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A FUZZY CLUSTERING APPROACH TO DIAGNOSIS OF CHANGE IN NATURAL STREAMFLOW REGIME

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Abstract: Climate change have changed natural streamflow regime in Canada. Understanding the regime shifts in natural streamflow is important in terms of effective water management and preparedness for facing potential threats to water, food and energy security in Canada. Conventional approaches to assess the change in natural flow regime consider one or more streamflow characteristics and apply statistical tests to extract the form and magnitude of change individually in the considered characteristics. Here we propose an alternative approach to diagnose the change in natural streamflow regime by characterizing the gradual shift in shape and variability around the long-term annual streamflow hydrographs, which inherently include multiple streamflow characteristics within. The proposed methodology is based on (1) considering a wide range of streamflow characteristics that together represent the long-term annual hydrographs and their associated natural variability; (2) clustering streamflow series based on these features into a set of physically-relevant streamflow classes; and (3) monitoring the gradual shift from one flow regime to others using a systematic approach. To test this framework, we consider the streamflow data from 106 natural Canadian streams during the common period of 1966 to 2010. Fuzzy clustering is used to cluster the streamflow series during this period, in which all streamflow series are associated to all clusters with certain degrees of belongingness. We then focus on natural streams in the province of Quebec and measure the gradual departure in degrees of belongingness using moving windows and take this information as an indicator for regime shift in natural streamflow regime. Based on this methodology, we diagnose some significant changes in shape and variability of annual expected hydrograph in Quebec, which provides a holistic understanding of recent changes in natural streamflow regime throughout the province.

1 INTRODUCTION

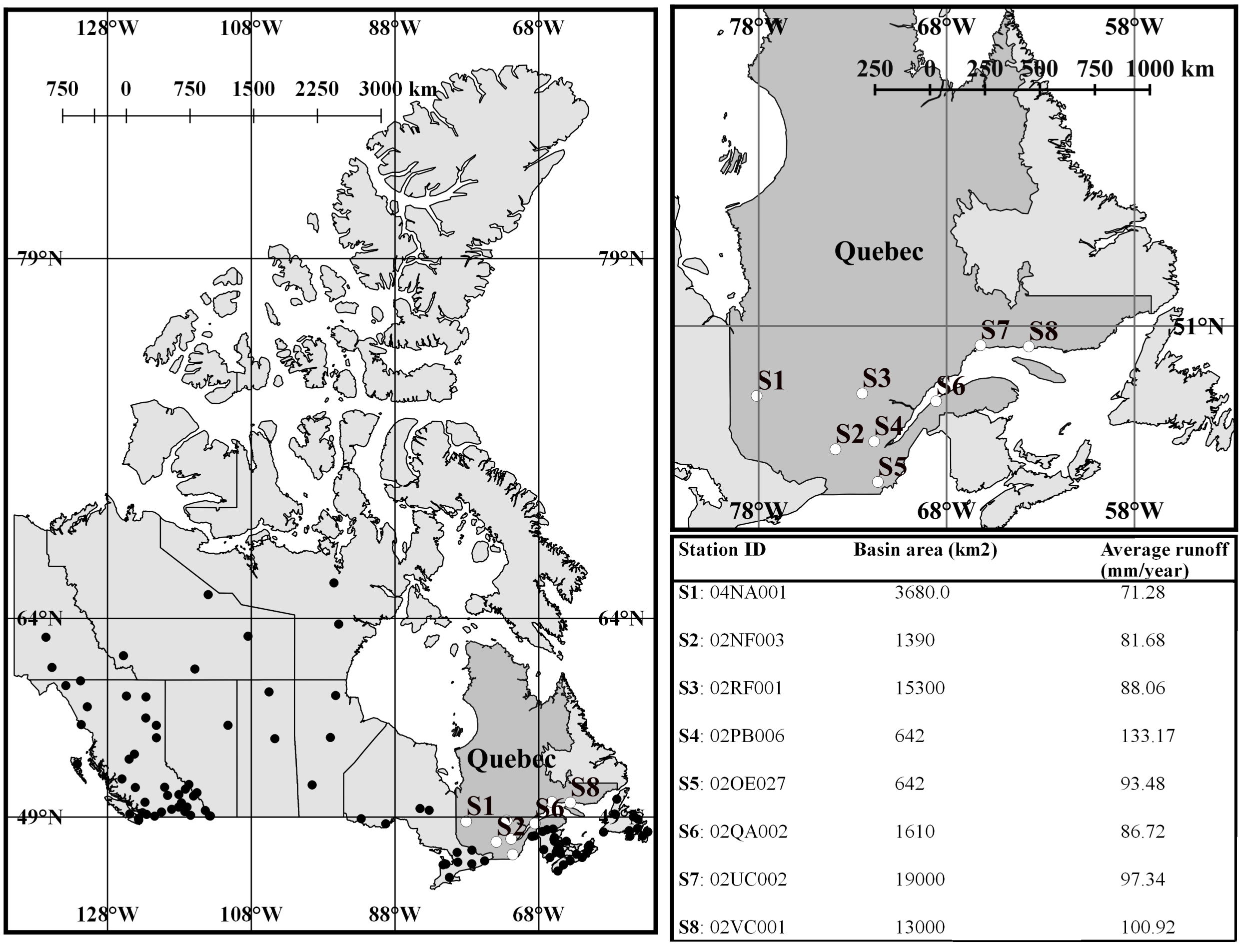
Climate change and variability have significantly changed natural streamflow regime globally. However, the warming climate and its effect on natural streamflow is more of a concern across higher latitude, particularly in Canada (e.g., Adamowski et al. 2013, Nazemi et al. 2017, O'Neil et al. 2017). Considering the extensive landmass of approximately 10 million square kilometers, the streamflow responses to climate change in Canada are subject to significant spatial variability (e.g., Burn et al. 2010, Whitfield 2012, Vormoor et al. 2015, Buttle et al. 2016). In western Canada, an increased in winter, decreased in summer runoff along with an earlier timing of spring peak flows have been observed in most of the snow-dominated watersheds (Whitfield and Cannon 2000, Barnett et al. 2005, Bawden et al. 2014). Glacial catchments display an increasing runoff, due to increase in glacier melt, whereas non-glaciated basins tend to show a decreasing runoff (Hinzman et al. 2005, Foy et al. 2011). Northern river systems in Arctic, have experienced significant changes in runoff, especially in winter and spring seasons (Vörösmarty et al. 2001, Shkolnik et al. 2017). In eastern Canada, a significant trend toward an earlier timing of high flows in most rivers located in eastern Ontario/western Quebec have been observed (Adamowski et al. 2013). Despite significant progresses, conventional approaches for diagnosing changes in streamflow regime focus on one or few flow characteristics separately. Climate change impacts however are more complex as it affects the entire hydrograph. This happens particularly in cold regions where both rain and snow play a key role (Kundzewicz et al. 2017, Hatami et al. 2018). As a result, understanding climate change effects on streamflow regime requires multifaceted approaches that consider various forms of change simultaneously together. In this study, we propose a novel approach to detect the impacts of climate change on flow regime as an entire continuum by characterizing the gradual shifts in the shape and variability around the long-term annual streamflow hydrographs, which inherently include multiple streamflow characteristics within. We first identify main Canadian natural streamflow classes by clustering 106 streams throughout the country. We then focus on eight natural streams in Quebec and systematically characterize the gradual departure from one streamflow class to others as a measure for regime shift in natural streamflow in the province.

2 DATA AND METHODOLOGY

We base our study on the 782 hydrometric stations within Canadian Reference Hydrometric Basin Network (RHBN; Water Survey of Canada, 2017, http://www.wsc.ec.gc.ca). These stations monitor unregulated streams and therefore are suitable the detection of climate change (Harvey et al., 1999). We search for the longest continuous common periods over all stations. This results into selection of 106 stations among the RHBN station pool. These stations include daily discharge values covering the period of 1966-2010 with less than 8% of missing data. The missing data are filled with mean daily values for the missing date over the whole period of data availability. The daily data are then converted into weekly and normalized by basin area to provide streamflow generated per square kilometer and therefore make the streamflow data comparable across all stations. These 106 stations are considered for identifying the main classes of natural streamflow in the country. Among those, we focus on eight streams in Quebec for understanding the regime shift. Figure 1 shows the locations of RHBN gauging stations located in Quebec. The right panel includes each station's name, ID, area of basin, and the average runoff per basin area.

First, we cluster the 106 selected RHBN stations into a set of physically-relevant clusters based on a set of hydrological features, selected from the Indicators of Hydrological Alteration (IHAs; Richter et al. 1996). In total, 30 hydrological features including, expected annual flow and its variation, expected monthly flows, variation of monthly flows, expected as well as variation in timing of low and high flow are selected. The values of these hydrological features can be calculated by software available by Mathews and Richter (2007). Having the hydrological features, we use fuzzy clustering algorithm (for details see Bezdek, 1981) to cluster the streamflow data into a finite number of overlapping groups. The clustering is the process of arranging streamflows into groups that are most similar with respect to their characteristics. In fuzzy clustering we assume each river can belong to clusters with certain degree of belongingness. One can then quantify the degree of alteration in memberships through the course of time. Having the hydrological feature vector for each gauging station, we divide them into a finite number of soft clusters weighted by their membership values such that the sum of distance between the observations and the designated cluster centroids is minimized. The number of clusters can be chosen based on the fuzzy validity indices (Srinivas et al. 2008)

The algorithm is implemented using MATLAB Fuzzy C-Means (FCM) in a multi-start configuration to avoid the problem of trapping in the local minima. We consider the first 10 years of 1966-1975 in the 106 stations for clustering, in which the centroids of clusters and the baseline degrees of membership are calculated for this period. For the 8 Quebec streams, we define a 10-years moving window (equal to the length of baseline) and slide it over the remaining period of 1976 to 2010 year by year. This enables us to detect the monotonic change in degree of memberships as a notion for evolution in streamflow regime. In each of moving window we calculate the degree of membership by measuring the distance of feature vectors from the centroids of clusters identified during the baseline period. Then, we rescale all memberships into the same range with minimum of zero and maximum of one to calculate the anomalies of memberships. This step in required to make the trends in memberships of clusters comparable in magnitude. In total for all windows, we obtain 36*8 membership values per each station over the whole period, each of which form a timeseries. We apply the Mann-Kendall trend test (Mann 1945, Kendall 1975) and estimate the Sen Slope on membership timeseries to quantify the changes in degree of memberships.



Station ID	Basin area (km2)	Average runoff (mm/year)
S1: 04NA001	3680.0	71.28
S2: 02NF003	1390	81.68
S3: 02RF001	15300	88.06
S4: 02PB006	642	133.17
S5: 02OE027	642	93.48
S6: 02QA002	1610	86.72
S7: 02UC002	19000	97.34
S8: 02VC001	13000	100.92

Figure 1: The locations of the 106 Reference Hydrological Basin Network (RHBN) gauging stations in Canada (left panel, shown in black dots); the locations of the eight gauging stations in Quebec are identified by white dots in upper right panel. The lower right panel summarizes the ID, area and annual runoff.

3 RESULTS AND DISCUSSION

Using the FCM, we identify six streamflow classes across Canada. Table 1 summarizes the six clusters (C1-C6) and their architype streams (i.e., the closest river to the centroids of each cluster). The C1 cluster resembles the pluvial regime, in which the heavy precipitation especially during winter, which is accompanied by a high variations is the main source of runoff. Low flows in summer occurs during summer for this flow regime. In C2 type, rain and snow both contribute to the runoff, termed as the pluvio-nival regime. Because of snowmelt, the high flow shifts to the spring. In this type, a period of rainfall in late fall is followed by light increase in discharge due to snowmelt in early spring. The C3 cluster resembles the glacial regime, which is characterized by the later onset of the peak flow that rises gradually and do not cease sharply. Glacial flows have a low runoff in winter, early spring high flows and a gradual recession along fall. C4 cluster features rivers which mostly belong to nivo-glacial regime, dominated by melting of seasonal snow and glaciers. This flow type is similar to nival regime, but peak flow occurs in June and July, and the glacier melt maintain flows during late summer and early fall. The C5 resembles nival regime, and can be featured by their short high flow in early spring with a sharp recession afterwards. They have a high variability over a year. C6 regime mostly resembles nivo-pluvial type with a low flow in early fall and late winter, which is characterized by two high flows in fall due to high precipitation and in spring due to snowmelt.

Table 1: Main regime clusters (first column), the architypes each cluster resemble to (second column), the representative river (closet station to the centroids; third column), and the spatial distribution of clusters across Canada.

Cluster	Architype	Main characteristics
C1	Pluvial	heavy precipitation, especially during winter, lower runoff during summer season, high variability in winter flows
C2	Pluvio-nival	runoff originated by both snow and rainfall, , the maximum discharge in spring
C3	Glacial	late and prolonged timing of the peak flow, low runoff in winter and spring,
C4	Nivo-glacial	runoff originated by melting of seasonal snow and glaciers, peak flow occurs late summer and ramin till early fall
C5	Nival	short high flow in early spring, very sharp recession, great variability
C6	Nivo-pluvial	two high runoff in fall due to high precipitation and in spring generated by snowmelt

The significance of trends ($\alpha = 0.05$) in anomaly of memberships was assessed by the Mann-Kendall test. The upward trends in anomalies of memberships show how much streamflow regime became closer to any the centroid of the cluster; whereas, downward trends explain the tendency of one streamflow regime to depart from a specific cluster. Figure 2 shows the changes in the degree of memberships along with trends in anomalies of memberships for eight RHBN stations located in Quebec. For S1 station, which mostly of type C3, there is a negative trend for C3 and C4 class; whereas, this is positive for other clusters. For S2 station, there is a negative trend for C5 cluster, while an upward trend detected for the other clusters. Station S3 shows a significant negative trend for C3 along with positive trends more toward C5 and C6. For Station S4, it is more dominated by a positive trends for C5 and C6, and negative trends for C1, C3 and C4. S7 and S8 that both are more of C4 regime show a positive trend toward C3 regime types. No significant trend is detected for S5 and S6 stations.

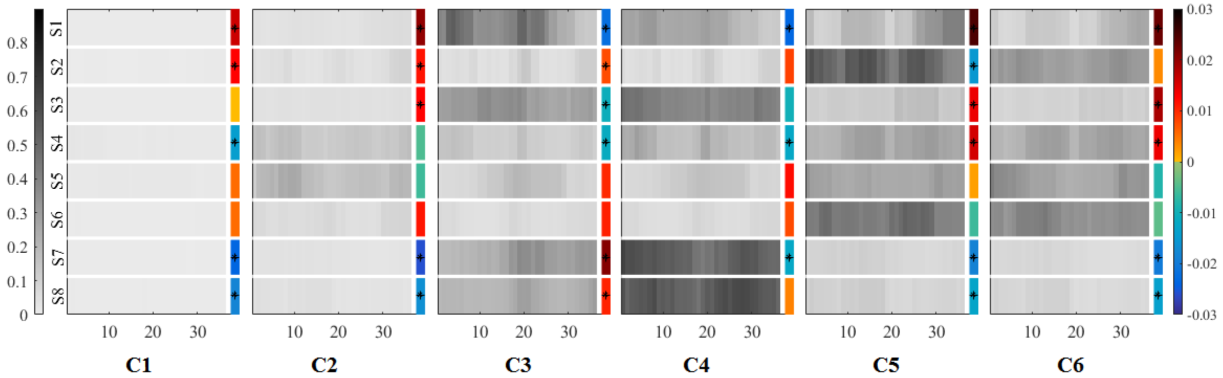


Figure 2: The degree of memberships to each cluster for studied RHBN stations as well as the trends in anomaly of memberships at each 10-years moving window. The left panels shown in shades of grey, display the memberships of each streamflow to each cluster in 10-years moving windows. The right panels shows the Sen's Slope value for the anomalies of memberships. The significance of trend is shown with black dots.

These upward and downward trends can be interpreted as the shift in flow regimes, each of which can be attributed to multiple changes in hydrological features. Figure 3 shows how hydrograph shapes are transforming through the course of time. The grey and the pink colors illustrate the first and last 10-years window for the period of 1967-2010. In S1 station, the shift from C3, C4 into C5 and C6 are mainly due to increasing winter flows, later and more variation of timing of low flow. In S2 station, decrease in spring flow as well as earlier timing of low flow result in shift from nival into more rain-dominated regimes (i.e., C1 and C2). In S3, the deviation of streamflow from the glacial regime into others can be attributed to increasing winter flows, later and less variation of timing of low flow. For the S4 station, later and less variation in timing of low flow is also the main cause of transition from C3 and C4 into C5 and C6. However, in S7, a shift toward a glacial regime is majorly due to decrease in winter and spring flows. In S7 the same pattern is exhibited which can be attributed to later and less variation in timing of high flow and low flow.

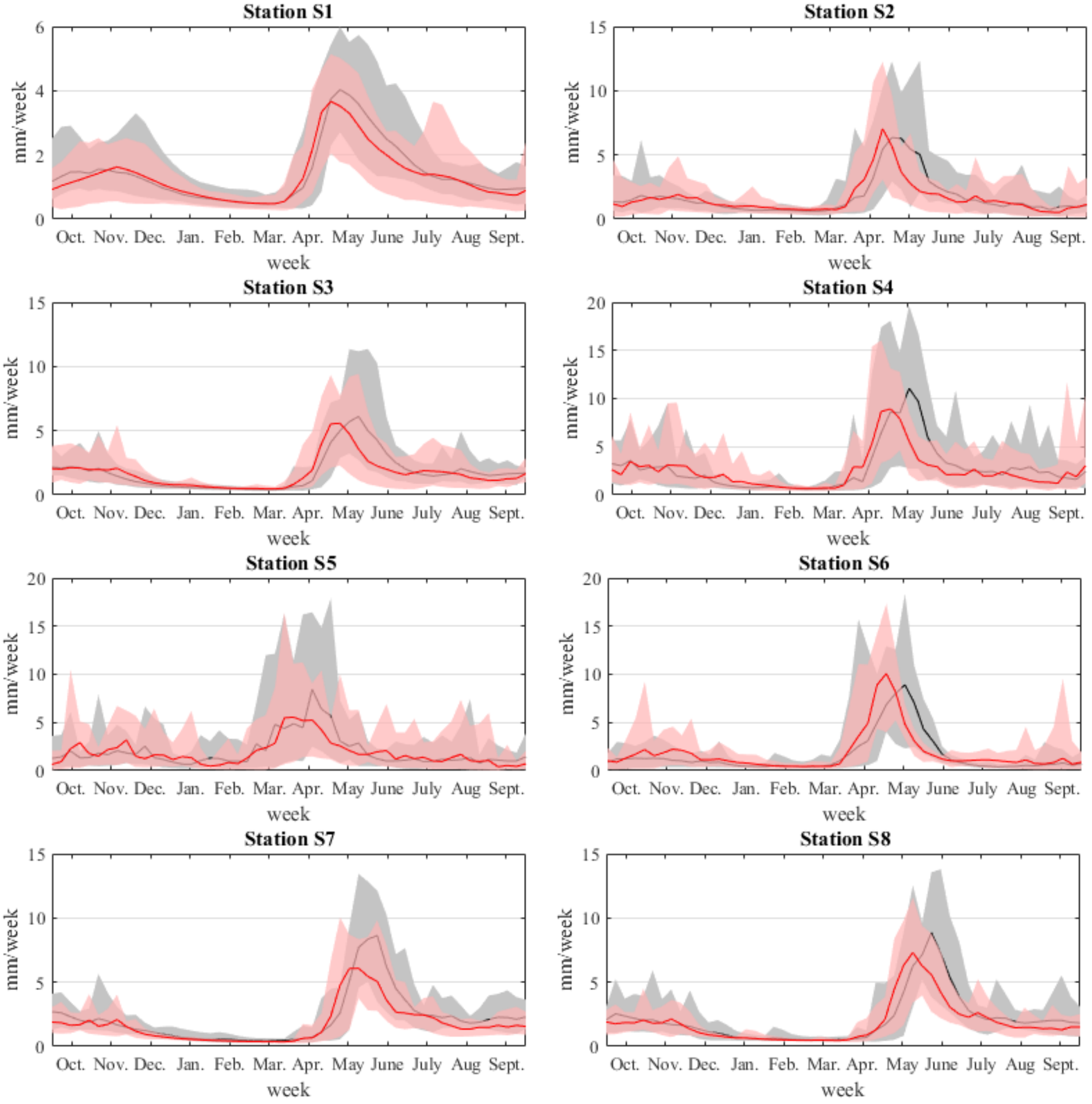


Figure 3: Eight RHBN gauging stations located in Quebec; the expected weekly mean and standard deviations of earliest 10-years (baseline) window shown in solid grey lines and the surrounding envelopes respectively. The pink colors are the latest 10-years window ones.

4 CONCLUSION

This study represents the change and transition of eight RHBN gauging stations in Quebec. As these stream reaches are unregulated, the observed changes can be attributed to climate change. Our analysis showed that the patterns of changes are different for stations located in east and west of the province. In stations located in southwest of Quebec, a clear pattern of change from glacial/nival regimes into more nival/pluvial is detected; whereas for stations located in east of Quebec, a shift toward more glacial regime is observed. The pattern of shift is however can be attributed to multiple hydrological features. The proposed framework provides the opportunity to understand the effects of these multiple changes in transformation of flow regimes. Future work is needed to understand the exact climate variables that drive these changes.

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