# CHANGING LAND USE, CLIMATE, AND HYDROLOGY IN THE WINOOSKI RIVER BASIN, VERMONT

A Thesis Presented

by

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# 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 also use random sampling and manual, point-based classification of recent and historical aerial imagery to quantify land use change over the past seventy years in the 2,704 $km^2$ Winooski River Basin of northern Vermont. 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 0.78 degrees Celsius (1.4 degrees Fahrenheit). Four sets of aerial photographs, taken at intervals of 12 to 29 years between 1937 and 2003 at thirty randomly selected sites, demonstrate that actively cleared land area has decreased by 14%, while forested land and impervious surfaces increased by 10% and 5%, respectively. 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 base flow.

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# Chapter 1: Introduction

## *Water in Society*

Water plays a crucial role in human society; through consumption, power generation, agriculture, and wastewater management, humans expend significant resources managing water. Agriculture relies on groundwater for irrigation; cities draw upon lakes and reservoirs for drinking water; hydroelectric dams power homes; and ecosystems thrive under specific conditions that must be maintained for success (Bennie and Hensley, 2001; Ludwig et. al., 2009). Meanwhile, humans have also focused many resources on keeping water out of places it does not belong. Cities such as New Orleans are built below sea level and exist at the mercy of pumps (*The Pumps that keep New Orleans Dry*, 1999), and cities have a stationary network of sewers and drains that evacuate water from the thousands of acres of impervious surfaces (Milly et al., 2008). It is with this important background in mind that we conduct this study, as an understanding of the trends and relationships in climate, discharge, and land use during the past century may better equip us to prepare for climate changes in the next.

## *Climate*

Climate drives the weather, which is documented and tracked by stations around the world. Climate change has become an important topic, with wide-ranging research focused on the magnitude and interactions associated with the factors that drive our climate (Climate Change and Water, 2008). By affecting precipitation and temperature, climate can drive long-term trends of increasing or decreasing discharge, or short or long term periodic oscillations. These oscillations, such as El Nino or the North Atlantic

Oscillation (NAO) are often superimposed over longer-term trends (Bradbury et al., 2002; Massei, 2008, 2009). Together, these drivers interact to yield day to day weather and ultimately help to determine the temperatures and amount of precipitation that falls at the basin scale.

Climate has been changing during the past century, with varying effects by region (IPPC, 2008). Studies around the world have shown changes as varied as the landscapes they affect. Major rivers in Europe have experienced a trend of warmer, dryer weather over the past century with decreasing flows (Climate Change and Water, 2008). In New England, rising temperatures have now been documented through direct measurement as well as antecedent observations for many years; temperature records throughout the region have shown an almost unanimous increase in temperature over the past century (Trombulak and Wolfson, 2004); while lakes in Maine have been on a general trend of earlier ice out dates from year to year (Hodgkins, 2005). Sea surface temperatures along the east coast have also documented a general warming trend over time (Friedland, 2007) and the Intergovernmental Panel on Climate Change (IPCC) reports that the Northeast is seeing progressively fewer days of frozen ground during the average winter months (Climate Change and Water, 2008).

The IPCC predicts that given current trajectories, New England will continue to see warming temperature in coming years (Climate Change and Water, 2008). Warmer winters are likely to produce less snowpack accumulation and earlier spring melts into the region’s rivers. Precipitation is expected to increase, especially in the number and severity of storms, but the widespread increase in temperature will encourage summer drying as the atmosphere's moisture capacity increases. With drier soils and increased frequency of storms, the potential for erosion and crop damage will increase, while earlier snowmelt will change water availability throughout the year.

There are natural periodicities that exist within the climate record. The North Atlantic Oscillation and El Nino are two examples of larger scale anomalies that force climate in regions around the world. El Nino exists as a result of sea surface temperature change reflecting changes in ocean circulation (El-Askary et al., 2004). While its effects are quite strong in some areas, El Nino's effect on New England is limited to the ability to cause more winter storms as well as milder winters (National Weather Service, 2006). The North Atlantic Oscillation is measured as the difference in sea surface pressures between the Azores High and Icelandic Low. An index defines this signal as being positive or negative, with positive years bringing more precipitation and warmer temperatures to the New England Region (Hurrell, 1995).

### *Land Use Change*

New England has seen a broad spectrum of land use during its post- colonial history. Following widespread settlement in Vermont in the early 1700's, the state experienced an increase in agriculture (Wessels, 1997). The popularity of sheep in Vermont and New England led to high levels of success for many farmers and an estimated 1.7 million sheep were in the state by 1840 (Wessels, 1997). This period represented peak agriculture in Vermont, but by the late 1800's the number of farms was declining due to economic completion from the midwest. The abandonment of many marginal upland farms led to a reorganization of agriculture in Vermont; the shift from sheep to dairy farming proved to be a way to survive for many farmers (Albers, 2000). The decreasing number of farms allowed for reforestation of the abandoned properties; despite renewed logging of these new forests, much of Vermont saw a boom in reforestation during the early 1900's (Eschele, 1975; Wessels, 1997). In the mid 1900's, Interstate 89 was constructed in Vermont; it cuts through the Green Mountains connecting Burlington to White River Junction, Vermont and on to New Hampshire. Land use history since then has been dominated by further reforestation and development.

### *Hydrologic Effects of Land Use*

Land use can have significant impacts on the amount and speed of runoff in a basin. While forests capture much precipitation through interception and infiltration, even more is evapotranspired by the trees (Hough, 1986). Open land, such as a pasture or cultivated land, allows less infiltration than forest, and is often more prone to runoff and overland flow, which can easily transport exposed soil from cultivated fields. Impermeable surfaces, such as roofs, parking lots, and roads allow no infiltration, forcing all water that falls onto them to runoff. The changing proportions of these land use types within a basin can have dramatic effects on discharge and response to storms, either increasing total yield in a flashier manner, or decreasing and smoothing the hydrograph (Zheng, 2008). Therefore, an estimation of land use change over time in the Winooski

River Basin reflects not only changes in the economic and social setting of the basin, but potential hydrologic changes affecting the behavior of runoff.

### *The Winooski River Basin*

The Winooski River Basin drains 2,704 km$^2$ of land that begins in the Green Mountains and ends at Lake Champlain (USGS, 2008). Hard metamorphic schists and phyllites dominate the mountains, while sedimentary rocks can be found in the lower Champlain Valley (Doolan, 1996; Mehrtens, 2001). Evidence of the last glaciation is frequent in the topography of this region; the Laurentide Ice Sheet was responsible for smoothing the topography of the mountains (Pair, 1997). In the process of retreating, the glaciers left behind an abundance of sediment ranging from glacial till in the uplands, sand and gravel along many valley walls, and permeable, fertile alluvium near river channels. The main stem of the Winooski River is supplemented by flow from several major tributaries including the Little, Mad, Dog, North Branch, and Huntington Rivers; all but the Huntington River are monitored by USGS gaging stations (USGS, 2008). Elevations within the basin rise from Lake Champlain (~95 m) to 1400 m in the mountains (VCGI, 2008). The population center of the basin is the greater Burlington area, and the other highest population centers are all located along the Winooski River at various points within the basin (U.S. Census, 2000).

This topography shapes Vermont's development history, as the interstate highway, railroad, and Winooski River all run parallel to one another for much of their routes. Additionally, the better soil of the river valleys and lowlands of the Champlain

Valley have maintained much of the remaining agriculture as well as housed developments and shopping centers (Eschele, 1976). One could argue that recent development is linked to proximity to the interstate highway but in reality the highway follows the Winooski Valley to avoid the more difficult upper slopes as well as to be accessible to the pre-existing towns that had been historically located along the river for transportation purposes. The convenience of this is well supported by the inaccessibility of many places in Vermont's Northeast Kingdom, which does not have an interstate highway and is notoriously more difficult to traverse.

Topography also plays an important role in climate. The wide ranging elevations in the Winooski River Basin cause an abundance of microclimates in the mountains. The physical process of increasing precipitation with elevation is seen in the Winooski Basin as expected, where average annual rainfall between Burlington airport and the highest point in the Winooski River Basin varies by over 40 inches (NOAA). While this elevation effect is clear, annual totals are vary homogeneously between stations over time.

### *Data Sources and Utilization*

Data for this study include river discharge, weather station, and land use change over time. River discharge data have been collected by U.S. Geological Survey gaging stations from 1930 to present at six locations within the basin. Two of these stations are located on the main stem of the Winooski River, while the other four are on the main tributaries. We acquired these data as daily averages, and then summed into months and years as well as examined for peak and low flows. Weather station precipitation and discharge data from six locations are included in this study. Many of the upland stations have limited coverage with periods of missing data as well as inconsistencies in site location. Some stations were closed and reestablished years later at a nearby site, presenting opportunity for elevation to affect the trends of precipitation and temperature. To test against these, we plotted precipitation at these inconsistent stations against the Montpelier weather station, which have more complete records, to ensure that there was no change in relationship. Following this analysis, we summed hourly data for precipitation and totaled these for months and years, while taking mean values of temperature in the same manner. Land use change data were derived from historical aerial photos, which were acquired for 1937/1942, 1962, 1974, and 2003 for thirty sites randomly selected throughout the basin. In calculating change over time at each of these sites, we demonstrate the average land use change over seventy years in the Winooski River Basin as a whole.

## *Temporal Changes within the Winooski River Basin*

Considering the evidence for climate change within the New England region, as well as the predictions for the future and the potential repercussions, we began this study with the central goal of identifying temporal changes in the precipitation, temperature, and discharge data and how these have interacted with land use change over the same period. This study is novel in that it uses publicly available flow and weather data as well as publicly available historical aerial photos to gain a comprehensive understanding of trends at the basin scale over the past seventy years of change.

# Chapter 2: Paper for submission to *The Journal of Environmental Management*

# Quantifying seventy years of land use change in the Winooski River Basin, northern Vermont

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## *Abstract*

To quantify land use change over the past seventy years in the 2,704 km$^2$ Winooski River Basin of northern Vermont, we used random sampling and manual, point-based classification of recent and historical aerial imagery. Analysis of four sets of aerial photographs, taken at intervals of 12 to 29 years between 1937 and 2003 at thirty randomly selected quadrats, demonstrated that actively cleared land area has decreased by 14%, while forested land and impervious surfaces increased by 10% and 5%, respectively. Forested quadrats are more common in basin uplands while quadrats with greater impervious area are more common in the lowlands and in close proximity to the Interstate Highway. The trends we quantify, which chronicle widespread reforestation of marginal agricultural lands abandoned over the past century, are consistent with land use history documented elsewhere in New England.

**Keywords:** Landcover, reforestation, impervious, runoff, land use analysis, aerial photograph

## *Introduction*

Landscapes are dynamic, the result of both natural processes and human activity. Over a human lifetime, significant changes in land use can occur, including the reversion of farmland to forest and increases in developed areas (Albers, 2000; Wessels, 1997). Quantifying land use change is critical for predicting and addressing impacts related to development (Foley et al., 2005; Milly; et. al, 2008). For example, runoff yields from impervious surfaces far exceed those of forests and have implications for water quality and storm water management (Forman and Alexander, 1998). Understanding the history of land use at a location can help explain contemporary issues such as erosion and flooding, and can provide guidance for the planning and design of future infrastructure.

While the importance of documenting land use changes is clear, measuring land use change over time is not straightforward (Thornton et al., 2007; Ulbricht and Heckendorf, 1998; Verburg et al., 2009). In many parts of the United States, federal, state, and local governments contracted for aerial photography over regular time intervals starting in the late 1930s making these images publicly available in many regions (Neigh et al., 2008). Although the images are available, quantifying land use change using unrectified, predominately panchromatic images of varying quality is difficult (Campbell, 2002). A common approach to land use quantification using aerial photographs involves scanning and digitization of the entire photograph, thus separating the image into polygons representing different land use types (Mapedza et al., 2003). Polygons can be defined manually, a time consuming process, or through a number of developed automated techniques (Neigh et al., 2008; Verburg et al., 2009) that are of uncertain reliability and accuracy, especially when older, panchromatic, or poorer quality aerial photographs are used (Campbell, 2002; Lillesand et al., 2004).

Here, we use random point sampling and manual land use classification of publicly available aerial photographs to quantify land use change over time in the Winooski River Basin of northern Vermont. We show that this technique is both practical and accurate and that the abandonment of farmland, the coming of the Interstate Highway, and subsequent suburbanization have all changed land use patterns significantly over the past 70 years.

## *Study Area*

### ***LANDSCAPE***

Until recently, northwestern Vermont's geology, topography, and varied landscapes strongly controlled the pattern of human land use (Jennison, 1989). Vermont's landscape is dominated by the rugged Green Mountains, which consist of hard metamorphic rock, rising to elevations over 1400 m, and forming 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 with productive farmlands (Doolan, 1996; Mehrtens, 2001). Glaciers covered the Green Mountains during the last glaciation 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).

### ***HISTORICAL CONTEXT***

The New England landscape has been used by humans since shortly after the glaciers receded. Before European settlers arrived in North America, Native American society made use of the resources of the New England landscape (Abrams and Nowacki, 2008). Forests during this time were kept open in many areas, primarily by the collection of wood and underbrush to fuel heating and cooking fires (Diekmann et al, 2007; Pyne, 1982). By the late 1600's, much of northeastern North America was colonized. Expansion of settlement into Vermont was limited until the defeat of the Native Americans during the French and Indian War, which led to the "great swarming time" in the early 1700's when settlers rapidly moved across New England in the wake of newfound safety (Wessels, 1997). During the 1700s, settlers logged land for building purposes, later burning brush and stumps for agriculture. This self-sufficient homestead period was successful for New England's new residents and by 1790 many of the New England towns in existence today were already established (Wessels, 1997).

As agriculture changed over time, so did the human footprint on the landscape. "Sheep Fever" took hold in 1810 when about 4,000 sheep were imported into Vermont in the wake of new tariffs on wool to encourage domestic production (Albers, 2000; Wessels, 1997). This agricultural movement was so popular that by 1840 the initial population of 4,000 sheep had expanded to 1.7 million (Wessels, 1997). Thirty years of intensive agricultural growth necessitated rapid clearing of the land; 75% of the New England landscape was cleared during this time. The substantial clearing of the landscape for agriculture by the mid 1800's set the stage for future Vermont agriculture, development, and this study (Jennison, 1989). As economic factors changed, many marginal upland farms were abandoned, which led to reforestation. By 1850, 50% of the farmers in Vermont had moved west (Eschholz, 1976; Wessels, 1997). Farmers who remained established lowland dairy farms in the river valleys with farms built on rich alluvial soils that could better sustain agricultural use because the land was flat and easy to till (Albers, 2000).

Cultural forces established during the last two centuries still drive land use change in the Winooski River basin. Early settlement, transport, and agricultural patterns, largely the result of topography and the location of rich, tillable land, caused much of northern Vermont's population to occupy the lowlands (Satterthwaite, 1976). The shift from sheep to dairy farming in the mid to late 1800s, along with the railroad, river, and road right of ways, all served to concentrate people in the lowlands along fertile valleys (Eschholz, 1976). Simultaneously, the abandonment of fields and pastures in the uplands, in favor of the valleys, initiated Vermont's reforestation during the mid 1800's (Wessels, 1997).

The construction of the Interstate Highway system along the Winooski River continued the pattern of intensive valley-bottom development during the 1960s and allowed those with the financial means to live in suburbs as the ease of commuting increased (Alig et al., 2004; Rose, 1979). Along with suburbanization there has been extended development including large "box" stores and associated parking areas, focused near highway access points (Liebs, 1995; Wassmer, 2002), Vermont's expression of the sprawling, "galactic city" (Lewis, 1995). Although the population in Vermont decreased for decades following the crash of sheep farming in the mid 1800s, for much of the last century it has been increasing at first slowly and then much more rapidly during the late 1900's (Albers, 2000; Wessels, 1997). Together, these forces have resulted in an increase in impervious surface areas from the construction of roads, homes, and businesses.

### *Methods*

We analyzed aerial photography at thirty quadrats, selected using the "random point generation" tool in the Hawth's Tools toolbar (ArcGIS 9.3), to derive land use changes in the Winooski River Basin over the past seventy years (Figure 2.1). At each location, a 3 km x 3 km quadrat was established. The random sampling design applied to our 30 quadrats represented about 10% of the basin area, and was used to quantify land use in the basin (Clark and Hardegree, 2005; Janke and Tinsley, 2005). For further analysis, we also divided the basin into two elevation classes around the mean basin elevation (400 m), *uplands* and *lowlands,* allowing us to examine land-use trends independently within each category.

The thirty quadrats are representative of the basin as a whole in terms of elevation; the mean elevation of the basin as well as the distribution of elevations closely matches those of the sampled quadrats (Figure 2.2). Within each quadrat, we established 300 random sampling points, with a forced minimum distance of 50 meters between each; these 300 points were generated using the same random point generator used to select the quadrats. A sample size of three hundred sample points was chosen based on accepted approaches in other point counting-based research, such as pollen analysis (Clark and Hardegree, 2005; Liu et al., 2007; Lupo et al., 2006; Velez et al., 2001).

For each quadrat, we acquired digital aerial imagery or hard copy aerial photos from the University of Vermont Map Library as well as Williston and Berlin, VT Natural Resource Conservation Service (NRCS) Image Libraries (Table 2.1). The earliest imagery is from 1937; but imagery from that date is not available for every quadrat, so it was supplemented with 1942 imagery for the remaining quadrats. Hard copy photography from 1937 or 1942, 1962, and 1974, were acquired for all quadrats, as well as 2003 digital orthorectified imagery, acquired as part of the USDA National Agricultural Imagery Program (NAIP) as 1m natural color digital orthophotographs. Hard copy photos were scanned and georeferenced in ArcGIS 9.3 to correct distortion and apply location coordinates to the standard image format. We georeferenced each image by selecting points on the photograph that are still identifiable today, such as road intersections, bridges, and buildings. By linking these ground control points on the scanned imagery with orthorectified 2003 imagery, each older, scanned image was transformed to match the newer imagery. Rectification was based on a minimum of ten control points (except for totally forested quadrats) and used a second order transformation to achieve an average root-mean-square error of ten pixels or less before using a nearest neighbor resampling approach. Heavily forested quadrats were georeferenced using hydrologic and topographic features as control points. This is a less accurate approach, but at these quadrats near total forest cover at all time steps makes georeferencing accuracy less important.

For each of the 300 random sample points, which remain stationary within each 9-$km^2$ quadrat, land use was classified into one of three categories based on interpretation of the aerial photographs (Table 2.2). "Actively Cleared" land consists of lawns, agricultural fields, grazed pastures, or any environment where tree growth is prevented. This broad category, while including many different land use types, is defined so as to represent areas less permeable than forested land but more so than pavement or buildings.

"Forested" defines any area where unrestricted woody vegetation growth is taking place. This includes forests, hedgerows, or abandoned farm fields at the point where successional brush and shrub growth becomes visible on the aerial imagery. "Impermeable" describes both dirt roads and paved roads, parking lots, buildings, or any other impermeable surface. These categories were chosen to describe three different levels of hydrologic behavior, ranging from the heavily forested landscape to the impermeable roads (Dunne and Leopold, 1996). Using these definitions, we categorized all points in each quadrat, generating data for the sampled subpopulation (n=30, 270 km$^2$); and then extrapolated our findings across the 2,704 km$^2$ basin.

Preliminary testing of our sampling design was performed to assess sample size and analyst impacts on resulting estimates. First, one analyst (W. Hackett) made two replicate analyses of the same image one month apart using the same 300 point locations; the results were similar: 21% vs 23% cleared land, 70% vs 70% forested land, and 7% vs. 6% impermeable surfaces. Hackett then twice counted 500 points on the same image and the results were similar to each other and to the data generated by counting 300 points (Table 2.3). To test for bias between different analysts, another analyst (L. Reusser) classified the same 300 points on the same image after explanation of the classification guidelines. The results, comparing the two analysts, were 31% vs 23% cleared land, 64% vs 70% forested land, and 4% vs 6% impervious surfaces. The primary difference between these results is the distinction between forest and cleared land. We suspect this discrepancy resulted from different perceptions of the transition between field, brush, and trees and emphasizes the importance of consistency in class definitions. Lastly, Hackett manually delineated land use classes and digitized the resulting polygons for one 3km x 3km quadrat. The resulting land use distribution estimate was most similar to the point-counted results for the second analyst (Table 2.3). The discrepancies emphasize that it is important to maintain a consistent sampling strategy and class definitions, using the same methods and analyst throughout all sampling. While classification accuracy may vary by analyst, the relative change over time is the goal of this type of study. All data in this paper were collected using consistent classification standards and techniques by a single analyst, W. Hackett.

### *Results*

Analysis of thirty randomly distributed quadrats across the Winooski River Basin revealed changing land use over time with a basin-wide increase in urbanization and forested land and a decrease in agricultural area (Table 2.2). In 1937, the basin averaged 23% actively cleared land, 4% impervious surfaces, and 72% forested land. Between 1937 and 1962, average actively cleared land dropped 7% while forested land rose 5% and impervious area increased by 1%. During the later part of the century (1962-2003), actively cleared land area continued to decrease while reforestation persisted along with increases in development. By 2003, the basin average land use had shifted to 9% actively cleared land, 9% impervious surfaces, and 82% forested land (Figure 2.3).

The pattern of land use and land use change in the Winooski Basin is not spatially homogeneous. Heavily developed and heavily forested quadrats are clustered. The upland elevations contained all of the five unchanged, mostly forested quadrats. Uplands tended to be more forested, undergo more agricultural abandonment, and have less development. Conversely, lowland regions contained all 11 quadrats that in 2003 had more than 10% impervious surfaces; compared to the upland quadrats, lowland quadrats contain more actively cleared land indicative of agricultural and suburban activity (Figure 2.3).

In addition to elevation, proximity to the Interstate Highway is associated with differences in contemporary land use and the intensity of land use change. Five of the seven analysis quadrats within 600 meters (the ecological “road effect zone” of Forman and Deblinger, 2000) and eight of the twelve sample quadrats within 5 km of the Interstate Highway have, in 2003, the greatest quadrat level proportions of impervious surfaces in the Winooski River Basin.

## *Discussion*

Analysis of aerial photography demonstrates conclusively that the landscape of northern Vermont has changed significantly over the past 70 years with forests replacing farmland. Much of the early imagery, that from the 1930’s and 1940’s, reveals relatively open landscapes with many farms that had either been recently abandoned or were still in operation. During this time step, vegetation is being actively cleared over more than 23% of the basin’s land area while agriculture remains a major landscape use. By 1962, actively cleared land represents only 16% of the basin land area, a notable decrease from only two decades before. In little more than 20 years, forests had taken back much of the cleared land. By 1974, vegetation was cleared on only 13% of land in Winooski River Basin and by 2003, less than 10% of the basin was open land kept clear of forests, a decrease of 378 km$^2$ or more than 50% since about 1940 (Figure 2.4).

Other land use analysis completed in Vermont as well as historical evidence corroborates and explains our results. In addition to farmland abandonment, changing practices in the dairy industry have led to a decrease in the grazing of cows in favor of dairy barns and yards (Saterthwaite, 1976). Due to this practice, even active farms have abandoned their pasture land, allowing forest succession to begin. Our results compare well with areal estimates of land use and land cover derived from 30-meter, 2001 LANDSAT imagery of the Lake Champlain Basin, which includes the Winooski River Basin (Vermont Center for Geographic Information, 2001). These data are similar to our manually classified, point-counted results in terms of impervious surface (8% vs. 9%) but differ slightly from our results for actively cleared land (16% vs 9%) and forested land (76% vs 82%). Discrepancies in the latter two categories are likely the result of different imagery scales and class definitions in terms of forest and brush compared to pasture and field.

Trends in land use over time differ between the uplands and the lowlands. Four of the five quadrats that experienced over 10% net reforestation are in the lowlands (Figure 2.5). Such lowland reforestation probably reflects the opportunity for cleared land to reforest compared to more of the upland locations which were already reforested in 1937. These data support the historical record that suggests that topography plays a strong role in human-landscape interaction and land use (Jennison, 1989). The thinner soils and steeper slopes of the uplands resulted in early farm abandonment and reforestation, much of which was completed before 1937.

A relatively high percentage of impervious area appears to be related to development, particularly that associated with construction catalyzed by the presence of the Interstate Highway (Figure 2.6). Of the six quadrats that experienced a decrease in forested land over the last seventy years, four of them are within 600 meters of Interstate 89, and five of the six are within 5 km. Although the location of the highway is elevation controlled (most of Interstate 89 is in the lowlands), there is clearly an additional association between highly developed quadrats and proximity to the highway.

Our data suggest there are specific trajectories of land use change. While some quadrats exhibit simple changes over time such as a consistent increase in forested area and a decrease in areas actively cleared, others show more complex, yet consistent, trajectories. At five out of the thirty sample quadrats, the data show an initial increase in forested land followed by a decrease between the 1972 and 2003. This trajectory only occurs in the lowlands, and four of the five quadrats are within 600 meters of the Interstate Highway. Additionally, these four lowland quadrats are also among those quadrats that showed the greatest increase in impervious area. Unlike the previous widespread farm abandonment in the late 1800's when abandoned farms were reforested, today many former farms become housing tracts and commercial developments (Murphy, 2005). Another trajectory exhibited at four quadrats, is an initial decrease in actively cleared area, followed by a later increase (Figure 2.7). Three of these four quadrats are in the lowlands and two of the four are within 600 meters of the highway, suggesting that development may be the driver behind this trend. The easy accessibility, gentle topography, and fertile soils that kept farms active longer in the lowlands now facilitate development.

The pattern and pace of land use changes we quantified are similar to those observed elsewhere in New England, but differ from the national average. We measured an increase in forested area over the past seventy years, with a decrease in actively cleared land and a slight increase in average impervious area (Figure 2.3). This trend is common in much of New England, which as a whole has been undergoing reforestation since the 1950's and in the early 1990's was estimated to be 60-85% forested (Foster, 1992), similar to the 82% we measured for the Winooksi Basin in 2003. Urbanized area across New England has also been on the rise and is now estimated to cover approximately 12% of the land (Alig et al., 2003), similar to what we measure (9%) for the Winooksi Basin in 2003. However there are departures from the regional average. Maine has largely reforested and is now 90% forested, with only 2.5% urban land (Platinga et al., 1999). Nationally, land use is trending in the opposite direction. The USDA estimated in 1997 that 11 million acres (0.5% total land area) of forest and cropland has been lost nationwide since 1992 while the country as a whole has been experiencing a net loss of forest land since the 1950's (Alig et al., 2004).

It is important to consider the scale at which our data are gathered. Results presented in this paper reflect 9 $km^2$ areas, which are taken together to derive average land use for the 2700 $km^2$ Winooski River Basin. These data provide an important overview of basin-scale change but underestimate the magnitude of change at local scales, particularly those of importance for hydrologic impacts including the generation of flashy run-off from large impermeable areas such as parking lots and the increased interconnectivity of impermeable surfaces. While the data we present may be of limited utility at local scales, they clearly indicate basin-wide trends in land use over time and are consistent with regional data generated by other means.

There are several important environmental implications for our findings. Reforestation of active agricultural lands, so prevalent in the uplands, is beneficial in several ways. The return of trees reduces sediment yield and nutrient export, potentially improving water quality (Atasoy et al., 2006; Forman and Alexander, 1998). Of global importance, is the significant sequestration of carbon as cultivated fields are allowed to reforest (Birdsey et al., 2006). Changing vegetation also causes the hydrology of these areas to change; flood runoff is reduced by increased infiltration and total annual stream discharge drops as evapotranspiration increases (Forman and Alexander, 1998; Juckem et al., 2008). While the increase in impervious area is small on a basin scale, some lowland quadrats experienced large increases in developed area. The implications of impervious areas on the landscape extend beyond hydrology, to specific impacts in terms of pollutants and habitat fragmentation (Forman and Deblinger, 2000).

## *Conclusions*

The dynamics of landscape change are complex, dependent on past history, and important for managing current and future landscapes. We show that the magnitude and trajectory of land use change over time can be quantified using point counting and manual classification of historical aerial photographs. Using a representative random set of 9,000 sample points scattered equally among 30 sample quadrats and analyzed for 4 different time steps representing more than 70 years of change, we show that reforestation dominates the overall history of the Winooski River Basin, Vermont. Subpopulations of the sample set show that landscape history differs between upland and lowland quadrats and with distance to the Interstate Highway system. The approach taken in this study is easily adaptable to other landscapes and can, at low cost and with minimal technology, provide a quantitative view of landscape change from which planners, scientists, and historians can all benefit.

## *Acknowledgements*

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## *Figure Captions*

Figure 2.1 The Winooski River Basin with 30 random sample quadrats overlain on map derived from USGS National Elevation Dataset 7.5' VT DEM, scale 1:24,000 provided by Vermont Center for Geographic Information. Sample quadrats are 3 km by 3 km square and were randomly generated using Hawth's Tools in ArcGIS 9.3. The basin is divided into uplands and lowlands around the mean elevation of 400 m.

Figure 2.2 Histogram of elevations across the Winooski River Basin, mean= 400 m (A) compared to a histogram of elevations of all 30 sample quadrats, mean= 400 m (B).

Elevation data derived from USGS National Elevation Dataset 7.5’ VT DEM, scale 1:24,000 provided by Vermont Center for Geographic Information.

Figure 2.3  Land use percentages over time in the uplands (U) and lowlands (L) of the Winooski River Basin.

Figure 2.4  Land use percentages shown as trends over time for the Winooski River Basin as the mean of all 30 sample quadrats (A), the uplands over 400 meters, n=10 (B), and lowlands below 400 meters, n=20 (C).

Figure 2.5  Quadrat 24, near Jericho, Vermont. A.  1937 photograph (image ID: 2-37) shows mostly rural area, cleared in the center of the image. B. 2003 image shows that much of this cleared land has been abandoned and reforested (orthophotography). C. Forested land area increases over time.

Figure 2.6  Quadrat 20 in Colchester Vermont.  A. 1937 photograph (image ID: 1-23, 1-33) shows an abundance of cleared land with urban area in the lower left of the image.  B. 2003 image (orthophotography) shows that some cleared land has reforested and urban area has increased, spreading north through the image.  C. Impervious surface increases over time at quadrat 20.

Figure 2.7 Quadrat 18 near Montpelier, VT. A. 1962 photograph (Image ID:48-110) showing the central Winooski River Basin before construction of Interstate 89. B. 2003 image (orthophotography) with highway and cleared land. C. Impervious surface and cleared land change at quadrat 18 with the installation of Interstate 89 between 1962 and 1974.

TABLE 2.1. Aerial photography used for land use analysis

| **Site** | **1937** (1:20,000) | **1942** (1:20,000) | **1962** (1:18,000) | **1974** (1:20,000) | **UTM[1] coordinates** |
|---|---|---|---|---|---|
| **1** | | 3-202, 1-122 | 47-158 | 16-146 | 4903760N, 702067E |
| **2** | | 6-129 | 25-261, 19-124 | 13-118, 13-214 | 4904921N, 675074E |
| **3** | | 10-41 | 23-97, 21-236 | 13-57 | 4888258N, 670688E |
| **4** | | 8-60 | 23-101 | | 4882504N, 668038E |
| **5** | | 1-90 | 48-20, 42-64 | 16-218, 18-44 | 4908982N, 707026E |
| **6** | | 7-183 | 49-23, 46-214 | 14-125, 14-46 | 4922732N, 680785E |
| **7** | | 1-86 | 42-61 | 16-213 | 4901697N, 708051E |
| **8** | | 4-200 | 44-251, 14-208 | 14-130, 14-208 | 4912533N, 684007E |
| **9** | | 1-117 | 48-22, 17-153 | 16-220, 16-141 | 4913168N, 704278E |
| **10** | | 6-216 | 51-89 | 14-216 | 4925883N, 686272E |
| **11** | | n/a | 50-31 | 12-132 | 4908989N, 667563E |
| **12** | | 1-83 | 42-57, 48-13 | 16-211 | 4896447N, 707156E |
| **13** | | 1-47 | 44-22, 36-187 | 26-24, 26-122 | 4893346N, 695532E |
| **14** | 2-33 | | 18-105 | 12-44, 12-128 | 4917398N, 662282E |
| **15** | | 6-102 | 29-118, 49-28 | 14-42, 13-208 | 4915701N, 676764E |
| **16** | | 7-142 | 50-81, 50-82 | 12-138 | 4898825N, 663420E |
| **17** | | 6-103 | 49-29 | 14-40 | 4912426N, 678654E |
| **18** | | 1-61 | 48-110 | 26-28, 15-50 | 4902719N, 690621E |
| **19** | | 6-198 | 44-254 | 14-205 | 4907958N, 685014E |
| **20** | 1-23, 1-33 | | 20-188, 20-189 | 4-106 | 4931073N, 644141E |
| **21** | | 3-211 | 47-65 | 16-61 | 4921317N, 698846E |
| **22** | | 4-194 | 44-261, 40-26 | 14-199 | 4897280N, 687331E |
| **23** | | 7-184 | 49-26 | 14-126, 14-44 | 4919137N, 679906E |
| **24** | 2-37 | | 18-109 | 12-125 | 4922765N, 662521E |
| **25** | | 6-216 | 53-237 | 15-37 | 4925323N, 689831E |
| **26** | 2-19, 1-57 | | 24-161, 24-47 | 5-137 | 4918829N, 654840E |
| **27** | | 7-149 | 50-74 | 12-132 | 4910624N, 663556E |
| **28** | | 7-145, 6-60 | 18-96, 24-165 | 12-037 | 4903351N, 660714E |
| **29** | | 6-217 | 44-246 | 14-213 | 4921587N, 685738E |
| **30** | | 6-124 | 25-257 | 13-114 | 4897137N, 674530E |

[1] UTM coordinates at northwest corner of sample quadrat, UTM NAD 83, Zone 18N.

[2] All hard copy aerial photographs were scanned from original panchromatic imagery. 1937/1942 imagery taken by Soil Conservation Service and Mark Hurd Air Mapping, 1962 imagery taken by Ammann International, 1974 imagery taken by Aerographics Corp. [3] 2003 imagery from National Agriculture Imagery Program, 1 m natural color.

Table 2.2 Land use percentages over time by quadrat

| | | 1937/ 1942 | | | 1962 | | | 1974 | | | 2003 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **C** | **F** | **I** | **C** | **F** | **I** | **C** | **F** | **I** | **C** | **F** | **I** |
| **1** | 59 | 36 | 6 | 47 | 48 | 5 | 45 | 49 | 6 | 25 | 69 | 6 |
| **2** | 20 | 76 | 4 | 13 | 82 | 5 | 8 | 85 | 8 | 4 | 86 | 10 |
| **3** | 18 | 78 | 4 | 16 | 79 | 5 | 11 | 79 | 10 | 9 | 79 | 13 |
| **4** | 1 | 99 | 0 | 0 | 100 | 0 | 0 | 100 | 0 | 0 | 100 | 0 |
| **5** | 32 | 63 | 4 | 24 | 72 | 4 | 16 | 78 | 5 | 15 | 80 | 5 |
| **6** | 21 | 77 | 1 | 13 | 86 | 1 | 4 | 91 | 5 | 6 | 86 | 7 |
| **7** | 18 | 81 | 1 | 9 | 91 | 1 | 8 | 92 | 2 | 5 | 93 | 2 |
| **8** | 15 | 81 | 4 | 9 | 87 | 4 | 9 | 87 | 4 | 5 | 88 | 7 |
| **9** | 35 | 62 | 3 | 24 | 72 | 4 | 22 | 74 | 4 | 14 | 81 | 5 |
| **10** | 13 | 85 | 2 | 4 | 93 | 2 | 1 | 96 | 3 | 3 | 91 | 6 |
| **11** | 0 | 99 | 0 | 0 | 100 | 0 | 0 | 100 | 0 | 0 | 100 | 0 |
| **12** | 6 | 93 | 1 | 4 | 95 | 1 | 4 | 95 | 1 | 2 | 97 | 1 |
| **13** | 36 | 58 | 6 | 29 | 67 | 4 | 27 | 65 | 8 | 11 | 75 | 14 |
| **14** | 32 | 58 | 5 | 19 | 69 | 8 | 19 | 66 | 11 | 17 | 66 | 13 |
| **15** | 28 | 64 | 7 | 20 | 71 | 8 | 18 | 73 | 8 | 17 | 69 | 13 |
| **16** | 0 | 100 | 0 | 6 | 93 | 1 | 6 | 93 | 1 | 6 | 93 | 1 |
| **17** | 31 | 50 | 16 | 23 | 58 | 17 | 13 | 62 | 23 | 15 | 61 | 23 |
| **18** | 30 | 62 | 6 | 23 | 70 | 6 | 25 | 64 | 10 | 13 | 93 | 13 |
| **19** | 18 | 74 | 6 | 13 | 78 | 6 | 11 | 79 | 8 | 14 | 77 | 8 |
| **20** | 39 | 46 | 15 | 24 | 51 | 25 | 22 | 46 | 32 | 16 | 39 | 45 |
| **21** | 20 | 77 | 3 | 8 | 88 | 4 | 6 | 89 | 4 | 3 | 91 | 5 |
| **22** | 30 | 64 | 6 | 12 | 81 | 7 | 8 | 84 | 8 | 7 | 85 | 8 |
| **23** | 60 | 28 | 9 | 38 | 48 | 10 | 28 | 56 | 12 | 23 | 60 | 15 |
| **24** | 16 | 81 | 2 | 1 | 95 | 2 | 1 | 95 | 2 | 1 | 94 | 2 |
| **25** | 0 | 100 | 0 | 0 | 100 | 0 | 0 | 100 | 0 | 0 | 100 | 0 |
| **26** | 39 | 55 | 6 | 33 | 60 | 7 | 27 | 64 | 9 | 16 | 69 | 15 |
| **27** | 16 | 83 | 2 | 6 | 59 | 2 | 4 | 94 | 2 | 2 | 96 | 2 |
| **28** | 12 | 83 | 5 | 11 | 85 | 4 | 5 | 89 | 6 | 3 | 90 | 7 |
| **29** | 0 | 100 | 0 | 0 | 100 | 0 | 0 | 100 | 0 | 0 | 100 | 0 |
| **30** | 43 | 49 | 7 | 40 | 44 | 15 | 29 | 52 | 17 | 22 | 60 | 19 |

C= Actively cleared, F= Forest, I= Impermeable

Table 2.3 Comparison of different analysis techniques at quadrat 18

| Analysis Technique | % Cultivated | % Forest | % Impervious |
|---|---|---|---|
| 300 Point (1)[1, 2] | 23 | 70 | 6 |
| 300 Point (2) | 21 | 70 | 7 |
| 500 Point (1) | 26 | 67 | 6 |
| 500 Point (2) | 24 | 68 | 6 |
| Polygon (1) | 33 | 63 | 4 |
| 300 Point, analyst 2 (1) | 31 | 64 | 4 |

[1] (1) or (2) Indicates first or second repetition of analysis.

[2] 300/500 Point indicates whether 300 or 500 points per quadrat were counted. Polygon describes analysis using manual polygon delineation. “Analyst 2” is the same point counting analysis performed by a second analyst.

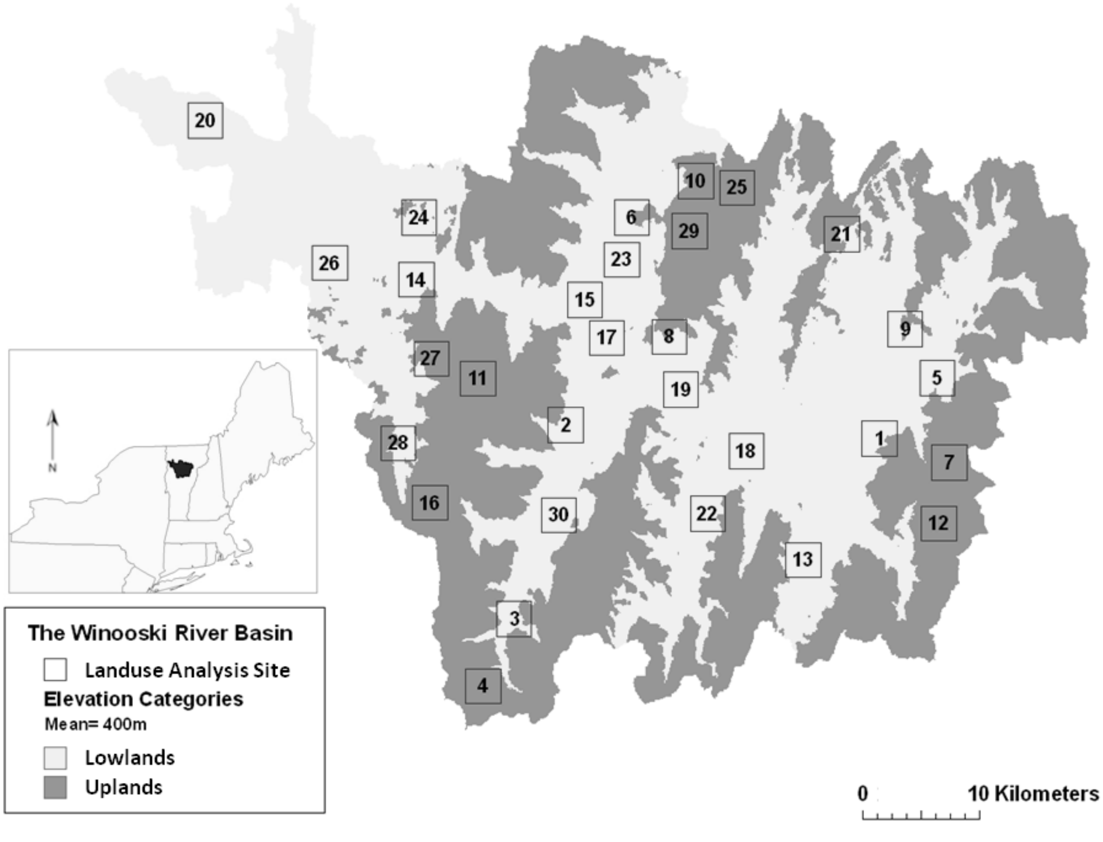

Figure 2.1.

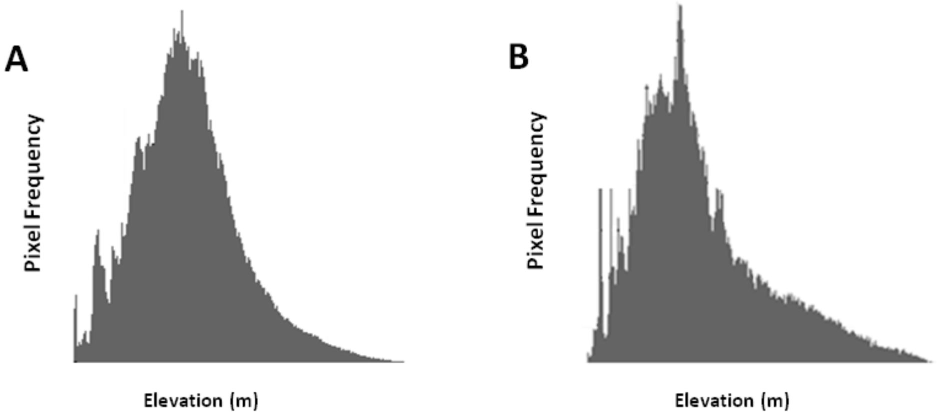

Figure 2.2

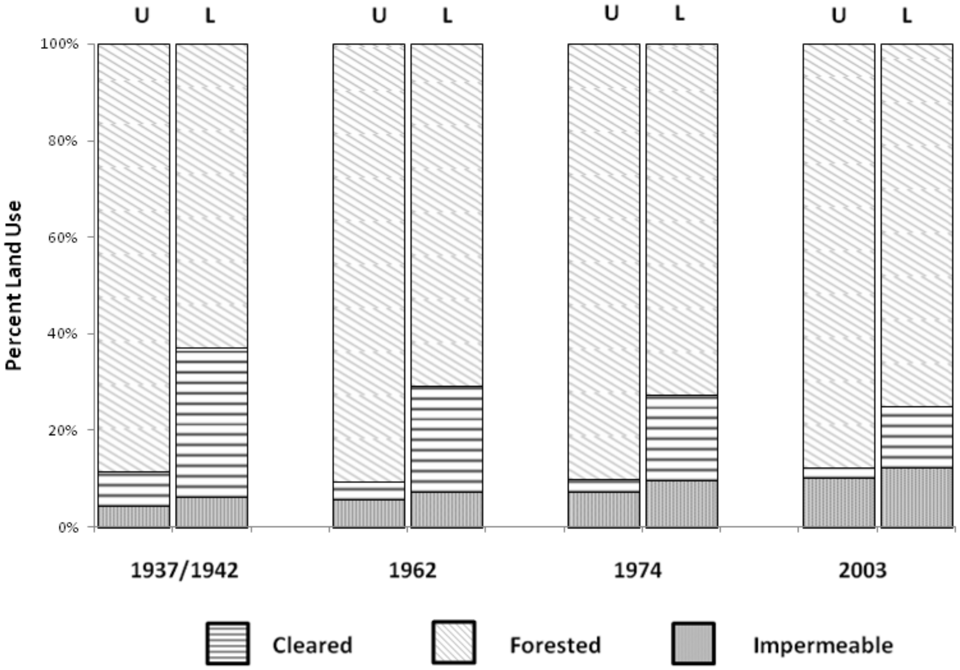

Figure 2.3

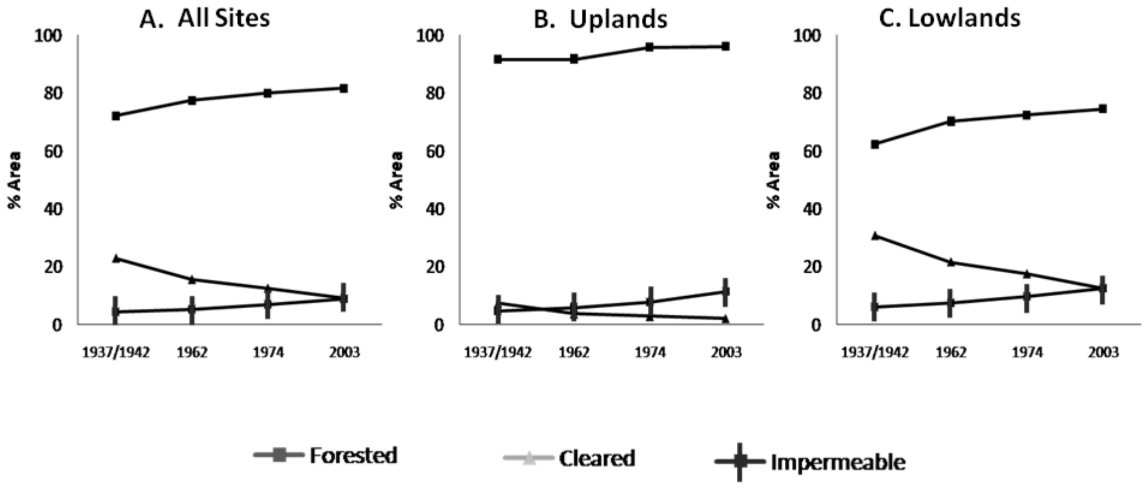

Figure 2.4

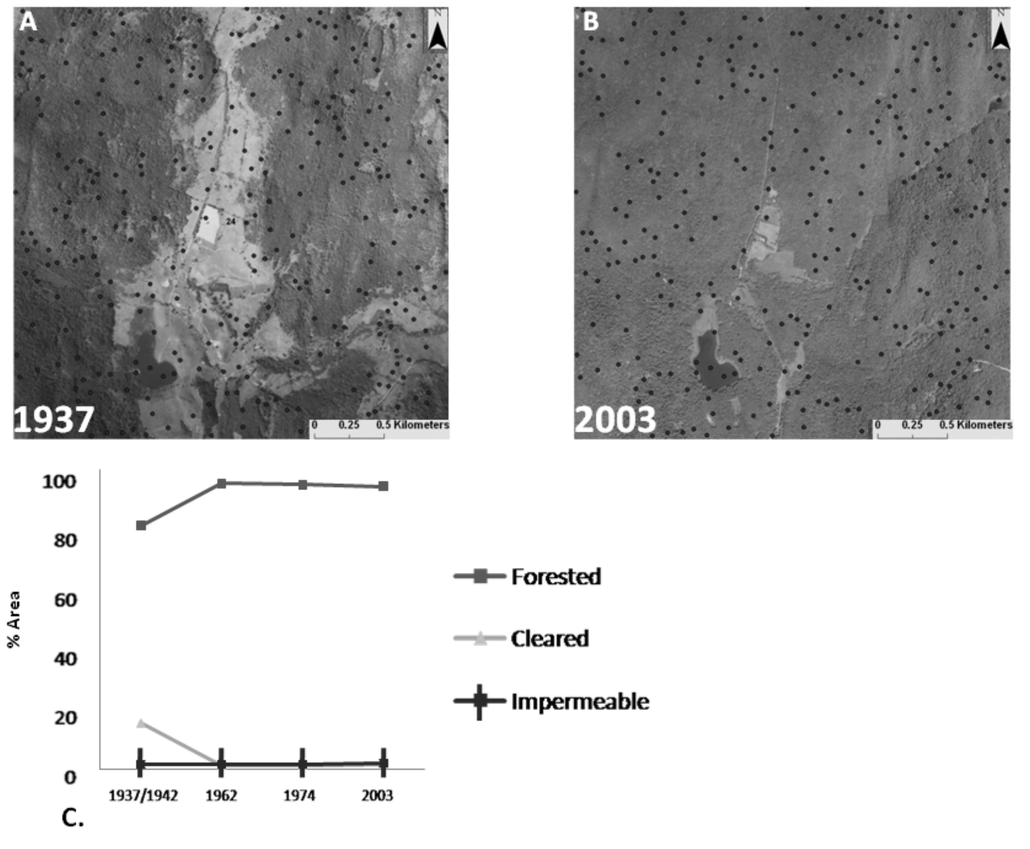

Figure 2.5

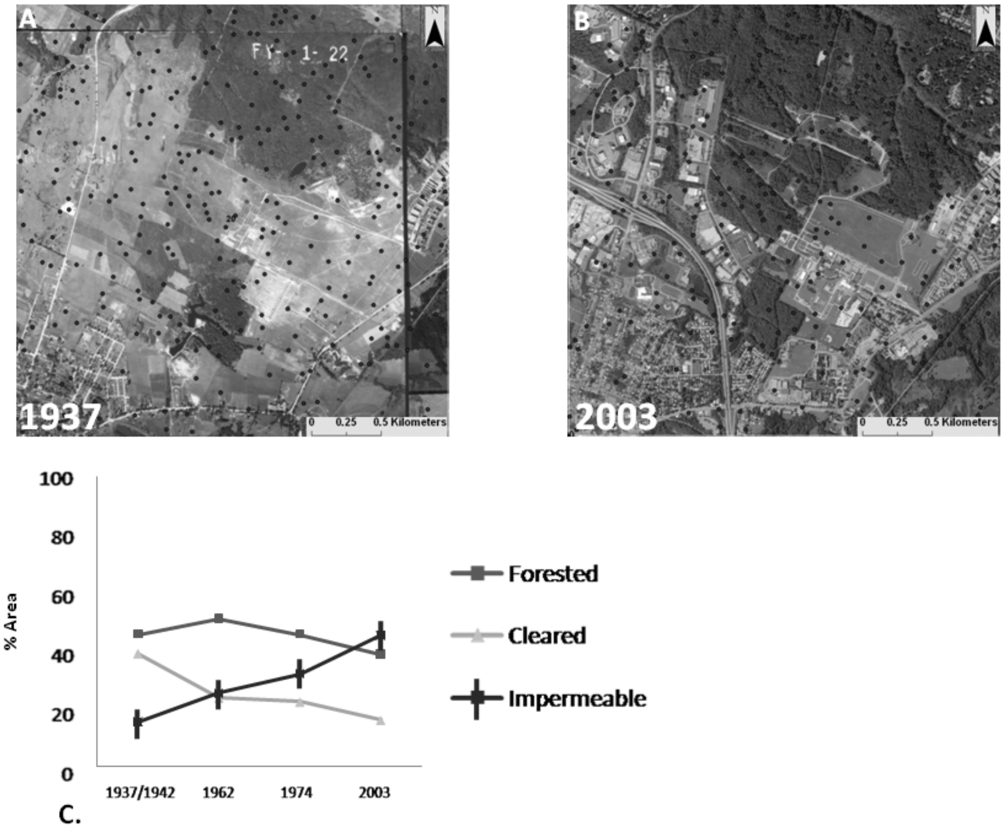
A
FY-1-22
1937
0 0.25 0.5 Kilometers
B
2003
0 0.25 0.5 Kilometers
100
80
60
40
20
0
% Area
1937/1942
1962
1974
2003
Forested
Cleared
Impermeable
C.

Figure 2.6

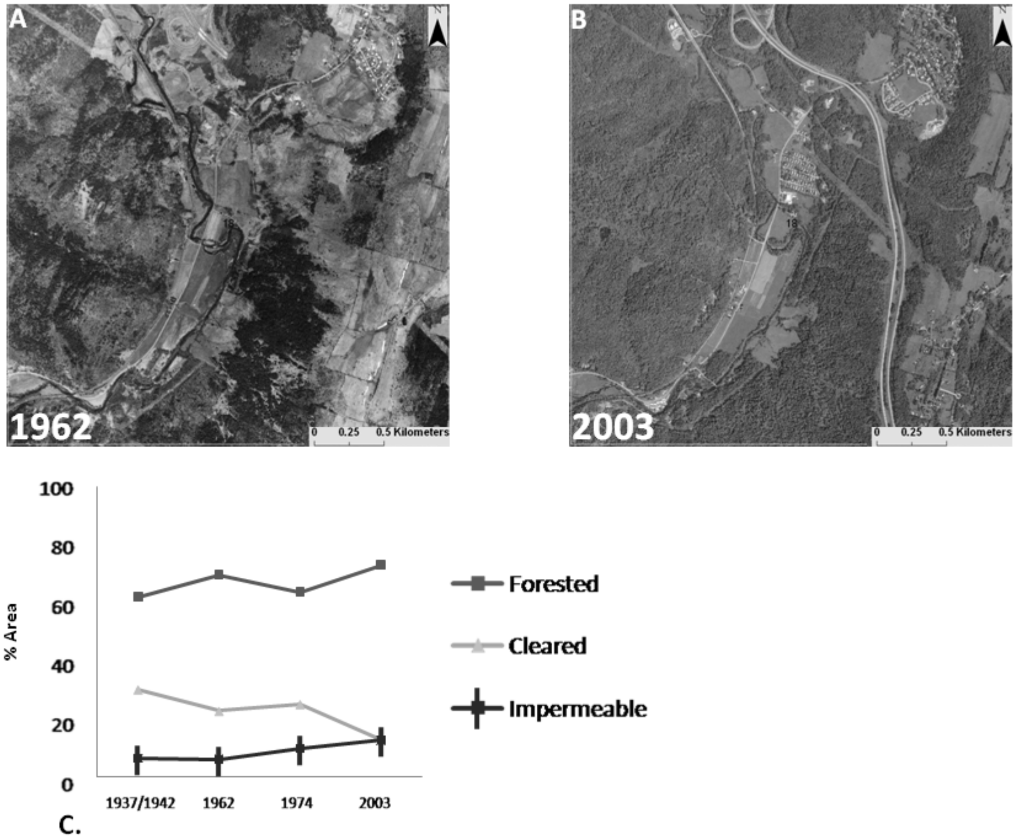
A
N
1962
0 0.25 0.5 Kilometers
B
N
18
2003
0 0.25 0.5 Kilometers
100
80
60
40
20
0
% Area
1937/1942
1962
1974
2003
C.
Forested
Cleared
Impermeable

Figure 2.7

# Chapter 3: Paper for submission to *The Journal of Hydrology*

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

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## *Abstract*

This study analyzes temporal trends and periodicity in seventy years of publicly available stream discharge and climate data for the 2,704 km$^2$ Winooski River Basin of northern Vermont and lake level data for adjacent Lake Champlain. We find a general increase in annual precipitation, discharge, and mean lake level with time. Stream discharge increases 18% over the period of record; precipitation increases by 14%. Over the last 70 years, mean annual temperature has increased at the Burlington, Vermont station by 0.8 degrees Celsius (1.4 degrees Fahrenheit). Spectral analysis of precipitation, discharge, and lake level data reveals a ~7.6 year periodicity, 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 signal, found in all weather and flow datasets, demonstrates that discharge is largely driven by precipitation. Changing climate and land use over the past 70 years appear to have together changed the seasonality of discharge and caused an increase in baseflow as well as mean annual discharge.

## *Introduction*

Global climate has been changing during the past century, with effects varying by region (Climate Change and Water, 2008). Major river basins in Europe have experienced warmer, dryer weather over the past century with decreasing flows (Climate Change and Water, 2008). In northeastern North America, temperature records show an almost unanimous increase in temperature over the past century (Trombulak and Wolfson, 2004) and the IPCC reports that northeastern North America is experiencing progressively fewer days of frozen ground during the average winter months (Climate Change and Water, 2008).

Because water is a critical resource for human society, understanding the effects of climate change on hydrologic systems at the basin scale is vital. Dependable precipitation catalyzes agriculture whereas river discharge and groundwater 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 and disrupt food production (Easterling, 1996). Shifting amounts and seasonal distribution of precipitation can strain urban infrastructure including wastewater treatment facilities, impoundments, and storm-water control systems, all of which are designed assuming stationarity in climate and thus stable amounts of precipitation and discharge (Milly, et al., 2008). Climate change has and will continue to alter regional weather, potentially exceeding the design capacity of engineered systems (O'Conner et al., 1999). With development comes more impermeable surfaces and more homes, businesses, and infrastructure increasing run-off efficiency and peak discharge (Dunne and Leopold, 1996; Zarriello et al; 1999). All of these changes have the potential to alter the relationship between precipitation, run-off, and river discharge.

## *CLIMATE DRIVERS*

### *Periodicity*

Climate and discharge records often exhibit cyclical behavior, driven through teleconnections by 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 generally include milder winters with more storms during warm El Niño years (National Weather Service, 2006). The North Atlantic Oscillation (NAO) is the difference in sea level air pressure between the Azores high (northwest of Africa) and the Icelandic low. Since the NAO is most active in the winter, the NAO index is usually calculated as the mean difference in these pressures during the winter months (Hurrell and Van Loon, 1997; Solow, 2002). The signal of drivers such as the NAO appears in many weather-related records; in Massachusetts, coastal sea surface temperatures show a correlation with the North Atlantic Oscillation activity over time (Nixon et al., 2004). In eastern North American, the NAO can bring increased storminess over long time scales (Norens et al, 2002) and wetter winters when the pressure index is positive or dryer winters when the index is negative (Hurrell, 1995).

### ***Long-term trends***

Climate change, detected as long-term trends in temperature and precipitation, can be natural or human-induced. Global average temperature increased slightly during the first half of the twentieth century; during the latter half of the twentieth century, more rapid warming took place (Climate Change and Water, 2008). Warming is also documented in eastern North America sea surface temperatures, which show an increase in the first half of the 1900s followed by a ~15 year decrease in temperature before resuming a warming trend for the latter half of the century (Friedland and Hare, 2007). This warming has been accompanied by a general increase in precipitation in northern latitudes (Climate Change and Water, 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 (Climate Change and Water, 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 et al; 2005).

## *PREDICTIONS FOR FUTURE CHANGE IN NEW ENGLAND*

Predictions for climate change in New England are consistent with recent observations. Precipitation is projected to increase over the mid to high latitudes, with a strong likelihood of an increase in frequency of heavy precipitation events (Climate Change and Water, 2008). Increased warming during the winter months is also projected to continue in New England, yielding thinner snowpacks that accumulate later in the fall and melt earlier in the spring (Hodgkins et al; 2003; Climate Change and Water, 2008). Summer warming and the higher moisture capacity of the atmosphere will cause the land surface to dry more quickly, providing more moisture for storm systems (OECD, 2008; Steele-Dunne et al., 2008) and, if the drying effect exceeds the amount of water added by increased precipitation, reducing baseflow. Warming will effect seasonality when coupled with increased precipitation which should increase discharge in the northern latitudes while rivers of Africa and Europe will experience less flow (Climate Change and Water, 2008). Precipitation increases are predicted to be especially prevalent in winter with little or no change in the summer (Hayhoe et al., 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 uncertainty over how the amplitude and frequency of these oscillations will change (Visbeck et al., 2001, Climate Change and Water, 2008).

## *RECENT CLIMATIC TRENDS IN NEW ENGLAND*

In New England, where western settlement began over 300 years ago, there are detailed records of temperature, precipitation, and discharge dating back nearly a century. These data reveal a general upward trend in regional temperature since the end of the Little Ice Age (Broecker, 2001). Temperatures oscillated throughout most of the 20th century before rising since the 1970's both on land and along the New England coast (Nixon et al; 2004, 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 and central New England due to an estimated 1.5 degrees Celsius (2.6 Fahrenheit) temperature increase (Hodgkins et al; 2005). The reduction of ice on New England's lakes is primarily correlated with March and April average temperatures, which have been warming. Precipitation has been increasing modestly, though there have been periods of drought particularly in the 1960's (Hurtt et al., 2001). In New England, streamflow has also been increasing with the annual center of mass and peak flows coming earlier reflecting 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, driven by melting snow, will decrease (Climate Change and Water, 2008).

## *COMPLEX INTERACTIONS*

Land use, affecting runoff amounts and discharge records, has changed significantly in New England over the past century. Colonial development in New England was primarily agricultural, which necessitated clearing much of the land; farming peaked in the late 1800's before economic pressures (competition from the Mid-West) and erosion of upland farms began to drive some farms to failure (Wessels, 1997, Albers, 2000). Since that time, large tracts of the New England landscape have reforested, changing the hydrology of these areas (Wessels, 1997). What were once cultivated fields or pastures were reforested, increasing evapotranspiration and reducing erosion (Juckem et al., 2008, Forman and Alexander, 1998). Coincident with and following reforestation, 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 in northern Vermont, 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 and Bierman, 2009).

## *STUDY DESIGN*

In this study, we use publicly available 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 between 1937 and 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 baseflow, 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 and the Winooski River Basin's landscape (Figure 3.1) are 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). Annual precipitation ranges from ~ 0.9 meters in the Champlain Valley to more than 1.7 meters in the mountains (NOAA, 1997). To the west of the Green Mountains, the Champlain Valley is underlain by sedimentary rocks and has subdued topography with rich, productive farmlands (Doolan, 1996; Mehrtens, 2001). The Laurentide Ice Sheet and pro-glaical lakes covered the Green Mountains during the last glaciation leaving 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 Weather Service (NWS) weather and United States Geological Survey (USGS) river discharge stations throughout the Winooski River Basin in northern Vermont. All except one station was installed in the decade following Vermont's 1927 flood of record (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) near the main-stem Winooski River confluence. The tributary sub basins are similar in terms of average elevation, slope, and landcover (Table 3.1). Additionally, a USGS lake level gage is maintained on Lake Champlain in Burlington, VT. National Weather Service Stations collect precipitation and discharge data from another six locations around the Winooski River Basin, providing daily data for at least the past sixty years. Some stations were closed and reestablished years later at a nearby site, presenting opportunity for elevation to affect the trends of precipitation and temperature. To test against these, we plotted precipitation at multi-location stations against the complete records of the Montpelier station to ensure that there was no change in the relationship when the station location changed. Following this preparation, we summed daily data for precipitation and totaled these for months and years, while taking mean values of temperature in the same manner.

### ***Methods***

To establish long term (multi-decadal) trends in the data, we linearly regressed values of discharge, precipitation, lake level, and temperature (~1930-2005) against time using bi-variate plots. We acquired these data as daily averages, which we then summed into months and years as well as querying the data for high and low (base) flows. We define high flows are the three highest 24-hour average flows per year. We repeated the regression process using monthly data to investigate changes in seasonality. Additionally, we regressed precipitation and discharge values from annual base and storm flows to determine if these events are increasing in frequency or severity. For each bi-variate plot, we determined a slope and tested the significance (using the p value) of a linear trend line over the period of record. This trend line then characterizes an overall increasing or decreasing trend in the data at a 90% significance level. To examine the relationships between precipitation, sub basins, and the overall basin discharge, we plotted precipitation against discharge to confirm the relationship between the two, and then calculated the annual percentage of flow contribution that each sub basin made to the total basin flow per year at the sub-basin outlet and plotted that as a trend over time. We defined a threshold for "extreme" storms as the smallest annual maximum precipitation event in the period of record (Madsen and Figdor, 2007); 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 (Madsen and Figdor, 2007). 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. Each resulting trend direction (up or down) and its p value were then compiled for comparison between stations; trends are highlighted in result tables if the regression has a p value <0.1.

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 of cyclic oscillations in the data. Then, using spectral analysis, we deconvolved the data into noise and signal, calculating significance levels for each spectral peak (Figure 3.2). Using "Auto Signal" (www.clecom.co.uk/science/autosignal), a program designed to identify cyclic signals in temporal data, we conducted a fast fourier transformation to filter out the red noise from the periodic signals. Removal of red noise better exposes the signal because spectral power increases with decreasing frequency as a result of the noise (Mancini, 2003). Geophysical and atmospherically forced data are typically filtered for red noise because it has a "memory" component while traditional white noise does not (Mancini, 2003, 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 (Figure 3.3). These linear trends are statistically significant, based on the p values of the trendlines for each plot, for four of the six discharge stations and all four weather stations (Table 3.2). The Lake Champlain gage height also shows a significant upward trend in level based on annual mean values. Annual totals of precipitation at Burlington Airport and runoff at all six USGS gaging stations are well correlated, with an $R^2$ of 0.64 between Burlington Airport and the Essex Junction gaging station for the entire period of record (Figure 3.4).

### *STORMS AND BASEFLOW*

The frequency (number per year) of strong storms is increasing significantly at two of the four stations (Table 3.3). However, while frequency of strong storms is increasing, 24-hour total precipitation totals during the three largest precipitation events per year are not. Two of the four stations also showed a significant decrease over time in the contribution of the 20 largest precipitation events to the total annual precipitation.

The total daily discharge during at least one of the three highest flow days per year decreased significantly at three of the six stations with insignificant downward trends at all six (Table 3.3). Conversely, total flow on all of the three lowest flow days per year (baseflow) showed statistically significant increases at all six stations.

### *MONTHLY ANALYSES*

There is a consistent increase in precipitation at all stations in the latter half of the year from August to December; this increase is significant ($p<0.1$) during at least one month between August and December at all five weather stations (Table 3.4). Four of the five weather stations show no significant trend in precipitation during February, May, June, or July.

Discharge increased at most stations during January, February, March, and November (Table 3.5). Decreasing flows occur in every station during at least one month between March and May, but with insignificant p values. There is no significant change in flow at four of the six stations in March and June. Monthly flows between July and December increase significantly at all stations, with the greatest significance in the last months of the year.

### ***TEMPERATURE***

Annual mean low and high temperatures trend significantly upward at the Burlington Airport by 0.09 and 0.12 degrees Celsius (0.16 and 0.22 degrees Fahrenheit) per decade, respectively; there is no significant change at Montpelier (Table 3.6). 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 showed a cooling trend, significant at the Montpelier station. Mean low or high monthly temperature showed significant increases at Burlington during March, April, August, and December. At Burlington, the spread between mean monthly low and high is getting wider in the spring months of March and April, with no significant change during the other nine months of the year (Figure 3.5).

## ***SPECTRAL ANALYSIS***

Spectral analysis of discharge, precipitation, temperature, and lake level records revealed statistically significant periodicity in each dataset (Figure 3.6). 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 four strongest spectral peaks in discharge and precipitation are between 7 and 8.5 years for all stations. Annual mean Lake Champlain water level gage height data has a period of 7.4 years. When annual indexes for the North Atlantic Oscillation (obtained online from NOAA Climate Prediction Center) were analyzed using spectral analysis, that record showed its strongest spectral peak at 7.6 years. Linear splines of each record revealed that runoff and precipitation signals were in phase with the NAO record, regardless of window size. Other climate oscillation records were also analyzed using spectral analysis, including the Pacific Decadal Oscillation and ENSO, but only the NAO had periods matching those of the dominant discharge and climate signals in the Winooski River basin.

## ***Discussion***

Over the past 70 years, northern Vermont has become wetter and warmer, consistent with trends noted in neighboring states (Huntington, 2003; Nixon et al., 2004). 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 3.7). The correlation of annual precipitation and discharge values ($R^2$

values, 0.5-0.7, Table 3.2) and similarity in the relative amplitude and phase of linear splines applied to both precipitation and discharge records (Figure 3.2) together indicate that changes in river discharge on an annual time scale are predominately driven by cyclical changes in precipitation – forced at least in part by the NAO. The cyclical precipitation signal (Figure 3.6) and the secular trend (Figure 3.7) are both clearly reflected in the mean annual gage height of Lake Champlain- the water body into which the Winooski River flows. The average annual lake level is rising over time, despite increased human consumption, along with precipitation and discharge.

The NAO effect 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 (1946 to 2006) for the Seine River Basin (Bradbury et al., 2002; Massei et al., 2008, 2009). In New England, Bradbury et al. (2002) found that stream discharge at stations across the region corresponded to NAO values; high NAO winters brought higher streamflows. The NAO also varies on longer time scales. Ice core records from Greenland and hydrologic records (interpreted as paleo storminess records, Noren et al., 2002) from New England show coincident phasing on 3000 year cycle interpreted as fluctuations in the Arctic Oscillation, an atmospheric index closely related to the NAO.

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 et al; 2005). Increasing precipitation, particularly during the fall months, is common to other areas in New England (Huntington, 2003). Temperatures in New England and New York have been increasing over the past century (Trombulak and Wolfson, 2004). Lake level records from Maine demonstrate that water 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 land use change on river discharge over the past 70 years are uncertain but likely minor in comparison to changing precipitation as evidenced by the strong correlation ($r^2$= 0.64) between runoff and precipitation (both of which have increased over the past 70 years by 18% and 14%, respectively) and the dominance of the NAO periodicity in the splined records. Several simple calculations and inferences support this conclusion. Documented increases in both impervious and forest cover are hydrologically offsetting, with the first increasing runoff and the second increasing infiltration. An area-weighted curve number runoff calculation using land use data from Hackett and Bierman. (2009) and annual precipitation data suggests that changing land use would increase potential runoff by less than 2%. Using annual run off volumes for the gage farthest downstream (Essex Junction) and precipitation (Burlington), we calculate a mean loss by evapotranspiration and groundwater of 42% of total basin input with a significant decreasing trend over the past 70 years.

There are some indications that land-use change over seventy years in the Winooski River Basin is subtly reflected by the discharge records. For example, although the frequency of large storms is increasing (Table 3.3), 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 despite increasing precipitation and discharge overall (Zheng et al; 2008). Similarly, the consistent and statistically significant increase in baseflow we noted at all stations (Table 3.3) likely reflects the interaction of land use change and increasing precipitation over time. Net reforestation on formerly cleared land in 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; changing land use to less-intensive agriculture and forest practices catalyzed the flow increase (De la Cretaz and Barten, 2007; Juckem et al., 2008).

Our results also suggest changing seasonality and a complex hydrologic response. Average temperature during the spring months is rising (Table 3.6), along with a significant increase in temperature spread between mean low and mean high during this time 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 3.4), discharge either decreases or remains unchanged with insignificant trends (Table 3.5) suggesting diminished contribution from a thinner spring snowpack. Unchanging or decreased discharge during April and May 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 evapotranspiration 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 the receiving body, 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 suggest some impact 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 runoff from 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 hydrologic system, particularly in terms of spring river discharge. The interactions between land use and climate drivers in the Winooski River Basin indicate that the dominant control on discharge is climate rather than land use at the annual, basin-scale. Our findings suggest that large drainage basins in humid, northeastern North America are likely to see significant changes in flow dynamics are a result of hydrologic responses to changing climate over the next decades and centuries. The assumption of stationarity, on which most flood hazard and thus many planning decisions are made, appears invalid for New England (Milly et al., 2008).

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## *Figure Captions:*

Figure 3.1- The Winooski River Basin drainage network showing US Geological Survey gaging stations, and National Weather Service weather stations. Base map From Vermont Center for Geographic Information.

Figure 3.2- Spectral analysis of annual precipitation at Burlington International Airport from 1930-2005; data from National Climate Data Center. Curved line represents 95% significance level.

Figure 3.3- Total annual precipitation at Waterbury, Vermont (W3 and W4) and annual discharge on the Mad River (D3), Vermont from 1943-1990; data from National Climate Data Center. Points represent annual data, sloping line represents linear regression, solid oscillating line is linear spline (lambda=1).

Figure 3.4- Total annual precipitation and annual sum of daily mean discharge at the Essex Junction USGS discharge station (USGS, 2008) for 1936-2005 are well correlated.

Figure 3.5- March mean high temperatures (A) and annual difference between March mean low and high temperatures (B) at the Burlington Airport. Points are annual data, sloping line is linear regression line, solid oscillating line is linear spline (lambda=1).

Figure 3.6- Summary of spectral analysis output showing four strongest spectral peaks for discharge, precipitation, temperature, and Lake Champlain level at each data collection site in the Winooski River Basin. Data source: USGS and NCDC.

Figure 3.7- Linear spline (jagged fit line)  illustrates regular oscillations which are in phase between (A) North Atlantic Oscillation index, (B) precipitation, (C) Winooski River discharge at Essex Junction (D) temperature at Burlington International airport, and (E) Lake Champlain gage height.  Linear fit is flat inclined line while mean is the horizontal line.  Vertical lines are for visually matching of peaks between datasets.

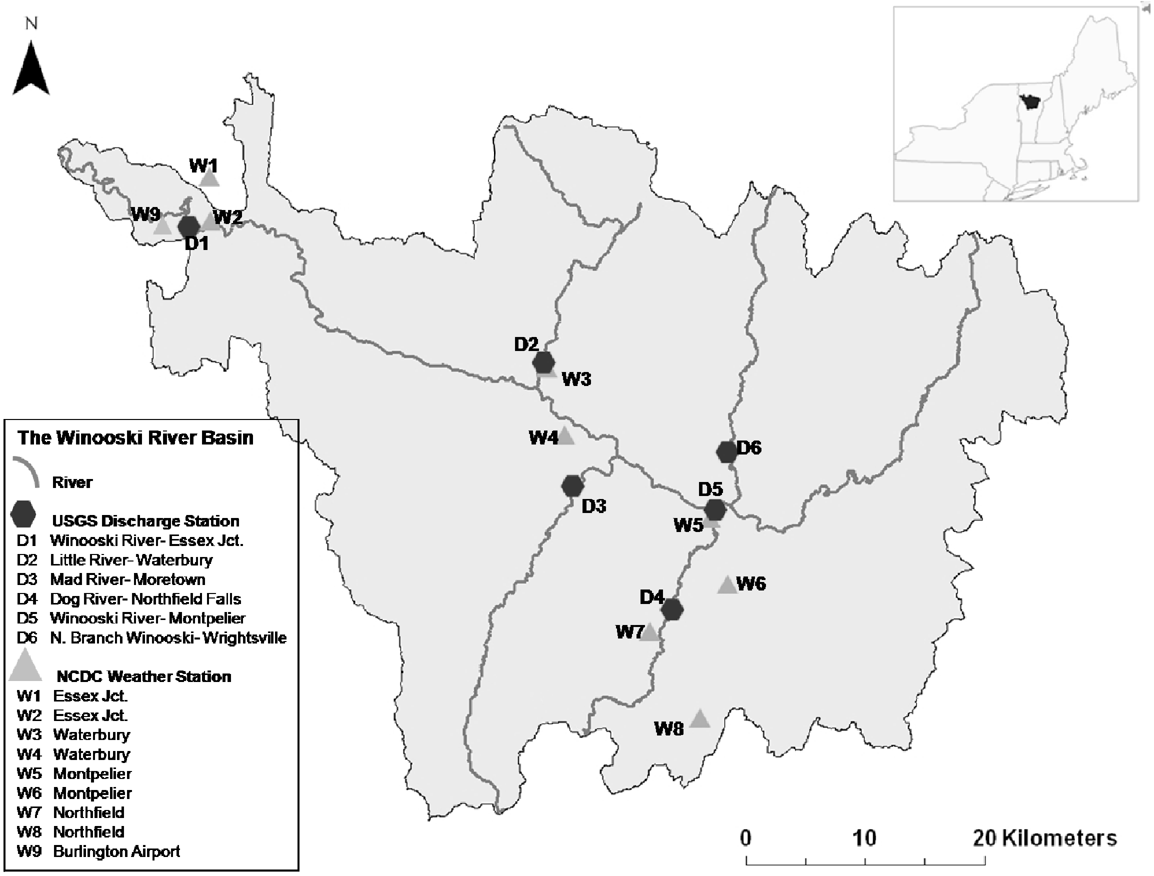


Figure 3.1

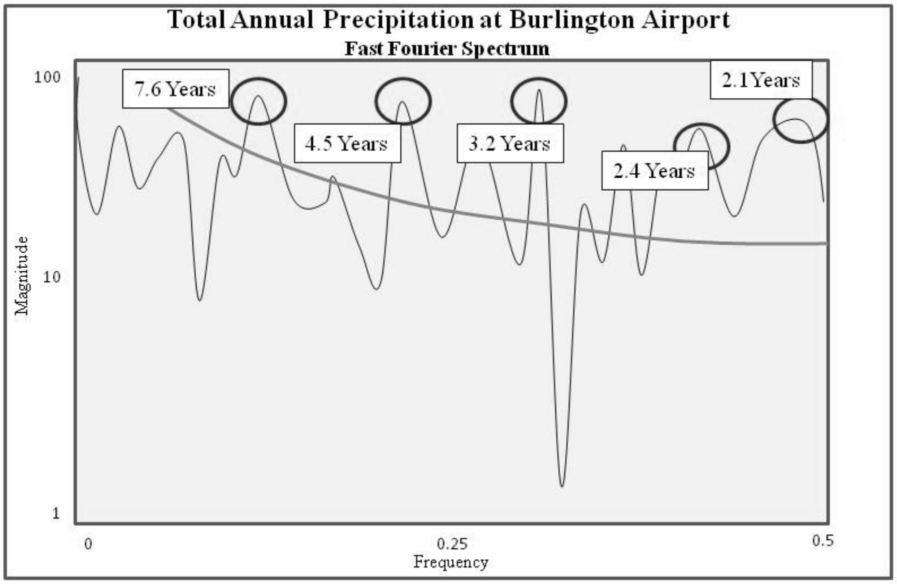


Figure 3.2

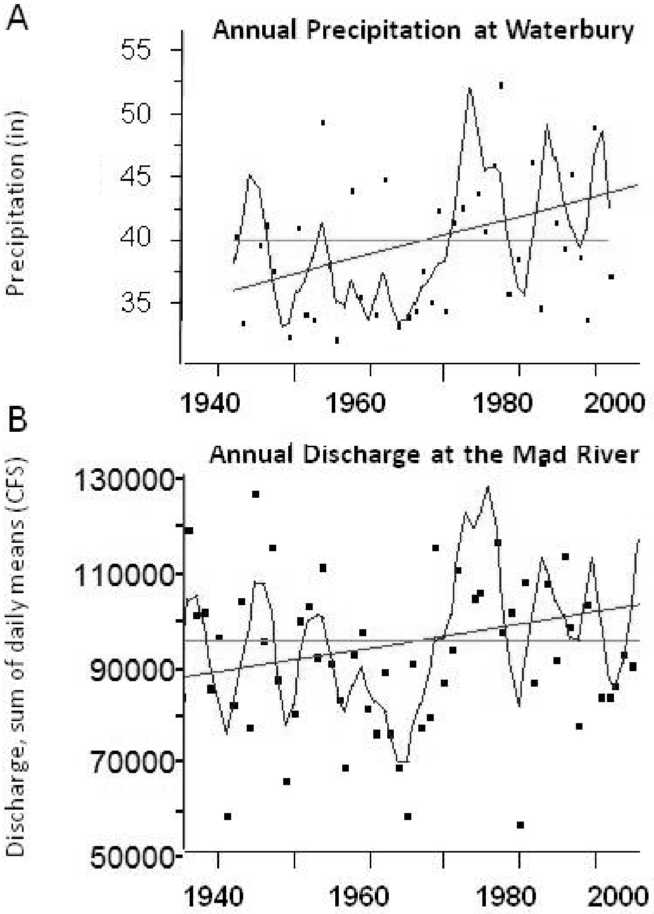

A
Annual Precipitation at Waterbury
Precipitation (in)
55
50
45
40
35
1940
1960
1980
2000
B
Annual Discharge at the Mad River
Discharge, sum of daily means (CFS)
130000
110000
90000
70000
50000
1940
1960
1980
2000

Figure 3.3

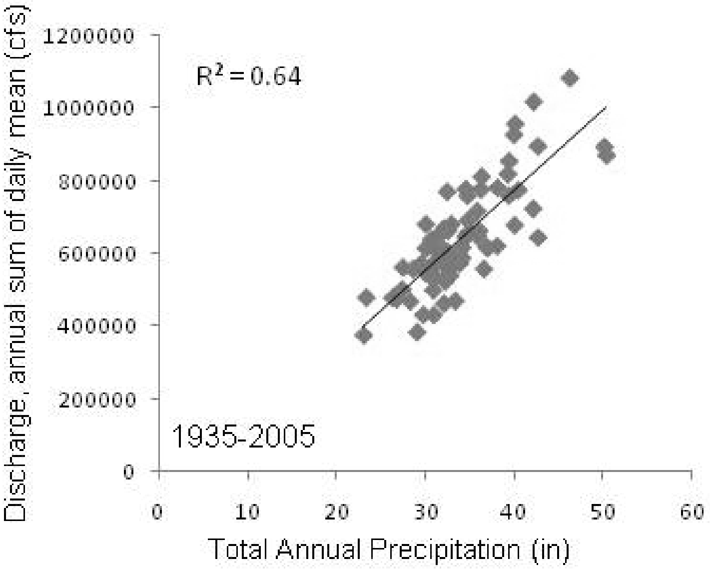


Figure 3.4

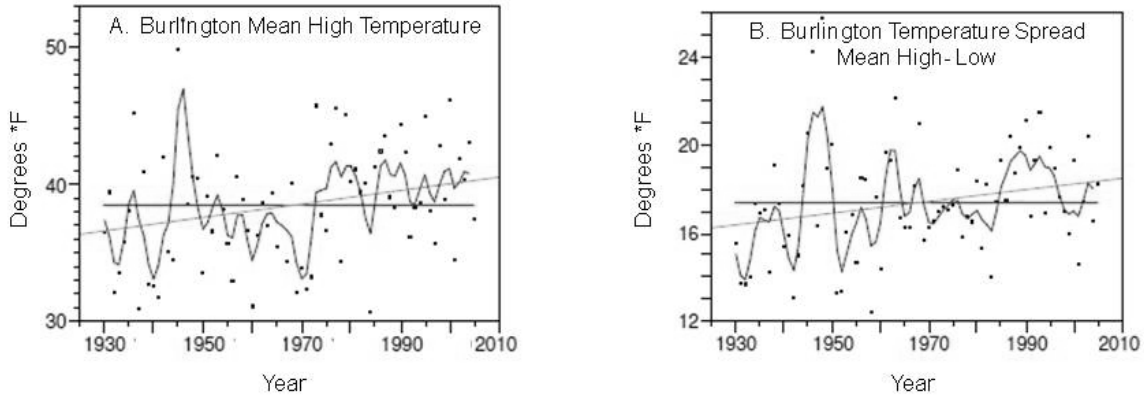


Figure 3.5

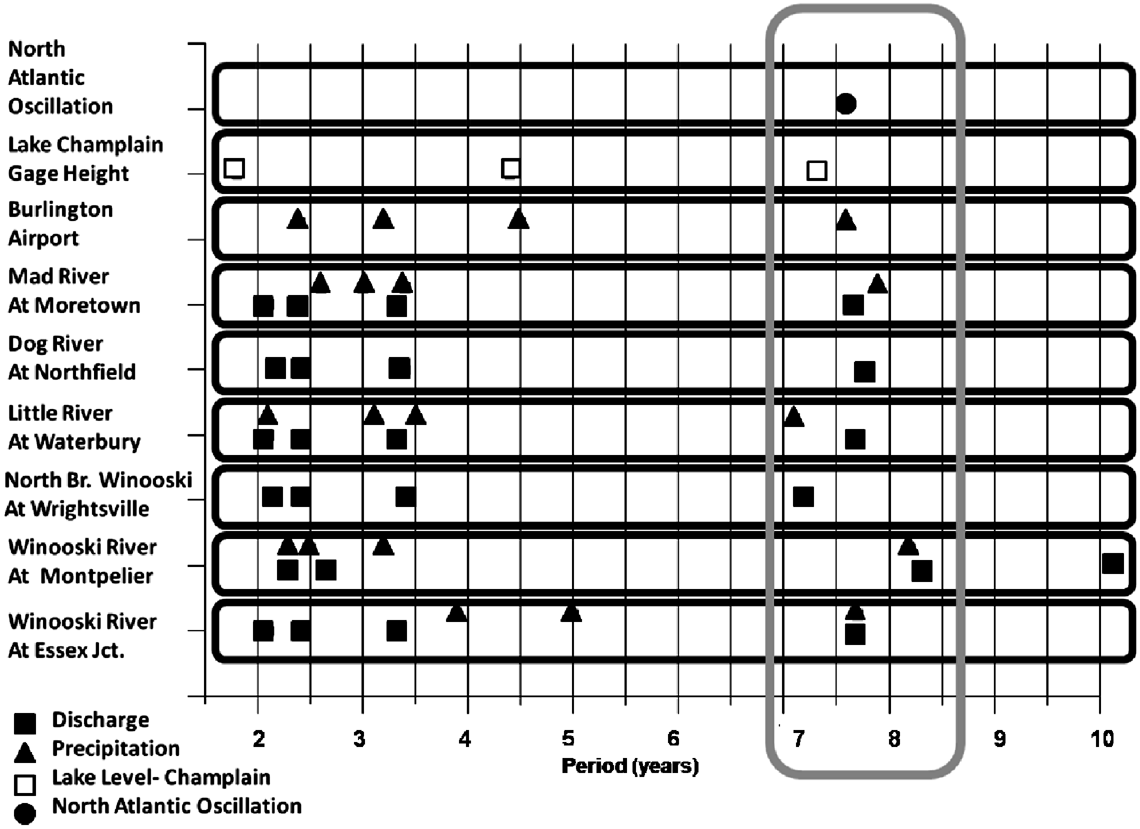

North Atlantic Oscillation
Lake Champlain Gage Height
Burlington Airport
Mad River At Moretown
Dog River At Northfield
Little River At Waterbury
North Br. Winooski At Wrightsville
Winooski River At Montpelier
Winooski River At Essex Jct.
■ Discharge
▲ Precipitation
□ Lake Level- Champlain
● North Atlantic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

Figure 3.6

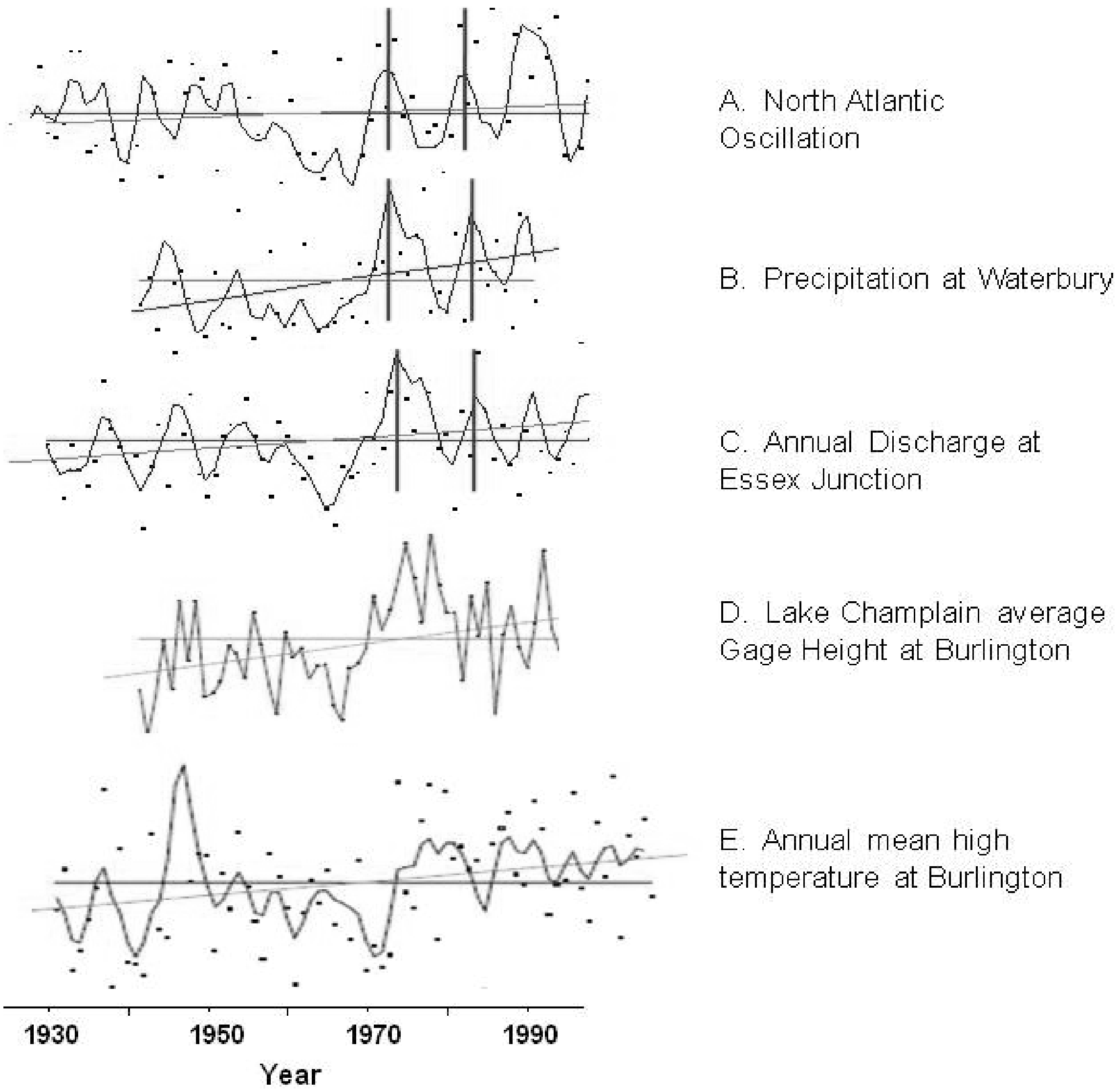

A. North Atlantic Oscillation
B. Precipitation at Waterbury
C. Annual Discharge at Essex Junction
D. Lake Champlain average Gage Height at Burlington
E. Annual mean high temperature at Burlington
1930
1950
1970
1990
Year

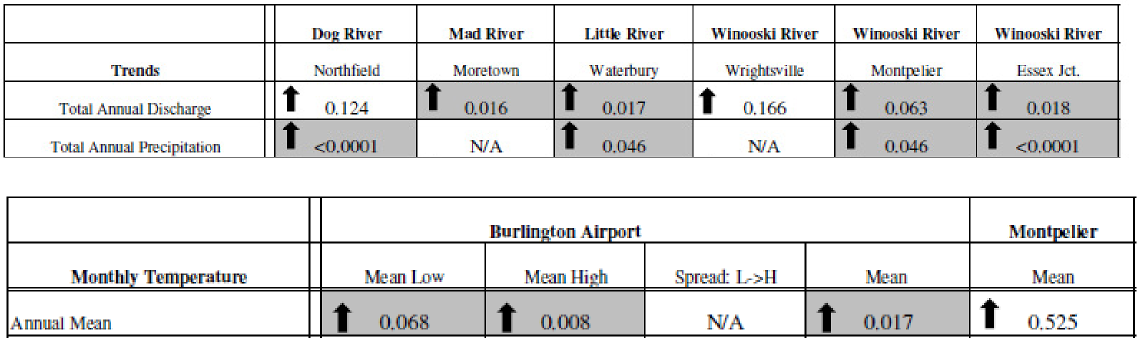
Figure 3.7

Table 3.1. Sub Basin Characteristics in the Winooski River Basin

| **Sub Basin** | **Area ($^{km2}$)** | **% Forest[1]** | **Lowest/highest elevation ($^{m}$)** | **Mean elevation ($^{m}$) setting** |
|---|---|---|---|---|
| Little River | 290 | 86% forest | 115/1340 | 450 |
| North Branch | 200 | 91% forest | 155/1100 | 430 |
| Mad river | 370 | 87% forest | 130/1240 | 480 |
| Dog River | 240 | 85% forest | 150/880 | 420 |

[1] Land use/ Land cover data from 2001 LANDSAT analysis of Vermont.

Table 3.2- Summary table of p values and regression trends for precipitation, discharge, and temperature over time in the Winooski River Basin, ~1930-2005.

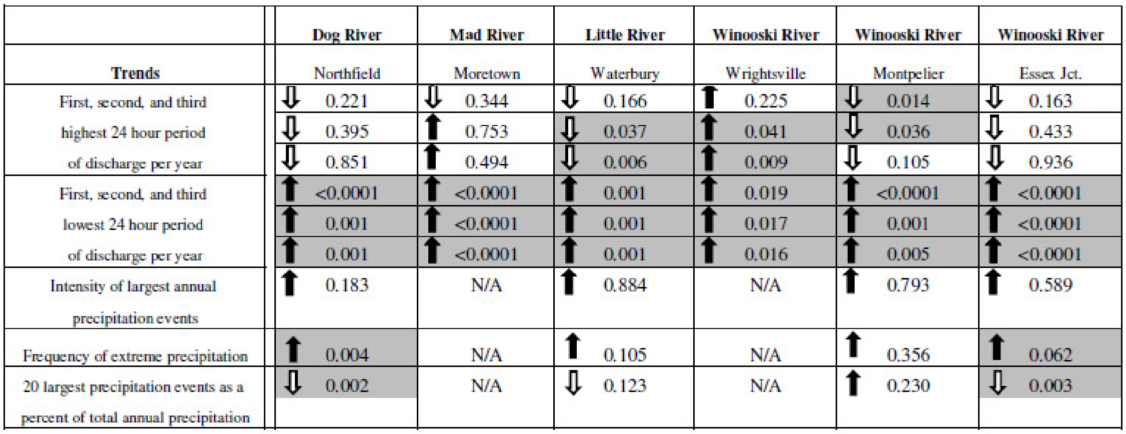


|  | **Dog River** | **Mad River** | **Little River** | **Winooski River** | **Winooski River** | **Winooski River** |
|---|---|---|---|---|---|---|
| **Trends** | Northfield | Moretown | Waterbury | Wrightsville | Montpelier | Essex Jct. |
| Total Annual Discharge | ↑ 0.124 | ↑ 0.016 | ↑ 0.017 | ↑ 0.166 | ↑ 0.063 | ↑ 0.018 |
| Total Annual Precipitation | ↑ <0.0001 | N/A | ↑ 0.046 | N/A | ↑ 0.046 | ↑ <0.0001 |

|  | **Burlington Airport** |  |  |  | **Montpelier** |
|---|---|---|---|---|---|
| **Monthly Temperature** | Mean Low | Mean High | Spread: L->H | Mean | Mean |
| Annual Mean | ↑ 0.068 | ↑ 0.008 | N/A | ↑ 0.017 | ↑ 0.525 |

¯Arrow shows direction of trend; solid arrow indicates upward trend, open arrow indicates downward trend, shaded cell indicates 90% significance level.
¯Q indicates discharge
¯Data from USGS and National Climate Data Center.

Table 3.3- Summary table of event statistics of precipitation and discharge in the Winooski River Basin, ~1930-2005.



| | **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 | ⬆ 0.753 | ⇩ 0.037 | ⬆ 0.041 | ⇩ 0.036 | ⇩ 0.433 |
| | ⇩ 0.851 | ⬆ 0.494 | ⇩ 0.006 | ⬆ 0.009 | ⇩ 0.105 | ⇩ 0.936 |
| 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 | ⬆ <0.0001 | ⬆ 0.001 | ⬆ 0.016 | ⬆ 0.005 | ⬆ <0.0001 |
| Intensity of largest annual precipitation events | ⬆ 0.183 | N/A | ⬆ 0.884 | N/A | ⬆ 0.793 | ⬆ 0.589 |
| 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 |

¯Arrow shows direction of trend; solid arrow indicates upward trend, open arrow indicates downward trend, shaded cell indicates 90% significance level.
¯Raw data from USGS and National Climate Data Center.

Table 3.4- Summary table of monthly precipitation trends in the Winooski River Basin, ~1930-2005.

| | **Dog River** | **Little River** | **Winooski River** | **Winooski River** | **Winooski River** | |
|---|---|---|---|---|---|---|
| **Monthly Precipitation** | Northfield | Waterbury | Burlington Airport | Montpelier | Essex Jct. | **# UP** |
| January | ▨ ⬆ 0.068 | ⬆ 0.145 | ⬆ 0.862 | ⇩ 0.464 | ▨ ⬆ 0.063 | 4 of 5 |
| February | ⬆ 0.540 | ⬆ 0.991 | ⇩ 0.699 | ▨ ⇩ 0.009 | ⇩ 0.874 | 2 of 5 |
| March | ▨ ⬆ 0.037 | ▨ ⬆ 0.053 | ⇩ 0.797 | ⇩ 0.184 | ▨ ⬆ 0.016 | 3 of 5 |
| April | ▨ ⬆ 0.005 | ⇩ 0.770 | ⇩ 0.749 | ⬆ 0.802 | ⬆ 0.125 | 3 of 5 |
| May | ⬆ 0.275 | ⇩ 0.921 | ⬆ 0.387 | ⬆ 0.583 | ⬆ 0.714 | 4 of 5 |
| June | ⬆ 0.275 | ⇩ 0.787 | ⬆ 0.959 | ⬆ 0.715 | ⬆ 0.519 | 4 of 5 |
| July | ⬆ 0.462 | ⇩ 0.875 | ⬆ 0.835 | ⬆ 0.718 | ⬆ 0.129 | 4 of 5 |
| August | ▨ ⬆ 0.013 | ▨ ⬆ 0.028 | ▨ ⬆ 0.064 | ▨ ⬆ 0.089 | ⬆ 0.162 | 5 of 5 |
| September | ⬆ 0.488 | ⬆ 0.233 | ⬆ 0.190 | ⬆ 0.321 | ⬆ 0.205 | 5 of 5 |
| October | ▨ ⬆ 0.021 | ⬆ 0.816 | ⬆ 0.394 | ⬆ 0.268 | ▨ ⬆ 0.088 | 5 of 5 |
| November | ⬆ 0.201 | ⬆ 0.410 | ▨ ⬆ 0.071 | ⬆ 0.635 | ⬆ 0.270 | 5 of 5 |
| December | ▨ ⬆ 0.055 | ⬆ 0.280 | ⬆ 0.622 | ⬆ 0.881 | ⬆ 0.400 | 5 of 5 |
| | 12 of 12 | 8 of 12 | 9 of 12 | 9 of 12 | 11 of 12 | **# UP** |

-Arrow shows direction of trend; solid arrow indicates upward trend, open arrow indicates downward trend, shaded cell indicates 90% significance level.
-"# UP" column and row are tallies of stations and months with increasing trends.
-Raw data from USGS and National Climate Data Center

Table 3.5- Summary table of monthly discharge trends in the Winooski River Basin, ~1930-2005.

| | **Dog River** | **Mad River** | **Little River** | **Winooski River** | **Winooski River** | **Winooski River** | |
|---|---|---|---|---|---|---|---|
| **Monthly Discharge** | Northfield | Moretown | Waterbury | Wrightsville | Montpelier | Essex Jct. | **# UP** |
| January | ⬆ 0.583 | ⬆ 0.462 | ▨ ⬆ 0.037 | ⬆ 0.357 | ⬆ 0.137 | ⬆ 0.232 | 6 of 6 |
| February | ⬆ 0.507 | ⬆ 0.163 | ⇩ 0.848 | ⬆ 0.168 | ▨ ⬆ 0.050 | ⬆ 0.132 | 5 of 6 |
| March | ⇩ 0.707 | ⬆ 0.486 | ⇩ 0.912 | ⬆ 0.575 | ⇩ 0.298 | ⬆ 0.730 | 3 of 6 |
| April | ⇩ 0.610 | ⇩ 0.327 | ▨ ⬆ 0.061 | ⇩ 0.312 | ⇩ 0.561 | ⇩ 0.472 | 1 of 6 |
| May | ⇩ 0.417 | ⇩ 0.419 | ⇩ 0.236 | ▨ ⇩ 0.061 | ⬆ 0.487 | ⇩ 0.520 | 1 of 6 |
| June | ⬆ 0.657 | ⬆ 0.563 | ⬆ 0.247 | ⬆ 0.518 | ⬆ 0.514 | ⬆ 0.436 | 6 of 6 |
| July | ▨ ⬆ 0.070 | ⬆ 0.296 | ⬆ 0.847 | ⬆ 0.168 | ⬆ 0.158 | ⬆ 0.157 | 6 of 6 |
| August | ▨ ⬆ 0.003 | ▨ ⬆ 0.008 | ⇩ 0.575 | ▨ ⬆ 0.003 | ▨ ⬆ 0.008 | ▨ ⬆ 0.006 | 5 of 6 |
| September | ⬆ 0.630 | ⬆ 0.276 | ⇩ 0.505 | ⬆ 0.328 | ⬆ 0.223 | ⬆ 0.162 | 5 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 |
| | 9 of 12 | 10 of 12 | 7 of 12 | 10 of 12 | 10 of 12 | 10 of 12 | **# UP** |

-Arrow shows direction of trend; solid arrow indicates upward trend, open arrow indicates downward trend, shaded cell indicates 90% significance level.
-"# UP" column and row are tallies of stations and months with increasing trends.
-Raw data from USGS and National Climate Data Center.

Table 3.6- Summary table for monthly and annual temperature statistics in the Winooski River Basin, ~1930-2005.

| | **Burlington Airport** | | | | **Montpelier** |
|---|---|---|---|---|---|
| **Monthly Temperature** | Mean Low | Mean High | Spread: L->H | Mean | Mean |
| January | ⇩ 0.845 | ⇩ 0.683 | ⇩ 0.702 | ⇩ 0.767 | ⇩ 0.471 |
| February | ⬆ 0.300 | ⬆ 0.109 | ⬆ 0.650 | ⬆ 0.189 | ⇩ 0.450 |
| March | ⬆ 0.314 | ▨ ⬆ 0.036 | ▨ ⬆ 0.041 | ⬆ 0.102 | ▨ ⬆ 0.049 |
| April | ⬆ 0.232 | ▨ ⬆ 0.032 | ▨ ⬆ 0.056 | ▨ ⬆ 0.065 | ⬆ 0.618 |
| May | ⬆ 0.514 | ⬆ 0.254 | ⬆ 0.314 | ⬆ 0.324 | ⬆ 0.426 |
| June | ⬆ 0.518 | ⬆ 0.267 | ⬆ 0.521 | ⬆ 0.302 | ⇩ 0.470 |
| July | ⬆ 0.208 | ⬆ 0.252 | ⬆ 0.962 | ⬆ 0.190 | ⬆ 0.862 |
| August | ▨ ⬆ 0.055 | ⬆ 0.121 | ⇩ 0.727 | ▨ ⬆ 0.069 | ⬆ 0.853 |
| September | ⬆ 0.446 | ⬆ 0.441 | ⬆ 0.961 | ⬆ 0.396 | ⇩ 0.384 |
| October | ⇩ 0.484 | ⇩ 0.373 | ⇩ 0.650 | ⇩ 0.371 | ▨ ⇩ 0.031 |
| November | ⬆ 0.255 | ⬆ 0.182 | ⬆ 0.589 | ⬆ 0.197 | ⇩ 0.710 |
| December | ▨ ⬆ 0.093 | ▨ ⬆ 0.069 | ⇩ 0.724 | ▨ ⬆ 0.075 | ⇩ 0.934 |

-Arrow shows direction of trend; solid arrow indicates upward trend, open arrow indicates downward trend, shaded cell indicates 90% significance level.

-Raw data from USGS and National Climate Data Center.

# Chapter 4: Conclusions

## *Summary of Findings*

Analysis of weather, discharge, and land use history over seventy years of record in the Winooski River Basin have shown increasing trends of precipitation, temperature, discharge and Lake Champlain's yearly average level as well as increases in forested and impervious cover, with a decrease in cleared land. Annual scale increases in precipitation and discharge, as well as the existence of a ~7.6 year North Atlantic Oscillation periodicity found throughout the system, emphasize the connection between atmospheric forcing, input to the hydrologic system through precipitation, and the output in river discharge. Despite changing land use over the past seventy years, there have been limited changes in the annual balance of this system, with little net change in the ratio between runoff or evapotranspiration.

Since climate has proven to be the dominant driver of hydrologic change in the basin, seasonality is an increasingly important consideration. Increasing temperatures in the winter and spring months have driven earlier snowmelts, which have caused increasing discharge levels throughout the early spring months. Meanwhile, decreasing discharge trends in the late spring and early summer despite no significant change in precipitation may be linked to evapotranspiration from reforestation over the same period. This is again a factor in the fall months, where there is little significant change in precipitation but significant increases in discharge at all discharge stations as the trees shut down.

The interactions between land use and climate drivers in the Winooski River Basin have shown that the dominant driver is climate more than land use at the annual, basin-scale. These interactions should be considered for all future planning in the Winooski or similar basins, as a continually changing climate as well as land use change will continue to cause changing trends in this region.

### *Opportunities for future research*

This comprehensive study of basin-scale temporal changes derived from publicly available data is a model for other areas. Perhaps most interesting would be to up-scale this study to a Lake Champlain investigation, using this technique in all of the sub basins within the Lake Champlain Basin. In addition to this opportunity, this method can be replicated most anywhere in the United States as long as these federal stations and aerial imagery are available.

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## *Appendix A: Digital spreadsheets of raw data*

United States Geological Survey and National Climate Data Center data used in this study, while publicly available, can be time consuming to acquire and organize. Therefore, the spreadsheets used for data analysis have been included with this document on a compact disk in Microsoft Excel format.