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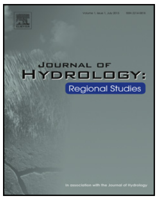

Changing climate increases discharge and attenuates its seasonal distribution in the northeastern United States

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ABSTRACT

Study region: The Hubbard Brook Experimental Forest is well-established as a Long-Term Ecological Research (LTER) site for climate change and anthropogenic impacts studies on hydrological processes. It is located at the headwater regions of the Merrimack Watershed, the fourth largest basin in New England, USA. The watershed is mostly forested (67%) with some developed regions (16%).

Study focus: We assessed the scale-dependency of streamflow response to climate variation, river regulation, and development for dry, average, and wet years using long-term precipitation and discharge records.

New hydrological insights for the region: The effects of basin scale were limited to discharges with exceedance probability less than 15% and greater than 60% and were expressed as lagged discharge in large sub-basins and earlier discharge in small catchments. Annual discharge responded to increases in annual precipitation but not to river regulation or land development. In general, the temporal trends showed less discharge in dry and greater discharge in wet hydrologic flow classes.

1. Introduction

Recently a better understanding of the physical processes governing the interactions among the land surface, ocean, and atmosphere has helped scientists improve projections of the response of watershed hydrology to future changes in climate (Jung et al., 2012; Pourmokhtarian et al., 2012). Increases in greenhouse gas emissions due to human activities are projected to increase global mean air temperature up to 5 °C by the end of the 21st century (Collins et al., 2013). Historical observations along with future climate projections for the northeastern United States have shown the influence of increases in temperature on the quantity, timing, and phase of precipitation (Bates et al., 2008; Hayhoe et al., 2007; Huntington et al., 2009). Although climate change is generally thought to be attended by more frequent extreme hydrological events (Armstrong et al., 2012; Collins, 2009; Karl and Knight, 1998; Madsen and Willcox, 2012), the conclusion is still debated and remains highly variable by regions (Dominguez et al., 2012; Zhu et al., 2012; Kiktev et al., 2003; Matonse and Frei, 2013; Pryor et al., 2009; Tebaldi et al., 2006; Wang et al., 2013). Based on climate projections for the 21st century, the northeastern United States is expected to experience increases in winter (1.4–6.7 °C) and summer (0.8–7.8 °C) temperatures (Pourmokhtarian et al., 2012) and increases in annual precipitation (~100 mm) (Campbell et al., 2011; Hayhoe et al., 2007). These changes are anticipated to cause less snowpack accumulation, earlier peak and attenuated spring flows, increasing summer precipitation

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and evapotranspiration which could either increase or decrease summer base flows (Campbell et al., 2011; Frumhoff et al., 2007; Hayhoe et al., 2007; Huntington and Billmire, 2014).

In order to study climate and human influences on watershed hydrology, appropriate streamflow indicators are needed to effectively characterize hydrologic variations (Beveridge et al., 2012; Poff et al., 1997; Richter et al., 1996). To date, approximately 200 streamflow indicators have been introduced to explain various aspects of discharge variations in water research and management (Gao et al., 2009; Kennard et al., 2010). It would be useful to come to consensus on independent indicators that are sufficient to address water research and management questions without redundancy (Beveridge et al., 2012; Olden and Poff, 2003). Indicators of discharge quantity and timing are important criteria in water resources planning and management and in-stream water rights. Such broad hydrometric indicators can be supplemented by metrics such as streamflow anomaly to parse data records by wet and dry years (Genz and Luz, 2012). For example, methods including the range of variability approach (RVA) (Richter et al., 1997) and the standardized precipitation index (SPI) (McKee et al., 1993) use standard deviation to establish the limits of the analyses.

The long-term hydroclimatological records of reference headwater reaches in experimental watersheds have been utilized to quantify the impacts of changing climate (Gallart et al., 2011; Hatcher and Jones, 2013; Nayak et al., 2010; Reba et al., 2011; Viviroli et al., 2011). For example, Campbell et al. (2011) observed an increase in annual water yield and changes in flow timing at the Hubbard Brook Experimental Forest (HBEF) in response to recent changes in climate. Increases in precipitation, decreases in snowpack accumulation, and decreases in evapotranspiration were deemed as major drivers of long-term hydrologic changes in the Northeast (Campbell et al., 2011; Huntington and Billmire, 2014).

At the river basin scale, the hydrologic response to climate change can be confounded by land use change or river regulation (Frans et al., 2013; Jiang et al., 2007; Kim et al., 2013; Lindström and Bergström, 2004). The study of hydrologic changes throughout a large basin, however, provides an opportunity to understand the scale-dependency of the response since climate change studies have mostly been performed at small headwater catchments rather than large developed or regulated downstream sub-basins (Whitfield et al., 2012).

The Merrimack Watershed is the fourth largest basin in New England which drains much of New Hampshire (NH) and northeastern portions of Massachusetts (MA) and has sufficient long stream gauge records for such study in the northeastern United States. The Executive Office of Energy and Environmental Affairs of MA has indicated the priorities of the Merrimack Watershed conservation program as current and future enhancement of the reliability of water supply, water quality improvement, and flood risk reduction. We define this research to provide information on how the results of climate change studies on HBEF catchments could be scaled for the Merrimack sub-basins.

The objective of this research is to assess recent temporal streamflow responses of the Merrimack Watershed to changes in climate and development using long-term precipitation and discharge data. We examine trends in precipitation and metrics of discharge quantity and timing in dry, average, and wet years distinguished by discharge anomalies along with the consideration of serial correlation that exists in hydrologic flow classes. We use multivariate statistical analyses to discover the most important indicators that can explain discharge variability at the HBEF catchments and the Merrimack sub-basins. We construct a baseline to fill the scale-dependency gap in climate and anthropogenic impacts studies that have been mostly performed on headwater catchments. We provide strategic information for water managers and policy makers to reexamine the efficiency of engineering resilience of the Merrimack Watershed in terms of water supply, dam operation rules, and potential dam removal under non-stationary climate and ongoing development.

2. Study area

The Merrimack Watershed drains 12,967 km^2 in NH and MA and is the fourth largest basin in New England (70:45W-72:15W, 42:00N-44:15N) (Fig. 1). Mean annual precipitation (October 1st–September 30th) over the period of 1904–2011 is 1200 mm and ranges from 700 to 1900 mm. Mean annual discharge (over the same period as precipitation) is 700 mm and varies from 124 mm in dry years (anomaly < -0.5) to 1500 mm in wet years (anomaly > 0.5). Average annual minimum and maximum temperatures are 1.6 °C and 13 °C, respectively. The entire Merrimack Watershed is mostly occupied by forested lands (67%) and developed regions (16%) (Fig. 1, Table 1). The impervious surfaces in the Merrimack Watershed are less than 3% except the southern more developed regions (>9%) (The Merrimack River Watershed Council). Population density is approximately 160 cap/km^2 concentrated in southern NH and northern MA (Census 2010).

The hydrography of the Merrimack Watershed is largely determined by the glaciations of the Appalachian Mountains in NH. The elevation difference between the highest and the lowest (sea level) points in the watershed is 914 m. The Merrimack River is formed by the confluence of Pemigewasset and Winnipesaukee rivers in Franklin, NH (Fig. 1) and flows for 185 km before it discharges into the Atlantic Ocean at Newburyport, MA (Executive Office of Environmental Affairs, The Commonwealth of Massachusetts, 2001). The Merrimack Watershed is highly regulated with 41 major dams operating for hydropower generation, flood control, recreation, and/or navigation (Fig. 1). The overall Merrimack Watershed water withdrawal is approximately 2.5 million cubic meters per day (659 million gallons per day) mostly for public supply (59% of total withdrawal) and thermoelectric demand (34% of total withdrawal) (Water Demand Analysis on Merrimack River Watershed, 2001).

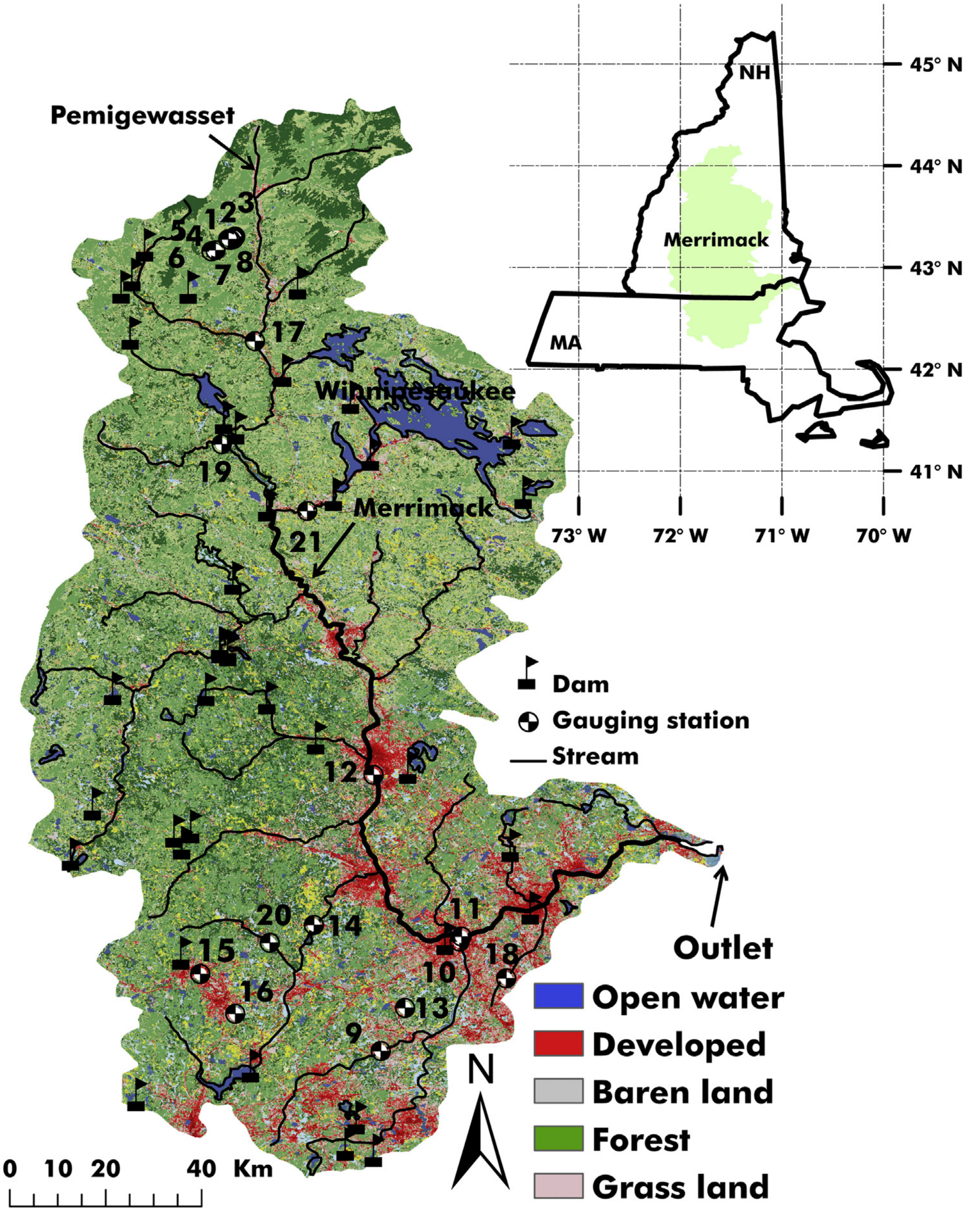

Fig. 1. The Merrimack Watershed: dams, gauging stations, streams, and land cover classification (National Land Cover Database 2006). The key to the site ID is presented in Table 1.

3. Material and methods

3.1. Data

Monthly estimates of precipitation and temperature were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly, 2004). Discharge data were obtained from 21 stations in the US Geological Survey (USGS) and HBEF gauge networks. The USGS currently operates 37 gauge stations within the Merrimack Watershed, of which 13 have continuous sufficient discharge records. In this study, we used records with greater than 30 years duration (median record length: 55 years) of which the earliest began in 1904 (Table 1) to evaluate both short and long-term responses of discharge to climate variation and development. Two USGS gauges represent reference catchments (Table 1) with minimum land disturbance and no artificial diversions or storage (Slack and Landwehr, 1992). The remaining gauges represent sub-basins with a history of hydraulic control and/or land development. Discharge data for each gauge were normalized by drainage area and expressed as depth in mm. Annual water yield was calculated by integrating instantaneous discharge rates from October 1st to September 30th.

Table 1
The description of the HBEF catchments and the Merrimack sub-basins. The reference (R), regulated (RG), and developed (D) sub-basins are also identified. The Merrimack Watershed land cover is presented based on the 2006 National Land Cover Database information.

ID	The description of study sites	Latitude	Longitude	Period of record	Drainage area (km^2)	Gauge datum (m)	Land cover (% of total)		
							Forested	Developed	Other[a]
1	HBEF-WS1 (R)	43.95	−71.73	1957–2011	0.1	488	98.7	0.4	0.8
2	HBEF-WS2 (R)	43.95	−71.72	1958–2011	0.2	503	98.7	0.4	0.8
3	HBEF-WS3 (R)	43.95	−71.72	1959–2011	0.4	527	98.7	0.4	0.8
4	HBEF-WS4 (R)	43.95	−71.73	1961–2011	0.4	442	98.7	0.4	0.8
5	HBEF-WS5 (R)	43.95	−71.73	1965–2011	0.2	488	98.7	0.4	0.8
6	HBEF-WS6 (R)	43.95	−71.74	1965–2011	0.1	549	98.7	0.4	0.8
7	HBEF-WS7 (R)	43.93	−71.77	1966–2011	0.8	619	98.7	0.4	0.8
8	HBEF-WS8 (R)	43.93	−71.76	1970–2011	0.6	610	98.7	0.4	0.8
9	Assabet River at Maynard, MA (D)	42.43	−71.45	1942–2011	300	43	47.5	35.2	17.4
10	Concord River below R Meadow Brook, at Lowell, MA (RG-D)	42.64	−71.30	1938–2011	795	21	40.7	41.7	17.7
11	Merrimack River BL Concord River at Lowell, MA (RG-D)	42.65	−71.30	1924–2011	11450	2	68.4	19.6	12.0
12	Merrimack River near Goffs Falls, below Manchester, NH (RG-D)	42.95	−71.46	1938–2011	8008	33	77.0	13.1	9.9
13	Nashoba Brook near Action, MA (D)	42.51	−71.40	1964–2011	33	47	45.8	35.3	18.9
14	Nashua River at East Pepperell, MA (RG-D)	42.67	−71.58	1936–2011	818	52	55.7	24.6	19.7
15	North Nashua River at Fitchburg, MA (RG-D)	42.58	−71.79	1973–2011	166	120	56.4	34.5	9.1
16	North Nashua River near Leominster, MA (D)	42.50	−71.72	1936–2010	285	81	54.4	32.3	13.3
17	Pemigewasset River at Plymouth, NH (R)	43.76	−71.69	1904–2011	1611	139	91.7	4.1	4.2
18	Shawsheen River near Wilimington, MA (D)	42.57	−71.21	1965–2011	95	25	17.1	73.2	9.7
19	Smith River near Bristol, NH (R)	43.57	−71.75	1919–2011	222	137	87.1	3.7	9.3
20	Squannacook River near West Groton, MA (D)	42.63	−71.66	1950–2011	165	74	76.5	10.0	13.5
21	Winnipesaukee River at Tilton, NH (RG-D)	43.44	−71.59	1938–2011	1220	135	62.3	27.9	9.9

[a] Other includes shrub, scrub, grassland, herbaceous, pasture, hay, cultivated crops, and wetland.

The HBEF is located at the headwater regions of the Merrimack Watershed and has high quality long-term measurements of hydroclimatological variables. Precipitation and discharge data of watersheds within the HBEF (Campbell, 2013a, b) complement the USGS stations located elsewhere in the Merrimack Watershed. Four catchments at the HBEF (WS 3, 6, 7, and 8) remain intact for climate variation studies. Four other HBEF catchments (WS 1, 2, 4, and 5) were experimentally manipulated to assess the impact of anthropogenic interventions (Table 1). HBEF catchments are small (<1 km^2) relative to Merrimack sub-basins (33–11450 km^2).

3.2. Hydrologic flow conditions

Discharge anomaly is a metric to distinguish among hydrologic flow classes (Genz and Luz, 2012). In this approach, annual cumulative discharge data are normalized by annual total and classified as dry, average, and wet based on the deviation from the long-term mean annual discharge, with one standard deviation as the criteria for differentiating hydrologic flow classes (Genz and Luz, 2012). Streamflow anomaly is computed as follows:

$$\text{Anomaly} = \frac{(Q_i - Q_m)}{\sigma} \tag{1}$$

where Q_i is the annual discharge (mm/WY) in year i; Q_m is the long-term mean annual discharge (mm/WY); and σ is the standard deviation (mm/WY). For this study, the three distinct hydrologic flow conditions of dry (anomaly < −0.5), average (−0.5 < anomaly < 0.5), and wet (anomaly > 0.5) years are established based on discharge anomaly (Genz and Luz, 2012).

3.3. Flow duration and flow distribution curves

A Flow Duration Curve (FDC) shows the relationship between discharge and its exceedance probability (Vogel and Fennessey, 1994). FDC links the magnitude and frequency of the discharge and represents the probability that discharge equals or exceeds a given value (Smakhtin, 2001). The FDCs developed in this study differentiate the discharge responses to changing climate, river regulation, and development for catchments and sub-basins with various drainage areas.

A Flow Distribution Curve (FDiC) shows the relationship between cumulative discharge past a stream gauge and day of water year. The quarter dates of cumulative annual discharge are convenient metrics of flow distribution, and the shift in timing of quarter discharge date is commonly used to identify differences among streams or among years for an individual stream (Burn, 2008; Court, 1962; Hodgkins et al., 2003; Hodgkins and Dudley, 2006, 2005; Moore et al., 2007; Regonda et al., 2005; Stewart et al., 2004). In this study, variations in the quarter- (timing-25%), half- (timing-50%), and three-quarter (timing-75%) annual discharge date are evaluated under changing climate, river regulation, and development for catchments and sub-basins with various drainage areas.

3.4. Mann–Kendall trend test and Sen's slope estimate

The Mann–Kendall (MK) trend test was proposed by Mann (1945) and developed by Kendall (1975) as a nonparametric distribution free statistical test to detect monotonic temporal trends in hydroclimatological parameters such as precipitation, discharge, and temperature (Helsel and Hirsch, 1992). The magnitude of trend is often computed by Sen's method which is a nonparametric median-based slope estimate of a hydroclimatological parameter (Sen, 1968).

The performance of trend tests could be questioned when applied to the entire period of record because they disregard long-term persistence, i.e., structural shift in the time series of a variable (Cohn and Lins, 2005). On the other hand, when the period of record is subdivided, the number of observations for each class decreases compared to the entire record and limits the power of analysis.

Although it is recommended to utilize at least 15–25 years of discharge record in order to evaluate spatiotemporal variations in metrics of hydrologic indicators (Genz and Luz, 2012; Kennard et al., 2010; Lins and Slack, 2005), MK can examine trends in series with at least four data points (Gilbert, 1987). We selected gauged sites with more than 30 years of data in order to have at least a decade of information in each hydrologic flow classes. In this study, cumulative annual discharge records are the basis of analysis along with three distinct hydrologic flow classes (dry, average, and wet) defined based on discharge anomalies (Genz and Luz, 2012). Both perspectives of examining the period of record and hydrologic flow classes have been used to provide insight into the hydrologic response to climate variation and development (Genz and Luz, 2012).

The discharge trends in each class of dry, average, and wet years could be computed with MK analysis and Sen's slope estimate since the unequally-spaced information in each hydrologic flow class resembles "missing at random (MAR)" approach which is dedicated to study specific class of information at a time (Osborne, 2013). Due to the influence of antecedent hydrologic condition on the current flow regime, i.e., a dry year following a dry year is likely to be drier, modified MK and Sen's method is used with the consideration of serial correlation among consecutive years with similar hydrologic flow condition (Yue and Wang, 2002). Trend analyses are performed with Microsoft® Excel 2007/XLSTAT©-Pro (Version 2.01, 2015, Addinsoft, Inc., Brooklyn, NY, USA). The software employs the methodology proposed by Yue and Wang, (2002) to consider serial correlation for MK analysis and Sen's slope estimate.

3.5. Multivariate statistical analyses

Multivariate statistical methods include Cluster Analysis (CA) (Hartigan, 1975), Linear Canonical Discriminant Analysis (LCDA) (Hotelling, 1936), Principal Component Analysis (PCA) (Hotelling, 1933; Pearson, 1901), and Factor Analysis (FA) (Spearman, 1904). CA is used to place similar objects into one representative group; LCDA, PCA, and FA will reduce data dimension by developing a set of new independent and uncorrelated features (Izenman, 2008). For example, Olden and Poff, (2003) used PCA to find sets of independent hydrologic indicators which could best explain the variability across streams in a region with diverse climate and geological conditions.

We employ multivariate statistical methods to evaluate spatial correlation of discharge metrics among the HBEF catchments and the Merrimack sub-basins. The reference category consists of 8 study catchments from HBEF and 2 sub-basins from the Merrimack Watershed. There are 11 gauged sub-basins within the Merrimack Watershed with different levels of disturbances including river regulation and/or land development. All multivariate statistical analyses were performed with SAS statistical analysis program (SAS Institute Inc., Cary, NC, USA- Version 9.2, 2009).

The preliminary multivariate statistical analyses on magnitude and timing trends of the Merrimack streamflow records show two separate clusters of results, i.e., a group of HBEF reference catchments as well as a group of the Merrimack reference, regulated and/or developed sub-basins (Fig. 2); therefore, we consider the drainage area along with current land cover/use condition to make significant statistical inferences and comparisons of discharge trends among the HBEF reference catchments and the Merrimack developed sub-basins.

Inside each cluster, three distinct sub-groups can be identified (Fig. 2). Catchments 1 and 3, catchments 2 and 5, and catchments 4, 6, 7, and 8 are formed the three HBEF sub-groups likely distinguished based on differences in elevation and

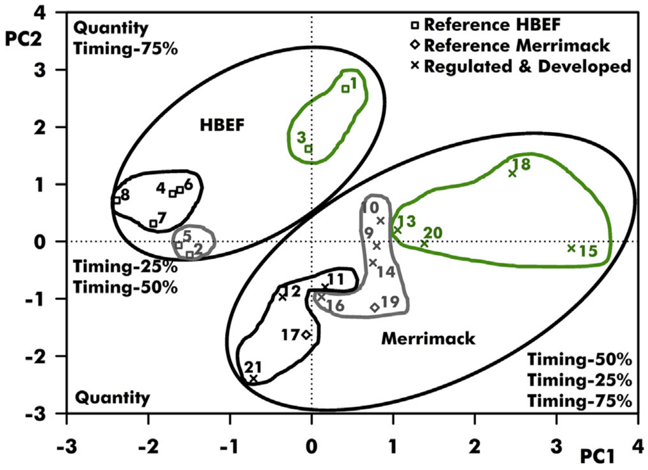

Fig. 2. PCA performed on discharge quantity and timing trends for the period of record. Two separate clusters of HBEF reference catchments as well as the Merrimack reference, regulated, and/or developed sub-basins were identified. The three distinct sub-groups inside each cluster reveal the scale-dependency of changes in the hydrologic response. The key to the site ID is presented in Table 1.

aspect. Within the Merrimack cluster, sub-groups are clearly distinguished by drainage area as small sub-basins 13, 15, 18, and 20 (33–166 km^2), medium sub-basins 9, 10, 14, 16, and 19 (222–818 km^2), and large sub-basins 11, 12, 17, and 21 (1220–11450 km^2). The small and large sub-groups are clearly distinguished by PCA but the intermediate sub-groups in both HBEF and Merrimack clusters have overlaps with either the small or large sub-groups. See Table 1 and Fig. 1 for the identification and location of these catchments and sub-basins.

4. Results

The results are presented in three separate sections. First, we assess the impacts of climate variation, river regulation, and land development on FDCs and FDiCs. Second, we present the results of the modified MK analyses and Sen's slope estimates for the quantity and timing indicators of annual discharge. In this section, we include sub analyses by hydrologic flow classes within each discharge record. Third, we employ multivariate statistical methods to assess patterns of historical discharge trends at the HBEF catchments and the Merrimack sub-basins. We also discuss the scale-dependency of the results emphasized by the PCA analysis.

4.1. The assessment of FDCs and FDiCs

4.1.1. FDCs

The FDCs are compared for the sub-groups within the HBEF cluster (Fig. 3a), the cluster of HBEF vs. the cluster of Merrimack (Fig. 3b), and the sub-groups within the Merrimack cluster (Fig. 3c). The exceedance probabilities (EPs) marked on FDCs represent the conditions where the impacts of drainage area, changing climate, river regulation, or development are distinguishable. Differences among the three sub-groups of catchments within the HBEF only emerged under high discharges with EP less than 15% (Fig. 3a). The discharge magnitude increased with increases in drainage area.

Discharge quantity responses to climate variation are differentiated from both river regulation and development on Fig. 3b. The area-normalized discharge magnitude was greater at the HBEF catchments compared to the Merrimack sub-basins. The FDC of the Merrimack reference sub-basins (ID: 17, 19) can be distinguished from the regulated and developed sub-basins (ID: 9-21 excluding 17, 19) at high discharge values with EP less than 20%.

The influence of drainage area on the response of the Merrimack sub-basins to climate variation, river regulation, and development are indicated on Fig. 3c. The scale of Merrimack sub-basins slightly affected discharges with EP less than 15% and greater than 60%. For discharges with EP less than 15%, the response of small sub-basins (ID: 13, 15, 18, 20) were distinct compared to the medium and the large sub-basins. When EP was greater than 60%, the highest values of low discharge conditions are found in the largest sub-basins (ID: 11, 12, 17, 21).

4.1.2. FDiCs

Similar comparisons were developed for FDiCs at the HBEF catchments and the Merrimack sub-basins (Fig. 4). From the three sub-groups of catchments within the HBEF, catchments with the largest (smallest) drainage areas showed the latest (earliest) discharge timing dates (Fig. 4a). As the drainage area increased, the differences in discharge timing dates increased from 3 days in the timing-25% to 10 days for the timing-75%.

The comparisons of discharge timing dates among the HBEF catchments and the Merrimack sub-basins revealed no scale-dependent patterns (Fig. 4b). The HBEF catchments showed earlier discharge timing-25% and -75%, while the timing date

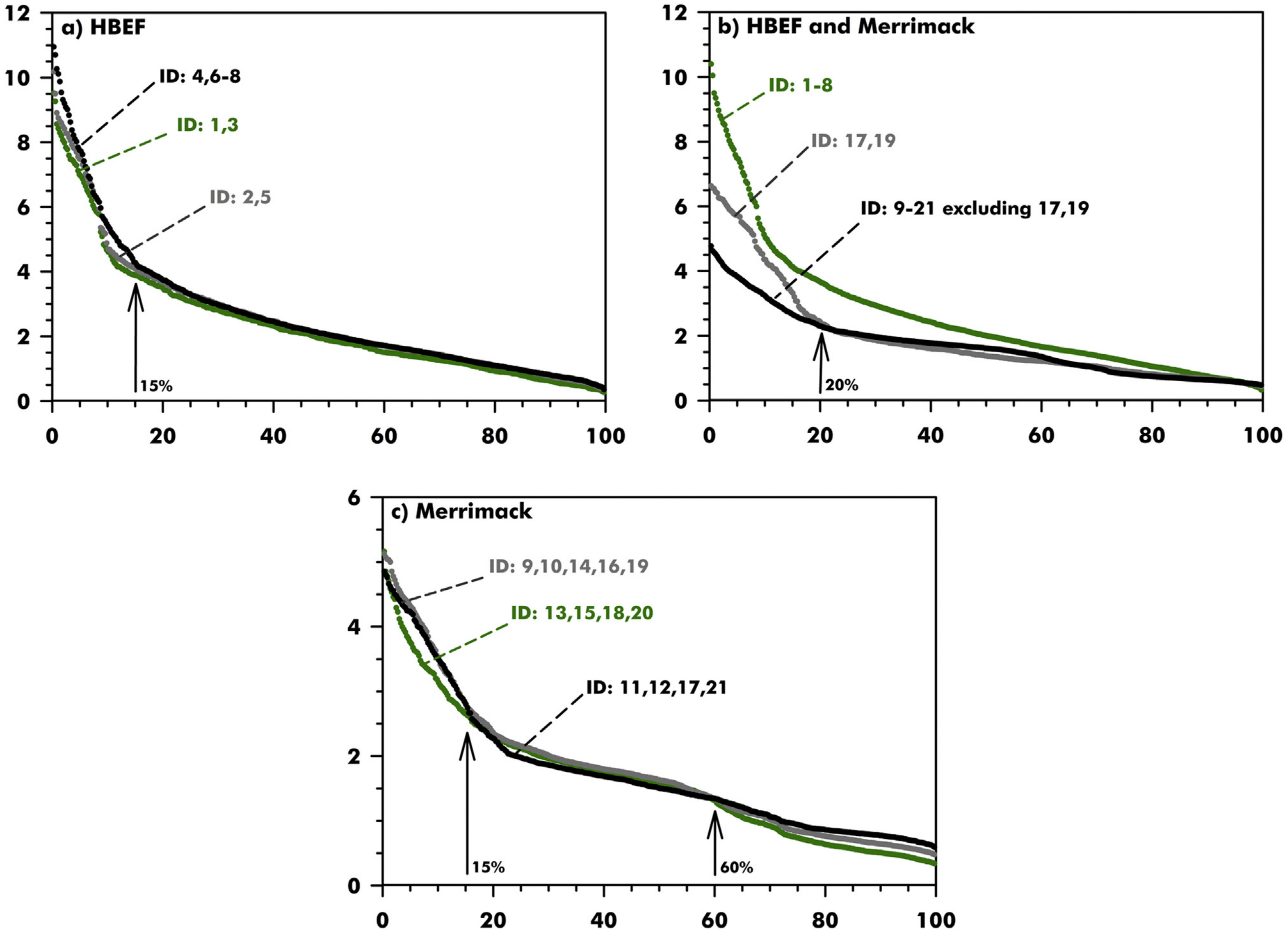

Fig. 3. Flow duration curves (FDCs) for the period of record comparing (a) three sub-groups based on drainage area within the HBEF cluster, (b) HBEF reference catchments with Merrimack reference, regulated, and/or developed sub-basins, (c) three sub-groups based on drainage area within the Merrimack cluster. The impacts of changing climate on discharge variation from river regulation and/or development as well as the impacts of drainage area could be differentiated at certain exceedance probabilities indicated by solid arrows on the FDCs. The key to the site ID is presented in Table 1.
X-axis label for this figure: exceedance probability (%).
Y-axis label for this figure: daily discharge (mm/day).

of 50% annual discharge occurred earlier for the Merrimack sub-basins. The Merrimack reference sub-basins (ID: 17, 19) showed the latest discharge timing dates compared to the HBEF catchments and the Merrimack developed sub-basins.

The influences of drainage area on discharge timing dates for the Merrimack sub-basins were similar to that observed for HBEF catchments (Fig. 4c). The sub-basins with the largest (smallest) drainage areas showed the latest (earliest) discharge timing dates. As the drainage area increased, the differences in discharge timing dates increased from 5 days in the timing-25% to 15 days for the timing-50% then decreased 14 days for the timing-75%.

4.2. Temporal discharge variations

4.2.1. Discharge quantity

The modified MK analyses showed significant (p-value ≤ 0.05) positive trends for precipitation and discharge for the HBEF catchments and the Merrimack sub-basins over the period of record (Table 2). Long-term increases in mean annual discharge (1–7 mm/WY) were consistent with increases in mean annual precipitation (1–7 mm/WY) throughout the Merrimack Watershed (Table 2).

The modified MK analyses indicated significant long-term trends in discharge for 44% of hydrologic flow class records. Sen's slope estimates for the average hydrologic flow class generally followed the same pattern as those for the period of record but at lesser magnitude. For example, annual discharge increased for 3 mm/WY on average for the period of record, while the average hydrologic flow class showed mean positive trend of 2 mm/WY. Moreover, the directions of Sen's slopes for hydrologic flow classes were sometimes different than those for the entire period of record (Table 2). Whereas discharge

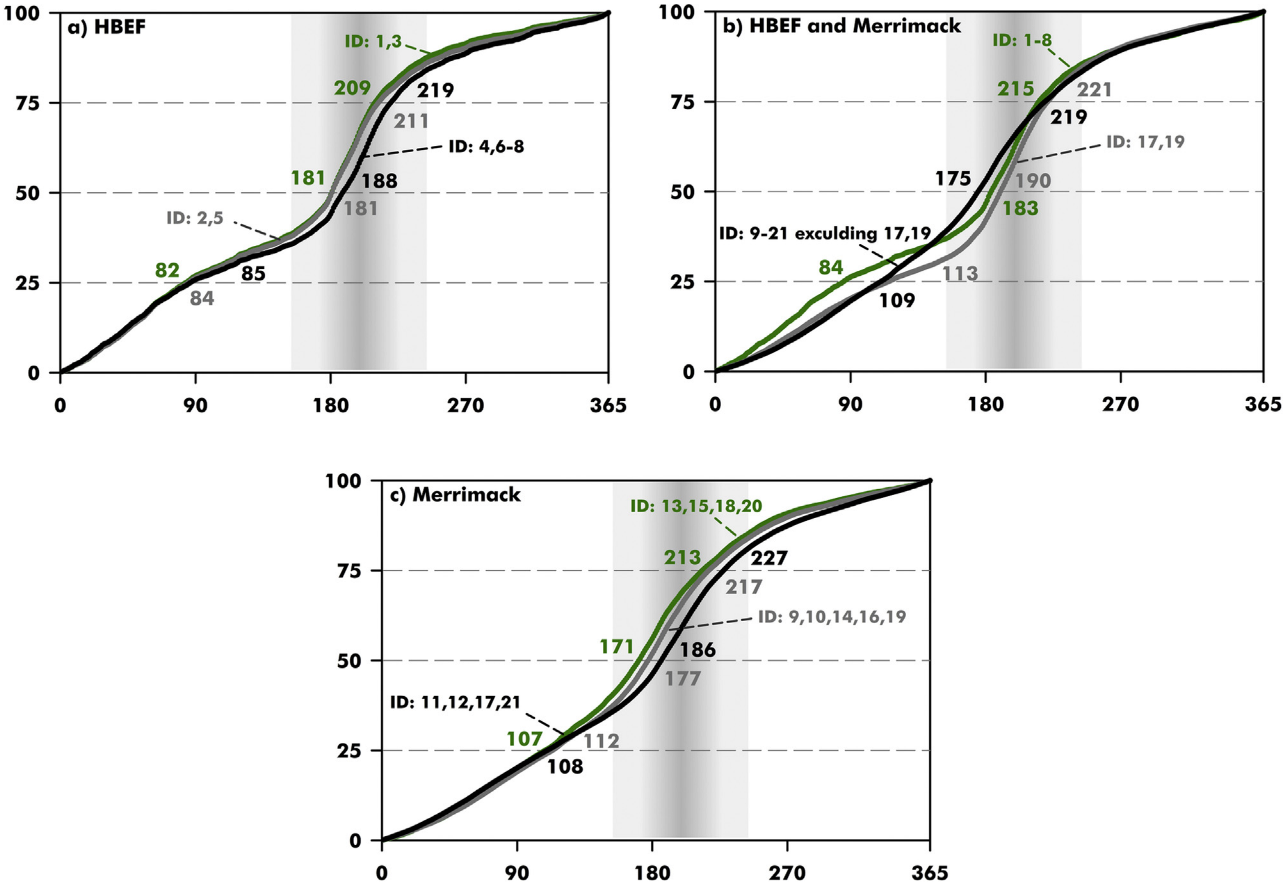

Fig. 4. Flow distribution curves (FDiCs) for the period of record comparing (a) three sub-groups based on drainage area within the HBEF cluster, (b) HBEF reference catchments with Merrimack reference, regulated, and/or developed sub-basins, (c) three sub-groups based on drainage area within the Merrimack cluster. The typical snowmelt period in the region starts from late March (Day 180) through early May (Day 220) marked by shaded ribbons on the FDiCs. The key to the site ID is presented in Table 1.
X-axis label for this figure: day of the water year (October 1st as day "0"–September 30th as day "365").
Y-axis label for this figure: normalized cumulative annual discharge (%).

trends for the period of record were all positive, the numbers of negative trends were greater for dry than for average and wet hydrologic flow classes.

Relative to the period of record, discharge quantity trends were steeper for extreme hydrologic flow classes (dry and wet) at 42% of the HBEF catchments and 26% of the Merrimack sub-basins (Table 2). In the dry hydrologic flow class, mean increases of 1 mm/WY in annual discharge was observed at the Merrimack sub-basins (Table 2); In contrast, the HBEF catchments showed greater positive and negative trends in annual discharge albeit the mean slope of change was positive (2 mm/WY). The modified MK and Sen's slope estimate for the HBEF wet hydrologic flow class showed mean increases in discharge for 8 mm/WY, while the mean slope of increase was much less (2 mm/WY) for the Merrimack sub-basins (Table 2).

The mean precipitation and discharge responses to changing climate decreased with increases in the HBEF catchments' drainage areas. In addition, within the Merrimack Watershed, trends in precipitation and discharge due to changing climate, river regulation, and development decreased with increases in drainage area. The HBEF catchments responded more strongly to changing climate than the Merrimack reference sub-basins. River regulation and land development lessened the impacts of changing climate except for the wet hydrologic flow class.

4.2.2. Discharge timing

We present variations in the metrics of discharge timing first for the period of record and then in finer detail for records subdivided by hydrologic flow classes (Table 3). The timing date of 25% annual discharge occurred 0.2–1 days/WY earlier (p-value $\leq$0.05) at 86% of the HBEF catchments and the Merrimack sub-basins. Similarly, the date of 50% discharge occurred 0.1 days/WY earlier and 75% discharge was delayed by 0.1 days/WY on average. The shifts to earlier and later flow timing dates for 50% and 75% of annual discharge were only significant (p-value $\leq$0.05) at 67% and 43% of the HBEF catchments and the Merrimack sub-basins, respectively.

Table 2
The modified MK trend test and Sen's slope estimate of precipitation and discharge magnitude for the HBEF catchments and the Merrimack sub-basins for the period of record and hydrologic flow classes of dry, average, and wet years (Analyses were performed on cumulative annual precipitation and discharge in mm/WY). The key to site ID is presented in Table 1.

ID	Drainage area (km^2)[a]	Precipitation trends		Discharge trends							
		Period of record		Period of record		Dry		Average		Wet	
		Sen's slope (mm/WY)	No. of years	Sen's slope (mm/WY)	No. of years	Sen's slope (mm/WY)	No. of years	Sen's slope (mm/WY)	No. of years	Sen's slope (mm/WY)	No. of years
1	0.1	6.1[*]	55	6.7[*]	55	2.4	18	0.9	22	12.7[*]	15
3	0.4	5.6[*]	53	5.5[*]	53	7.6[*]	17	6.6[*]	21	5.8[*]	15
2	0.2	5.6[*]	54	3.1[*]	54	10.0[*]	15	1.6[*]	23	11.2[*]	16
5	0.2	5.2[*]	47	4.7[*]	47	−1.2	17	2.7	17	2.6	13
6	0.1	5.0[*]	47	5.5[*]	47	−0.0	18	4.7[*]	17	14.3[*]	12
4	0.4	6.7[*]	51	5.3[*]	51	4.5[*]	16	2.2	24	0.2	11
8	0.6	4.4[*]	42	3.8[*]	42	−5.4[*]	16	1.4	14	8.5[*]	12
7	0.8	5.2[*]	46	3.5[*]	46	−4.5	15	3.0[*]	18	6.2[*]	13
13	33	6.7[*]	48	2.2[*]	48	2.3	13	0.3	19	−1.1	16
18	95	5.3[*]	47	3.4[*]	47	4.1	14	6.3[*]	18	5.1[*]	15
20	165	2.0[*]	62	2.3[*]	62	−0.5	17	1.9	25	1.7	20
15	166	1.2	39	2.5	39	−0.9	11	2.9[*]	15	−2.3	13
19	222	2.6[*]	93	1.0[*]	93	0.6[*]	31	0.3	35	4.1[*]	27
16	285	2.5[*]	75	2.5[*]	75	−1.7	22	0.2	30	−1.4[*]	23
9	300	3.3[*]	70	3.0[*]	70	1.4	20	0.8	27	0.1	23
10	795	3.3[*]	74	4.1[*]	74	0.2	25	1.4	25	2.3[*]	24
14	818	2.7[*]	76	2.7[*]	76	−0.5	24	2.9[*]	28	0.7	24
21	1220	2.7[*]	74	1.3[*]	74	4.0[*]	21	−0.1	34	3.5[*]	19
17	1611	1.5[*]	108	0.8[*]	108	−0.5	31	0.3	46	3.4[*]	20
12	8008	1.6[*]	74	1.8[*]	74	4.2[*]	23	0.6	27	3.6[*]	24
11	11450	2.4[*]	88	2.3[*]	88	0.5	26	−0.2	36	1.1[*]	26

[*] Statistically significant trend (p-value $\leq$0.05).

[a] The HBEF catchments and the Merrimack sub-basins are ordered by drainage area from smallest to largest.

For the average hydrologic flow class at the HBEF catchments, the mean dates of 25%, 50%, and 75% discharge significantly shifted earlier by 2.5 days/WY, 1.1 days/WY, and 1.1 days/WY, respectively (Table 3). The Merrimack sub-basins experienced the significant earlier mean timing dates of 25% and 75% annual discharge for 0.9 days/WY and 0.6 days/WY, respectively for the average flow class. The later flow timing date of 50% annual discharge (0.1 days/WY) was significant (p-value $\leq$0.05) at 70% of the Merrimack sub-basins.

Similar to discharge quantity, the magnitude and direction of discharge timing trends may differ from the entire record when considering extreme hydrologic flow classes. Results for the dry hydrologic flow class showed a pattern of significant later discharge timing dates of 2.2 days/WY and 0.4 days/WY for 25% and 75% discharge at the HBEF reference catchments, respectively. The earlier flow timing date 50% of annual discharge (1.2 days/WY) was only significant (p-value $\leq$0.05) at 25% of the HBEF catchments. The dates of 25% and 75% discharge for the Merrimack sub-basins shifted earlier by 1.0 days/WY and 0.1 days/WY, respectively. The later flow timing date 50% of annual discharge (0.1 days/WY) was only significant (p-value $\leq$0.05) at 38% of the Merrimack sub-basins.

The wet hydrologic flow class showed significantly earlier (later) mean timing dates of 25% (75%) discharge of 2.4 days/WY (0.9 days/WY) for both the HBEF catchments and the Merrimack sub-basins. The significant earlier timing at the HBEF catchments for 75% discharge timing date (2.7 days/WY on average) was in contrast with the significant mean later timing date (1.3 days/WY) at the Merrimack sub-basins.

The magnitude of trends in discharge timing dates due to changing climate increased with increases in drainage area and elevation at the HBEF. In addition, the discharge timing trends for the Merrimack sub-basins due to changing climate, river regulation, and development increased with increases in drainage area, with the exception of the timing dates of 50% and 75% annual discharge which indicated no specific patterns. The discharge timing dates at the HBEF catchments responded more strongly to changing climate than the Merrimack reference sub-basins. River regulation and land development muted the signal of changing climate only for the timing dates of 50% and 75% annual discharge except for the wet hydrologic flow class.

4.3. Spatial patterns in discharge variation

We performed Principal Component Analysis (PCA) on discharge quantity and timing trends over the period of record and within hydrologic flow classes. PCA inferred results from the 16-by-16 correlation matrix, i.e., 1 discharge quantity and 3 discharge timing indicators (total of 4 indicators) for the period of record and three hydrologic flow classes. The loadings of hydrologic indicators on each Principal Component (PC) were used to evaluate the importance of the metrics in explaining patterns of discharge variations at the HBEF catchments and the Merrimack developed sub-basins (Olden and Poff, 2003).

Table 3
The modified MK trend test and Sen's slope estimate of discharge timing for the HBEF catchments and the Merrimack sub-basins for the period of record and hydrologic flow classes of dry, average, and wet years (Analyses were performed on the quarter dates of normalized cumulative annual discharge in %). Negative (positive) trends represent earlier (later) discharge timing dates. The key to site ID is presented in Table 1. The number of years of data in each class is presented in Table 2.

ID	Drainage area (km^2)[a]	Timing 25%- Sen's slope (days/WY)				Timing 50%- Sen's slope (days/WY)				Timing 75%- Sen's slope (days/WY)			
		Period of record	Dry	Average	Wet	Period of record	Dry	Average	Wet	Period of record	Dry	Average	Wet
1	0.1	–0.3[*]	0.1	–0.1	–1.7[*]	–0.1	0.2	0.3	0.7	0.3[*]	0.5[*]	0.3	–0.5
3	0.4	–0.3[*]	1.8	–1.1[*]	–2.4[*]	–0.2[*]	0.1	–0.8[*]	0.7	0.2[*]	1.0[*]	–0.6[*]	0.7
–													
2	0.2	–0.6[*]	–1.0	–0.4	–4.1[*]	–0.3[*]	–0.1	–0.7[*]	–1.3[*]	0.0	0.6[*]	–0.2	–2.7[*]
5	0.2	–0.4[*]	2.0[*]	–3.2[*]	–4.1[*]	–0.2[*]	0.1	–1.6[*]	0.1	–0.1[*]	0.4	–1.5[*]	–0.9
													–
6	0.1	–0.5[*]	3.0[*]	–4.6[*]	–4.3[*]	–0.2[*]	0.1	–1.4[*]	0.2	0.0	0.3	–1.6[*]	–0.1
4	0.4	–0.6[*]	2.1	–1.7[*]	–4.9[*]	–0.2[*]	0.0	–0.9[*]	0.4	0.0	0.5	–0.7[*]	–0.4
8	0.6	–0.8[*]	0.1	–0.7	–5.0[*]	–0.3[*]	–1.4[*]	0.0	0.2	0.1	–0.2	–0.4	0.4
7	0.8	–0.7[*]	1.7[*]	–1.8[*]	–4.6[*]	–0.3[*]	–1.0[*]	–1.2[*]	0.1	0.1	–0.4[*]	0.1	0.1
–													
13	33	–0.4[*]	–0.5	–0.3	–0.2	0.1	1.5[*]	0.7[*]	0.4	0.2[*]	2.6	0.3	0.6
18	95	–0.2	–1.4	–1.2[*]	1.4[*]	0.2[*]	1.1	0.2	2.8[*]	0.3[*]	0.8	–0.4	3.3[*]
20	165	–0.1	0.6	0.1	0.5	0.0	–0.4	0.4[*]	–0.2	0.2[*]	0.8[*]	0.2	0.6[*]
15	166	0.2	-0.6	1.0	0.6	0.2[*]	1.4	1.6[*]	–0.4	0.2	–1.0	0.3	2.0[*]
–													
19	222	–0.2[*]	–0.3	0.2	–2.0[*]	-0.1[*]	0.2[*]	–0.4[*]	–0.2[*]	0.1[*]	0.3[*]	–0.1	0.5[*]
16	285	–0.3[*]	–0.6	–0.7[*]	–0.3	0.0	–0.4[*]	0.1	–0.5[*]	–0.1	–0.3	0.0	–0.4
9	300	–0.3[*]	–1.0[*]	–0.8[*]	1.0[*]	0.0	–0.1	0.1	0.7[*]	0.1	0.3	–0.3	1.2[*]
10	795	–0.2[*]	–0.2[*]	–0.2	0.1	0.0	0.1	0.5[*]	0.0	0.1	0.4	0.3	0.0
14	818	–0.3[*]	–0.7	–0.2	–0.1	0.0	–0.2	0.0	0.3	0.1	0.0	–0.2	1.2[*]
–													
21	1220	–0.3[*]	0.2	–0.3	–2.0[*]	–0.2[*]	0.0	–0.6[*]	0.0	–0.2[*]	–1.2[*]	–0.9[*]	1.3[*]
17	1611	–0.4[*]	–1.6[*]	–0.8[*]	–1.0[*]	–0.1[*]	–0.3[*]	–0.2[*]	–0.3	0.0[*]	–0.3[*]	–0.3[*]	0.3[*]
12	8008	–0.4[*]	–1.2[*]	–0.2	–1.7[*]	–0.1[*]	0.0	–0.6[*]	–0.3	0.0	–0.1	–0.5[*]	0.3
11	11450	–0.3[*]	–0.3	–0.3	–0.3[*]	–0.1[*]	–0.3[*]	–0.2[*]	–0.1	0.0	–0.2	0.0	0.2

[*] Statistically significant trend (p-value ≤ 0.05).

[a] The HBEF catchments and the Merrimack sub-basins are ordered by drainage area from smallest to largest.

The first and the second PC together explained 72% of the variations in discharge quantity trends data. For both reference catchments and developed sub-basins, trends for the period of record and for the dry hydrologic flow classes were relatively more important and had higher loadings on PC1 and PC2. For trends in discharge timing, PC1 and PC2 explained 67% of the variation in hydrologic trends data. For both reference catchments and developed sub-basins, trends of annual and wet discharge timing-50% were relatively more important and had higher loadings on PC1 and PC2.

5. Discussion

5.1. Discharge quantity

Knowledge of the available water yield at particular times of the year is important for water planners. Annual and seasonal center of the volume dates are useful flow timing indicators for most stream types (Hodgkins et al., 2003, 2005; Hodgkins and Dudley, 2005). We defined flow metrics of cumulative annual discharge (quantity) and the day of the year when particular fractions of annual flow discharged from the catchment outlet (timing and distribution).

Storage of water associated with lakes and manmade reservoirs and urbanization alter the relationship between precipitation and discharge. In the small reference catchments of the HBEF with no river regulation or land development, Hamburg et al. (2013) found very high correlation coefficient between precipitation and discharge ($r = 0.96$). The Merrimack sub-basins have drainage areas two orders of magnitude larger than the HBEF catchments. Although river regulation and land development in the Merrimack Watershed have lessened the correlation between precipitation and discharge ($r = 0.85$, p-value <0.0001), precipitation remains the dominant driver of discharge variation.

We found significant positive trends (p-value ≤ 0.05) for annual precipitation at the Merrimack Watershed (4 mm/WY on average) for records with median length of 55 years of which the earliest began in 1904. Although few were statistically significant, Brown et al. (2010) reported upward trends in 1870–2005 precipitation for 40 sites across the Northeast. Hamburg et al. (2013) assessed precipitation data for WS3 and WS7 at the HBEF over the period of 1958–2005 and found insignificant trends in precipitation (p-value ≤ 0.1). However, Campbell et al. (2011) extended the record to 2008 and found significant increases of 3 mm/WY in precipitation (p-value ≤ 0.05). Our results for the Merrimack Watershed were consistent with Campbell et al. (2011) demonstrating how much sensitive MK trend test and Sen's slope estimate are to the length of record and serially correlated data. Since there were studies showing either no trends in precipitation for the Northeast (Velpuri and Senay, 2013) or finding significant positive trends (Frumhoff et al., 2007; Huntington et al., 2009; Huntington and Billmire, 2014) coupled with large decadal variability in precipitation (Hayhoe et al., 2007), a large basin-scale assessment of hydrologic response to climate variation should be of interest.

All the significant discharge trends (p-value $\leq$0.05) for the period of record were positive and consistent across the Merrimack Watershed (Table 2). The average hydrologic flow class also followed the same pattern as the period of record with two exceptions (sub-basins 11 and 21) mainly due to river regulation. The Merrimack reference sub-basins with larger drainage areas (ID: 17, 19) showed smaller trends (resiliency to climate forcing which could be due to more storage), while the smaller catchments at HBEF exhibited greater discharge trends (on average five times greater).

The decreased sample size challenged the ability to return significant trends for catchments with short records and for extreme hydrologic flow classes with little representation. It was obvious that longer data records had the greater likelihood of showing statistically significant trends in the Merrimack Watershed especially when data were parsed into hydrologic flow classes.

In order to evaluate spatiotemporal variations in metrics of hydrologic indicators, at least 15–25 years of discharge record is required (Genz and Luz, 2012; Kennard et al., 2010; Lins and Slack, 2005). If the numbers of dry, average, and wet years were similar, the study sites would need to have at least 45 years of data. This criterion would have caused 38% loss in information; therefore we decided to retain study sites with at least a decade of information in each hydrologic flow class. Since catchments with short period of records increased the likelihood of misleading results across a region (Kundzewicz and Robson, 2000), the decreased number of data in each hydrologic flow class (compared to the period of record) is clearly a limitation to our study. Consequently, it may be advisable to include samples with less than 15 years of information in recent but not long-term hydrologic flow response assessment.

Mean annual discharge decreased at 38% of the HBEF catchments and the Merrimack sub-basins (mostly forested) under the dry hydrologic flow class despite the increases in mean annual precipitation. This pattern was likely due to increases in groundwater recharge and evapotranspiration in the Northeast (Huntington and Billmire, 2014; Kramer et al., 2015). However, HBEF catchments have been shown to have decreasing evapotranspiration and the advanced timing of the snowmelt (Campbell et al., 2011) which may increase the period of groundwater recharge. Under the wet hydrologic flow class, increases in discharge were strongly coupled with increases in precipitation. Snowmelt period (late March through early May) had a lower contribution (24%) to annual discharge in the wet hydrologic flow class compared to the contribution of 32% to the dry hydrologic flow class (not shown). Under wet climate conditions, annual discharge was more influenced by summer rainfall rather than spring precipitation and snowpack runoff.

Although annual discharge increased for all study catchments over their entire period of records, more of the negative discharge trends were evident over dry hydrologic flow class while stronger positive trends were observed in wet hydrologic flow class. Since these findings were based on historical data, patterns could raise concerns for water managers. Understanding variations in annual discharge under dry and wet hydrologic flow classes provides insight on the effects of drought and flood events for the northeastern United States as global climate models project more extreme flow events for the region during the 21st century (Campbell et al., 2011; Hayhoe et al., 2007; IPCC, 2013; Kim et al., 2013; Pourmokhtarian et al., 2012; Trenberth, 2011; Wang and Zhang, 2008).

The impacts of development on annual discharge showed mixed results under extreme hydrologic flow classes. In both dry and wet hydrologic flow classes, the impacts of development were in the opposite direction as climate variations (Table 2). Under dry hydrologic flow class, annual discharge increased at both the HBEF catchments (1.7 mm/WY on average) and the Merrimack sub-basins (1.0 mm/WY on average) which suggested a small contribution of river regulation and urbanization on discharge response under dry climate condition. For the wet hydrologic flow class, annual discharge increased at the HBEF catchments (7.7 mm/WY on average) and with much lower rate at the Merrimack sub-basins (1.6 mm/WY on average) possibly due to increases in summer temperature over the Northeast (Frumhoff et al., 2007; Hamburg et al., 2013) which increased both plant water usage (increases in evapotranspiration due to more available water) and human water demand.

River regulation and land development can either accelerate or attenuate annual discharge patterns driven by climate variation. Discharges with exceedance probabilities greater than 20% were similarly influenced by climate variation and land development, while high discharges were mostly impacted by climate variation rather than development (Fig. 3b). Lake Winnipesaukee stores large quantities of water (approximately 2.3 billion cubic meters) with regulated release into the Merrimack River. The FDC at the lake outlet had a very mild slope as a result of regulation which shows the resiliency of the lake to changing climate (not shown). The influences of drainage area on low discharge values (EP greater than 60%) were much more noticeable at the Merrimack sub-basins with more storage and milder slope compared to the small HBEF catchments on steep terrain. The impacts of drainage area on high discharge values (EP less than 15%) varied neither with basin storage nor slope.

The interpretation of PCA results is challenging (Jolliffe, 2002). A closer look at Fig. 2 revealed that the catchments or sub-basins with similar precipitation trends were clustered together. The reference sub-basin 17 was located near the developed sub-basin 12 which both showed similar precipitation trends (Table 2). The reference sub-basin 19 was neighbored to developed sub-basins 11, 14, and 16 since their precipitation trends were similar as well (Table 2). The comparison of discharge trends for a reference sub-basin (ID: 19, Table 2) and a developed sub-basin (ID: 16, Table 2) which showed the significant precipitation trends over the period of record, led us conclude that in the absence of a reservoir to attenuate excess water draining an urbanized area, increases in discharge at a developed sub-basin could be twice that of a reference sub-basin experiencing similar rates of precipitation increase.

5.2. Discharge timing

In the northeastern United States, seasonal variations in precipitation, temperature, and evapotranspiration govern changes in seasonal discharge quantity and timing (Hodgkins and Dudley, 2005). Spring discharge is driven by both spring precipitation and snowmelt discharge with the latter being sensitive to temperature change (Hodgkins et al., 2003). Over 25 years starting from 1976, March through May air temperatures have increased in New England (Hodgkins et al., 2003); meanwhile, annual snow to precipitation ratio has decreased over the past 50 years (through 2000) due to decreases in snowfall and increasing rainfall (Huntington et al., 2004). These phenomena have caused earlier snowmelt and when accompanied by spring rainfall, change the quantity and timing of spring discharge (Frumhoff et al., 2007). After the snowmelt period (late March through early May), the distribution of discharge has became more uniform throughout the year in the Merrimack Watershed (Fig. 4) because the attenuation of spring discharge has been compensated by increases in rainfall during spring and summer.

The superimposed impacts of river regulation and land development (Fig. 4c) on discharge distribution seem to be dominated by the impacts of development since the shape of the FDiC was not as similar as smoothed discharge distribution for a regulated sub-basin. The FDiCs of Lake Winnipesaukee were uniform throughout the year due to its considerable storage. The timing dates of the discharge for the lake were insensitive to changes in hydrologic flow classes and period of records.

Researchers have analyzed metrics of discharge timing for the Northeast. Hodgkins et al. (2003) and Hodgkins and Dudley (2005) reported 1–2 weeks earlier flow timing date of 50% discharge day (from January 1 to May 31, average 68 years of discharge record from 1903 to 2000) in New England. The winter-spring center-of-volume date showed high negative correlation ($r = -0.72$, $p < 0.0001$) with March through April air temperatures (Hodgkins and Dudley, 2005). Streamflow responds differently to historical increases in average March–May temperatures (Hodgkins and Dudley, 2006). In March, streamflow increases in response to snowmelt (earlier snowmelt due to increases in solar radiation, greater wind speed, and higher humidity) and precipitation (an increase in the ratio of winter rain to snow) (Huntington et al., 2004). May streamflow decreases due to earlier loss of winter snow pack (Hodgkins and Dudley, 2005).

In this study, we assessed variations in timing date of 25%, 50%, and 75% of annual discharge. Trends for the period of record, average and wet hydrologic flow classes showed earlier timing dates of 25% annual discharge at the HBEF catchments and the Merrimack sub-basins. Climate change impact on winter hydrology made the timing date of 25% discharge day (during December through February) occurred earlier at the HBEF catchments than the Merrimack developed sub-basins (Table 3). For the Merrimack sub-basins, development controlled the direction and magnitude of discharge timing alteration. The impacts of changing climate on annual discharge may be enhanced or muted by development. For instance, DeWalle et al. (2000) found greater impact of development than climate change on annual discharge throughout the United States (no study sites in NH) which was in contrary to our analyses of FDCs and FDiCs for the HBEF reference catchments and the Merrimack developed sub-basins.

The timing date for 50% of annual discharge is a robust metric of the spring discharge especially when the date is close to the centroid of the snowmelt hydrograph (Burn, 2008; Court, 1962; Moore et al., 2007; Regonda et al., 2005; Stewart et al., 2004). Hamburg et al. (2013) found 0.2 days/year (WS3, 1958–2005) to 0.3 days/year (WS7, 1966–2005) earlier spring flow center-of-volume date (CVD) at the HBEF. Results for Pemigewasset River at Plymouth showed 0.19 days/yr earlier CVD (1904–2004). Campbell et al. (2011) reported earlier spring CVD for 0.2–0.5 days/WY at HBEF and insignificant trends in the fall CVD (1969–2008). Hodgkins and Dudley (2006) reported earlier occurrence of winter-spring streamflow for 0.1 days/year in the northeastern United States in the period of 1913–2002.

In the Merrimack Watershed, the timing date of 50% discharge day generally occurred between March and April. Spring snowmelt and precipitation controlled the variations of the timing date of 50% discharge day (Fig. 4). The impact of climate change on spring discharge generation was stronger than development effect, which likely is due to stored water in reservoirs during the spring season and then regulated release afterwards through control structures.

The timing date of 75% discharge day occurred sometime between May and July. Development had less impact on flow timing over the summer season. Summer rainfall controlled the variation in the timing date of 75% discharge day for both the HBEF catchments and the Merrimack sub-basins (Fig. 4).

6. Conclusions

We assessed trends in stream hydrologic responses of the Merrimack Watershed, the fourth largest watershed in New England, due to climate variation, river regulation, land development and differences in drainage area. Historical precipitation and discharge data along with current land cover information were used to analyze metrics of discharge quantity and timing. Discharge variations were evaluated in three distinct hydrologic flow classes of dry, average, and wet years which were defined based on discharge anomalies. Applying modified MK trend test and Sen's slope estimate over the period of record for each catchment failed to consider the impacts of different climate regimes within the time frame of our analysis; therefore, the data record was parsed among hydrologic flow classes.

In the Merrimack Watershed, low flows were similarly influenced by climate variation and land development; high flows were more impacted by climate variation than development. The scale of the Merrimack sub-basins affected both high and low discharges with EP less than 15% and greater than 60%, respectively. The sub-basins with the largest (smallest) drainage areas showed the latest (earliest) discharge timing dates.

Annual discharge showed positive trends regardless of river regulation, land development, and period of record. Increases in annual discharge were consistent with increases in annual precipitation. Trends in precipitation and discharge due to changing climate, river regulation, and development decreased with increases in drainage area. Although precipitation and discharge were correlated in the Merrimack Watershed, regulation and land development diminished the correlation coefficient compared to reference catchments.

The timing dates of 25% and 50% annual discharge have been occurring earlier at the HBEF catchments and the Merrimack sub-basins, while the timing date of 75% annual discharge has been occurring late. The trend magnitude of discharge timing dates increased with increases in the drainage areas of the HBEF catchments. At the Merrimack sub-basins, only the timing date of 25% annual discharge increased with increases in drainage area. River regulation and land development muted the signal of changing climate only for the timing dates of 50% and 75% annual discharge.

The results for the two extreme hydrologic flow classes, which showed less discharge in drier and more discharge in wetter hydrologic flow classes, provide strategic information for water managers and policy makers to reexamine the efficiency of the engineering resilience of the Merrimack in terms of the water storage, dam operation rules, and potential dam removal under non-stationary climate and ongoing development.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.12.057.

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