June 2017

The interacting hydrologic responses to changing climate, watershed physical characteristics, river regulation, and land development in the northeastern United States

Rouzbeh Berton
Syracuse University

Recommended Citation

Berton, Rouzbeh, "The interacting hydrologic responses to changing climate, watershed physical characteristics, river regulation, and land development in the northeastern United States" (2017). *Dissertations - ALL*. 720.
https://surface.syr.edu/etd/720

Abstract

In this dissertation, the scale-dependency of hydrologic responses due to changing climate and regime shifts of large-scale circulation patterns and their teleconnection patterns were evaluated using long-term precipitation and discharge records in sub-basins with no development, and extensive development and riverine impoundments of the Merrimack River watershed. The Merrimack (New Hampshire-Massachusetts) is a 13,000 km^2 forested (67%) watershed located in the northeastern United States. The overarching goal of this dissertation was to assess hydrologic responses to the potential effects of changing climate in sub-basins experiencing a range of development in order to help guide sustainable water management in the Merrimack River watershed and other northeastern basins. The objective of this research was to integrate hydroclimatic observations across basin size and anthropogenic disturbances (i.e. river regulation and land development) to understand the dynamic of hydrologic alterations under a changing climate.

This dissertation consists of three research phases. In phase I, I assessed the interacting hydrologic responses to changing climate, watershed physical characteristics, river regulation, and land development under dry, average, and wet hydrologic conditions using long-term precipitation and discharge data of the Merrimack River watershed. I found that the effects of basin scale were limited to high (exceedance probability of less than 15%) and low (exceedance probability of greater than 60%) discharge events and were expressed as lagged discharge in larger sub-basins and earlier discharge in smaller headwater catchments. Annual discharge responded to increases in annual precipitation regardless of river regulation or land development. In general, the temporal trends showed greater decreasing trends in discharge under dry and

greater increasing trends in discharge under wet hydrologic conditions compared to average years.

In phase II, I explored the effects of Atlantic Multi-decadal Oscillation (AMO: metric of Sea Surface Temperature anomalies of the North Atlantic Ocean typically over 0-80°N) and North Atlantic Oscillation (NAO: metric of Sea-Level Pressure anomalies over the Atlantic sector 20°-80°N, 90°W-40°E) regime shifts on hydrologic responses to evaluate whether the intensified inter-annual variability in discharge is explained by natural climate cycles. I focused on AMO and NAO regime shifts of the early 1950s, 1970s, and 2000s and the effects on hydrology of the Merrimack River watershed. AMO regime shifts were strongly synchronized and preceded both precipitation and discharge across all study sites by one to two years, while NAO regime shifts indicated weaker associations. I found that all responses tended towards greater extremes from each regime shift to the next. Across many different ecological discharge indicators, high percentile values increased across regimes, while low percentile values decreased between regimes (with a few exceptions).

In phase III, I evaluated the potential for discharge estimation considering annual or seasonal AMO and NAO teleconnection patterns with precipitation and discharge. When AMO was extremely positive (greater than 0.2), the magnitudes of annual precipitation and discharge correlation coefficients with AMO were obscured by river regulation or land development. In contrast, during the extreme negative phase of AMO (less than -0.2), river regulation and land development amplified the effects of changing climate on precipitation and discharge variations. AMO was positively associated with precipitation and discharge, while NAO showed a negative linkage. AMO positive phase was correspondent with average-to-wet discharge conditions at headwater catchments. When basin scale increased, confidence in the estimation of discharge conditions decreased for downstream developed sub-basins compared to headwater undisturbed catchments.

The results from this research indicated that the Merrimack River watershed is expected to experience increases in discharge in the future and changing in timing and the seasonal distribution of this discharge; therefore development should be avoided on flood plains. Furthermore, the current reservoir storage capacity in the Merrimack should be improved in order to accommodate excess water input and minimize flood damage. Future research should target changes in the magnitude and timing of high discharge events in order to develop adaptation strategies for aging hydraulic infrastructure in the region. This dissertation will provide information for watershed planners and managers to inform future sustainable water use in the Merrimack River watershed and other northeastern basins.

The interacting hydrologic responses to changing climate, watershed physical characteristics, river regulation, and land development in the northeastern United States

By:

Rouzbeh Berton

B.Sc., Zanjan University, Zanjan, Iran, 2003

M.Sc., Sharif University of Technology, Tehran, Iran, 2006

DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Civil Engineering

Syracuse University

May 2017

Acknowledgements

I would like to express my heartfelt gratitude and appreciation to my advisor Professor Charles T. Driscoll who gave me the freedom to pursue my own topic of interest for my research while providing me incredible scientific and financial support. Dr. Driscoll takes time to listen to his students and this is best reflected in his brilliant comments, feedback, and questions he poses to them. He is able to balance the students' weaknesses with their strengths. He is fully aware of the obstacles faced by the international students when they write in a language other than their own. In order not to undermine a student's confidence, he simply points out an error with a simple comment: "this is not clear". He gives students total freedom to develop their own ideas and ways to achieve them rather than imposing his own methods. I have learnt a great deal from Dr. Driscoll but two in particular are lifetime lessons. First is not to personalize things and second is not to force people to do things the way you want it done. He is and will always remain one of the most influential people in my life.

I would like to thank Syracuse University and the Department of Civil and Environmental Engineering for the PhD admission and for the assistantship awards. I would extend my gratitude to the National Science Foundation Long Term Ecological Research (NSF-LTER) program for their financial support in conducting the current research and the travel expenses which allowed me to present my findings at local, regional, and national conferences.

I would definitely like to thank each and every one of my committee members, Dr. Paul Barten, Dr. Christa Kelleher, Dr. John Campbell, Dr. David Chandler, and Dr. Jane Read for their constructive feedback and suggestions which have substantially improved the quality of my research. I was blessed to have such a knowledgeable and passionate committee which never

refused to assist me and devoted their time in order to ease my progress. Without their help and support the completion of this dissertation would not have been possible.

I would like to thank Dr. Raymond Letterman, my teaching and research mentor who accepted me as his TA and with whom I had the honor of working on the NYC Water Project. I am also grateful for his continued support. I would like to thank Dr. Svetoslava Todorova, a great teaching and research mentor, who nominated me for the "2014-2015 Outstanding Teaching Assistant Award (OTA)" and Dr. Sam Salem, the Department Chair, for the endorsement of my nomination. I want to extend my gratitude to whom recommended me to graduate school for the OTA award, Dr. Douglas Call, Dr. Raymond Letterman, Dr. Andria Costello Staniec, and two of my undergraduate students Siavash Bashiriyeh and Katayoun Mokhtarzadeh. I would also like to thank Dr. Cliff Davidson and Dr. Chris Johnson for their help and support. I would definitely like to thank Dr. Ataei, Dr. Steinberg, Dr. Condon, and Dr. Salem for providing me with teaching assistantship position during my last semester studying at Syracuse University.

Since arriving in the United States in August 2009, I have got to know many great people whose knowledge and experience have tremendously helped me to adapt to the new culture and overcome my homesickness. I would specifically like to thank my very best friend Dr. Ali Goshayeshi who has treated me like one of his own family members. I cherish every moment of our great friendship and value his support and encouragement not only during my PhD program but through the many difficult moments in my life. I would also like to express my gratitude to my very best and special friend Niki Ashouri who has given me tremendous emotional and mental support throughout the last year of my PhD study.

I would also like to thank our dearest family friend, Touria Ghaffari for her true friendship and great support during my PhD study. In addition, I would like to express my great appreciation to my best friends Dr. Ebrahim Soltani, Dr. Kaveh Zamani, Dr. Mehrzad Boroujerdi, and Dr. Siamak Malek Mohammadi for their encouragements towards pursuing my dreams. I specially want to thank Fariba Rahmanzadeh, the Assistant Director of Slutzker Center for International Services at Syracuse University, for her help, support, and mainly for her true friendship.

Special thanks to my conversation partners Jina Kim, Justin Freedman, Laura Thompson, and Savannah Janette Siu for their friendship and helping me improve my language skills while enjoying the intellectual conversations with them. I am greatly thankful to CIE Department staff, Elizabeth Buchanan, Maureen Hale, Mickey Hunter, Heather Kirkpatrick, Mary Margaret Koppers, Linda Lowe, and Mario Montesdeoca for their kindness, patience, help, and support. In addition, I had the honor of working with the staff of graduate school Dr. Peg De Furia, Kathleen M. Joyce, Shawn Loner, Terrie Monto, and Glenn Wright and I would like to thank them all for their friendship and support.

Finally, I would like to express my deepest gratitude to those who have been my pillars of strength, to the ones whose unconditional love, emotional and mental support have always helped me to fulfill my dreams; to my dear mother Mahyar, to my dear father Naser, and to my dear lovely sister Anousheh. Their encouragement founded in me the motivation to pursue and complete this degree. I dedicate this dissertation to Mayhar, Naser, and Anousheh.

To my dear parents and sister

Table of contents

List of tables

List of figures

1- Introduction

In this dissertation, I address three problems in the field of water resources and hydrological studies: 1- How climate change signals manifested through changes in river discharge, vary from small headwater reference catchments to downstream regulated or developed sub-basins; 2- How regime shifts in AMO and NAO phenomena may influence the frequency of extreme discharge events; and 3- How discharge and hydrologic conditions change in response to teleconnection of AMO and NAO.

The analyses of hydrological indicators may shed light on the open-ended question of whether the long-term trends are true signals of climate change or they are just “noise” or natural climatic variability (Peters et al., 2013). The long-term hydroclimatological records of reference headwater reaches in experimental watersheds have been utilized to quantify the effects of changing climate (Gallart et al., 2011; Hatcher and Jones, 2013; Nayak et al., 2010; Reba et al., 2011; Viviroli et al., 2011). Initial studies have mostly focused on small headwater catchments rather than large developed or regulated downstream sub-basins (Whitfield et al., 2012). Although they are inherently complex, the study of hydrologic changes throughout large basins provides an opportunity to understand the scale-dependency of the potential response to climate change. Consequently, research is needed to extend the work of the long-term ecological research (LTER) program on undisturbed headwater catchments to larger downstream basins influenced by river regulation, forest conversion, and land development (LTHERS: Long-Term Human Environmental Research Stations) (Jones et al., 2012; Wilbanks and Kates, 1999).

Two common measures of long-term shifts in the Northeast climate are the Atlantic Multi-decadal Oscillation (AMO) and North Atlantic Oscillation (NAO) (Armstrong et al., 2013; Bradbury et al., 2003, 2002a, 2002b; Kingston et al., 2007; Mazouz et al., 2013; Peng et al., 2013; Smith et al., 2010; Tootle et al., 2005). While the mechanisms associated with the NAO and AMO are well studied, the effects of the AMO and NAO on patterns of discharge across basin scales and levels of disturbances are less clear. As discharge integrates the effects of temperature and precipitation variations over a seasonal time scale, the primary characteristics of discharge provide valuable information regarding the response of water resources to changing climate (McCabe and Wolock, 2014). The study of the influence of AMO and NAO regime shifts on basin hydrology may determine whether the intensified inter-annual variability in discharge is explained by natural climate cycles. Discharge may exhibit a lagged relationship with AMO and NAO. Monitoring the variations of annual/seasonal AMO and NAO can provide information on how discharge may vary in the years/seasons that follow.

The overarching goal of this dissertation is to assess hydrologic responses to the potential effects of changing climate in a complex watershed, which varies from relatively undisturbed forested headwaters to highly developed downstream reaches, in order to improve understanding of future water resources availability in the northeastern United States. This research is focused on climate change effects study of the Merrimack, a 13,000 km^2 forested watershed which drains mostly New Hampshire (NH) and northern Massachusetts (MA) and is the fourth largest basin in New England. I exploit monthly estimates of precipitation and temperature from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly, 2004), discharge data from 21 stations in the US Geological Survey (USGS) and Hubbard Brook Experimental Forest (HBEF) gauge networks, and monthly AMO and NAO indices from the National Center for Atmospheric Research (NCAR) (Hurrell, 2015; Trenberth et al., 2015). Several approaches and tools were utilized to accomplish the objectives in three research phases. The three phases of this dissertation are: 1) assessment of the scale-dependency of discharge response to climate variation for dry, average, and wet years, and considering land development and river regulation in the Merrimack River watershed (NH-MA); 2) exploration of the influence of AMO and NAO regime shifts on basin hydrology; and 3) estimation of future hydrologic discharge conditions considering the teleconnection patterns of AMO and NAO with discharge.

1-1- Objectives and hypotheses

The objectives of this research are to:

1- Assess temporal discharge responses to climate variation using long-term precipitation and discharge data and considering sub-basin area and development;

2- Evaluate the potential influences of AMO and NAO regime shifts on the magnitude and timing of high and low percentiles of discharge; and

3- Determine the probability for extreme discharge conditions (i.e., dry and wet years/seasons) which coincide with the extreme positive and negative phases of AMO or NAO.

A review of the literature on recent findings on climate effects and anthropogenic impacts on water resources has led me to develop the following hypotheses for my PhD research (Chapter 5-7):

Hypothesis 1 (Chapter 5): Regional analyses of hydrology in northeastern United States have shown increases in discharge and shift in its timing due to long-term climate variations associated with increases in precipitation, decreases in snowpack accumulation, and greater winter rainfall. ***In the Merrimack River watershed, total annual discharge has increased with a shift toward earlier spring peak and higher summer discharges. However, the pattern of discharge response is not uniform across years, i.e. more discharge decrement in drier and more discharge increment in wetter years is anticipated compared to historical patterns.***

Hypothesis 2 (Chapter 5): The temporal and spatial responses of discharge to climate change are dependent on hydrological and hydraulic alterations along with the scale of the basin. ***In developed reaches of the Merrimack River watershed, changes in discharge metrics are less clear compared to headwater regions due to the attenuation of the climate signals by basin size, river regulation, and/or percentage of development.***

Hypothesis 3 (Chapter 6): There were early 1970s hydroclimatic regime shifts in the northeastern United States consistent with AMO and NAO regime shifts. ***Variations in the magnitude and frequency of high and low discharge events for the Merrimack River watershed are associated with regime shifts in both AMO and NAO depending on basin size, river regulation, and/or development.***

Hypothesis 4 (Chapter 7): Summer and winter discharge anomalies in the northeastern United States are associated with extreme phases of NAO index. ***In the Merrimack River watershed, discharge anomalies indicate annual/seasonal lagged teleconnection patterns with variations in extreme positive and negative phases of both AMO and NAO which are attenuated by basin size, river regulation, and/or development.***

In Chapter 2, I provide a review of relevant literature for the dissertation. In Chapter 3, I provide a brief description of the Merrimack River watershed. In Chapter 4, I describe the materials and methods used in this dissertation.

To test these hypotheses, I have developed the following approaches to the dissertation:

1- I 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 these hydrologic flow classes. I use multivariate statistical analyses to discover how discharge may vary with regards to geomorphology of the Merrimack River watershed in addition to land use/cover characteristics. By including regulated and developed sub-basins, I am able to explore how land disturbance and river regulation influence riverine responses to changing climate (Chapter 5);

2- I examine regime shift points of the annual time series of AMO, NAO, precipitation, and discharge corresponding to catchments of varying sizes and levels of human development. I evaluate differences in discharge record between periods of regime shifts. I evaluate variations in the frequencies of low and high extreme values for several indicators of hydrologic alteration, including the monthly discharge magnitude, duration, and timing indicators before and after the AMO and NAO regime shifts (Chapter 6); and

3- I compare differences in discharge conditions during extreme positive and negative phases of AMO and NAO. I examine annual and seasonal correlations between precipitation and discharge and the extreme phases of AMO and NAO at zero-, one-, or two- year/season lags. I introduce a simple, but novel approach to estimate a confidence band for near-term prediction of extreme dry and wet discharge conditions with regards to the extreme phases of AMO and NAO (Chapter7).

In phase I (Chapter 5), I assessed the scale-dependency of the hydrologic responses to changing climate using long-term precipitation and discharge records for the Merrimack River watershed, and considering watershed physical characteristics, river regulation, and land development. In phase II (Chapter 6), I explored the influences of AMO and NAO regime shifts on hydrologic responses of the Merrimack reference headwater catchments compared to downstream developed sub-basins to evaluate whether the intensified inter-annual variability in discharge is explained by the natural climate cycle. In phase III (Chapter 7), I evaluated the potential to estimate discharge in response to annual and seasonal AMO and NAO teleconnection patterns. The final chapter (Chapter 8) of this dissertation provides synthesis of the major findings of my research and their applications followed by suggestions for future work.

2- Literature review

2-1- The effects of changing climate on hydrologic response

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., 2016, 2012). Increases in greenhouse gas emissions due to human activities are projected to increase global mean air temperature by 2-3°C at the end of the 21st century (Collins et al., 2013). 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; O'Gorman and Schneider, 2009; Vose et al., 2012), this conclusion is still debated and remains highly variable by region (Dominguez et al., 2012; Jianting Zhu et al., 2012; Kiktev et al., 2003; Matonse and Frei, 2013; Melillo et al., 2014; Pryor et al., 2009; Tebaldi et al., 2006; Wang 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). Based on climate projections for the 21st century, the northeastern United States is expected to undergo increases in winter (1.4 to 6.7°C) and summer (0.8 to 7.8°C) temperatures (Pourmokhtarian et al., 2016, 2012) and increases in annual precipitation (~100 mm) (Campbell et al., 2011; Hayhoe et al., 2007; Pourmokhtarian et al., 2016). These changes are predicted to cause less snow accumulation, earlier peak flow, attenuated spring flows, increasing summer precipitation and evapotranspiration which could either increase or decrease summer base flows, respectively

(Campbell et al., 2011; Frumhoff et al., 2007; Hayhoe et al., 2007; Huntington and Billmire, 2014).

Changes in seasonal and annual temperature, evapotranspiration, precipitation, and discharge can have important consequences on ecosystem structure and function (Peters et al., 2013). Among those variables, discharge can be an appropriate indicator for changing climate since it is the net result of spatial and temporal variations in both precipitation and evapotranspiration. Human disturbances such as water withdrawal and reservoir storage are also affecting discharge and streamflow regimes (Dingman, 2015). In order to study climate and human influences on watershed hydrology, appropriate discharge indicators are needed to effectively characterize hydrologic variations (Beveridge et al., 2012; Poff et al., 1997; Richter et al., 1996).

The appropriate indicator should provide information on discharge magnitude, timing, duration, frequency, or rate of change according to research questions. To date, approximately two hundred 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 develop a consensus on a subset of these two hundred possibilities to clearly identify 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 (Black et al., 2005). Such broad hydrometric indicators can be supplemented by metrics such as discharge anomaly to parse data records by wet, and dry years (Genz and Luz, 2012). Extreme wet and dry conditions are determined by how far the discharge responses are deviated from the long-term mean. Moreover, 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 catchments have been utilized to quantify the effects of changing climate (Gallart et al., 2011; Hatcher and Jones, 2013; Nayak et al., 2010; Reba et al., 2011; Viviroli et al., 2011). The analyses of hydrological indicators may shed light on the open-ended question of whether long-term trends are true signals or just “noise” or natural climatic variability (Peters et al., 2013). 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 New Hampshire (NH) response to recent changes in climate. Increases in precipitation, decreases in snowpack accumulation, and decreases in evapotranspiration were identified as major potential drivers of long-term hydrologic changes at the HBEF and at the broader scale, of the northeastern United States (Campbell et al., 2011; Huntington and Billmire, 2014).

At the river basin scale, the hydrologic response to climate change can be confounded by land cover/use change, urbanization, and/or river regulation (Frans et al., 2013; Jiang et al., 2007; Kim et al., 2013; Lindström and Bergström, 2004). Land use/cover change and urbanization can affect precipitation since forty percent of annual land precipitation globally comes from transpiration (Dingman, 2015). Highly irrigated regions have been shown to generate disproportionate quantities of local precipitation (DeAngelis et al., 2010). In contrast, deforestation decreases evapotranspiration and consequently can reduce humidity (de la Crétaz and Barten, 2007). The existence of either natural or manmade reservoirs increase storage and increases in evaporation from the lake surface thus may increase precipitation for downwind areas (Degu et al., 2011).

Urbanization may change hydrologic response since the surface temperature of developed regions is typically higher than the undeveloped sites due to the higher rate of solar radiation absorbed by buildings and impervious surfaces (de la Crétaz and Barten, 2007). The urban "heat island effect" is also enhanced by industrial and motorized vehicles emissions. The increases in temperature can contribute to increase convective uplift, leading to increased precipitation downwind of the city center (Dingman, 2015). Urban development can increase the magnitude of total precipitation by 9-17% as well as the frequency of heavy rainfall (>25 mm) (Changnon, 1981; Huff and Changnon, 1973; Knight and Davis, 2009; Villarini et al., 2011). The enhancements of temperature and precipitation in urbanized regions have the potential to increase summer discharge, groundwater recharge, and sewer flow (Huff, 1977). Additionally, the growing season can be extended and water quality can be degraded (e.g., warmer streamflow decreases dissolved oxygen concentration and adversely affects aquatic life) (de la Crétaz and Barten, 2007; Solecki et al., 2005).

Although it is inherently complex, the study of hydrologic changes throughout large basins provides an opportunity to understand the scale-dependency of the potential response to climate change. Initial studies have mostly focused on small headwater catchments rather than large developed or regulated downstream sub-basins (Whitfield et al., 2012). Hence, the potential for urban development to influence watershed hydrologic response becomes an interesting topic for research. Consequently, research is needed to extend the work of the Long-Term Ecological Research (LTER) program on undisturbed headwater catchments to larger downstream basins influenced by river regulation, forest conversion, and land development (LTHERS: Long-Term Human Environmental Research Stations) (Jones et al., 2012; Wilbanks and Kates, 1999). This research could help to compare the influence of anthropogenic activities on hydrologic responses to the potential effects of changing climate.

2-2- The effects of large-scale circulation patterns regime shifts on hydrologic response

Over the conterminous United States, changing climate is altering hydrology in a variety of ways. This includes changes to the type of winter precipitation, the timing and volume of spring peak discharge, the magnitude of summer low discharge, and changes in evapotranspiration (Campbell et al., 2011; Collins et al., 2013; Déry and Wood, 2004; Frumhoff et al., 2007; Hidalgo et al., 2009; Huntington et al., 2009; Huntington and Billmire, 2014; Kam and Sheffield, 2016; Mauget, 2003). Many studies have quantified these hydrologic alterations, but drivers of change are still uncertain. In particular, there is no consensus on whether long-term variations in patterns of discharge are the result of long-term climate cycles, and how these long-term climate cycles propagate through basins with varying sizes and biophysical and development characteristics (Bradbury et al., 2003; Hannaford and Marsh, 2006, 2008; Ishak et al., 2013; Panda et al., 2013; Seager et al., 2011).

Two common measures of long-term shifts in the Northeast climate are the Atlantic Multi-decadal Oscillation (AMO) and North Atlantic Oscillation (NAO) (Armstrong et al., 2013; Bradbury et al., 2003, 2002a, 2002b; Kingston et al., 2007; Mazouz et al., 2013; Peng et al., 2013; Smith et al., 2010; Tootle et al., 2005). The AMO is an index of Sea Surface Temperature (SST) anomalies with phase changes approximately every 30 to 40 years (Enfield et al., 2001; Gray, 2004; Kerr, 2000). Mechanistically, the AMO phase change interferes with the Thermohaline circulation, a current of warm surface water connecting the Southern Hemisphere to the North Atlantic (Deser et al., 2010). When AMO is extremely positive (negative), it slows down (speeds up) the oceanic circulation (Collins et al., 2014; Roller et al., 2016), directly altering SST. The SST variations over the tropical Atlantic Ocean induced by AMO can influence tropical cyclone activity (Roller et al., 2016) and bring warm, moist air into the eastern

US leading to extreme precipitation in the region (Roller et al., 2016). The positive phase of AMO modulated by the sign of PDO (Pacific Decadal Oscillation) is often associated with reduced annual rainfall over the most of the US noticeably for droughts in the 1930s and 1950s, and in particular, over the eastern Mississippi basin (Enfield et al., 2001; Kavvada et al., 2013; Luce et al., 2016; McCabe et al., 2004). Conversely, water surplus in the Mississippi basin may be due to the negative phase of AMO (Enfield and Cid-Serrano, 2006; Rogers and Coleman, 2003). In the upper Missouri River basin and the Great Basin, the positive (negative) AMO phase is correspondent to less (more) extreme precipitation, while in the lower Colorado River Basin more (less) extreme precipitation occurs (Peng et al., 2013). Inland basins experience drier conditions during the AMO negative phase whereas coastal basins have more winter precipitation and coastal storms (Bradbury et al., 2003, 2002b).

The NAO index represents Sea-Level Pressure (SLP) anomalies and has positive and negative phases that may last between 3 and 10 years (Hurrell et al., 2003; Visbeck et al., 2001). The NAO phase change may affect the location, frequency, and intensity of storm tracks (developed in the western Atlantic due to cyclones formation resulting from contrasting heat capacity of the land and ocean) in the northeastern US (Hurrell, 1995; Serreze et al., 1997). When the NAO is positive, the pressure gradient between Icelandic low and Azores high is large with a dominant low-pressure system (Bradbury et al., 2002a). In the Northeast, positive NAO index is associated with increases in temperature and annual precipitation and favors more winter rainfall than snowfall (Bradbury et al., 2003, 2002a; Collins, 2009; Hurrell, 1995; Kingston et al., 2007; Lins and Slack, 1999; Mazouz et al., 2013). When NAO phase is negative, the pressure gradient between the Icelandic Low and the Azores High is small (Hurrell, 1995). When the Icelandic Low is abnormally high, the jet stream over Greenland and meridional flow is frequently blocked (north-south meridian) in the North Atlantic region (Bradbury et al., 2002a), facilitating a cold trough, a southward shift in the polar front jet (Roller et al., 2016) and polar air penetration along the Northeast Coast. The associated low air temperatures, increased snowfall, more frequent coastal storms including nor'easters, and alterations to both winter and summer streamflow are well documented (Armstrong et al., 2013; Bradbury et al., 2002a, 2002b; Collins, 2009; Durkee et al., 2008; Hartley and Keables, 1998; Hurrell, 1995; Kingston et al., 2007, 2007; Marshall et al., 2001; Roller et al., 2016; Steinschneider and Brown, 2011). A prolonged negative NAO is often attended by increased streamflow along the Northeast coast and decreased runoff in inland basins (Bradbury et al., 2002b; Steinschneider and Brown, 2011).

While the mechanisms associated with the NAO and AMO are well studied, their influence on patterns of discharge across basin scales and levels of disturbances is less clear. As discharge integrates the effects of temperature and precipitation variations over a seasonal time scale, the primary characteristics of discharge provide valuable information regarding the response of water resources to changing climate (McCabe and Wolock, 2014). The discharge response may also differ depending on catchment properties (e.g. basin size, soil depths and type, vegetation, channel slope, topographic index, drainage density) (McGrane et al., 2014; Razavi and Coulibaly, 2013; Sawicz et al., 2014; Sivakumar et al., 2013) in addition to anthropogenic disturbances (e.g. land development, river regulations including dams and reservoirs) (Poff et al., 2015). To best study the effects of AMO and NAO regime shifts on watershed hydrology, a set of indicators should be chosen that clearly represent the primary characteristics of discharge. These primary characteristics, identified as descriptors of 'the natural flow regime' (Poff et al., 1997), include magnitude (important in water resources studies and water quality problems), timing (crucial in determination of discharge distribution throughout the water year, soil moisture availability, and water quality), frequency and duration (significant impacts on ecosystem structure and function) (Beveridge et al., 2012; Gao et al., 2009; Hurd et al., 1999; Kennard et al., 2010; Olden and Poff, 2003; Poff et al., 1997; Richter et al., 2006, 1996). In this research, I quantify changes in discharge using the indicators of hydrologic alteration (IHA), a suite of metrics that quantify the primary ecological characteristics of discharge (Richter et al., 1997, 1996).

With respect to both discharge and precipitation, several shifts have been observed across the northeastern US, including a prominent shift in the magnitude and frequency of records during the early 1970s which have been attributed to regime shifts of several large-scale circulation patterns primarily AMO and NAO (Armstrong et al., 2012; Collins, 2009; Douglas and Fairbank, 2011; Hodgkins, 2010; Huntington et al., 2009; Mauget, 2003; McCabe and Wolock, 2002; Rice and Hirsch, 2012; Villarini and Smith, 2010). In this study, I use time series of AMO, NAO, precipitation, and discharge to identify regime shifts with a sequential step-change detection algorithm (Rodionov, 2004). This algorithm allows detection of multiple regime shift points beyond the well-studied hydroclimatic shift in the Northeast during the 1970s. The relationships of AMO and NAO with discharge responses may not be synchronous, as these indices (AMO, in particular) are affected by the delayed thermal memory of the ocean as opposed to climate system (Bradbury et al., 2002a; Hartley and Keables, 1998; Karnauskas et al., 2009; Roller et al., 2016). This research could help investigate how ecological discharge indicators may respond with lags to regime shifts associated with changes in AMO and NAO regimes in the northeastern US.

2-3- Opportunities for discharge prediction with respect to variations in synoptic-scale phenomena

Teleconnection often refers to the contradictory seasonal variations which occur simultaneously (*connected*) in regions that are thousands of kilometers apart (*tele*) (Hurrell et al., 2003); for instance a cold winter with considerable snowfall in the Northeast vs. a mild winter in Europe with abundant rainfall due to variations in Atlantic circulation patterns. Since atmospheric and oceanic circulation patterns control variations in air temperature and precipitation, changes in discharge over the Northeast may be teleconnected to changes in AMO or NAO (Seager et al., 2012). Although the nature of variations in AMO and NAO is stochastic, determining a possible level of predictability is of great interest (Gillett et al., 2002). The increasing trend in northern hemisphere land and sea surface temperatures over the past 40 years is believed to be teleconnected to NAO variations (Gillett et al., 2002; Hurrell, 1996; Thompson et al., 2000).

The NAO is the well studied teleconnection index due to its impacts on the hydroclimate of the northern hemisphere (Armstrong et al., 2013, 2012; Gillett et al., 2002; Hoerling et al., 2001; Hurrell et al., 2003; King and Kucharski, 2006; Lu et al., 2004; Osborn, 2011; Rind et al., 2005a, 2005b; Sutton and Hodson, 2003). Most research on NAO teleconnection patterns focus on summer and winter seasons when the deviation of SST and SLP are greatest (Gillett et al., 2002). Generally, the variations in NAO are unpredictable, so NAO explains only a portion of the climate variability over the North Atlantic (Gillett et al., 2002). For instance, NAO explained up to 31% of winter temperature variations in the Northern Hemisphere for the 1950-2000 period (Gillett et al., 2002). Nevertheless, the positive trends in both NAO and precipitation trends since 1960 over the Atlantic Ocean may indicate increasing prediction strength (Gillett et al., 2002).

Coleman and Budikova (2013) found a teleconnection pattern between summer discharge anomalies in the Northeast and extreme phases of NAO up to three seasons in advance. I hypothesize that the temporal annual or seasonal changes in dry and wet discharge events could be explained by variations in the extreme phases of AMO and NAO together, which to the best of my knowledge has never been addressed. In this study, differences in discharge conditions during extreme positive and negative phases of AMO and NAO are compared, and annual and seasonal correlations between precipitation and discharge and the extreme phases of AMO and NAO are examined at zero-, one-, or two- year/season lags (total of 15 scenarios). In this study, I introduce a simple, but novel approach to estimate a confidence band for near-term prediction of wet, average, and dry discharge conditions from the historic relative frequency of occurrence with regards to the extreme phases of AMO and NAO. This research could help to investigate the teleconnection patterns of AMO and NAO with precipitation and discharge variations in order to understand the implications for future water resources management in the northeastern US.

3- Study site

3-1- General information

The Merrimack River watershed encompasses almost 13,000 km^2 of New Hampshire (NH) and northeastern Massachusetts (MA) (Figure 3-1). The Merrimack River watershed is under the influence of subarctic climate in the north (White Mountain area), with humid continental climate with either warm (coastal) or hot (inland) summers (Köppen climate classification). Over the period of 1904 to 2014, the mean annual precipitation (PRISM) and discharge (US Geological Survey: USGS, ID: 17, Table 3-1) (October 1st through September 30th) are 1060 mm (±167) and 772 mm (±158), respectively. For the same period, the mean monthly minimum and maximum temperatures are -0.6°C (±9.3) and 12.3°C (±10.4) at Plymouth NH (PRISM).

The dominant land cover in the Merrimack River watershed is forest (67%), with developed regions comprising 16% of the area mainly in downstream regions, i.e. southern NH and northern MA (Figure 3-1, Table 3-1). The headwaters of the Merrimack River watershed also include the Hubbard Brook Experimental Forest (HBEF), where long-term hydroclimatic information are available for climate change studies at small catchment scales. The total impervious surface area in the Merrimack watershed is less than 3%. However, in urbanized areas in the southern portion of the watershed, total impervious are is greater than 9% (Xian et al., 2011), at or near the threshold that is often associated with substantial changes in localized streamflow (de la Crétaz and Barten, 2007). Population density is approximately 160 people/km^2, with most of population concentrated in southern NH and northern MA (US Census Bureau 2010).

The Merrimack River originates at the confluence of Pemigewasset River and the Winnipesaukee River in Franklin, NH (Figure 3-1) 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 difference between the highest and the lowest (sea level) elevation in the watershed is 914 m. The Merrimack River is highly regulated with 41 major dams operating for hydropower generation, flood control, recreation, and/or navigation (Figure 3-1). The overall 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).

Within the Merrimack River watershed, I focus on 21 sites with a range of less than a square kilometer drainage area up to 11,450 km^2 (Figure 3-1, Table 3-1). Ten reference catchments have minimal land disturbance with no impoundment or river regulation. The remaining gauges represent sub-basins with a history of hydraulic control and land cover/use change including local urbanization (Table 3-1).

3-2- Geology and soil order

New England has been mostly formed by volcanic island arcs in the geologic eras of Ordovician (485.4 million years ago or Mya), Silurian (443.8 Mya), and Devonian (419.2 Mya) (Skehan, 2001). The bedrock is heavily metamorphosed and igneous (Olcott, 1995). The overlying layer is generally glacial conglomerates which are composed of limestone, sandstone, shale, and granite. Limestone (0.032-189 m/yr), sandstone (0.0095-189 m/yr), shale ($3\times10^{-6}-0.063$ m/yr), and granite (3×10^{-6}-0.0032 m/yr) indicate low hydraulic conductivity (Heath, 1983). The long range for hydraulic conductivity is mainly due to secondary porosity.

The Merrimack watershed is geologically formed during the Ordovician period while the upstream orogenesis processes began from the end of Ordovician period and continued into the Devonian and the Silurian eras. The hydrography of the Merrimack watershed is largely determined by the glaciations of the Appalachian Mountains of NH (de la Crétaz and Barten, 2007).

The average depth of the saturated zone (groundwater table) below the soil surface in the upstream, middle reaches, and downstream regions of the Merrimack varies with the range of 0-5, 0.5-11, and 0-20 meters, respectively (for downstream regions located in NH the range is 7-20 meters while for northern MA the range varies between 0-5 meters) (USGS Groundwater Watch Information).

The upstream soil order of the Merrimack is Spodosols while downstream regions are mostly covered by Entisols and Histosols. Spodosols are acidic well-drained soils developed in under hardwood or coniferous forests in cool, wet climate (largely unsuitable for agriculture). Entisols and Histosols are deposited soils developed in regions with wet growing season (more than 400 mm of rain during 80% of the growing season) (Brady and Weil, 2008; de la Crétaz and Barten, 2007).

3-3- Land use/cover types and historical trends

The upstream of the Merrimack River watershed is part of the Northeastern Highlands ecoregion with relatively low population density (McMahon et al., 2001). The Northeastern Highlands ecoregion is mostly covered by northern hardwood and spruce-fir forests (Gallant et al., 2004). Open high hills could be recognizable over the northern New Hampshire, while low ridges are more typical landscape features in the central and southwest portions of the state (Gallant et al., 2004; Skehan, 2001).

The historical pattern of forest conversion to farmland was largely ended by the mid-1800s; the farm lands were subsequently abandoned (in the late-1800s and early-1900s) and quickly returned to forested conditions (de la Crétaz and Barten, 2007; Drummond and Loveland, 2010; Hart, 1968). Logging was relatively common in western Maine and northern New Hampshire; small-scale agriculture and tourism were prevalent in other parts of the Merrimack River watershed (Kambly, 2006). The grand total change per decade among all land use/cover classes for the Northeastern Highlands ecoregion has risen from 2.3% (±1.3%) in late 1970s to 6.2% (±2.4%) in early-2000s; the average annual rate of change increased from 0.3 in early-1970s to 0.8 in late-1990s (Kambly, 2006).

Although there is 4% decrease in forested land since 1970s, it still covers 80% of the lands in the ecoregion (Loveland and Acevedo, 2006). Developed lands have increased from 1.8% in early 1970s to 2.3% in early 2000s (i.e., almost 30% change in the percent of developed lands) (Soulard and Sleeter, 2012). For the 30-yr period (1973-2000), 41% of forested lands were mechanically disturbed; one-third of the mechanically disturbed lands naturally restored into grassland/shrubland; one-fifth of grassland/shrubland reforested again (Kambly, 2006). Only 2% of the forested lands were turned into developed regions (Drummond and Loveland, 2010; Sleeter et al., 2013).

The southernmost portion of the Merrimack River watershed is part of the Northeastern coastal zone (McMahon et al., 2001). Similar to the highlands ecoregion, hardwood forest is still dominant with limited coastal/inland wetland (Auch, 2006). Development has been increased from 23% to 27% in the period of 1973-2000 (17% net change) due to 50% increases in the population (Loveland et al., 1999; Vogelmann et al., 2001). Development has resulted in a 4% loss in forest cover from 1973 to 2000 (Drummond and Loveland, 2010; Loveland and Acevedo, 2006; Sleeter et al., 2013; Soulard and Sleeter, 2012).

The land use/cover trends for the Merrimack River watershed over the period of 1973-2000 closely follow the general patterns for the northeastern United States. There is a net 3.5-4.8% decrease in the Merrimack forested area for the period of 1973-2000; In the meanwhile, downstream urbanized regions have experienced an increase in development rate for 4.8-6.2% (Loveland et al., 1999; Loveland and Acevedo, 2006). The overall rate of land cover/land use change for the Merrimack River watershed is higher in upstream regions (8.8-14.4%) than downstream developed regions (4.1-8.7%) (Gallant et al., 2004; Loveland et al., 2002).

Table 3-1- 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 River watershed land cover is presented based on the 2006 National Land Cover Database information.

ID	The description of study sites	Latitude Longitude	Gauge datum (m)	Drainage area (km^2)	Slope (%)	Land cover (% of total)			Period of record	Mean annual precipitation (mm/WY)	Mean annual discharge (mm/WY)
						Forested	Developed	Other*			
1	HBEF-WS1 (R)	43.95 -71.73	488	0.1	18.6	98.7	0.4	0.8	1957 2011	1350	863
2	HBEF-WS2 (R)	43.95 -71.72	503	0.2	18.5	98.7	0.4	0.8	1958 2011	1351	958
3	HBEF-WS3 (R)	43.95 -71.72	527	0.4	12.1	98.7	0.4	0.8	1959 2011	1355	863
4	HBEF-WS4 (R)	43.95 -71.73	442	0.4	15.6	98.7	0.4	0.8	1961 2011	1389	920
5	HBEF-WS5 (R)	43.95 -71.73	488	0.2	15.4	98.7	0.4	0.8	1965 2011	1421	916
6	HBEF-WS6 (R)	43.95 -71.74	549	0.1	15.8	98.7	0.4	0.8	1965 2011	1453	944
7	HBEF-WS7 (R)	43.93 -71.77	619	0.8	12.4	98.7	0.4	0.8	1966 2011	1486	978
8	HBEF-WS8 (R)	43.93 -71.76	610	0.6	14.0	98.7	0.4	0.8	1970 2011	1496	961
9	Assabet River at Maynard, MA (RG-D): Occasional diurnal fluctuation at low flow by mills upstream; greater regulation prior to 1969. Since 1962, high flow affected by retarding reservoirs and, since 1970, occasional release at low flow by these reservoirs.	42.43 -71.45	43	300	5.9	47.5	35.2	17.4	1942 2011	1144	585
10	Concord River below R Meadow Brook, at Lowell, MA (RG-D): Low flow regulated by mills upstream. Daily discharge includes undiverted water from 92.6 mi^2 in basins of Sudbury River and Lake Cochituate. Prior to December 1961, diversion upstream for use by city of Lowell.	42.64 -71.30	21	795	5	40.7	41.7	17.7	1938 2011	1126	756
11	Merrimack River BL Concord River at Lowell, MA (RG-D): Daily discharge includes water released from 210 mi^2 in basins of Sudbury and Nashua Rivers and Lake Cochituate. Flow regulated by power plants, by Franklin Falls Reservoir since 1942, and by Squam, Newfound, Winnipesaukee, Winnisquam, and other lakes and reservoirs upstream.	42.65 -71.30	2	11450	---	68.4	19.6	12.0	1924 2011	1118	620

Table 3-1- Continued

ID	The description of study sites	Latitude Longitude	Gauge datum (m)	Drainage area (km^2)	Slope (%)	Land cover (% of total) Forested	Developed	Other*	Period of record	Mean annual precipitation (mm/WY)	Mean annual discharge (mm/WY)
12	Merrimack River near Goffs Falls, below Manchester, NH (RG-D): Records generally good except those for estimated daily discharges which are generally poor. Flow regulated by power plants, by Franklin Falls Reservoir since 1942, and by Squam, Newfound, Winnipesaukee, Winnisquam, and other lakes and reservoirs upstream.	42.95 -71.46	33	8008	---	77.0	13.1	9.9	1938 2011	1053	612
13	Nashoba Brook near Action, MA (D): Records good except those for estimated daily discharge, which are poor. Occasional regulation since 1967 by pond upstream.	42.51 -71.40	47	33	2.4	45.8	35.3	18.9	1964- 2011	1156	564
14	Nashua River at East Pepperell, MA (RG-D): Extremes and daily discharge include water released while diverting flow of Nashua River for use of Boston metropolitan district and water diverted into basin from Ware River Basin since 1955 for municipal use of Fitchburg. Prior to October 1981, water diverted around station through plant of James River–Pepperell Co. was added to daily figures. Flow regulated by power plant immediately upstream.	42.67 -71.58	52	818	10	55.7	24.6	19.7	1936- 2011	1138	657
15	North Nashua River at Fitchburg, MA (RG-D): Flow regulated by mills and reservoirs upstream. Flow affected by diversions for municipal use.	42.58 -71.79	120	166	---	56.4	34.5	9.1	1973- 2011	1198	675
16	North Nashua River near Leominster, MA (RG-D): Flow regulated by mills, reservoirs, and waste-water treatment plants upstream. Flow affected by diversions from 2.1 mi^2 above outlet of Ashby Reservoir for municipal use. Prior to Dec. 15, 2006, gage located 0.5 mi upstream old mill dam at different datum.	42.50 -71.72	81	285	---	54.4	32.3	13.3	1936- 2010	1164	645

Table 3-1- Continued

ID	The description of study sites	Latitude Longitude	Gauge datum (m)	Drainage area (km^2)	Slope (%)	Land cover (% of total)			Period of record	Mean annual precipitation (mm/WY)	Mean annual discharge (mm/WY)
						Forested	Developed	Other*			
17	Pemigewasset River at Plymouth, NH (R): For water years 2014 and 2015, records good except estimated daily discharges which are poor. Stage-discharge relationship at times is affected by variable slope. Some diurnal fluctuation during period 1940-52 caused by power plants upstream.	43.76 -71.69	139	1611	---	91.7	4.1	4.2	1904-2011	1046	770
18	Shawsheen River near Wilmington, MA (RG-D): Diversion upstream at times each year since 1973 for municipal supply of Burlington.	42.57 -71.21	25	95	---	17.1	73.2	9.7	1965-2011	1181	579
19	Smith River near Bristol, NH (R): For water years 2014 and 2015, records good except estimated daily discharges which are fair. Prior to 1954, some diurnal fluctuation caused by small mill upstream; greater fluctuation prior to 1941.	43.57 -71.75	137	222	---	87.1	3.7	9.3	1919-2011	1063	595
20	Squannacook River near West Groton, MA (RG-D): Occasional regulation at low flow by mill upstream; regulation greater prior to 1961. Entire flow from 2.16 mi2 upstream from outlet of Ashby Reservoir diverted for municipal supply of Fitchburg except for occasional periods of spill.	42.63 -71.66	74	165	5.1	76.5	10.0	13.5	1950-2011	1172	627
21	Winnipesaukee River at Tilton, NH (RG-D): For water years 2014 and 2015, records good. Flow regulated by power plants prior to 1967 and by Winnipesaukee (station 01080000), Winnisquam 4.5 mi upstream, Wentworth, Merrymeeting, and other lakes upstream.	43.44 -71.59	135	1220	---	62.3	27.9	9.9	1938-2011	1083	534

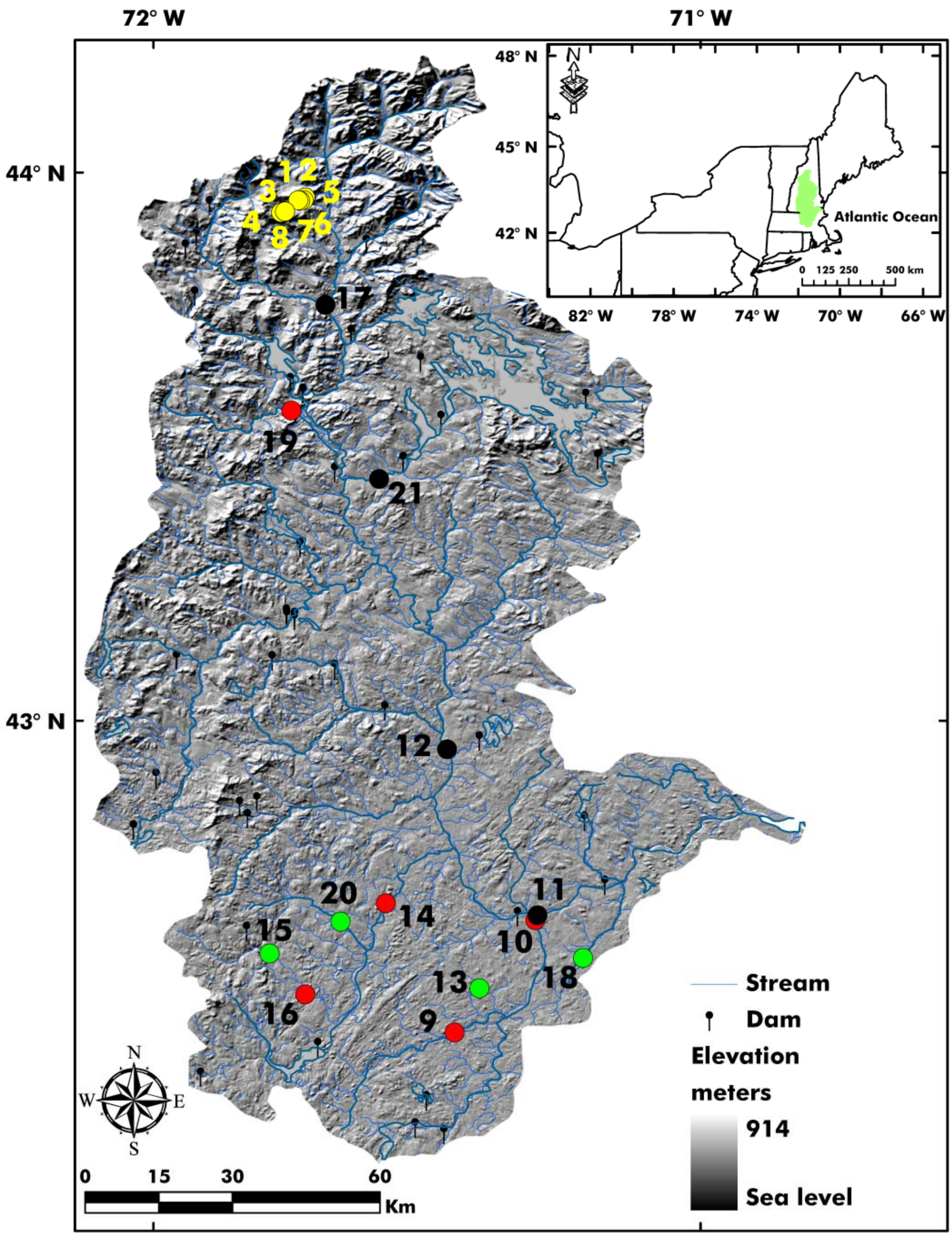

Figure 3-1a- The Merrimack River watershed: Dams, gauging stations, streams, and topography are indicated (Shaded relief for northeastern U.S. and Canada, North Atlantic LCC, 2016 accessible at http://bit.ly/2lmbYXS). The key to the site ID number is presented in Table 3-1 (A larger version of the land cover map appears on the next page, Figure 3-1b). Yellow dots represent HBEF catchments (0.1-0.8 km^2). Small-scale sub-basins (ID: 13, 15, 18, and 20; 33-166 km^2) are distinguished by green dots, while intermediate-scale (ID: 9, 10, 14, 16, and 19; 222-818 km^2) and large-scale sub-basins (ID: 11, 12, 17, and 21; 1220-11450 km^2) are marked by red and black dots, respectively.

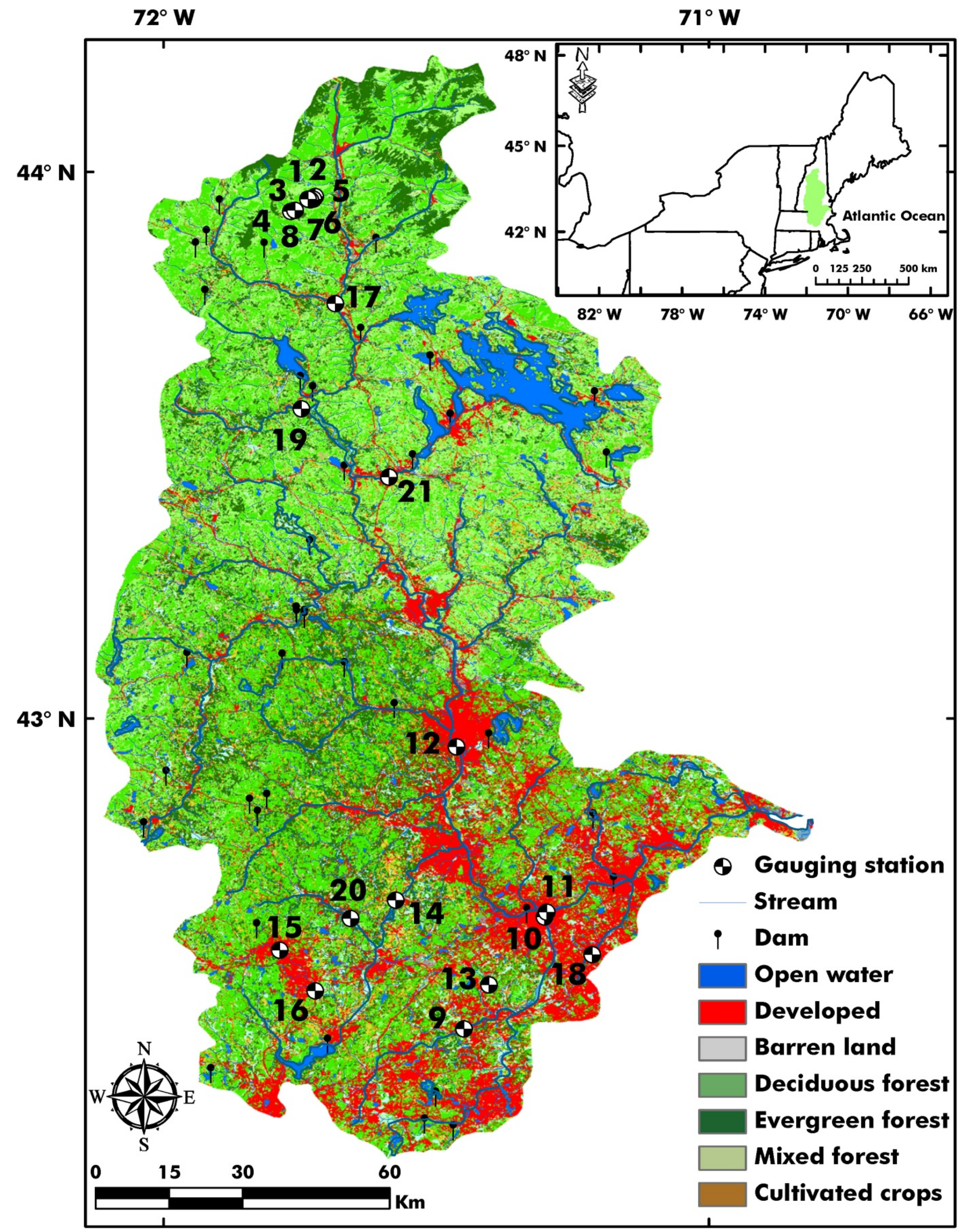

Figure 3-2b- The Merrimack River watershed: Dams, gauging stations, streams, and land cover classification are indicated (National Land Cover Database, 2006 accessible at http://bit.ly/2k8JNLU). The key to the site ID number is presented in Table 3-1.

4- Material and methods

4-1- Data

4-1-1- *Precipitation and discharge data*

Monthly estimates of precipitation and temperature for the catchments and sub-basins considered in this study were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly, 2004). The monthly precipitation information (in mm) was derived from PRISM based on the geographic location of each gauging station. Subsequently, annual precipitation was computed by integrating monthly values over the water year (Oct 1st to Sep 30th).

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 River watershed, of which 13 have continuous and sufficient discharge records. In this study, I used records of more than 30 years duration (median record length: 55 years) of which the earliest began in 1904 (Table 3-1) to evaluate both short- and long-term responses of discharge to climate variation and development.

Two USGS gauges (ID No. 17 and 19) represent reference catchments (Table 3-1) with minimal land disturbance and no artificial diversions or storage (Slack and Landwehr, 1992). The remaining gauges represent sub-basins with histories 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 for the “water year” extending from October 1st to September 30th in order to minimize the variation in watershed storage when the transpiration is limited or negligibly small and, consequently, soil moisture and groundwater storage reach their annual maxima (Dingman, 2015).

The HBEF is located at the headwater region of the Merrimack River watershed and has high quality long-term measurements of hydroclimatological variables. Precipitation and discharge data of catchments within the HBEF (Campbell, 2013a, 2013b) complement the USGS stations located elsewhere in the Merrimack watershed. Four catchments at the HBEF (WS 3, 6, 7, and 8) serve as reference sites for changing climate studies. Four other HBEF catchments (WS 1, 2, 4, and 5) were experimentally manipulated to assess the effects of anthropogenic interventions (Table 3-1). HBEF catchments are small (<1 km^2) relative to Merrimack sub-basins (33-11450 km^2) (http://www.hubbardbrook.org/ and http://waterwatch.usgs.gov/).

4-1-2- *Atlantic Multi-decadal Oscillation (AMO) data*

The AMO is an index of Sea Surface Temperature (SST) anomalies typically averaged over 0-80°N in the North Atlantic Ocean (Enfield et al., 2001; Kerr, 2000). As mentioned earlier, the AMO phase changes approximately every 30 to 40 years with potential impacts on both ocean and atmospheric circulation (Delworth and Mann, 2000; Enfield et al., 2001; Kavvada et al., 2013; Vianna and Menezes, 2013). The AMO has been observed through instrumentation since 1856 (Enfield et al., 2001) and is calculated from the Kaplan monthly SST dataset (Kaplan et al., 1998, 1997). I use annual water year AMO values averaged from monthly AMO indices provided by National Center for Atmospheric Research (NCAR) for the period of 1857 to 2014 (Trenberth et al., 2015).

4-1-3- *North Atlantic Oscillation (NAO) data*

The principal component-based (PC-based) index of NAO is the time series of the leading Empirical Orthogonal Function (EOF) of Sea-Level Pressure (SLP) anomalies over the Atlantic sector (20°-80°N, 90°W-40°E) (Hurrell et al., 2003). The NAO index quantifies atmospheric mass transfer between the high pressure center at Azores Island and low pressure at Iceland (Peng et al., 2013; Visbeck et al., 2001). As previously mentioned, the NAO positive or negative phases may last 3 to 10 years (Hurrell et al., 2003) which correspond to changes in wind speed and direction that affects heat and moisture transport between land and ocean (Hurrell, 1995; Roller et al., 2016).

The NAO index information is also provided by NCAR. NAO has been observed by instrumentation since 1899 (Armstrong et al., 2012). Since the centers of atmospheric troughs and ridges change throughout the year, PC-based NAO may better represent variations in SLP of the Atlantic than station-based NAO (Hurrell et al., 2003). Monthly NAO values were averaged over the water year to calculate the mean annual NAO (WY 1900-2014) (Hurrell, 2015).

4-1-4- *Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO) data*

While the primary focus of this manuscript is AMO and NAO, I also assessed shift points in PDO and ENSO, but there has been no general agreement on the impact of Pacific teleconnection patterns on Northeast hydroclimate. Indices of PDO and ENSO are provided by US National Oceanic and Atmospheric Administration (NOAA). PDO has been observed by instrumentation since 1855 (Mantua et al., 1997), while ENSO has been recorded since 1871 (Rayner et al., 2003). Mean annual water year values of PDO and ENSO values were calculated for water years 1855-2014 and 1871-2014, respectively.

4-1-5- *Data transformation*

Discharge data from each study site were divided by drainage area and expressed as depth in mm. The temporal scales of this study were annual (water year: Oct 1st to Sep 30th) as well as seasonal (spring: March-April-May, summer: June-July-August, fall: September-October-November, and winter: December-January-February). Since I wanted to investigate how much of the abnormality in precipitation and discharge could be explained by variation in SST and SLP anomalies, I computed the standardized monthly precipitation and discharge as follows (Coleman and Budikova, 2013):

$$Anomaly_{m,y} = \frac{log\,X_{m,y} - \bar{X}\left(log\,X_m\right)}{STDEV\left(log\,X_m\right)} \qquad \text{(Equation 1)}$$

where $log\,X_{m,y}$ is a monthly log-transformed value for water year "y", $\bar{X}\left(log X_m\right)$ is the long-term average of all the log-transformed monthly values, and $STDEV\left(log\,X_m\right)$ is the standard deviation of all the log-transformed values.

In order to isolate natural from forced variability and to emphasize extreme events, information regarding the neutral phases of AMO and NAO ($\mu - 0.5\sigma \le x \le \mu + 0.5\sigma$) were removed and the extreme positive and negative phases were defined as half the standard deviation of the long-term mean (positive phase: $x > \mu + 0.5\sigma$; negative phase: $x < \mu - 0.5\sigma$) Coleman and Budikova (2013). Considering the long-term mean and standard deviation, I defined the extreme positive (negative) phase of AMO as greater (less) than 0.2 (-0.2). The extreme positive (negative) phase of NAO would consist of values greater (less) than 0.5 (-0.5) (Figure 4-1).

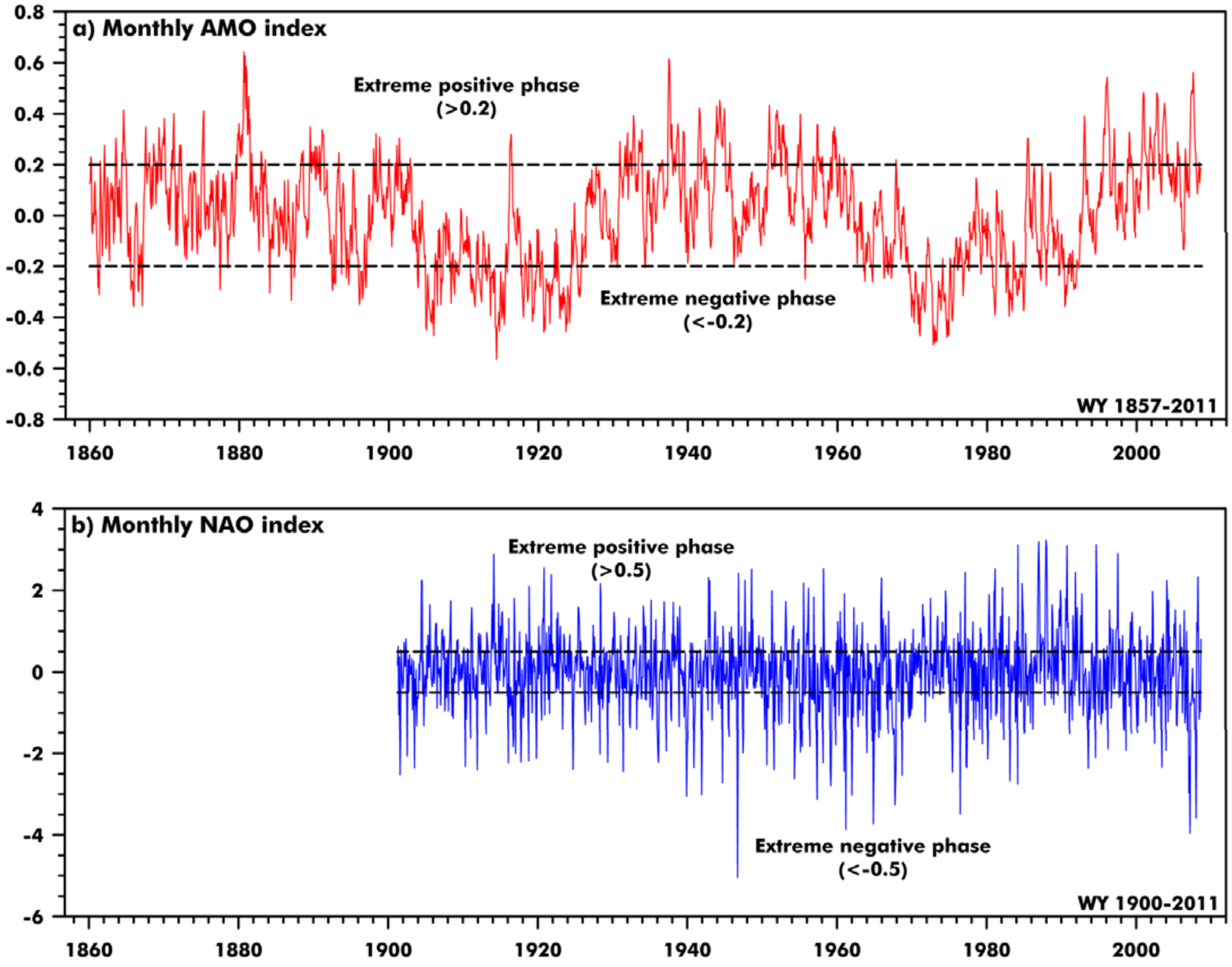

Figure 4-1- The monthly time series of: a) AMO with extreme positive (≥ 0.2) and negative (≤ -0.2) phases b) NAO with extreme positive (≥ 0.5) and negative (≤ -0.5) phases. Water year begins at October 1st and ends at September 30th.

4-2- Methods

4-2-1- *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, or 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:

$$\text{Anomaly} = (Q_i - Q_m) / \sigma \qquad \text{(Equation 2)}$$

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 discharge conditions of dry ($\text{anomaly} < -0.5$), average ($-0.5 < \text{anomaly} < 0.5$), and wet ($\text{anomaly} > 0.5$) years are established based on discharge anomaly (Genz and Luz, 2012).

4-2-2- *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 help to differentiate the discharge responses to different regimes of AMO and NAO in addition to changing climate, river regulation, and development for catchments and sub-basins spanning a wide range of drainage areas.

A Flow Distribution Curve (FDiC) shows the relationship between the cumulative discharge passing a stream gauge and the day of water year. The quarter-flow (i.e., 25%) 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- (25%), half- (50%), and three-quarter (75%) of annual discharge dates are evaluated under changing climate, river regulation, and development for catchments and sub-basins with varying drainage areas.

4-2-3- *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 a 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, that is, the 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 hydrologic class decreases relative to the entire record. This approach will decline the power of analysis and will increase the probability of type II error (fail to reject the null hypothesis of "no trend" when the trend actually exists) (Yue and Pilon, 2004).

Although it is recommended to use at least 15 to 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 be used to examine trends in series with at least four data points (Gilbert, 1987). As noted earlier, I selected gauged sites with more than 30 years of data in order to have at least a decade of information when annual discharge data were parsed into three hydrologic flow classes of dry, average, and wet. In this study, spatiotemporal trends in annual discharge magnitude and timing are analyzed as well as trends in three distinct hydrologic flow classes of dry, average, and wet years. 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 designed to study specific class of information at a time (Osborne, 2013). Because of the potential influence of antecedent hydrologic conditions on the current flow regime (i.e., the "carry over" effect of a dry year following a dry year), a modified version of the 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.

4-2-4- *Multivariate statistical analysis*

Multivariate statistics is a procedure identifying the representative factors among a set of independent variables that best explain a dependent variable (Izenman, 2008). Multivariate statistical methods used in this study 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 methods are generating independent (orthogonal) linear combinations of the original variables which can explain the highest amount of variation among the data (Izenman, 2008). For example, Olden and Poff, (2003) used PCA to find the sets of independent hydrologic indicators that could best explain the variability across streams in a region with diverse climate and geological conditions.

I used multivariate statistical methods to evaluate spatial correlation of discharge metrics among the reference and regulated/developed categories. The reference category consists of eight study catchments from HBEF and two sub-basins from the Merrimack watershed. There are eleven gauged sub-basins within the Merrimack watershed with different levels of disturbance, 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 initial multivariate statistical analyses of magnitude and timing trends in the Merrimack streamflow records showed two distinct 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) (Figure 4-2). Therefore, I used 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 developed sub-basins in other downstream portions of the Merrimack watershed.

Furthermore, inside each cluster, three distinct sub-groups can be identified (Figure 4-2). Catchments 1 and 3, catchments 2 and 5, and catchments 4, 6, 7, and 8 formed three HBEF sub-groups related to differences in elevation, slope, and aspect. Within the Merrimack cluster, sub-groups are clearly distinguished by drainage area as: small-scale sub-basins 13, 15, 18, and 20 (33-166 km^2), intermediate-scale sub-basins 9, 10, 14, 16, and 19 (222-818 km^2), and large-scale 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 3-1 and Figure 3-1 for the identification and location of these catchments and sub-basins.

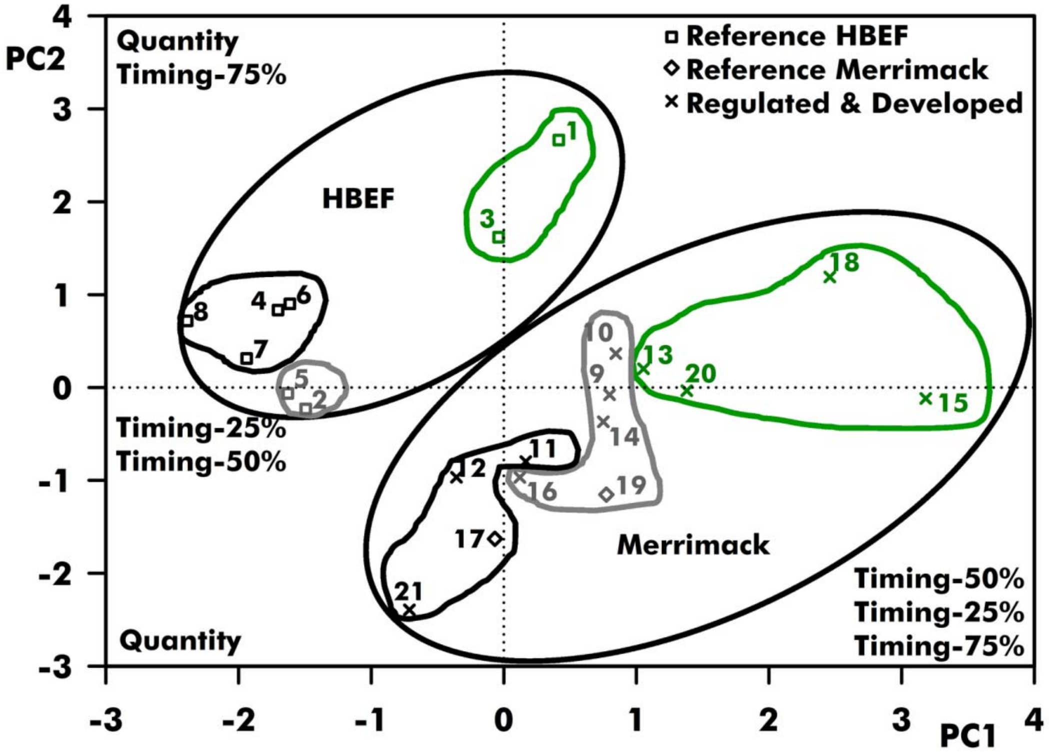

Figure 4-2- PCA performed on discharge quantity and timing trends for the period of record. Two separate clusters of HBEF reference catchments as well as the Merrimack reference, regulated, and/or developed sub-basins were identified. The three distinct sub-groups inside each cluster reveal the scale-dependency of changes in the hydrologic response. The key to the site ID is presented in Table 3-1.

4-2-5- *Regime shift detection method*

The regime shift detection method described by (Rodionov, 2004) identifies discontinuities in the time series of a variable. A step-change or regime shift is a transition in the time series of a variable from one state (regime) to either higher or lower state (Rodionov, 2015). The shift occurs when the long-term average of a variable over a new regime becomes significantly different from the long-term average of an initial regime (Rodionov, 2005, 2004). This method is a sequential analysis which does not require pre-assumptions about the timing of shifts. Moreover, it is able to detect multiple shifts over the time series of a variable.

Rodionov (2004) suggested the following algorithm to detect regime shifts. First, a cut-off length is defined for regimes lasting L years or longer within the time series of the variable X. Next, the difference (*diff*) between the long-term mean values of two successive regimes is calculated and the statistical significance of the difference is examined with the Student's t-test:

$$diff = t\sqrt{\sigma_L^2/L} \qquad \text{(Equation 3)}$$

where *t* is a t-distribution parameter with *2L-2* degrees of freedom at α level of significance, σ_L^2 average of the variances of all *L*-year regimes in the period of record (the assumption of equal variance for both regimes). Following this, the mean value of variable *X* is calculated for the first regime (i.e. $\bar{x}_{R_1}$). A shift to regime R_2 is expected when X_i (i=L+1) exceeds the $\bar{x}'_{R_2} = \bar{x}_{R_1} \pm diff$ range. If X_i does not exceed $\bar{x}'_{R_2}$, $\bar{x}_{R_1}$ is recalculated and the next X_i is considered. Otherwise, X_i is a candidate for the beginning date of a new regime R_2.

If a shift is detected, the Regime Shift Index (RSI) is calculated as:

$$RSI_{i,j} = \sum_{i=j}^{j+m} x_i^*/L\sigma_L \text{, m=0, 1, …, L-1} \qquad \text{(Equation 4)}$$

$x_i^* = X_i - \bar{x}'_{R_2}$ (for up shift) or $x_i^* = \bar{x}'_{R_2} - X_i$ (for down shift).

The shift point is not confirmed when *RSI* is less than zero. In this case, *RSI* should set to be zero for X_i. Next, an additional time step is added, a new value for $\bar{x}'_{R_2}$ is calculated, and the shift is again evaluated using the method specified above. When a shift is confirmed ($RSI>0$), the actual mean value is calculated for the new regime $\bar{x}_{R_2}$. Finally, a new regime R_3 can be detected that begins from year $i=j+1$.

The software for implementing this algorithm is freely available for download (http://www.beringclimate.noaa.gov/regimes/). The algorithm also includes a procedure for removing the impact of serial correlation (red noise) on regime shift point detection, known as the IP4 (Inverse Proportionality with 4 corrections) procedure (Rodionov, 2006). I chose a confidence level of $\alpha = 0.1$ for the analysis. In the implementation of this software, I considered different cut-off lengths (L=5, 10-40 with 10-year increments) to detect regimes of five years or longer. I also considered cut-off lengths of L=3 to avoid missing NAO regimes that may last three years or longer. No new shift points emerged besides those already detected with cut-off length of five years or greater.

I used the regime shift detection method described above to determine change points across time series of precipitation and discharge at each of 21 study sites. I also applied this regime shift detection method for AMO over the period 1857 to 2014 and NAO over the period 1900 to 2014. To test whether detected regime shift points were an artifact of record length, I applied the method to the entire time series mentioned above and to AMO and NAO records shortened to the length of each discharge record.

4-2-6- ***Indicators of hydrologic alteration (IHA) and range of variability approach (RVA)***

In this section, I introduce two concepts, the IHA and RVA, which I used to evaluate changes in ecological discharge indicators across different climatic regimes. I assessed changes in discharge using IHA, a suite of metrics that quantify the primary ecological characteristics of discharge (Richter et al., 1997, 1996). This suite of indicators has previously been used to evaluate the responses of ecological discharge indicators to regime shifts (step changes) due to impoundment, river regulation, or urban development (Black et al., 2005; Fernández et al., 2012; Martin et al., 2012; Poff et al., 1997; Richter et al., 1996). The pre-regime shift observations were utilized as a reference to determine the extent of discharge alteration after the step-change (Richter et al., 1997). The indicators of hydrologic alteration include the following metrics:

- Monthly magnitudes of discharge: Monthly discharge was computed from a summation of daily average values, normalized by the drainage area expressed as mm/month. The monthly water availability is an important metric for water resource analysis and water quality problems.
- Baseflow index: The baseflow index was calculated as the mean of all the annual 24-hr low discharge values normalized by the total mean of natural log-transformed discharge (Poff and Ward, 1989). Baseflow index provides valuable information for aquatic ecosystems, mainly due to the importance of baseflow on summer streamflow temperature (Hodgkins and Dudley, 2011).
- No flow days: The number of zero days was the sum of zero discharge days. The increases in the number of zero days can result in water stress to plants largely during the growing season.

- The dates of maximum and minimum discharge: The annual water year day number for maximum or minimum discharge (*IHAs, Ver. 7.1*, 2009). Changes in dates of minimum and maximum discharge are critical to the life cycle of river habitats (Poff et al., 2010).

To explore the effects of shifts in AMO and NAO on extreme discharge responses, I employed the range of variability approach to calculate water year ecological discharge indicators during each regime. The RVA considers either the standard deviation of the mean (parametric analysis) or the percentile of the median (non-parametric analysis) to define the natural range of variability for a discharge indicator (Richter et al., 1997). The frequency of events may change from pre- to post-regime shift period which can be quantified HAI (Richter et al., 1997, 1996). The HAI evaluates the extent of change in high ("$> \overline{x} + \sigma$" or "$> Mdn + \%ile$") and low ("$< \overline{x} - \sigma$" or "$< Mdn - \%ile$") RVA boundaries for a discharge indicator. A positive (negative) HAI demonstrates the increase (decrease) in frequency of a discharge indicator from the pre-shift to the post-shift regime with a maximum value of infinity (with a minimum value of -1) (*IHAs, Ver. 7.1*, 2009; Richter et al., 1997, 1996). In this study, I defined the 10^{th} and 90^{th} percentiles as low and high RVA boundaries, respectively (i.e. $Mdn \pm 40th\%ile$). I quantified HAI values for each of the indicators listed above between concurrent regime shifts across all Merrimack sub-basins.

4-2-7- *t-Test*

The group t-test was performed to verify the hypothesis that mean standardized discharge was different between the AMO and NAO extreme phases. The test followed the Cochran approximation (Cochran and Cox, 1950) which assumes that the distribution of normalized discharge for extreme phases of AMO or NAO has unequal variance. The uniformly most powerful unbiased (UMPU) confidence intervals were computed considering the equal-tailed 95% confidence limit. The t-test was performed with the SAS statistical analysis program (SAS Institute Inc., Cary, NC, USA- Version 9.2, 2009).

4-2-8- *Pearson correlation coefficient*

The correlation coefficients were computed with the SAS statistical analysis program (SAS Institute Inc., Cary, NC, USA- Version 9.2, 2009). Pearson, Spearman, and Kendall procedures were utilized to assess the correlations of AMO and NAO with precipitation and discharge. The correlation coefficients were determined for HBEF catchments (ID: 1-8, drainage area of 0.1-0.8 km^2) and small (ID: 13, 15, 18, and 20, drainage area of 33-166 km^2), intermediate (9, 10, 14, 16, and 19, drainage area of 222-818 km^2), and large (11, 12, 17, and 21, drainage area of 1220-11450 km^2) Merrimack sub-basins (Berton et al., 2016). The Merrimack sub-basins had various levels of development and/or river regulation which were not linked to basin scale.

4-2-9- *Hydrologic flow conditions, relative frequency of occurrence and probability*

Cumulative discharge data were classified as dry, average, and wet based on one standard deviation distance from the long-term mean (Genz and Luz, 2012). For this study, the three distinct hydrologic flow classes of dry (anomaly < -0.5), average (-0.5 < anomaly < 0.5), and wet (anomaly > 0.5) years were established based on discharge anomaly.

In order to define discharge conditions corresponding to AMO and NAO extreme phases, I developed a discharge time series for each study site for annual and seasonal temporal scales. I identified the extreme positive and negative phases of AMO and NAO on an annual and seasonal discharge time series and determined if the condition of discharge corresponded with the AMO or NAO phases. The relative frequency of the annual or seasonal wet, average, and dry discharge events were calculated by dividing the number of specific events by the total number of outcomes.

Relative frequency could be an unbiased estimator of probability. For instance, the coin toss experiment does not necessarily return an equal frequency of heads and tails. The outcome is a set of random numbers which when sorted from largest to smallest, asymptotically would reach 50%, the theoretical probability of having a head or a tail. Utilizing that concept, I found the relative frequency of having a wet, average, or dry year among the HBEF catchments and the Merrimack sub-basins. For each basin scale group, the relative frequencies were ordered in descending value and an exponential decay function was regressed through the historic relative frequency of occurrence for wet, average, and dry discharge events with regards to the extreme phases of AMO and NAO. While the function was decaying, the tail asymptotically merged into and stabilized at the theoretical probability of the event. In order to reduce the uncertainty, a 95% confidence band was computed which contained the actual but unknown probability of the population.

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

The objective of this chapter is to assess temporal streamflow responses of the Merrimack watershed to changes in climate using long-term precipitation and discharge data under conditions of limited and extensive development. I 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 exist in hydrologic flow classes. I use multivariate statistical analyses to discover how discharge may vary with regards to geomorphology of the Merrimack watershed in addition to land use/cover characteristics. By including regulated and developed sub-basins, I am able to explore the relationship of climate change effects and land development impacts. This approach builds upon earlier studies that focused on undisturbed headwater catchments. This analysis also provides preliminary 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.

The results of this chapter are presented in three separate sections. First, I assess the effects of climate variation, river regulation, and land development on flow duration curves (FDCs) and flow distribution curves (FDiCs). Second, I present the results of the modified Mann-Kendall analyses and Sen’s slope estimates for the quantity and timing indicators of annual discharge. In this section, I include an analysis by hydrologic flow classes within each discharge record. Third, I employ multivariate statistical methods to assess patterns of historical discharge trends at the HBEF catchments and the Merrimack sub-basins associated with geomorphology or land use/cover characteristics. I also discuss the scale-dependency of the results generated by the PCA analyses. I will close the discussion with a focused analysis on the interactive effects of changing climate and land development. This analysis represents hydroclimatic information for selective study sites at a daily time scale differed by hydrologic discharge classes in order to closely examine the effects of changing climate from land development (i.e. river regulation and/or urbanization).

5-1- Results

5-1-1- *Flow duration curves (FDCs)*

The FDCs are compared for the sub-groups within the HBEF cluster (Figure 5-1a), the cluster of HBEF versus the cluster of Merrimack (Figure 5-1b), and the sub-groups within the Merrimack cluster (Figure 5-1c). The exceedance probabilities (EPs) marked on FDCs represent the conditions where the impacts of 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 exceedance probabilities less than 15% (Figure 5-1a). The discharge magnitude increased with increases in drainage area.

Discharge quantity responses to climate variation are differentiated from both river regulation and development on Figure 5-1b. 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 Figure 5-1c. The size 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 intermediate 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).

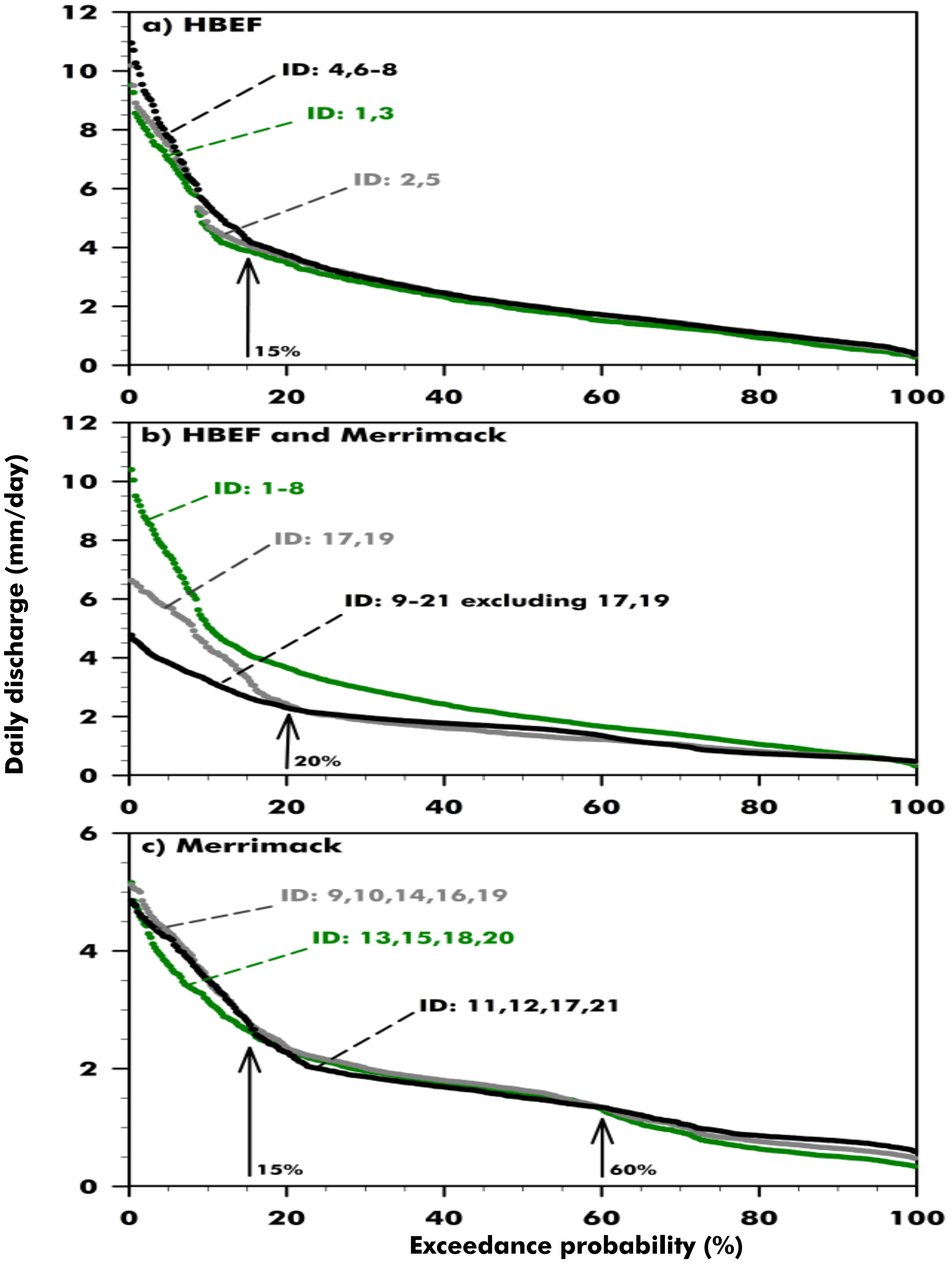

Figure 5-1- Flow Duration Curves (FDCs) for the period of record comparing a) three sub-groups based on drainage area within the HBEF cluster; b) HBEF reference catchments with Merrimack reference, regulated, and/or developed sub-basins; and c) three sub-groups based on drainage area within the Merrimack cluster, i.e. small-scale sub-basins (ID: 13-18-20-15, 33-166 km^2); intermediate-scale sub-basins (ID: 19-16-9-10-14, 222-818 km^2); and large-scale sub-basins (ID: 21-17-12-11, 1220-11450 km^2). 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 3-1.

5-1-2- *Flow distribution curves (FDiCs)*

Similar comparisons were developed for FDiCs for HBEF catchments and the Merrimack sub-basins (Figure 5-2). From the three sub-groups of catchments within the HBEF, catchments with the largest drainage areas showed the latest discharge timing dates contrary to small catchments with earlier timing dates (Figure 5-2a). 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 consistent scale- or size-dependent patterns (Figure 5-2b). The HBEF catchments showed earlier discharge timing-25% and -75%, while the timing date of 50% annual discharge occurred earlier for the Merrimack sub-basins. The larger Merrimack reference sub-basins (ID: 17, 19) showed the latest discharge timing dates compared to the smaller 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 (Figure 5-2c). The largest sub-basins showed later discharge timing dates, while the smallest sub-basins had earliest 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%.

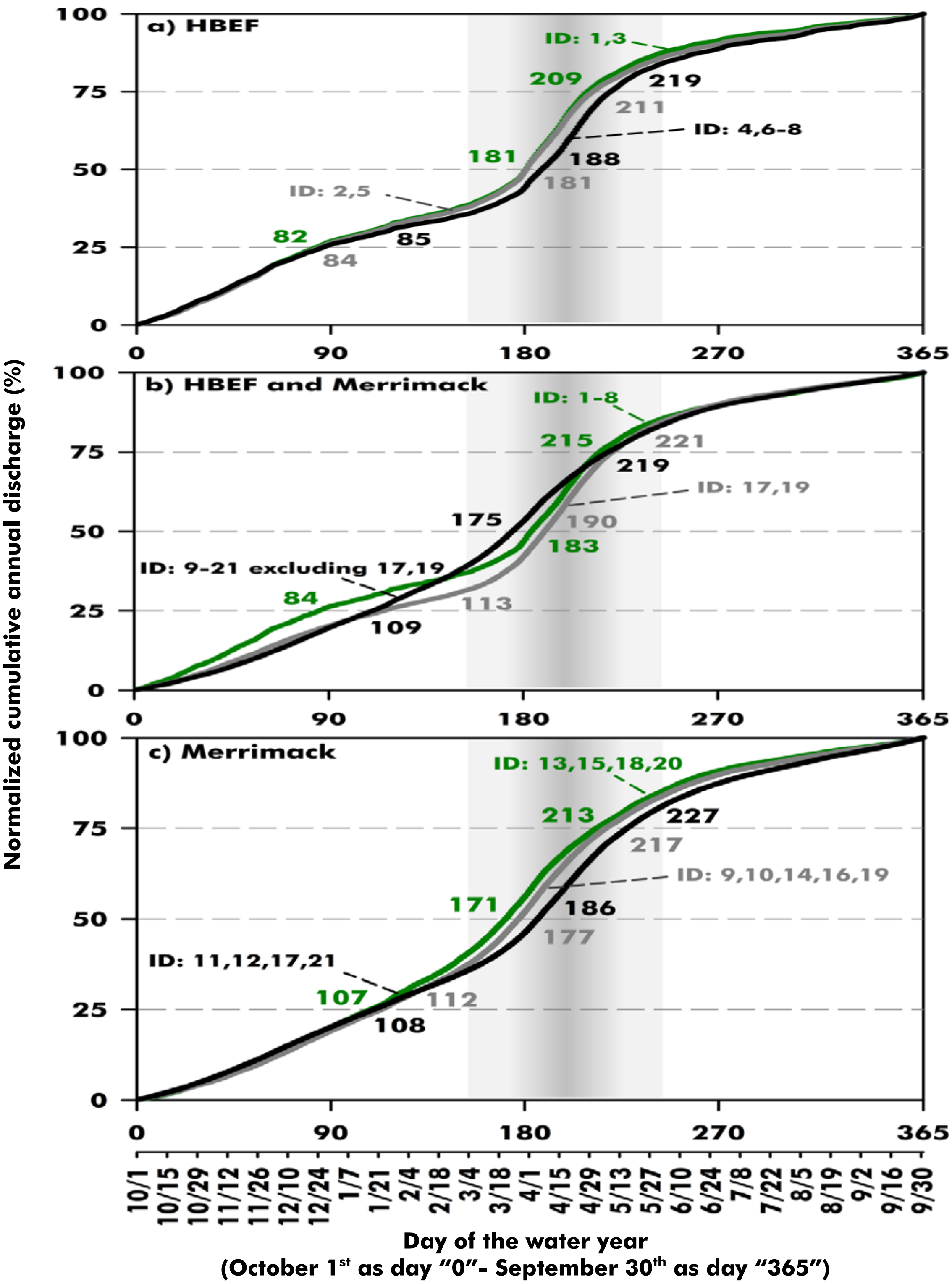

Figure 5-2- Flow Distribution Curves (FDiCs) for the period of record comparing a) three sub-groups based on drainage area within the HBEF cluster; b) HBEF reference catchments with Merrimack reference, regulated, and/or developed sub-basins; and c) three sub-groups based on drainage area within the Merrimack cluster i.e. small-scale sub-basins (ID: 13-18-20-15, 33-166 km^2); intermediate-scale sub-basins (ID: 19-16-9-10-14, 222-818 km^2); and large-scale sub-basins (ID: 21-17-12-11, 1220-11450 km^2). 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 3-1.

5-1-3- *Temporal variations of discharge magnitude*

The modified Mann-Kendall (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 5-1). Long-term increases in mean annual discharge (1 to 7 mm/WY) were consistent with increases in mean annual precipitation (1 to 7 mm/WY) throughout the Merrimack River watershed (Table 5-1).

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 a 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 5-1). Whereas discharge trends for the period of record were all positive, the numbers of negative trends were greater for dry than for average or 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 5-1). In the dry hydrologic flow class, negligibly small mean increases of 1 mm/WY in annual discharge was calculated at the Merrimack sub-basins (Table 5-1); In contrast, the HBEF catchments showed greater positive and negative trends in annual discharge albeit the small 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 5-1).

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 smaller HBEF catchments responded more strongly to changing climate than the Merrimack reference sub-basins. River regulation and land development lessened the relative effects of changing climate except for the wet hydrologic flow class.

Table 5-1- The modified Mann-Kendall 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 3-1.

			Precipitation trends		**Discharge trends**							
			Period of record		**Period of record**		**Dry**		**Average**		**Wet**	
ID		**Drainage area (km^2)****	**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	**Small-scale**	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	**Intermediate-scale**	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	**Large-scale**	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≤0.05).

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

5-1-4- *Temporal variations of discharge timing*

I 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 5-2). The timing date of 25% annual discharge occurred 0.2 to 1 days/WY earlier (p-value ≤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 ≤0.05) at 67% and 43% of the HBEF catchments and the Merrimack sub-basins, respectively. While statistically significant, the small change in timing may be related to the use of an annual time step. Especially on small experimental catchments, a monthly or daily time step could reveal substantially larger climate change effects. This working hypothesis could be tested in a subsequent study.

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 5-2). The Merrimack sub-basins evinced statistically 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 also significant (p-value ≤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 consistent pattern of 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 ≤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 ≤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 significantly 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 mean magnitude of trends in the 25% and 50% discharge timing dates related to changing climate increased with increases in drainage area at the HBEF catchments. In addition, the mean magnitude of 25% 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. The confounding effects of river regulation and land development appear to have muted the signal of changing climate only for the timing dates of 50% and 75% annual discharge except for the wet hydrologic flow class.

Table 5-2- The modified Mann-Kendall 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 3-1. The number of years of data in each class is presented in Table 5-1.

ID		Drainage area (km^2)**	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	**Small-scale**	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	**Intermediate-scale**	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	**Large-scale**	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 ($p\text{-value} \leq 0.05$).

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

5-1-5- *Spatial patterns in discharge variation*

I 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., one discharge quantity and three discharge timing indicators (total of four indicators) for the period of record (Figure 4-2) and the three hydrologic flow classes (not shown). 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 sub-basins (Olden and Poff, 2003).

The first and the second PC together explained 72% of the variations in the 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.

5-2- Discussion

5-2-1- *Clusters inferred by principal component analysis (PCA)*

The PCA results would imply a more coherent physical meaning with the greater degree of variation the dependent variables explained. Consequently, the interpretation of PCA results is challenging (Hamel et al., 2015; Jolliffe, 2002). The PCA analysis results (Figure 4-2) indicated two distinct groups of the HBEF catchments and the Merrimack sub-basins clustered based on drainage area. However, the sub-clusters within each group did not show a concise pattern with reference to the physical characteristics of a basin.

Within HBEF cluster, catchments with similar precipitation trends mainly grouped together (Table 5-1). Catchments 1 and 3 shared similar aspect, elevation range, mean annual precipitation, and mean annual water yield with different drainage areas and slopes. These catchments (1 and 3) are far removed from catchments 2, 4, 5, and 6 whereas they all shared the same aspect. This path may suggest part of the variation (28%) among discharge trends that PCA analyses were not able to explain.

Catchments 2 and 5 formed a reasonable cluster since they had similar drainage area, slope, aspect, elevation range, mean annual precipitation, mean annual water yield, and an extreme treatment (clear-cut harvesting). The third sub-cluster consisted of catchments 4, 6, 7, and 8 shared relatively similar slopes, mean annual precipitation, and mean annual water yield, while differed in drainage area and aspect.

At HBEF, the physical characteristics of catchments did not affect the high association between precipitation and discharge ($r=0.96$, $p\text{-value}<0.05$) due to steep slope, low storage volume (the granite bedrock and till avert deep seepage), and wet soil condition. Throughout the Merrimack River watershed where the correlation between precipitation and discharge declined ($r= 0.85$, $p\text{-value}<0.0001$), hydrologic responses were affected by basin's drainage area, elevation gradient, storage, and land use/cover along with river regulation and urbanization.

A closer look at Figure 4-2 revealed that the sub-basins with similar precipitation trends were clustered together. The reference sub-basin 17 is located near the developed sub-basin 12 which both shared similar precipitation trends (Table 5-1). The reference sub-basin 19 is adjacent to developed sub-basins 11, 14, and 16 and their precipitation trends are similar as well (Table 5-1).

The comparison of discharge trends for a reference sub-basin (ID: 19, Table 5-1) and a developed sub-basin (ID: 16, Table 5-1) which show the significant precipitation trends over the period of record, led me to conclude that in the absence of a reservoir to attenuate stormflow from an urbanized area, increases in discharge at a developed sub-basin could be twice that of a reference sub-basin with similar rates of precipitation increase.

5-2-2- *Flow duration curves (FDCs)*

With respect to PCA results, the FDCs of HEBF catchments were slightly different from the other sub-basins at high discharge rates (Figure 5-1a). The differences in discharge response for catchments “4, 6-8” from catchments “1, 2, 3, 5” could be due to greater drainage area, steeper slope, storage, and elevation range. When averaged, HBEF hydrologic response indicated distinct patterns from the Merrimack sub-basins especially under high and low discharge conditions (Figure 5-1b). Part of the differences could be explained by differences in precipitation type (i.e., the proportion of rain and snow), magnitude, duration, and frequency at higher elevations (orographic effect) in the headwater catchments in addition to river regulation and land development in developed sub-basins (Dingman, 2015; Smith et al., 2011).

River regulation and land development have the potential to accelerate or attenuate annual discharge patterns driven by climate variation. River regulation makes streamflow less time-variable in addition to lessen peak discharge signals (Grill et al., 2015). Increases in impervious surfaces alters the contribution of groundwater to discharge from 95% in forested catchments to 20% in urbanized basins with stormwater collection systems (de la Crétaz and Barten, 2007). The urban heat island effect has the potential to increase ET and thereby decreases discharge (McGrane, 2016). On the other hand, urbanization can increase the magnitude of total precipitation (9-17%) as well as the frequency of heavy rainfall (>25 mm) (Changnon, 1981; Huff and Changnon, 1973; Knight and Davis, 2009; Villarini et al., 2011).

The greater drainage area and milder slopes of the Merrimack sub-basins than HBEF catchments have moderated the high discharge response (Figure 5-1b). Changes in land/use cover, river regulation, and urban development has offsetting effects suggesting the response of reference sub-basin 17 and 19 was similar to Merrimack developed sub-basins for medium-to-low discharge events. The higher baseflow at HBEF may have different drivers such as larger summer storms due to orographic effects at higher elevations or decreases in ET (Campbell et al., 2011; Smith et al., 2011). Other reasons include steep slope, thin and highly permeable soil, and limited residence time of soil water with respect to evapotranspiration.

Within the Merrimack (Figure 5-1c), increases in drainage area and decreases in forested lands would be expected to increased high discharge rates (de la Crétaz and Barten, 2007). The response is moderated by surface water storage such as Lake Winnipesaukee that impounds large quantities of water (approximately 2.3 billion cubic meters) with regulated releases into the Merrimack River. The influences of drainage area on low discharge values (EP greater than 60%) were much more noticeable at the downstream Merrimack sub-basins where the thick glacial deposits provided more subsurface flow, more permeability, and more groundwater storage and recharge to the streams (Figure 5-1c).

5-2-3- *Flow distribution curves (FDiCs)*

In the northeastern United States, seasonal variations in precipitation, temperature, and evapotranspiration govern changes in seasonal discharge quantity and timing (Hodgkins and Dudley, 2005). The discharge timing variations are directly linked to rainfall and snowmelt events. The snowmelt period usually begins from March and may extend, in some years, until early-May (Dingman, 2015). Spring discharge is driven by both spring precipitation and snowmelt discharge with the latter being sensitive to energy balance and air temperature changes (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 become more uniform throughout the year in the Merrimack River watershed (Figure 5-2) because the attenuation of spring discharge has been roughly counterbalanced by increases in rainfall during spring and summer. The larger available storage in the larger HBEF catchments (ID: 4, 6, 7, 8) slightly moved the discharge timing later for a week compared to smaller HBEF catchments (ID: 1, 2, 3, 5) (Figure 5-2a). The contribution of storage to later discharge timing became more pronounced after the snowmelt period and the beginning of the growing season.

The effect of climate change on spring discharge generation was stronger than the impacts of development. The spring season is when stored water in reservoirs is typically at an annual maximum, demand for water and hydropower is low, and spillway or regulated releases are substantial. The earlier discharge timing of 25% for HBEF catchments compared to the Merrimack sub-basins are best explained by comparative watershed size, presence or absence of reservoirs, and total basin storage (Figure 5-2b). Water is transported faster in mountainous watersheds and streams relative to coastal sites due to differences in precipitation intensity and duration, higher elevation gradients, and differences in geology—shallow glacial till over crystalline rock (Nippgen et al., 2016). The larger Merrimack sub-basins with mild slope, more storage, and regulated streams released water up to a month later compared to HBEF catchments (Figure 5-2b).

The earlier discharge timing 50% at the regulated and developed sub-basins could be due to the effects of flood control dams and the type (rain versus snow) and magnitude of precipitation at lower elevation sites. Six flood control dams located in New Hampshire (Blackwater Dam in Webster, Edward MacDowell Lake in Peterborough, Franklin Falls Dam in Franklin, Hopkinton-Everett Lakes in Hopkinton, Otter Brook Lake in Keene, and Surry Mountain Lake in Surry) have changed the natural flow regime of the Merrimack streams (Figure 5-2b).

The reservoir water level of a flood control dam is drawn down to a minimum storage before the peak annual discharge associated with snowmelt in order to be able to effectively mitigate spring flooding. Less snow accumulation (orographic effect) and earlier snowmelt (higher temperature) at low elevation developed sub-basins contributed to the earlier discharge timing-50%. Regulated release from the flood control dams along with more storage at larger sub-basins typically meant the discharge timing-75% occurred for almost a week later compared to the unregulated HBEF headwater catchments (Figure 5-2b). As noted earlier, larger sub-basins with more storage and milder slopes contributed to a later discharge timing date (Figure 5-2c).

5-2-4- *Significance of basin-scale study*

The uncertainties regarding the hydrologic assessment of a watershed under changing climate include, but are not limited to, the highly variable nature of hydrologic events (both intra- and inter-annual variation), large-scale teleconnectivity of hydrologic processes, and study scale since many hydrologic processes are well characterized at the experimental watershed scale (e.g., HBEF) but exceedingly difficult to model at the river basin scale with mixed land use (Dingman, 2015; Montanari et al., 2009; NRC, 2008). Nevertheless, in the context of 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.

5-2-5- *Influence of record length*

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). 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 River watershed especially when data were parsed into hydrologic flow classes.

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 cause a 38% loss in information; therefore I 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, Z.W. and Robson, A., 2000), the decreased number of observations in each hydrologic flow class (compared to the period of record) is clearly a limitation to this 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.

5-2-6- *Linkage of discharge with precipitation*

Increases in precipitation rate and duration vary greatly from one basin to another (Barry and Chorley, 1987). The irregularities in spatial and temporal variations of precipitation may be due to orographic effect or localized convective storm events (Dingman, 2015), and not necessarily a changing climatic regime. Even extreme rainfall events could be generated by orographic effects (Smith et al., 2011). For central New England, changes in elevation are responsible for almost 80% of spatial variation in precipitation—with consequent effects on low, mean, and high discharge conditions (Dingman, 1981; Dingman et al., 1988).

The discharge response to changes in precipitation can vary differently for headwater catchments from downstream developed sub-basins partially due to the storage of water associated with aquifers, lakes, and manmade reservoirs along with urbanization. When storage is low, discharge response is more sensitive to variations in precipitation rather than evapotranspiration. As the basin storage increases, discharge becomes more responsive to variations in both precipitation and temperature (with corresponding increases in evapotranspiration). The existence of a reservoir in a watershed reduces, by design, the time variability of streamflow, increases the residence time of water in rivers (from 15 days to 1-2 months), and increases evaporation in the region (Dingman, 2015).

In the small reference catchments of the HBEF with no river regulation or land development and state-of-the-science instrumentation, 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 ($r= 0.85$, $p\text{-value}<0.0001$), this relation is still impressive in view of the challenges of open channel flow measurements and the development of robust rating curves (discharge versus water level).

I found small, yet significant positive trends ($p\text{-value} \leq 0.05$) for annual precipitation at the Merrimack River watershed (4 mm/WY on average) for records with median length of 55 years of which the earliest began in 1904. Hamburg et al. (2013) assessed precipitation data for WS3 and WS7 at the HBEF over the period of 1958 to 2005 and found insignificant trends in precipitation ($p\text{-value}\leq 0.1$). However, Campbell et al., (2011) extended the record to 2008 and found significant increases of 3 mm/WY in precipitation ($p\text{-value}\leq 0.05$). My results for the HBEF discharge were consistent with Campbell et al., (2011) demonstrating how sensitive Mann-Kendall trend test and Sen's slope estimate are to the length of record, serially correlated data, and the particular attributes of the dataset.

5-2-7- *Temporal variations of discharge magnitude*

Seasonal trends in precipitation alone do not forecast seasonal discharge variations because runoff generation is highly dependent on antecedent soil conditions and cumulative evapotranspiration (Ivancic and Shaw, 2015). For New England, annual maximum discharge typically occurs in the spring for northern high elevation basins while fall events are more typical of southern coastal and developed regions (Magilligan and Graber, 1996). For Merrimack, 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% in the dry hydrologic flow class. Under wet climate conditions (i.e., increased soil wetness) summer rainfall had a larger relative influence than spring precipitation and snowmelt on annual water yield than the dry and average conditions.

All the significant discharge trends (p-value ≤0.05) for the period of record were positive and consistent across the Merrimack River watershed (Table 5-1). The average hydrologic discharge 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).

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. 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. The positive discharge trends during dry periods across the Merrimack River watershed were in agreement with 4% increases in global river discharge for each 1 °C increases in air temperature (Gedney et al., 2006); the differences in response indicate that other drivers such as land cover/use change rather than changes in evapotranspiration can control discharge variation especially during dry periods (Vose et al., 2012).

5-2-8- *Temporal variations of discharge timing*

In the Northeast, simultaneous snowmelt and rainfall events in spring generally result in maximum discharge. The seasonality index (I_s) for precipitation in the Northeast is 10% which implies the low degree of seasonality (Dingman, 2015). Although precipitation is evenly distributed throughout the year, the discharge seasonal distribution is non-uniform. One-fourth of discharge is concentrated in only one month of spring (simultaneous snowmelt and rainfall events). In contrast, only about one-tenth of the annual discharge occurs in summer months of June-August. Summer rain events are typically moderated by the cumulative effect of evapotranspiration and associated increases in available soil water storage (de la Crétaz and Barten, 2007; Dingman, 2015).

Quantification 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). I defined the day of the year when 25%, 50%, and 75% of annual flow discharged from the catchment outlet. Earlier timing dates of 25% annual discharge (December through February) occurred at smaller-scale catchments and sub-basins within the Merrimack River watershed mainly due to earlier snowmelt as a result of increases in winter temperature (Hodgkins and Dudley, 2006).

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). The timing date for 50% of annual discharge occurs sometime between days 170-190 (March-April) in the Northeast (Beck et al., 2015). Hodgkins and Dudley, (2006) reported earlier occurrence of winter-spring streamflow for 0.1 days/yr in the northeastern United States in the period of 1913-2002.

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. 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 the Pemigewasset River at Plymouth showed 0.19 days/year earlier CVD (1904-2004). Campbell et al., (2011) reported earlier spring CVD for 0.2 to 0.5 days/WY at HBEF and insignificant trends in the fall CVD (1969-2008).

In the Merrimack River 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. Winter rainfall (especially in January) will exacerbate the earlier timing date for 50% of annual discharge since January rainfall and temperature are positively associated (Hodgkins et al., 2003). The effect 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.

5-3- A focused evaluation of the interactive effects of changing climate and land development

5-3-1- *Introduction*

In this section, I examined hydroclimatic information at a daily time scale for dry, average, and wet hydrologic conditions to closely assess the effects of changing climate from anthropogenic disturbances (i.e. river regulation and/or land development). I made comparisons among the gauged sub-basins in the Merrimack River watershed to find the most representative sub-basins to examine urbanization effects relative to a forested reference sub-basin. For instance, the hydrologic response of a reference catchment at HBEF was compared to Pemigewasset, a larger reference sub-basin located at downstream region of HBEF. HBEF catchments have drainage areas that range from 0.1-0.8 km^2, while three sub-basins used for more detailed analyses have drainage areas averaging 161 km^2. Due to considerable differences in drainage area, the differences in HBEF hydrologic response were distinctively larger than Pemigewasset inappropriate either for a useful comparison or to explore the contribution of development in discharge variations.

Consequently, the selection was narrowed down to three study sites of equivalent size i.e. Smith (ID: 19, forest, area=222 km^2), Squannacook (ID: 20, suburban, area=165 km^2), and Shawsheen (ID: 18, urban, area=95 km^2). In this experimental comparison, Smith was the forested reference sub-basin located at upstream regions of the Merrimack, while Squannacook and Shawsheen were treatment sub-basins located at downstream developed areas. Smith, Squannacook, and Shawsheen had 3, 10, and 73 percent of developed land, respectively. Moreover, Squannacook was used to be a rural area with newly urban development; Shawsheen was an older residential sub-basin with recently suburban development.

At an annual time scale the discharge response may exhibit similar amplitudes, whereas in daily time-step the amplitudes may be much different. Therefore, the effects of land use/cover differences could be more evident at a daily time scale. The daily temporal scale analyses were made with climatographs (Figure 5-3 to Figure 5-5), double mass curves (Figure 5-6 to Figure 5-8), flow duration curves (Figure 5-9), and flow distribution curves (Figure 5-10) for three distinct hydrologic discharge conditions of average (1970), wet (1976), and dry (1989) years.

The differences in hydrologic responses of reference sub-basin were compared and contrasted with the other two treatment sites in terms of percentage of development and hydrologic condition. Generally, 5-10% impervious surfaces is the threshold of hydrologic change in developed areas (de la Crétaz and Barten, 2007). Since average year may better represent the overall hydrologic responses, it became the focus of the analyses of hydrologic conditions.

The results were presented in three sections. First, the correlation coefficients of daily discharge magnitude along with discharge timing characteristics were compared and contrasted with regards to key physical attributes of the study sites (Table 5-3). Second, the climatographs were compared and contrasted for the reference sub-basin with two treatment sites in the representative dry, average, and wet years. Finally, I performed similar comparisons on double mass curves, flow duration curves, and flow distribution curves.

5-3-2- *Key physical attributes of study sub-basins*

The key physical attributes of representative study sites are presented in Table 5-3 along with hydrometric information, discharge correlation coefficients, and discharge timing dates for average, wet, and dry hydrologic conditions. Shawsheen (urban) has a mild slope (less than 15%) compared to Smith (forest) and Squannacook (suburban) in addition to having the lowest mean basin elevation. Shawsheen and Squannacook have the base flow index greater than 0.35 which indicates a larger groundwater contribution to surface flow in treatment sub-basins. Shawsheen has shorter flow paths and a more rapid flow response than the other study sites due to greater drainage density (Table 5-3).

Generally, it was expected to observe more precipitation at higher altitudes due to orographic effects. However, annual precipitation values for treatment sites were greater than reference sub-basin located at higher altitude. This may be due to stronger influence of coastal lows on climatology of Squannacook and Shawsheen than orographic effects on precipitation generating mechanisms at Smith (Collins et al., 2014). On the other hand, urban development can also increase precipitation for 9-17% at treatment sites due to heat island effect on the formation of local convective storms (Changnon, 1981; Huff, 1977; Huff and Changnon, 1973; Knight and Davis, 2009; Villarini et al., 2011).

With increases in the percentage of development, the interactive effects of changing climate and land development became more complex. The hydrologic responses of suburban and urban (treatment) sub-basins were consistently different from the reference forested sub-basin using a high-resolution daily time step for the analyses (Table 5-3). In 1970 with average hydrologic discharge condition, increases in developed land from 3% (Smith) to 10% (Squannacook) resulted in 29% differences in hydrologic response. In contrast, there was only 12% difference in discharge response of two treatment sites which was pronounced in wet year (18%) and became even more noticeable in dry year (23%).

During the dry year, besides a high ET rate, the unsaturated soil conditions increased residence time of soil moisture, potentially offsetting the effects of impervious surfaces on discharge increment. Therefore, the correlation coefficients were higher in dry year compared to average and wet years. In contrast, during the wet year there was enough moisture available to increase subsurface flow and groundwater flow rates after evaporative demands were met. Consequently, the differences in hydrologic response due to development became more pronounced and the correlation coefficients declined.

Discharge timing dates at treatment sub-basins were distinctive from the forested reference sub-basin, especially in relation to median discharge timing date for the entire hydrologic conditions of average, wet, and dry year. Due to lower winter temperature, more snow accumulation, and higher ET rate in growing season, a longer period was required for a certain volume of annual water yield discharged from the forested sub-basin. The earlier discharge timing dates of suburban and urban sub-basins could be the reflection of higher winter temperature, less snowpack, lower ET rate, and more impervious surfaces.

Table 5-3- The key physical characteristics of the representative study sites (Smith: forest, Squannacook: suburban, and Shawsheen: urban) along with hydrometric information, discharge correlation coefficients, and discharge timing dates for average, wet, and dry hydrologic conditions.

	Study sites' physical characteristics															
	Forested (%)				Developed (%)											
Study site	**1971**	**1985**	**1999**	**2006**	**1971**	**1985**	**1999**	**2006**	**Area (km^2)**	**Gauge elevation (m ASL)**	**Mean basin elevation (m)**	**Storage (%)**	**Main channel length (km)**	**Drainage density (1/km)**	**Stream slope (%)**	**Base flow index**
Smith	---	---	---	87	---	---	---	4	222	137	384	4	35	0.16	0.4	0.457
Squannacook	89	86	83	77	5	8	10	10	165	74	261	5	24	0.15	0.8	0.547
Shawsheen	40	35	33	17	44	49	57	73	95	25	48	7	18	0.19	0.1	0.506

	1970 (average hydrologic discharge condition)							
	Precipitation mm/WY	**Discharge mm/WY**	**Correlation coefficients**			**Discharge timing dates (day of the WY)**		
			Smith	**Squannacook**	**Shawsheen**	**25%**	**50%**	**75%**
Smith	950	610	1	0.71	0.61	92	182	204
Squannacook	1229	707	---	1	0.88	90	141	191
Shawsheen	1363	696	---	---	1	87	133	189
	1976 (wet hydrologic discharge condition)							
Smith	1241	800	1	0.54	0.34	87	179	221
Squannacook	1231	727	---	1	0.82	63	131	179
Shawsheen	1233	782	---	---	1	69	125	188
	1989 (dry hydrologic discharge condition)							
Smith	967	483	1	0.81	0.66	176	199	227
Squannacook	1094	556	---	1	0.77	106	199	245
Shawsheen	1138	368	---	---	1	130	195	239

5-3-3- *Climatographs*

A climatograph is constructed with water balance parameters for a watershed of interest. In this study, the climatograph indicates measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS) in mm/day for three representative sites (Figure 5-3 to Figure 5-5). For the calculation of snowmelt contribution to discharge, a range of melt-rate coefficient (0.1 to 2 mm/°C) was tested iteratively to determine the best-fit value (Anderson, 1973). At melt-rate coefficient of 1 mm/°C, discharge responses were synchronized with total rainfall and snowmelt for all three study sites.

The climatographs indicated that land cover/land use effects had larger influences on the hydrologic response of sub-basins (of similar size subjected to comparable weather conditions) than inter-annual variations in precipitation, air temperature, and PET (Figure 5-3a-c). Peak discharge events likely occurred in February and April in Smith (forest) and Squannacook (suburban) with equal or less than 10% developed lands. At Shawsheen (urban), due to higher percentage of development and urban heat island effect, there was a secondary peak discharge period in December. For all three sub-basins, regardless of percentage of development, peak discharge mechanism was rain-on-snowmelt processes occurring mostly during March and April.

Unlike the considerable influence on peak discharge events, the percentage of development did not indicate a significant effect on low discharge conditions that began in June and continued towards October (Figure 5-3a-c). In contrast, potential evapotranspiration was affected by urbanization. Potential evapotranspiration increases beginning in March, reaching its peak value during the growing season in June and July (4-5 mm/day) then declining to 1-0.5 mm/day in November. For Shawsheen (urban), PET extended into early-December as a consequence of higher temperature in urbanized regions.

Compared to an average year, wet year peak discharge events mainly were concentrated in April for Smith (forest), while Squannacook (suburban) and Shawsheen (urban) peak discharge events occurred in February (Figure 5-4a-c). The upstream river regulations in the wet year moderated and spread peak discharge values over a longer period i.e. February through April. However, due to higher percentage of development, Shawsheen indicated annual peak discharge value twice as great as Squannacook. Low discharge events in a wet year, for treatment sub-basins, began in June and lasted only through September instead of October in average year.

In dry hydrologic condition, peak discharge events still occurred in April for the reference sub-basin (Smith); however besides the typical June-October low discharge season, there was a secondary low discharge season began from October and continued until March during the period of snow accumulation (Figure 5-5a-c). As the developed area increased, the snowmelt period became shorter during dry conditions (March only) mainly due to less snow accumulation and earlier snowmelt. The secondary low discharge period for treatment sites did not last as long as the reference sub-basin (Smith) and only occurred during December. Generally moving from north to south of the Merrimack, snow had prominent effects on Smith discharge response while both Squannacook (suburban) and Shawsheen (urban) responses appeared to be more strongly influenced by rain-on-snowmelt mechanisms.

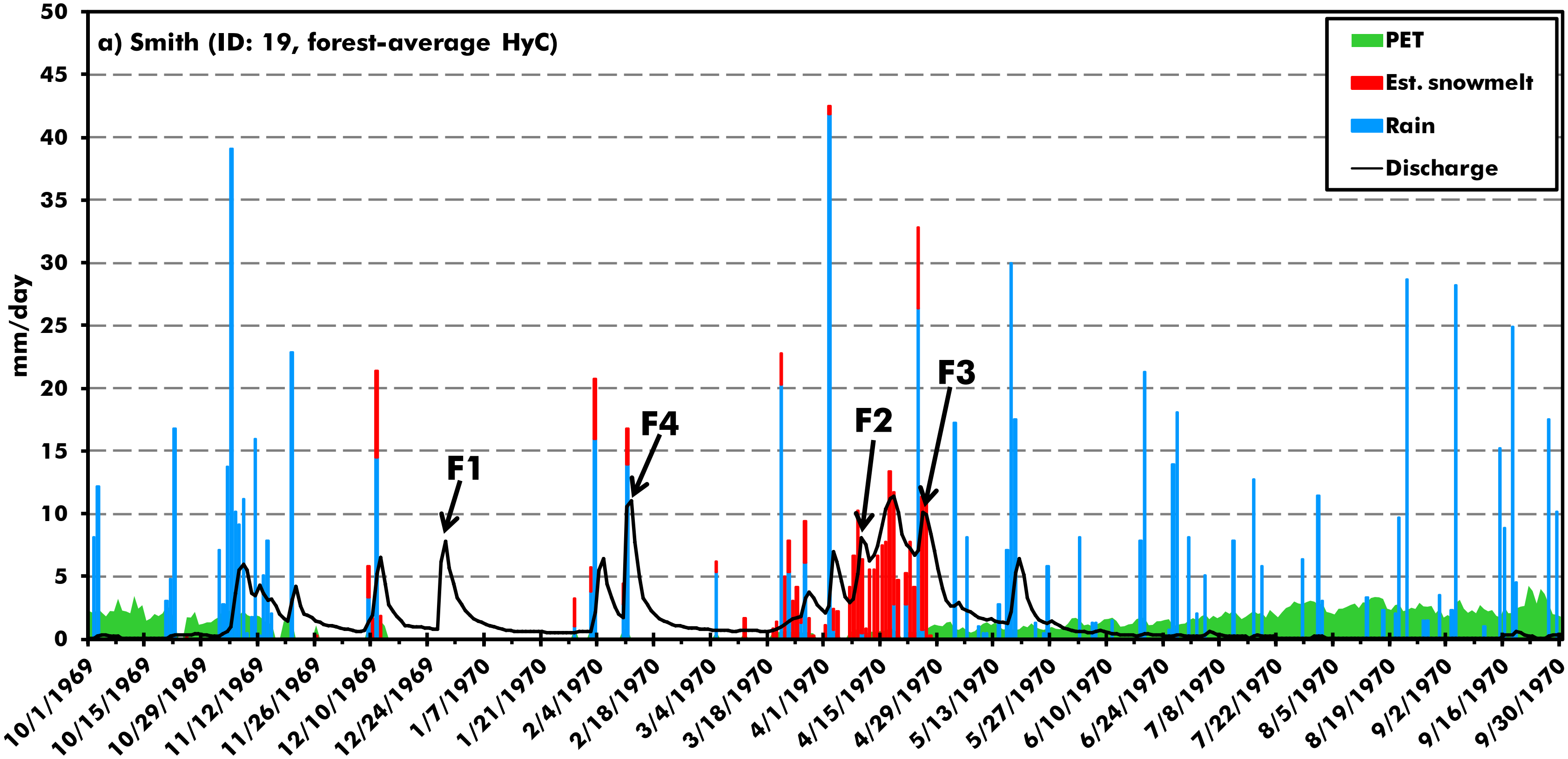

Figure 5-3a: Measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS), mm/day, for Smith River near Bristol (USGS 01078000), New Hampshire, October 1st 1969-September 30th 1970 (WY 1970). The labels on the plot are correspondent to inflection points on cumulative double mass curves of average year presented on Figure 5-6a and –b.

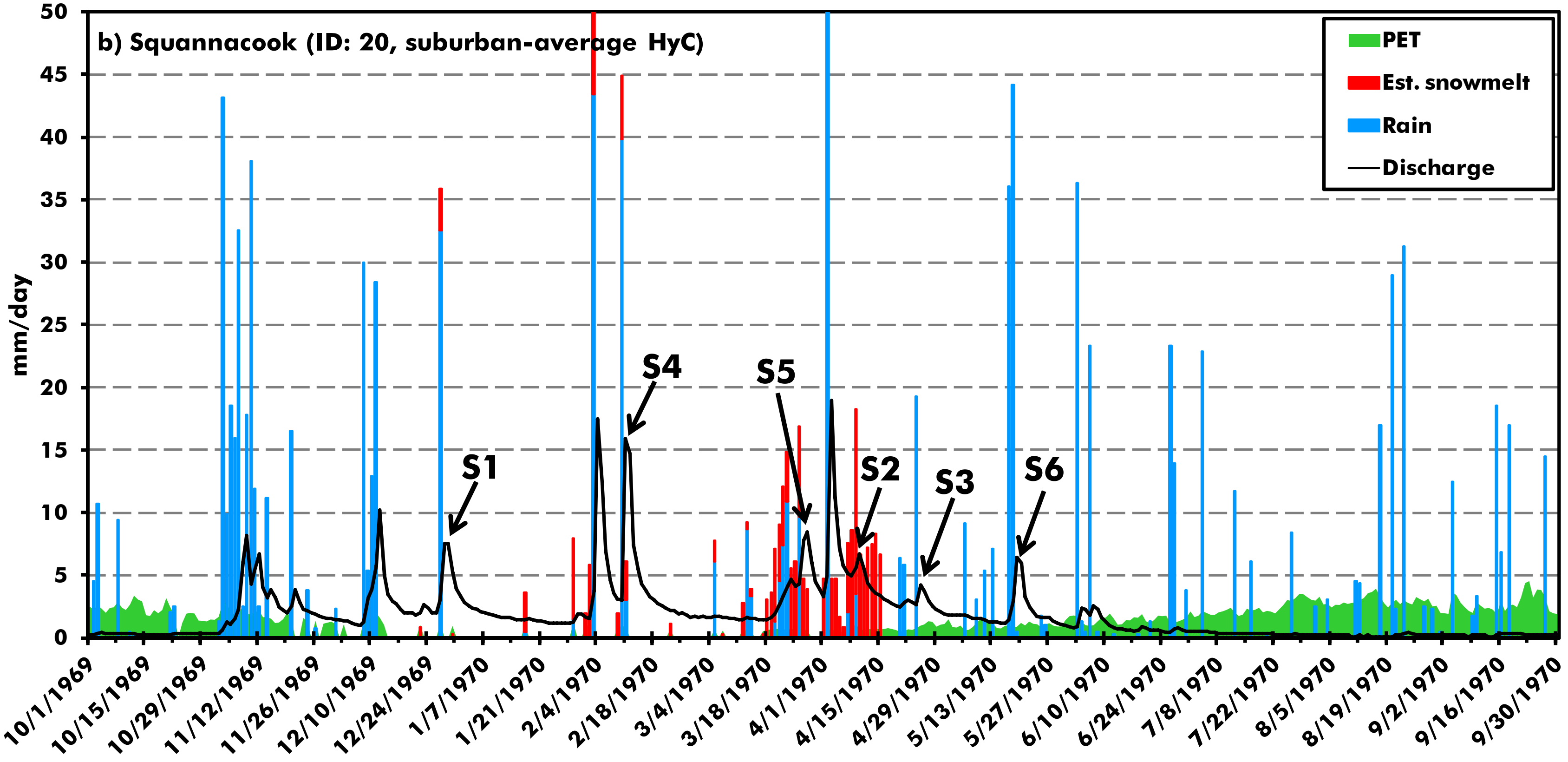

Figure 5-3b: Measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS), mm/day, for Squannacook River near West Groton (USGS 01096000), Massachusetts, October 1st 1969-September 30th 1970 (WY 1970). The labels on the plot are correspondent to inflection points on cumulative double mass curves of average year presented on Figure 5-6a and –c. Note: Y-axis truncated to 50 mm (February 3rd 1970 = 51 mm; April 2nd 1970 = 60 mm).

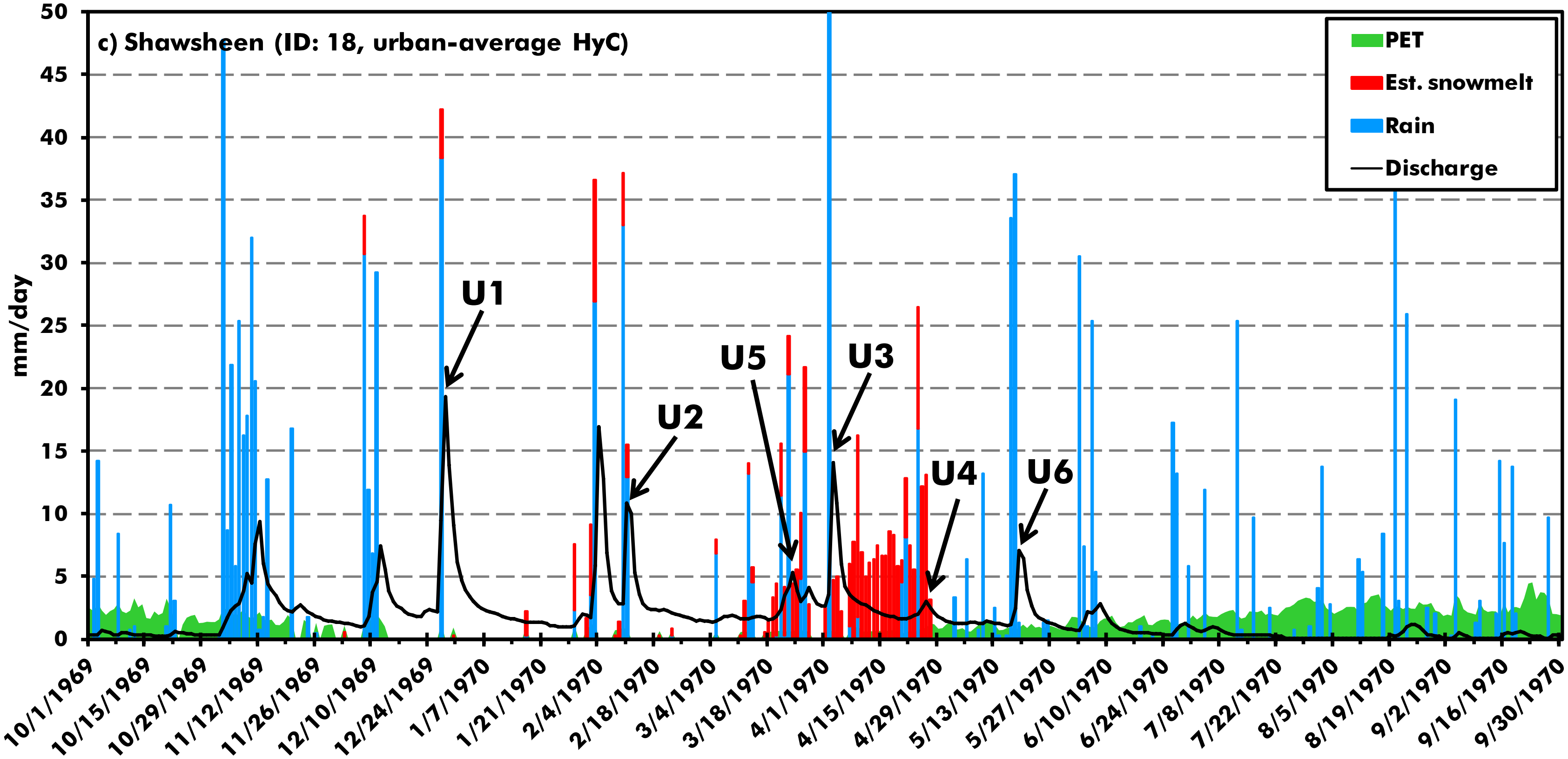

Figure 5-3c: Measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS), mm/day, for Shawsheen River near Wilmington (USGS 01100600), Massachusetts, October 1st 1969-September 30th 1970 (WY 1970). The labels on the plot are correspondent to inflection points on cumulative double mass curves of average year presented on Figure 5-6b and –c. Note: Y-axis truncated to 50 mm (April 2nd 1970 = 68 mm).

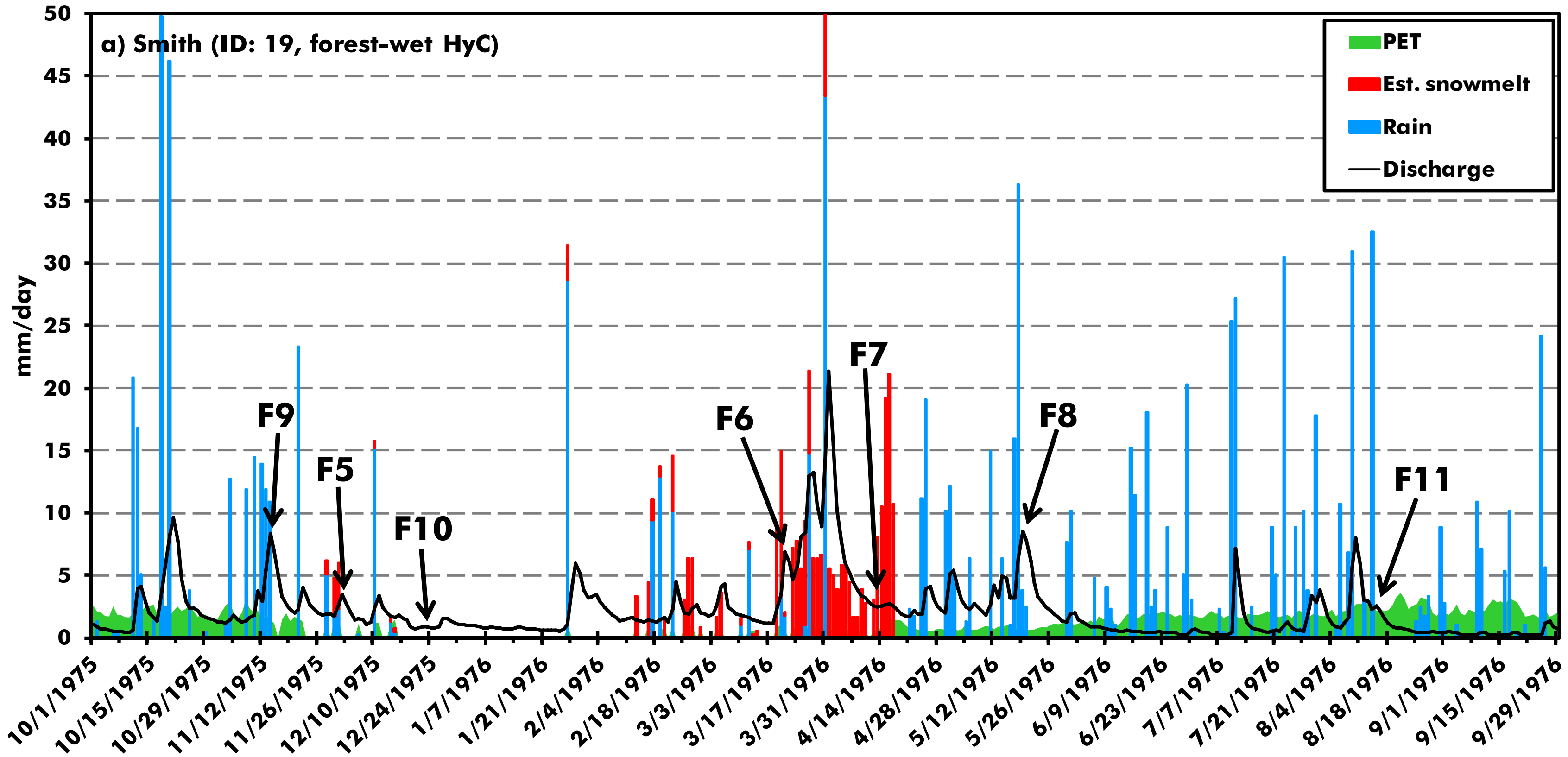

Figure 5-4a: Measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS), mm/day, for Smith River near Bristol (USGS 01078000), New Hampshire, October 1st 1975-September 30th 1976 (WY 1976). The labels on the plot are correspondent to inflection points on cumulative double mass curves of wet year presented on Figure 5-7a and –b.

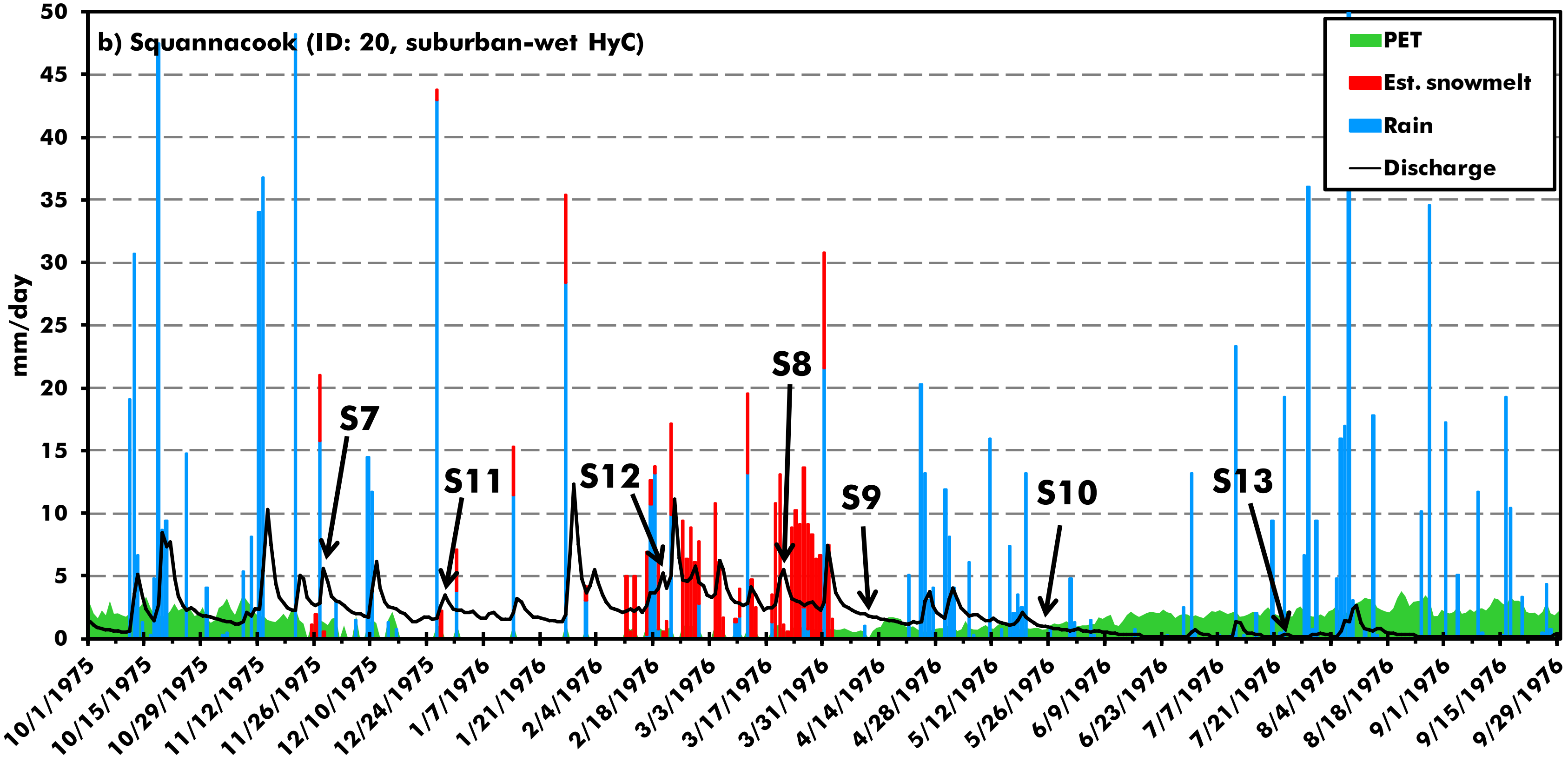

Figure 5-4b: Measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS), mm/day, for Squannacook River near West Groton (USGS 01096000), Massachusetts, October 1st 1975-September 30th 1976 (WY 1976). The labels on the plot are correspondent to inflection points on cumulative double mass curves of wet year presented on Figure 5-7a and –c.

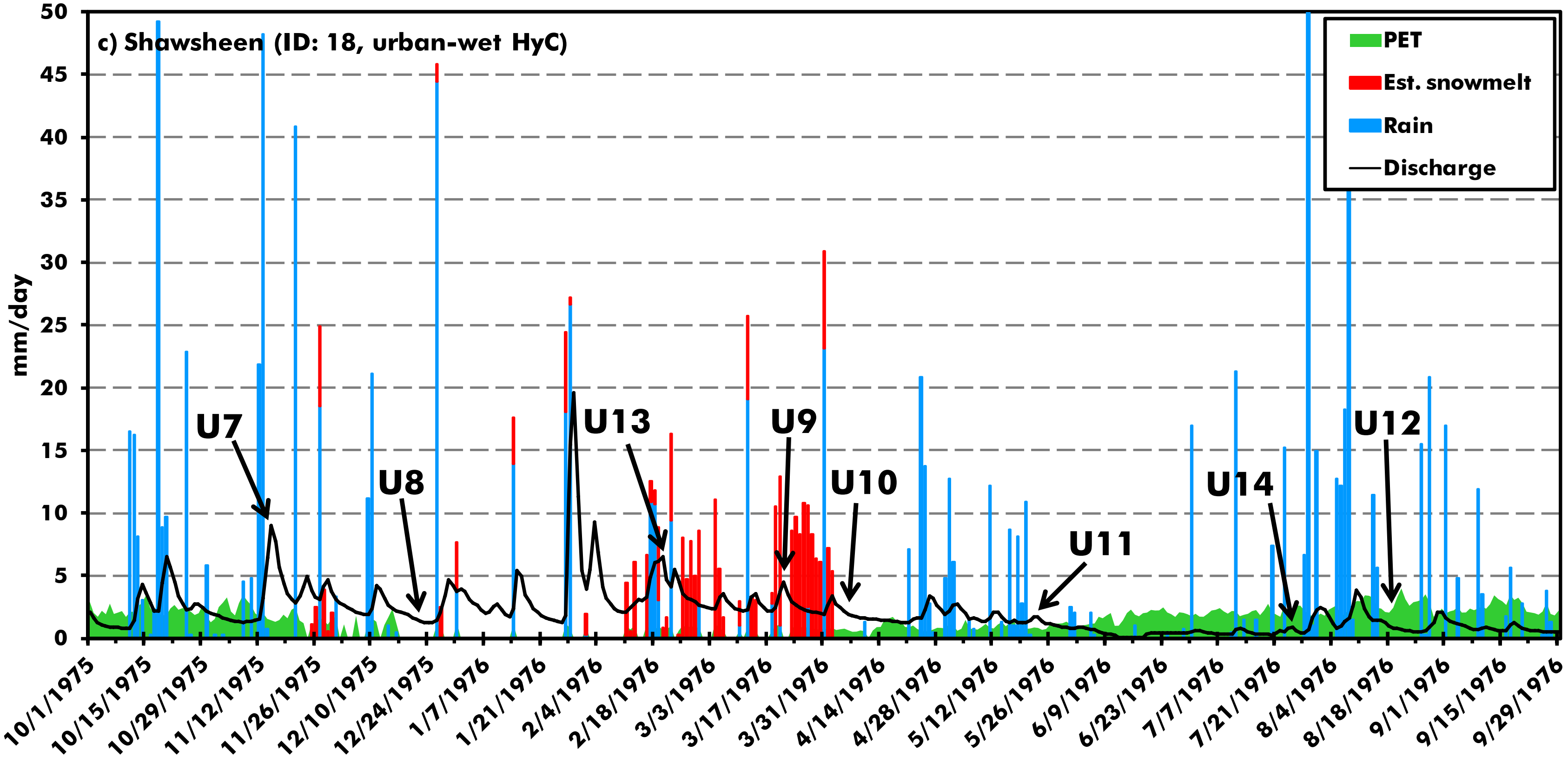

Figure 5-4c: Measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS), mm/day, for Shawsheen River near Wilmington (USGS 01100600), Massachusetts, October 1st 1975-September 30th 1976 (WY 1976). The labels on the plot are correspondent to inflection points on cumulative double mass curves of wet year presented on Figure 5-7b and –c. Note: Y-axis truncated to 50 mm (July 29th 1976 = 64 mm).

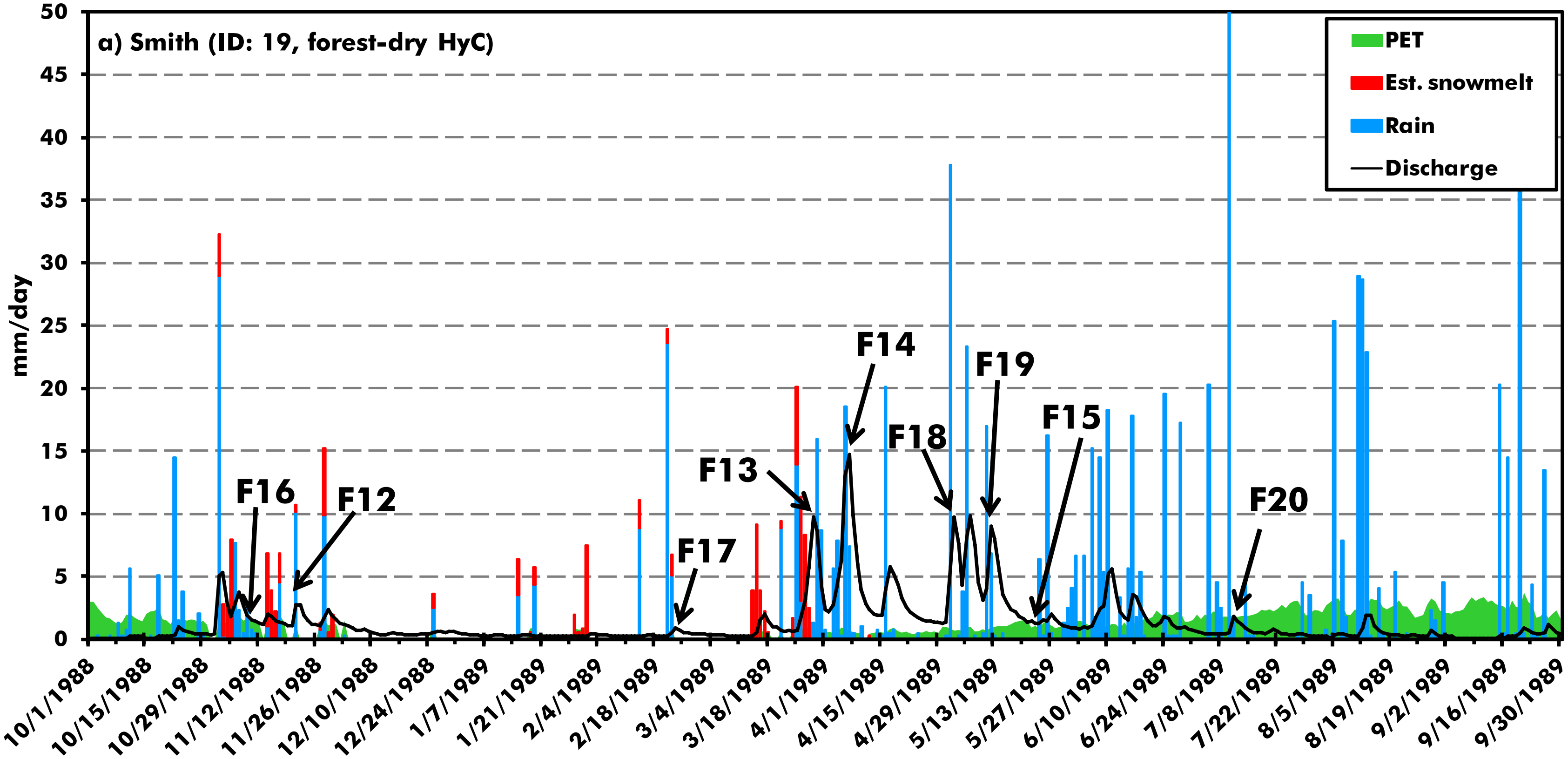

Figure 5-5a: Measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS), mm/day, for Smith River near Bristol (USGS 01078000), New Hampshire, October 1st 1988-September 30th 1989 (WY 1989). The labels on the plot are correspondent to inflection points on cumulative double mass curves of dry year presented on Figure 5-8a and –b.

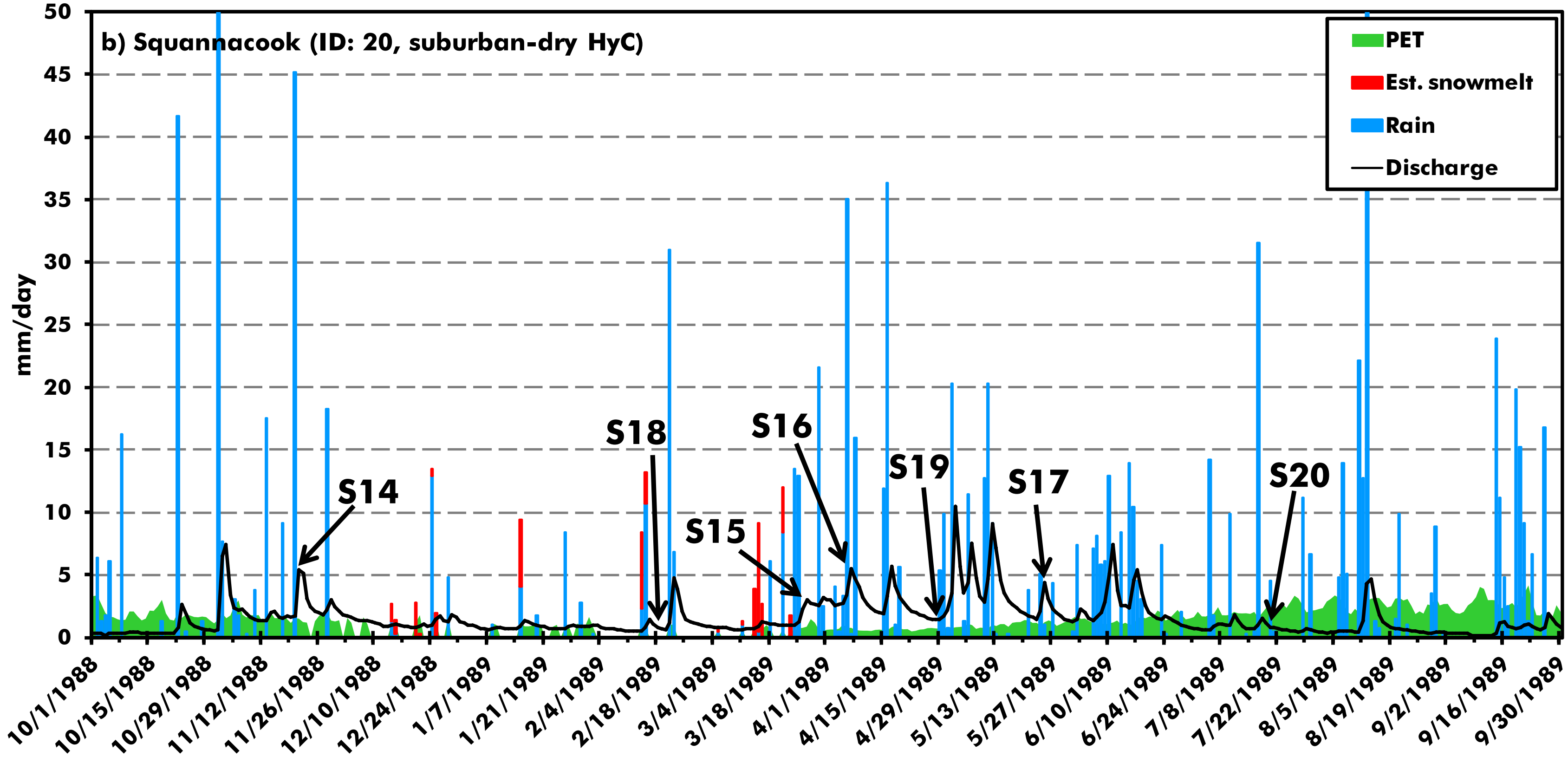

Figure 5-5b: Measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS), mm/day, for Squannacook River near West Groton (USGS 01096000), Massachusetts, October 1st 1988-September 30th 1989 (WY 1989). The labels on the plot are correspondent to inflection points on cumulative double mass curves of dry year presented on Figure 5-8a and –c. Note: Y-axis truncated to 50 mm (November 1st 1988= 56 mm; August 13th 1989 = 61 mm).

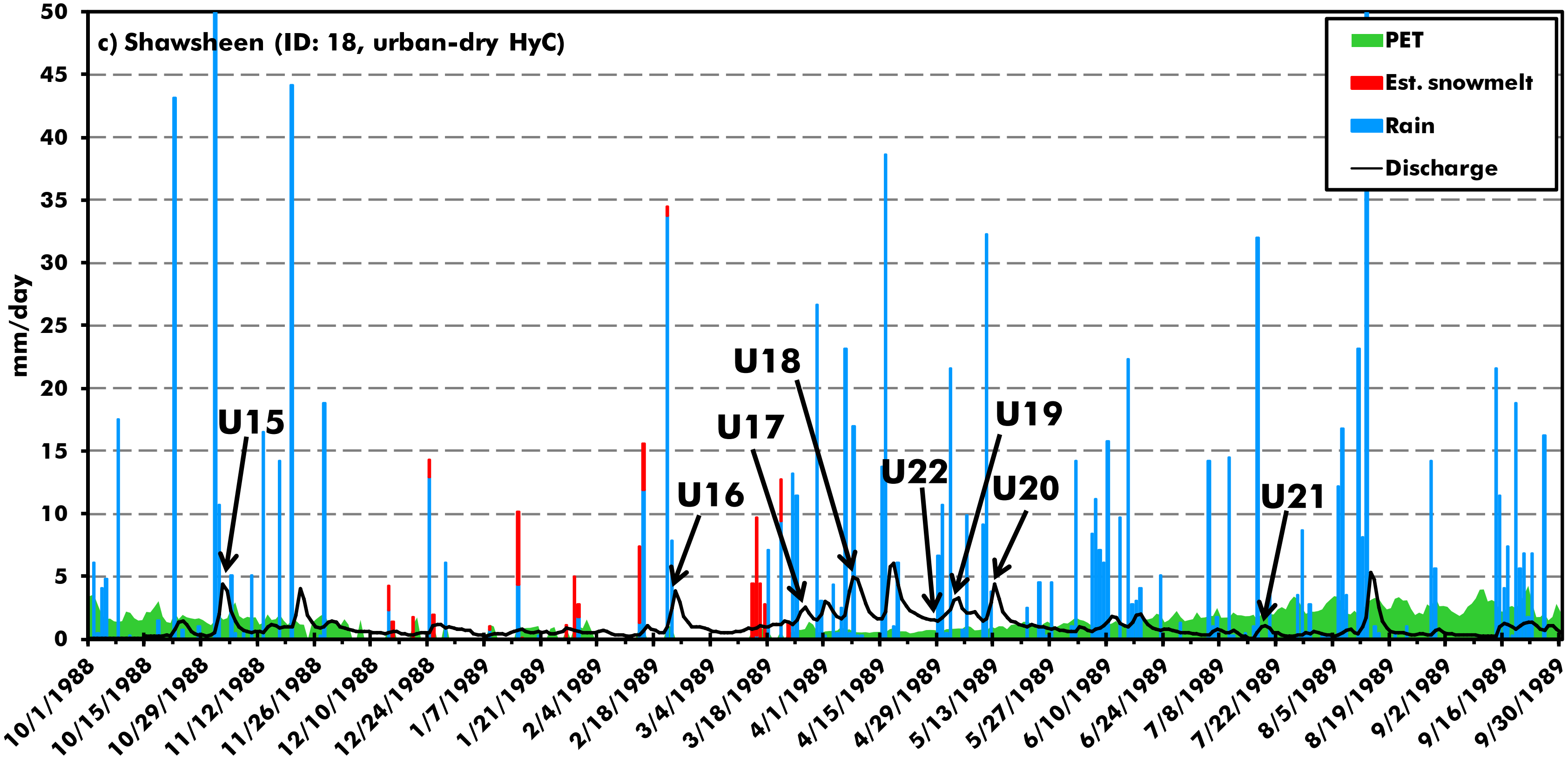

Figure 5-5c: Measured rainfall (NOAA), estimated snowmelt, calculated Hamon PET, and measured discharge (USGS), mm/day, for Shawsheen River near Wilmington (USGS 01100600), Massachusetts, October 1st 1988-September 30th 1989 (WY 1989). The labels on the plot are correspondent to inflection points on cumulative double mass curves of dry year presented on Figure 5-8b and –c. Note: Y-axis truncated to 50 mm (November 1st 1988= 76 mm; August 13th 1989 = 53 mm).

5-3-4- *Cumulative double mass curve*

A double mass curve is a traditional method used to detect differences in hydrologic response of watersheds with different land cover/use (Gao et al., 2011). A cumulative plot of two sites is linear when hydrological or watershed conditions remain consistent over time. If external forces affect a system of interest, inflection points in the slope of a mass curve can be observed (Searcy et al., 1960). The double mass curves of the reference sub-basin with two treatment sub-basins showed inflection points mostly corresponding with the peak discharge events (Figure 5-6 to Figure 5-8 and Figure 5-3 to Figure 5-5). This problem indicates the more pronounced effect of development (impervious surfaces and overland flow) on high rather than low discharge events.

The cumulative discharge located above or below the 1:1 line indicated the strength of the hydrologic response for that particular sub-basin over the other. For instance, for 1970 as a representative of average hydrologic condition, the double mass curves of Smith (forest) against suburban (Squannacook) and urban (Shawsheen) sub-basins were located below 1:1 line which indicated that the interactive effects of climate and development on treatment sites were greater than the effect of changing climate alone on reference sub-basin (Figure 5-6a and -b). When the two treatment sub-basins were compared, the one with higher percentage of development indicated a stronger response until the end of snowmelt season in April-May (Figure 5-6c). Later during summer and fall, the suburban site indicated stronger response to both climate and development than urban sub-basin probably due to overriding effects of ET during the growing season.

The differences in hydrologic response of forested sub-basin with treatment sub-basins were more noticeable under wet and dry discharge conditions emphasized by more inflection points on double mass curves (Figure 5-7 and Figure 5-8). In general, the superimposed effects of changing climate and land development were greater than the individual control of changing climate on hydrologic response mainly during the high discharge seasons i.e. winter through spring. The overriding effect of ET for both forested and less developed sub-basins forced greater response to changing climate than interactive effects of climate and development mainly in summer and in dry hydrologic condition.

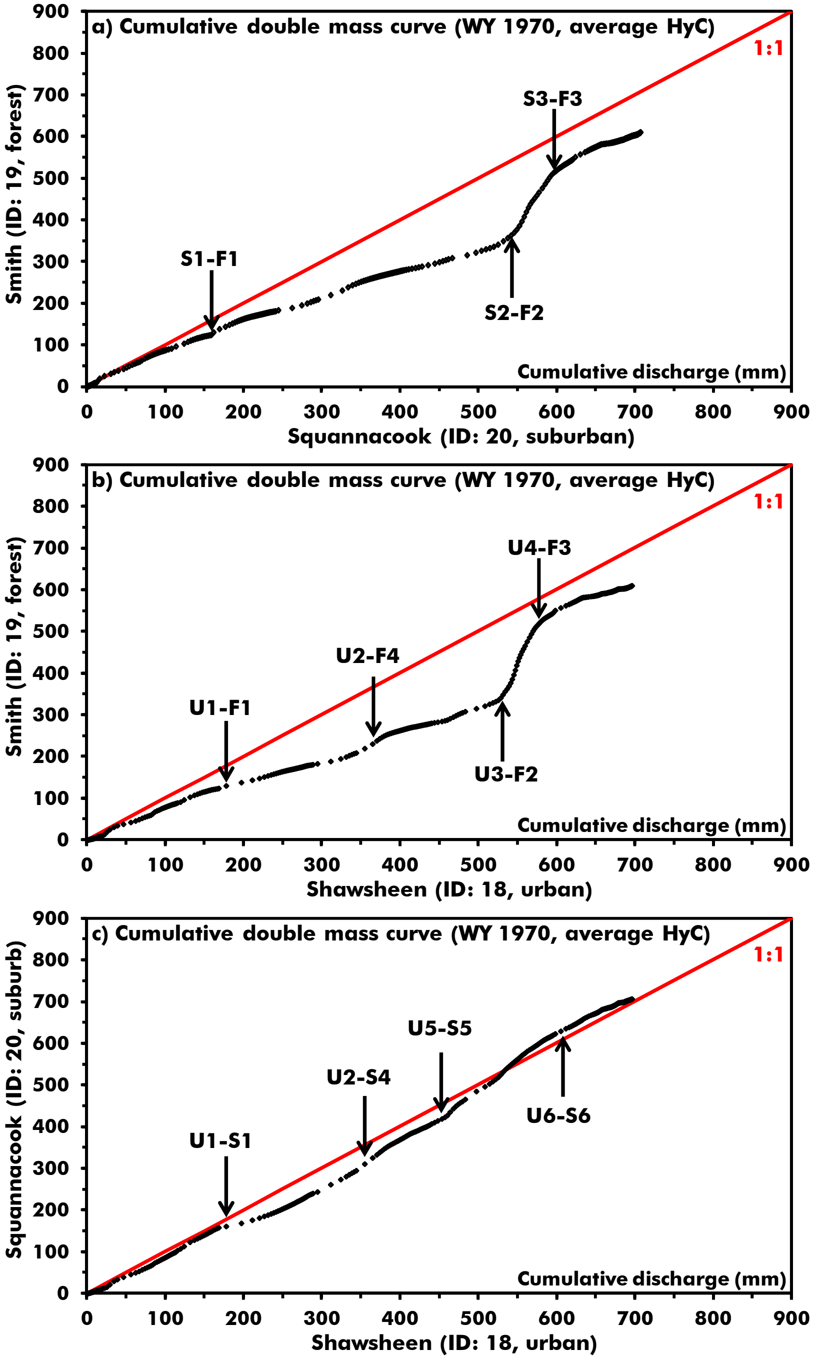

Figure 5-6a-c: Cumulative double mass curve of 1970 representing average hydrologic discharge condition. The dates and discharge conditions corresponding with inflection points can be found on Figure 5-3a-c.

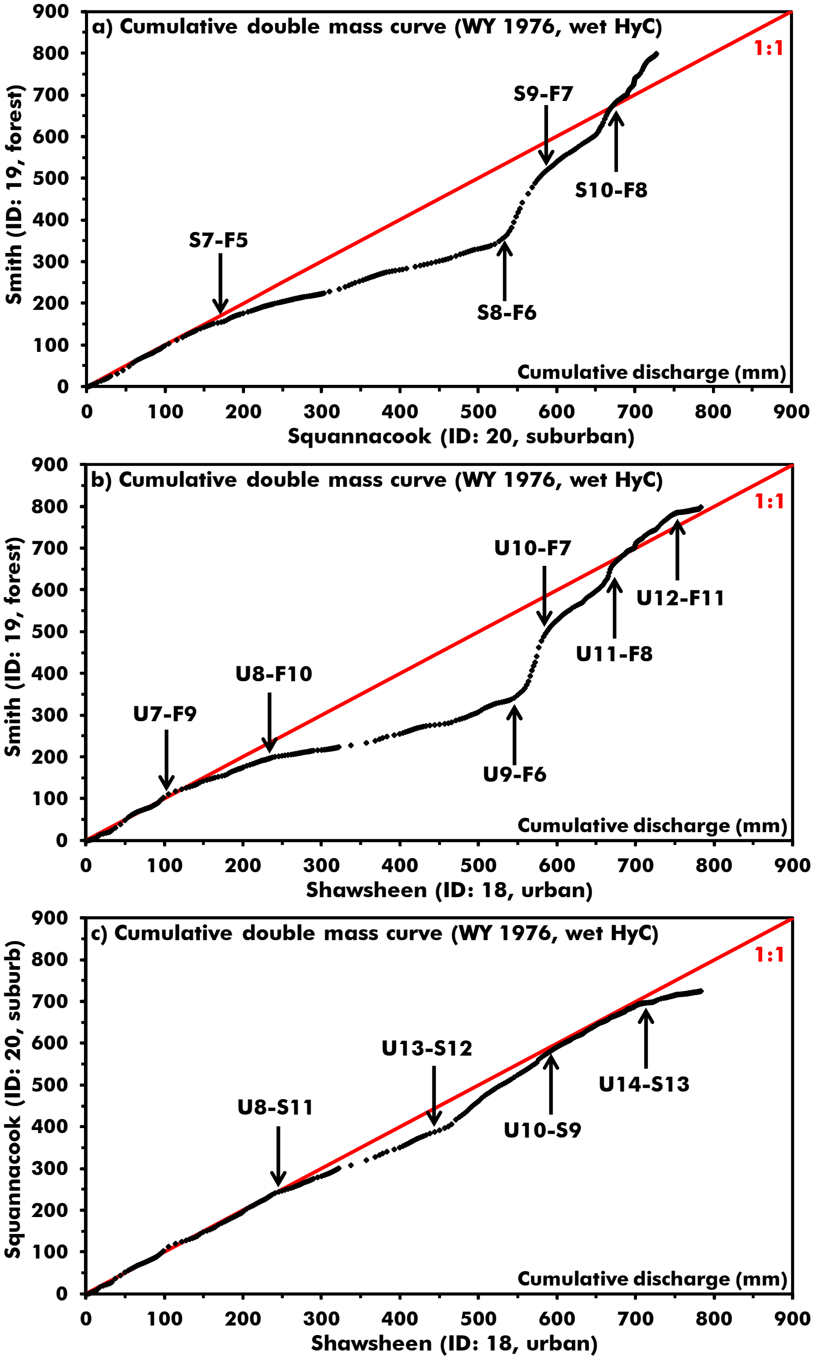

Figure 5-7a-c: Cumulative double mass curve of 1976 representing wet hydrologic discharge condition. The dates and discharge conditions corresponding with inflection points can be found on Figure 5-4a-c.

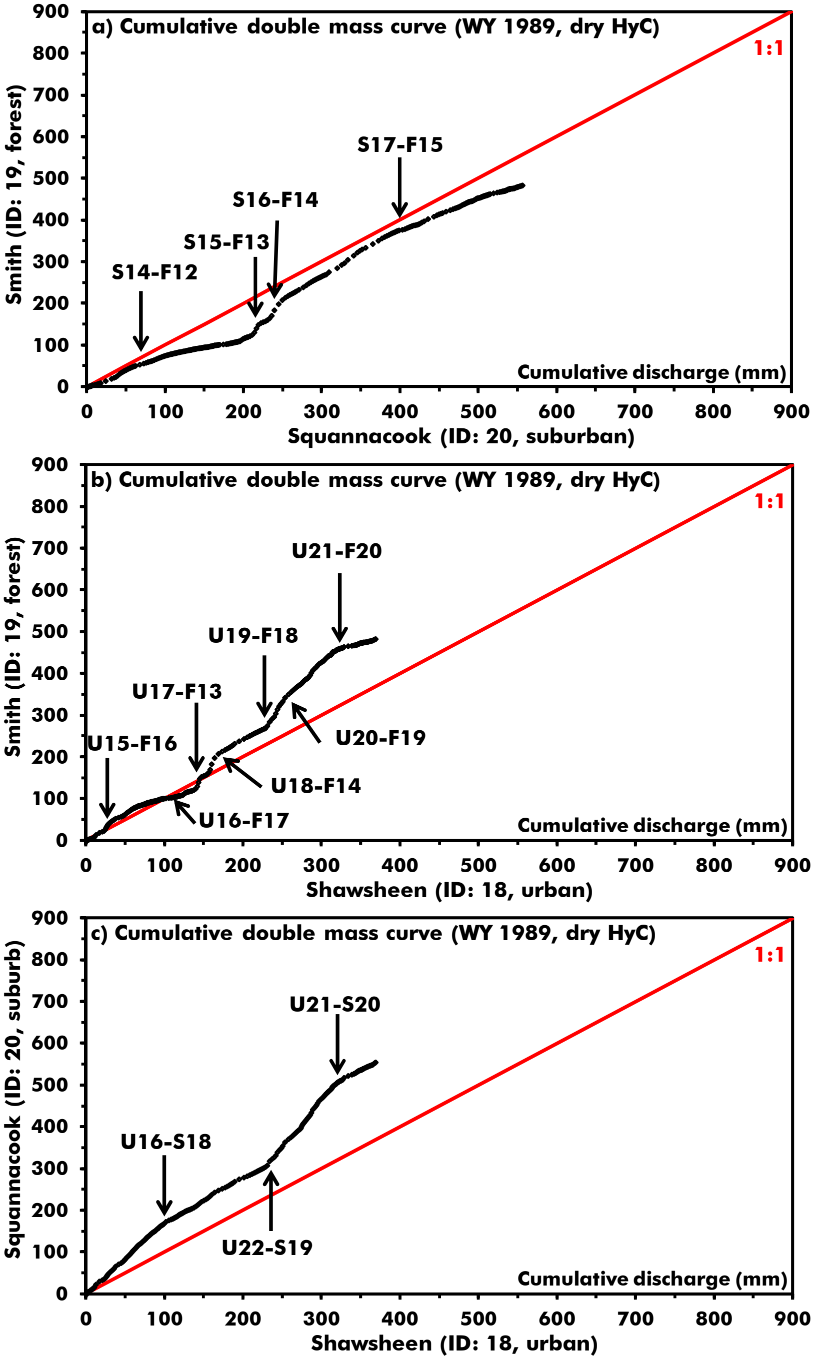

Figure 5-8a-c: Cumulative double mass curve of 1989 representing dry hydrologic discharge condition. The dates and discharge conditions corresponding with inflection points can be found on Figure 5-5a-c.

5-3-5- *Flow duration and flow distribution curves*

With more impervious surfaces, theoretically, one should expect higher high and lower low discharge events, while river regulation may moderate both high and low discharge conditions. Only in wet hydrologic condition when enough water was available for saturating soil and ET, as the percentage of developed lands increased, the high discharge events for Shawsheen (urban) became greater than both Squannacook (suburban) and Smith (Forest). It appears that decreases in groundwater recharge for urban site was more pronounced under wet hydrologic conditions, therefore Shawsheen low discharge events were lower than Squannacook and Smith (Figure 5-9b).

As shown in the comparative analyses, the relative effect of land development on hydrologic response to climate change is complex. The hydrologic responses of the suburban and urban sub-basins were relatively close as shown by the flow duration and flow distribution curves for average, wet, and dry hydrologic conditions using a high-resolution daily time step for analyses. Most of the watersheds in the northeastern US are characterized by a mix of forest, agricultural and urban land cover/use. The wide-range of differences in land covers, i.e. relative proportions and spatial distribution can result different hydrologic responses with complex ecological effects, which may challenge watershed water management strategies.

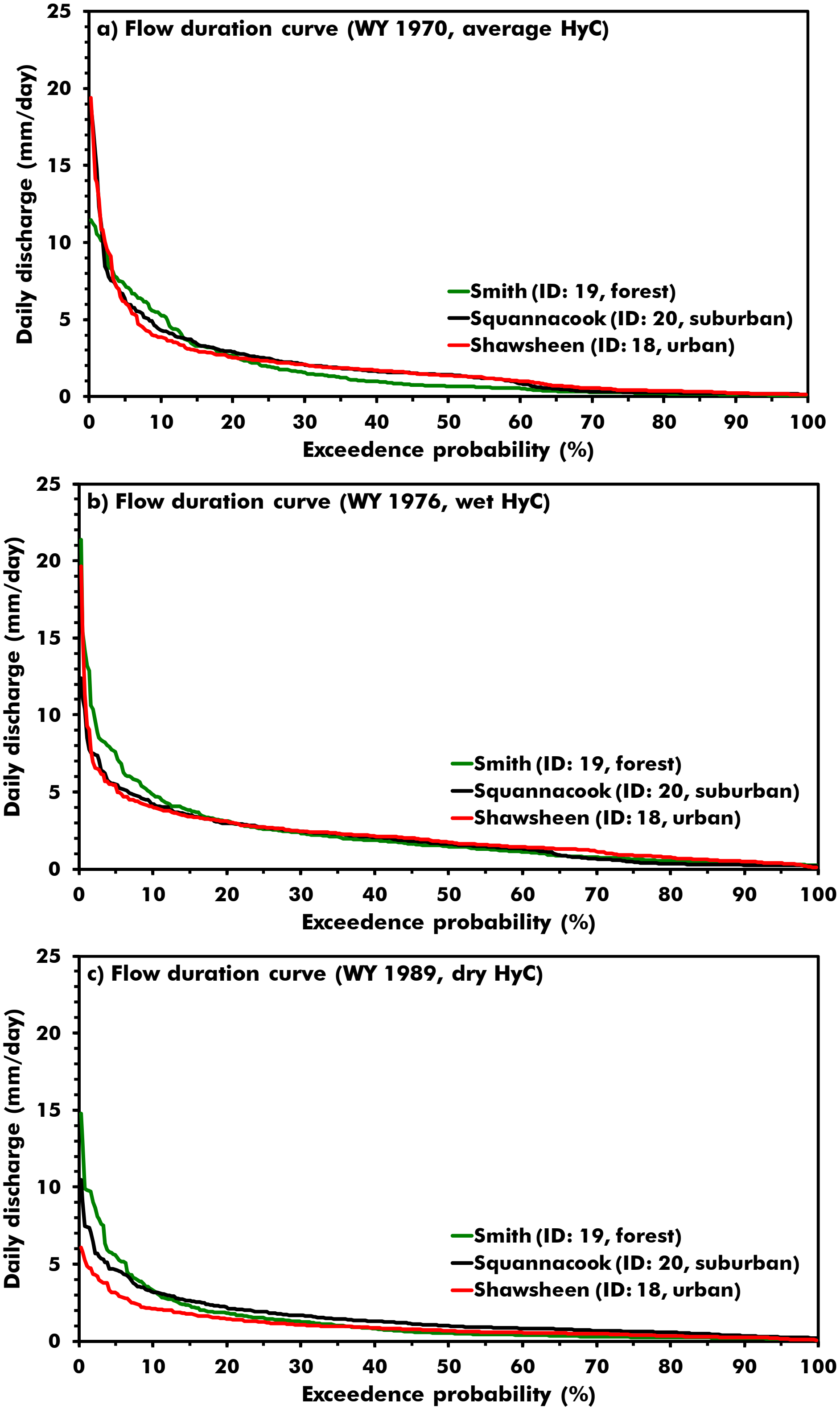

Figure 5-9a-c: Flow duration curves (FDCs) of three representative sub-basins of different land cover (forest, suburban, urban) for average (1970), wet (1976), and dry (1989) hydrologic conditions.

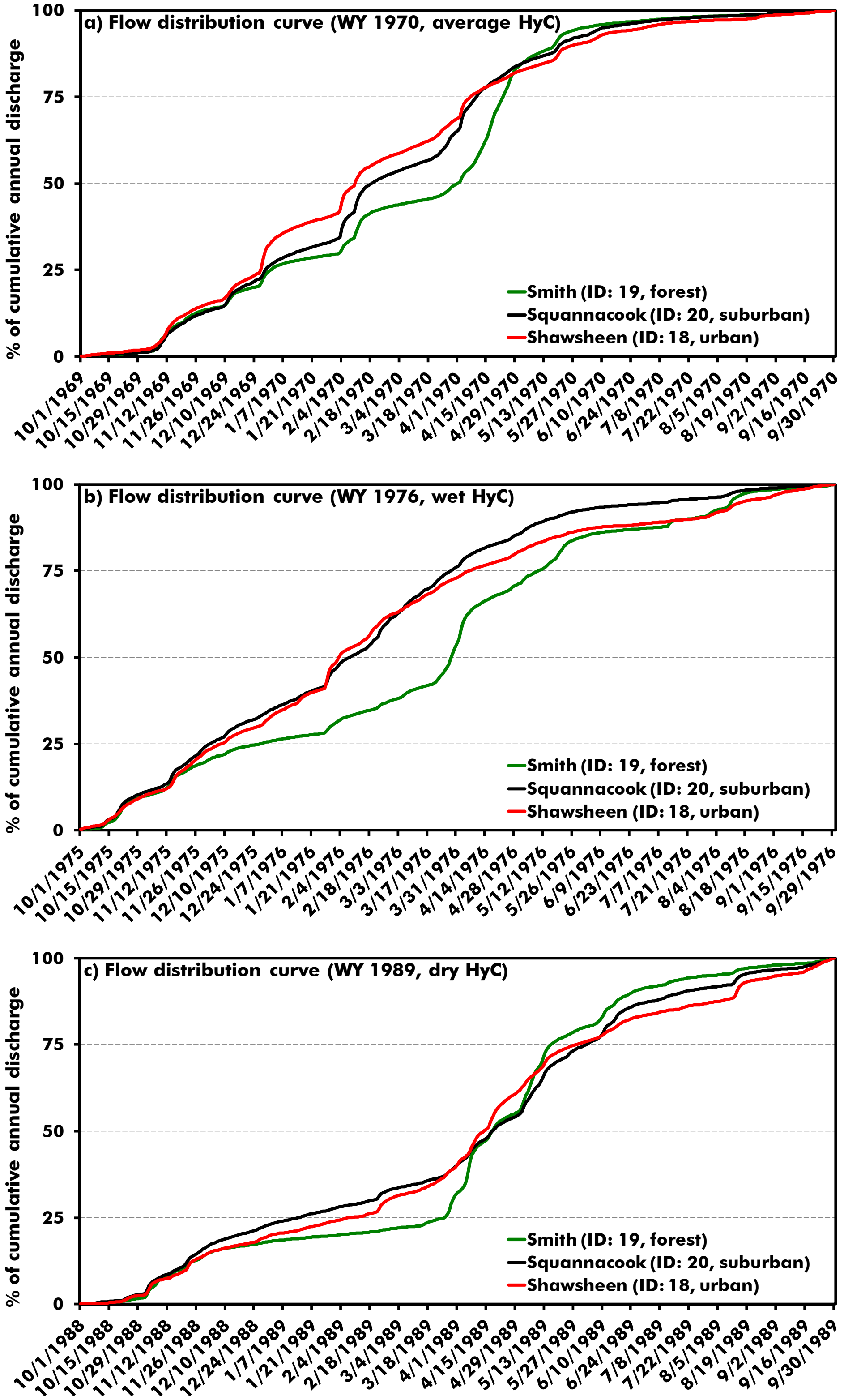

Figure 5-10a-c: Flow distribution curves (FDiCs) of three representative sub-basins of different land cover (forest, suburban, urban) for average (1970), wet (1976), and dry (1989) hydrologic conditions.

5-4- Summary and concluding remarks

I assessed trends in stream hydrologic responses of the Merrimack River watershed 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. Applying modified Mann-Kendall 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 the analysis; therefore, the data record was parsed among hydrologic discharge classes of dry, average, and wet years.

Increases in mean annual discharge (1 to 7 mm/WY) were consistent with increases in mean annual precipitation (1 to 7 mm/WY) throughout the Merrimack River watershed. Discharge varied differently among hydrologic discharge classes, i.e. more of the negative discharge trends were evident over dry years, while stronger pronounced positive trends were observed in wet years. The scale of the Merrimack sub-basins affected both high (exceedance probability of less than 15%) and low (exceedance probability of greater than 60%) discharge events. The greater drainage area, milder slopes, and surface water storages of the Merrimack sub-basins compared to HBEF catchments have moderated discharge response to changing climate likely due to land development. In the absence of a reservoir to attenuate stormflow from an urbanized area, increases in discharge at a developed sub-basin could be twice that of a reference sub-basin with similar rates of precipitation increase.

Generally moving from north to south of the Merrimack, snow had prominent effects on discharge response while the responses of southern sub-basins appeared to be more strongly influenced by rain-on-snowmelt mechanisms. The earlier timing dates of 25% and 50% annual discharge in winter and spring accompanied by later timing date of 75% annual discharge clearly indicated a shift towards earlier snowmelt and a likely subsequent low summer baseflow which were known as climate change footprints on hydrologic response in the northeastern United States. The sub-basins with the largest drainage areas showed the latest discharge timing dates, while smallest sub-basins indicated the earliest discharge timing dates.

With increases in the percentage of development, the interactive effects of changing climate and land development became more complicated since at an annual time scale the discharge response may exhibit similar amplitudes, whereas in daily time-step the amplitudes may be much different. Land cover/land use effects had larger influences on the hydrologic response of sub-basins (of similar size subjected to comparable weather conditions) than inter-annual variations in precipitation, air temperature, and potential evapotranspiration. Unlike the considerable influence on peak discharge events, the percentage of development did not indicate a significant effect on low discharge conditions.

In general, the superimposed effects of changing climate and land development were greater than the individual control of changing climate on hydrologic response mainly during the high discharge seasons i.e. winter through spring. The overriding effect of evapotranspiration for both forested and less developed sub-basins forced greater response to changing climate than interactive effects of climate and development mainly in summer and in dry hydrologic discharge condition.

As shown in the comparative analyses, the relative effect of land development on hydrologic response to climate change is complex. Most of the watersheds in the northeastern US are characterized by a mix of forest, agricultural and urban land cover/use. The wide-range of differences in land covers (i.e. relative proportions and spatial distribution) can result different hydrologic responses with complex ecological effects, which may challenge watershed water management strategies. The results for the two extreme hydrologic flow classes, which showed greater decreasing trends in discharge under dry and greater increasing discharge trends under wet hydrologic conditions compared to average flow class, provide strategic information for water managers and policy makers to reexamine 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.

In this phase of the dissertation, analysis showed that compared to headwater undisturbed catchments, discharge responses in downstream developed sub-basins due to changing climate were either amplified (by increases in precipitation due to urban heat island effects, more impervious surfaces, shorter flow path, greater drainage density, decreases in ET) or masked (by milder slope, more surface and groundwater storage, regulated streams). The interactive effects of changing climate and development were greater than changing climate alone mainly during high discharge seasons. Moreover, the temporal trends showed greater decreasing trends in discharge under dry and greater increasing trends in discharge under wet hydrologic conditions compared to average years.

The results from this chapter have been partially published as: Berton, R., Driscoll, C.T., Chandler, D.G., 2016. Changing climate increases discharge and attenuates its seasonal distribution in the northeastern United States. Journal of Hydrology: Regional Studies 5, 164–178. doi:10.1016/j.ejrh.2015.12.057. Another publication is under preparation as: Berton, R., Driscoll, C.T., Barten, P.K., Campbell J.L., 2017. Climate change and land use effects on streamflow discharge and timing.

6- The responses of ecological discharge indicators to regime shifts of Atlantic Multi-decadal Oscillation and North Atlantic Oscillation in the northeastern United States

The objective of this chapter is to evaluate potential linkages between regime shifts in climate circulation patterns, including the AMO and NAO, with precipitation and discharge magnitude and timing indicators. I specifically address two objectives: (1) when do regime shifts in AMO, NAO, precipitation, and discharge for Merrimack sub-basins occur, and are they synchronous?; (2) how do these synchronous shifts affect ecological indicators of discharge? I examine regime shift points of the annual time series of AMO, NAO, precipitation and discharge corresponding to catchments of varying sizes and levels of human development. Next, I evaluate differences in discharge record between periods of regime shifts using discharge indicators with important implications for water quantity and quality management. This approach builds upon earlier studies that focused on the early 1970s hydroclimate regime shifts which were in agreement with AMO and NAO regime shifts. This investigation provides a compelling opportunity for studying hydrological regime shifts associated with changes in AMO and NAO regimes in the northeastern US. This approach will inform how ecological discharge indicators may respond to regime shifts in large-scale climate circulation patterns, an outcome that will provide information for watershed planners and managers to inform future sustainable water use in the Merrimack River watershed and other northeastern basins.

The results of this chapter are presented in three separate sections. I first provide analysis of ‘regime shift points’ for AMO, NAO, precipitation, and discharge time series for each study site. Second, I divide the data record into pre- and post- regime shift periods to contrast any differences in hydrologic response across regimes. The magnitude and frequency of discharge are compared via FDCs for the HBEF catchments and Merrimack sub-basins with similar regime shift points. Finally, I evaluate variations in the frequencies of extreme values for several indicators of hydrologic alteration, including the monthly discharge magnitude, duration, and timing indicators across regime shifts in the early 1950s, 1970s, and 2000s. For these analyses, the study sites are categorized based on drainage area from small headwater HBEF catchments to the Merrimack's small-, intermediate-, and large-scale sub-basins, many of which have a history of hydraulic control and/or land development.

6-1- Results

6-1-1- *Regime shift points*

For the AMO record (1857-2014), the regime shift detection method found a total of eight regime shifts. Regime durations ranged from eight to 38 years, with a median length of 13 years (Figure 6-1a). Before 1970, regime shifts in AMO occurred approximately every 30 years, while after 1970 the regime duration decreased to seventeen years or less. It appears that long-term oscillations of AMO shifted to a shorter duration after the 1970s with greater magnitudes of positive and negative states (Figure 6-1a). The AMO index for 1971-1979 was more negative compared to the 1902-1931 period. Likewise, AMO for the period of 2002-2014 was more positive compared to the regime of 1931-1964 (Figure 6-1a).

Across the NAO record (1900-2014), I identified four regime shifts, with regime durations between eight and 52 years and a median length of 20 years (Figure 6-1b). After 1970, the regime duration decreased to eight years. The regime of 1951-1972 was strongly negative compared to the recent regime of 1996-2014, while the positive NAO regime of 1989-1996 was anomalously higher than 1972-1989 regime (Figure 6-1b).

I found nine regime shifts in the PDO record (1855-2014), with regime durations between seven and 23 years and a median length of 16 years (Figure 6-1c). The PDO regimes were mostly negative (7 regimes) with three slightly positive regimes. However, ENSO exhibited five slightly different regimes of ten to 82 years duration (median of 18 years). The ENSO mean state remained negative across all regimes (Figure 6-1d).

The most common shift points shared across AMO, NAO, precipitation, and discharge records are shown in Figure 6-2 alongside record lengths for the HBEF catchments and Merrimack sub-basins. Both precipitation and discharge records have common regime shift points in 1951-1952 (29% of study sites), 1972-1973 (57% of study sites) and 2003-2004 (81% of study sites). The discharge regime shifts of 1973 and 2004 were common among all HBEF catchments (Figure 6-2). The small-scale sub-basins showed shifts in 1972 and 2005. The intermediate-scale sub-basins showed shifts in 1952, 1972, and 2003. Finally, the large-scale sub-basins showed three shifts in 1951, 1972, and 2004. Note that only one of the small sub-basins had a record that extended before 1950.

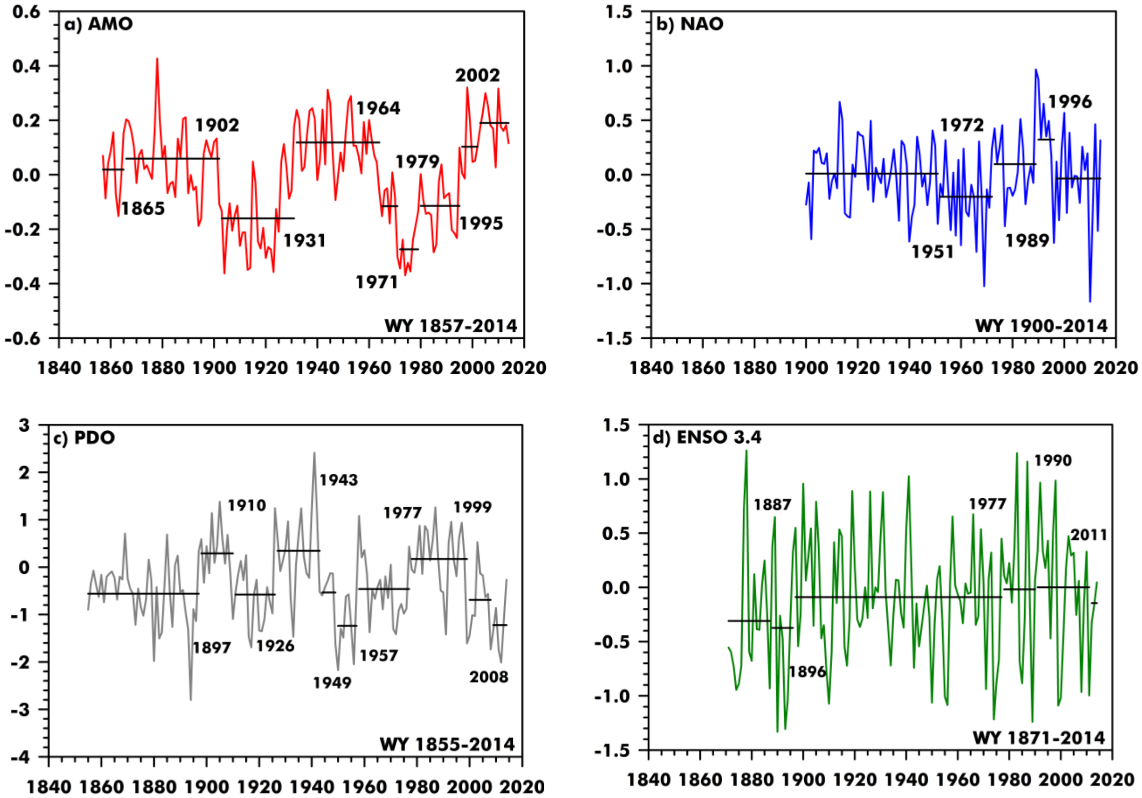

Figure 6-1- Annual time series of: a) Atlantic Multi-decadal Oscillation index (AMO); b) North Atlantic Oscillation index (NAO); c) Pacific Decadal Oscillation index (PDO); d) El Niño–Southern Oscillation index (ENSO 3.4). The dates of significant shifts in the long-term mean are indicated. Water year begins at October 1st and ends at September 30th.

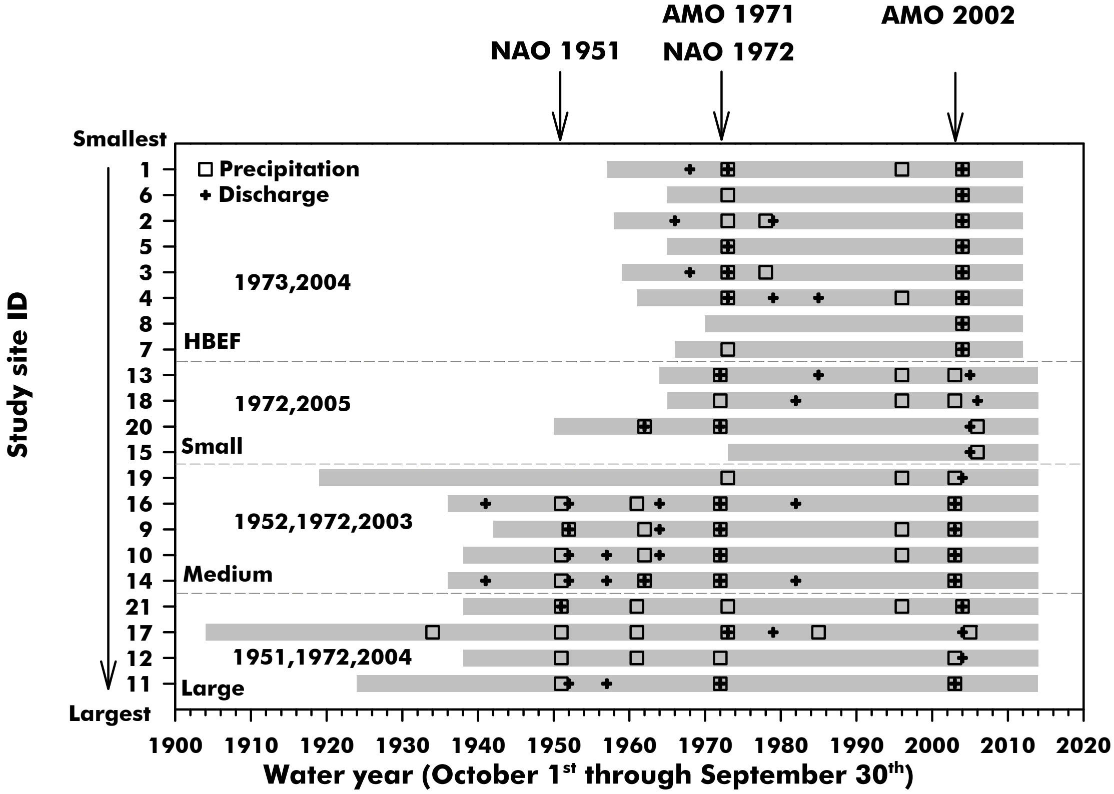

Figure 6-2- The regime shift points of precipitation and discharge for the HBEF catchments and Merrimack sub-basins. The gray bars indicate period of streamflow records whereas the times of the shifts are represented by square (precipitation), and plus (discharge). The shifts in precipitation and discharge are in synchronous with 1-2 years earlier regime shifts in AMO or NAO. The key to the site ID is presented in Table 3-1. The HBEF catchments (1-8) and the Merrimack sub-basins (9-21) are ordered by drainage area from smallest to largest. The selected shift points for further analyses on discharge variation are indicated for HBEF catchments and Merrimack sub-basins differentiated by scale.

6-1-2- *Synchrony in regime shifts across records*

I focus my analyses on regime shifts common to AMO, NAO, precipitation, and discharge. These include correspondence of the 1951-1952, 1972-1973, and 2003-2004 shifts in precipitation and discharge with the 1951 shift in AMO, the 1972 and 1973 shifts in AMO and NAO, and the 2002 shift in AMO, respectively. No concurrent regime shifts in precipitation or discharge existed for the AMO regime shifts of 1979, 1987, and 1995 or the NAO shifts of 1977, 1989, and 1996. Also, there were no regime shifts in PDO or ENSO synchronous with either AMO and NAO or precipitation and discharge (Figure 6-1c-d).

6-1-3- *Flow duration curves (FDCs)*

To investigate the scale-dependency of hydrologic response to different regime shifts, I compared FDCs for HBEF catchments and Merrimack sub-basins prior-to and following regime shifts of 1950s, 1970s, and 2000s (Figure 6-3a-d). I represented the differences of FDCs between two selected periods to better depict discharge responses to distinct discharge regimes (Figure 6-3e-h). Generally, for the same exceedance probability (EP), the magnitude of discharge was greater for the period of 2004-2014 compared to other periods. The high discharge events (EP less than 20%) exhibited greater discharge before 1952 than 2004-2014 only at large-scale sub-basins of the Merrimack (Figure 6-3d).

The FDCs were averaged over all HBEF catchments and presented for each distinct regime to facilitate comparison and avoid redundancy (Figure 6-3a). Differences in FDCs across regimes were most distinct at high discharge values (EP less than 10%), while they were similar for intermediate discharge events with EP between 30-40% (Figure 6-3e). In the range of EP 10-

80%, the 2005-2012 period was characterized by greater high discharge values compared to the other regimes.

The discharge shifts in the small-scale sub-basins (33-166 km^2) of the Merrimack (Figure 6-3b) were less distinctive than the HBEF catchments (Figure 6-3a). The 2006-2014 meteorology yielded greater high discharge values (EP < 10%) than the 1973-2005 regime (Figure 6-3f). The high discharge values (EP < 10%) for 2006-2014 were almost identical to pre-1973 discharge events (Figure 6-3b). For small-scale developed and/or regulated sub-basins, intermediate and low discharges (EP > 10%) were similar across regime shifts (Figure 6-3f).

The intermediate-scale sub-basins (222-818 km^2) were most different at high and low discharge events and most similar at intermediate discharge events (EP 10-60%; Figure 6-3c and Figure 6-3g). The responses of large-scale sub-basins (1220-11450 km^2) to different discharge regimes were confounded by Lake Winnipesaukee, a regulated sub-basin with considerable storage (even prior to 1949 when the Lakeport dam replaced by a concrete structure) in the headwater region of the Merrimack (Figure 6-3d). Intermediate-to-low discharge events (20% < EP < 65%) changed with the same rate for regimes pre-1952, 1952-1972 and 1973-2004. The most variable responses to different meteorological conditions could be identified for high and low discharge events (EP < 20% and EP > 65%).

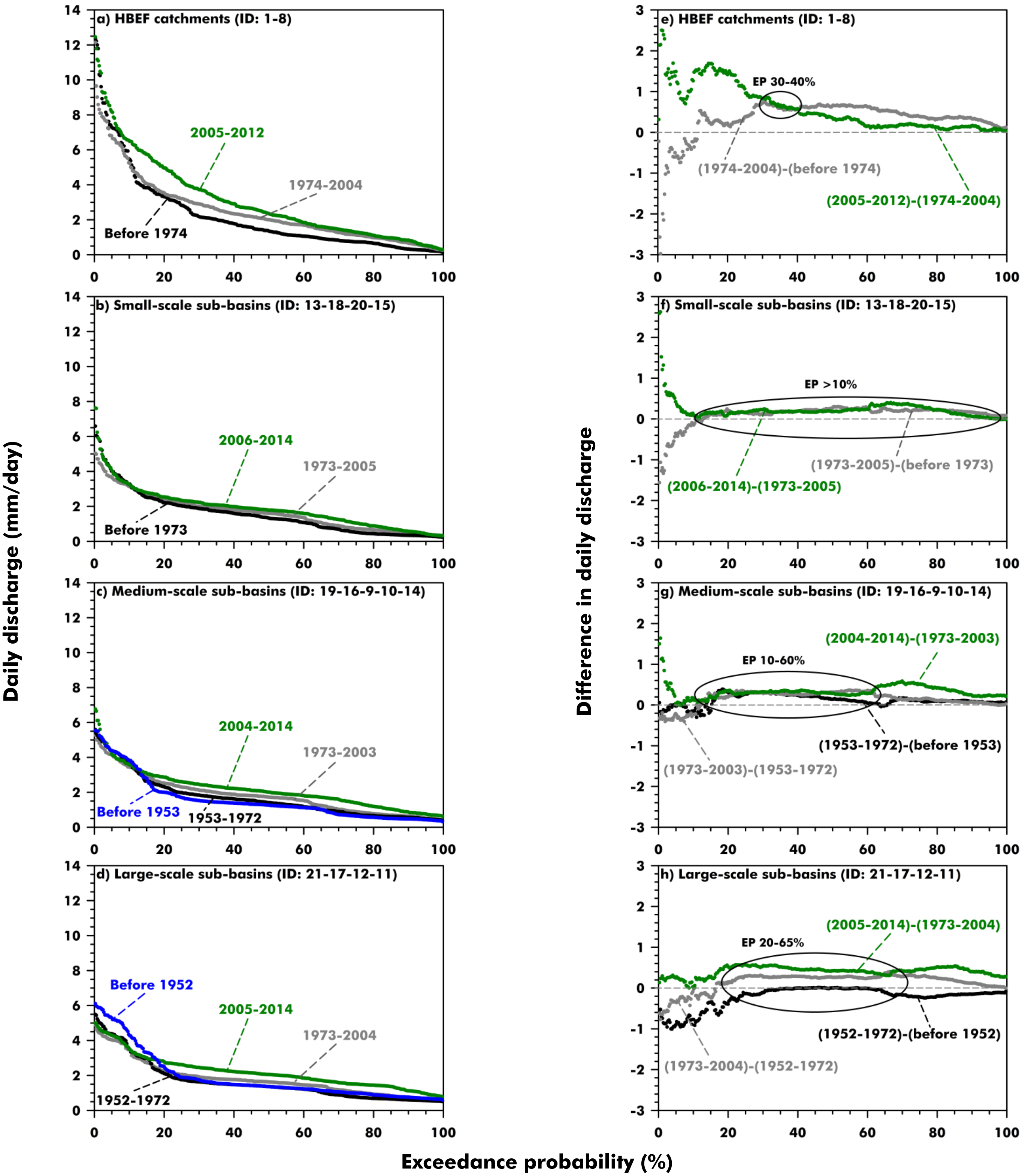

Figure 6-3- FDCs and their differences before and after the regime shifts in: a-e) the HBEF catchments with two shifts of 1973 and 2004 (ID: 1-8); b-f) the Merrimack small-scale sub-basins with two shifts of 1972 and 2005 (ID: 13-18-20-15, 33-166 km^2); c-g) the Merrimack intermediate-scale sub-basins with three shifts of 1952, 1972, and 2003 (ID: 19-16-9-10-14, 222-818 km^2); d-h) the Merrimack large-scale sub-basins with three shifts of 1951, 1972, and 2004 (ID: 21-17-12-11, 1220-11450 km^2). The key to the site ID is presented in Table 3-1. The ranges for similar differences across regimes are also indicated.

6-1-4- *Hydrologic alteration index (HAI) for ecological indices associated with discharge*

Hydrological and ecological discharge indicators provide information on the availability of water resources and most importantly the environmental components of discharge that affect ecosystem structure and function. Using RVA, I analyzed the extent of change in the frequency of high and low percentiles of these indicators, calculated per year, before and after the regime shifts in AMO and NAO. The HAI associated with 90th percentile discharge (less frequent discharge events) and 10th percentile discharge (more frequent discharge events) are shown for each indicator and each set of sub-basins in Figure 6-4. The HAI compared responses during the most extreme years across each regime, and values were calculated for concurrent periods of time.

6-1-4-1- HBEF catchments

After the two major shifts of the 1970s and the 2000s in AMO or NAO regimes, HBEF catchments showed increased high percentile monthly discharge for October (HAI = 3.3), December, January, May, August, and September (Figure 6-4a). In contrast, the frequencies of low percentile discharge decreased (maximum change in October discharge, HAI=-2.0) with the exception of April (HAI=4.6) and May (HAI=0.7). For November, February-April, and June, the 1970s shift changed the frequency of high discharge percentile in a different direction than the 2000s. The 2000s shift decreased the frequency of the low discharge percentile contrasting with the 1970s shift.

After the 1970s and the 2000s shifts, the HBEF catchments experienced increases in the frequency of high percentile number of zero days (HAI=1.1) and baseflow index (HAI=0.1), along with a later date of minimum flow (HAI=0.5) and an earlier date of maximum flow

(HAI=-0.2) (Figure 6-4a). Unlike baseflow index (HAI=-0.5), the frequencies of low percentile date of minimum discharge (the earliest of the early dates of minimum discharge, HAI=1.5), and date of maximum discharge (HAI=3.5) increased. Neither the 1970s nor the 2000s regime shifts altered the frequencies of low percentile number of zero days.

6-1-4-2- Small-scale Merrimack sub-basins

Within the Merrimack small-scale sub-basins (33-166 km^2), the frequencies of high (low) percentile monthly discharge values increased (decreased) after shifts in the 1970s and 2000s, except for April and May (February, April, and September) (Figure 6-4b). Changes to high percentile monthly discharge were greater after the 2000s shift than the 1970s shift except for January and May. The greatest increase and decrease in the frequency of high (low) percentile discharge occurred in January (April) and April (December), respectively (Figure 6-4b).

The cumulative effects of 1970s and 2000s shifts at the small-scale sub-basins of the Merrimack have led to increases in the frequencies of high percentile of baseflow index (HAI=1.4) and date of maximum discharge (HAI=1.2) (Figure 5b). In contrast, the frequency of high percentile date of minimum discharge decreased (HAI=-0.1), while no impacts were evident on number of zero days (Figure 6-4b). Apart from the baseflow index (HAI=0.4), the frequencies of low percentile date of minimum and date of maximum discharge have decreased (HAI=-0.6).

6-1-4-3- Intermediate-scale Merrimack sub-basins

For the intermediate-scale sub-basins (222-818 km^2), the frequencies of high percentile monthly discharge values increased after the shifts of 1950s, 1970s, and 2000s most notably in October (HAI=3.2) (Figure 6-4c). The alterations in the frequencies of low percentile monthly discharge decreased after the three shifts except for April, July, and September; the greatest decrease occurred in December and February (HAI=-1.4). There were no consistent patterns on the dominancy of each shift on monthly discharge alteration.

After the 1950s, 1970s, and 2000s shifts at the Merrimack intermediate-scale sub-basins, the magnitude of high percentile baseflow index (HAI=1.8) and date of maximum discharge (HAI=0.7) increased except for date of minimum discharge (HAI=-0.5) (Figure 6-4c). On the other hand, the frequencies of low percentile date of minimum discharge (HAI=-0.01) and date of maximum discharge (HAI=-0.4) decreased, while baseflow index increased (HAI=2.2). No consistent patterns were observed on the dominancy of each shift on the alteration of discharge duration or timing indices.

6-1-4-4- Large-scale Merrimack sub-basins

The Merrimack large-scale sub-basins (1220-11450 km^2) experienced increases in both low and high discharge percentiles after each shift, contrasting the decreases in the frequency of low percentile December through March discharges (Figure 6-4d). The greatest alteration in the frequency of high percentile discharge was evident in March (HAI=4.5). The frequency of low percentile discharge exhibited the greatest change in December (HAI=-2.0), April (HAI=1.3), and September (HAI=1.3). The 1951 (2004) shift notably affected June through October low (high) discharge percentile compared to 1972 and 2004 shifts (1951 and 1972 shifts).

These sub-basins also exhibited decreases in the highest percentiles for the baseflow index (HAI=-0.6) and earlier date of minimum discharge (HAI=-0.8). In contrast, the frequency of high percentile of date of maximum discharge increased (HAI=0.5) while no impacts were evident on number of zero days (Figure 6-4d). The frequencies of low percentile baseflow index (HAI=5.1) and date of minimum discharge (HAI=0.3) have increased except date of maximum discharge (HAI=-1.0). The number of zero days did not indicate any alteration in the frequency of high or low discharge percentiles.

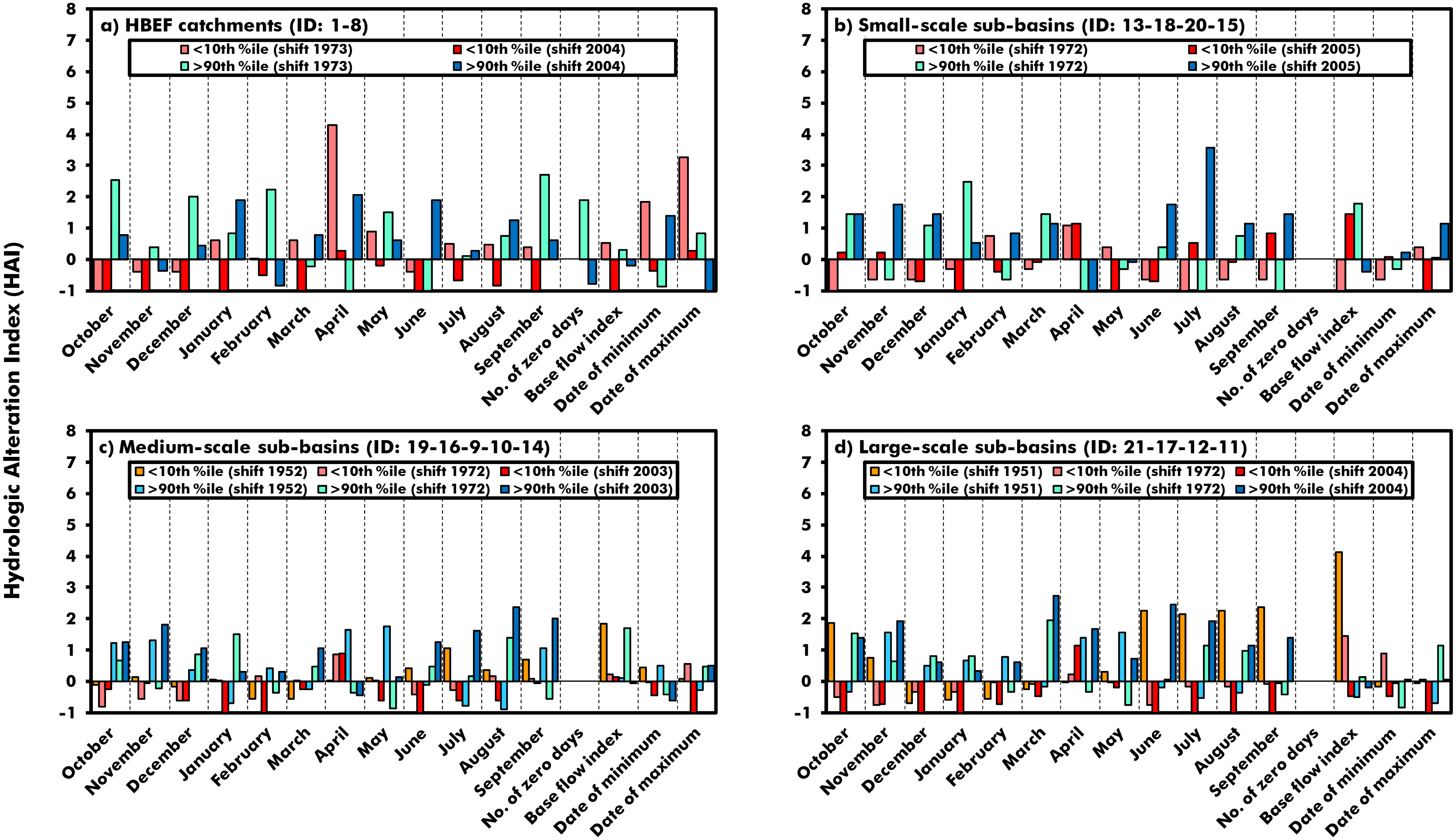

Figure 6-4- Hydrologic alteration index (HAI) for monthly discharge magnitude, annual discharge duration and timing for: a) the HBEF catchments with two shifts of 1973 and 2004 (ID: 1-8); b) the Merrimack small-scale sub-basins with two shifts of 1972 and 2005 (ID: 13-18-20-15, 33-166 km^2); c) the Merrimack intermediate-scale sub-basins with three shifts of 1952, 1972, and 2003 (ID: 19-16-9-10-14, 222-818 km^2); d) the Merrimack large-scale sub-basins with three shifts of 1951, 1972, and 2004 (ID: 21-17-12-11, 1220-11450 km^2). The HAI index compares the frequency of the 10th (low) and 90th (high) percentiles of discharge indicators before and after the regime shifts. The key to the site ID is presented in Table 3-1.

6-2- Discussion

6-2-1- *Major difference between regime shift and phase change*

I found that the mean state (regime) of AMO and NAO indices have changed periodically with the median lengths of 13 and 20 years, respectively (Figure 6-1a-b). AMO has cool (negative) and warm (positive) phases that may persist for 20-40 years, while NAO is dominated by phase changes of up to every 10 years (Kaplan et al., 1998, 1997; Kavvada et al., 2013; Vianna and Menezes, 2013). The comparison of regime shift and phase change durations revealed that AMO had higher frequency regimes than its phase duration, while the NAO phase change occurred twice as frequently as its regime change. Note the median regime shift length should not be mistaken with AMO or NAO classic phase duration. The shift in the long-term average values (mean state) of AMO or NAO index may occur even within the same phase. For example, there has been no phase change in AMO since 1995 (positive phase), however, a regime shift was evident in 2002 moving to the stronger positive regime (Figure 6-1a).

6-2-2- *Sensitivity analysis of regime shift detection method*

The regime shift detection method required an initial estimate for regime duration (L, cut-off length) at a specified confidence level (α). I found that increasing the cut-off length improved the ability to detect regimes with even slight changes in the mean state of a variable. I also found that by changing the confidence level from 0.05 to 0.1, short duration regimes were indicated (Rodionov, 2004). Consequently, with L=5, 10-40 years with decadal increments and α=0.1, more regimes were identified (Figure 6-1 and Figure 6-2). When the time series was prewhitened and serial correlation was removed, the identified shifts indicated that the variations observed in the time series were more than a reflection of red noise and may be provoked by external forcing (Hsieh et al., 2005; Rodionov, 2006; Rudnick and Davis, 2003).

6-2-3- *AMO and NAO regime shifts*

The method performed well in detecting the well-studied 1970s AMO and NAO regime shifts in the northeastern US (Armstrong et al., 2012; Collins, 2009; Douglas and Fairbank, 2011; Hodgkins, 2010; Huntington et al., 2009; Mauget, 2003; McCabe and Wolock, 2002; Rice and Hirsch, 2012; Villarini and Smith, 2010). When the serial correlation among data along with cut-off length greater than 10 years were considered, I identified additional hydrologic changes in the Merrimack River watershed in the early 1950s and 2000s (Figure 6-2).

The 1950s shift was only identified for intermediate- and large-scale sub-basins in the Merrimack which have longer periods of record. The 1950s shift corresponded to greater winter snowfall regime in New England stimulated by changes in the state of NAO (Hartley and Keables, 1998). The 1996 shifts in NAO increased the Atlantic tropical storm activities that eventually triggered warmer SST in the 5-10 years that followed (the early 2000s shift in AMO) (Delworth et al., 2016). The three shifts of 1950s, 1970s, and 2000s in AMO and/or NAO left consistent traces on precipitation and discharge regimes in the Merrimack River watershed (Figure 6-2).

6-2-4- *PDO and ENSO regime shifts*

Several studies have documented teleconnection patterns between large-scale climate circulations and hydrologic response in the northeastern US (e.g. Armstrong et al., 2012, 2013, Bradbury et al., 2002a, 2002b, 2003). Over New England, Ning and Bradley (2014) found that variations in annual precipitation could be mostly explained by AMO and NAO rather than PDO or ENSO. The correlation coefficients (ρ) between the time series of the second dominant EOF and the large-scale climate circulation patterns indicated stronger associations of AMO (ρ=0.24) and NAO (ρ=0.20) with precipitation variations compared to PDO (ρ=0.07) or ENSO (ρ=0.06) (Ning and Bradley, 2014).

The strengths of PDO and ENSO teleconnection patterns with the Northeast hydroclimate remain uncertain (Bradbury et al., 2003; Kuss and Gurdak, 2014; Nalley et al., 2016; Ning and Bradley, 2014; Ropelewski and Halpert, 1986; Schubert et al., 2016; Steinschneider and Lall, 2016; Tootle et al., 2005). In order to examine whether the Pacific large-scale climate circulation patterns had an influence on Merrimack hydroclimate, I also analyzed PDO and ENSO regime shifts (Figure 6-1c-d). PDO (1897-1910-1926-1943-1949-1957-1977-1999-2008) and ENSO (1887-1896-1977-1990-2011) shift points did not coincide with the Merrimack precipitation or discharge regime shifts.

6-2-5- *Precipitation and discharge regime shifts*

At HBEF catchments, there were two consistent shifts of 1973 and 2004 (catchments 2, 6, 7, and 8 also indicated a shift in 1973 for α = 0.2). The shift points for the entire Merrimack sub-basins were less consistent than HBEF catchments. The 1950s, 1970s, and 2000s shifts in precipitation and discharge were associated with AMO variations, while NAO was only linked to the 1970s shift. Thus, I concluded that the patterns of AMO variations have closer correspondences to the hydrologic responses of the Merrimack than patterns of NAO (Figure 6-2).

As indicated by my findings, AMO (1964-1979-1995) or NAO (1989-1996) shifts may not have affected precipitation and discharge regimes over the entire Merrimack River watershed. Only one shift in precipitation was detected (1996; synchronized with NAO regime shift) in only 40% of the study sites (8 out of 21). As precipitation and discharge are highly correlated in the Merrimack River watershed (Berton et al., 2016), I anticipated it would not be possible to detect shifts for discharge, which my results confirmed (Figure 6-2).

The 1960s discharge shift detected in the intermediate-scale sub-basins of Merrimack was likely induced by river regulation (Table 3-1). While land use/cover change and urban development could also affect the hydrologic response (Sarmiento, 2010) and confuse discharge-teleconnection patterns (Sheldon and Burd, 2014), I found the regime point detection algorithm was able to identify this shift despite the effects of upstream retention by a reservoir (moderate stormflow and maintain higher low discharge events; study site ID: 9) and drinking/municipal water withdrawals (decrease discharge volume; study sites ID: 10, 14, and 16).

6-2-6- *Lagged hydrologic response to AMO and NAO variations*

Due to large heat capacity, ocean thermal memory is much longer than the climate system (Karnauskas et al., 2009). Therefore, there may often be a lag time between oceanic indices regime shifts and changes in precipitation or discharge regimes (Kalra and Ahmad, 2009; Nalley et al., 2016; Roller et al., 2016). However, the physical processes during a lag between climate processes and hydrologic responses remain unclear and poorly characterized (Dickinson et al., 2014). The most probable physical explanation for lags could be the effects of climate circulation patterns on antecedent conditions such as soil moisture, storage, and groundwater that affect the mechanisms of runoff generation (Maurer et al., 2004; Sheldon and Burd, 2014). Given that

Merrimack is a groundwater importer watershed [the ratio of annual river flow/(P-ET) is 1.5-1.6 >1] (Schaller and Fan, 2009), the physical interpretation for lags is easier to justify for downstream regulated/developed sub-basins with more mild slope and storage than headwater undisturbed catchments with steep slopes and limited storage (Roller et al., 2016).

Lag times of 1-2 years in downstream sub-basins may be explained by changes to groundwater storage (Figure 6-2). For example, the lag time between precipitation and ground water levels ranged from 3 to 16 years on the North Atlantic Coastal Plain (Kuss and Gurdak, 2014). The Merrimack bedrock is mainly composed of limestone (0.032-189 m/yr), sandstone (0.0095-189 m/yr), shale (3×10^{-6}-0.063 m/yr), and granite (3×10^{-6}-0.0032 m/yr) with low hydraulic conductivity (Heath, 1983). When upstream study sites experience either dry or wet hydrologic conditions, similar conditions were observed in downstream regulated or developed sub-basins after a 1-2 year delay (Berton et al., 2016). Therefore, the slow groundwater discharge could explain the 1-2 years lagged hydrologic response of the downstream developed sub-basins of the Merrimack to AMO and NAO variations compared to upstream undisturbed catchments (Figure 6-2). Quantifying a lag time could provide an opportunity for discharge prediction with respect to oceanic indices' regime shifts to help inform watershed management (Coleman and Budikova, 2013; Steinschneider and Brown, 2011).

6-2-7- *Flow duration curves (FDCs)*

The FDCs of different climate regimes were noticeably distinctive for HBEF headwater catchments compared to the Merrimack sub-basins (Figure 6-3a-d). The recent (2005-2012) increases in high discharge percentiles were greater for HBEF undisturbed catchments (Figure 4a) than Merrimack regulated and/or developed sub-basins (Figure 6-3b-d). This pattern may be due to increases in the intensity of precipitation rather than magnitude (Hoerling et al., 2016; Karl and Knight, 1998; Wuebbles et al., 2014), which would generate large high discharge events (Luce et al., 2016). The higher discharge events in upstream undisturbed catchments were modulated by river regulation and storage at downstream developed sub-basins; therefore, FDCs in these sub-basins are similar through time.

I note that the behavior of discharge at the Merrimack River watershed is highly dependent on basin scale (Figure 6-3e-h). Small-scale sub-basins indicated dissimilarities only for high discharge events (Figure 6-3f), while both high and low discharge events differed in the intermediate- and large-scale sub-basins (Figure 6-3g-h). The pattern is in contrast with the tendency for decreases in the variations of high and low discharge events with increases in basin scale (Wood et al., 1988). In large basins (>1000 km^2) with more ground and surface water storage, the probability of extreme discharge events due to extreme precipitation decreases compared to small catchments (Ivancic and Shaw, 2015). Unlike river regulation, land development results in changes in extreme discharge events due to increases to impervious surfaces (de la Crétaz and Barten, 2007). This dissimilarity in responses under high and low discharge conditions may provide a plausible explanation for the inconsistent response to extreme events in regulated and/or developed sub-basins (Berton et al., 2016; Brandes et al., 2005; DeWalle et al., 2000; Eng et al., 2013; Homa et al., 2013; Konrad and Booth, 2002; Lerner, 2002; Poff et al., 2006; Rose and Peters, 2001).

6-2-8- *Teleconnectivity of AMO and NAO with discharge*

Physical linkages can be made between large-scale Atlantic circulations and high percentile discharge variations in the northeastern US (Bradbury et al., 2002c; Collins, 2009; Kingston et al., 2007; Tootle et al., 2005). In the early 1970s, increases in high flow percentiles were associated with a shift to stronger negative AMO (cold SST in North Atlantic) (Mauget and Cordero, 2014). As sea surface temperature decreased, near-surface air temperature cooled and therefore sea-level pressure increased (Mazouz et al., 2013). Cold SST anomalies were linked to less inland precipitation and greater coastal winter snow storms (due to colder surface air) in the northeastern US (Bradbury et al., 2003). During this period, the positive NAO and negative AMO phases invigorated the Icelandic Low that moved cold Arctic air to the west region of Iceland and Greenland and favored low temperature in winter and early spring in New England (Hurrell, 1996, 1995). In the Merrimack River watershed, low temperatures led to late snow melt and therefore longer duration high discharge events and maintained higher baseflow conditions (Mazouz et al., 2013).

After the 2000s regime shift (Figure 6-2), positive AMO and NAO regimes corresponded to more frequent high discharge conditions in New England (Kingston et al., 2007). An increase in winter rainfall due to the prevailing positive NAO regime (post-1970s) likely exacerbated high discharge events in the Merrimack River watershed (Armstrong et al., 2013; Collins, 2009; Hannaford and Marsh, 2008; Hurrell et al., 2003). High discharge events within the Merrimack were mainly generated by coastal lows (nor'easters storms) through rain-on-snowmelt events (Collins et al., 2014; Villarini, 2016). Although NAO and discharge are positively correlated in New England (Armstrong et al., 2012; Bradbury et al., 2002a; Kingston et al., 2007; Mazouz et al., 2013; Steinschneider and Brown, 2011), other factors such as atmospheric circulation, snow hydrology, and basin storage likely affect the relationship of discharge with teleconnection patterns (Coleman and Budikova, 2013; Kingston et al., 2007) leading to a diverse set of discharge responses.

6-2-9- *Frequency of high percentile discharge*

In the Merrimack River watershed, the high percentile of discharge exhibited seasonal variation (Figure 6-4). At the HBEF catchments and Merrimack sub-basins, I found increases in the frequency of high percentile discharge for summer (Jun-Aug), fall (Sep-Nov), and winter (Dec-Feb) were greater than spring (Mar-May) regardless of drainage area, river regulation, and/or development after the regime shifts (Figure 6-4). Although precipitation is fairly evenly distributed throughout the water year in New England (Huntington et al., 2009; Karl and Knight, 1998; Magilligan and Graber, 1996), there was stronger association between extreme precipitation and discharge events in rain-on-snowmelt season (Mar-May) than other seasons (Frei et al., 2015). Consequently, changes in hydrologic responses could be attributed to an increase in the ratio of winter rain to snow, earlier loss of winter snow pack, and increases in potential evapotranspiration for the non-snowpack season in agreement with previous climate change studies performed on the Northeast (Berton et al., 2016; Campbell et al., 2011; Frei et al., 2015; Hodgkins and Dudley, 2005; Huntington et al., 2004).

The changes in summer and fall precipitation were more noticeable across New England. However, perhaps in part due to higher potential evapotranspiration and less soil moisture availability during the growing season, the increases in cold months precipitation have had more influence on discharge variation (Hoerling et al., 2016). As the intensity of summer precipitation increased, the antecedent soil moisture condition and snowpack have become relatively less important contributing factors to runoff generation (Fang and Pomeroy, 2016; Frei et al., 2015). Increases in the magnitude of fall and winter precipitation across conterminous United States (Ivancic and Shaw, 2015; Luce et al., 2016), while accompanied by lower evapotranspiration rate, could generate more extreme discharge events. Earlier peak discharge (Hodgkins et al., 2003; Hodgkins and Dudley, 2006), along with frozen soil in winter (acts as an impervious surface), compel a shift in high percentile discharge events from late spring towards early spring and late winter in the Merrimack River watershed (Figure 6-4).

6-2-10- *Low discharge percentile*

The frequency of low percentile monthly discharges decreased in summer, fall, and winter in the Merrimack River watershed (Figure 6-4). Karl and Knight (1998) reported increases in the low discharge quantiles over the Northeast due to increases in the upper 10th percentile of daily precipitation, which is consistent with our results for low discharge conditions at HBEF catchments and Merrimack sub-basins (Figure 6-4). More frequent spring low discharge conditions in spite of increases in spring rainfall (Karl and Knight, 1998; Lins and Slack, 2005) may be due to positive trends in groundwater withdrawal (Konikow, 2015; Sadri et al., 2016), increases in evapotranspiration as atmospheric demand increases in the Northeast (Huntington and Billmire, 2014; Poshtiri and Pal, 2016; Sadri et al., 2016), or earlier loss of snowpack linked to higher winter temperature (Hodgkins and Dudley, 2006). However, the effects of river regulation and land development on low discharge events are spatially variable (Kam and Sheffield, 2016). For instance, Sadri et al. (2016) found positive trend for low discharge conditions in upstream of the Merrimack (0.2 m^3/sec.yr, 1951-2005) and negative trends for downstream regions (-0.2 m^3/sec.yr, 1951-2005).

6-2-11- *Baseflow*

In the Merrimack River watershed, the baseflow index, representing the contribution of sub-surface flow to stream networks, increased at upstream reference catchments (Figure 6-4a) unlike downstream regulated and/or developed sub-basins (Figure 6-4b-d). Small headwater catchments are more affected by decreases in baseflow than downstream regions because of limited groundwater supply to first order streams compared with larger rivers (Ficklin et al., 2016; Knouft and Chu, 2015). On the other hand, enhanced baseflow increases water yield and discharge variability of downstream basins (Ficklin et al., 2016). Consequently, variation in baseflow places headwater streams at greater risks for alterations in ecosystem structure and function than downstream sub-basins.

6-2-12- *Dates of minimum and maximum discharge events*

The frequency of high percentile date of minimum discharge increased with increases in drainage area, implying a shift in lowest discharge events towards the end of the summer (Figure 6-4). This pattern is likely as a result of increases in summer precipitation over the Northeast (Campbell et al., 2011; Frumhoff et al., 2007; Hayhoe et al., 2007; Huntington and Billmire, 2014). The frequency of high percentile date of maximum discharge has decreased (moved earlier) with increases in sub-basins size (Figure 6-4). This result is in agreement with earlier timing of spring peak discharge due to earlier snowmelt (Frumhoff et al., 2007).

6-2-13- *Effects of river regulation and land development*

The variations in the percentage of development and type of regulation within small-, intermediate-, and large-scale sub-basins may raise concern regarding the scale-dependency of my results (Figure 6-4b-d). In order to address this limitation, I selected three representative sites with distinct percentages of land development; the Smith sub-basin (ID: 19, 4% developed, forest; small sub-basin, upstream), the Squannacook basin (ID: 20, 10% developed, suburban;

small sub-basin, middle reach) and the Shawsheen basin (ID: 18, 73% developed, urban; intermediate sub-basin, downstream). The individual responses of these sub-basins to external forcing were well-matched with the mean response. For the Smith sub-basin, there were several inconsistencies with the mean response mainly for discharge timing and duration indicators.

Based on the responses of these basins given the variability in the level of regulation or human impact, I propose the following interpretation for watershed management. For the Smith sub-basin (forest), positive trends in annual precipitation across the Merrimack (Berton et al., 2016) suggest that management practices should focus on measures to prevent flooding in summer, fall, and winter. Early snowmelt and peak discharge in spring also raises concerns regarding drought conditions at late spring and summer. In the Squannacook sub-basin (suburban), current operating rules regulating upstream water resources may not be adapted to year-round high discharge events along with longer duration of low discharge conditions in fall. In the Shawsheen sub-basin (urban), I found extremes in high and low discharge events were increasing (e.g., higher discharge becoming higher, lower discharge becoming lower). Given these highly variable discharge magnitudes, management practices should focus on measures to mitigate against flooding and drought. A shift toward more extreme discharge events specifically after the 2000s regime shifts requires adaptive management policies for the Merrimack River watershed in an era of changing climate.

6-3- Summary and concluding remarks

I utilized precipitation and discharge data of the Merrimack River watershed to provide information on the potential influence of AMO and NAO regime shifts on precipitation and discharge time series as well as ecological discharge indicators. Using the regime shift detection method, I identified several regime shifts, including a recent hydrologic regime shift in the Merrimack River watershed in the early 2000s. Finally, I used the HAI concept (Richter et al., 1997, 1996) to assess the differences in the high and low discharge percentiles of several ecological discharge indicators prior-to and post AMO or NAO shifts of the early 1950s, 1970s, and 2000s.

In the Merrimack River watershed (for the period of record), I found that precipitation and discharge indicated three consistent shifts in the early 1950s, 1970s, and 2000s which were teleconnected to AMO or NAO regime shifts with 1-2 year lag time (Figure 6-2). AMO regime shifts were strongly synchronized and preceded both precipitation and discharge across all study sites by 1 to 2 years, while NAO regime shifts indicated weaker associations. The synchrony of these shift points suggest that teleconnection patterns exist between the oceanic indices and changes to hydrologic regimes across the Merrimack River watershed.

The comparison of FDCs among different meteorological regimes revealed that the differences in high and low discharge conditions were scale dependent (Figure 6-3). As the area of the sub-basins increased, the differences in discharge response increased for extreme discharge events. I found that all responses tended towards greater extremes from each regime shift to the next. Across many different indicators, high percentile values increased across regimes, while low percentile values decreased across regimes (with a few exceptions). Many of the greatest differences in discharge responses were evident at small-scale unregulated catchments, suggesting that regime shifts of large-scale climate circulation patterns may affect water availability for ecosystems.

While I noted that climate change and anthropogenic disturbances such as river regulation or land development may have counteracting effects on discharge variations (DeWalle et al., 2000), I found moderated hydrologic responses between regimes for FDCs and ecological indicators as the drainage area increased. As I saw in this study, the spatial complexity of hydrologic responses to changing climate necessitates a reevaluation of large-scale water management decisions at both large and local scales. Increases in extreme discharge conditions may require adaptive redesign for current infrastructure and preventive water management in smaller sub-basins responding to changing climate regimes (Demaria et al., 2016).

Analysis from this phase of the dissertation revealed that AMO regime shifts were strongly synchronized and occurred one to two years before both precipitation and discharge across all study sites, while NAO regime shifts exhibited weaker associations. All hydrologic responses tended towards greater extremes from each regime shift to the next. Many of the largest differences in discharge responses were evident at small-scale unregulated catchments, while the responses became more complex and muted with the drainage area increases and watershed development.

The results from this chapter have been prepared for publication as: Berton, R., Driscoll, C.T., Chandler, D.G., Kelleher, C., 2017. The responses of ecological discharge indicators to regime shifts of Atlantic Multi-decadal Oscillation and North Atlantic Oscillation in the northeastern United States. Submitted to the Hydrological Sciences Journal, Revised and Ready to Resubmit.

7- The near-term prediction of drought and flooding conditions in the Northeastern United States based on extreme phases of Atlantic Multi-decadal Oscillation and North Atlantic Oscillation

The objective of this chapter is to identify hydroclimatic teleconnection patterns between variations in Atlantic circulation patterns with seasonal precipitation and discharge anomalies in the northeastern United States. This research provides the opportunity to study the teleconnection between hydrologic variables and large-scale climate circulation patterns in addition to how those patterns may become obscured by human disturbances such as river regulation or urban development. In this study, I compare differences in discharge conditions during extreme positive and negative phases of AMO and NAO. I examine annual and seasonal correlations between precipitation and discharge and the extreme phases of AMO and NAO at zero-, one-, or two- year/season lags. I introduce a simple, but novel approach to estimate a confidence band for near-term prediction of extreme dry and wet discharge conditions with regards to the extreme phases of AMO and NAO. This approach builds upon earlier studies that focused on seasonal discharge prediction in undisturbed reference catchments with respect to NAO variations in the northeastern US. This investigation will help inform Merrimack water managers to develop adaptation strategies for aging hydraulic infrastructure in the region to accommodate excess water input and minimize flood damage.

The results of this chapter are presented in three separate sections. First, I assess whether the differences in normalized discharge were statistically significant between the extreme phases of AMO or NAO. Second, I present the annual and the seasonal correlation coefficients of precipitation and discharge with the extreme phases of AMO and NAO. Third, I determine the relative frequency of occurrence for extreme discharge conditions i.e. dry and wet events in regards to the extreme phases of AMO and NAO. The relative frequencies were employed to estimate the probability of occurrence for dry or wet discharge conditions 1-2 years/seasons ahead. All analyses were performed with zero-, one-, or two- year (season) lags given to AMO and NAO.

7-1- Results

7-1-1- *Normalized annual/seasonal discharge in extreme phases of AMO and NAO*

I investigated the AMO and NAO teleconnection patterns with discharge in annual and seasonal temporal scales (2×5 scenarios) including 0-2 years/seasons lag time given to AMO and NAO (3 scenarios, total of 30). I looked for signals that could be observed in headwater catchments (the research scientists' concern) and then transitioned towards downstream sub-basins (the water resources managers' concern). In order to be considered as predictive, the discharge lagged response had to be evident among HBEF and large sub-basins or HBEF and the entire Merrimack River watershed. AMO and NAO are large-scale circulation patterns; therefore, their footprints on the hydrology of the Merrimack should be observable in both the HBEF catchments and the Merrimack sub-basins.

The results of t-tests to determine if the mean normalized annual and seasonal discharges were different between extreme positive and negative phases of AMO and NAO, are described in Table 7-1. I examined three levels of significance (0.05, 0.1, 0.2). At p-value$\leq$0.2, the common scenarios among either HBEF and large sub-basins or HBEF and the entire Merrimack River watershed were revealed. A group of study sites (HBEF and small, intermediate, and large-scale sub-basins) was considered to have a significant pattern when at least two study sites within the group showed statistically significant results.

The relationship of discharge response to AMO and NAO with a time lag may provide opportunities to predict discharge conditions in advance and inform management actions. These relationships are identified by an asterisk (*) in Table 7-1 and will be introduced as predictive scenarios hereafter. There were three scenarios corresponding to AMO with time lags in which discharge conditions may be predictable throughout the year and throughout the Merrimack River watershed (current year, fall, and winter discharge conditions predicted by previous year, summer, and spring AMO, respectively). Only summer discharge could be predicted by previous winter NAO (2 seasons lag time).

Table 7-1- The statistically significant (p-value≤0.2) scenarios where the mean standardized annual/seasonal discharges were different between the extreme phases of AMO and NAO.

	Discharge				
AMO	**Annual**	**Spring**	**Summer**	**Fall**	**Winter**
no lag	HBEF, Large	HBEF, Small, Intermediate	HBEF	HBEF, Large	----
1 year/season lag	**HBEF, Large***	HBEF	----	**HBEF, Small, Intermediate, Large***	HBEF
2 years/seasons lag	----	----	Intermediate, Large	HBEF	**HBEF, Large***
NAO					
no lag	----	----	HBEF	----	HBEF, Small, Intermediate, Large
1 year/season lag	----	----	Intermediate, Large	----	Small, Intermediate
2 years/seasons lag	----	Small	**HBEF, Large***	Small	----

*Since climate circulation patterns act at large spatial scales, the differences in discharge should be significant throughout the entire basins' scales. Therefore, bold scenarios marked by asterisks could be tested for the potential discharge prediction opportunities.

7-1-2- *The annual/seasonal correlations of precipitation and discharge with AMO and NAO*

The percentages of statistically significant correlations (p-value≤0.2) for predictive scenarios are presented in Table 7-2. The magnitude of correlation coefficients for AMO and NAO with precipitation and discharge are shown in Figure 7-1 (only predictive scenarios). The 95% confidence intervals for correlations in Figure 7-1 were computed based on the number of sites within four categories of the HBEF headwater catchments (ID: 1-8, drainage area of 0.1-0.8 km^2) and small (ID: 13, 15, 18, and 20, drainage area of 33-166 km^2), intermediate (9, 10, 14, 16, and 19, drainage area of 222-818 km^2), and large (11, 12, 17, and 21, drainage area of 1220-11450 km^2) Merrimack sub-basins (Berton et al., 2016). Unlike Spearman's rho and Kendall tau, Pearson's correlation statistics suggested consistent spatial patterns throughout the Merrimack River watershed; therefore it was chosen to illustrate the results of the analyses. If the mean standardized discharge was statistically different in the extreme phases of AMO or NAO, compared with the strength of Pearson's correlation coefficients, may indicate the potential of discharge prediction relating to AMO and NAO variations.

When AMO was equal to or greater than 0.2, the magnitudes of annual correlation coefficients were obscured by river regulation or land development. AMO was positively associated with precipitation and discharge for HBEF catchments (annual-1 year lag, $r_{precipitation}$=+0.8, $r_{discharge}$=+0.6), while the strength of the relationship declined to $r_{precip, dis}$=+0.5 for large sub-basins of the Merrimack (Figure 7-1a). NAO was negatively correlated with annual precipitation and discharge (annual-1 year lag, r_{precip}=-0.5, r_{dis}=-0.4) at HBEF, whereas weak correlations were evident for large regulated or developed sub-basins (Figure 7-1a). Seasonal correlations (i.e. fall-1 season lag and winter-2 seasons lag) did not vary greatly among different basin-scales with river regulation or land development.

When AMO was extremely positive, the summer NAO (summer-1 lag) was more informative than the annual NAO (Figure 7-2a to Figure 7-5a). The strongest correlation of AMO and NAO with precipitation and discharge was observed at HBEF catchments (Figure 7-2a). AMO and precipitation showed a strong positive correlation (annual-1 year lag, r_{precip}=+0.8, Figure 7-1a), while NAO showed a strong negative correlation with precipitation and discharge (fall-2 seasons lag, $r_{precip, dis}$=-0.8, Figure 7-2a).

Unlike extreme positive AMO, when AMO was extremely negative (≤-0.2), river regulation and land development amplified the impacts of changing climate on precipitation and discharge variations in annual 1 year-lag and fall 1 season lag scenarios (Figure 7-1b). AMO and NAO were negatively correlated with precipitation and discharge at both the annual and seasonal time-scales. There was no apparent basin-scale effect on the strength of correlations during the negative phase of AMO. The NAO signals became stronger in the negative phase of AMO compared to its positive phase (Figure 7-1b). The strongest correlations of AMO with precipitation and discharge were observed in the HBEF catchments (Figure 7-2b), and intermediate (Figure 7-4b) and large (Figure 7-5b) Merrimack sub-basins (r_{precip}=-0.5 and r_{dis}=-0.4). For NAO, the strongest correlation with precipitation and discharge occurred in the large sub-basins of the Merrimack (annual 1 year-lag, r=-0.3, Figure 7-1b). Winter NAO was strongly associated with spring precipitation and discharge at HBEF catchments (spring-1 season lag, r_{precip}=+0.5 and r_{dis}=+0.4, Figure 7-2b).

During extreme positive or negative phases of NAO, there were no consistent patterns associated with precipitation and discharge variations even though the magnitude or direction of the correlation coefficients were different for HBEF catchments compared to the Merrimack large sub-basins (Figure 7-1c). Alternatively, the NAO interactions with AMO highlighted some associations. During the positive phase of NAO, winter AMO was negatively correlated with summer precipitation and discharge in HBEF catchments (summer-2 seasons lag, r_{precip}=-0.2 and r_{dis}=-0.3, Figure 7-1c). When NAO was extremely negative, winter AMO was positively correlated with summer precipitation and discharge in HBEF catchments (summer-2 seasons lag, r_{precip}=+0.5 and r_{dis}=+0.2, Figure 7-1c).

The effects of basin-scale on either strength or direction of correlations were clearly identifiable between HBEF and large-scale sub-basins (Figure 7-1c). The strongest correlations occurred in the small-scale sub-basins when NAO was extremely positive; fall AMO was strongly correlated with spring precipitation and discharge (spring-2 seasons lag, r_{precip}=-0.8 and r_{dis}=-0.9, Figure 7-3c). Positive fall NAO showed a strong linkage with winter precipitation (winter-1 season lag, r_{precip}=+0.5, Figure 7-3c), while negative fall NAO was strongly correlated with spring discharge (spring-2 seasons lag, r_{dis}=-0.6, Figure 7-3d).

Table 7-2- The percentage of significant correlation coefficients within the groups of HBEF catchments and Merrimack small, intermediate, and large sub-basins (p-value≤0.2).

	Annual- 1 year lag		**Fall- 1 season lag**				**Winter-2 seasons lag**	
AMO≥0.2	**HBEF**	**Large**	**HBEF**	**Small**	**Intermediate**	**Large**	**HBEF**	**Large**
AMO:Precipitation	100	100	0	0	0	25	25	0
AMO:Discharge	75	100	0	0	0	0	25	25
NAO:Precipitation	50	0	0	0	0	0	0	25
NAO:Discharge	25	0	0	0	0	0	0	0
AMO≤-0.2								
AMO:Precipitation	50	75	0	0	20	25	0	0
AMO:Discharge	37.5	0	0	0	0	0	0	0
NAO:Precipitation	0	25	0	25	20	0	0	0
NAO:Discharge	0	50	0	0	0	0	12.5	0

	Summer- 2 seasons lag	
NAO≥0.5	**HBEF**	**Large**
AMO:Precipitation	0	0
AMO:Discharge	25	0
NAO:Precipitation	0	25
NAO:Discharge	0	0
NAO≤-0.5		
AMO:Precipitation	100	0
AMO:Discharge	37.5	0
NAO:Precipitation	25	50
NAO:Discharge	0	0

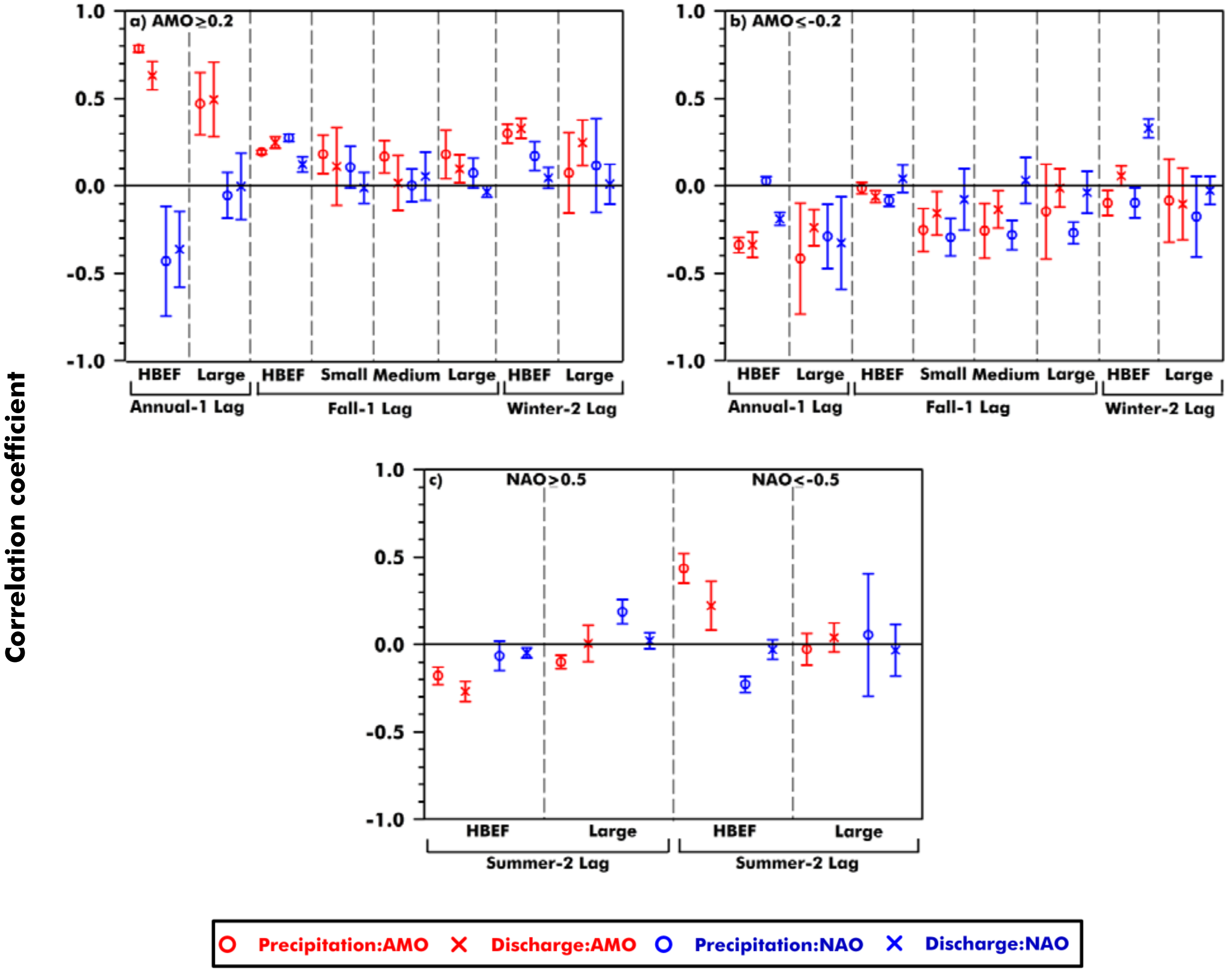

Figure 7-1- The mean correlation coefficients of precipitation and discharge with AMO, NAO at zero-, one-, or two- year/season lags: a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5. Error bars represent the lower and upper limits of 95% confidence intervals.

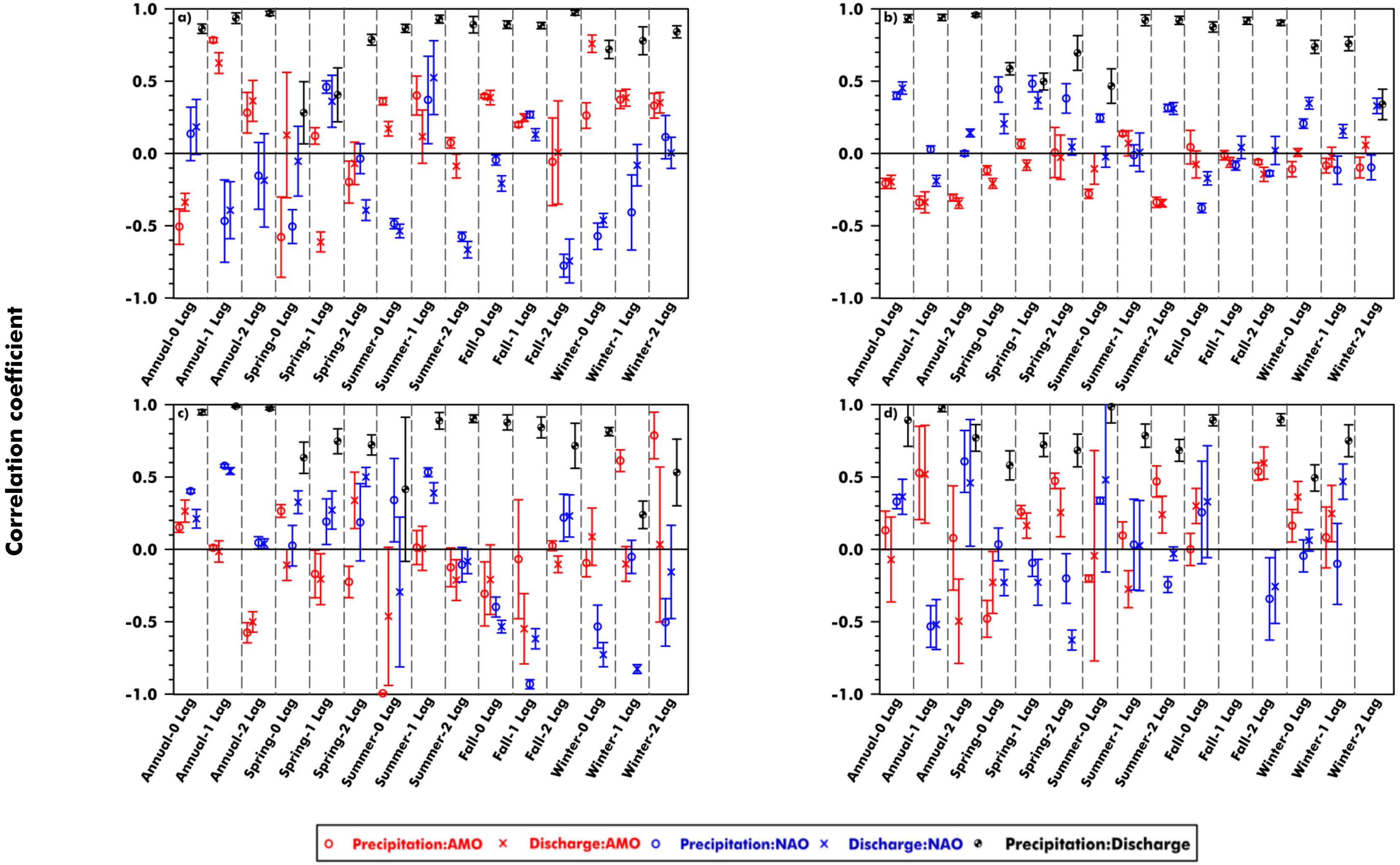

Figure 7-2- The mean correlation coefficients of precipitation and discharge with AMO, NAO at zero-, one-, or two- year/season lags for the HBEF catchments: a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5. Error bars represent the lower and upper limits of 95% confidence intervals.

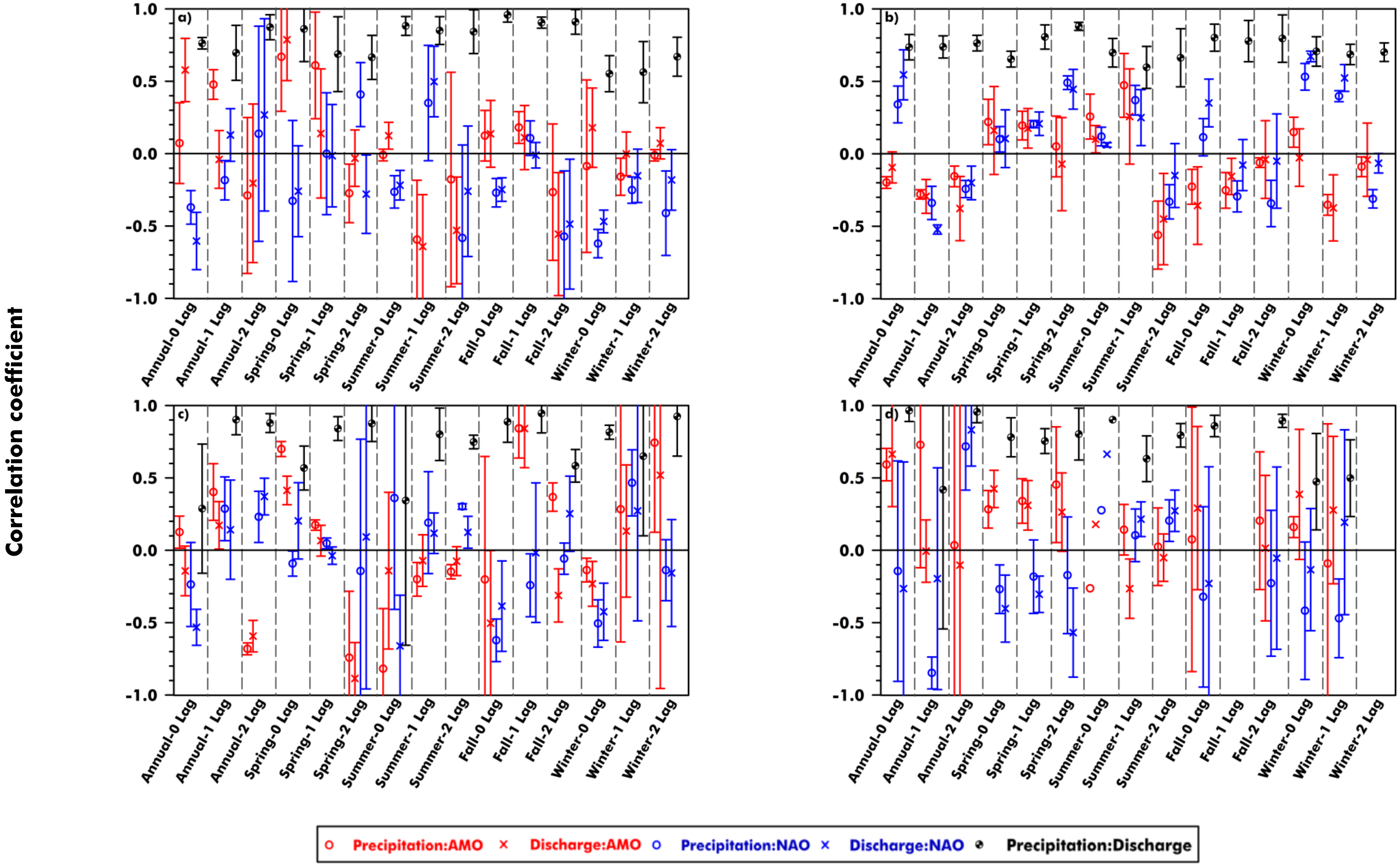

Figure 7-3- The mean correlation coefficients of precipitation and discharge with AMO, NAO at zero-, one-, or two- year/season lags for the Merrimack small-scale sub-basins (ID: 13-18-20-15, 33-166 km^2): a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5. Error bars represent the lower and upper limits of 95% confidence intervals.

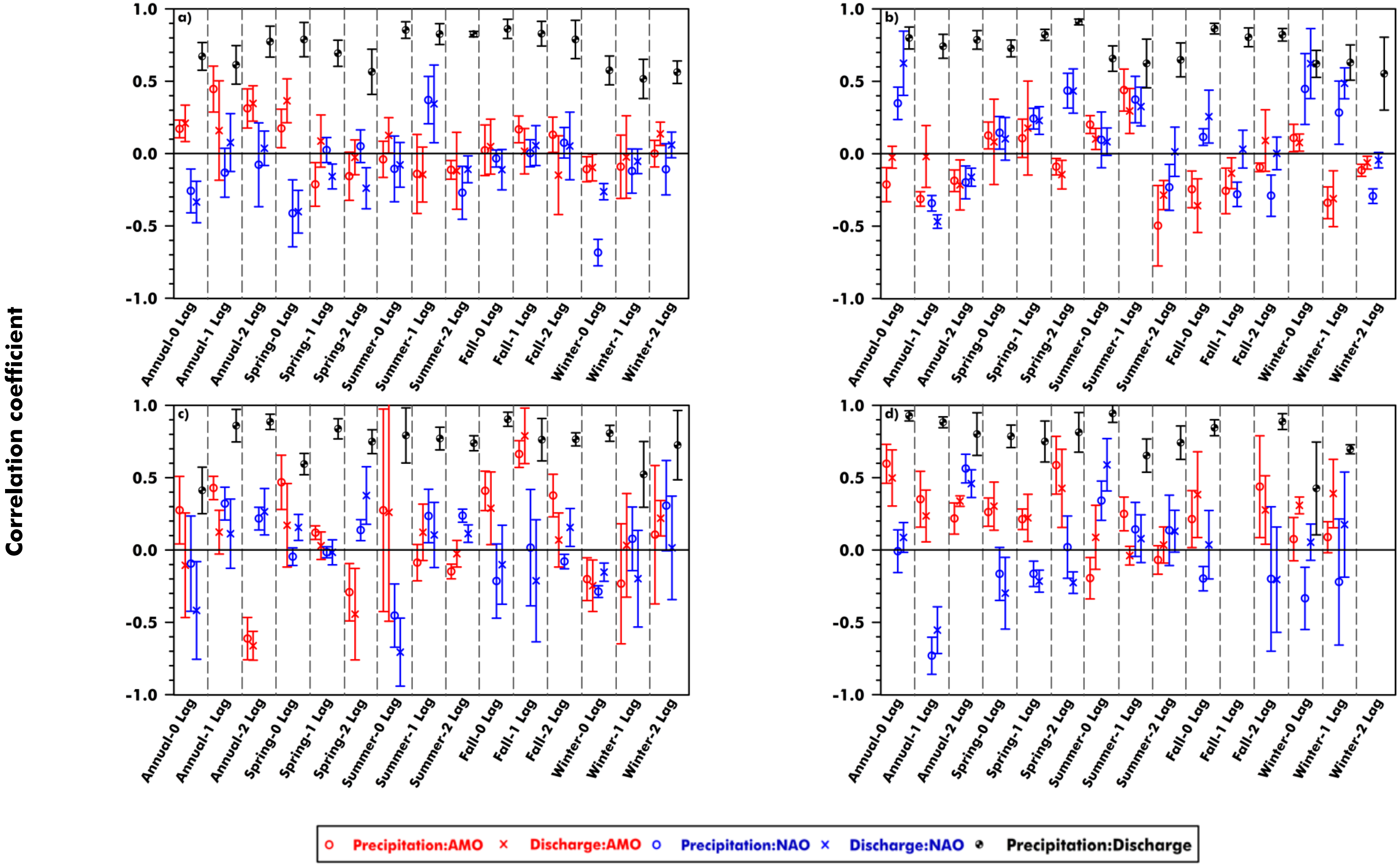

Figure 7-4- The mean correlation coefficients of precipitation and discharge with AMO, NAO at zero-, one-, or two- year/season lags for the Merrimack intermediate-scale sub-basins (ID: 9-10-14-16-19, 222-818 km^2): a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5. Error bars represent the lower and upper limits of 95% confidence intervals.

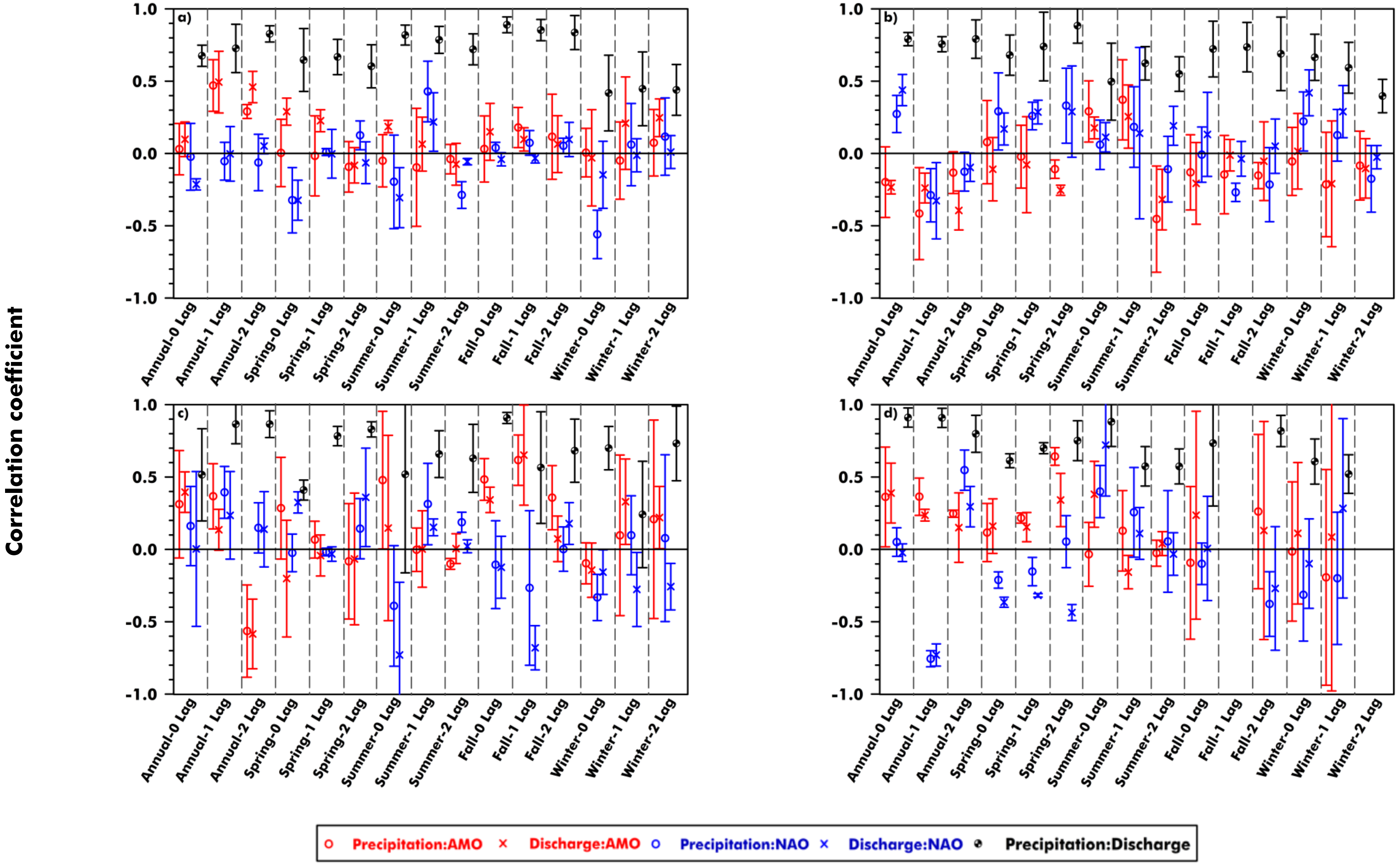

Figure 7-5- The mean correlation coefficients of precipitation and discharge with AMO, NAO at zero-, one-, or two- year/season lags for the Merrimack large-scale sub-basins (ID: 11-12-17-21, 1220-11450 km^2): a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5. Error bars represent the lower and upper limits of 95% confidence intervals.

7-1-3- *Relative frequency of occurrence and probability*

The probability of having wet, average, and dry years in HBEF catchments and Merrimack sub-basins is shown in Figure 7-6. When AMO was extremely positive (≥0.2), the probabilities of average and wet discharge conditions in HBEF catchments were as high as 61% and 58%, respectively and the chance of having dry discharge conditions was as low as 12% (Figure 7-6a). After the extreme positive summer AMO, the fall (fall-1 season lag) and winter (winter-2 seasons lag) discharge conditions were wet (HBEF catchments and Merrimack sub-basins). As the basin scale increased, the probability of wet, average, and dry discharge conditions decreased (Figure 7-6a).

During the extreme negative phase of AMO (≤-0.2) in HBEF catchments, the previous year's negative AMO caused wet discharge (annual-1 year lag, 40%) and average annual discharge conditions (annual-1 year lag, 55%) (Figure 7-6b). Negative summer AMO coincided with dry discharge conditions in the fall (fall-1 season lag, as high as 56% in HBEF catchments). The probability of wet, average, and dry discharge conditions decreased as drainage area increased (Figure 7-6b).

When winter NAO was extremely positive (≥0.5) in HBEF catchments, average and wet summer discharge conditions were probable 46% and 40% of the time, respectively (summer-2 seasons lag, Figure 7-6c). The chance of having dry discharge conditions in summer (summer-2 seasons lag) was 20-36%. The extreme negative phase of NAO (≤-0.5) mostly corresponded to average rather than dry or wet discharge conditions (Figure 7-6c). Negative winter NAO could be an indicative of average spring discharge conditions (spring-1 seasons lag, 47%) and dry summer discharge conditions (summer-2 seasons lag, 43%). Similar to the extreme negative phase of AMO, as the drainage area increased, the probability of having wet, average, and dry discharge conditions diminished (Figure 7-6c).

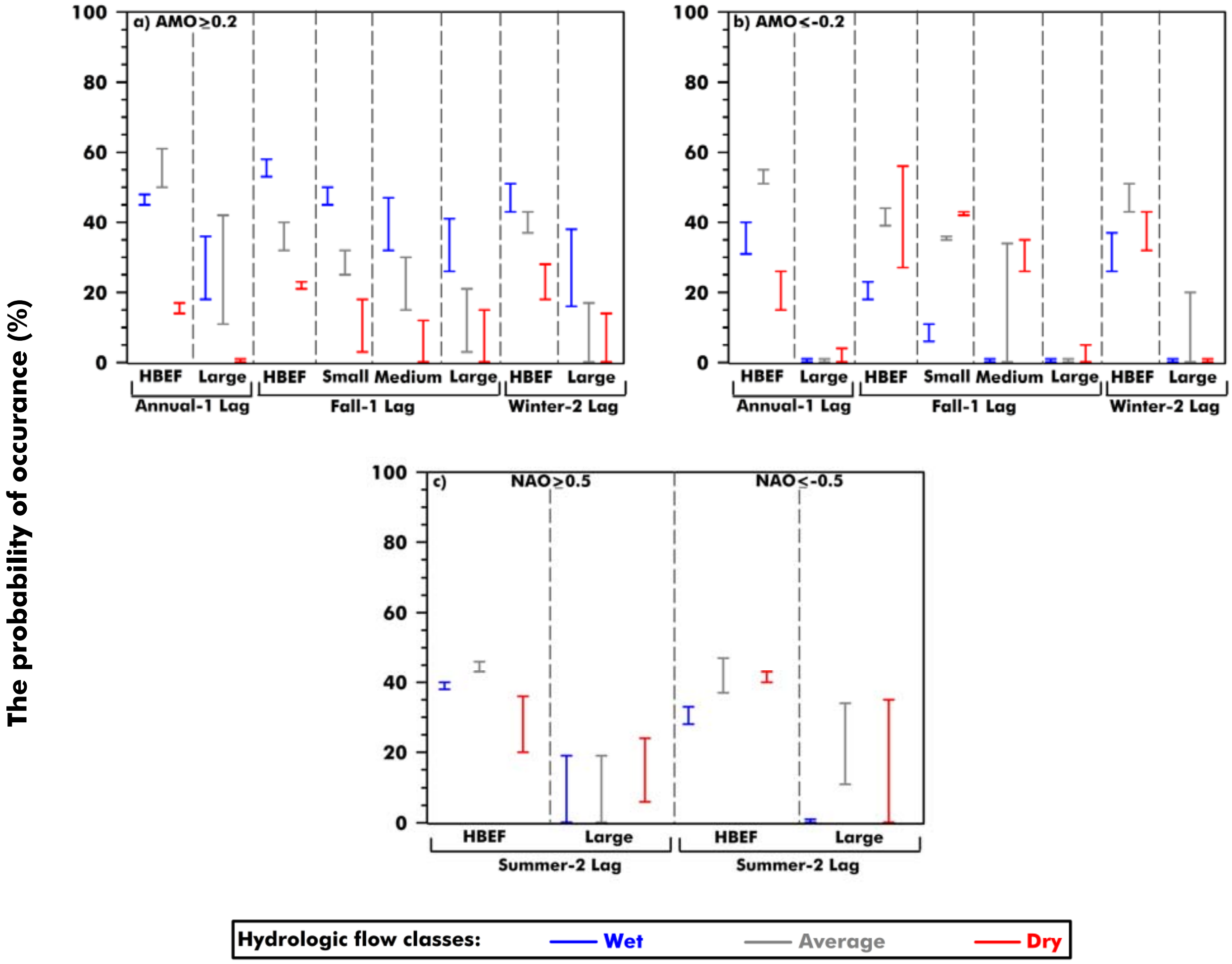

Figure 7-6- The 95% confidence band for occurrence probability of dry, average, and wet discharge conditions at zero-, one-, or two- year/season lags: a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5.

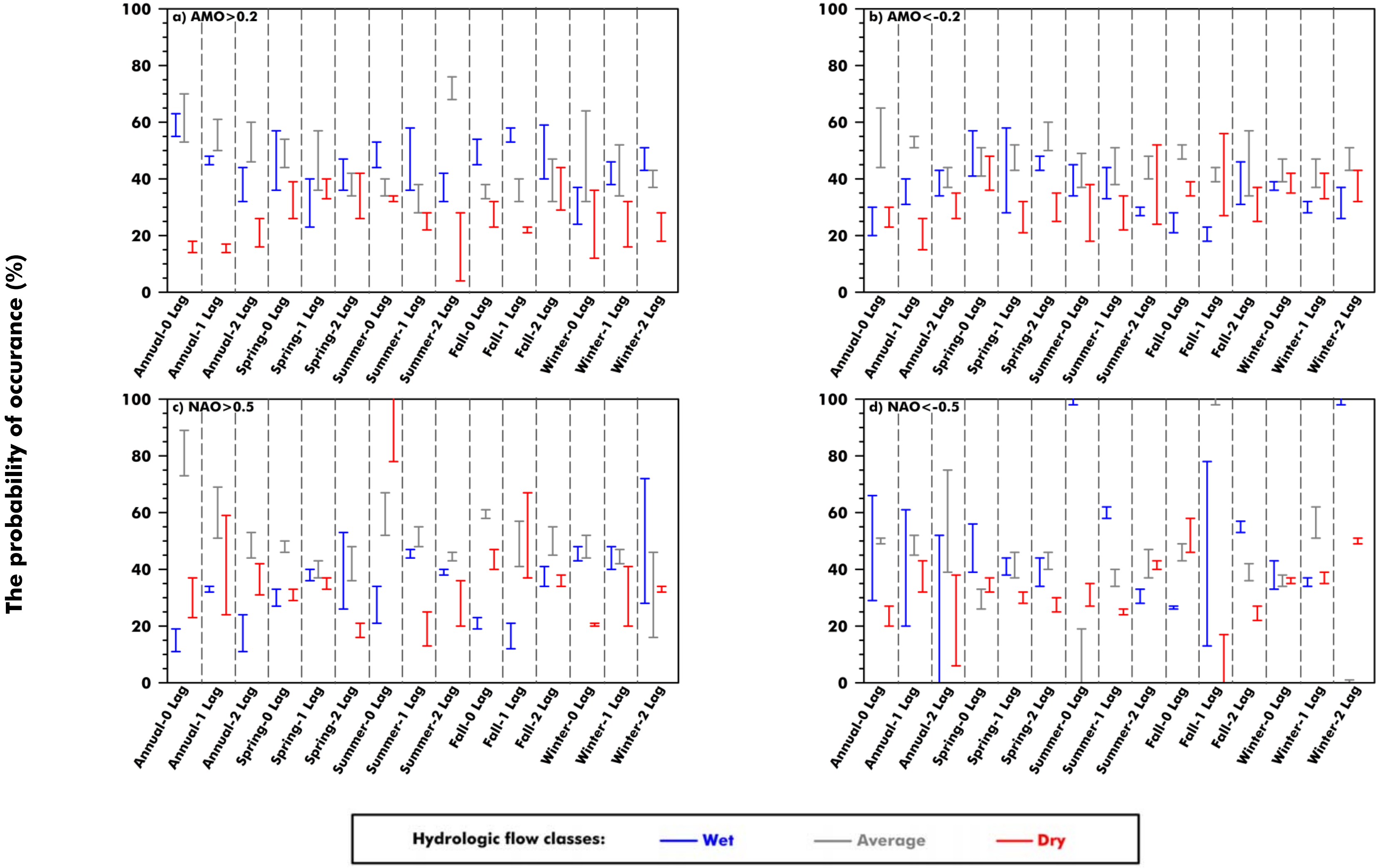

Figure 7-7- The occurrence probability of dry, average, and wet discharge conditions at zero-, one-, or two- year/season lags for the HBEF catchments: a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5. Error bars represent the lower and upper limits of 95% confidence intervals.

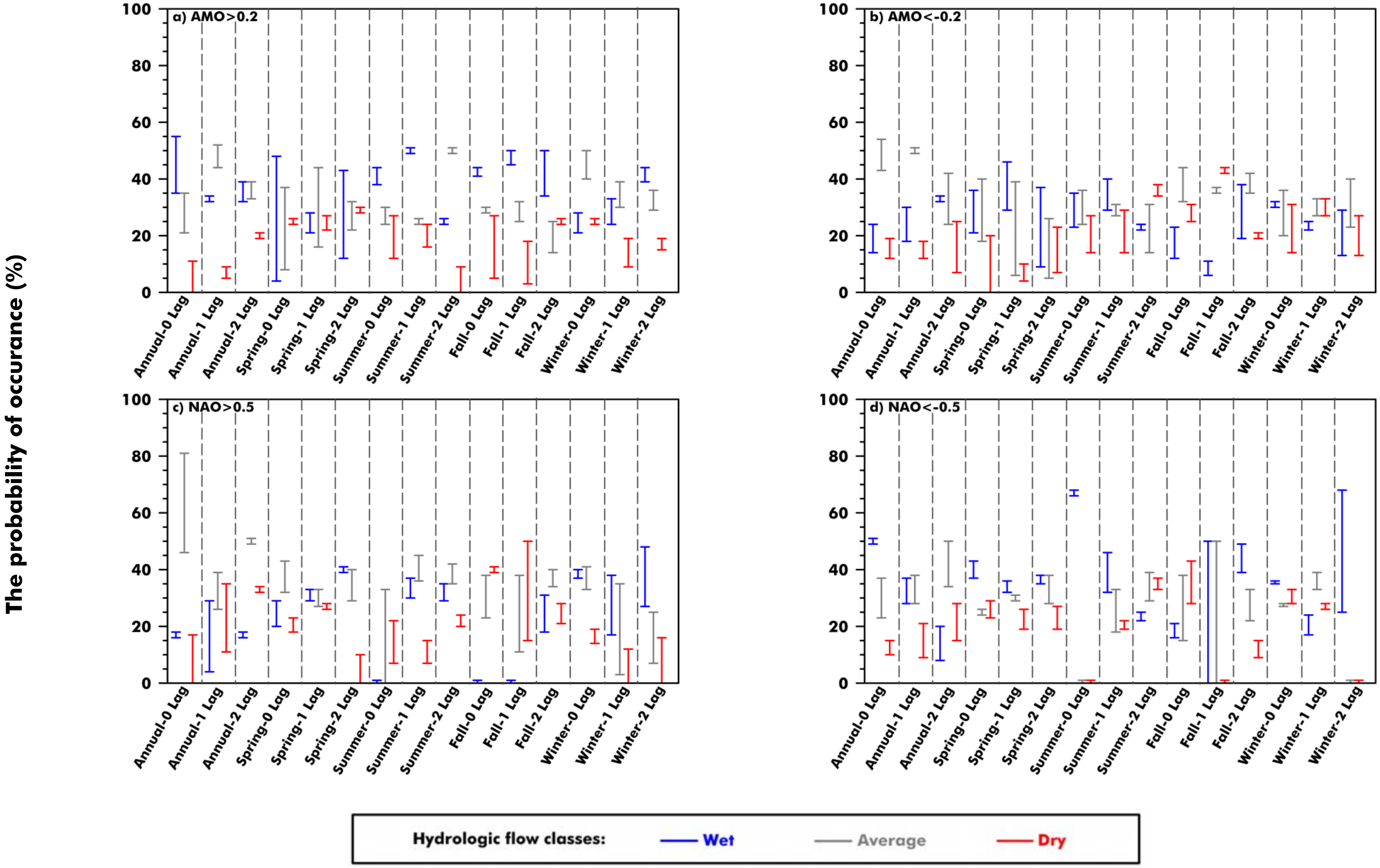

Figure 7-8- The occurrence probability of dry, average, and wet discharge conditions at zero-, one-, or two- year/season lags for the Merrimack small-scale sub-basins (ID: 9-10-14-16-19, 222-818 km^2): a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5. Error bars represent the lower and upper limits of 95% confidence intervals.

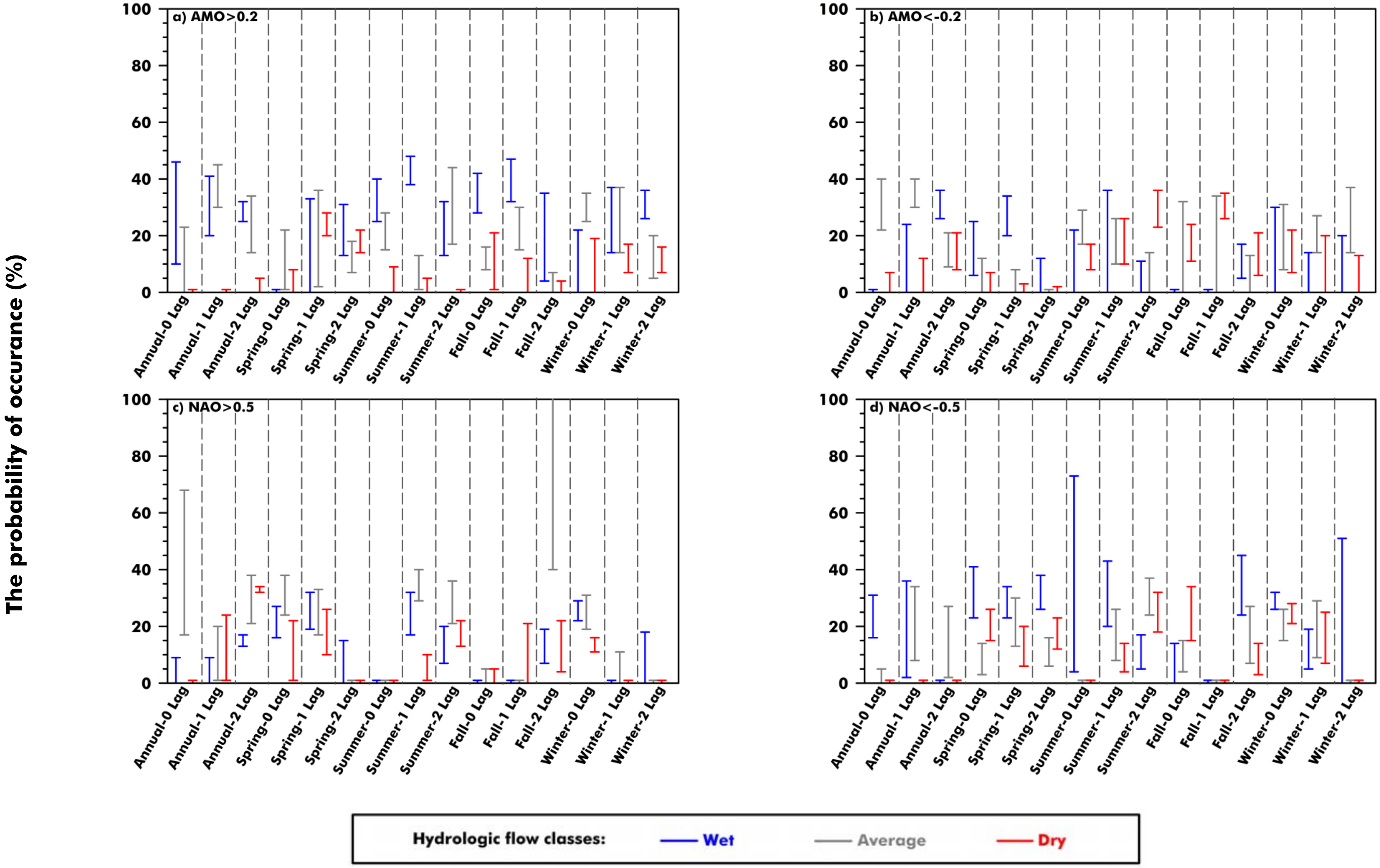

Figure 7-9- The occurrence probability of dry, average, and wet discharge conditions at zero-, one-, or two- year/season lags for the Merrimack intermediate-scale sub-basins (ID: 9-10-14-16-19, 222-818 km^2): a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5. Error bars represent the lower and upper limits of 95% confidence intervals.

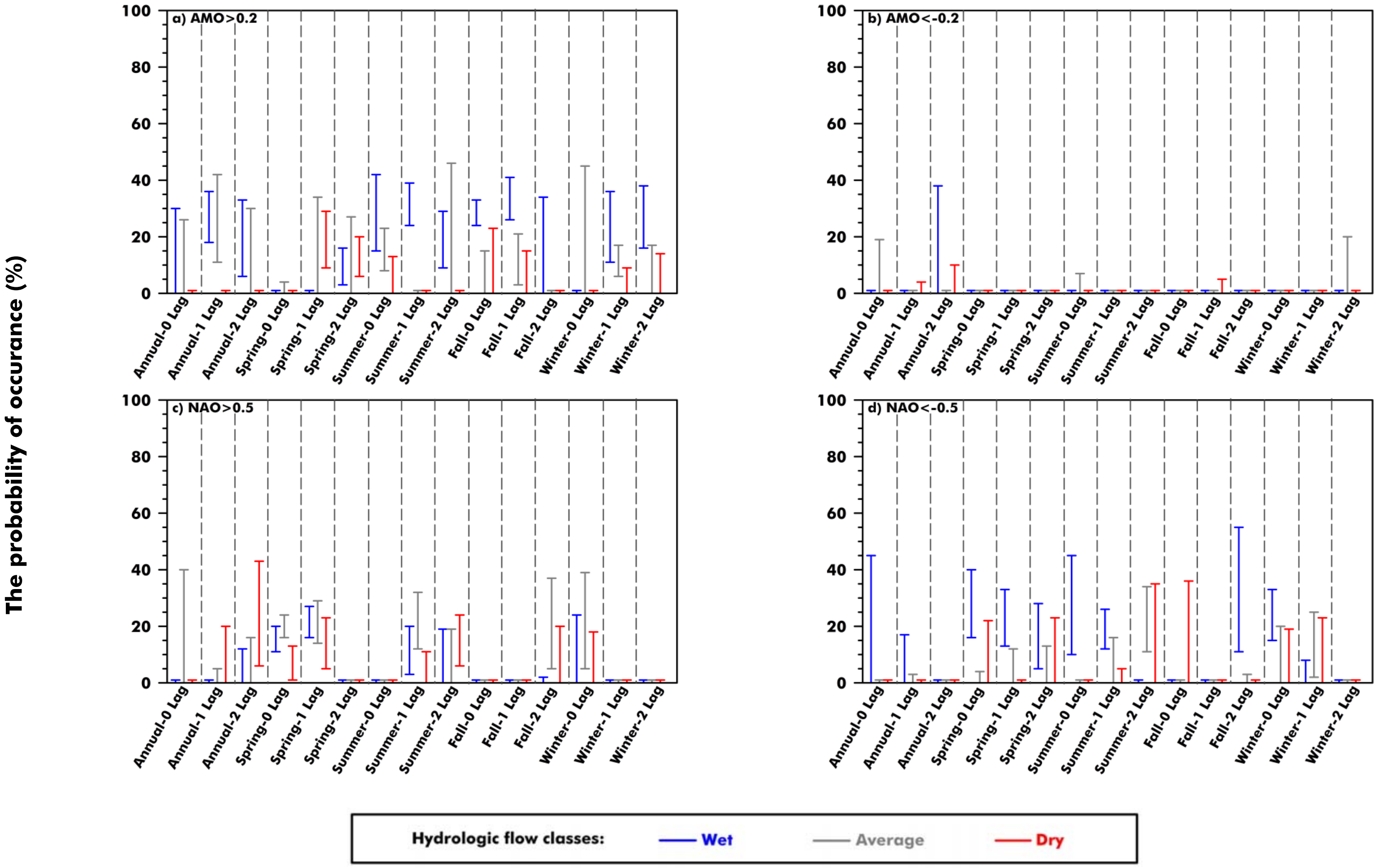

Figure 7-10- The occurrence probability of dry, average, and wet discharge conditions at zero-, one-, or two- year/season lags for the Merrimack large-scale sub-basins (ID: 11-12-17-21, 1220-11450 km^2): a) AMO≥0.2, b) AMO≤-0.2, c) NAO≥0.5 and ≤-0.5. Error bars represent the lower and upper limits of 95% confidence intervals.

7-2- Discussion

7-2-1- *Undisturbed catchments opposed to regulated and/or developed sub-basins*

Climate change studies have mostly been performed on reference catchments (Falcone, 2011; Falcone et al., 2010), although human-impacted sub-basins are usually larger and have longer hydrologic data records (Hannaford and Buys, 2012). In order to assess the scale-dependency of teleconnection patterns, the hydrologic information of developed sub-basins with a range of drainage areas should be used, albeit with caution (Hannaford et al., 2013; Viviroli et al., 2012).

In the undisturbed catchments of the HBEF with no streamflow controls or land disturbance and state-of-the-science instrumentation, Hamburg et al., (2013) reported strong association between precipitation and discharge (r=0.96). The Merrimack sub-basins have drainage areas 2-3 orders of magnitude larger than the HBEF catchments. River regulation and land development in the Merrimack River watershed have weakened the association between precipitation and discharge (r= 0.85, p-value<0.0001) (Berton et al., 2016).

When the correlation of precipitation-discharge declined towards the Merrimack downstream sub-basins, development overwhelmed the impacts of the extreme positive phase of AMO on discharge patterns, while the extreme negative phase of AMO was amplified in developed sub-basins (Figure 7-1). The irregularities in spatial and temporal variations of precipitation due to orographic effect or localized convective storm events (Barry and Chorley, 1987; Dingman, 2015) may also obscure teleconnection patterns. For central New England, changes in elevation are responsible for almost 80% of spatial variation in precipitation— consequently with effects on low, mean, and high discharge conditions (Dingman, 1981; Dingman et al., 1988).

7-2-2- *Statistical significance*

I chose a p-value less than 0.2 to check the statistical significance of the mean normalized annual and seasonal discharges between the extreme positive and negative phases of AMO and NAO (Table 7-1). This may raise concern on the detection of noise over the actual signal. Although lower p-values can certify the detection of signal over noise (Yuan and Martinson, 2000), it should also be considered that the notion of statistical significance becomes less important in studying obscure climate phenomena (Cohn and Lins, 2005; Koutsoyiannis and Montanari, 2007). For instance, if it takes a certain amount of time for a region to respond to an external forcing, it will take much longer for a basin to show a detectable signal (Hansen and Stone, 2015). Therefore, statistically insignificant signals observed at smaller scale studies should be taken into account as they can become significant in the near future with updated information and improved understanding of little-known systems.

7-2-3- *Lag time*

The ocean has a much longer thermal memory than the climate system due to its large heat capacity (Karnauskas et al., 2009). Therefore, there would be a lag time between changes in the state of oceanic indices and the effects on the state of precipitation or discharge (Roller et al., 2016). Alternatively, the morphology of a basin (i.e. soil type, discharge path distance, discharge path gradient, or basin scale) may cause a delay in discharge response to climate variations (Armstrong et al., 2013; McGuire et al., 2005). In addition, there is a chance that the lag-time may have statistical meaning that does not match with the physical hydrologic processes (Roller et al., 2016).

The importance of finding a lagged linkage between AMO and NAO with discharge is not limited to predictive opportunities. Relationships including annual or seasonal time lags in the Merrimack River watershed can provide enough time for local organizations to take preventive measurements against flooding or drought conditions. According to the results of this study, the Merrimack River watershed would likely experience a greater than average discharge condition in the near-term future; therefore, development should be avoided on flood plains (Figure 7-6). In case of dry conditions (AMO≤-0.2, fall-1 season lag and NAO≤-0.5, summer-2 seasons lag), water conservation measures such as artificial groundwater recharge, reducing water leakage from pipe distribution systems, and reducing water withdrawals should be considered (Enfield and Cid-Serrano, 2006).

7-2-4- *AMO teleconnection patterns with discharge*

Discharge variability in North America is highly influenced by AMO variation (McCabe et al., 2008), especially in the fall (Kavvada et al., 2013). Studies across the conterminous United States have found an association of the AMO positive phase with dry conditions for basins farther from the coast (Enfield et al., 2001; Kavvada et al., 2013). The impacts of local micro climate may challenge the validity of regional findings. For instance, in the Merrimack River watershed, the extreme positive AMO in summer requires special attention as it may manifest in wet fall and winter discharge conditions (Figure 7-7 to Figure 7-10).

The AMO negative phase was linked to more winter precipitation and coastal storms specifically for coastal regions (Bradbury et al., 2003, 2002c; Enfield and Cid-Serrano, 2006). The extreme negative phase of AMO in the Merrimack River watershed mostly corresponded with wet-to-average discharge conditions, while dry conditions were observed at sub-basins near to coastal areas. Wet conditions may necessitate the reevaluation of hydraulic structures to determine whether they are adequate to sustain a changing climate.

7-2-5- *NAO teleconnection patterns with discharge*

Positive NAO favors more winter rainfall in New England (Bradbury et al., 2003). When winter NAO was extremely positive, due to increases in winter rainfall, summer discharge in the Merrimack experienced average condition (suumer-2 seasons lag). Over the Northeast, negative winter NAO and its intra-seasonal variability have been shown to increase snowfall (Bradbury et al., 2002b; Hartley and Keables, 1998; Kingston et al., 2007) and decrease summer discharge (Bradbury et al., 2002a; Collins, 2009; Durkee et al., 2008). However, these patterns were not evident for the Merrimack River watershed, where discharge conditions remained wet to average (Figure 7-6c). A wet spring at the Merrimack River watershed as a result of negative winter NAO (spring-1 season lag) was inconsistent with studies by Bradbury et al. (2002b) and Hartley and Keables (1998) who suggested that negative NAO corresponded to more snowfall and colder temperatures in the Northeast.

7-2-6- *Interactive AMO and NAO teleconnection patterns with discharge*

In the northeastern United States, NAO has been found to be correlated with hydroclimatic variables (Armstrong et al., 2012; Bradbury et al., 2002a, 2002b; Mazouz et al., 2013). Winter NAO has been positively linked to spring and summer SSTs which may be responsible for warm season discharge variations in the Connecticut River Basin (Steinschneider and Brown, 2011). In this study, the interactive AMO and NAO teleconnection with precipitation and discharge in the

Merrimack River watershed indicated that teleconnection patterns could be confounded by season, lag time, basin size, and phases of AMO or NAO.

A positive NAO phase along with a negative phase of AMO led to low temperatures in eastern Canada which was linked to delayed, more frequent, and longer duration spring peak discharge (Hurrell, 1996, 1995; Mazouz et al., 2013). In the Merrimack River watershed, positive winter NAO (≥0.5) and negative winter AMO (≤-0.2) resulted in wet to average discharge conditions in spring (spring-1 season lag, Figure 7-7b-c to Figure 7-10b-c). When winter AMO was extremely negative, summer discharge was in dry-to-average condition in HBEF and became dry as the basin size increased (summer-2 seasons lag, Figure 7-7b to Figure 7-10b).

7-3- Summary and concluding remarks

I studied the linkage between AMO and NAO with both annual and seasonal discharge variations. I looked for potential opportunities to predict discharge conditions with respect to extreme phases of AMO or NAO. I studied NAO teleconnectivity to summer discharge variations in the northeastern United States using the approach of Coleman and Budikova (2013) in order to verify their findings for the Merrimack River watershed. In addition to NAO, I evaluated whether AMO was annually or seasonally associated with discharge variations.

The mean annual and seasonal standardized discharges were different for the extreme positive and negative phases of AMO (≥0.2, ≤-0.2) and NAO (≥0.5, ≤-0.5). Statistically significant scenarios (denoted by asterisk (*) in Table 7-1) were chosen to study the correlation coefficients of AMO and NAO with precipitation and discharge especially with regards to basin size. The impacts of basin size on teleconnection patterns were clear under the extreme positive phase of

AMO. When AMO was greater than 0.2, the magnitude of annual correlation coefficients were obscured by river regulation or land development. In contrast, during the extreme negative phase of AMO, river regulation and land development amplified the impacts of changing climate on precipitation and discharge variations. AMO was positively associated with precipitation and discharge, while NAO showed negative linkage (Figure 7-1).

There were interactive AMO and NAO teleconnection patterns with discharge. The AMO phase change did not affect the direction of NAO correlations with precipitation or discharge, but amplified the hydrologic response to NAO signals. When NAO was greater than 0.5, a negative link between NAO and AMO with precipitation and discharge could be identified, while the extreme negative phase of NAO indicated both positive and negative associations with either precipitation or discharge (Figure 7-1).

When AMO was extremely positive (≥0.2), the probabilities of average and wet discharge conditions in HBEF catchments were as high as 61% and 58%, respectively (Figure 7-6). During the extreme negative phase of AMO (≤-0.2), the probability of having extreme dry and wet discharge conditions increased (Figure 7-6b). Negative summer AMO was related to dry discharge conditions in the fall (fall-1 season lag, as high as 56% in HBEF catchments). When winter NAO was extremely positive (≥0.5) in HBEF catchments, average and wet summer discharge conditions were probable 46% and 40% of the time, respectively (summer-2 seasons lag, Figure 7-6c). The negative winter NAO requires special attention as it may manifest in a probability of dry summer discharge conditions of up to 43%. As the basin scale increased, confidence in the prediction of discharge conditions decreased compared to headwater catchments.

The results from this research indicated that the Merrimack River watershed is expected to experience increases in discharge along with changes in discharge timing and its seasonal distribution in the future; therefore development should be avoided on flood plains. Furthermore, the current reservoir storage capacity in the Merrimack should be improved in order to accommodate excess water input and minimize flood damage. Future research should target changes in the magnitude and timing of high discharge events in order to develop adaptation strategies for aging hydraulic infrastructure in the region.

This phase of the dissertation showed that when AMO was in an extreme positive phase (drought condition), the magnitude of seasonal precipitation and discharge correlation coefficients with AMO were obscured by river regulation or land development. In contrast, during the extreme negative phase of AMO (wet condition), river regulation and land development amplified the effects of changing climate on precipitation and discharge variation. As the basin scale increases, confidence in the estimation of discharge conditions decreases for downstream developed sub-basins compared to headwater undisturbed catchments.

The results from this chapter have been prepared for publication as: Berton, R., Driscoll, C.T., Adamowski, J.F., 2017. The near-term prediction of drought and flooding conditions in the northeastern United States with regard to extreme phases of AMO and NAO. Submitted to the Journal of Hydrology, Under Review.

8- Synthesis and suggestions for future research

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). These changes will likely affect watershed hydrology manifested in less snow accumulation, earlier peak flow, attenuated spring flows, increasing summer precipitation and evapotranspiration which could either increase or decrease summer base flows, respectively (Campbell et al., 2011; Frumhoff et al., 2007; Hayhoe et al., 2007; Huntington and Billmire, 2014). The overall findings of this dissertation confirm the above hydrologic alterations as responses to changing climate, which can have important consequences on ecosystem structure and function.

For this research, I exploited precipitation and discharge information for 21 study sites of varying sizes and levels of human development located in the northeastern United States. The variability among study sites characteristics provided me the opportunity to examine how hydrologic response to changing climate may differ with basin scale, land cover, and land development. As discharge integrates the effects of temperature and precipitation variation over a seasonal time scale, the primary characteristics of discharge provide valuable information regarding the response of water resources to changing climate (McCabe and Wolock, 2014). In this study, the changes in discharge magnitude and timing trends across the Merrimack River watershed indicated that, at headwater undisturbed catchments, discharge responses due to changing climate were either amplified (by increases in precipitation due to urban heat island effects, more impervious surfaces, shorter flow path, greater drainage density, decreases in ET) or masked (by milder slope, more surface and groundwater storage, regulated streams) at downstream developed sub-basins.

As mentioned earlier, many studies have quantified hydrologic alterations in the Northeast, but drivers of these changes are still uncertain. In particular, there is no consensus on whether long-term variations in patterns of discharge are the result of long-term climate cycles, and how these long-term climate cycles propagate through basins with varying drainage areas and characteristics (Bradbury et al., 2003; Hannaford and Marsh, 2006, 2008; Ishak et al., 2013; Panda et al., 2013; Seager et al., 2011). Two common measures of long-term shifts in the Northeast climate are AMO and NAO (Armstrong et al., 2013; Bradbury et al., 2003, 2002a, 2002b; Kingston et al., 2007; Mazouz et al., 2013; Peng et al., 2013; Smith et al., 2010; Tootle et al., 2005). While the mechanisms associated with the NAO and AMO are well studied, their influence on patterns of discharge across basin scales and levels of disturbances is less clear. In this research, I indicated that AMO and NAO had lagged teleconnection patterns with seasonal discharge which may either be amplified (by land development) or obscured (by river regulation) at downstream developed sub-basins compared to headwater undisturbed catchments. Moreover, the lagged teleconnectivity can provide potential opportunities to estimate extreme discharge conditions. These estimates can help water managers and policy makers to develop adaptive redesign for aging hydraulic infrastructure and improve future water management to address non-stationarity (Demaria et al., 2016).

In phase I of my dissertation, I assessed the scale-dependency of interacting hydrologic responses to changing climate, watershed physical characteristics, river regulation, and land development. The results indicated that magnitude and direction of hydrologic responses can differ under dry (dry years became drier) and wet (wet years became wetter) hydrologic conditions compared to average years. Additionally, this phase provided a high-resolution daily time step analysis to closely examine the effects of changing climate under different conditions of watershed development (i.e. river regulation and/or land development). I found that the effects of basin scale were limited to high and low discharge events and were expressed as lagged discharge in larger sub-basins and earlier discharge in smaller catchments. Annual discharge responded to increases in annual precipitation regardless of river regulation or land development. The greater drainage area, milder slopes, and surface water storage of the down slope Merrimack sub-basins have moderated discharge responses to changing climate compared to headwater catchments (HBEF). The earlier timing dates of 25% and 50% annual discharge in winter and spring accompanied by later timing date of 75% annual discharge clearly indicated a shift towards earlier snowmelt and a likely subsequent low summer baseflow which have been previously established as climate change footprints on hydrologic responses in the northeastern United States. In general, the superimposed effects of changing climate and land development were greater than the effects of changing climate alone on hydrologic response mainly during the high discharge seasons (i.e., winter through spring). The findings of this research phase highlights that differences in land cover (i.e. relative proportions and spatial distribution), result different hydrologic responses with complex ecological effects, which will likely confound watershed water management strategies.

In phase II of this dissertation (Chapter 6), I explored the effects of AMO and NAO regime shifts on hydrologic responses to evaluate whether the intensified inter-annual variability in discharge is explained by natural climate cycles. The results indicated that AMO regime shifts were strongly synchronized and preceded both precipitation and discharge by one to two years across all study sites, while NAO regime shifts indicated weaker associations. I found that all responses tended towards greater extremes from each regime shift to the next. Across many different ecological discharge indicators, high percentile values of these indicators increased across regimes, while low percentile values decreased across regimes (with a few exceptions). Many of the largest differences in discharge responses were evident at small-scale unregulated catchments, suggesting that regime shifts of large-scale climate circulation patterns may affect water availability for headwater ecosystems. While I noted that climate change and human development such as river regulation or urbanization may have counteracting effects on discharge variations (DeWalle et al., 2000), I found moderated hydrologic responses between regimes for FDCs and ecological indicators as the drainage area increased. This study indicates that spatial complexity of hydrologic responses to changing climate necessitates a reevaluation of large-scale water management decisions at both large and local scales. Increases in extreme discharge conditions highlight the necessity of an adaptive redesign for current infrastructure and preventive water management in smaller sub-basins responding to changing climate regimes (Demaria et al., 2016).

In phase III of this dissertation (Chapter 7), I evaluated the potential to estimate discharge considering annual or seasonal AMO and NAO teleconnection patterns. The results indicated that AMO positive phase was correspondent with average-to-wet discharge conditions at headwater catchments. I found that when AMO was in an extreme positive phase (drought condition), the magnitude of seasonal precipitation and discharge correlation coefficients with AMO were obscured by river regulation or land development. In contrast, during the extreme negative phase of AMO (wet condition), river regulation and land development amplified the effects of changing climate on precipitation and discharge variation. AMO was positively associated with precipitation and discharge, while NAO showed a negative linkage. The negative phase of summer AMO caused dry conditions in the following fall mostly in the headwater catchments. The positive winter NAO led to average-to-wet discharge condition in the subsequent summer, while the negative phase corresponded with dry discharge condition in the following summer. When the basin scale increased, confidence in the estimation of discharge conditions decreased for downstream developed sub-basins compared to headwater undisturbed catchments. This study indicates that under greater-than-average discharge conditions in the future, the current reservoir storage capacity should be improved in order to accommodate excess water input and minimize flood damage.

The results of this dissertation provide valuable insights on how climate change signals may vary from headwater catchments to downstream sub-basins due to differences in catchment properties, in addition to land development and river regulation, including dams and reservoirs. However, there are still many areas of uncertainty in the hydrological understanding of the response of complex watersheds to changing climate, and how watershed development influences those patterns. The subsequent research suggestions could provide improved assessments of climate change effects on watershed hydrology:

- Developed a web-based screening model to monitor trends in air temperature, discharge, and precipitation over years of record, dry-average-wet years, and regime shifts;
- Use a Bayesian approach to project future trends from historical information;
- Conduct a cross-region comparison of different basins to verify the validity of these findings for regions with different climatic conditions;
- Study the impacts of disconnected compared to connected impervious surfaces on hydrologic response for this study representative sub-basins with different levels of urban development;

- Study the effects of groundwater on buffering the climate and anthropogenic drivers on surface water hydrology;
- Study nonlinear teleconnection patterns of AMO and NAO with precipitation and discharge;
- Study the possible effects of Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) indices on the hydrological processes of the Northeast in high-resolution seasonal and monthly time steps;

9- References

Anderson, E.A., 1973. National Weather Service river forecast system: Snow accumulation and ablation model, NOAA Tech. Memo. U.S. Dep. Commerce, Silver Springs, MD.

Armstrong, W.H., Collins, M.J., Snyder, N.P., 2013. Hydroclimatic flood trends in the northeastern United States and linkages with large-scale atmospheric circulation patterns. Hydrological Sciences Journal. doi:10.1080/02626667.2013.862339

Armstrong, W.H., Collins, M.J., Snyder, N.P., 2012. Increased frequency of low-magnitude floods in New England. Journal of the American Water Resources Association 48, 306–320.

Auch, A.F., 2006. Land Cover Change in the Eastern United States: Northeastern Coastal Zone. U. S. Geological Survey.

Barry, R.G., Chorley, R.J., 1987. Atmosphere, Weather, and Climate, 5th ed. Methuen.

Bates, B., Kundzewicz, Z.W., Wu, S., Palutikof, J. (Eds.), 2008. Climate change and water., Technical Paper of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change (IPCC), Geneva.

Beck, H.E., de Roo, A., van Dijk, A.I.J.M., 2015. Global Maps of Streamflow Characteristics Based on Observations from Several Thousand Catchments. J. Hydrometeor 16, 1478–1501. doi:10.1175/JHM-D-14-0155.1

Berton, R., Driscoll, C.T., Chandler, D.G., 2016. Changing climate increases discharge and attenuates its seasonal distribution in the northeastern United States. Journal of Hydrology: Regional Studies 5, 164–178. doi:10.1016/j.ejrh.2015.12.057

Beveridge, D., Curry, R.A., St-Hilaire, A., 2012. Selecting hydrologic indices for the prairie provinces. River Research and Applications 28, 1595–1608. doi:10.1002/rra.1548

Black, A.R., Rowan, J.S., Duck, R.W., Bragg, O.M., Clelland, B.E., 2005. A method for classifying river flow regime alterations for the EC Water Framework Directive. Aquatic Conservation: Marine and Freshwater Ecosystems 15, 427–446. doi:10.1002/aqc.707

Bradbury, J.A., Dingman, S.L., Keim, B.D., 2002a. New England drought and relations with large scale atmospheric circulation patterns. Journal of the American Water Resources Association 38, 1287–1299.

Bradbury, J.A., Keim, B.D., Wake, C.P., 2003. The influence of regional storm tracking and teleconnections on winter precipitation in the Northeastern United States. Annals of the Association of American Geographers 93, 544–556.

Bradbury, J.A., Keim, B.D., Wake, C.P., 2002b. US east coast trough indices at 500 hPa and New England winter climate variability. Journal of climate 15, 3509–3517.

Bradbury, J.A., Keim, B.D., Wake, C.P., 2002c. US East Coast trough indices at 500 hPa and New England winter climate variability. Journal of climate 15, 3509–3517.

Brady, N.C., Weil, R.R., 2008. The Nature and Properties of Soils, 15th ed. Pearson Prentice Hall.

Brandes, D., Cavallo, G.J., Nilson, M.L., 2005. Baseflow trends in urbanizing watersheds of the Delaware River Basin. JAWRA 41, 1377–1391. doi:10.1111/j.1752-1688.2005.tb03806.x

Burn, D.H., 2008. Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. Journal of Hydrology 352, 225–238. doi:10.1016/j.jhydrol.2008.01.019

Campbell, J., 2013a. Daily precipitation by watershed data (1956-2011) in the Hubbard Brook Experimental Forest. Hubbard Brook Data Archive, North Woodstock, NH.

Campbell, J., 2013b. Daily streamflow by watershed (1956-2011) in the Hubbard Brook Experimental Forest. Hubbard Brook Data Archive, North Woodstock, NH.

Campbell, J.L., Driscoll, C.T., Pourmokhtarian, A., Hayhoe, K., 2011. Streamflow responses to past and projected future changes in climate at the Hubbard Brook Experimental Forest, New Hampshire, United States. Water Resources Research 47, 15 pp. doi:10.1029/2010WR009438

Changnon, S.A. (Ed.), 1981. Metromex- A review and summary. American Meteorological Society, Boston, MA.

Cochran, W.G., Cox, G.M., 1950. Experimental designs. John Wiley & Sons, Inc., New York, NY.

Cohn, T.A., Lins, H.F., 2005. Nature's style: Naturally trendy. Geophysical Research Letters 32. doi:10.1029/2005GL024476

Coleman, J.S.M., Budikova, D., 2013. Eastern U.S. summer streamflow during extreme phases of the North Atlantic Oscillation. Journal of Geophysical Research: Atmospheres 118, 4181–4193. doi:10.1002/jgrd.50326

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., Wehner, M., 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. Cambridge University Press, Cambridge, United Kingdom-New York, NY, USA.

Collins, M.J., 2009. Evidence for changing flood risk in New England since the late 20th century. Journal of the American Water Resources Association 45, 279–290.

Collins, M.J., Kirk, J.P., Pettit, J., DeGaetano, A.T., McCown, M.S., Peterson, T.C., Means, T.N., Zhang, X., 2014. Annual floods in New England (USA) and Atlantic Canada: synoptic climatology and generating mechanisms. Physical Geography 35, 195–219. doi:10.1080/02723646.2014.888510

Court, A., 1962. Measures of streamflow timing. Journal of Geophysical Research 67, 4335–4339. doi:10.1029/JZ067i011p04335

Daly, C., 2004. PRISM Climate Group. Oregon State University, Corvallis, OR.

de la Crétaz, A.L., Barten, P.K., 2007. Land use effects on streamflow and water quality in the northeastern United States. CRC Press, Boca Raton, FL.

DeAngelis, A., Dominguez, F., Fan, Y., Robock, A., Kustu, M.D., Robinson, D., 2010. Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States. Journal of Geophysical Research 115. doi:10.1029/2010JD013892

Degu, A.M., Hossain, F., Niyogi, D., Pielke, R., Shepherd, J.M., Voisin, N., Chronis, T., 2011. The influence of large dams on surrounding climate and precipitation patterns. Geophysical Research Letters 38, 7 pp. doi:10.1029/2010GL046482

Delworth, T.L., Mann, M.E., 2000. Observed and simulated multidecadal variability in the Northern Hemisphere. Climate Dynamics 16, 661–676.

Delworth, T.L., Zeng, F., Vecchi, G.A., Yang, X., Zhang, L., Zhang, R., 2016. The North Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere. Nature Geoscience 9, 509–512. doi:10.1038/ngeo2738

Demaria, E.M.C., Palmer, R.N., Roundy, J.K., 2016. Regional climate change projections of streamflow characteristics in the Northeast and Midwest U.S. Journal of Hydrology: Regional Studies 5, 309–323. doi:10.1016/j.ejrh.2015.11.007

Déry, S.J., Wood, E.F., 2004. Teleconnection between the Arctic Oscillation and Hudson Bay river discharge. Geophysical Research Letters 31. doi:10.1029/2004GL020729

Deser, C., Alexander, M.A., Xie, S.-P., Phillips, A.S., 2010. Sea Surface Temperature Variability: Patterns and Mechanisms. Annual Review of Marine Science 2, 115–143. doi:10.1146/annurev-marine-120408-151453

DeWalle, D.R., Swistock, B.R., Johnson, T.E., McGuire, K.J., 2000. Potential effects of climate change and urbanization on mean annual streamflow in the United States. Water Resources Research 36, 2655–2664. doi:10.1029/2000WR900134

Dickinson, J.E., Hanson, R.T., Predmore, S.K., 2014. HydroClimATe-Hydrologic and climatic analysis toolkit (Techniques and Methods No. 4–A9). U.S. Geological Survey.

Dingman, S.L., 2015. Physical Hydrology, 3rd ed. Waveland Press, Inc.

Dingman, S.L., 1981. Elevation: a major influence on the hydrology of New Hampshire and Vermont, USA. Hydrological Sciences Bulletin 26, 399–413. doi:10.1080/02626668109490904

Dingman, S.L., Seely-Reynolds, D.M., Reynolds, R.C., 1988. Application of Kriging to Estimating Mean Annual Precipitation in a Region of Orographic Influence. JAWRA Journal of the American Water Resources Association 24, 329–339. doi:10.1111/j.1752-1688.1988.tb02991.x

Dominguez, F., Rivera, E., Lettenmaier, D.P., Castro, C.L., 2012. Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models. Geophysical Research Letters 39, L05803. doi:10.1029/2011GL050762

Douglas, E., Fairbank, C., 2011. Is Precipitation in Northern New England Becoming More Extreme? Statistical Analysis of Extreme Rainfall in Massachusetts, New Hampshire, and Maine and Updated Estimates of the 100-Year Storm. Journal of Hydrologic Engineering 16, 203–217.

Drummond, M.A., Loveland, T.R., 2010. Land-use Pressure and a Transition to Forest-cover Loss in the Eastern United States. BioScience 60, 286–298. doi:10.1525/bio.2010.60.4.7

Durkee, J.D., Frye, J.D., Fuhrmann, C.M., Lacke, M.C., Jeong, H.G., Mote, T.L., 2008. Effects of the North Atlantic Oscillation on precipitation-type frequency and distribution in the eastern United States. Theor Appl Climatol 94, 51–65. doi:10.1007/s00704-007-0345-x

Enfield, D.B., Cid-Serrano, L., 2006. Projecting the risk of future climate shifts. International Journal of Climatology 26, 885–895. doi:10.1002/joc.1293

Enfield, D.B., Mestas-Nuñez, A.M., Trimble, P.J., 2001. The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S. Geophysical Research Letters 28, 2077–2080. doi:10.1029/2000GL012745

Eng, K., Wolock, D.M., Carlisle, D.M., 2013. River flow changes related to land and water management practices across the conterminous United States. Science of The Total Environment 463–464, 414–422. doi:10.1016/j.scitotenv.2013.06.001

Executive Office of Environmental Affairs, The Commonwealth of Massachusetts, 2001. Merrimack River-A Comprehensive Watershed Assessment Report. Devens, MA.

Falcone, J., 2011. GAGES-II: Geospatial attributes of gages for evaluating streamflow (vector digital data). U.S. Geological Survey, Reston, Virginia.

Falcone, J.A., Carlisle, D.M., Wolock, D.M., Meador, M.R., 2010. GAGES: A stream gage database for evaluating natural and altered flow conditions in the conterminous United States. Ecology 91, 621.

Fang, X., Pomeroy, J.W., 2016. Impact of antecedent conditions on simulations of a flood in a mountain headwater basin: Antecedent Condition on Flooding in a Mountain Headwater Basin. Hydrological Processes 30, 2754–2772. doi:10.1002/hyp.10910

Fernández, J.A., Martínez, C., Magdaleno, F., 2012. Application of indicators of hydrologic alterations in the designation of heavily modified water bodies in Spain. Environmental Science & Policy 16, 31–43. doi:10.1016/j.envsci.2011.10.004

Ficklin, D.L., Robeson, S.M., Knouft, J.H., 2016. Impacts of recent climate change on trends in baseflow and stormflow in United States watersheds: U.S. Baseflow and Stormflow Trends. Geophysical Research Letters 43, 5079–5088. doi:10.1002/2016GL069121

Frans, C., Istanbulluoglu, E., Mishra, V., Munoz-Arriola, F., Lettenmaier, D.P., 2013. Are climatic or land cover changes the dominant cause of runoff trends in the Upper Mississippi River Basin? Geophysical Research Letters 40, 1104–1110. doi:10.1002/grl.50262

Frei, A., Kunkel, K.E., Matonse, A., 2015. The Seasonal Nature of Extreme Hydrological Events in the Northeastern United States. Journal of Hydrometeorology 16, 2065–2085. doi:10.1175/JHM-D-14-0237.1

Frumhoff, P.C., McCarthy, J.J., Melillo, J.M., Moser, S.C., Wuebbles, D.J., 2007. Confronting climate change in the U.S. Northeast: Science, impacts, and solutions. Synthesis report of the Northeast Climate Impacts Assessment (NECIA). Union of Concerned Scientists (UCS), Cambridge, MA.

Gallant, A.L., Loveland, T.R., Sohl, T.L., Napton, D.E., 2004. Using an Ecoregion Framework to Analyze Land-Cover and Land-Use Dynamics. Environmental Management 34, S89–S110. doi:10.1007/s00267-003-0145-3

Gallart, F., Delgado, J., Beatson, S.J.V., Posner, H., Llorens, P., Marcé, R., 2011. Analysing the effect of global change on the historical trends of water resources in the headwaters of the Llobregat and Ter river basins (Catalonia, Spain). Physics and Chemistry of the Earth, Parts A/B/C 36, 655–661. doi:10.1016/j.pce.2011.04.009

Gao, P., Mu, X.M., Wang, F., Li, R., 2011. Changes in streamflow and sediment discharge and the response to human activities in the middle reaches of the Yellow River. Hydrology and Earth System Sciences 15, 1–10. doi:10.5194/hess-15-1-2011

Gao, Y., Vogel, R.M., Kroll, C.N., Poff, N.L., Olden, J.D., 2009. Development of representative indicators of hydrologic alteration. Journal of Hydrology 374, 136–147. doi:10.1016/j.jhydrol.2009.06.009

Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C., Stott, P.A., 2006. Detection of a direct carbon dioxide effect in continental river runoff records. Nature 439, 835–838. doi:10.1038/nature04504

Genz, F., Luz, L.D., 2012. Distinguishing the effects of climate on discharge in a tropical river highly impacted by large dams. Hydrological Sciences Journal 57, 1020–1034. doi:10.1080/02626667.2012.690880

Gilbert, R.O., 1987. Statistical Methods for Environmental Pollution Monitoring. John Wiley & Sons, Inc., New York, NY.

Gillett, N.P., Graf, H.F., Osborn, T.J., 2002. Climate Change and the North Atlantic Oscillation, in: Hurrell, J.W., Kushnir, Y., Otterson, G., Visbeck, M. (Eds.), The North Atlantic Oscillation: Climatic Significance and Environmental Impact, Geophysical Monograph Series. American Geophysical Union, Washington DC.

Gray, S.T., 2004. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. Geophysical Research Letters 31. doi:10.1029/2004GL019932

Grill, G., Lehner, B., Lumsdon, A.E., MacDonald, G.K., Zarfl, C., Reidy Liermann, C., 2015. An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. Environmental Research Letters 10, 015001. doi:10.1088/1748-9326/10/1/015001

Hamburg, S.P., Vadeboncoeur, M.A., Richardson, A.D., Bailey, A.S., 2013. Climate change at the ecosystem scale: a 50-year record in New Hampshire. Climatic Change 116, 457–477. doi:10.1007/s10584-012-0517-2

Hamel, P., Daly, E., Fletcher, T.D., 2015. Which baseflow metrics should be used in assessing flow regimes of urban streams?: Baseflow Metrics for Assessing Flow Regime of Urban Streams. Hydrological Processes 29, 4367–4378. doi:10.1002/hyp.10475

Hannaford, J., Buys, G., 2012. Trends in seasonal river flow regimes in the UK. Journal of Hydrology 475, 158–174. doi:10.1016/j.jhydrol.2012.09.044

Hannaford, J., Buys, G., Stahl, K., Tallaksen, L.M., 2013. The influence of decadal-scale variability on trends in long European streamflow records. Hydrology and Earth System Sciences 17, 2717–2733. doi:10.5194/hess-17-2717-2013

Hannaford, J., Marsh, T., 2006. An assessment of trends in UK runoff and low flows using a network of undisturbed catchments. International Journal of Climatology 26, 1237–1253. doi:10.1002/joc.1303

Hannaford, J., Marsh, T.J., 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. International Journal of Climatology 28, 1325–1338. doi:10.1002/joc.1643

Hansen, G., Stone, D., 2015. Assessing the observed impact of anthropogenic climate change. Nature Climate Change 6, 532–537. doi:10.1038/nclimate2896

Hart, J.F., 1968. Loss and abandonment of cleared farm land in the Eastern United States. Annals of the Association of American Geographers 58, 417–440. doi:10.1111/j.1467-8306.1968.tb01645.x

Hartigan, J.A., 1975. Clustering algorithms, Wiley series in probability and mathematical statistics. Wiley, New York.

Hartley, S., Keables, M.J., 1998. Synoptic associations of winter climate and snowfall variability in New England, USA, 1950–1992. International Journal of Climatology 18, 281–298. doi:10.1002/(SICI)1097-0088(19980315)18:3<281::AID-JOC245>3.0.CO;2-F

Hatcher, K.L., Jones, J.A., 2013. Climate and streamflow trends in the Columbia River Basin: evidence for ecological and engineering resilience to climate change. Atmosphere-Ocean 51, 436–455. doi:10.1080/07055900.2013.808167

Hayhoe, K., Wake, C.P., Huntington, T.G., Luo, L., Schwartz, M.D., Sheffield, J., Wood, E., Anderson, B., Bradbury, J., DeGaetano, A., 2007. Past and future changes in climate and hydrological indicators in the US Northeast. Climate Dynamics 28, 381–407. doi:10.1007/s00382-006-0187-8

Heath, R.C., 1983. Basic ground-water hydrology. US Geological Survey, U.S . Geological Survey Water-Supply Paper 2220, 86 p.

Helsel, D.R., Hirsch, R.M., 1992. Statistical methods in water resources. Elsevier Science, New York.

Hidalgo, H.G., Das, T., Dettinger, M.D., Cayan, D.R., Pierce, D.W., Barnett, T.P., Bala, G., Mirin, A., Wood, A.W., Bonfils, C., Santer, B.D., Nozawa, T., 2009. Detection and Attribution of Streamflow Timing Changes to Climate Change in the Western United States. Journal of Climate 22, 3838–3855. doi:10.1175/2009JCLI2470.1

Hodgkins, G.., Dudley, R.., Huntington, T.., 2003. Changes in the timing of high river flows in New England over the 20th Century. Journal of Hydrology 278, 244–252. doi:10.1016/S0022-1694(03)00155-0

Hodgkins, G.A., 2010. Historical changes in annual peak flows in Maine and implications for flood-frequency analyses. U. S. Geological Survey.

Hodgkins, G.A., Dudley, R.W., 2011. Historical summer baseflow and stormflow trends for New England rivers. Water Resources Research 47, n/a-n/a. doi:10.1029/2010WR009109

Hodgkins, G.A., Dudley, R.W., 2006. Changes in the timing of winter–spring streamflows in eastern North America, 1913–2002. Geophysical Research Letters 33, 5 pp. doi:10.1029/2005GL025593

Hodgkins, G.A., Dudley, R.W., 2005. Changes in the magnitude of annual and monthly streamflows in New England, 1902-2002. Scientific Investigations Report 44.

Hodgkins, G.A., Dudley, R.W., Huntington, T.G., 2005. Summer low flows in New England during the 20th Century. Journal of the American Water Resources Association. 41, 403–412. doi:10.1111/j.1752-1688.2005.tb03744.x

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X.-W., Wolter, K., Cheng, L., 2016. Characterizing Recent Trends in U.S. Heavy Precipitation. Journal of Climate 29, 2313–2332. doi:10.1175/JCLI-D-15-0441.1

Hoerling, M.P., Hurrell, J.W., Xu, T., 2001. Tropical Origins for Recent North Atlantic Climate Change. Science 292, 90–92. doi:10.1126/science.1058582

Homa, E.S., Brown, C., McGarigal, K., Compton, B.W., Jackson, S.D., 2013. Estimating hydrologic alteration from basin characteristics in Massachusetts. Journal of Hydrology 503, 196–208. doi:10.1016/j.jhydrol.2013.09.008

Hotelling, H., 1936. Relations between two sets of variates. Biometrika 28, 321–377. doi:10.1093/biomet/28.3-4.321

Hotelling, H., 1933. Analysis of a complex of statistical variables into principal components. Journal of Educational Psychology 24, 417–441. doi:10.1037/h0071325

Hsieh, C., Glaser, S.M., Lucas, A.J., Sugihara, G., 2005. Distinguishing random environmental fluctuations from ecological catastrophes for the North Pacific Ocean. Nature 435, 336–340. doi:10.1038/nature03553

Huff, F.A., 1977. Effects of the urban environment on heavy rainfall distribution. JAWRA Journal of the American Water Resources Association 13, 807–816. doi:10.1111/j.1752-1688.1977.tb02064.x

Huff, F.A., Changnon, S.A., 1973. Precipitation modification by major urban areas. Bull. Amer. Meteor. Soc. 54, 1220–1232. doi:10.1175/1520-0477(1973)054<1220:PMBMUA>2.0.CO;2

Huntington, T.G., Billmire, M., 2014. Trends in Precipitation, Runoff, and Evapotranspiration for Rivers Draining to the Gulf of Maine in the United States*. Journal of Hydrometeorology 15, 726–743. doi:10.1175/JHM-D-13-018.1

Huntington, T.G., Hodgkins, G.A., Keim, B.D., Dudley, R.W., 2004. Changes in the proportion of precipitation occurring as snow in New England (1949-2000). J. Climate 17, 2626–2636. doi:10.1175/1520-0442(2004)017<2626:CITPOP>2.0.CO;2

Huntington, T.G., Richardson, A.D., McGuire, K.J., Hayhoe, K., 2009. Climate and hydrological changes in the northeastern United States: recent trends and implications for forested and aquatic ecosystems. Canadian Journal of Forest Research 39, 199–212.

Hurd, B., Leary, N., Jones, R., Smith, J., 1999. Relative regional vulnerability of water resources to cliamte change. Journal of the American Water Resources Association 35, 1399–1409. doi:10.1111/j.1752-1688.1999.tb04224.x

Hurrell, J.W., 2015. The Climate Data Guide: NAO index (PC-based). National Center for Atmospheric Research.

Hurrell, J.W., 1996. Influence of variations in extratropical wintertime teleconnections on northern hemisphere temperature. Geophysical Research Letters 23, 665–668. doi:10.1029/96GL00459

Hurrell, J.W., 1995. Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. Science 269, 676–679. doi:10.1126/science.269.5224.676

Hurrell, J.W., Kushnir, Y., Visbeck, M., Otterson, G., 2003. An overview of the North Atlantic Oscillation, in: Hurrell, J.W., Kushnir, Y., Otterson, G., Visbeck, M. (Eds.), The North Atlantic Oscillation: Climate Significance and Environmental Impact, Geophysical Monograph Series. American Geophysical Union, Washington DC, pp. 1–35.

IHAs, Ver. 7.1, 2009. . The Nature Conservancy.

Ishak, E.H., Rahman, A., Westra, S., Sharma, A., Kuczera, G., 2013. Evaluating the non-stationarity of Australian annual maximum flood. Journal of Hydrology 494, 134–145. doi:10.1016/j.jhydrol.2013.04.021

Ivancic, T.J., Shaw, S.B., 2015. Examining why trends in very heavy precipitation should not be mistaken for trends in very high river discharge. Climatic Change 133, 681–693. doi:10.1007/s10584-015-1476-1

Izenman, A.J., 2008. Modern multivariate statistical techniques, Springer Texts in Statistics. Springer, New York.

Jiang, Y., Zhou, C., Cheng, W., 2007. Streamflow trends and hydrological response to climatic change in Tarim headwater basin. Journal of Geographical Sciences 17, 51–61. doi:10.1007/s11442-007-0051-8

Jianting Zhu, Mark C. Stone, William Forsee, 2012. Analysis of potential impacts of climate change on intensity–duration–frequency (IDF) relationships for six regions in the United States. Journal of Water and Climate Change 3, 185–196. doi:10.2166/wcc.2012.045

Jolliffe, I.T., 2002. Principal Component Analysis, Springer Series in Statistics. Springer-Verlag, New York, Secaucus, NJ.

Jones, J.A., Creed, I.F., Hatcher, K.L., Warren, R.J., Adams, M.B., Benson, M.H., Boose, E., Brown, W.A., Campbell, J.L., Covich, A., others, 2012. Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites. BioScience 62, 390–404.

Jung, I.W., Moradkhani, H., Chang, H., 2012. Uncertainty assessment of climate change impacts for hydrologically distinct river basins. Journal of Hydrology 466–467, 73–87. doi:10.1016/j.jhydrol.2012.08.002

Kalra, A., Ahmad, S., 2009. Using oceanic-atmospheric oscillations for long lead time streamflow forecasting. Water Resources Research 45, n/a-n/a. doi:10.1029/2008WR006855

Kam, J., Sheffield, J., 2016. Changes in the low flow regime over the eastern United States (1962–2011): variability, trends, and attributions. Climatic Change 135, 639–653. doi:10.1007/s10584-015-1574-0

Kambly, S., 2006. Land Cover Change in the Eastern United States: Northeastern Highlands. U. S. Geological Survey.

Kaplan, A., Cane, M.A., Kushnir, Y., Clement, A.C., Blumenthal, M.B., Rajagopalan, B., 1998. Analyses of global sea surface temperature 1856–1991. Journal of Geophysical Research: Oceans 103, 18567–18589. doi:10.1029/97JC01736

Kaplan, A., Kushnir, Y., Cane, M.A., Blumenthal, M.B., 1997. Reduced space optimal analysis for historical data sets: 136 years of Atlantic sea surface temperatures. Journal of Geophysical Research: Oceans 102, 27835–27860. doi:10.1029/97JC01734

Karl, T.R., Knight, R.W., 1998. Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States. Bulletin of the American Meteorological Society 79, 231–241. doi:10.1175/1520-0477(1998)079<0231:STOPAF>2.0.CO;2

Karnauskas, K.B., Seager, R., Kaplan, A., Kushnir, Y., Cane, M.A., 2009. Observed Strengthening of the Zonal Sea Surface Temperature Gradient across the Equatorial Pacific Ocean. Journal of Climate 22, 4316–4321. doi:10.1175/2009JCLI2936.1

Kavvada, A., Ruiz-Barradas, A., Nigam, S., 2013. AMO's structure and climate footprint in observations and IPCC AR5 climate simulations. Climate Dynamics 41, 1345–1364. doi:10.1007/s00382-013-1712-1

Kendall, M.G., 1975. Rank Correlation Methods. Griffin, London.

Kennard, M.J., Mackay, S.J., Pusey, B.J., Olden, J.D., Marsh, N., 2010. Quantifying uncertainty in estimation of hydrologic metrics for ecohydrological studies. River Research and Applications 26, 137–156. doi:10.1002/rra.1249

Kerr, R.A., 2000. A North Atlantic Climate Pacemaker for the Centuries. Science 288, 1984. doi:10.1126/science.288.5473.1984

Kiktev, D., Sexton, D.M., Alexander, L., Folland, C.K., 2003. Comparison of modeled and observed trends in indices of daily climate extremes. Journal of Climate 16, 3560–3571.

Kim, J., Choi, J., Choi, C., Park, S., 2013. Impacts of changes in climate and land use/land cover under IPCC RCP scenarios on streamflow in the Hoeya River Basin, Korea. Science of The Total Environment 452–453, 181–195. doi:10.1016/j.scitotenv.2013.02.005

King, M.P., Kucharski, F., 2006. Observed Low-Frequency Covariabilities between the Tropical Oceans and the North Atlantic Oscillation in the Twentieth Century. J. Climate 19, 1032–1041. doi:10.1175/JCLI3677.1

Kingston, D.G., McGregor, G.R., Hannah, D.M., Lawler, D.M., 2007. Large-Scale Climatic Controls on New England River Flow. Journal of Hydrometeorology 8, 367–379. doi:10.1175/JHM584.1

Knight, D.B., Davis, R.E., 2009. Contribution of tropical cyclones to extreme rainfall events in the southeastern United States. Journal of Geophysical Research 114. doi:10.1029/2009JD012511

Knouft, J.H., Chu, M.L., 2015. Using watershed-scale hydrological models to predict the impacts of increasing urbanization on freshwater fish assemblages. Ecohydrology 8, 273–285. doi:10.1002/eco.1506

Konikow, L.F., 2015. Long-Term Groundwater Depletion in the United States. Groundwater 53, 2–9. doi:10.1111/gwat.12306

Konrad, C.P., Booth, D.B., 2002. Hydrologic trends associated with urban development for selected streams in the Puget Sound Basin, western Washington. US Geological Survey.

Koutsoyiannis, D., Montanari, A., 2007. Statistical analysis of hydroclimatic time series: Uncertainty and insights. Water Resources Research 43, n/a-n/a. doi:10.1029/2006WR005592

Kundzewicz, Z.W., Robson, A. (Eds.), 2000. Detecting Trend and Other Changes in Hydrological Data, World Climate Program- Water. WMO/UNESCO, WCDMP-45, WMO/TD 1013, Geneva, Switzerland.

Kuss, A.J.M., Gurdak, J.J., 2014. Groundwater level response in U.S. principal aquifers to ENSO, NAO, PDO, and AMO. Journal of Hydrology 519, 1939–1952. doi:10.1016/j.jhydrol.2014.09.069

Lerner, D., 2002. Identifying and quantifying urban recharge: a review. Hydrogeology Journal 10, 143–152. doi:10.1007/s10040-001-0177-1

Lindström, G., Bergström, S., 2004. Runoff trends in Sweden 1807–2002. Hydrological Sciences Journal 49, 69–83.

Lins, H.F., Slack, J.R., 2005. Seasonal and regional characteristics of US streamflow trends in the United States from 1940 to 1999. Physical Geography 26, 489–501.

Lins, H.F., Slack, J.R., 1999. Streamflow trends in the United States. Geophys. Res. Lett. 26, 227–230. doi:10.1029/1998GL900291

Loveland, T.R., Acevedo, W., 2006. Land-cover change in the eastern United States. US Geological Survey.

Loveland, T.R., Sohl, T., Sayler, K., Gallant, A., Dwyer, J., Vogelmann, J., Zylstra, G., Wade, T., Edmonds, C., Chaloud, D., others, 1999. Land Cover Trends: Rates, Causes, and Consequences of Late-Twentieth Century U.S. Land Cover Change. EPA Research Plan.

Loveland, T.R., Sohl, T.L., Stehman, S.V., Gallant, A.L., Sayler, K.L., Napton, D.E., 2002. A strategy for estimating the rates of recent United States land-cover changes. Photogrammetric Engineering and Remote Sensing 68, 1091–1099.

Lu, J., Greatbatch, R.J., Peterson, K.A., 2004. Trend in Northern Hemisphere Winter Atmospheric Circulation during the Last Half of the Twentieth Century. J. Climate 17, 3745–3760. doi:10.1175/1520-0442(2004)017<3745:TINHWA>2.0.CO;2

Luce, C.H., Vose, J.M., Pederson, N., Campbell, J., Millar, C., Kormos, P., Woods, R., 2016. Contributing factors for drought in United States forest ecosystems under projected future climates and their uncertainty. Forest Ecology and Management 380, 299–308. doi:10.1016/j.foreco.2016.05.020

Madsen, T., Willcox, N., 2012. When it rains, it pours-Global Warming and the Increase in Extreme Precipitation from 1948-2011. Environment America Research & Policy Center.

Magilligan, F.J., Graber, B.E., 1996. Hydroclimatological and geomorphic controls on the timing and spatial variability of floods in New England, USA. Journal of Hydrology 178, 159–180. doi:10.1016/0022-1694(95)02807-2

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13, 245–259. doi:10.2307/1907187

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. Bull. Amer. Meteor. Soc. 78, 1069–1079. doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2

Marshall, J., Kushnir, Y., Battisti, D., Chang, P., Czaja, A., Dickson, R., Hurrell, J., McCartney, M., Saravanan, R., Visbeck, M., 2001. North Atlantic climate variability: phenomena, impacts and mechanisms. International Journal of Climatology 21, 1863–1898. doi:10.1002/joc.693

Martin, E.H., Kelleher, C., Wagener, T., 2012. Has urbanization changed ecological streamflow characteristics in Maine (USA)? Hydrological Sciences Journal 57, 1337–1354. doi:10.1080/02626667.2012.707318

Matonse, A.H., Frei, A., 2013. A Seasonal Shift in the Frequency of Extreme Hydrological Events in Southern New York State. Journal of Climate 26, 9577–9593. doi:10.1175/JCLI-D-12-00810.1

Mauget, S.A., 2003. Multidecadal regime shifts in US streamflow, precipitation, and temperature at the end of the twentieth century. Journal of Climate 16, 3905–3916.

Mauget, S.A., Cordero, E.C., 2014. Optimal Ranking Regime Analysis of Intra-to Multidecadal US Climate Variability. Part II: Precipitation and Streamflow*. Journal of Climate 27, 9027–9049.

Maurer, E.P., Lettenmaier, D.P., Mantua, N.J., 2004. Variability and potential sources of predictability of North American runoff. Water Resources Research 40, n/a-n/a. doi:10.1029/2003WR002789

Mazouz, R., Assani, A.A., Rodríguez, M.A., 2013. Application of redundancy analysis to hydroclimatology: A case study of spring heavy floods in southern Québec (Canada). Journal of Hydrology 496, 187–194. doi:10.1016/j.jhydrol.2013.05.035

McCabe, G.J., Betancourt, J.L., Gray, S.T., Palecki, M.A., Hidalgo, H.G., 2008. Associations of multi-decadal sea-surface temperature variability with US drought. Quaternary International 188, 31–40. doi:10.1016/j.quaint.2007.07.001

McCabe, G.J., Palecki, M.A., Betancourt, J.L., 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. Proceedings of the National Academy of Sciences 101, 4136–4141.

McCabe, G.J., Wolock, D.M., 2014. Variability Common to Global Sea Surface Temperatures and Runoff in the Conterminous United States. Journal of Hydrometeorology 15, 714–725. doi:10.1175/JHM-D-13-097.1

McCabe, G.J., Wolock, D.M., 2002. A step increase in streamflow in the conterminous United States. Geophysical Research Letters 29, 2185. doi:10.1029/2002GL015999

McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrological Sciences Journal 61, 2295–2311. doi:10.1080/02626667.2015.1128084

McGrane, S.J., Tetzlaff, D., Essery, R., Soulsby, C., 2014. Do catchment characteristics explain differences in coherence and trends in hydroclimatic behaviour in an upland region? Hydrology Research 45, 817. doi:10.2166/nh.2014.147

McGuire, K.J., McDonnell, J.J., Weiler, M., Kendall, C., McGlynn, B.L., Welker, J.M., Seibert, J., 2005. The role of topography on catchment-scale water residence time. Water Resources Research 41, n/a-n/a. doi:10.1029/2004WR003657

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales, in: Proceedings of the 8th Conference on Applied Climatology. pp. 179–183.

McMahon, G., Gregonis, S.M., Waltman, S.W., Omernik, J.M., Thorson, T.D., Freeouf, J.A., Rorick, A.H., Keys, J.E., 2001. Developing a spatial framework of common ecological regions for the conterminous United States. Environmental Management 28, 293–316. doi:10.1007/s002670010225

Melillo, J.M., Richmond, T.T., Yohe, G. (Eds.), 2014. Climate change impacts in the United States. U.S. Global Change Research Program.

Montanari, A., Shoemaker, C.A., van de Giesen, N., 2009. Introduction to special section on Uncertainty Assessment in Surface and Subsurface Hydrology: An overview of issues and challenges: INTRODUCTION TO SPECIAL SECTION. Water Resources Research 45, 4 pp. doi:10.1029/2009WR008471

Moore, J.N., Harper, J.T., Greenwood, M.C., 2007. Significance of trends toward earlier snowmelt runoff, Columbia and Missouri Basin headwaters, western United States. Geophysical Research Letters 34, n/a-n/a. doi:10.1029/2007GL031022

Nalley, D., Adamowski, J., Khalil, B., Biswas, A., 2016. Inter-annual to inter-decadal streamflow variability in Quebec and Ontario in relation to dominant large-scale climate indices. Journal of Hydrology 536, 426–446. doi:10.1016/j.jhydrol.2016.02.049

Nayak, A., Marks, D., Chandler, D.G., Seyfried, M., 2010. Long-term snow, climate, and streamflow trends at the Reynolds Creek Experimental Watershed, Owyhee Mountains, Idaho, United States. Water resources research 46, 15 pp. doi:10.1029/2008WR007525, 2010

Ning, L., Bradley, R.S., 2014. Winter precipitation variability and corresponding teleconnections over the northeastern United States. Journal of Geophysical Research: Atmospheres 119, 7931–7945. doi:10.1002/2014JD021591

Nippgen, F., McGlynn, B.L., Emanuel, R.E., Vose, J.M., 2016. Watershed memory at the Coweeta Hydrologic Laboratory: The effect of past precipitation and storage on hydrologic response. Water Resources Research 52, 1673–1695. doi:10.1002/2015WR018196

NRC (Ed.), 2008. Hydrologic effects of a changing forest landscape. National Academies Press, Washington, D.C.

O'Gorman, P.A., Schneider, T., 2009. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. Proceedings of the National Academy of Sciences 106, 14773–14777.

Olcott, P.G., 1995. Ground Water Atlas of the United States, Hydrologic investigations. US Geological Survey, Reston, VA.

Olden, J.D., Poff, N.L., 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications 19, 101–121. doi:10.1002/rra.700

Osborn, T.J., 2011. Variability and Changes in the North Atlantic Oscillation Index, in: Vicente-Serrano, S.M., Trigo, R.M. (Eds.), Hydrological, Socioeconomic and Ecological Impacts of the North Atlantic Oscillation in the Mediterranean Region, Advances in Global Change Research. Springer Netherlands, pp. 9–22.

Osborne, J.W., 2013. Best practices in data cleaning: A complete guide to everything you need to do before and after collecting your data. SAGE Publications, Inc., California United States.

Panda, D.K., Kumar, A., Ghosh, S., Mohanty, R.K., 2013. Streamflow trends in the Mahanadi River basin (India): Linkages to tropical climate variability. Journal of Hydrology 495, 135–149. doi:10.1016/j.jhydrol.2013.04.054

Pearson, K., 1901. On lines and planes of closest fit to systems of points in space. Philosophical Magazine Series 6 2, 559–572. doi:10.1080/14786440109462720

Peng, J., Yu, Z., Gautam, M.R., 2013. Pacific and Atlantic Ocean influence on the spatiotemporal variability of heavy precipitation in the western United States. Global and Planetary Change 109, 38–45. doi:10.1016/j.gloplacha.2013.07.004

Peters, D.P.C., Laney, C.M., Lugo, A.E., Collins, S.L., Driscoll, C.T., Groffman, P.M., Grove, J.M., Knapp, A.K., Kratz, T.K., Ohman, M.D., Waide, R.B., Yao, J., 2013. Long-Term Trends in Ecological Systems- A Basis for Understanding Responses to Global Change.pdf (Technical Bulletin No. 1931). United States Department of Agriculture-Agricultural Research Service.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime. BioScience 47, 769–784. doi:10.2307/1313099

Poff, N.L., Bledsoe, B.P., Cuhaciyan, C.O., 2006. Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems. Geomorphology 79, 264–285. doi:10.1016/j.geomorph.2006.06.032

Poff, N.L., Brown, C.M., Grantham, T.E., Matthews, J.H., Palmer, M.A., Spence, C.M., Wilby, R.L., Haasnoot, M., Mendoza, G.F., Dominique, K.C., Baeza, A., 2015. Sustainable water management under future uncertainty with eco-engineering decision scaling. Nature Climate Change 6, 25–34. doi:10.1038/nclimate2765

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O' ™Keefee, J.H., Olden, J.D., Rogers, K., Tharme, R.E., Warner, A., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology 55, 147–170. doi:10.1111/j.1365-2427.2009.02204.x

Poff, N.L., Ward, J.V., 1989. Implications of Streamflow Variability and Predictability for Lotic Community Structure: A Regional Analysis of Streamflow Patterns. Can. J. Fish. Aquat. Sci. 46, 1805–1818. doi:10.1139/f89-228

Poshtiri, M.P., Pal, I., 2016. Patterns of hydrological drought indicators in major U.S. River basins. Climatic Change 134, 549–563. doi:10.1007/s10584-015-1542-8

Pourmokhtarian, A., Driscoll, C.T., Campbell, J.L., Hayhoe, K., 2012. Modeling potential hydrochemical responses to climate change and increasing CO2 at the Hubbard Brook Experimental Forest using a dynamic biogeochemical model (PnET-BGC). Water Resources Research 48, 13 p. doi:10.1029/2011WR011228

Pourmokhtarian, A., Driscoll, C.T., Campbell, J.L., Hayhoe, K., Stoner, A.M.K., Adams, M.B., Burns, D., Fernandez, I., Mitchell, M.J., Shanley, J.B., 2016. Modeled ecohydrological responses to climate change at seven small watersheds in the northeastern United States. Global Change Biology. doi:10.1111/gcb.13444

Pryor, S.C., Howe, J.A., Kunkel, K.E., 2009. How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA? International Journal of Climatology 29, 31–45. doi:10.1002/joc.1696

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C., Kaplan, A., 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J. Geophys. Res. 108, n/a-n/a. doi:10.1029/2002JD002670

Razavi, T., Coulibaly, P., 2013. Classification of Ontario watersheds based on physical attributes and streamflow series. Journal of Hydrology 493, 81–94. doi:10.1016/j.jhydrol.2013.04.013

Reba, M.L., Marks, D., Winstral, A., Link, T.E., Kumar, M., 2011. Sensitivity of the snowcover energetics in a mountain basin to variations in climate. Hydrological Processes 25, 3312–3321. doi:10.1002/hyp.8155

Regonda, S.K., Rajagopalan, B., Clark, M., Pitlick, J., 2005. Seasonal cycle shifts in hydroclimatology over the western United States. Journal of Climate 18, 372–384.

Rice, K.C., Hirsch, R.M., 2012. Spatial and temporal trends in runoff at long-term streamgages within and near the Chesapeake Bay Watershed (Scientific Investigations No. 2012–5151). U.S. Geological Survey (USGS).

Richter, B., Baumgartner, J., Wigington, R., Braun, D., 1997. How much water does a river need? Freshwater Biology 37, 231–249. doi:10.1046/j.1365-2427.1997.00153.x

Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10, 1163–1174. doi:10.1046/j.1523-1739.1996.10041163.x

Richter, B.D., Warner, A.T., Meyer, J.L., Lutz, K., 2006. A collaborative and adaptive process for developing environmental flow recommendations. River Research and Applications 22, 297–318. doi:10.1002/rra.892

Rind, D., Perlwitz, J., Lonergan, P., 2005a. AO/NAO response to climate change: 1. Respective influences of stratospheric and tropospheric climate changes. Journal of Geophysical Research: Atmospheres 110, D12107. doi:10.1029/2004JD005103

Rind, D., Perlwitz, J., Lonergan, P., Lerner, J., 2005b. AO/NAO response to climate change: 2. Relative importance of low- and high-latitude temperature changes. Journal of Geophysical Research: Atmospheres 110, D12108. doi:10.1029/2004JD005686

Rodionov, S., 2015. A Sequential Method of Detecting Abrupt Changes in the Correlation Coefficient and Its Application to Bering Sea Climate. Climate 3, 474–491. doi:10.3390/cli3030474

Rodionov, S.N., 2006. Use of prewhitening in climate regime shift detection. Geophysical Research Letters 33, 4 p. doi:10.1029/2006GL025904

Rodionov, S.N., 2005. A brief overview of the regime shift detection methods, in: Large-Scale Disturbances (Regime Shifts) and Recovery in Aquatic Ecosystems: Challenges for Management toward Sustainability. UNESCO-ROSTE/BAS Workshop on Regime Shifts, Varna, Bulgaria. pp. 17–24.

Rodionov, S.N., 2004. A sequential algorithm for testing climate regime shifts. Geophysical Research Letters 31, 4 p. doi:10.1029/2004GL019448, 2004

Rogers, J.C., Coleman, J.S.M., 2003. Interactions between the Atlantic Multidecadal Oscillation, El Niño/La Niña, and the PNA in winter Mississippi Valley stream flow. Geophysical Research Letters 30, 25: 1-4. doi:10.1029/2003GL017216

Roller, C.D., Qian, J.-H., Agel, L., Barlow, M., Moron, V., 2016. Winter Weather Regimes in the Northeast United States. Journal of Climate 29, 2963–2980. doi:10.1175/JCLI-D-15-0274.1

Ropelewski, C.F., Halpert, M.S., 1986. North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation (ENSO). Mon. Wea. Rev. 114, 2352–2362. doi:10.1175/1520-0493(1986)114<2352:NAPATP>2.0.CO;2

Rose, S., Peters, N.E., 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. Hydrological Processes 15, 1441–1457. doi:10.1002/hyp.218

Rudnick, D.L., Davis, R.E., 2003. Red noise and regime shifts. Deep Sea Research Part I: Oceanographic Research Papers 50, 691–699. doi:10.1016/S0967-0637(03)00053-0

Sadri, S., Kam, J., Sheffield, J., 2016. Nonstationarity of low flows and their timing in the eastern United States. Hydrology and Earth System Sciences 20, 633–649. doi:10.5194/hess-20-633-2016

Sarmiento, S.E., 2010. Response of the Mackenzie River Basin lakes to climate variability. University of Houston, United States -- Texas.

Sawicz, K.A., Kelleher, C., Wagener, T., Troch, P., Sivapalan, M., Carrillo, G., 2014. Characterizing hydrologic change through catchment classification. Hydrology and Earth System Sciences 18, 273–285. doi:10.5194/hess-18-273-2014

Schaller, M.F., Fan, Y., 2009. River basins as groundwater exporters and importers: Implications for water cycle and climate modeling. Journal of Geophysical Research 114. doi:10.1029/2008JD010636

Schubert, S.D., Stewart, R.E., Wang, H., Barlow, M., Berbery, E.H., Cai, W., Hoerling, M.P., Kanikicharla, K.K., Koster, R.D., Lyon, B., Mariotti, A., Mechoso, C.R., Müller, O.V., Rodriguez-Fonseca, B., Seager, R., Senevirante, S.I., Zhang, L., Zhou, T., 2016. Global Meteorological Drought: A Synthesis of Current Understanding with a Focus on SST Drivers of Precipitation Deficits. Journal of Climate 29, 3989–4019. doi:10.1175/JCLI-D-15-0452.1

Seager, R., Naik, N., Vogel, L., 2011. Does Global Warming Cause Intensified Interannual Hydroclimate Variability? J. Climate 25, 3355–3372. doi:10.1175/JCLI-D-11-00363.1

Seager, R., Pederson, N., Kushnir, Y., Nakamura, J., Jurburg, S., 2012. The 1960s drought and the subsequent shift to a wetter climate in the Catskill mountains region of the New York City Watershed*. Journal of Climate 25, 6721–6742. doi:10.1175/JCLI-D-11-00518.1

Searcy, J.K., Hardison, C.H., Langein, W.B., 1960. Double-mass curves; with a section fitting curves to cyclic data (No. 1541–B), Water Supply Paper. US Geological Survey, Washington, DC.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's Tau. Journal of the American Statistical Association 63, 1379–1389. doi:10.2307/2285891

Serreze, M.C., Carse, F., Barry, R.G., Rogers, J.C., 1997. Icelandic Low Cyclone Activity: Climatological Features, Linkages with the NAO, and Relationships with Recent Changes in the Northern Hemisphere Circulation. J. Climate 10, 453–464. doi:10.1175/1520-0442(1997)010<0453:ILCACF>2.0.CO;2

Sheldon, J., Burd, A., 2014. Alternating Effects of Climate Drivers on Altamaha River Discharge to Coastal Georgia, USA. Estuaries and Coasts 37, 772–788. doi:10.1007/s12237-013-9715-z

Sivakumar, B., Singh, V.P., Berndtsson, R., Khan, S.K., 2013. Catchment classification framework in hydrology: challenges and directions. Journal of Hydrologic Engineering.

Skehan, J.W., 2001. Roadside Geology of Massachusetts, 1st ed. Mountain Press.

Slack, J.R., Landwehr, J.M., 1992. Hydro-Climatic Data Network: A U.S. Geological Survey streamflow data set for the United States for the study of climate variations, 1874 - 1988 (Open File Report). US Geological Survey, Reston, VA.

Sleeter, B.M., Sohl, T.L., Loveland, T.R., Auch, R.F., Acevedo, W., Drummond, M.A., Sayler, K.L., Stehman, S.V., 2013. Land-cover change in the conterminous United States from 1973 to 2000. Global Environmental Change 23, 733–748. doi:10.1016/j.gloenvcha.2013.03.006

Smakhtin, V.Y., 2001. Low flow hydrology: a review. Journal of Hydrology 240, 147–186. doi:10.1016/S0022-1694(00)00340-1

Smith, J.A., Baeck, M.L., Ntelekos, A.A., Villarini, G., Steiner, M., 2011. Extreme rainfall and flooding from orographic thunderstorms in the central Appalachians. Water Resources Research 47, n/a-n/a. doi:10.1029/2010WR010190

Smith, J.A., Villarini, G., Baeck, M.L., 2010. Mixture Distributions and the Hydroclimatology of Extreme Rainfall and Flooding in the Eastern United States. J. Hydrometeor 12, 294–309. doi:10.1175/2010JHM1242.1

Solecki, W.D., Rosenzweig, C., Parshall, L., Pope, G., Clark, M., Cox, J., Wiencke, M., 2005. Mitigation of the heat island effect in urban New Jersey. Environmental Hazards 6, 39–49. doi:10.1016/j.hazards.2004.12.002

Soulard, C.E., Sleeter, B.M., 2012. Late twentieth century land-cover change in the basin and range ecoregions of the United States. Regional Environmental Change 12, 813–823. doi:10.1007/s10113-012-0296-3

Spearman, C., 1904. “ General intelligence,” objectively determined and measured. The American Journal of Psychology 15, 201–292.

Steinschneider, S., Brown, C., 2011. Influences of North Atlantic climate variability on low-flows in the Connecticut River Basin. Journal of Hydrology 409, 212–224. doi:10.1016/j.jhydrol.2011.08.038

Steinschneider, S., Lall, U., 2016. Spatiotemporal Structure of Precipitation Related to Tropical Moisture Exports over the Eastern United States and Its Relation to Climate Teleconnections. Journal of Hydrometeorology 17, 897–913. doi:10.1175/JHM-D-15-0120.1

Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2004. Changes in snowmelt runoff timing in western North America under “a business as usual”climate change scenario. Climatic Change 62, 217–232.

Sutton, R.T., Hodson, D.L.R., 2003. Influence of the Ocean on North Atlantic Climate Variability 1871–1999. J. Climate 16, 3296–3313. doi:10.1175/1520-0442(2003)016<3296:IOTOON>2.0.CO;2

Tebaldi, C., Hayhoe, K., Arblaster, J., Meehl, G., 2006. Going to the Extremes. Climatic Change 79, 185–211. doi:10.1007/s10584-006-9051-4

Thompson, D.W.J., Wallace, J.M., Hegerl, G.C., 2000. Annular Modes in the Extratropical Circulation. Part II: Trends. J. Climate 13, 1018–1036. doi:10.1175/1520-0442(2000)013<1018:AMITEC>2.0.CO;2

Tootle, G.A., Piechota, T.C., Singh, A., 2005. Coupled oceanic-atmospheric variability and U.S. streamflow. Water Resources Research 41, W12408. doi:10.1029/2005WR004381

Trenberth, K., Zhang, R., National Center for Atmospheric Research Staff, 2015. The Climate Data Guide: Atlantic Multi-decadal Oscillation (AMO). National Center for Atmospheric Research.

Velpuri, N.M., Senay, G.B., 2013. Analysis of long-term trends (1950–2009) in precipitation, runoff and runoff coefficient in major urban watersheds in the United States. Environmental Research Letters 8, 024020. doi:10.1088/1748-9326/8/2/024020

Vianna, M.L., Menezes, V.V., 2013. Bidecadal sea level modes in the North and South Atlantic Oceans. Geophysical Research Letters 40, 5926–5931. doi:10.1002/2013GL058162

Villarini, G., 2016. On the seasonality of flooding across the continental United States. Advances in Water Resources 87, 80–91. doi:10.1016/j.advwatres.2015.11.009

Villarini, G., Smith, J.A., 2010. Flood peak distributions for the eastern United States. Water Resources Research 46, W06504. doi:10.1029/2009WR008395

Villarini, G., Smith, J.A., Baeck, M.L., Vitolo, R., Stephenson, D.B., Krajewski, W.F., 2011. On the frequency of heavy rainfall for the Midwest of the United States. Journal of Hydrology 400, 103–120. doi:10.1016/j.jhydrol.2011.01.027

Visbeck, M.H., Hurrell, J.W., Polvani, L., Cullen, H.M., 2001. The North Atlantic Oscillation: Past, present, and future. Proceedings of the National Academy of Sciences 98, 12876–12877.

Viviroli, D., Archer, D.R., Buytaert, W., Fowler, H.J., Greenwood, G.B., Hamlet, A.F., Huang, Y., Koboltschnig, G., Litaor, M.I., López-Moreno, J.I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M., Woods, R., 2011. Climate change and mountain water resources: overview and recommendations for research, management and policy. Hydrology and Earth System Sciences 15, 471–504. doi:10.5194/hess-15-471-2011

Viviroli, D., Schädler, B., Schmocker-Fackel, P., Weiler, M., Seibert, J., 2012. On the risk of obtaining misleading results by pooling streamflow data for trend analyses. Water Resources Research 48, W05601. doi:10.1029/2011WR011690

Vogel, R.M., Fennessey, N., 1994. Flow-duration curves I: New interpretation and confidence intervals. Journal of Water Resources Planning and Management 120, 485–504.

Vogelmann, J.E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., Van Driel, N., 2001. Completion of the 1990s National Land Cover Data set for the conterminous United States from Landsat thematic mapper data and ancillary data sources. Photogrammetric Engineering and Remote Sensing 67, 650–662.

Vose, J.M., Peterson, D.L., Patel-Weynand, T., 2012. Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the US (General Technical Report No. PNW-GTR-870). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Wang, D., Hagen, S.C., Alizad, K., 2013. Climate change impact and uncertainty analysis of extreme rainfall events in the Apalachicola River basin, Florida. Journal of Hydrology 480, 125–135. doi:10.1016/j.jhydrol.2012.12.015

Water Demand Analysis on Merrimack River Watershed, 2001. . Merrimack River Watershed Council, Lawrence MA.

Whitfield, P.H., Burn, D.H., Hannaford, J., Higgins, H., Hodgkins, G.A., Marsh, T., Looser, U., 2012. Reference hydrologic networks I. The status and potential future directions of national reference hydrologic networks for detecting trends. Hydrological Sciences Journal 57, 1562–1579. doi:10.1080/02626667.2012.728706

Wilbanks, T.J., Kates, R.W., 1999. Global change in local places: how scale matters. Climatic change 43, 601–628. doi:10.1023/A:1005418924748

Wood, E.F., Sivapalan, M., Beven, K., Band, L., 1988. Effects of spatial variability and scale with implications to hydrologic modeling. Journal of Hydrology 102, 29–47.

Wuebbles, D.J., Kunkel, K., Wehner, M., Zobel, Z., 2014. Severe Weather in United States Under a Changing Climate. Eos, Transactions American Geophysical Union 95, 149–150. doi:10.1002/2014EO180001

Xian, G., Homer, C., Dewitz, J., Fry, J., Hossain, N., Wickham, J., 2011. The change of impervious surface area between 2001 and 2006 in the conterminous United States. Photogrammetric Engineering & Remote Sensing 77, 758–762.

Yuan, X., Martinson, D.G., 2000. Antarctic sea ice extent variability and its global connectivity*. Journal of Climate 13, 1697–1717.

Yue, S., Pilon, P., 2004. A comparison of the power of the t test, Mann-Kendall and bootstrap tests for trend detection / Une comparaison de la puissance des tests t de Student, de Mann-Kendall et du bootstrap pour la détection de tendance. Hydrological Sciences Journal 49, 21–37. doi:10.1623/hysj.49.1.21.53996

Yue, S., Wang, C.Y., 2002. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. Water Resources Research 38, 1068. doi:10.1029/2001WR000861

10- Curriculum vitae

EDUCATION

Ph.D., Civil Engineering, 2017

- SYRACUSE UNIVERSITY, *Civil and Environmental Engineering Department*, Syracuse, NY
- Dissertation Topic: "***The Interacting Hydrologic Responses to Changing Climate, Watershed Physical Characteristics, River Regulation, and Land Development in the Northeastern United States***"
- Advisor: Prof. ***Charles T. Driscoll***

M.Sc., Hydraulic Structures Engineering, 2006

- SHARIF UNIVERSITY OF TECHNOLOGY, *Civil Engineering Department*, Tehran, Iran
- Thesis Topic: "***The Determination of Concrete Nonlinear Parameters in RCC Dams Using Experimental Results***"

B.Sc., Civil Engineering, 2003

- ZANJAN UNIVERSITY, *Civil Engineering Department*, Zanjan, Iran

RESEARCH AREAS

"**The Interacting Hydrologic Responses to Changing Climate, Watershed Physical Characteristics, River Regulation, and Land Development in the Northeastern United States**", Ph.D. Dissertation, (2011- to Present): Funded by Civil and Environmental Engineering Department
Performed in Civil and Environmental Engineering Department at Syracuse University, Syracuse, NY

- Studied the confounding effects of changing climate, river regulation, and land development on hydrologic response differentiated by geographical location and basin scale; studied the annual/seasonal teleconnection patterns of Sea Surface Temperature (Atlantic Multi-Decadal Oscillation: AMO) and Sea-Level Pressure (North Atlantic Oscillation: NAO) with watershed hydrology across the Northeastern United States.

Major Findings:

- Discovered the high dependency of hydrologic response on watershed's physical attributes
- Found more severe drought and flooding conditions in the northeastern US than the past century
- Diagnosed stronger response of Northeast hydrology to AMO than NAO variations
- Suggested further restriction on floodplain development due to more severe flooding in the Northeast

"**Reducing the Rate of Leakage from the Delaware Aqueduct Using Calcium Carbonate Precipitate**" (2010-2013): Funded by New York City Department of Environmental Protection
Performed in Civil and Environmental Engineering Department at Syracuse University, Syracuse, NY

- Studied the precipitation patterns of different dosage of Calcium Carbonate in mitigating leakage through the concrete liner of aqueducts.

Major Findings:

- Succeeded the complete blockage of water leakage in experimental crack units
- Determined the optimum dosage of Calcium Carbonate for blocking the leakage while meeting EPA drinking water standards
- Reduced of the leakage without interfering with the city water distribution

"**Static and Dynamic Analysis of Roller Compacted Concrete (RCC) Dams**" (2008-2009): Funded by Ministry of Science and Technology and Ministry of Energy
Performed in Civil Engineering Department at Sharif University of Technology, Tehran, Iran

- Assessed and estimated in situ characteristics of RCC required for nonlinear structural analysis of RCC dams.

Major Findings:

- Substantiated the nonlinear behavior of RCC
- Estimated precise and realistic values for RCC compressive strength, tensile strength, and fracture energy
- Synchronized model response with prototype due to realistic estimation of RCC in situ characteristics

PUBLICATIONS

Berton, R., Driscoll, C. T., Adamowski, J. F. (2017) "*The Near-Term Prediction of Drought and Flooding Conditions in the Northeastern United States with Regard to Extreme Phases of AMO and NAO*", Submitted to the Journal of Hydrology, Under Review

Berton, R., Driscoll, C. T., Chandler, D. G., Kelleher, C. (2017) "*The Responses of Ecological Discharge Indicators to Regime Shifts of Atlantic Multi-decadal Oscillation and North Atlantic Oscillation in the Northeastern United States*", Submitted to the Hydrological Sciences Journal, Revised and Ready to Resubmit

Berton, R., Driscoll, C. T., Chandler, D. G., (2016) "*Changing Climate Increases Discharge and Attenuates its Seasonal Distribution in the Northeastern United States*", Journal of Hydrology: Regional Studies, Vol. 5, PP. 164-178, DOI: 10.1016/j.ejrh.2015.12.057

Noorzad, A., **Berton, R.**, Ghaemian, M., Mazloumi, A., (2012) "*Determining the Fracture Energy of Roller Compacted Concrete Using Experimental Test Results*", Journal of Concrete Technology (in Persian)

Berton, R., Mazloumi, A., Ghaemian, M., (2009) "*Estimation of Fracture Parameters Using Experimental Test Results for Nonlinear Seismic Analysis of Jahgin RCC Gravity Dam*", International Water Power and Dam Construction, Journal of Dam Engineering, Vol. XX, Issue 1, PP. 5-38

Mazloumi, A., **Berton, R.**, Ghaemian, M., (2006) "*Experimental Tests for Determination of Fracture Parameters and Nonlinear Seismic Analysis of Jahgin RCC Dam*", International Congress on Computational Mechanics and Simulation (ICCMS-06), India

Berton, R., Mazloumi, A., (2006) "*Roller Compacted Concrete Specifications in Dams*", Road and Structure Monthly Magazine, No. 28, Iran (in Persian)

Berton, R., Berton, M., (2006) "*Learning and Instructing Methods*", 8th Iranian Mathematics Education Conference, ShahreKord, Iran (in Persian)

CONFERENCE PRESENTATIONS

Berton, R., Shaw, S. B., Chandler, D. G., Driscoll, C. T., (2015) "*Seasonal Discharge Predictions in regards to Temporal Variations of AMO and NAO in the Northeastern United States*", 52th Annual Hubbard Brook Cooperators' Meeting, Oral Presentation, Hubbard Brook, NH

Berton, R., Shaw, S. B., Chandler, D. G., Driscoll, C. T., (2015) "*Historical Climate Data Help Predict Future Water Availability*", 3-Minute Thesis Competition, Oral Presentation, Syracuse University, Syracuse, NY

Berton, R., Shaw, S. B., Chandler, D. G., Driscoll, C. T., (2014) "*The Use of Oceanic Indices Variations Due to Climate Change to Predict Annual Discharge Variations in Northeastern United States*", AGU Fall Meeting, Poster Presentation, San Francisco, CA

Berton, R., Shaw, S. B., Chandler, D. G., Driscoll, C. T., (2014) "*The Prediction of Annual Discharge Due to Oceanic Indices Variations in the Northeastern United States*", New England Graduate Student Water Symposium, Oral/Poster Presentation, University of Massachusetts Amherst, Amherst, MA

Berton, R., Driscoll, C. T., Shaw, S. B., Chandler, D. G., (2014) "*The Teleconnection of Merrimack Hydrology to AMO and NAO Oceanic Indices*", 51th Annual Hubbard Brook Cooperators' Meeting, Oral Presentation, Hubbard Brook, NH

Berton, R., Driscoll, C. T., Chandler, D. G., (2014) "*The Teleconnection of Streamflow Variations with Large-Scale Oceanic Variables in the Merrimack Watershed, NH-MA*", NUNAN Lecture & Research Day, Poster Presentation, Syracuse University, Syracuse, NY

Berton, R., Driscoll, C. T., Chandler, D. G., (2014) "*Hydrologic Response of the Merrimack Watershed (NH-MA) to Variations in Sea Surface Temperature and Sea Level Pressure*", Graduate Research Symposium, Poster Presentation, Syracuse University, Syracuse, NY

Berton, R., Driscoll, C. T., Chandler, D. G., (2014) "*The Assessment of Climate and Anthropogenic Impacts on*

Watershed Hydrology: A Case Study of the Merrimack Watershed, NH-MA", 3-Minute Thesis Competition, Oral Presentation, Syracuse University, Syracuse, NY

Berton, R., Driscoll, C. T., Chandler, D. G., (2013) "*Climate Regime Shifts and Streamflow Responses in the Merrimack Watershed, NH-MA*", AGU Fall Meeting, Poster Presentation, San Francisco, CA

Berton, R., Driscoll, C. T., Chandler, D. G., (2013) "*The Impact of Climate Regime Shift on Long-Term Spatiotemporal Trends of Hydrologic Variables in Developed Regions: A Case Study of the Merrimack Watershed, NH-MA*", Syracuse CoE Symposium on Environmental and Energy Systems, Oral Presentation, Syracuse, NY

Berton, R., Driscoll, C. T., Chandler, D. G., (2013) "*The Impact of Climate Regime Shift on Long-Term Temporal Trends of Hydrologic Variables: A Case Study of the Merrimack Watershed, NH-MA*", NUNAN Lecture & Research Day, Poster Presentation, Syracuse University, Syracuse, NY

Berton, R., Driscoll, C. T., Chandler, D. G., (2013) "*Assessing Climate and Anthropogenic Impacts on Long-Term Spatiotemporal Streamflow Variations: Merrimack Watershed, NH-MA*", 50th Annual Hubbard Brook Cooperators' Meeting, Oral Presentation, Hubbard Brook, NH

Berton, R., Driscoll, C. T., Chandler, D. G., (2013) "*A Comparison between Runoff Trends in a Headwater Basin and More Developed Watersheds: A Case Study of the Merrimack Watershed, NH-MA*", The Geological Society of America- Northeastern Meeting, Oral Presentation, Bretton Woods, NH

Berton, R., Driscoll, C. T., Chandler, D. G., (2012) "*Long-Term Trends in Streamflow for the Merrimack River Basin, NH-MA*", American Chemical Society- Northeast Regional Meeting, Oral Presentation, Rochester, NY

Berton, R., Driscoll, C. T., Chandler, D. G., (2012) "*A Preliminary Look at Climate Change Signals by Analyzing Streamflow Data for the Merrimack River Basin, NH-MA*", 49th Annual Hubbard Brook Cooperators' Meeting, Oral Presentation, Hubbard Brook, NH

TECHNICAL SKILLS

Languages: *SAS* (Statistical Analysis System); *R* (Statistical Computing and Graphics); *FORTRAN*

Software: *GIS* (Geographic Information System); *IHA* (The Indicators of Hydrologic Alteration); *AQTESOLV* (Advanced Software for Pumping Tests, Slug Tests, and Constant-Head Tests); *NSAG-DRI* (Nonlinear Seismic Analysis of Concrete Gravity Dams Including Dam-Reservoir Interaction); *EAGD84* (Earthquake Analysis of Concrete Gravity Dams); *FRAC-DAM* (Fracture Analysis of Concrete Gravity Dams); *CADAM* (Computer Aided Stability Analysis of Gravity Dams); *MINITAB* (Statistical and Process Management)

TEACHING EXPERIENCE

Teaching Assistant (2009-2016)

Civil and Environmental Engineering Department, Syracuse University, Syracuse, NY

- Applied Environmental Microbiology; Civil and Environmental Engineering Design; Environmental Chemistry and Analysis; Principal of Fluid Mechanics; Treatment Processes in Environmental Engineering; Water Resources Engineering
    - Developed exam materials; conducted recitation sessions; conducted laboratory experiments; managed and coordinated lab activities; developed assignment’s answer key; graded quizzes, homework assignments, and laboratory reports; conducted office hours; evaluated term project/presentation; tutored and instructed students

Private Tutor (1999-2009)

Tehran, Iran

- Advanced Engineering Mathematics; Analysis of Structures; Calculus (I, II, and III); Differential Equations and Matrix Algebra; Dynamics; Engineering Probability and Statistics; Fluid Mechanics; Hydraulic Engineering; Mechanics of Solids; Numerical Computations; Soil Mechanics; Statics
- Graduate and Undergraduate University Entrance Exam Preparation

- Young Mathematician Institute, Advanced High School Mathematics
- Mathematics and Informatics Institute, Advanced High School Mathematics
- Collaboration on Creating Mathematics Self-Study Books for Elementary, Middle and High School Students
- Translation of Technical and Academic Articles to Persian (Native Language)

PROFESSIONAL EXPERINCE

Senior RCC Dam Expert (2006-2009): Department for Design of Embankment Dams & Concrete Technology, Moshanir (Power Engineering Consultants) *and* Iran Water Resources Management Co. (IWRM), Ministry of Energy, Tehran, Iran

- Created project-specific procedures and standards for in situ characteristics of RCC which prevented financial waste, saved time, and provided strategy for efficient RCC dam construction.
- Developed a technical note on cement specifications and prepared a report on optimizing cement delivery for RCC projects. These documents became a reference among engineering consultants in Iran.
- Collaborated with a "Special Expert Panel" responsible for assessing/approving Iran water resources projects.
- Designed and implemented Information Management Policy to serve as a tool for thorough assessment of water resources projects.

Staff Engineer (2001-2003): Sazvarehno *and* Istabon Engineering Consultants, Tehran, Iran

- Designed and analyzed earthquake-resistant steel and concrete structures.

LANGUAGE SKILLS

English (Fluent)
Persian (Native)

UNIVERSITY SERVICES AND ACTIVITIES

Reviewer (2015-Present)
"ASCE Journal of Hydrologic Engineering"
Teaching Mentor (2014-2015)
"International Student Orientation Program"
- Led/moderated "The American classroom", "Adjusting to a New Culture", and "Living in Syracuse" sessions

Committee Member (2014-2016)
"Excellence in Graduate Education Faculty Recognition Award" Selection Committee
President (2014-2015)
"Persian Student Association (PSA)" at Syracuse University

HONORS AND DISTINCTIONS

Outstanding Teaching Assistant Award (2014-15)

First place of NUNAN Research Day Poster Competition (2013), Civil and Environmental Engineering Department Award, Syracuse University, Syracuse, NY

Teaching Assistantship, Syracuse University (2009-present)

Third Place of the "Elites and Educators" Award (2006), Ministry of Science and Technology-Military Service, Tehran, Iran

First Place of the Hydraulic Structures Engineering Group (2003), Civil Engineering Department, Sharif

University of Technology, Tehran, Iran

Top 1% in Civil Engineering Nation-Wide Graduate University Entrance Exam (2003), Iran
Top 5% in Nation-Wide Undergraduate University Entrance Exam (1997), Iran

PROFESSIONAL AFFILIATIONS

- The Long-Term Ecological Research (LTER) (2014-to Present)
- The Geophysical Society of America (AGU) (2011-to Present)
- American Society of Civil Engineers (ASCE) (2011-to Present)
- Geological Society of America (GSA) (2011-to Present)
- Iranian Tunneling Association (IRTA) (2004-to Present)
- Iranian Concrete Institute (ICI) (2004-to Present)
- Iranian National Committee on Large Dams (IRCOLD) (2004-to Present)

GRADUATE COURSEWORK

- Advanced Engineering Mathematics
- Advanced Hydraulic
- Analysis of Variance
- Applied Environmental Microbiology
- Biogeochemistry
- Chemistry of Soil and Natural Surfaces
- Design and Analysis of Concrete Dams
- Design and Analysis of Tunnels
- Environmental Chemistry and Analysis
- Water Quality Modeling
- Finite Element Methods and Applications
- Geographic Information Systems
- Hydraulic Models
- Hydraulic Structures Design
- Hydrogeology
- Multivariate Statistical Methods
- Transport Processes in Environmental Engineering
- Vibration of Structures
- Water and Hydraulic Seminar
- Water Resources Management