Changes in the wintertime hydroclimatic regime in St. John River, Maine, USA

Jong-Suk Kim, Shaleen Jain and Taesam Lee

ABSTRACT

Changes in the flow regime in snowmelt- and ice-dominated rivers have important implications for navigation, flood hazard, recreation, and ecosystems. We investigated recent changes in the high flows of the St. John River basin in Maine, USA, with a view to quantify changes in high-flow characteristics, as well as extreme event estimates. The results analyzed herein demonstrate shifts in springtime streamflow as well as in emergent wintertime (January–February) streamflow over the past four decades. A Poisson-based regression approach was applied to develop a model for the diagnosis of weather-climate linkage. The sensitivity of episodic warm weather events to the negative phase of the Tropical–Northern Hemisphere (TNH) atmospheric teleconnection pattern is evident. Although a modest sample size of historical data on the weather-climate linkage imposes a limit in terms of reliability, the approach presented herein shows a modest role of the TNH pattern, in response to the warm phase of El Niño/Southern Oscillation, as one of the factors that contribute to hydroclimate variability in the St. John River basin. This diagnostic study sought to investigate the changes in the wintertime streamflow regime and the relative linkages with short-term concurrent weather events, as well as large-scale climatic linkages. This improved an understanding of hydrological extremes within a climatological context and offers new knowledge to inform water resources planning and decision-making.

Key words | episodic warming, hydroclimate variability, teleconnection patterns, weather-climate linkage

HIGHLIGHTS

- Diagnosis on changes in the wintertime flow regime for St. John River.
- Identified climate precursors that engender a significant change.
- Changes in flood frequency were identified.
- A novel statistical methodology using quantile regression to identify the exact time windows of change.
- A statistical analysis approach is broadly used for other locations experiencing linear and nonlinear hydroclimatic changes.

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INTRODUCTION

The wintertime streamflow regime in temperate and polar climates has important implications for navigation, ice breakup, ice jams, flooding, and public safety. The interrelationships between the hydrologic regime, ecosystem function, and societal vulnerability motivate efforts to carefully characterize temporal changes in streamflow statistics, frequency of hydrologic extremes, and, in general, climate-induced hydrologic nonstationarity. Climatic oscillations and trends embedded within the envelope of hydroclimatic variability make difficult the task of identifying critical thresholds, such as snow to rain transitions and their impacts on the flow regime. There is mounting evidence of trends toward increases in the winter and spring streamflow in snowmelt-driven river systems (Khattak et al. 2011; Makarieva et al. 2009).

Shifts in the seasonal and annual flow regimes are sensitive to interannual temperature variability and warming trends. In regions where ocean–atmosphere teleconnection patterns modulate climatic variability, significant departures in precipitation and temperature from long-term seasonal averages are often observed. As a result, the commingling of trends and interannual variability can accelerate changes in streamflow regimes. In the northeastern United States, analysis of historical streamflow records indicates the earlier timing of the springtime runoff pulse and indications of hydrologic change (Dhakal & Palmer 2020) and a trend toward decreasing ice thickness and early ice out in Maine lakes (Beyene & Jain 2015, 2020).

Although numerous studies have assessed trends in the magnitude and timing of annual maximum floods and streamflow volumes (Jain & Lall 2000; Hodgkins & Dudley 2005; Jay & Naik 2011; Chang et al. 2014), limited attention has been devoted to studying the increasing high flows emerging in wintertime that may cause unanticipated shifts in seasonal and annual flow regimes. Changes in the frequency of hydrologic extreme, the emergence of high-flow events in the relatively quiescent winter season, and the redistribution of streamflow volume from a dominant springtime pulse to one that includes episodic high flows during winter require attention and new analysis approaches. From the standpoint of adaptation, the ability to predict these unusual shifts would be quite useful for decision-making and policy reassessments to meet the objectives of water resources systems and sustain existing aquatic ecosystems.

This study focuses on identifying the large-scale climate precursors and basin-scale hydrologic variables that control the flood regime for the St. John River in Maine, USA. A central premise in efforts to characterize and understand the regional impacts of climate variability and change is that hydrologic estimations are amenable to incorporation into nonstationary climate information. This, in turn, introduces important questions that new methodologies must address in order to remain salient to climatic concerns: (a) What are the critical characteristics of the change in the flow regime? (b) Within the context of flood frequency analysis, what level of sensitivity do the key parameters have to individual climatic precursors and their past and future trajectories? (c) What are the appropriate methodologies to identify the relevant hydroclimatic drivers that downscale the signature and footprint of changes in the global climate system to a regional or river basin scale?

DATA AND STUDY AREA

Daily discharge data for the St. John River at Fort Kent (USGS station no. 0101400) from an 81-year streamflow archive maintained by the U.S. Geological Survey (http://waterdata.usgs.gov/nwis) were analyzed in this study, as shown at the right top panel of Figure 1. Temperature and precipitation data from continuous daily records were used, which met specific data completeness criteria. The precipitation data were obtained from the NOAA CPC (Climate Prediction Center) based on daily data (see details at http://www.cdc.noaa.gov/data/gridded/data.unified.html). However, complete and qualified temperature data are not available at the Fort Kent station because of missing data. Therefore, the temperature of a grid point (47.25°N and 68.50°W), 7.1 km away from the station, was derived by reanalysis over the period 1948–2016. Monthly geopotential height and sea surface temperature (SST) data were used from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis from 1948 to 2016, on
a 2.5° latitude × 2.5° longitude grid and a 2.0° latitude × 2.0° longitude grid, respectively (online at http://www.cdc.noaa.gov/data/gridded/). Standardized northern hemisphere teleconnection indices were acquired from the NOAA Climate Prediction Center (online at https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml).

**ANALYSIS METHODS**

Hydroclimatic trends observed during the past four decades were evaluated on the basis of quantile regression (Koenker 2005; Barbosa 2008) to clarify the change in the magnitude and timing of the streamflow. The 95% confidence limits were used in this analysis. The relationship between temperature and precipitation was analyzed on the basis of flow events, as well as ice jam and breakup that occurred during the coldest months of winter (January–February, JF).

The temperature considered was the maximum of the daily temperatures recorded on the date of the seasonal peak flow event and the three preceding days. Precipitation was regarded as the total precipitation from December 1 to the date of the seasonal peak flow event. Winter flows are significantly related to temperature, especially in snowmelt-dominated watersheds. Therefore, we used quantile regression to quantify and determine the changes in temperature trends. Dynamical hydroclimatic covariates were included on the maps for geopotential height and SST using correlation analysis. Pearson’s correlation estimates with $p < 0.05$ for the time series were considered statistically significant. We also identified climate precursors most relevant for nonstationary analysis and potential shifts in flood frequency in a changing climate for winter during the periods from 1927 to 1971 and 1972 to 2016.

It has become increasingly noticeable that hydrologic regimes in snowmelt-dominated watersheds have undergone significant changes in the magnitude and timing of hydroclimatic variability. A focus on the last 67 years (1950–2016), therefore, was pursued to identify the diagnostic characteristics of winter hydrologic variables in local weather and climate. A Poisson-based regression approach was applied...
to develop a model for the enhanced explanation and prediction of weather–climate linkages. Here, a generalized linear model was applied for fitting the Poisson model. In the regression model, the number of peak days, where temperature exceeded the threshold, was used as the response variable of interest. Predictors of count numbers of peak temperature include the major circulation pattern, such as the Tropical–Northern Hemisphere (TNH) pattern. The statistical analysis performed in this study utilized the R computational platform and the available packages therein (R Core Team 2020).

RECENT HYDROCLIMATIC CHANGES

An important impact of natural and anthropogenic climate change has been observed in the seasonal cycle of hydroclimatic variables such as temperature and precipitation, as well as streamflow (for example, Regonda et al. 2005; Kim & Jain 2011). Changes in timing and seasonal distribution of regional hydroclimatology can significantly affect water resource management, bird migration (Miller-Rushing et al. 2008), timing of the first bloom of plants (Cayan et al. 2001), and anadromous fish migration (Huntington et al. 2003). In winter, temperature and precipitation highly affect streamflow and snow accumulation. Temperatures increase as part of trends and interannual fluctuations and more rain falls instead of snow resulting in less water storage in the snowpack. Such increases may cause earlier runoff and peak flows in snowmelt-dominated watersheds (Aguado et al. 1992; Regonda et al. 2005; Burn 2008). In addition to socioeconomic effects, dynamic winter breakup and ice jamming can also have severe ecological consequences (Beltaos et al. 2003).

A quantile regression methodology was used to quantify and determine the significance of trends in the historical daily average streamflow. Seasonal variations in the 90th quantile of streamflow for the St. John River basin in Maine, USA, are presented in Figure 1. Approximately 58.5% of the annual flow of daily streamflow during 1927–2016 occurred during the March–June (MAMJ) season. The seasonal fraction flow volume in the JF season was 4.6 and 14.3% for the September–November (SON) season. The annual streamflow volume has a relatively high coefficient of variation (CV) of 1.04. Therefore, the St. John River streamflow is most likely related to snowmelt in springtime. The highest variability is in the MAMJ season (CV = 0.56). The JF and SON seasons present relatively modest variability in streamflow volume with seasonal CVs of 0.20 and 0.24, respectively. Figure 1(a) shows the changes in the 90th flood quantile over the two periods 1927–1971 and 1972–2016 based on long-term averaged seasonal streamflow cycles. These results indicate that the flow hydrograph has shifted dramatically during the more recent period, and that peak streamflow has also increased by 10.9%. During the SON season, the seasonal flow volume increases by 10.3%. However, flow volumes have increased moderately by 3.2% in annual flow and decreased by 1.1% in the MAMJ season. The winter flow volume (the JF season) differs significantly (increase by 35.2%) between the two periods. Figure 1(b) shows the upper quantile trend (0.50, 0.67, 0.75, and 0.90) in the daily streamflow time series. The statistical significance of each trend was evaluated by computing the p-value in each quantile. Trends with $p < 0.05$ were considered statistically significant.

During the early spring season (March–April), there is an upper quantile trend of increased streamflow followed by decreased streamflow in the May–June season. Although streamflows are likely to increase or decrease intermittently in the summer and fall seasons, in most cases, the trends are not statistically significant. Statistically significant trends in the upper quantiles of streamflow appear after the middle of January in the later winter season (IF). Unusual shifts in seasonal and annual streamflow impact on riverine species, including the life cycle of native and homing species. This analysis seeks to provide improved identification of the emergent flow regime and the assessment of substantial interannual variability in streamflow stemming from the effects of temperature and precipitation variability and change.

Figure 2 shows a trend in the seasonal maximum flow (the JF season). The variability in daily streamflow during the JF season is summarized for each year using a boxplot (0.1, 0.25, 0.5, 0.75, and 0.9 quantile levels). The upper quantile shows trends toward increases in the JF season. The dotted line indicates a statistically significant trend in the seasonal maximum flow (the JF season) at the 90% confidence level. These temporally coherent trends in winter events clarify the nature and extent of shifts in the
springtime flood regime, as well as the emergent wintertime flow regime stemming from episodic warming and precipitation.

Figure 3 shows the empirical probability distribution between temperature and precipitation, which is obtained as the product of two univariate kernels. The main objective of this analysis is to identify the seasonal high-flow sensitivity to episodic warming and precipitation. The shape of each density estimate is represented by contours containing quantiles (0.25, 0.50, and 0.75) of the data. These are superimposed to clearly illustrate how temperature and precipitation have changed during seasonal high flows (the JF season). The contours show the relationship between 4-day maximum temperature and total precipitation rate based on high flows (upper quartile), interquartile range flows (square symbols), low flows (lower quartile), and ice jam and breakup (circles) during the coldest winter months (the JF season). In most cases, high-flow (upper quartile) events are shown above \(-5^\circ C\), and some events were caused by ice jam and breakup. Table 1 provides the correlation of temperature for selected upper quantiles (0.85, 0.875, 0.90, 0.925, 0.95, and 0.975). It is noteworthy that statistically significant correlations with TNH are limited to the upper tail of the daily temperature distribution for the JF season. To this end, Beyene & Jain (2015) have shown that while teleconnection patterns may show modest correlations with wintertime temperature metrics, the cumulative effect over the winter period is significant for: (a) the accumulated freezing degree days and (b) probability distributions of daily wintertime temperatures for several locations across Maine.

Figure 2 | Historical variations in daily streamflow (JF) and its extremes for the St. John River over the period 1927–2016. The gray shaded circles highlight the seasonal maximum flood for each year. The dotted line shows a linear trend and the solid line represents a trend of the seasonal maximum flood using LOWESS (locally weighted linear regression) with an 11-year span. For each year, the variability is summarized using a boxplot (0.1, 0.25, 0.5, 0.75, and 0.9 quantile levels are shown).
the next sections, we discuss potential shifts in the flood frequency of high flows stemming from these episodic warm weather events, as well as the regional and global climate precursors.

**EMERGENT HIGH-FLOW FREQUENCY AND CLIMATE-RELATED NONSTATIONARITY**

Recently, Collins (2009) investigated the trends in a long-term annual flood series of New England watersheds in order to provide better estimates of flood magnitudes and frequencies under the prevailing hydroclimatic conditions. However, unusually warm episodes in winter and spring also cause changes in the flow regime. In Figure 4, potential shifts in high-flow frequency in northern Maine are shown. The annual series of seasonal peak flows for the St. John River basin at Fort Kent were used. The streamflow records are classified into two periods: Period I (1927–1971) and Period II (1972–2016). In Figure 4, changes in flood frequency for seasonal high flows are shown using a lognormal distribution. The key values used for comparing the two periods are the ratios of seasonal high flow according to return periods. The flow frequency curve indicates

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**Table 1** Correlation analysis (the JF season)

<table>
<thead>
<tr>
<th></th>
<th>(T_{0.25})</th>
<th>(T_{0.50})</th>
<th>(T_{0.75})</th>
<th>(P_{0.25})</th>
<th>(P_{0.50})</th>
<th>(P_{0.75})</th>
<th>(Q_{\text{seasonal}})</th>
<th>Flood</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNH</td>
<td>–0.199</td>
<td>–0.372</td>
<td>–0.294</td>
<td>–0.073</td>
<td>–0.070</td>
<td>–0.223</td>
<td>–0.218</td>
<td>–0.172</td>
</tr>
</tbody>
</table>

Hydroclimatic variables: temperature (\(T\)), precipitation (\(P\)), and total seasonal discharge (\(Q_{\text{seasonal}}\)). \(P\) and \(T\) subscripts refer to the seasonal quantiles from daily data. Spearman’s correlation estimates shown in boldface are statistically significant at the 5% level. Northern Hemisphere teleconnection pattern: Tropical/Northern Hemisphere (TNH).
that dramatic shifts in flow frequency are observed between the two periods. For example, the seasonal maximum discharge of 50- and 100-year flood return periods increases by 2.22 and 2.16, respectively, with a lognormal distribution. These results are similar to a log-Pearson Type III distribution, but the increases are more significant with values of 2.88 and 3.21, respectively.

In this context, we analyzed temperature variability for potential linkages to the changes in flow statistics and frequency of hydrologic extremes. We examined the temperature trends using a quantile regression approach. In Figure 5(a), the fraction of flow was plotted against the ratio of total water flow per year. The linear regression indicates that there are no significant trends in the years prior to 1970. However, upward trends have increased in recent years. Figure 5(b) shows temperatures grouped by year during the period from 1948 to 2016. The median temperature does not indicate any significant trends. Alternatively, higher quantile values signify an increasing trend (see the section ‘Analysis methods’ for details). No significant trends are observed in the years prior to 1980. However, the past 30 years clearly have upward trends evident in winter high flows. Changes in the high-flow regime that have emerged in recent years are considered a significant challenge for engineering, design, and analysis.

**HYDROLOGIC CHANGE WITHIN THE CONTEXT OF WEATHER AND CLIMATE**

Global atmospheric teleconnections, which affect climate and weather, have an important role in connecting the atmosphere with oceans in different regions. Changes in teleconnection patterns are often related to temperature, precipitation, wind, and pressure patterns (Hurrell 1995; Ottersen et al. 2001; Liu & Alexander 2007). The TNH pattern significantly modulates the Pacific jet stream into North America, as well as cold Canadian air into the north-central United States. The TNH pattern is significantly associated with surface temperatures and is a prominent mode during wintertime (see more details at https://www.cpc.ncep.noaa.gov/data/teledoc/tnh.shtml). Furthermore, sea surface temperatures (SSTs) show persistence on seasonal to longer time scales, which strongly influence the evolution of seasonal weather patterns, for example, related to the El Niño/Southern Oscillation (ENSO). In the analysis pursued here, we focus on TNH and SST that are two large-scale climatic variables as important correlates of the wintertime temperature in the St. John River basin.

Figure 6 shows the correlation among SSTs at each grid point. In Figure 6(a), the SSTs are not significantly
correlated or show coherent patterns with the surface temperature index. This is not unusual for the northeastern United States hydroclimate; however, the geopotential height patterns do show a coherent local relationship, one of interest from the standpoint of increasing the likelihood of episodic wintertime warming events. Figure 6(b) presents the correlation between the TNH index and the geopotential heights and the SSTs. Beyene & Jain (2015) showed that the negative phase of the TNH index favors milder winter temperature in Maine. The analysis results also show that the negative TNH pattern is presented when tropical Pacific Ocean regions are in a warm episodic condition, alongside a consistent geopotential height pattern. Correlations among hydroclimatic variables and the TNH pattern are summarized in Table 1. The correlation of the TNH pattern with local temperature is statistically significant. The potential linkages between the TNH patterns and episodic warming events are investigated next.

A Poisson-based regression approach was first applied to the count numbers of peak days with temperatures exceeding the identified temperature threshold (as shown in Figure 3) with the TNH index as the independent variable. The Poisson regression coefficients are summarized in Table 2. The p-value indicates that a set of independent variables (TNH) explains a significant proportion of variance in dependent variables (warm day counts) at a significant level. The modest relationship between warm event counts and the TNH events offers an interesting perspective regarding the potential modulation of the wintertime flow regime. Detailed analyses are required for
a more comprehensive understanding of sensitive linkages between weather–climate and changes in the flow regime.

SUMMARY AND CONCLUSIONS

We investigated both basin-scale hydrologic variables and large-scale climate precursors in order to find methods to downscale the footprint of changes in the region and characterize the local effects for climate-informed decision-making and management. The results of this study can be summarized as follows:

1. The hydroclimatic trends observed from quantile regression have clarified the dramatic shifts in the magnitude and timing of seasonal flow over the last four decades. The peak flow during the period from 1972 to 2016 has increased by 10.9% compared to the earlier part of the period (1927–1971). Changes in spring and summer flow regimes do not have a significant difference; however, the seasonal flow volume for the SON season increased more than 10.3%. In particular, the winter flow volume (the JF season) has a distinctive change (35.2%) with increasing tendencies. These changes result from the commingling effects of episodic warm temperature and precipitation.

2. Flood frequency has dramatic shifts in seasonal high flows for the St. John River basin at Fort Kent. The flood discharge of 50- and 100-year frequency in Period II indicated 2.22 and 2.16, respectively, times the difference in Period I (1927–1971) and Period II (1972–2016) with a lognormal distribution. When log-Pearson Type III distribution was applied, there was a 2.88 and 3.21 times greater difference. This type of change in difference is associated with an increased extreme flow that results from the abnormally warm episodes after the 1980s. This may be a perplexing challenge for both engineers and decision-makers.

3. The study analyzed the change in SST in the tropical Pacific Ocean region and its correlation with seasonal hydroclimatic variables related to seasonal teleconnection patterns. The TNH pattern has a statistically significant correlation with the local surface temperature in the northeastern United States. In addition, the results of the Poisson regression show that there is no particular correlation between the positive phase of the TNH
pattern and the frequency of warm episodic events in Northern Maine. However, in the negative phase of the TNH pattern, episodic warm-weather events respond to it sensitively. The results presented in this study show that the change of the TNH pattern in response to the warm phase of the ENSO is one of the factors that contribute to wintertime hydroclimate variability in the St. John River basin.

There are three important implications of this study. First, unusually warm episodes that occur during winter and spring induce changes in the flow regime. These warm episodes are a response to external forces associated with atmospheric circulation patterns, such as the TNH pattern in the northern United States, which are driven by time-varying global SST. Second, hydroclimatic covariates that have a dynamical basis are the most reliable indices of the future impacts on hydrologic extremes. The results from multiple climate change projections can be tailored to incorporate changes in identified covariates. This, in turn, allows an assessment of the potential shifts in flood frequency in a changing climate. Finally, understanding the mechanism of sensitivity linkages between weather and climate is particularly important for developing nonstationary flood frequency. This study contributes to the diagnostic identification of weather–climate linkages that can offer a better understanding of hydrological extremes within a climatological context and provide useful guidance for decision-making and policy reassessments.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (http://waterdata.usgs.gov/nwis/dv?referred_module=sw&site_no=01014000&cb_00060=on&begin_date=1900-10-01&format=rdb).

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