control water quality level in rivers in different seasons (Garizi *et al.* 2011). Considering these, the dependence of riverine water quality in different flow regimes was examined. In this paper, three flow regimes (low, medium, and high flows) were divided according to flow magnitude. The determination of the cut-off values for dividing flow regimes was conducted through observing hydrographs and scatter plots between water quality and flow, and experimentally running CA for water quality parameter group. Basically, the low flow cut-off should be close to the flow magnitude before the prominent increase in early spring. The medium flow cut-off was determined using the ratio of 1.4 defined

as below:

$$\frac{\text{Peak flow} - \text{Medium flow cut-off}}{\text{Medium flow cut-off} - \text{Low flow cut-off}} = 1.4$$

The low, medium, and high flow regimes were defined as below the low flow cut-off, between the low and medium flow cut-offs, and above the medium flow cut-off, respectively. Figure 4 displays the average hydrograph of daily average flow over the study period and the flow cut-offs determined at the upstream station (05AA024) on the Oldman River, as an example. The calculated Spearman correlation coefficients of water quality parameters and flow in the low, medium, and high flow regimes are reported in Tables 1–3 for the Athabasca, Bow, and Oldman Rivers, respectively.

As illustrated in Tables 1–3, several water quality parameters were found to be dependent on flow consistently in different flow regimes at several locations. For instance, SO_4^{2-} is significantly negatively correlated with flow in all three flow regimes at AB05BH0010 on the Bow River. TURB is, in general, significantly positively correlated with flow in all flow regimes at the stations on the Athabasca and Oldman Rivers; however, the degree of the dependency appears to vary among different flow regimes. In contrast, significant but opposite dependency between some water quality parameters and flow was observed in the three

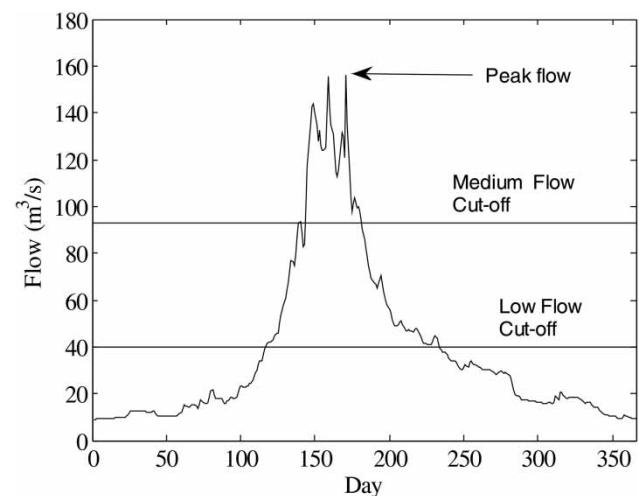


Figure 4 | The average hydrograph of daily average flow over the study period (1988–2014) and the determined flow cut-off values at the upstream station (05AA024) on the Oldman River.

Table 1 | Spearman correlation coefficients between water quality and flow in low flow (LF), medium flow (MF), and high flow (HF) regimes, respectively, on the Athabasca River

Station Flow regime	At Athabasca Town (AB07BE0010)			Fort McMurray 100 m above the confluence with Horse River (AB07CC0030)		
	LF (150)	MF (97)	HF (69)	LF (95)	MF (75)	HF (58)
Chl- <i>a</i>	0.509	0.192	– 0.317	0.336	0.712	– 0.535
WT	0.266	0.542	–0.151	0.087	0.666	–0.039
DO	0.517	– 0.568	–0.009	0.335	– 0.682	0.049
TURB	0.565	0.563	0.636	0.268	0.617	0.576
DOC	0.064	0.145	0.346	0.264	–0.009	0.386
TP	– 0.187	0.443	0.601	–0.007	0.501	0.691
TN	– 0.238	0.082	0.528	–0.171	0.131	0.552
pH	0.350	– 0.207	– 0.477	0.284	0.202	– 0.387
Cl [–]	– 0.549	– 0.225	0.025	– 0.604	– 0.617	– 0.281
SO ₄ ^{2–}	– 0.721	– 0.579	– 0.454	– 0.576	– 0.570	– 0.269
SC	– 0.778	– 0.667	– 0.500	– 0.616	– 0.800	– 0.505

Significant correlation coefficients are in boldface and numbers in parentheses are sample sizes.

Table 2 | Spearman correlation coefficients between water quality and flow in low flow (LF), medium flow (MF), and high flow (HF) regimes, respectively, on the Bow River

Station Flow regime	Bow R. at Cochrane (AB05BH0010)			Bow R. below Carseland dam (AB05BM0010)			Bow R. near Ronalane bridge (AB05BN0010)		
	LF (171)	MF (66)	HF (48)	LF (84)	MF (61)	HF (24)	LF (239)	MF (64)	HF (20)
Chl- <i>a</i>	0.130	–0.182	– 0.340	0.033	0.131	–0.106	0.024	0.342	–0.378
WT	0.307	0.534	– 0.316	– 0.247	–0.024	–0.374	– 0.260	0.328	–0.005
DO	– 0.220	– 0.445	0.367	0.160	–0.008	0.563	0.264	– 0.450	0.054
TURB	0.032	0.181	0.527	0.065	–0.170	– 0.508	0.309	0.275	0.466
DOC	0.150	0.118	0.277	0.041	–0.132	0.008	– 0.232	0.183	0.155
TP	–0.085	0.039	0.459	0.047	–0.167	–0.243	0.152	0.301	0.312
TN	–0.030	0.066	0.282	0.081	–0.148	0.127	0.271	– 0.292	0.139
pH	0.239	–0.166	–0.187	0.053	–0.052	–0.030	– 0.253	0.218	–0.350
Cl [–]	0.053	–0.176	0.161	0.018	–0.170	0.336	0.054	– 0.459	–0.442
SO ₄ ^{2–}	– 0.211	– 0.497	– 0.310	0.054	–0.075	0.197	– 0.420	– 0.323	–0.243
SC	–0.124	– 0.511	–0.089	0.074	0.009	0.348	–0.039	– 0.348	–0.405

Significant correlation coefficients are in boldface and numbers in parentheses are sample sizes.

flow regimes. For example, TP at AB07BE0010 on the Athabasca River and TN at AB05AD0010 and AB05AG0010 on the Oldman River are significantly negatively correlated with flow in the low flow regime; whereas they are significantly positively dependent on flow in both the medium and high flow regimes. TN at AB05BN0010 on the Bow River is significantly positively correlated with flow in the low flow regime; whereas it is significantly negatively

dependent on flow in the medium flow regime. All these results demonstrate that the dependency and/or the degree of dependency of water quality on flow varies among flow regimes, which might be ascribed to different pollution sources and/or physical processes governing water quality in the rivers under different flow regimes.

Among these investigated water quality parameters, the concentrations of the water quality parameters that are

Table 3 | Spearman correlation coefficients between water quality and flow in low flow (LF), medium flow (MF), and high flow (HF) regimes, respectively, on the Oldman River

Station flow regime	Near Brocket (AB05AB0070)			Above Lethbridge at highway 3 (AB05AD0010)			At highway 36 bridge north of Taber (AB05AG0010)		
	LF (141)	MF (47)	HF (15)	LF (221)	MF (77)	HF (24)	LF (238)	MF (63)	HF (23)
Chl- <i>a</i>	-0.216	-0.230	0.000	0.317	0.404	0.186	0.131	0.309	0.155
WT	0.731	-0.278	0.129	0.298	0.099	-0.380	0.408	-0.229	-0.426
DO	-0.683	0.022	0.298	-0.217	-0.220	0.203	-0.308	-0.218	0.286
TURB	0.423	-0.058	0.543	0.404	0.596	0.548	0.511	0.534	0.716
DOC	0.440	0.185	0.110	0.392	0.128	0.245	0.362	-0.053	0.145
TP	0.250	0.207	0.564	0.187	0.611	0.558	0.003	0.350	0.612
TN	0.066	0.237	0.398	-0.248	0.336	0.432	-0.404	0.418	0.454
pH	-0.113	-0.525	0.157	0.303	-0.076	-0.421	0.371	-0.322	-0.427
Cl ⁻	-0.269	0.020	0.358	-0.053	-0.275	0.351	-0.550	-0.419	0.059
SO ₄ ²⁻	-0.636	-0.016	-0.393	-0.364	-0.360	0.023	-0.350	-0.279	0.139
SC	-0.534	0.039	-0.500	-0.222	-0.207	-0.222	-0.381	-0.122	-0.175

Significant correlation coefficients are in boldface and numbers in parentheses are sample sizes.

associated with particulate solids, e.g., TURB and TP, in general, show an increase with the increase of flow; furthermore, their dependency on flow is stronger in the medium/high flow regimes than that in the low flow regime. Thus, it is certain that non-point source pollutants washed off by surface runoff can be ascribed to the primary cause of elevated TURB and TP levels in the medium/high flow regimes (Malan & Day 2002). It should be noted that pollutant resuspension from river beds can also contribute to the elevated levels of TURB and TP (Baen 2013). In contrast, dissolved pollutants (e.g., Cl⁻ and SO₄²⁻) and SC generally decrease with the increase of flow, which is the result of dilution of relative constant loading from either point and/or non-point source pollution (Bouza-Deaño et al. 2008). TN appears to generally increase with flow in the medium/high flow regimes whereas it decreases with the increase of flow in the low flow regime. These results might be explained by the fact that the dilution effect of flow on TN is predominant in the low flow regime, while the increase of flow can mobilize/transport more TN into rivers in the medium/high flow regimes. Note that the responses of the above-mentioned water quality parameters to flow at the stations on the Bow River, especially AB05BH0010 (upstream station) and AB05BM0010 (mid-stream station), appear to largely deviate from the general patterns observed on the Athabasca and Oldman Rivers.

The Bow River watershed upstream of the midstream station AB05BM0010 is heavily affected by anthropogenic activities as the most populated community center, the city of Calgary, is situated there. It is not surprising that consistent dependency on flow was not observed for water quality parameters including Chl-*a*, DOC, DO, pH, and WT.

Categorization of water quality response to flow

As mentioned above, the water quality parameters, in general, respond to flow qualitatively and/or quantitatively differently. The CA categorized these water quality parameters into a total of eight groups based on their quantitative response to flow (namely, the Spearman correlation coefficient between water quality parameters and flow). A schematic diagram (Figure 5) shows the variation patterns of the water quality parameters with flow in the form of the concentration-flow curve for the eight groups. Table 4 provides the list of the water quality parameters falling in the groups at all water quality monitoring stations on the Athabasca, Bow, and Oldman Rivers.

As illustrated in Figure 5, Group 1 shows the overall increase of water quality concentrations with flow in all three flow regimes; while in contrast, Group 2 demonstrates the decreasing pattern with the increase of flow, in general. The water quality parameters in Groups 3–7 also depend on

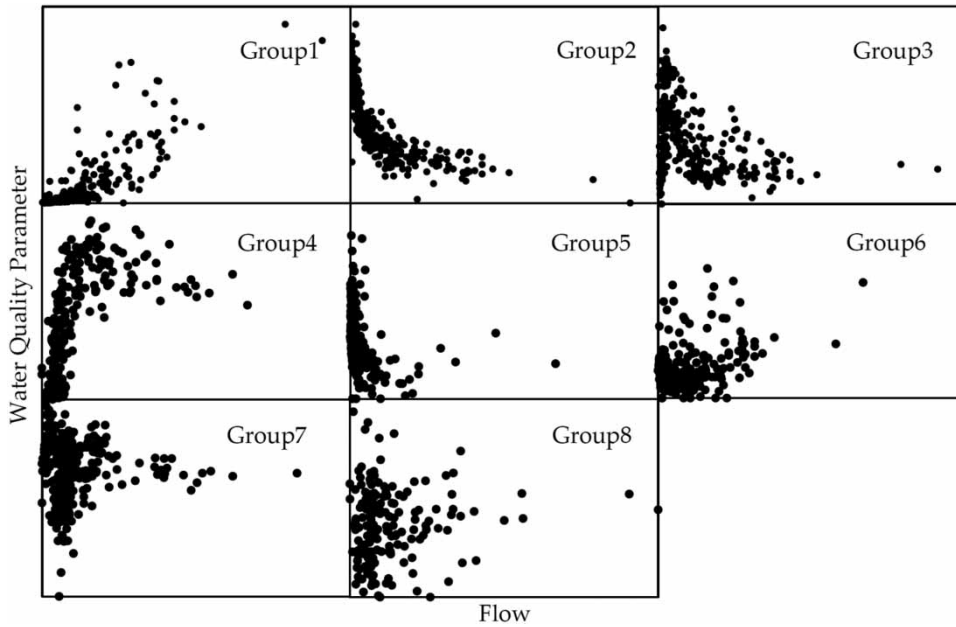


Figure 5 | Schematic diagram of the eight groups (Groups 1–8) describing the different water quality responses to flow. Water quality parameters categorized in these groups at all stations are listed in Table 4.

Table 4 | Categorization of water quality response to flow at the stations on the Athabasca, Bow, and Oldman Rivers

Station	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
Athabasca River								
AB07BE0010 (midstream)	TURB	Cl^- , SO_4^{2-} , SC	DO, pH	Chl- <i>a</i> , WT	–	TP, DOC, TN	–	–
AB07CC0030 (downstream)	TURB, TP, DOC, TN	Cl^- , SO_4^{2-} , SC	DO	Chl- <i>a</i> , WT, pH	–	–	–	–
Bow River								
AB05BH0010 (upstream)	TURB, TP, TN, DOC	SO_4^{2-} , SC	Chl- <i>a</i> , pH	WT	DO	–	–	Cl^-
AB05BM0010 (midstream)	–	–	–	–	–	–	–	Chl- <i>a</i> , WT, pH, DO, TN Cl^- , SC TURB, TP DOC, SO_4^{2-}
AB05BN0010 (downstream)	TURB, TP	Cl^- , SC, SO_4^{2-}	DO, TN	–	–	–	Chl- <i>a</i> , pH, WT, DOC	–
Oldman River								
AB05AB0070 (upstream)	TURB, DOC, TP, TN	SO_4^{2-} , SC	WT	–	Chl- <i>a</i> , pH	Cl^- , DO	–	–
AB05AD0010 (midstream)	TURB, TP, Chl- <i>a</i> , DOC	DO, Cl^- , SO_4^{2-} , SC	–	pH, WT	–	TN	–	–
AB05AG0010 (downstream)	TURB, Chl- <i>a</i> , DOC	DO, Cl^- , SO_4^{2-} , SC	pH, WT	–	–	TP, TN	–	–

flow but they behave differently in different flow regimes. In Group 3, the parameters demonstrate a large variation and positively correlate with flow in the low flow regime followed by an overall decrease with the increase of flow in the medium and/or high flow regimes. The variation pattern of Group 4 is similar to that of Group 3, however the water quality concentration also increases with the increase of flow in the medium flow regime. Oppositely to Group 4, water quality parameters in Group 5 decrease with the increase of flow in both the low and medium flow regimes in general; while they tend to increase with the increase of flow in the high flow regime. The variation pattern of the water quality parameters in Group 6 is similar to that of Group 5 except that the increase of flow leads to the increase of water quality concentrations in the medium flow regime. Water quality parameters in Group 7 generally decrease with the increase of flow in both the low and high flow regimes, but they increase with flow in the medium flow regime. Water quality parameters whose concentrations do not obviously depend on flow in all flow regimes are categorized into Group 8.

It can be seen from Table 4 that many water quality parameters (e.g., TURB, TP, SO_4^{2-} , Cl^- , SC, etc.) generally respond to flow consistently (except at the midstream station on the Bow River), while their quantitative dependency on flow can vary spatially on a river. Conversely, the flow response of some water quality parameters, e.g., TN and DOC on the Athabasca River, and TN, WT, and pH on the Oldman River, and all water quality parameters on the Bow River, demonstrates spatial variation on the rivers. For instance, the response of DOC to flow on the Athabasca River is categorized into Groups 6 and 1 at the midstream and downstream stations, respectively. The response of DO to flow at the water quality stations on the Bow River falls into three completely different groups, Groups 5, 8, and 3; and the variation pattern of pH on the Oldman River is categorized into Groups 5, 4, 3 at the upstream, midstream, and downstream stations, respectively.

When comparing the three rivers, many water quality parameters, in general, show a similar response to flow along the rivers except the Bow River. Large changes in the water quality responses to flow along the Bow River might be ascribed to the impacts of various anthropogenic activities (including agricultural activities) concentrated in

the middle and downstream watersheds, which could largely alter pollutant sources and, consequently, the behavior of water quality parameters (Akbar 2013). On the Athabasca and Oldman Rivers, water quality parameters including TURB, SC, Cl^- , and SO_4^{2-} in general, respond consistently to flow along the rivers, while other water quality parameters spread out in two or three different groups. All the results imply a lesser degree of anthropogenic influence imposed on the water quality on the Athabasca and Oldman Rivers compared to the Bow River.

The investigated water quality parameters can be broadly grouped into two distinct categories. One category of the parameters, which are directly affected by point and/or non-point pollution sources, includes TURB, TP, TN, Cl^- , SO_4^{2-} , and SC. As shown in Table 4, these parameters were generally classified into either Groups 1, 2, or 6. The consistent increase of concentrations with flow characterized by Group 1 is mainly caused by the wash off of non-point source pollutants by surface runoff and resuspension of pollutants in the river pathways (Helsel & Hirsch 2002). Thus, non-point sources primarily contribute to the increase of concentrations with the increase of flow. The water quality parameters, TURB and TP, are generally following the concentration-flow pattern characterized by Group 1, and in addition, TN at several stations is also categorized into the same group. The water quality parameters classified into Group 2, which shows water quality concentrations decreasing with the increasing flow, are predominantly affected by point sources (e.g., effluent from wastewater treatment plants). Point sources often discharge pollutants at relatively constant rates, and thus the increase of flow dilutes the pollutants and thus pollutant concentrations decrease. Dissolved inorganic pollutants (e.g., Cl^- , SO_4^{2-} , and SC) are often classified into Group 2 and thus point source contribution is dominant (Kundzewicz & Krysanova 2010). Note that TP and/or TN are also classified into Group 6 at the midstream station on the Athabasca River and the midstream and downstream stations on the Oldman River, and Groups 3 and 8 at the midstream and downstream stations on the Bow River. The concentration-flow curve of Group 6 indicates that the contribution of point sources is dominant in the low flow regime and the contribution of non-point sources is more significant in the medium and high flow regimes; while the concentration-flow

curve of Group 8 suggests that both point and non-point sources contribute approximately equally in all flow regimes. At the downstream station on the Bow River, the increase of TN concentration with flow in the low flow regime and the decreasing TN concentration with flow in the medium and high flow regimes (Group 3) suggest that non-point source contributes more in the low flow regime and less in the medium and high flow regimes. Therefore, both point and non-point sources contribute TN and TP to the rivers at the stations, and their relative contributions would determine their overall response to flow in different flow regimes.

As for the above-mentioned water quality parameters, their strong dependence on flow was demonstrated in general. Thus, it is apparent that their levels are different in the different flow regimes. Furthermore, the response of the water quality parameters to flow in general is quantitatively different in different flow regimes, as the calculated correlation coefficient is different in quantity in the flow regimes. Conversely, the differences in the qualitative responses (positive or negative) to flow among the flow regimes were demonstrated in several water quality parameters (e.g., TN and TP), which could be ascribed to different contribution sources (point source, non-point source, or their combination) in the flow regimes. Therefore, different management strategies are needed in different flow regimes. These results also advocate the need to take flow into consideration when managing riverine water quality.

As for other water quality parameters, such as WT primarily affected by meteorological conditions, and pH, DO, DOC, and Chl-*a*, which might be impacted by biological activities of riverine plants (e.g., growth, photosynthesis, and respiration) as well as aquatic microorganism activities to a certain degree, they were classified into different groups on the rivers. Thus, the management of these water quality parameters to meet their requirements would be challenging, as more complicated processes are involved.

CONCLUSION

Many investigated water quality parameters demonstrated prominent intra-annual variation, which is either similar or opposite to that of flow. In addition, the water quality parameters generally responded to flow differently

(quantitatively and/or qualitatively) in the three flow regimes (low, medium, and high flow regimes) according to the results from the correlation analysis and CA. All these illustrated that flow is one of the primary influential factors of the intra-annual variation of water quality in riverine environments. The results from CA, which categorized water quality parameters into eight distinct groups for the three rivers, confirmed the different flow response of these water quality parameters. In particular, a water quality parameter could respond to flow differently (qualitatively) among the flow regimes. The different responses to flow in different flow regimes could be ascribed to the different contribution of different pollution sources or the different governing mechanisms. All the results implied that it is very challenging to manage riverine water quality due to the fact that different pollutant sources might contribute to elevated concentrations and the relative contribution of different sources can be different under different flow regimes. Therefore, different management strategies are needed under different flow regimes. In addition, guidelines should provide different thresholds for different flow regimes for more efficient management. Although this paper used the data collected from three major rivers in Alberta, Canada, the concept of managing riverine water quality considering flow regimes and the approach adopted for dividing flow regimes might be applicable for other rivers beyond the geographical location studied in this paper.

Although the determination of the flow cut-off values for dividing flow regimes for conducting the correlation analysis and CA in this paper was subjective to some degree in addition to site-specific, the flow division approach could be adopted into management practices as the results successfully demonstrated the similarity/difference among water quality parameters in terms of their response to flow in different flow regimes. Owing to the different physical and chemical properties of different pollutants, different cut-off values might be needed to stratify data for different water quality parameters. In addition, other natural factors such as meteorological condition (e.g., temperature and rainfall) and ambient environment could also affect water quality in riverine environments. As a result, data stratification in multiple dimensions might be necessary, ideally to establish management targets and strategies. Further research on these topics is recommended for future study.

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