# Cyclical and Increasing Precipitation and Runoff in the Winooski River Basin, Northern Vermont

**Formatted for:**
**Journal of Hydrology**

**Draft #-class- 4/5/09**


**William R. Hackett[a*], Paul R. Bierman[b], Lance E. Besaw[c], and Donna M. Rizzo[d]**

***- Denotes Corresponding Author**

[* a] Department of Geology, University of Vermont
180 Colchester Ave., Burlington VT 05405, USA
Email- William.Hackett@uvm.edu, phone: 315-657-8101

[b] Department of Geology and School of Natural Resources, University of Vermont
180 Colchester Ave., Burlington VT 05405, USA
Email- Paul.Bierman@uvm.edu, phone: 802-656-4411

[c] College of Engineering and Mathematical Sciences, University of Vermont
33 Colchester Ave., Burlington VT 05405, USA
Email- Lance.Besaw@cems.uvm.edu, phone: 802-999-6573

[d] College of Engineering and Mathematical Sciences, University of Vermont
33 Colchester Ave., Burlington VT 05405, USA
Email- Donna.Rizzo@cems.uvm.edu, phone: 802-656-1495

## Abstract

This study analyzes temporal trends and periodicity in seventy years of publicly available stream discharge and climate data for the Winooski River Basin of northern Vermont as well as lake level data for adjacent Lake Champlain. We find a general increase in annual precipitation discharge, and mean lake level with time in the basin; discharge increases 18% over the period of record while precipitation increases by 14%. Over the last 70 years, mean annual temperature has increased at the Burlington Vermont station by 1.4 degrees." Spectral analysis of precipitation, discharge and lake level data show a ~7.6 year periodicity, which is in phase with the North Atlantic Oscillation (NAO); higher than average precipitation and discharge are most likely when the NAO is in a positive mode. The NAO relationship demonstrates that discharge is largely controlled by precipitation, anthropogenic changing climate and changing land use over the past 70 years appear to have subtly changed the seasonality of discharge and caused an increase in baseflow.

## Introduction

Water is a critical resource for human society. Dependable precipitation catalyzes agriculture whereas river discharge supplies water for drinking, irrigation, and aquatic ecosystems (Bennie and Hensley, 2001; Ludwig et. al., 2009). Changing seasonality, precipitation and temperature regimes can all affect agriculture thereby disrupting food production (Easterling, 1996). Changing amounts and seasonal distribution of precipitation can strain urban infrastructure including wastewater treatment facilities, impoundments, and storm water runoff control systems, which are designed assuming stationarity in climate and this precipitation and discharge (Milly, et al., 2008). Climate change has and will continue to change the properties of regional weather, potentially exceeding the design capacity of these systems. Development brings more impermeable surfaces and more densely structured and immobile homes, businesses, and infrastructure increasing run-off efficiency and peak discharge (Dunne and Leopold, 1996; Zarriello et. al., 1999).

Climate and discharge records often exhibit cyclical behavior, driven through teleconnections to atmospheric and oceanic changes (Labat, 2006; *Decade to Century Scale Climate Variability and Change, 1998*). For example, El Nino/ Southern Oscillation (ENSO), a sea surface temperature change reflecting changes in ocean circulation has been linked on a variety of timescales to precipitation and discharge records in western North America (El-Askary et al., 2004). Its effects on eastern North America are generally limited to milder winters with more storms during warm El Niño years (National Weather Service, 2006). The North Atlantic Oscillation (NAO) is traditionally defined as the difference in sea level pressures between the Azores high and Icelandic low and since the NAO is most active in the winter, it is usually calculated as being the mean difference in these pressures during the winter months (Hurrell and Van Loon, 1997; Solow, 2002). In eastern North American, NAO activity can bring increased storminess over long time scales and wetter winters when the index is positive or dryer winters when the index is negative (Hurrell, 1995, Norens et al., 2002). These data are found in New England, where Massachusetts coastal sea surface temperatures exhibit some correlation with the North Atlantic Oscillation index during the winter months (Nixon et al; 2003).

Climate change, detected as long-term trends in the amount and distribution of temperature and precipitation, can be natural or human-induced. Global average temperature increased slightly during the first half the twentieth century; during the latter half of the 1900's, the most rapid warming trend documented took place (IPCC, 2008). This is also documented in east coast sea surface temperatures, which show an increase in the first half of the 1900's followed by a ~15 year decrease in temperature before resuming a warming trend for the latter half of the century (Friedland, 2007). This warming has been accompanied by a general increase in precipitation in the northern latitudes (IPCC, 2008). An increase in warm season storm frequency in many areas of North America has also been documented; the result perhaps of increased moisture-holding capacity of the warming atmosphere (OECD, 2008). Warming has decreased the amount of seasonally frozen ground (IPCC, 2008) and warmer winter temperatures have reduced snowpack in many areas, causing earlier ice breakup on lakes as well as higher early spring flows with earlier snowmelt (Hodgkins, 2005).

There is general agreement regarding the overall effects of global warming on the hydrologic cycle. Precipitation is projected to increase over the mid to high latitudes, with a strong likelihood of an increase in frequency of heavy precipitation events (Chen, 2005; IPCC, 2008). Increased warming during the winter months is also projected to continue, yielding thinner snowpacks that accumulate later in the fall and melt earlier in the spring (Hodgkins, 200*; IPCC, 2008). Summer warming and the higher moisture capacity of the atmosphere will cause the land surface to dry more quickly, reducing baseflow and providing more moisture for storm systems (OECD, 2008; Steele-Dunne et al., 2008). Warming will effect seasonality which, coupled with increased precipitation, is projected to continue to increase discharge in the northern latitudes while rivers of Africa and Europe will experience less flow (IPCC, 2008). Precipitation increases are predicted to be especially prevalent in winter with little or no change in the summer (Hayhoe, 2007). Increasing temperatures and changes in moisture availability will likely change atmospheric and sea surface conditions, affecting oscillations such as ENSO and the NAO; however, there is disagreement over how the amplitude and frequency of these oscillations will change (Rodbell, ’99; IPCC, 2008).

In New England, where western settlement dates back over 300 years, there are detailed records of temperature, precipitation and discharge dating back nearly a century. In New England, there has been a general upward trend in regional temperature since the end of the Little Ice Age (Broecker, 2001). Temperatures oscillated through most of the 20th century before rising since the 1970’s both on land and along the New England coast (Davis; et al, 1979; Nixon et al; 2003, Hayhoe, 2007). These warming temperatures are corroborated by earlier ice out in New England’s lakes, which are ice free on average 16 days earlier than a century ago in southern/ central New England because of an estimated 2.6 degree temperature increase (Hodgkins, 2005). The reduction of ice on New England’s lakes is primarily correlated with March and April temperatures, which have been warming. Precipitation has been increasing to a modest degree, though there have been periods of drought particularly in the 1960’s (Hurtt and Hale,****). In New England, streamflow has also been increasing with the center of mass and peak flows coming earlier with earlier snowmelt in the spring (Huntington, 2003).

Climate change predictions for New England suggest that summer flows will decrease as a longer growing season and increased evapotranspiration remove more water from the land surface (Huntington, 2003). The change in seasonality will drive much of this change, as increasing winter flows will be fueled by earlier snowmelt and precipitation as rain instead of snow while spring discharge will decrease (IPCC, 2008).

Landuse, which affects run-off efficiency and thus discharge records has changed, significantly in New England over the past century. Colonial development in New England was primarily agricultural; farming peaked in the late 1800’s as economic pressures (competition from the mid west) and erosion of upland farms began to drive some farms to failure (Wessels, 1997, Albers, 2000). Since this time, much of New England has reforested; changing the hydrology of these areas (Wessels, 1997). What were once cultivated fields or pastures were overtaken by forest, increasing evapotranspiration and reducing erosion (Juckem et al., 2008, Forman and Alexander, 2008). Coincident and following reforestation however, there has been an increase in development and thus impervious surfaces (Liebs, 1995; Wassmer, 2002). Over the last 70 years in the Winooski River basin, land use has changed significantly, with forested area increasing from 72% to 82%, open fields decreasing from 23% to 9%, and impervious surfaces increasing from 4% to 9% (Hackett et al., 2009).

This study uses daily weather, river discharge, and lake level data from the Winooski River Basin in northern Vermont to identify temporal trends and periodicities in climate and river flow from 1937 to 2005. We examine the relationship between precipitation, discharge, and lake level and test for relationships to cyclical drivers including ENSO and the NAO. Because changing climate will likely affect the seasonality of temperature and precipitation, we also examine base flows, storm frequency and intensity, and seasonality. Using land cover data over the period of record (Hackett et al., 2009), we speculate about the relative effects of development and climate change on the changing timing and magnitude of discharge that we detected in flow records of the Winooski River and its tributaries.

## Study Area

Vermont's landscape is dominated by the rugged Green Mountains, which consist of hard metamorphic rock, rise to elevations over 1400 m, and form the headwaters of the 2,704 $km^2$ Winooski River Basin (USGS NWIS, 2008). To the west, the Champlain Valley is underlain by sedimentary rocks and has a more subdued topography and richer, more productive farmlands (Doolan, 1996; Mehrtens, 2001). Glaciers once covered the Green Mountains and left behind substantial quantities of sediment in the form of stony, impermeable glacial till in the mountains, well-drained sand and gravel along some valley walls, dense clay in many valley bottoms, and permeable, fertile alluvium near river channels (Doll, 1970). There is generally more exposed rock and less soil at higher elevations (Doll, 1970; Wessels, 1997).

**Data Sources**

We tested for temporal trends and cyclicity by analyzing publicly available data from federally monitored National Climate Data Center (NCDC) weather and United States Geological Survey (USGS) river discharge stations throughout the Winooski River Basin in northern Vermont (Figure 1). Discharge stations were installed in the early 1900's at six locations within the basin; all except one station was installed in the decade following the 1927 flood, which is the flood of record in Vermont (USGS, 2008; Chartuk, 1997). Two stations monitor the main channel of the Winooski River and the four others gage discharge on major tributaries (the Little, Dog, Mad, and North Branch Winooski) where they discharge into the main stem Winooski River. The * River sub basin is dominated by *(hydro info), *(geomorph info), and *(land cover) (Table 1). Additionally, a USGS lake level gage is maintained on Lake Champlain in Burlington, VT. National Weather Service Stations provide data from another six locations around the Winooski River Basin. These stations provide daily data for at least the past sixty years.

**Methods**

To establish long term (multi-decadal) trends in the data, we linearly regressed annual average values of discharge, precipitation, lake level, and temperature (~1930-2005) against time (Figure 2). We repeated this process using monthly data to investigate changes in seasonality. Additionally, we examined the magnitude and intensity of storm precipitation and discharge as well as the characteristics of base flow over time. For each bi-variate plot, we determined a slope and tested through the significance (p value) of a linear trend line over the period of record. To examine the relationships between sub basins and the overall basin discharge, we analyzed the annual percentage contribution each sub basin makes to the total basin flow over time. We defined a threshold for large storms as the smallest annual maximum precipitation event in the period of record. Using that rainfall total as a threshold, we then examined the frequency of extreme storms per year, the total precipitation delivered by the largest three storms each year, as well as the total precipitation delivered over the 20 wettest days of each year. To determine whether the there was a temporal trend in high and low flows, we calculated the three highest and then the three lowest discharge days per year. Temperature analysis includes trends in mean monthly lows and highs, as well as trends of the difference between low and high means for each month.

To test for natural periodicities in the data, we applied a linear spline with a fit of lambda=1 to the plotted records to identify the phase and amplitude of cyclic oscillations in the data. Then, using spectral analysis, we deconvolved the data into noise and signal (Figure 3). Using "Auto Signal" (REF), we conducted a fast fourier transformation on these data in order to filter out the red noise from the periodic signals. Removal of red noise to better exposed the signal because spectral power increases with decreasing frequency as a result of the noise (REF).

Geophysical and atmospherically forced data are typically filtered adjusted for red noise because it has a "memory" component while traditional white noise does not (Overland et al., 2006; Shulz and Mudelsee, 2002).

## Data and Results

*ANNUAL RECORDS*

Considered on an annual scale, both precipitation and discharge have been increasing over the past ~70 years. These trends are statistically significant (at the 80% confidence level) for all six discharge stations and all four weather stations (Table 2). Annual totals of precipitation at Burlington Airport and runoff at the gaging stations are well correlated with $R^2$ values ranging between 0.5 and 0.7 for the entire period of record. Runoff and precipitation are better correlated between 1963-2005 ($R^2$ between 0.5 and 0.7, $\mu$= 0.61) than between 1935-1962 ($R^2$ between 0.3 and 0.5, $\mu$= 0.39) (Figure 4). The percentage of water contributed to the mainstem Winooski River from two headwater basins (Wrightsville and Montpelier) decreased over time (at the 95% confidence level). In contrast, the percent of water contributed by the Little River, which is dammed, increased over time (Table 2).

*STORMS AND BASEFLOW*

The frequency (number per year) of extreme precipitation events is increasing, significant at the 90% confidence level at two stations (Table 3). However, while frequency of strong storms may be increasing, the intensity of these events is not. Only one of the four weather stations had an increase in intensity of storms at the 90% significance level. Three of the four stations also showed a decrease over time in the contribution of the 20 largest precipitation events to the total annual precipitation.

The total daily discharge during the three highest flow days per year decreased at five of the six stations at significance levels ranging from 0.5 to 0.1 (Table 3). Conversely, total flow on the three lowest flow days per year (baseflow) showed statistically significant (95% confidence level) increases in flow at all stations.

*MONTHLY ANALYSES*

There is a consistent increase in precipitation at all stations in the latter half of the year from August to November; three of the five weather stations show a significant (at the 95% confidence level) increase in precipitation (Table 4). Four of the stations show no change during February, May, or June.

Discharge has increased over most months of the year at most stations (Table 5). Diminished flow occurs only between March and May and is significant at the 90% confidence level for only one station during only one month (May). Monthly flows between July through December increase in discharge at most stations, with the greatest significance (smallest p-values) in the last months of the year.

*TEMPERATURE*

Annual mean low and high temperatures trend significantly (at the 95% confidence level) upward at the Burlington Airport 0.16 and 0.22 degrees Fahrenheit per decade, respectively; there is no significant change in Montpelier (Table 6). When these data were separated into monthly mean, mean low, and mean high records, every month showed an increasing mean, low, and high temperature except for October, which had a decrease of low significance at Burlington ($p = 0.37$- 0.48) and greater significance at Montpelier ($p = 0.031$). At Burlington, the spread between mean monthly low and high is getting wider in the spring months of March, April, and May, with no significant change during the other nine months of the year (Figure 5).

*SPECTRAL ANALYSIS*

Spectral analysis of discharge, precipitation, temperature, and lake level records revealed statistically significant periodicity in each (Figure 6). Using annual data, the periods with the four strongest spectral densities were identified and compared between individual stations. Results showed a clustering of periods between 2 and 3.5 years in both the precipitation and discharge data at all stations. The fourth spectral peak in discharge and precipitation is between 7 and 8.5 years for all stations. Annual mean Lake Champlain water level gage height data also show a period at 7.4 years. When annual indexes for the North Atlantic Oscillation (obtained from NOAA) were analyzed using spectral analysis, that record showed its strongest spectral peak at 7.6 years.

**Discussion**

Over the past 70 years, northwestern Vermont has become wetter and warmer, consistent with trends noted in nearby states (Huntington, 2003; Nixon et al., 2003). Superimposed on these secular trends is a periodic variation (7 to 8 year cyclicity) in precipitation, temperature, river discharge and lake level that most likely reflects NAO status (Figure 7). The robust correlation of annual precipitation and discharge values ($R^2$ values, 0.5-0.7, Table 2) and the similarity in relative amplitude and phase of linear splines applied to both precipitation and discharge records (Figure 2) together indicate that changes in river discharge on an annual time scale are predominately driven by changes in precipitation. The cyclical precipitation signal (Figure 6) and the secular trend (Figure 7) are both clearly reflected in the level of Lake Champlain- the receiving body into which the Winooski River flows. The average annual lake level is rising over time along with precipitation and discharge.

The NAO affect on northern New England climate and thus riverine discharge is consistent with findings around the North Atlantic on a variety of time scales. For example, a similar study conducted in France found a 5 to 8 year periodicity in precipitation and discharge records (1946to 2006) for the Seine River Basin (Massei, 2008, 2009). In New England, Bradbury et al., 2002 found that stream discharge stations across the region corresponded to NAO values; low NAO winters were found to bring lower streamflows. The NAO also varies on longer time scales. Ice core records from Greenland and paleostorminess records from New England show coincident phasing on 3000 year cycle interpreted as long time scale fluctuations in the Arctic Oscillation, an atmospheric index closely related to the NAO (Noren et al., 2002).

The increase in mean annual temperature and precipitation over the last 70 years in the Winooski River Basin is consistent with a variety of direct and proxy records collected elsewhere in New England. For example, warming is reflected well by central New England lakes that are ice free an average of 16 days earlier than a century ago (Hodgkins, 2005). Increasing precipitation, particularly during the fall months, is common to other areas in New England (Huntington, 2003) while temperature in New England and New York have also been increasing over the past century (Trombulak and Wolfson, 2004). Lake level records from Maine suggest that lake levels today are higher than they have been during most or all of the last 10,000 years suggesting long-term increases in precipitation (Dieffenbacher-Krall and Nurse, 2005)

The effects of landuse change over the past 70 years on river discharge are uncertain but likely minor in comparison to changing precipitation as evidenced by the strong correlation between runoff and precipitation and the dominance of the NAO periodicity in the splined records. Although documented increases in both forest and impervious cover are offsetting hydrologically, with one increasing runoff and the other increasing infiltration, our analysis suggests subtle responses to landuse change. For example, although the frequency of large storms is increasing (Table 3), their intensity is not and over the last 70 years, these largest storms are contributing less to annual discharge totals. Changing land use, to a more forested basin, may be responsible for this shift as the heavily forested landscape makes the basin less flashy, increasing flows for moderate events (Zheng, 2008).

The consistent and statistically significant increase in baseflow we noted at all stations (Table 3) likely reflects the interaction of landuse change and increasing precipitation over time. Net reforestation of the basin has increased infiltration, which coupled with rising precipitation offsets increased evapotranspiration from both more trees and higher annual temperatures (Hough, 1986). This inference is supported by the observation that the strongest trends of increasing baseflow occur in the fall months, when evapotranspiration begins to shut down and the trees play less of a role in capturing precipitation and groundwater (Dunn and Mackay, 1995). Similar trends in baseflow were found in Iowa, where the increase in baseflow and discharge in general could not be explained by increased precipitation alone; instead changing landuse to less intensive agriculture and forest practices exacerbated the flow increase (De la Cretaz and Barten, 2007; Juckem et al., 2008).

Our results hint at changing seasonality and a complex hydrologic response. Average temperature during the spring months is rising (Table 6), along with an increase in the temperature variability during this time (significant at the 95% confidence level at Burlington and Montpelier stations). Earlier warming diminishes the snowpack and increases evapotranspiration as vegetation buds out earlier in the season (Huntington, 2003; Thompson and Clark, 2008). These effects are consistent with our observation that although March precipitation in the Winooski River Basin has increased (Table 4), discharge either decreases of remains unchanged (Table 5) suggesting less contribution from a thinner snowpack. Unchanging or decreased discharge during April to June may result, despite the increased precipitation, from increased water demand by vegetation and a decrease in the late spring snowmelt (Huntington, 2003). By May, the forest is evapotranspiring significant amounts of water (Huntington, 2003). The reforestation-driven increase in ET is best reflected in this month as stations in every sub basin show a decrease in discharge despite unchanging levels of precipitation.

## Conclusions

Analysis of climate, discharge and lake level records in the Winooski River Basin, a large northern New England watershed, shows clearly that temperature, precipitation, discharge, and the level of Lake Champlain have all increased over the last 70 years. Superimposed on these secular trends is a strong, sub-decadal periodicity consistent with large scale climatic forcing by atmospheric dynamics, specifically the North Atlantic Oscillation. The amount of precipitation is the most important variable affecting runoff; however, the data hint at effects of both land use change and shifting seasonality. Reforestation has increased the hydrologic importance of evapotranspiration, an effect that appears to be offset wholly or in part by increasing precipitation and the creation of impervious surfaces. Despite the increase in forest cover, baseflows are rising. Warmer winter temperatures, as well as earlier spring warming, are beginning to change the dynamics of the system, particularly in terms of spring river discharge.

**Acknowledgements**

Research supported in part by a fellowship to Hackett and summer support for Bierman under NSF grant NSF EPS-0701410 (Vermont EPSCoR). We thank the 2009 University of Vermont Critical Writing class for their review of an early draft of this paper.

**References**

Still working on these….

Albers, 2000
Bennie and Hensley, 2001;
Bradbury et al., 2002
Broecker, 2001
Chartuk, 1997
Chen, 2005
Davis; et al, 1979
De la Cretaz and Barten, 2007
*Decade to Century Scale Climate Variability and Change, 1998*
Dieffenbacher-Krall and Nurse, 2005
Doll, 1970
Doolan, 1996;
Dunn and Mackay, 1995
Dunne and Leopold, 1996;
Easterling, 1996
El-Askary et al., 2004)
Forman and Alexander, 2008
Friedland, 2007
Hackett et al., 2009
Hayhoe, 2007
Hodgkins, 2003
Hodgkins, 2005

Hough, 1986
Huntington, 2003
Hurrell and Van Loon, 1997;
Hurrell, 1995,
Hurtt and Hale,****).
IPCC, 2008
Juckem et al., 2008,
Labat, 2006;
Liebs, 1995;
Ludwig et. al., 2009
Massei, 2008, 2009
Mehrtens, 2001
Milly, et al., 2008
National Weather Service, 2006
Nixon et al; 2003
Noren et al., 2002
Norens et al., 2002
OECD, 2008
Overland et al., 2006;
Rodbell, ’99
Shulz and Mudelsee, 2002
Solow, 2002
Steele-Dunne et al., 2008
Thompson and Clark, 2008
Trombulak and Wolfson, 2004
USGS, 2008;
Wassmer, 2002
Wessels, 1997,
Zarriello et. al., 1999
Zheng, 2008

**Figure Captions:**

Figure 1- The Winooski River Basin showing US Geological Survey gaging stations and National Climate Data Center weather stations.  Base map From Vermont Center for Geographic Information.

Figure 2- Total annual precipitation at Waterbury, Vermont and annual discharge on the Mad River, Vermont from 1943-1990- raw data from National Climate Data Center.

Figure 3- Auto Signal output showing spectral analysis of annual precipitation at Burlington International Airport from 1930-2005- raw data from National Climate Data Center.  Curved lines represent confidence levels- all peaks are above the 95% significance level

Figure 4- Mean annual precipitation and discharge at the Essex Junction USGS discharge station (USGS, 2008) for (A) 1936-1965 and (B) 1966-2005 are well correlated.

Figure 5- March mean high temperatures (A) and annual difference between March mean low and high temperatures (B) at the Burlington Airport.

Figure 6- Summary of spectral analysis (using Auto Signal) output showing four strongest spectral signals for discharge, precipitation, temperature, and Lake Champlain level in the Winooski River Basin- raw data from USGS and NCDC.

Figure 7- Linear spline illustrates regular oscillations which are in phase between (A) precipitation, (B) Lake Champlain gage height, (C) Annual mean high temperature at Burlington, and (D) North Atlantic Oscillation index records, and (E) Winooksi River discharge at Essex.

## Figures

Table 1. Sub Basin Characteristics[1]

| Sub Basin | Area | Landcover | Geomorphic setting | Hydrologic setting |
|---|---|---|---|---|
| Little River | | | | |
| North Branch | | | | |
| Mad river | | | | |
| Dog River | | | | |

[1] This will include this basic info for the sub basins.

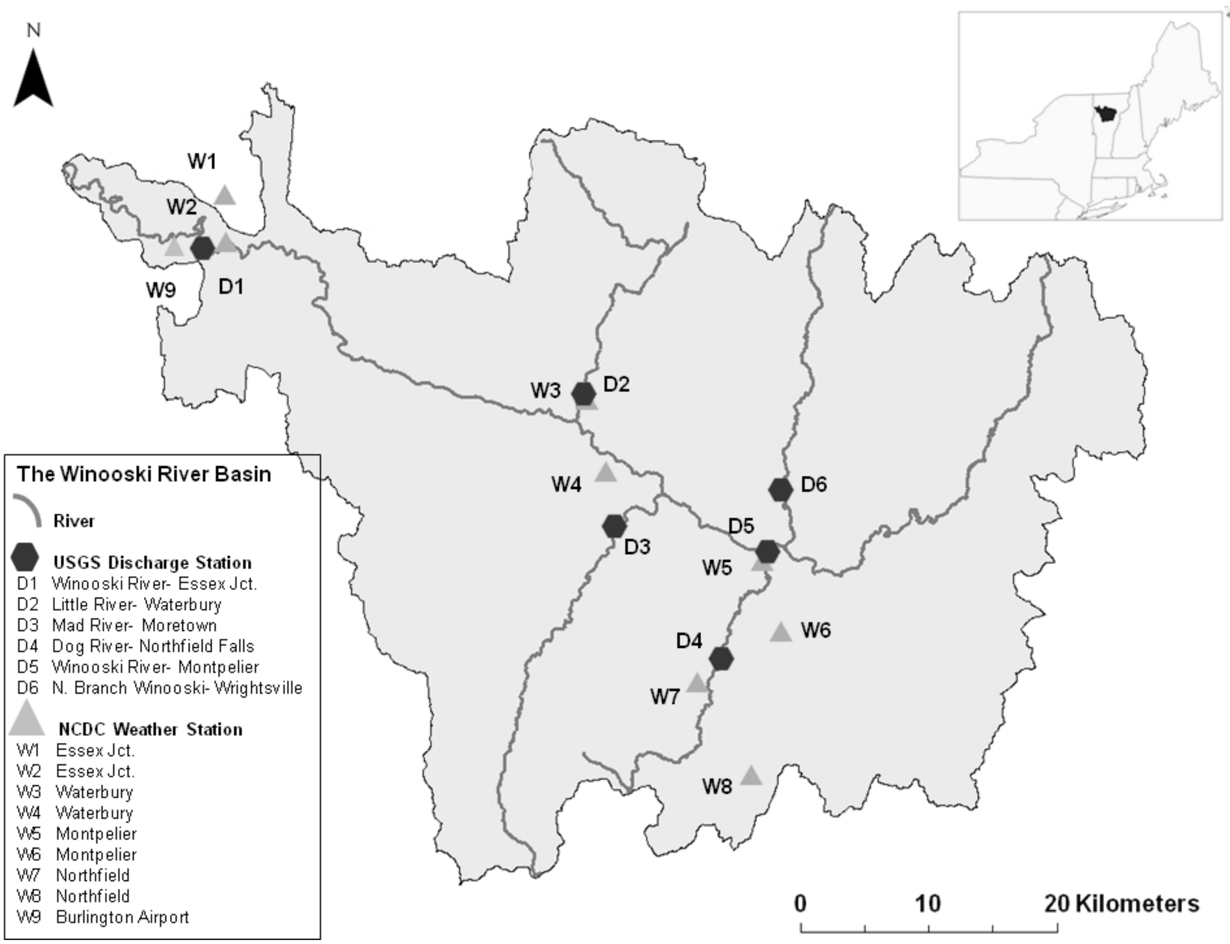


Figure 1.

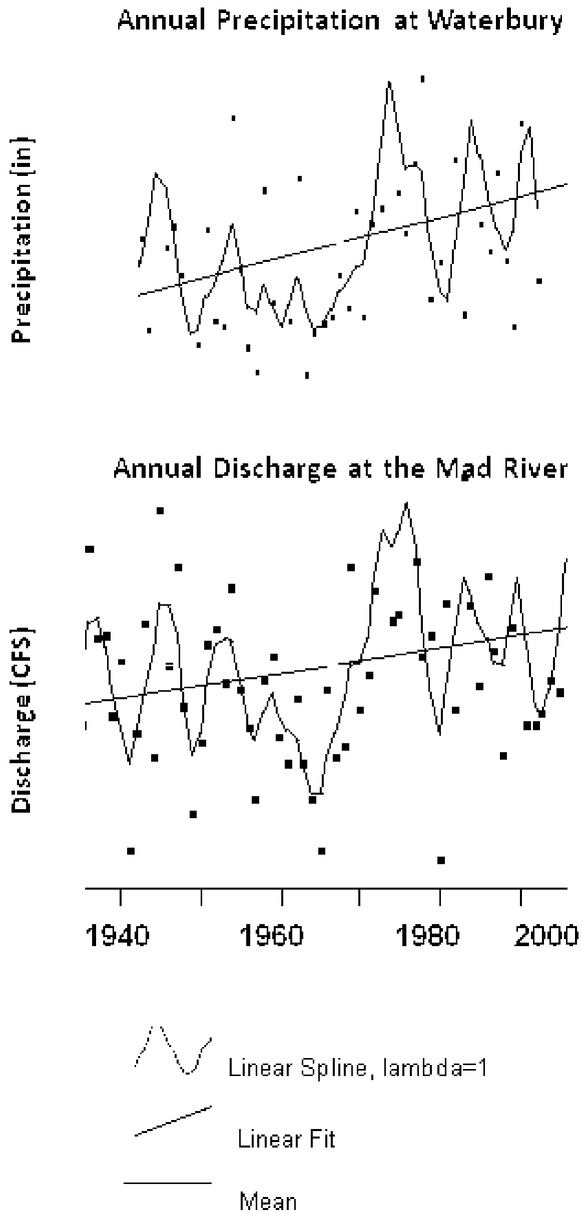
Annual Precipitation at Waterbury
Precipitation (in)
Annual Discharge at the Mad River
Discharge (CFS)
1940
1960
1980
2000
Linear Spline, lambda=1
Linear Fit
Mean

Figure 2.

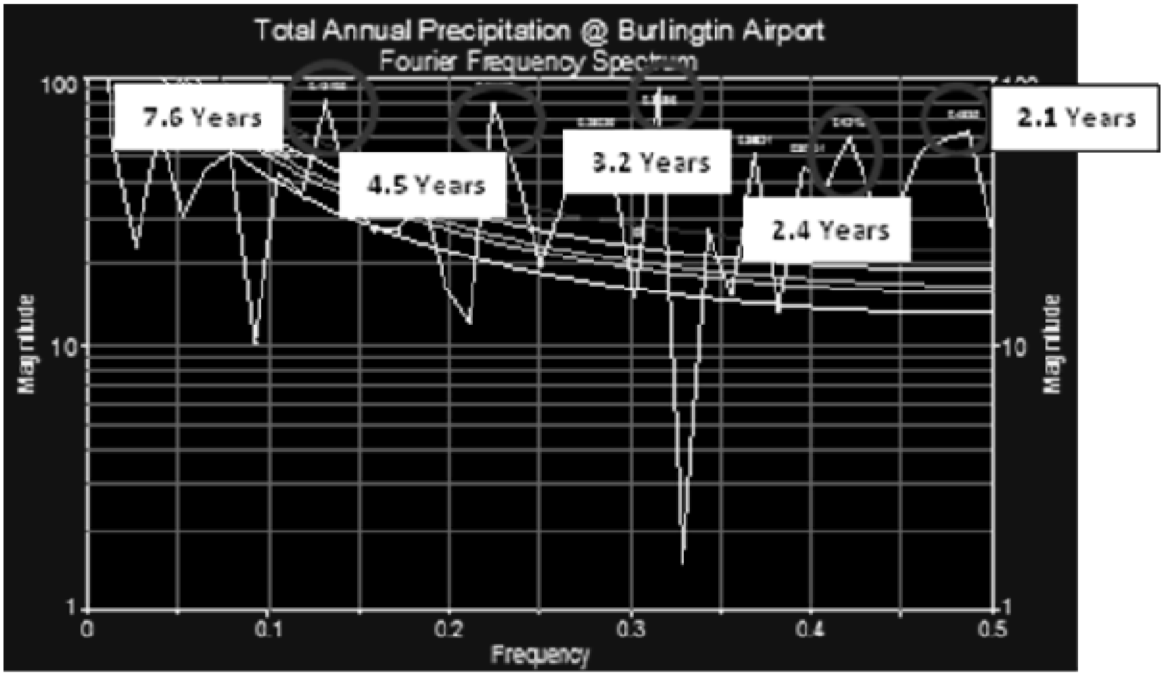


Figure 3. (to be re-drawn with white background)

Table 2- Summary table of annual statistics of precipitation, discharge, and temperature in the Winooski River Basin.

| P Values | **Dog River** | **Mad River** | **Little River** | **Winooski River** | **Winooski River** | **Winooski River** |
|---|---|---|---|---|---|---|
| **Trends** | Northfield | Moretown | Waterbury | Wrightsville | Montpelier | Essex Jct. |
| Total Annual Discharge | ⇧ 0.124 | ⬆ *0.016* | ⬆ *0.017* | ⇧ 0.166 | ⬆ 0.063 | ⬆ *0.018* |
| Total Annual Precipitation | ⬆ *<0.0001* | N/A | ⬆ *0.046* | N/A | ⬆ *0.046* | ⬆ *<0.0001* |
| Influence on Total Basin Q | ⇩ 0.482 | No Change | ⇧ 0.104 | ⬇ 0.080 | ⬇ 0.005 | N/A |
| Q vs. BTV Precipitation '36-'62 | $R^2$= 0.2927 | $R^2$= 0.3894 | $R^2$= 0.4551 | $R^2$= 0.4272 | $R^2$= 0.3726 | $R^2$= 0.4261 |
| Q vs. BTV Precipitation '63-'05 | $R^2$= 0.6269 | $R^2$= 0.6446 | $R^2$= 0.5454 | $R^2$= 0.5737 | $R^2$= 0.5793 | $R^2$= 0.6899 |

| P Values | **Burlington Airport** | | | | **Montpelier** |
|---|---|---|---|---|---|
| **Monthly Temperature** | Mean Low | Mean High | Spread: L->H | Mean | Mean |
| Annual Mean | ⬆ 0.068 | ⬆ *0.008* | N/A | ⬆ 0.017 | **No Change** |

[1]Arrow shows direction of trend; solid arrow indicates 90%, open arrow 50%, and italics 95% significance level.

[2]Q indicates discharge, BTV indicates Burlington Airport.

[3]Raw data from USGS and National Climate Data Center.

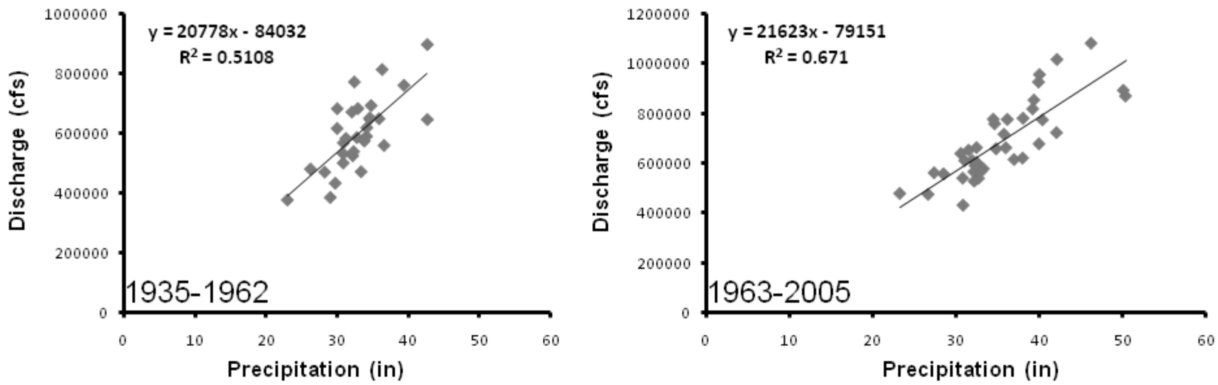


Figure 4.

Table 3- Summary table of event statistics of precipitation and discharge in the Winooski river Basin.

| P Values | Dog River | Mad River | Little River | Winooski River | Winooski River | Winooski River |
|---|---|---|---|---|---|---|
| **Trends** | Northfield | Moretown | Waterbury | Wrightsville | Montpelier | Essex Jct. |
| First, second, and third highest 24 hour period of discharge per year | ⇩ 0.221 | ⇩ 0.344 | ⇩ 0.166 | ⇧ 0.225 | ⬇ *0.014* | ⇩ 0.163 |
| | ⇩ 0.395 | **No Change** | ⬇ *0.037* | ⬆ *0.041* | ⬇ *0.036* | ⇩ 0.433 |
| | **No Change** | ⇧ 0.494 | ⬇ *0.006* | ⬆ *0.009* | ⇩ 0.105 | **No Change** |
| First, second, and third lowest 24 hour period of discharge per year | ⬆ *<0.0001* | ⬆ *<0.0001* | ⬆ *0.001* | ⬆ *0.019* | ⬆ *<0.0001* | ⬆ *<0.0001* |
| | ⬆ *0.001* | ⬆ *<0.0001* | ⬆ *0.001* | ⬆ *0.017* | ⬆ *0.001* | ⬆ *<0.0001* |
| | ⬆ *0.001* | ⬆ *0.000* | ⬆ *0.001* | ⬆ *0.016* | ⬆ *0.005* | ⬆ *0.000* |
| Intensity of largest annual precipitation events | ⇧ 0.183 | N/A | **No Change** | N/A | **No Change** | **No Change** |
| Frequency of extreme precipitation | ⬆ 0.004 | N/A | ⇧ 0.105 | N/A | ⇧ 0.356 | ⬆ 0.062 |
| 20 largest precipitation events as a percent of total annual precipitation | ⬇ 0.002 | N/A | ⇩ 0.123 | N/A | ⇧ 0.230 | ⬇ 0.003 |

[1]Arrow shows direction of trend; solid arrow indicates 90%, open arrow 50%, and italics 95% significance level.

[2]"No Change" indicates p values which are below 50% significance level.

[3]Raw data from USGS and National Climate Data Center.

Table 4- Summary table of monthly precipitation trends in the Winooski River Basin.

| P Values | Dog River | Mad River | Little River | Winooski River | Winooski River | Winooski River | |
|---|---|---|---|---|---|---|---|
| **Monthly Precipitation** | Northfield | Moretown | Waterbury | Burlington Airport | Montpelier | Essex Jct. | **# UP** |
| January | ⬆ 0.068 | N/A | ⇧ 0.145 | **No Change** | ⇩ 0.464 | ⬆ 0.063 | 3 of 5 |
| February | **No Change** | N/A | **No Change** | **No Change** | ⬇ *0.009* | **No Change** | 0 of 5 |
| March | ⬆ *0.037* | N/A | ⬆ *0.053* | **No Change** | ⇩ 0.184 | ⬆ *0.016* | 3 of 4 |
| April | ⬆ *0.005* | N/A | **No Change** | ⇧ 0.387 | **No Change** | ⇧ 0.125 | 3 of 5 |
| May | ⇧ 0.275 | N/A | **No Change** | **No Change** | **No Change** | **No Change** | 1 of 5 |
| June | ⇧ 0.275 | N/A | **No Change** | **No Change** | **No Change** | **No Change** | 1 of 5 |
| July | ⇧ 0.462 | N/A | **No Change** | **No Change** | **No Change** | ⇧ 0.129 | 2 of 5 |
| August | ⬆ *0.013* | N/A | ⬆ *0.028* | ⬆ 0.064 | ⬆ 0.089 | ⇧ 0.162 | 5 of 5 |
| September | ⇧ 0.488 | N/A | ⇧ 0.233 | ⇧ 0.190 | ⇧ 0.321 | ⇧ 0.205 | 5 of 5 |
| October | ⬆ *0.021* | N/A | **No Change** | ⇧ 0.394 | ⇧ 0.268 | ⬆ 0.088 | 4 of 5 |
| November | ⇧ 0.201 | N/A | ⇧ 0.410 | ⇧ 0.071 | **No Change** | ⇧ 0.270 | 4 of 5 |
| December | ⬆ *0.055* | N/A | ⇧ 0.280 | **No Change** | **No Change** | ⇧ 0.400 | 3 of 5 |
| | 11 of 12 | | 6 of 12 | 5 of 12 | 3 of 12 | 9 of 12 | **# UP** |

[1]Arrow shows direction of trend; solid arrow indicates 90%, open arrow 50%, and italics 95% significance level.

[2]"No Change" indicates p values which are below 50% significance level.

[3]"# UP" column and row are tallies of stations and months with increasing trends.

[4]Raw data from USGS and National Climate Data Center

Table 5- Summary table of monthly discharge trends in the Winooski River Basin.

| P Values | Dog River | Mad River | Little River | Winooski River | Winooski River | Winooski River | |
|---|---|---|---|---|---|---|---|
| **Monthly Discharge** | Northfield | Moretown | Waterbury | Wrightsville | Montpelier | Essex Jct. | **# UP** |
| January | **No Change** | ⇧ 0.462 | ⬆ *0.037* | ⇧ 0.357 | ⇧ 0.137 | ⇧ 0.232 | 5 of 6 |
| February | **No Change** | ⇧ 0.163 | **No Change** | ⇧ 0.168 | ⬆ *0.050* | ⇧ 0.132 | 4 of 6 |
| March | **No Change** | ⇧ 0.486 | **No Change** | **No Change** | ⇩ 0.298 | **No Change** | 1 of 6 |
| April | **No Change** | ⇩ 0.327 | ⬆ 0.061 | ⇩ 0.312 | **No Change** | ⇩ 0.472 | 1 of 6 |
| May | ⇩ 0.417 | ⇩ 0.419 | ⇩ 0.236 | ⬇ 0.061 | ⇧ 0.487 | **No Change** | 0 of 6 |
| June | **No Change** | **No Change** | ⇧ 0.247 | **No Change** | **No Change** | ⇧ 0.436 | 2 of 6 |
| July | ⬆ 0.070 | ⇧ 0.296 | **No Change** | ⇧ 0.168 | ⇧ 0.158 | ⇧ 0.157 | 5of 6 |
| August | ⬆ *0.003* | ⬆ *0.008* | **No Change** | ⬆ *0.003* | ⬆ *0.008* | ⬆ *0.006* | 5 of 6 |
| September | **No Change** | ⇧ 0.276 | **No Change** | ⇧ 0.328 | ⇧ 0.223 | ⇧ 0.162 | 4 of 6 |
| October | ⬆ *0.016* | ⬆ *0.005* | ⬆ *0.048* | ⬆ *0.034* | ⬆ 0.077 | ⬆ *0.006* | 6 of 6 |
| November | ⬆ *0.020* | ⬆ *0.012* | ⬆ *<0.0001* | ⇧ 0.155 | ⬆ *0.015* | ⬆ *0.008* | 6 of 6 |
| December | ⬆ 0.093 | ⬆ *0.019* | ⬆ *0.003* | ⇧ 0.185 | ⬆ *0.025* | ⬆ *0.006* | 6 of 6 |
| | 5 of 12 | 9 of 12 | 5 of 12 | 8 of 12 | 9 of 12 | 9 of 12 | **# UP** |

[1]Arrow shows direction of trend; solid arrow indicates 90%, open arrow 50%, and italics 95% significance level.

[2]"No Change" indicates p values which are below 50% significance level.

[3]"# UP" column and row are tallies of stations and months with increasing trends.

[4]Raw data from USGS and National Climate Data Center.

Table 6- Summary table for monthly and annual temperature statistics in the Winooski River Basin.

| P Values | Burlington Airport | | | | Montpelier |
|---|---|---|---|---|---|
| **Monthly Temperature** | Mean Low | Mean High | Spread: L->H | Mean | Mean |
| January | **No Change** | **No Change** | **No Change** | **No Change** | ⇩ 0.471 |
| February | ⇧ 0.300 | ⇧ 0.109 | No Change | ⇧ 0.189 | ⇩ 0.450 |
| March | ⇧ 0.314 | ⬆ *0.036* | ⬆ *0.041* | ⇧ 0.102 | ⬆ *0.049* |
| April | ⇧ 0.232 | ⬆ *0.032* | ⬆ 0.056 | ⬆ 0.065 | **No Change** |
| May | **No Change** | ⇧ 0.254 | ⇧ 0.314 | ⇧ 0.324 | ⇧ 0.426 |
| June | **No Change** | ⇧ 0.267 | **No Change** | ⇧ 0.302 | ⇩ 0.470 |
| July | ⇧ 0.208 | ⇧ 0.252 | **No Change** | ⇧ 0.190 | **No Change** |
| August | ⬆ 0.055 | ⇧ 0.121 | **No Change** | ⬆ 0.069 | **No Change** |
| September | ⇧ 0.446 | ⇧ 0.441 | **No Change** | ⇧ 0.396 | ⇩ 0.384 |
| October | ⇩ 0.484 | ⇩ 0.373 | **No Change** | ⇩ 0.371 | ⬇ *0.031* |
| November | ⇧ 0.255 | ⇧ 0.182 | **No Change** | ⇧ 0.197 | **No Change** |
| December | ⬆ 0.093 | ⬆ 0.069 | **No Change** | ⬆ 0.075 | **No Change** |
| Annual Mean | ⬆ 0.068 | ⬆ *0.008* | N/A | ⬆ 0.017 | **No Change** |

[1]Arrow shows direction of trend; solid arrow indicates 90%, open arrow 50%, and italics 95% significance level.

[2]"No Change" indicates p values which are below 50% significance level.

[3]Raw data from USGS and National Climate Data Center.

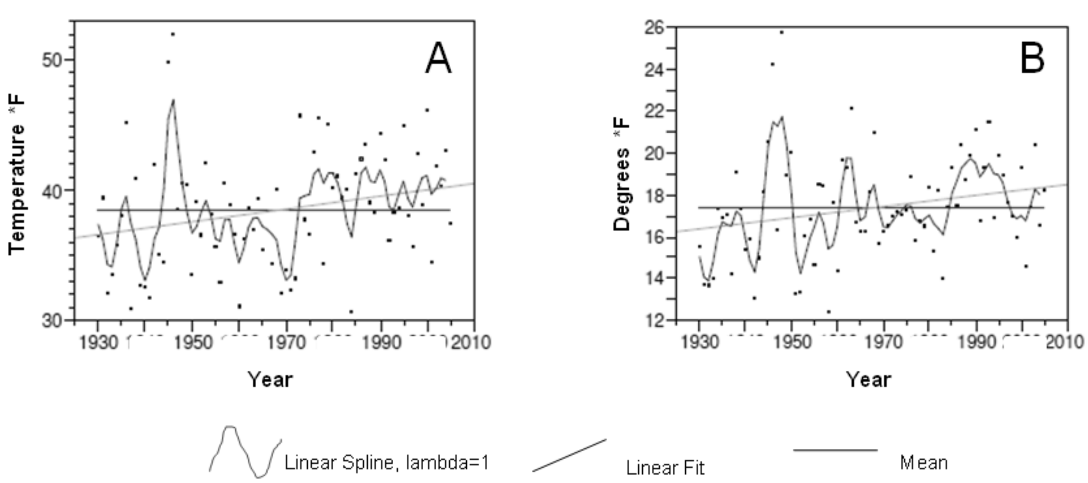


Figure 5.

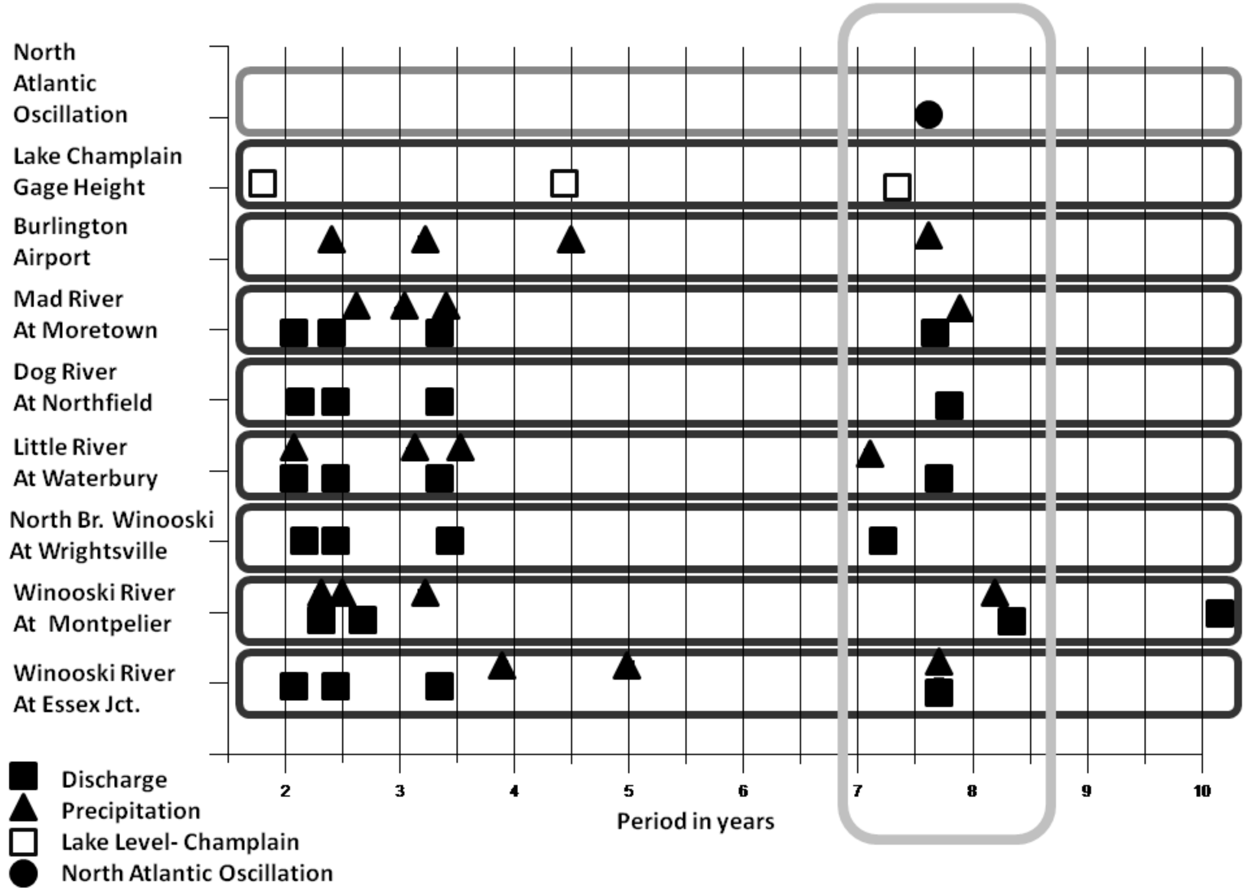
North
Atlantic
Oscillation
Lake Champlain
Gage Height
Burlington
Airport
Mad River
At Moretown
Dog River
At Northfield
Little River
At Waterbury
North Br. Winooski
At Wrightsville
Winooski River
At Montpelier
Winooski River
At Essex Jct.
2
3
4
5
6
7
8
9
10
Period in years
Discharge
Precipitation
Lake Level- Champlain
North Atlantic Oscillation

Figure 6.

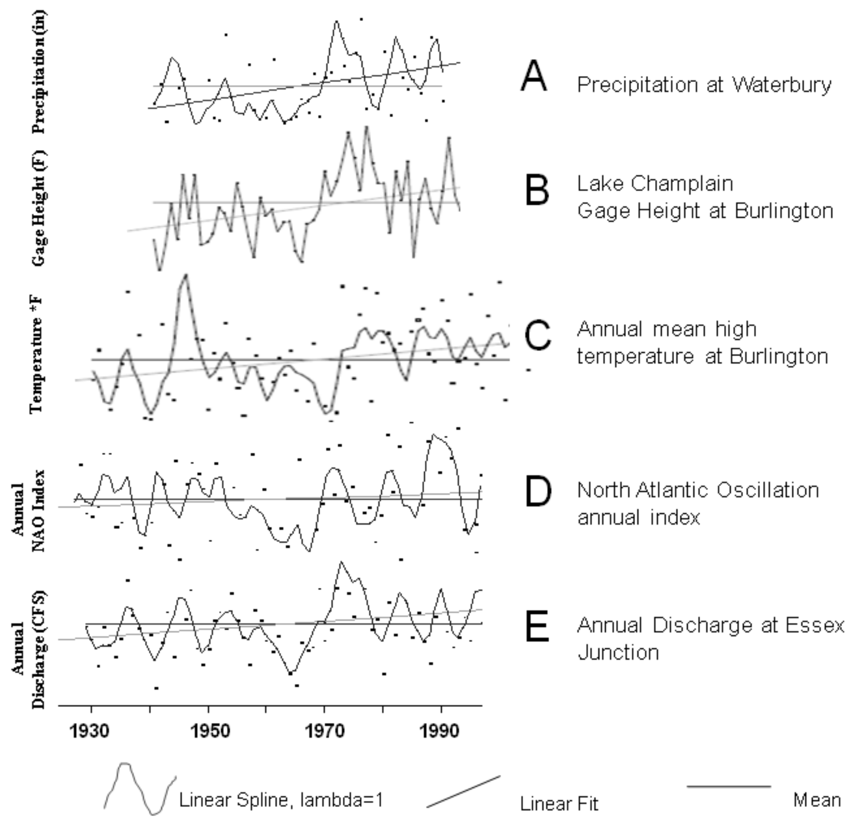
Precipitation (in)
A
Precipitation at Waterbury
Gage Height (F)
B
Lake Champlain
Gage Height at Burlington
Temperature °F
C
Annual mean high
temperature at Burlington
Annual
NAO Index
D
North Atlantic Oscillation
annual index
Annual
Discharge (CFS)
E
Annual Discharge at Essex
Junction
1930
1950
1970
1990
Linear Spline, lambda=1
Linear Fit
Mean

Figure 7.