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INCREASED FREQUENCY OF LOW-MAGNITUDE FLOODS IN NEW ENGLAND[1]

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ABSTRACT: Recent studies document increasing precipitation and streamflow in the northeastern United States throughout the 20th and early 21st Centuries. Annual peak discharges have increased over this period on many New England rivers with dominantly natural streamflow – especially for smaller, more frequent floods. To better investigate high-frequency floods (<5-year recurrence interval), we analyze the partial duration flood series for 23 New England rivers selected for minimal human impact. The study rivers have continuous records through 2006 and an average period of record of 71 years. Twenty-two of the 23 rivers show increasing trends in peaks over threshold per water year (POT/WY) – a direct measure of flood frequency – using the Mann-Kendall trend test. Ten of these trends had $p < 0.1$. Seventeen rivers show positive trends in flood magnitude, six of which had $p < 0.1$. We also investigate a potential hydroclimatic shift in the region around 1970. Twenty-two of the 23 rivers show increased POT/WY in the post-1970 period when comparing pre- and post-1970 records using the Wilcoxon rank-sum test. More than half of these increases have $p < 0.1$, indicating a shift in flow regime toward more frequent flooding. Region wide, we found a median increase of one flood per year for the post-1970 period. Because frequent floods are important channel-forming flows, these results have implications for channel and floodplain morphology, aquatic habitat, and restoration.

(KEY TERMS: floods; climate variability; hydroclimatology; aquatic habitat; New England; restoration.)

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INTRODUCTION

Importance of High-Frequency Floods

Frequent, low-magnitude floods dictate alluvial channel morphology. Catastrophic floods (i.e., those that occur less frequently than once in every 10 years), despite their erosive capabilities, transport a relatively small portion of total sediment flux through a channel because they occur so infrequently. In many drainage basins, floods occurring, on average, once a year account for 50% of total sediment flux out of the basin; 90% of sediment flux is transported by flows occurring at least once every five years (Wolman and Miller, 1960). Although catastrophic floods are usually responsible for channel avulsions, stream barrier breaches (e.g., dams), and transporting large bed-load particles, floods occurring every one or two years are more active agents in shaping the prevailing channel dimensions because of their frequency and ability to erode and transport

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bank and bed material (Leopold and Wolman, 1960; Pickup and Warner, 1976; Andrews, 1980).

Frequent, low-magnitude floods are also important for riparian and aquatic habitat. Biota have evolved to be well suited to their environment, which in a river system includes bed substrate type, sediment transport rate, and flow regime (Bunne and Arthington, 2002). Floods can shape community structure directly, for example, by mortality through bed scour, burial, or removal from suitable habitat. Frequent, low-magnitude floods also indirectly shape communities by acting as a disturbance agent by altering nutrient distribution, rearranging sediment, and removing individual organisms, creating "patchiness" that fosters biodiversity (Bendix, 1997). Furthermore, comparatively frequent floods that overtop channel banks provide a connection between the river and its floodplain, exchanging nutrients, organisms, and sediment (Junk *et al.*, 1989; Poff, 2002). Recognizing the geomorphic and ecologic importance of high-frequency floods, river restoration practitioners have identified floods with recurrence intervals (RIs) typically in the range of one to two years ($Q_{1\text{-}2}$) as important channel design criteria (Rosgen, 1996). There have also been significant efforts to more precisely identify the RIs of these "channel-forming" flows for specific regions – that is, "regional curves" – to better support restoration design (e.g., White, 2001; Sweet and Geratz, 2003).

Given the significance of high-frequency floods for channel morphology, ecology, and restoration, changes in flood regime will have important implications for channel process, function, and management. The geomorphic and ecological effects of flood regime changes caused by anthropogenic flow regulation and land cover change are well documented in the literature (Hammer, 1972; Arnold *et al.*, 1982; Rood and Mahoney, 1990; Booth and Jackson, 1997; Moscrip and Montgomery, 1997; Fitzpatrick *et al.*, 2005). For example, Rood and Mahoney (1990) showed that the spatial patterns of ecosystem structure, partially determined by the low-intermediate magnitude flood regime, were sensitive to a shift in that flood regime via regulation and the consequent changes in the frequency and duration of floodplain inundation. Booth and Jackson (1997) found that increased flood frequency following watershed urbanization, which increases flood magnitude and frequency by increasing surface runoff, resulted in channel widening and/or incision and degraded aquatic habitat. The effects of urbanization on flooding, channel form, and aquatic habitat suggest the type and degree of changes we might expect from hydroclimatic increases in flood magnitude and frequency recently documented in New England.

Hydroclimatic Flood Trends in the Northeastern United States

Collins (2009) and Hodgkins (2010) documented increasing annual flood magnitudes at New England stream gauges with dominantly natural streamflow. Their findings are consistent with precipitation trend research that shows a 10% increase in total precipitation across the conterminous United States (U.S.) that is disproportionately caused by an increased frequency and intensity of events in the upper 10th percentile of the daily precipitation distribution (Karl and Knight, 1998; Min *et al.*, 2011). Trends in low exceedance probability precipitation events have been particularly pronounced in the Northeast U.S. (Groisman *et al.*, 2001; Madsen and Figdor, 2007; Spierre and Wake, 2010; Douglas and Fairbank, 2011). The precipitation and flood data from that region suggest that increases have occurred as a step change around 1970 (Groisman *et al.*, 2001; Collins, 2009; Hodgkins, 2010; Villarini and Smith, 2010; Douglas and Fairbank, 2011), which is a date other investigators have identified in trend analyses of various hydrologic variables in the eastern U.S. (McCabe and Wolock, 2002; Mauget, 2003).

These changes are consistent with expectations of an intensified hydrologic cycle in some areas of the planet as a consequence of anthropogenic climate warming (Huntington, 2006). However, Collins (2009) noted that the timing of step increases in New England flooding is generally synchronous with a well-documented phase change in the low-frequency variability of the North Atlantic Oscillation (NAO), an upper atmospheric circulation pattern that affects climate variability in the eastern U.S. and other areas of the Northern Hemisphere. He found a weak, but statistically significant, positive, lagged correlation between the NAO and New England floods. Bradbury *et al.* (2002a,b) and Kingston *et al.* (2007) have also found weak, but statistically significant, positive relationships between the NAO and New England streamflow. Although the NAO is a persistent feature of upper atmospheric circulation and is thus an expression of natural climatic variability, recent research has suggested that anthropogenic climate change may be related to the dominantly positive phase since 1970 (Hoerling *et al.*, 2001; Sutton and Hodson, 2003; Lu *et al.*, 2004; King and Kucharski, 2006) and could continue it (Rind *et al.*, 2005).

Because New England annual maximum flood series (AMS) show step changes around 1970, Collins (2009) constructed statistical flood frequency estimates using different time windows and showed that curves made using post-1970 data estimated higher discharges at a given annual exceedance probability than those using the pre-1970 data. Interestingly,

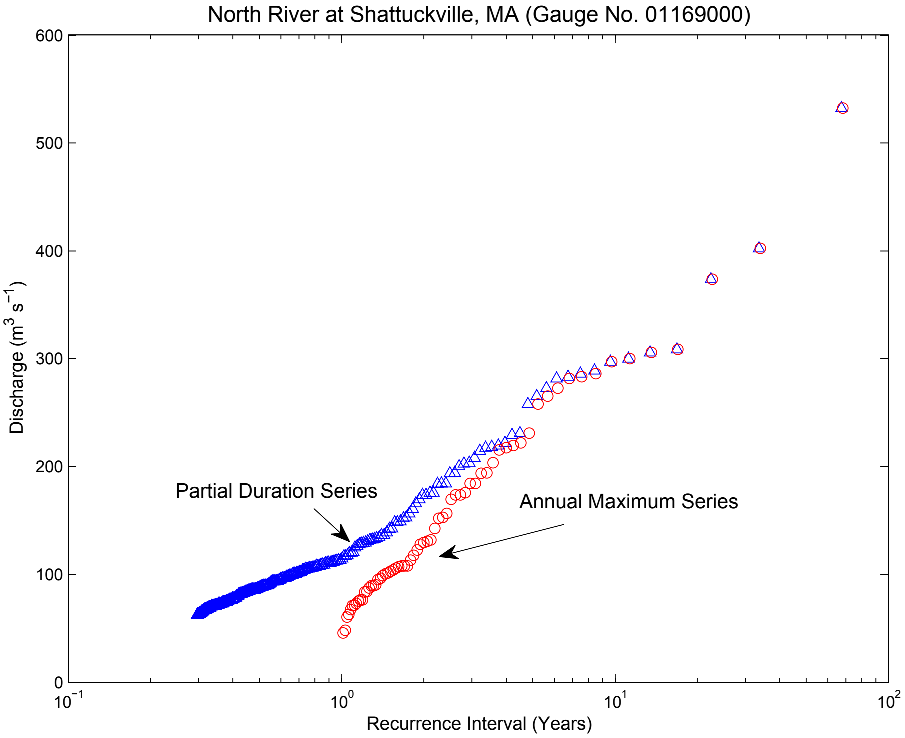

FIGURE 1. Example of Magnitude and Frequency Estimates Calculated Using the PDS Compared With Those Calculated Using the AMS. The PDS includes many more low-magnitude events and thus calculates a greater discharge for floods recurring, on average, at least once every 10 years.

high-frequency events showed the largest proportional increases. This finding motivates our study. Here, we explore these high-frequency floods in greater detail by analyzing the partial duration flood series (PDS) for a subset of the rivers Collins (2009) investigated. We also investigate relationships between New England floods and the NAO. In contrast to the AMS, which records only the largest flood of each year, the PDS includes all floods greater than, or equal to, a specified threshold discharge (TD) and thus incorporates many more low-magnitude, high-frequency events (Figure 1). The PDS therefore allows for more robust analyses of high-frequency floods and, importantly, it provides a means for a direct measure of flood frequency trends by enabling analyses of changes in annual threshold exceedances.

METHODS

Data Sources

We obtained PDS data from the U.S. Geological Survey (USGS) state offices. We selected gauges from the USGS Hydro-Climatic Data Network (HCDN), a compilation of river gauges that are minimally affected by human use and are the best available representation of natural streamflow throughout the U.S. (Slack and Landwehr, 1992). Collins (2009) analyzed 28 HCDN streams in New England that had at least 56 continuous years of record until water year (WY; October 1 to September 30) 2006 and were unaffected by flow regulation. We focus on 23 of the rivers researched by Collins (2009), with the same criteria for inclusion of data (Table 1 and Figure 2). Five gauging stations used by Collins did not have PDS records available. At 4 of the 23 gauging stations we analyzed, the PDS was not recorded in the early years. Therefore, the period of record for these rivers is truncated compared with the period of record Collins (2009) analyzed. The shortest period of record in this study is 59 years, and the longest 81 years, with an average of 71 years (Table 1). The rivers are distributed throughout New England, with at least two gauges in each state, except for Rhode Island. The rivers drain diverse locations, from the lowlands of southern Connecticut to mountainous western Maine, and include a broad watershed size range (10 to 7,000 km^2), with a median around 250 km^2. Eastern Massachusetts and Rhode Island are not well represented, primarily because of the changing land use and river regulation in these areas.

TABLE 1. Gauges Used in This Study, Shown on Figure 2.

Number on Figure 2	USGS Gauge Station Number	USGS Gauge Station Name	Drainage Area (km^2)	Period of Continuous Record	Threshold Discharge (m^3/s)
1	01010500	St. John River at Dickey, ME	6,941	1947-2006	764.6
2	01022500	Narraguagus River at Cherryfield, ME	588	1948-2006	56.6
3	01031500	Piscataquis River near Dover-Foxcroft, ME	772	1931-2006	113.3
4	01038000	Sheepscot River at North Whitefield, ME	376	1939-2006	31.1
5	01047000	Carrabassett River near North Anson, ME	914	1926-2006	169.9
6	01052500	Diamond River near Wentworth Location, NH	394	1942-2006	101.9
7	01055000	Swift River near Roxbury, ME	251	1930-2006	68.0
8	01057000	Little Androscoggin River near South Paris, ME	190	1932-2006	28.3
9	01064500	Saco River near Conway, NH	997	1930-2006	246.4
10	01073000	Oyster River near Durham, NH	31.5	1935-2006	4.8
11	01076500	Pemigewasset River at Plymouth, NH	1,611	1928-2006	356.8
12	01078000	Smith River near Bristol, NH	222	1934-2006	32.6
13	01121000	Mount Hope River near Warrenville, CT	74	1941-2006	11.3
14	01134500	Moose River at Victory, VT	195	1947-2006	28.3
15	01137500	Ammonoosuc River at Bethlehem Junction, NH	227	1940-2006	76.5
16	01142500	Ayers Brook at Randolph, VT	79	1940-2006	9.9
17	01144000	White River at West Hartford, VT	1,787	1929-2006	328.5
18	01169000	North River at Shattuckville, MA	231	1940-2006	62.3
19	01181000	West Branch Westfield River at Huntington, MA	244	1936-2006	76.5
20	01188000	Burlington Brook near Burlington, CT	10.6	1932-2006	4.0
21	01193500	Salmon River near East Hampton, CT	259	1929-2006	36.8
22	01196500	Quinnipiac River at Wallingford, CT	298	1932-2006	25.5
23	01204000	Pomperaug River at Southbury, CT	195	1933-2006	39.6

Notes: ME, Maine; NH, New Hampshire; CT, Connecticut; VT, Vermont; MA, Massachusetts.

All threshold discharges were published in USGS annual water data reports except for the two Massachusetts gauges, which were provided via email on 2009-01-30.

The dominant flood-producing mechanism varies between watersheds based on their elevation and distance from the ocean, including frontal and convective rainfall, snowmelt, rain-on-snow events, and hurricanes (Magilligan and Graber, 1996). Despite variations in watershed attributes, several hydroclimatic characteristics apply to all of the rivers. Much of the flooding occurs in March and April, produced by snowmelt and/or precipitation on frozen, impermeable soil. Precipitation in New England is relatively well distributed throughout the year with about 10 cm of rainfall per month, although it increases slightly in coastal areas in autumn (Magilligan and Graber, 1996).

We obtained NAO indices from the National Center for Atmospheric Research (NCAR) (see http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html, *accessed* October 2011). We used the annual principal component (PC)-based index and the winter (December-March; DJFM) PC-based index. The PC-based index is composed of the leading empirical orthogonal function of sea level pressure anomalies over the Atlantic from 20 to 80° N and 90° W to 40° E. The PC-based index is a better representation of the state of the NAO than station-based indices because it is not spatially limited and can track the NAO as its centers of action migrate throughout the year (Hurrell *et al.*, 2003).

The Partial Duration Series

Although the AMS includes only the highest instantaneous discharge observed in a given WY, the PDS includes as a flood any streamflow greater than, or equal to, a fixed TD. The TD for a river is often set as the smallest annual maximum discharge observed over a long record, or as a value that is expected to be equaled or exceeded three to four times per year (Langbein, 1949). Any discharge that equals or exceeds the TD is then recorded as a flood peak over threshold (POT). The PDS includes many more data points than the AMS, which gives it better resolution for analyzing trends in high-frequency, low-magnitude floods – many of which are not recorded in the annual flood series (Sweet and Geratz, 2003). The PDS time series for the gauges we evaluated were obtained from the USGS and are defined by the TDs established by them for each gauge (Table 1).

The USGS performs various data quality reviews, including efforts to assure that only independent events are reported for each PDS (Julie Kiang, USGS, 2009, personal communication). We conducted a limited investigation to verify this by comparing the watershed response times of five drainages representative of the basin size classes in our study (10^1, 10^2, and 10^3 km^2) with the minimum duration sepa-

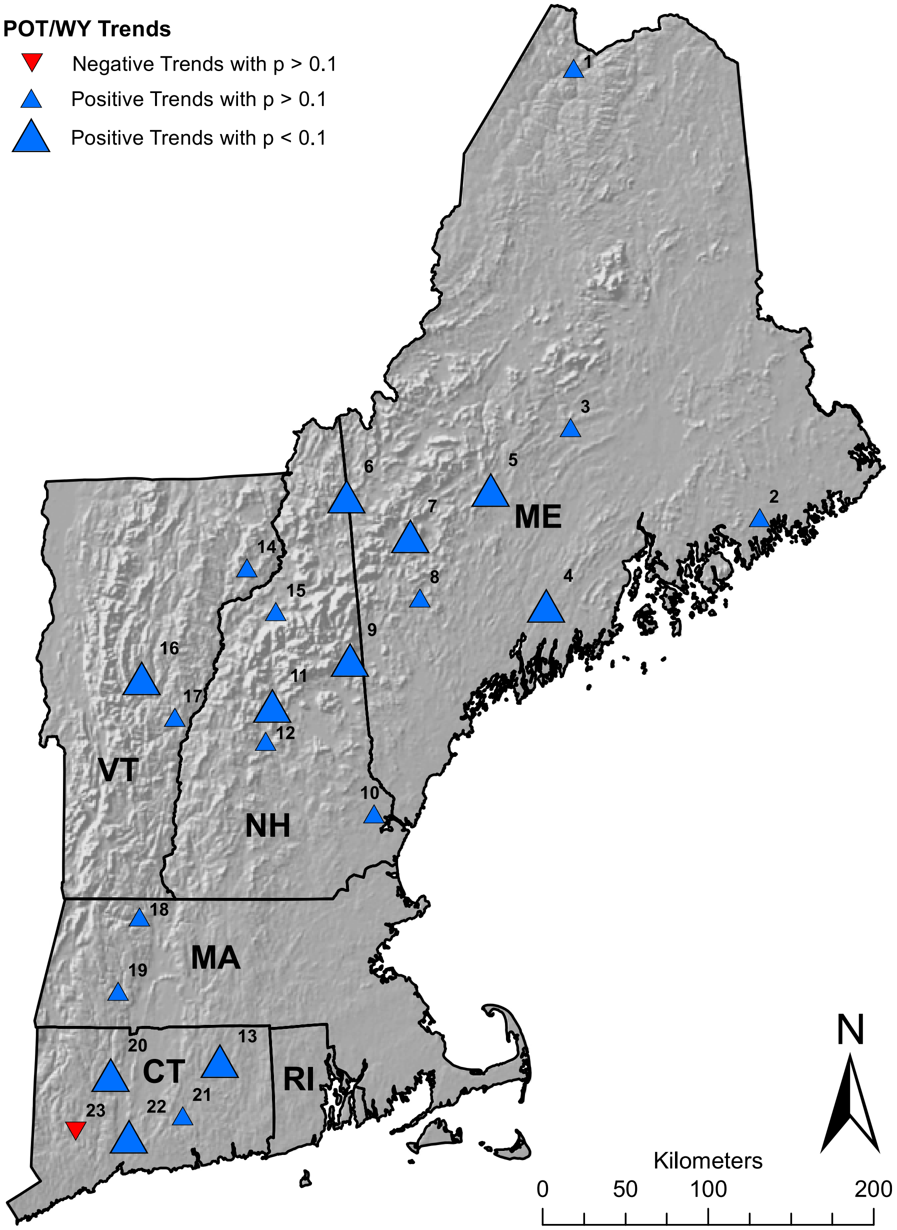

FIGURE 2. Spatial Distribution of Flood Frequency (POT/WY) Trends.

rating recorded partial peaks in those basins. We used centroid lag-to-peak (T_{LPC}), measured in hours, as a rough measure of response time (Dingman, 2002) and estimated parameters for our representative watersheds using USGS StreamStats (Ries *et al.*, 2008). For all five watersheds, we found that the comparatively few events that are close in time in each PDS are at least separated by the watershed response time (i.e., T_{LPC}), with nearly all cases separated by five times T_{LPC} or longer. The USGS includes the annual peak discharge in the PDS for years in which streamflow never surpasses the TD, a circumstance that occurs in comparatively dry years. In this study, we omitted these events to establish a consistent definition of a flood (flow greater than, or equal to, the TD) throughout the time series and thus maintain a true PDS.

Trend Analyses

We used the nonparametric Mann-Kendall trend test to evaluate temporal trends in both flood frequency (i.e., the number of times flow exceeded the TD in a water year; POT/WY) and magnitude (i.e., discharge). The Mann-Kendall test is a rank-based, nonparametric test that describes the strength of the monotonic relationship between the test variables, which in our study were time and POT/WY (frequency trends) or time and discharge (magnitude trends) (Helsel and Hirsch, 2002).

We calculated trend magnitudes for our analyses of flood discharge trends using the Kendall-Theil robust line with Sen slope, which we present as percent changes over the period of record. We did not calculate trend magnitudes for the analyses of flood frequency (i.e., POT/WY) trends because the discrete form of the data resulted in many ties between data points, which confounds computing trend magnitude estimates via the Kendall-Theil robust line.

Investigating NAO Linkages

Collins (2009) found a correlation at $p < 0.1$ between the winter NAO index and a series of averaged standardized departures for 23 New England flood series lagged by one year (e.g., the winter NAO index from December 1940 to March 1941 compared with the average standardized departures of annual peaks for WY 1942; lag-one). We continued investigating the linkage between the NAO and New England flooding by comparing a time series of total POT/WY for the whole region with the annual and winter PC-based NAO indices. We summed the POT/WY for the 19 gauging stations with records beginning in WY 1941 or earlier to create a set of total POT/WY. We used 1941 as a start date to keep a long record length while excluding as few gauges as possible. We then performed a nonparametric Kendall's tau correlation analysis between the annual and winter NAO indices and the time series of total POT/WY for the region. We investigated both direct comparisons between the NAO time series and the POT/WY time series (e.g., the NAO index from 1941 with the POT/WY from WY 1941; concurrent indices) and a comparison of the NAO time series with the POT/WY lagged by one year.

Evaluating Potential Step Changes in Flood Series

We investigated potential step changes in flood magnitude and frequency around the year 1970, a date around which hydroclimatic shifts have been documented in the eastern U.S. and elsewhere (McCabe and Wolock, 2002; Mauget, 2003; Collins, 2009; Massei *et al.*, 2009; Hodgkins, 2010; Villarini and Smith, 2010; Douglas and Fairbank, 2011). To do so, we used the nonparametric Wilcoxon rank-sum test. For each time series, we separate the data into two subseries at 1970 and test whether the two subseries show a difference in flood magnitude or flood frequency (POT/WY) between them. Any floods occurring before October 1, 1970 were placed in one group (pre-1970) and events occurring between October 1, 1970 and September 30, 2006 were placed in another group (post-1970).

Persistence and Spatial Correlation

The Mann-Kendall and Wilcoxon rank-sum tests, and many others that assume independent and identically distributed (IID) data, may overestimate trend significance if the data are serially correlated (i.e., one data point influences the value of another). PDS data can be serially correlated in frequency (i.e., floods occur in temporal clusters) and/or in magnitude (i.e., the magnitude of one flood affects that of a subsequent event). Because other investigators have noted temporal clustering of floods in PDS time series (i.e., some years having more POT than other years; Cunnane, 1979; Robson *et al.*, 1998), we estimated the *p*-values for our trend (Mann-Kendall) and step trend (rank-sum) tests for the POT/WY time series using both conventional methods that assume data independence (IID) and Monte-Carlo resampling techniques that estimate *p*-values directly from the data and require no assumption of independence. We also did so for our Kendall's tau correlations to investigate linkages between the NAO and POT/WY. We use the methods of Robson *et al.* (1998) and Kundzewicz and Robson (2000) to conduct permutation tests (resampling without replacement) on our data, creating the null distributions of our test statistics by randomly block permuting each POT/WY time series 1,000 times in WY blocks. We present both conventional and permutation test *p*-values with our Mann-Kendall and rank-sum test results for the POT/WY time series to demonstrate that any effect of serial correlation in frequency is modest (Table 2). Changnon and Kunkel (1995) report a similar finding for PDS data they evaluated from upper Midwest stream gauges. We also found that the conventional test *p*-values and permutation test *p*-values for our Kendall's tau correlations between NAO indexes and POT/WY data were virtually the same, thus we only report the conventional test *p*-values.

We evaluated serial correlation in flood magnitude differently: for each PDS we smoothed the data using locally weighted regression (LOESS) and calculated Kendall's tau between the residuals and lag-one residuals (Cleveland and Devlin, 1988; Helsel and Hirsch, 2002). LOESS smoothed time series ("LOESS smooths" or "smooths") are created by segmenting the data series, fitting a polynomial regression line to each portion, and then merging the series, resulting in a best-fit line that well describes variance between the variables. Because the smooth line is determined

TABLE 2. Temporal Trends in Flood Frequency (POT/WY) and Rank-sum Results.

Number on Figure 2	Gauge Station	Frequency Trend	Mann-Kendall p	Monte-Carlo p	Median POT/WY Pre-1970	Median POT/WY Post-1970	Change in POT/WY	Percent Change	Rank-sum Direction	Rank-sum p	Monte-Carlo p
1	St. John R.	+	0.274	0.246	2	2	**0**	**0.0**	**+**	**0.087**	**0.044**
2	Narraguagus R.	+	0.169	0.160	3	4	1	33.3	+	0.263	0.242
3	Piscataquis R.	**+**	**0.089**	0.100	3	3	0	0.0	+	0.133	0.124
4	Sheepscot R.	**+**	**0.072**	**0.090**	2	3	**1**	**50.0**	**+**	**0.037**	**0.036**
5	Carrabassett R.	**+**	**0.089**	**0.088**	2	3	**1**	**50.0**	**+**	**0.098**	0.100
6	Diamond R.	+	0.105	**0.084**	1	2	1	100.0	+	0.104	0.114
7	Swift R.	**+**	**0.061**	**0.050**	2	4	**2**	**100.0**	**+**	**0.039**	**0.046**
8	Little Androscoggin R.	+	0.101	0.110	3	3	**0**	**0.0**	**+**	**0.084**	0.100
9	Saco R.	**+**	**0.070**	**0.084**	2	3	**1**	**50.0**	**+**	**0.032**	**0.026**
10	Oyster R.	+	0.929	0.916	2	2	0	0.0	+	0.641	0.688
11	Pemigewasset R.	**+**	**0.079**	**0.090**	2	3	**1**	**25.0**	**+**	**0.088**	**0.090**
12	Smith R.	+	0.541	0.504	1	2	1	100.0	+	0.132	0.114
13	Mount Hope R.	**+**	**0.009**	**0.014**	4	6	**2**	**50.0**	**+**	**0.001**	**0.002**
14	Moose R.	+	0.170	0.154	3	3	0	0.0	+	0.221	0.210
15	Ammonoosuc R.	+	0.230	0.260	2	2	0	0.0	–	0.807	0.768
16	Ayers Br.	**+**	**0.081**	**0.086**	3	3	**0**	**0.0**	**+**	**0.063**	**0.056**
17	White R.	+	0.540	0.568	2	2	0	0.0	+	0.194	0.230
18	North R.	+	0.143	0.150	2	4	**2**	**100.0**	**+**	**0.018**	**0.038**
19	West Branch Westfield R.	+	0.477	0.540	2	3	**1**	**50.0**	**+**	**0.085**	**0.084**
20	Burlington Br.	**+**	**0.011**	**0.014**	2	4	**2**	**100.0**	**+**	<**0.001**	**0.002**
21	Salmon R.	+	0.148	0.138	3	4	**1**	**33.3**	**+**	**0.017**	**0.022**
22	Quinnipiac R.	**+**	<**0.001**	**0.002**	3	8	**5**	**166.7**	**+**	<**0.001**	**0.002**
23	Pomperaug R.	–	0.738	0.678	3	3	0	0.0	+	0.588	0.592
	Median				2	3	1	33.3			

Note: Test results with $p < 0.1$ are bolded.

only by the data, it does not require *a priori* knowledge of the relationship between variables (Helsel and Hirsch, 2002). We used a smoothing parameter of 0.5. Only four (17%) of our time series showed evidence for lag-one serial correlation in magnitude. We evaluated the effect of this serial correlation on our flood magnitude trend and step trend investigations by systematically removing events close in time in the affected time series until the data were no longer serially correlated and then rerunning our statistical tests (Helsel and Hirsch, 2002). For each cluster of events where we removed data, we retained the largest event. Because we found that we obtained substantially the same statistical results (test statistics and estimated p-values) from our resampled data series as we did from the full data series, and only a minority of our time series were affected, we report only our results from the full data series for our flood magnitude trend and step trend tests (Table 3).

Cohn and Lins (2005) and Koutsoyiannis and Montanari (2007) showed that reporting the statistical significance (p-values) of trends observed via the Mann-Kendall test, and others like it that assume the underlying flood-generating process is random, may be meaningless when long-term persistence (LTP) is present. However, trend direction and magnitude estimates are not similarly affected by LTP. As LTP can neither be verified nor discounted for the flood series analyzed in this study, all trend directions and magnitudes are reported and p-values are used simply as thresholds to indicate the relative trend strength with no assertion of statistical significance (Douglas and Fairbank, 2011). Reporting p-values also allows us to present our results in a manner consistent with most previous hydrologic trend studies. We evaluate relative trend strength with $p < 0.1$ as a threshold value. This approach is appropriate because trends in hydrologic time series are important on engineering and planning time scales (10^1-10^2 years) even if they may not be statistically significant over longer time periods (10^2-10^4 years and longer) (Collins, 2009; Douglas and Fairbank, 2011).

Douglas *et al.* (2000) and Lettenmaier *et al.* (1994) have shown that spatial correlation of streamflow records can substantially reduce the number of independent sites for statistical analyses. However, we do not evaluate regional trends using a single test statistic and thus avoid the need to explicitly account for spatial correlation (McCabe and Wolock, 2002; Lins and Slack, 2005; Collins, 2009). We statistically analyze the flood records for each gauge site independently and simply tabulate the station results.

TABLE 3. Temporal Trends in Flood Magnitude and Rank-sum Results.

Number on Figure 2	Gauge Station	Magnitude Trend	Percent Change (%)	Mann-Kendall p	Rank-sum Direction	Rank-sum p
1	St. John R.	+	7.96	0.325	**+**	**0.038**
2	Narraguagus R.	−	−1.48	0.798	−	0.816
3	Piscataquis R.	**+**	**13.91**	**0.071**	+	0.177
4	Sheepscot R.	+	9.14	0.148	+	0.256
5	Carrabassett R.	+	3.78	0.583	+	0.497
6	Diamond R.	+	6.48	0.242	+	0.483
7	Swift R.	**+**	**21.55**	**0.023**	+	0.137
8	Little Androscoggin R.	**−**	**−10.71**	**0.071**	−	0.212
9	Saco R.	+	10.98	0.114	+	0.172
10	Oyster R.	+	1.02	0.900	−	0.582
11	Pemigewasset R.	+	10.40	0.112	+	0.161
12	Smith R.	−	−1.40	0.835	−	0.545
13	Mount Hope R.	**+**	**17.57**	**0.007**	**+**	**0.048**
14	Moose R.	+	5.53	0.425	+	0.543
15	Ammonoosuc R.	**+**	**13.96**	**0.031**	**+**	**0.015**
16	Ayers Br.	−	−5.03	0.419	−	0.114
17	White R.	+	1.78	0.705	+	0.831
18	North R.	**+**	**15.94**	**0.028**	**+**	**0.020**
19	West Branch Westfield R.	+	12.08	0.100	**+**	**0.010**
20	Burlington Br.	−	−1.58	0.837	−	0.956
21	Salmon R.	0	0.00	0.972	+	0.963
22	Quinnipiac R.	+	8.29	0.133	**+**	**0.052**
23	Pomperaug R.	**+**	**9.63**	**0.089**	**+**	**0.016**

Note: Test results with $p < 0.1$ are bolded.

Statistical Flood Frequency Estimates

For stations that showed evidence of step changes in POT/WY ($p < 0.1$), we investigated how flood frequencies estimated using the different time periods (pre- and post-1970) differ. To do this, we calculated RIs using the formula

$$\mathrm{RI} = \frac{1}{\lambda q_\mathrm{e}}, \tag{1}$$

where λ is the arrival rate (i.e., the average number of floods per year), and q_e is the exceedance probability of the data point, calculated with the Weibull plotting position formula

$$q_\mathrm{e} = \frac{m}{n+1}, \tag{2}$$

where m is an event's rank (a rank of 1 indicating the largest event), and n is the number of floods in the record (Stedinger *et al.*, 1993). We performed this calculation for each flood to estimate how frequently a flood of a given magnitude can be expected to occur. We calculated RIs two ways: (1) using only data from the pre-1970 sample defined above, and (2) using only the data from the post-1970 sample.

We focus our analyses of flood frequency estimates on the one- to five-year RIs (i.e., Q_1-Q_5) because estimates using the PDS produce similar results for RIs >10 years as the AMS (Langbein, 1949) (Figure 1), and Collins (2009) did a similar analysis of the AMS for these gauges. The PDS produces different flood magnitude and frequency estimates than the AMS for comparatively high-frequency floods because it includes more data points for smaller floods. For floods with estimated RIs <10 years, the PDS estimates a higher frequency (i.e., smaller RI) for a given discharge than the AMS (Figure 1) (Langbein, 1960). Focusing our temporal comparisons of PDS-generated flood frequency estimates on the comparatively high-frequency floods enables a more detailed understanding of any changes in magnitude estimates for flows important for channel morphology and aquatic habitat.

RESULTS AND DISCUSSION

POT/WY Trends: A Direct Measure of Changes in Flood Frequency

Twenty-two of 23 stations (96%) showed increasing trends (+) in POT/WY (i.e., the number of flood events per WY increased, see Figure 2 and Table 2).

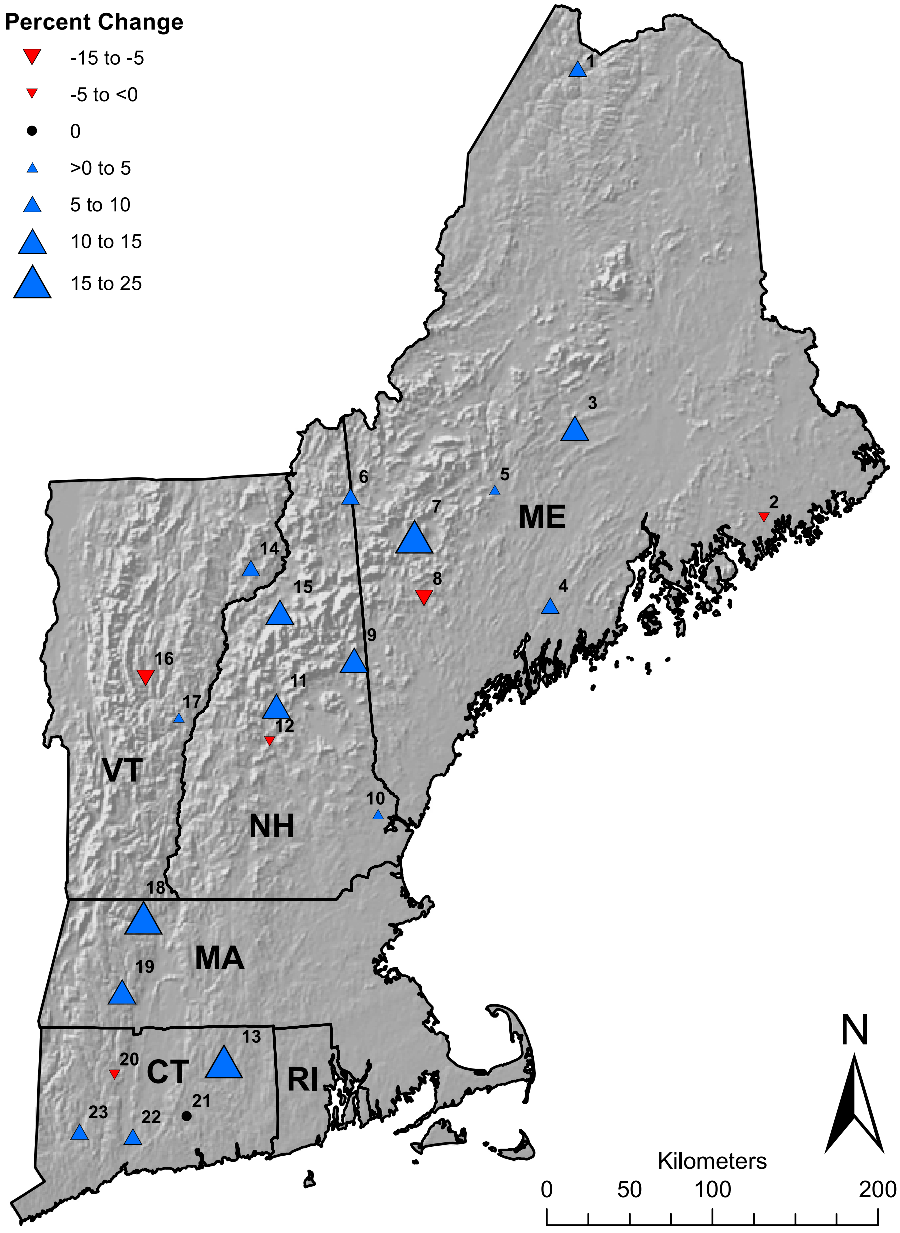

FIGURE 3. Spatial Distribution of Flood Magnitude Trends, Reported as Percent Change.

Ten (45%) increasing trends had $p < 0.1$. Only one river showed a decreasing trend (−) in POT/WY, which was weak. We found upward trends in coastal areas and inland, in mountainous regions and in lowlands, and across a wide range of longitude and latitude, suggesting that floods are occurring more frequently throughout New England as a whole (Figure 2). Despite this broad distribution of upward trends, we found a nearly significant negative correlation between gauge latitude and the magnitude of change in median POT/WY (i.e., gauges farther south showed larger changes in median POT/WY over the period of record; $\tau = -0.233$, $p = 0.103$).

Flood Magnitude Trends

We expected this study to find weaker flood magnitude trends than Collins (2009) because the PDS includes many more low-magnitude events than the AMS, therefore diluting the influence of high-magnitude events on trend analyses. Indeed, 17 of the 23 rivers (74%) in our study showed increasing trends in flood magnitude over time (Figure 3 and Table 3), slightly weaker than Collins' results, which found increasing trends at 25 of 28 gauges (89%). Of the 17 increasing trends in our study, 6 (35%) had $p < 0.1$ compared to 10 (40%) with $p < 0.1$ in Collins (2009).

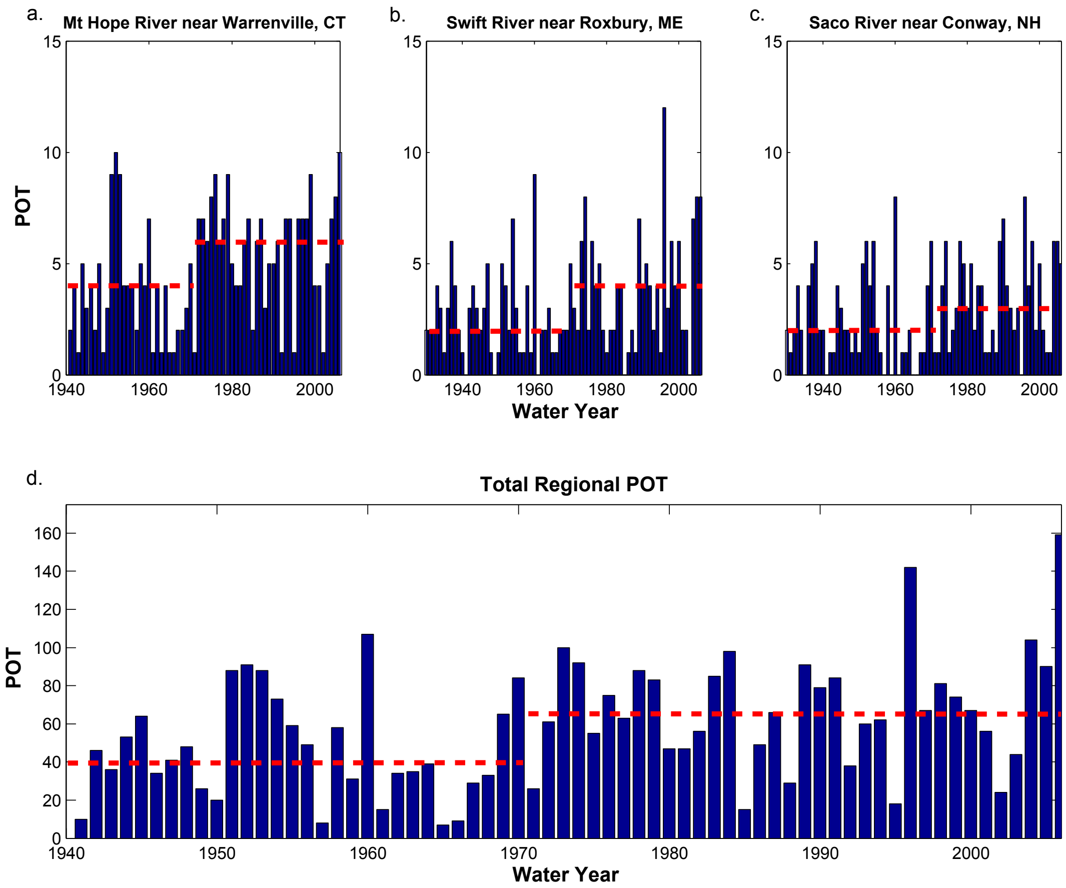

FIGURE 4. Histograms of POT/WY Over Time. All rivers depicted show evidence for a step increase in flood frequency around 1970. Dashed lines indicate the median POT/WY for the pre- and post-1970 periods. POT on the "Total Regional POT" figure represent the summation of POT/WY for all study gauges active since 1941.

Five gauging stations showed decreasing trends, with one $p < 0.1$. One gauge showed no trend. Similar to the AMS results (Collins, 2009), trends are relatively evenly distributed throughout the study region (Figure 3).

Evidence for a Step Increase in New England Flooding

Twenty-two of 23 rivers (96%) show greater POT/WY in the post-1970 period via the Wilcoxon rank-sum test, in agreement with the widespread monotonic upward trend in POT/WY shown by the Mann-Kendall test but further suggesting step increases rather than gradual upward trends (Table 2). Fourteen (61%) rank-sum tests showed $p < 0.1$ via the conventional test (12, or 52%, via the permutation test). One river showed weak evidence for decreasing POT/WY post-1970 (Table 2). We also calculated median POT/WY for each river pre- and post-1970 and found a median increase of one flood per year region-wide, a median percent change of 33% (Table 2 and Figure 4). When looking only at the gauges with $p < 0.1$, the median percent change in median POT/WY pre- and post-1970 increased to 50%. The Quinnipiac River exhibited the largest change, with an increase in median POT/WY of five after 1970, a 167% increase.

Seventeen rivers have larger magnitude floods in the post-1970 subseries, seven (41%) of which have $p < 0.1$ via the Wilcoxon rank-sum test (Table 3). The remaining six rivers show comparatively weak evidence for smaller magnitude floods post-1970.

Statistical Flood Frequency Estimates

High-frequency events (e.g., Q_1 to Q_5) are geomorphically important and are traditionally considered channel-forming flows because they are able to entrain and transport bed sediment and erode channel banks. As discussed above, flood frequency estimates constructed using the PDS calculate shorter

RIs for a given discharge than the AMS (Figure 1). Therefore, the Q_1 and $Q_{1.5}$ calculated using the PDS are similar in magnitude to the $Q_{1.5}$ and Q_2 calculated by the AMS (Langbein, 1949). Flows in this magnitude range account for the majority of sediment flux from a watershed, and they often overtop channel banks and deposit sediment on the floodplain (Wolman and Miller, 1960). These processes are most relevant in self-formed, alluvial rivers where adequate sediment supply and flow competence allow the river to construct and modify the channel morphology, which is not the norm in New England.

The watersheds studied here bear the imprint of continental glaciation during the late Pleistocene, and the rivers typically have imposed-form, nonalluvial channels with gravel and bedrock beds. Because glacial and bedrock geologic histories dictate fluvial geomorphology, the traditional idea of bankfull flow does not apply (Snyder *et al.*, 2008; Wilkins and Snyder, 2011). Additionally, working south of the glacial limit in Pennsylvania and Maryland, Walter and Merritts (2008) found that apparent floodplains are actually fill terraces composed of sediments stored behind (now breached) mill dams. This situation may be relevant in New England, which has a similar history of Colonial-era small dam construction (Walter and Merritts, 2008; Strouse and Snyder, 2010). Despite these caveats, high-frequency events transport coarse bed load in New England rivers (Snyder *et al.*, 2008) and changes in flood magnitude are therefore important to substrate characteristics, channel morphology, and aquatic ecology.

To analyze how the estimated magnitudes of these high-frequency flows change if you recognize a hydroclimatic shift around 1970, we compared statistical flood frequency estimates computed using PDS data from the pre-1970 period with those of the post-1970 period for every gauging station with evidence of a step change in POT/WY ($p < 0.1$) around 1970. For nearly every study gauge, RIs calculated using post-1970 data estimate larger discharges for a given frequency than those using the pre-1970 data (Table 4). Flows occurring at least once every one to two years (RI ≤ 2) showed the greatest median discharge increases, ranging from 28% to 33% (Table 4). The substantial increase in the estimated discharge of frequent floods means that New England rivers may be mobilizing bed sediment more often, possibly resulting in higher sediment flux and accelerated rates of channel modification.

TABLE 4. Summary of the Percent Changes in Estimated Discharges for Given Recurrence Intervals (RIs) Between the Pre- and Post-1970 Subseries for 14 Gauges That Have Rank-sum Tests With $p < 0.1$ (Table 2).

	Statistical Flood Frequency Estimates			
	Q_1	$Q_{1.5}$	Q_2	Q_5
Minimum % change	0.9	3.3	−7.1	−6.9
Maximum % change	54.4	55.8	67.4	56.3
Median % change	28.3	30.1	33.1	16.3
Gauges with increases	14	14	13	13
Gauges with decreases	0	0	1	1

Notes: Q_1 indicates the estimated discharge for a flood with a one-year RI, $Q_{1.5}$ the estimated discharge of a 1.5-year RI flood, and so on.

Correlation Between the NAO and POT

Like Collins (2009), we found no correlation between the annual PC-based NAO index and total POT/WY for the region, regardless of whether we compared concurrent indices or lagged the total POT/WY for the region by one year. Additionally, we found no trend between the winter (DJFM) index and total POT/WY when comparing concurrent indices. We did find a relatively strong correlation between the lag-one total POT/WY and the winter index ($\tau = +0.212$; $p = 0.012$). Collins (2009) found a similar lagged relationship between the NAO and New England annual peaks and Tootle *et al.* (2005) also found a lagged relationship between a coupled NAO/ENSO index and annual New England streamflow. There is only a six-month gap between the winter NAO index, ending March 31, and the lag-one WY, beginning October 1. We believe this gap may be short enough that a positive (negative) winter NAO can predispose the following WY toward more (less) flooding by affecting antecedent conditions, such as soil moisture, into the next WY. Recent research suggests mechanisms by which this may occur. Steinschneider and Brown (2011) document positive correlations between winter and spring NAO phases and subsequent summer sea surface temperatures, precipitation, and streamflow in New England.

CONCLUSION

We found widespread upward trends in POT/WY – a direct measure of increasing flood frequency – on New England rivers. Twenty-two of 23 study gauges selected for climate sensitivity show increasing trends in POT/WY through the analysis of long-term PDS records (Figure 2 and Table 2). Ten (45%) of these trends had $p < 0.1$. Trends in flood magnitude are slightly weaker, with 17 of 23 study gauges showing increasing trends; six (35%) of which had $p < 0.1$ (Figure 3 and Table 3). We found evidence for a step increase in POT/WY around 1970 on more than half of the rivers, and seven rivers show evidence for a step increase in flood discharge, supporting recent studies noting change points in time series of various hydrologic variables around that time (e.g., McCabe and Wolock, 2002; Collins, 2009; Hodgkins, 2010; Villarini and Smith, 2010) (Tables 2 and 3). Total POT/WY for the region shows a lagged correlation with the winter NAO index, similar to the lagged relationship Collins (2009) documented between the NAO and AMS flood magnitudes.

New England rivers appear to be shifting toward flow regimes that flood more frequently and with greater magnitude. Statistical flood frequency estimates calculated using pre-1970 data, or even the entire record, may underestimate discharges calculated from post-1970 data alone – particularly for high-frequency, low-magnitude events. Frequent events, particularly the $Q_{1.5}$ and Q_2, show the largest increases in estimated discharge, increasing by 30% and 33%, respectively (Table 4).

As noted by Collins (2009), increasing trends in regional flooding over the last century are especially surprising considering the widespread reforestation of New England during that time, which would be expected to dampen flooding trends. Before the mid-19th Century, large areas of New England were cleared to harvest timber or to create land for farming and pastures for grazing livestock. Since the 1880s, though, forests have been steadily regrowing across the region (Foster *et al.*, 2003, 2010). In landscapes reverting to forest from grasslands, streamflow has been shown to decrease by 45% on average (Bosch and Hewlett, 1982). Reforestation also reduces flood peaks by intercepting rainfall and encouraging the conversion of overland flow to groundwater flow, which moves through the subsurface at a much slower rate and thus takes longer to reach stream channels (Brauman *et al.*, 2007). New England flood magnitudes and POT/WY should therefore be decreasing if there were no changes in climatological forcing.

Our findings suggest that New England channels may be actively changing to accommodate more frequent high flows. Urbanization has been shown to increase the frequency and magnitude of flood peaks as well as cause changes in channel morphology – including incision and/or widening (e.g., Hammer, 1972; Leopold, 1973; Arnold *et al.*, 1982; Booth, 1990; Booth and Jackson, 1997; Fitzpatrick *et al.*, 2005). One might expect the increase in flood frequency and magnitude documented here to also produce channel widening and/or deepening, depending on local geomorphic (such as bedrock controls on longitudinal profiles and coarse sediment sources) and riparian vegetation conditions. McBride *et al.* (2008) observed late 20th Century widening and incision of reforested reaches in Vermont, and attributed these changes to the influence of riparian vegetation. Our results suggest that changes in hydrology may also be an important influence on the trajectory of channel change. Episodic or prolonged geomorphic changes in stream channels brought about by a hydroclimatic shift could be a stressor for certain aquatic organisms and/or communities just as similar hydrograph changes caused by urbanization have stressed aquatic communities (e.g., Moscrip and Montgomery, 1997).

Recognizing the geomorphic and habitat importance of high-frequency floods, stream restoration designers practicing natural channel design typically size channels to convey Q_1-Q_2 flood discharges (e.g., Rosgen, 1996; Wilcock, in press). Our research, which suggests that New England stream channels may be actively adjusting to changing hydroclimate, and in many cases may also have the hydrologic effects associated with changing land use superimposed on hydroclimatic changes, highlights a frequent challenge of applying natural channel design to a given stream reach: static design discharges for watersheds with dynamic hydrologic and geomorphic conditions. Notwithstanding that difficulty, and other concerns with applying natural channel designs (e.g., Wilcock, in press), stream restoration is a multimillion dollar industry nationally and regionally (Bernhardt *et al.*, 2005) and we believe stream restoration practitioners can improve their channel designs by considering hydroclimatic shifts in the design process. Design discharge estimates are frequently taken from outdated studies or calculated from an outdated flood record. Our research shows that these estimates can be improved by using gauge data that include the modern hydroclimatic period (post-1970) where available, or by using recently updated regional regression equations (Roland and Stuckey, 2007; NOAA, 2011). Choosing the PDS rather than the AMS, if available, can further improve magnitude estimates of high-frequency floods.

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