Streamflow variability and hydroclimatic change at the Bear Brook Watershed in Maine (BBWM), USA

Jong-Suk Kim · Shaleen Jain · Stephen A. Norton

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Abstract Seasonal variations in streamflow and the associated hydrologic extremes impart significant temporal structure to watershed-scale chemical fluxes. Consequently, a careful characterization of the episodic-to-seasonal and longer-term streamflow variations is a first step toward developing a comprehensive view of the temporal dynamics of watershed processes in a changing climate. Here we analyze a nearly two-decade-long streamflow record for the East Bear subwatershed within the Bear Brook Watershed in Maine (BBWM) (USA) to understand the envelope of streamflow variability by season, with a particular focus on the high flow events that have a disproportionately large impact on the biogeochemical processes and fluxes. Interannual and longer-term variations in a number of derived statistical metrics of hydrologic variability are examined. Our analysis shows substantial interannual and longer-term variability in seasonal flow volumes and peak flows. Furthermore, a long, unimpaired streamflow record for the Narraguagus River (a proximate watershed to the BBWM) is examined with a view to understand the relative coherence in hydrologic variability, as well as quantifying the decadal and longer-term hydrologic variations in this region. We find that the streamflow variability in the two watersheds shows similarity in all seasons. A moving window analysis to assess the changing flood potential over time indicates upward trends in the recent decades. Spring season (March–May) flood estimates show a near-monotonic trend over the 1949–2008 record. Finally, empirical relationships between streamflow and large-scale atmospheric circulation patterns highlight the regional and global climatic drivers of hydrologic extremes in this region, including impacts from remnants of Atlantic hurricanes.

Keywords Hydrologic change · Watershed fluxes · Hydrogeochemistry · Climate change · Bear Brook Watershed in Maine

Introduction

The dynamical variations in the biogeochemical fluxes in a watershed are inextricably tied to the attendant hydrologic variability and changes.
Changes in hydrologic fluxes (for example, flow volumes and high flow event frequency and duration), therefore, are likely to modulate the biogeochemical function and cycles, thus determining the future trajectory of ecosystem function and health (Poff et al. 1997; Hodgkins et al. 2003; Collins 2009). To this end, in the Bear Brook Watershed in Maine (BBWM) region, a key consideration is that of understanding the changes in the seasonality of streamflow, magnitude and frequency of high flow events, fluctuations in the seasonal runoff volume, and the moisture sources associated with high flow events.

Stream chemistry in forested catchments is strongly dependent on season because of biological processing (vegetative uptake and mineralization) of certain compounds in short supply. In particular, concentrations of potassium (K), magnesium (Mg), phosphorus (P), and nitrate (NO₃⁻) may be strongly seasonally controlled (Navrátil et al. 2010). As the watershed size increases, mixing of relatively new water with older water during discharge events causes a damping of this seasonality signal and a temporal prolongation of any surviving seasonality in chemistry. Varying discharge results in changing proportions of water following certain flow paths. In well-drained systems, such as BBWM, overland flow is relatively rare. Increasing discharge is associated with an expansion of the riparian zone away from the stream channel, and greater contact of groundwater with shallow organic-rich soils, prior to groundwater emergence into the stream (Pellerin et al. 2002; Hornberger et al. 1991). Typical changes in stream chemistry associated with increasing discharge include depressed pH and alkalinity; increased dissolved organic carbon (DOC), NO₃⁻, and monomeric ionic aluminum (Al); and decreased base cations (Ca, Mg, Na, K) (Laudon and Norton 2010).

Variations of season temperature and precipitation, collectively, have the capability of changing the timing and extent of high discharge events, thus altering the seasonality of stream chemistry and likely the fluxes of chemicals from the watershed (Navrátil et al. 2010). In this paper, we analyze the daily mean discharge at the East Bear watershed as well as the Narraguagus River with records of 20- and 60-year length, respectively. Three important considerations motivate the analysis presented here:

1. An understanding of the seasonality of streamflow, and delineation of principal flow seasons and their precursors in the large-scale atmospheric and ocean systems is a prerequisite to link watershed-scale changes in biogeochemical fluxes to the regional and global climate (for example, Likens 2004).

2. Coupled hydrologic and biogeochemical cycles operate at multiple time scales, ranging from episodic to seasonal, annual, decadal, and longer; consequently, an understanding of trends and variations at these time scales has the potential to elucidate mechanisms that dominated the biogeochemical fluxes and transitions in the past, and will likely be important in the future.

3. Changes in streamflow, induced by climate, reflect a range of large-scale hydroclimatic linkages that vary by season and have associated antecedents in the coupled ocean–atmosphere system. Thus, joint analysis of the hydrologic and climatic patterns coincident with the high flow events affords an opportunity to understand the regional sensitivity to global climatic variations and change.

Data and methods

The BBWM is a paired, forested watershed research site located in eastern Maine (44°52′15″ N latitude, 68°06′25″ W longitude), approximately 40 km inland from the Atlantic Ocean. The BBWM consists of two streams (East Branch Bear Brook and West Branch Bear Brook), with the 10.3 and 11.0 ha contiguous watersheds, respectively. Henceforth, East Branch Bear Brook is called East Bear. The watershed lies on the upper 210 m of the southeast slope of Lead Mountain, with a maximum elevation of 475 m. The mean temperature is about 4.9°C. Precipitation averages about 1,400 mm per year, but locally has ranged from 700 to 1,900 mm. The BBWM has a continental climate, with a mild maritime influence (Norton et al. 1999). The Narraguagus River is located near the BBWM running through the

We examined daily runoff data for the East Bear subwatershed (USGS 01022294; http://waterdata.usgs.gov/usa/nwis/uv?01022294) and the proximate Narraguagus River (USGS 01022500; http://waterdata.usgs.gov/usa/nwis/uv/?01022500) to understand the envelope of streamflow variability and develop a comprehensive view of the temporal dynamics of watershed processes in a changing climate. The BBWM drainage contributes to the Narraguagus. Daily discharge data from both watersheds, maintained by the U.S. Geological Survey, were considered as minimally affected by human influences such as streamflow regulation, urbanization, or groundwater pumping (Slack and Landwehr 1992; Dudley and Hodgkins 2005). We analyzed the first two decades of the East Bear record (1989–2008), which overlaps the Narraguagus River’s streamflow record (1949–2008). We compare streamflow data between these two stations through various statistical metrics including seasonal flow volumes, peak flows, and the timing of high flow events. We evaluated the relative coherence of East Bear and the Narraguagus River in hydrologic variability, as well as quantified the decadal and longer-term hydrologic variations in this region. We also focus on evaluating the potential shifts in flood frequency for high flow events during the various seasons, which may have a large impact on the biogeochemical processes and fluxes. Temporal changes in the frequency of seasonal high flow are evaluated using a 30-year moving window analysis. To understand how large-scale atmospheric circulation patterns modulate the regional and basin-scale hydrologic variables, we used 850-hPa geopotential height patterns and integrated moisture flux estimates coincident with the high flow episodes in the East Bear and Narraguagus River to understand the atmospheric circulation and moisture pathways in the atmosphere associated with select extreme events. The atmospheric data are based on the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis project (Kistler et al. 2001). Integrated moisture flux is obtained by multiplying the specific humidity and wind components from the surface to 300 mb. Composite maps for the geopotential heights and moisture flux are computed based on a grid-point wise averaging over a 4-day time window, beginning 2 days before the occurrence day to 1 day after the occurrence day of the high flow episode. In addition, historical records for the tropical cyclone tracks from the Atlantic Ocean were obtained from NOAA Coastal Services Center (http://www.csc.noaa.gov/digitalcoast/tools/hurricanes/) to identify the cases where remnants of these storms engender high flow events.

Hydrologic variations

Daily mean discharge variability is summarized as quantiles for each watershed. Figure 1 shows that the streamflow has a distinct seasonal character, with high discharge in the late fall, winter, and spring seasons. Low flows occur predominantly during the summer and early fall seasons. There is a strong synchrony between the seasonal evolution of streamflow for the East Bear (1989–2008) and the Narraguagus River (1989–2008). Furthermore, seasonal cycles of the interquartile range (IQR in Fig. 1, a robust measure of variability) of discharge show similarities in various seasons.

Seasonal changes in flow volume

Based on the seasonal variations in the median discharge and variability, we use four flow seasons for a detailed analysis—November–February (NDJF), March–May (MAM), June–July (JJ), and August–October (ASO) (Fig. 2). For East Bear, the fraction of the year flow volume is 38%, 45%, 5%, and 12%, respectively. The seasonal flow volumes are 36%, 44%, 6%, and 14% for the Narraguagus River, confirming the similarity in the hydrologic regime across the two watersheds. However, considering differences stemming from candidate factors such as drainage area, snow-covered areas, and storm duration and spatial
Fig. 1 Long-term quantile trends in the seasonal cycle of streamflow over the period 1989–2008.

a Flow quantiles for the Narraguagus River.
b Flow quantiles for the East Bear Brook River.
c Interquartile range (the difference between the 75th and 25th percentile of daily flows) for flow in the Narraguagus River.
d Interquartile range for flow in East Bear Brook River. All lines show 15-day smoothed variables.

extent, East Bear discharge shows a higher variability in all four seasons. The annual coefficient of variation (COV, the ratio of standard deviation to mean) for discharge during the four seasons for the East Bear is 0.87, while that for the Narraguagus is 0.68. Due to lower values of mean flow and high variability, streamflow variability is highest in the JJ and ASO seasons. Furthermore, seasonal COV is higher for East Bear (COV = 0.84, 0.68, 1.43, 2.22) than for the Narraguagus River (COV = 0.71, 0.55, 0.84, 0.98).

Seasonal flow for the two watersheds has substantial year-to-year variability (Fig. 2). During the NDJF season, the standardized flow volume during the 1999–2002 drought was persistently low, exceeding 1 standard deviation ($\sigma$). While the effects from this drought are less evident in other seasons, the longer record for the Narraguagus River shows multiple instances of successive 2-year dry periods (departures from the mean exceeding $1\sigma$) in the NDJF season. No significant long-term trends (based on a linear regression analysis) occur in the seasonal flow volume records. For the early fall season (ASO), high flow volume events on the Narraguagus River (exceeding $1\sigma$) occurred in 1996 ($1.81\sigma$), 2005 ($2.18\sigma$), and 2008 ($1.75\sigma$). The BBWM record has corresponding flow events to the Narraguagus River that show unusually high flow volumes in 1996 ($1.67\sigma$), 2005 ($1.92\sigma$), and 2008 ($1.99\sigma$). The longer record of the Narraguagus River shows two events exceeding $2\sigma$ in 1960 ($2.35\sigma$) and 1970 ($2.42\sigma$).

Seasonal changes in peak flow

For each season, a few years show some differences in the standardized peak flow magnitudes in the East Bear and Narraguagus River records, likely stemming from storm characteristics, and local temperature and snowpack variability (Fig. 3). For the NDJF season, peak flow on the Narraguagus River (exceeding $1\sigma$ from mean) occurred in 2006 and 2007; however, the
corresponding peaks for the East Bear show only modest departures from the mean. The East Bear record has a high flow event of magnitude $2.4\sigma$ in 1996. The longer Narraguagus record shows three historical events exceeding $2\sigma$ in 1960, 1970, and 1976. During the spring season (MAM), the largest flow event on East Bear occurred during 1989, with a magnitude similar to the corresponding high flow event on the Narraguagus River, both events exceeding magnitude of $2\sigma$. East Bear also experienced high flow events during 1998 ($1.53\sigma$) and 2005 ($1.41\sigma$). For the JJ and ASO seasons, no statistically significant trends in the seasonal flow were identified. Flow peaks during the JJ season have relatively smaller standard deviations. During the year 2006, both East Bear and the Narraguagus River experienced an unusually high flow event of $2.7\sigma$ magnitude. The longer record of Narraguagus River shows a $3.78\sigma$ event during 1961 as well as a $2.47\sigma$ event during 1979. The seasonal streamflow during the 2006 JJ season also mirrored the unusually high flow volumes, $3.22\sigma$ for East Bear and $3.34\sigma$ for the Narraguagus River. For the early fall season (ASO), the seasonal streamflow shows that the Narraguagus River flow was persistently higher during 1973–1981. During 2005, both East Bear and the Narraguagus River had unusual peak flow events, $2.33\sigma$ for East Bear and $3.17\sigma$ for the Narraguagus River. Furthermore, with a magnitude similar to the corresponding high flow event on the Narraguagus River, the largest flow event on East Bear occurred during 2003 ($1.48\sigma$). For the summer and early fall seasons, the analyses show that there is substantial interannual variability in streamflow.

We evaluated the timing of seasonal peak flow at the Narraguagus River for the years of data corresponding to the period of record (1989–2008) at the East Bear (Fig. 4). For a majority of years,
Seasonal peak flows were standardized by the long-term mean and standard deviation of flows (1989–2008).

The occurrence day of peak flow at the East Bear matches with peak day at the Narraguagus River in the four seasons. However, some high flow episodes show considerable difference in the date of the events. Numerous factors including response time for rainfall, differences in timing of snowmelt, snowpack water content, and storm duration and spatial extent are likely responsible for these observed differences. To the extent that high flow events have a disproportionally large impact on biogeochemical fluxes, the analysis of co-variability in hydrology for the two streams provides a useful window into the short- and long-term variability of these extreme events and their impacts on watershed-scale fluxes.

Interannual and long-term variations in various statistical metrics of hydrologic variability confirm co-variability of seasonal streamflow between the East Bear and the Narraguagus River. To understand the decadal and longer-term hydrologic variations, potentially stemming from natural and anthropogenic climate influences, we pursued a moving window analysis of high flow events and large-scale atmospheric circulation patterns associated with select events.

**Potential shifts in flood frequency for high flows**

The high flow events and their attendant variability determine the envelope of hydrologic and biogeochemical flux variability from the East Bear. The longer record for the Narraguagus River is a useful proxy archive of hydrologic variability for this region and East Bear. In this regard, long-term changes in the magnitude of seasonal peak flows are of particular interest. Here, we examine changes in the magnitude of high flow events (or seasonal flood) using flood frequency analysis applied to a 30-year moving window to quantify
temporal changes in high flow frequency for each of the four seasons. We computed the 50-year return period floods based on the 30-year moving window and fitted to a lognormal distribution (Fig. 5). Repeated sampling of data, using 30 randomly picked events and subsequently estimating the 50-year return period event was used to determine the 90% confidence level (dashed lines in Fig. 5). Lognormal distribution is characterized based on the mean and standard deviation of log-transformed peak flow data. The utility of pursuing a flood frequency analyses is that it allows a simultaneous assessment of the commingling effects of changes in the mean and variability of streamflow in a multidecadal time window. In other words, a 30-year moving window helps assess the slow variations in climate (multidecadal oscillations and secular trends) and at the same time the higher frequency effects are captured by the mean and standard deviations estimates. Thus, the moving window, empirical assessment of the non-stationarity captures the joint effect of the changes in the mean and variability over time.

For the NDJF season, the estimates show substantial decadal scale variability with a modest decrease over the 1949–2008 period (Fig. 5a). In the spring season (MAM), there is a near-monotonic increase over the 60-year record. Changes in the spring flood potential are particularly important for transport and variability of dissolved organic carbon, among other constituents (Hornberger et al. 1994). As a result, long-term trends have the potential to dramatically alter the timing and intensity of carbon cycling in the watersheds. During the JJ season, the overall variability in seasonal high flow is relatively small compared to the other season. While our analysis revealed no statistically
significant long-term change in the flood potential (Fig. 5c), a modest increase in the magnitude of high flow events occurs. The flood potential during the early fall season (ASO) decreased up to the mid-1990s, then steeply increased in recent years. In Fig. 6, we show the annual maximum flood (AMF) time series by season. This analysis affords a diagnosis of the relative importance (based on magnitude) and long-term trends of the seasonal floods. Of particular interest is the relatively large number of AMF events during the MAM and NDJF seasons. However, in the past decade, ASO seasonal floods have emerged as the AMF (in 2004, 2006, and 2008). There is no significant trend in annual maximum floods (Fig. 6). The emergence of early fall season floods as the AMF is likely to have important bearing on the DOC and other chemical fluxes.

**Empirical relationship between streamflow and large-scale atmospheric circulation patterns**

Extreme hydrologic events have precursors in large-scale atmospheric circulation, especially the atmospheric moisture flux, although local hydrologic conditions are important (Mo and Berbery 2004; Dominguez and Kumar 2005). To understand how atmospheric moisture transport controls the sensitivity of the regional flood regime is a critical step to improve prediction of basin-scale hydrologic variability (Dominguez and Kumar 2005). The moisture pathways and source regions impact the magnitude of hydrologic fluxes as well as the chemical composition of precipitation, including marine aerosols. In this section, we investigate the regional large-scale climatic variations leading up to the individual high flow
**Fig. 6** Daily streamflow from the Narraguagus River in Maine over the period 1949–2008. Annual maximum flow time series (solid line) shows with appropriate labeling for the season during which the event occurred. The distribution of seasonal flows is shown with different symbols. The 90th percentile of total flows is shown in the dotted line.

![Graph showing daily streamflow from the Narraguagus River in Maine over the period 1949–2008.](image)

**Fig. 7** Seasonal peak flow events during the August–October season in the Narraguagus River, Maine. *Inset* the seasonal time series for the 1949–2008 record. Daily streamflows in four high flow years (2003, 2005, 2006, and 2008) are plotted with different color lines.

![Graph showing seasonal peak flow events in the Narraguagus River, Maine.](image)
episodes. In Fig. 7, seasonal maximum flows (ASO) at the Narraguagus River are shown in the small panel. Four high flows from summer to fall are highlighted for the period of record coincident with the period of record at the East Bear (1989–2008). For these four cases, we examined the distribution of moisture flux and atmospheric circulation pattern that are archetypal of the moisture pathways during this season. Figure 8a shows the 4-day cumulative moisture flux, coincident with the 2005 high flow event at the Narraguagus River. The positive and negative geopotential height anomalies (departures from the mean state) show consistent circulation and movement of moisture to the Narraguagus and East Bear region. While the 2003 and 2005 events have moisture antecedents in the tropics (Fig. 8a and c), with favorable circulation patterns for moisture movement to the watershed region, the 2006 events (Fig. 8d) show a negative circulation.

**Fig. 8** Four-day composite patterns for the geopotential height and the gridded integrated moisture flux from the NCEP–NCAR reanalysis. **a** Composite variables coincident with the 2005 event. **b** Composite variables coincident with the 2008 event. The green line represents the path of Hurricane Hanna. **c** Composite variables coincident with the 2003 event. **d** Composite variables coincident with the 2006 event. The contour lines show 850 mb geopotential height composite anomalies (departures from the long-term mean) of variables. Mean patterns are computed by averaging the time series at each grid point for the 1968–1996 period. The positive composite anomalies are shown in blue line and negative values are in red. The integrated moisture flux (kg/ms) composite mean is shown by vectors. Composite variables were considered within a window ranging from 2 days before the occurrence of seasonal flood to 1 day after the occurrence day of seasonal flood during the August–October season.
anomaly over the Great Lakes region, extending into the northeastern United States, with moisture flux along the eastern seaboard. The high flow event in 2008 (Fig. 8b) was related to the weakening Hurricane Hanna. Hurricane Hanna formed east-northeast of the northern Leeward Islands on August 28, 2008. It became an extra-tropical storm as it exited Massachusetts, and its remnants caused rainfall in Maine and northeastern Canada. Analysis of individual high flow events and their atmospheric analog provides a broader context to understand the integrated evolution of watershed hydrologic and chemical processes. The analysis also highlights that future changes in the moisture sources will not only impact the magnitude of floods but also modulate the chemical fluxes and deposition, thus potentially setting the future trajectory for chemical fluxes and cycling in Maine’s watersheds.

Conclusions

A joint analysis of the seasonal flow volumes and high flow events was pursued for the East Bear and Narraguagus River, Maine, USA. Seasonal cycle of stream flow and substantial interannual and longer-term variations occur for the four seasons (NDJF, MAM, JJ, and ASO). The seasonal flows and floods for the two watersheds show high coherence, with some flood events showing differences in their timing. The March–May season shows highest coherence in timing due to the dominant snowmelt processes. For the Narraguagus River, a seasonal flood frequency analysis, applied to a 30-year moving window, revealed changes in the 50-year flood potential over the 1949–2008 period. The moving window analysis captures the commingling effects due to changes in both the mean and standard deviation over time. Floods estimates show an upward trend during the past decade for all seasons. These trends are particularly pronounced in the MAM, ASO, and JJ seasons. The MAM season shows a monotonic increase in flood frequency over the length of the record. This trend, although not statistically significant, may have important impacts on a number of biogeochemical processes that are seasonally coupled to the snowmelt. Rapid increase in the flood estimates for the ASO season has resulted in the timing of annual maximum flood shift to the ASO season during three recent years (2004, 2006, and 2008). There is no previous incidence of such high flows during ASO seasons; historically, the AMF events are largely concentrated in the MAM and NDJF seasons.

Changes in hydrologic flux may have considerable influence on the dynamical variations in the biogeochemical fluxes, thus determining the future trajectory of ecosystem function and health. Consequently, the analysis presented suggests that a careful characterization of the episodic-to-seasonal and longer-term streamflow variations is a first step toward developing a comprehensive view of the temporal dynamics of watershed processes in a changing climate. The results broaden the understanding of the impact of seasonal flows and extreme hydrologic events in imparting a structure to the seasonal flux and cycling of chemical components at East Bear. Long-term variability and trends illuminate the need to carefully analyze hydrologic and chemical records for potential changes in the seasonality of chemical transport processes as well as flux thresholds that may have important long-term consequences for the watershed chemistry.

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