RELATIONSHIP BETWEEN CLIMATE, HYDROLOGY, AND LANDUSE IN THE WINOOSKI RIVER BASIN OF NORTHERN VERMONT

A Thesis Proposal Presented

By

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To

The Faculty of the Geology Department

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1.0 Introduction

The presence of humans on earth has changed the rate and dynamics of many surficial processes while also altering the hydrologic behavior of many landscapes (Hooke, 2000). Human impact is best evidenced by its contribution to the sediment load in rivers, estimated worldwide to be approximately 10 GT per year (Hooke, 1994). Additionally, the shift of landuse from forest to urban or agriculture has led to increasing amounts of precipitation running off into channels (Harden, 2006; Sahagian, 2000; Burton, 1997). This changing surface hydrologic environment has been compounded by a variable climate (Burns et al., 2007). Together, these changes will have direct effects on the future of society, forcing new water management philosophies throughout the world (Milly, et al., 2008; Zarriello, 1999).

Recognizing the need for understanding the impacts of a changing landscape and a changing climate, this study focuses on the Winooski River drainage basin in northern Vermont and seeks to understand how the character and response of its hydrologic system have changed in the past century. In an effort to quantify hydrologic changes that have taken place, seventy years of historical data from six U.S. Geological Survey discharge stations and nine NOAA weather stations are being analyzed along with historical aerial and ground-level imagery of the area.

2.0 Objectives

I will address several specific research questions using daily weather and discharge data for the Winooski River Basin. The overall goal of these analyses will be to determine if and how discharge and key weather variables including precipitation, temperature, humidity, solar input, and wind speed have changed over the period of record (Table 1). I will also analyze the data to determine if there are changes in the frequency and intensity of storms and the way in which streamflows have responded to these "extreme" hydrologic events. My analysis will allow for the identification of climate driven changes in precipitation - including both gradual climate change and natural oscillations (Barnett, 2008). Once the runoff and climatic records are well understood, remaining changes in the relationship between precipitation and discharge can be accounted for by changes in landuse, which will be quantified using historical imagery. Lastly, an Artificial Neural Network (ANN), a model, will be used to understand complex linkages between weather and discharge records and to predict future discharge as a function of changing climatic conditions.

Table 1. Source stations for discharge (USGS) and weather (NWS/NOAA) data

Discharge Gage	Years of Coverage	Basin Area (km^2)	USGS Station ID
Winooski River at Essex Jct.	1929-2005	2,704	04290500
Winooski River at Montpelier	1915-1922 & 1929-	1,028	04286000
Winooski River at Wrightsville	1934-2005	179	04285500
Little River at Waterbury	1936-2005	287	04289000
Mad River at Moretown	1929-2005	360	04288000
Dog River at Northfield Falls	1935-2005	197	04287000

Weather Station	Years of Coverage	Elevation (m)
Essex Junction	1937-1960	104
Essex Junction	1971-2007	73
Waterbury 3	1941-1958	143
Waterbury 2	1958-1992	232
Montpelier 2	1999-2007	162
Barre Montpelier AP	1948-2007	343
Northfield	1923-1974, 1994-2007	204
Northfield 3	1974-1994	429
Mt. Mansfield	1954-2007	1204

3.0 Study Area

The Winooski River drains 2,704 km^2 in northern Vermont (Figure 1) from the mountains, into the Champlain Valley, and ultimately discharges into Lake Champlain (USGS NWIS, 2008). The basin, and Vermont in general, have undergone significant changes in landuse during the past century. The historical predominance of agriculture in northern Vermont since European settlement kept much of the landscape cleared to provide crop fields and pasture land as well as to sustain the logging industry (Albers, 2000). Changing landuse caused increased erosion as the land was deforested and the soil weakened with the removal of effective root cohesion (Jennings et al., 2003; Bierman et al., 2005; Bierman et al., 1997). Agriculture reached its peak in Vermont in 1880 with 35,522 farms (Albers, 2000). As erosion made many upland farms less productive, agriculture began to decline overall while sheep farms became more prominent, replacing many dairy farms. When marginal hill farms were abandoned, the population in Vermont became more structured around river valleys and rail lines and reforestation began to take place. While some reforestation was a result of farm abandonment, in response to concerns about erosion large-scale tree-planting efforts also took place in the 1920's-1940's (Albers, 2000).

More recently, parts of northern Vermont have seen significant urban growth and development with attendant hydrological changes. In some areas, these changes are linked to the construction of Interstate 89, mostly in the 1960's, which allowed for dependable transportation and associated development (Albers, 2000). Along with the construction of the highway, both residential and commercial development have further contributed to hydrologic change in northern Vermont by increasing the amount of paved area for roads, as well as space taken up by buildings (Sanford and Stroud, 1997). The record of this development is quite good in the form of aerial imagery of the study area.

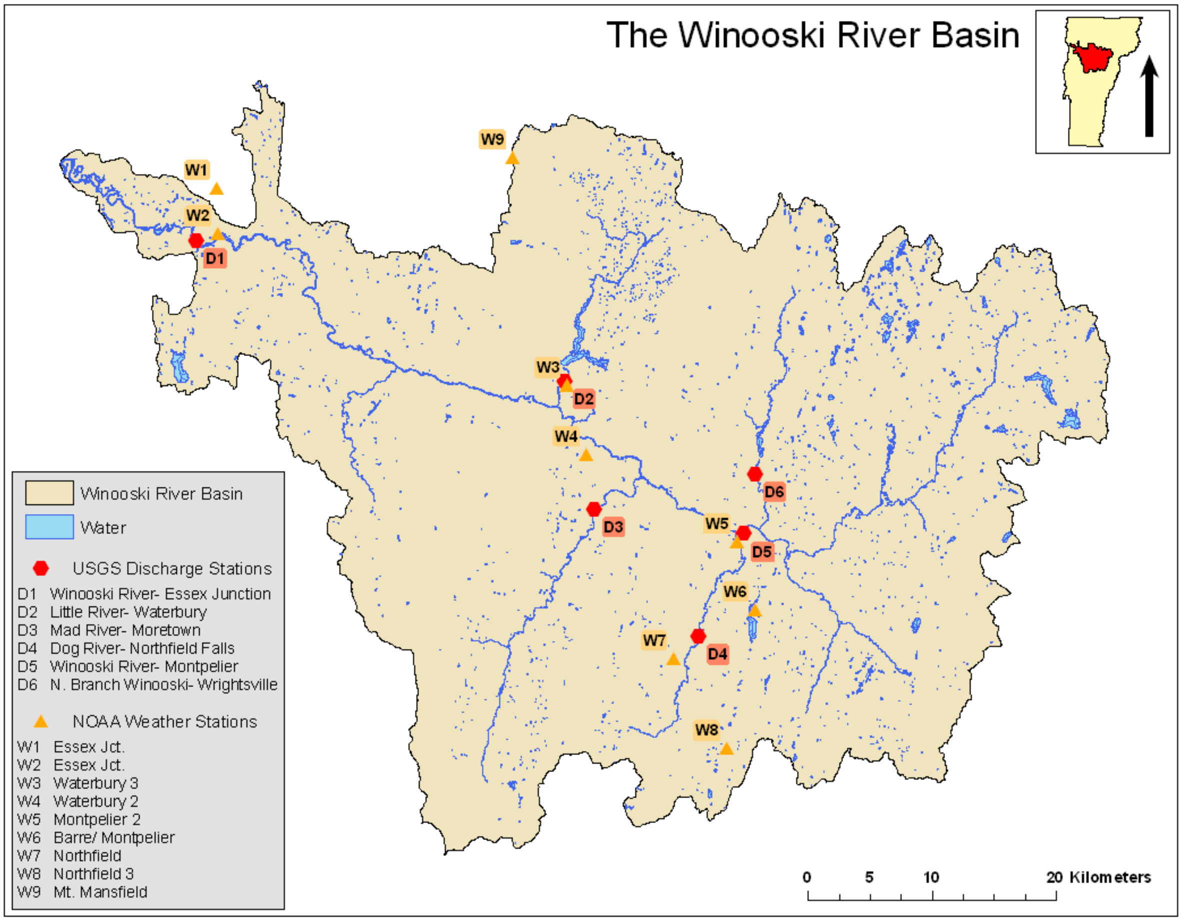


Figure 1. The Winooski River Basin with USGS discharge and NOAA weather stations as well as the Mt. Mansfield weather station (W9) for data reference at elevation. Station locations are taken from USGS and NOAA station listings. Hydrography base map is from The Vermont Center for Geographic Information.

The landscape of the Winooski Basin is drained by five major tributaries which flow into the Winooski River between Montpelier and Lake Champlain. The Mad River, Dog River, Little River, and North Branch of the Winooski River are all monitored by USGS stream gauging stations, while the Huntington River remains ungaged. Land cover is largely forested in the upper regions, while moderate development is primarily located in the stream valleys (Albers, 2000). Bedrock is primarily schist and phyllite in the mountains with Cambro-Ordivician siliclastic rocks and carbonates to the west in the Champlain Valley Region (Doolan, 1996; Mehrtens, 2001). There is an abundance of glacial till at elevation, stratified glacial sediments in the valleys, and alluvium near river channels. Unconsolidated cover varies widely throughout the basin, with less material at the higher elevations and more in the valleys (Doll, 1970).

4.0 Background

4.1 Natural Variability and Periodicity

Climatic drivers such as the North Atlantic Oscillation (NAO) and El Nino Southern Oscillation (ENSO) can force regular periodicities in precipitation (Hurrell, 1995; Labat, 2006; Enfield, 1999; *Decade to Century Scale Climate Variability and Change*, *1998)*. The NAO is a climatic factor that varies on different time scales from weeks to millennia and is controlled by the difference in sea surface pressure between the Azores High and Icelandic Low (Vallis, 2008). "High NAO winters" or a positive NAO indicate a greater than average difference in sea-surface air pressures between the Azores High and Icelandic Low. This condition leads to a decrease in arctic air input over northeastern North America which causes warm and wet winters. In contrast, a negative NAO yields colder winters over the northeastern US with greater snow totals (Hurrell, 1995; Visbeck et al., 2001). Similarly, ENSO is another climate phenomena linked to the Pacific Ocean, where higher than normal sea surface temperatures disrupt currents and can bring mild winters and greater precipitation to northeastern North America (El-Askary et al., 2004; McPhaden, 1999). These periodic precipitation forcings should then translate into discharge periodicities.

In a 2003 study of the historical river discharge records, Pekarova et al. observed several periodicities, many of which were common across most of the world's largest rivers. Given its proximity to our study area, the record of the St. Lawrence River, which drains the Great Lakes to the Atlantic Ocean, is most relevant. Pekarova et al. found that the St. Lawrence showed 28, 14, and 8 year periodicities in discharge. Similar periodicities have been observed in other eastern North America climate records ranging from river discharge in Florida (Labat, 2006) to biogenic population response in Rhode Island (Hubeny et al., 2004).

4.2 The Hydrology of Landuse

Landuse affects the response of the land to precipitation (Barrett et al., 1998). More pervious surfaces will decrease the amount of runoff as precipitation infiltrates instead of running off (Haselbach, 2005). A simple example of this would be two small streams with fields bordering one and parking lots the other. If the slopes and drainage areas are equal and a torrential downpour occurs, the parking lot basin will produce more runoff than the field basin. Additionally, if one were to examine the hydrograph for the storm in each basin, the parking lot stream's hydrograph would be "flashy" in that if will show a steep and immediate rise and peak in flow followed by a quick return to base flow (Ziegler, 1997; Verbunt et al., 2005). Conversely, the field basin's hydrograph will see a somewhat slower response leading to a lower overall peak flow, and a more prolonged return to baseflow (Zarriello, 1999). Forest can further change the setting as the trees are able to intercept and consume (transpire) some of the precipitation (Dunne and Leopold, 1996).

The permeability differences between forested land, open fields/meadows, and paved/roofed surfaces cause significant differences in the behavior of precipitation once it reaches the ground (Raymond, 2008).

Landuse changes between these categories will cause differences over time in the amount and speed of runoff into waterways of the Winooski Basin. Therefore, a quantification of landuse changes in the study area should correlate with changes in the nature of discharge both for individual storm hydrographs and coarser-resolution annual totals. With the quantification and identification of hydrologic changes in the Winooski Basin will come a greater understanding of the nature of changing hydrology in a changing environment.

There are studies in other parts of the United States which provide an idea of what results we might expect in the Winooski Basin. A recent study of the Mississippi River found that basins that were primarily forested responded differently to precipitation than agriculturally dominated basins. In forested basins, increases in discharge over the historical record of data are well explained by the increases in precipitation over the same period. However, basins containing mostly agricultural land (>70%) have experienced an increase in flow which is greater than the precipitation increase (Raymond et al., 2008). This relationship has been credited to the conversion of forest to cropland in these areas. Similar trends may be observed in the Winooski Basin as landuse varies between individual sub-basins.

At Los Penasquitos Creek in California, urbanized area increased from 9% to 37% over 27 years. Over the same period, total runoff increased over 200% while annual precipitation remained the same (White and Greer, 2006). Both annual median and minimum flows in the watershed increased with urbanization. A study in Camillus, NY modeled increased urbanization and impervious area for the Nine Mile Creek Basin (Zarriello, 1999). They found that future development was unlikely to significantly increase the frequency or magnitude of large storm floods, but they predicted that the frequency and magnitude of moderate storm flooding will increase. They also noted that the response to increased impervious surface is less significant in the winter than summer because the ground is saturated and/or frozen during winter months and thus permeabilities are low.

4.3 Climate and Landuse: Compounding Variables

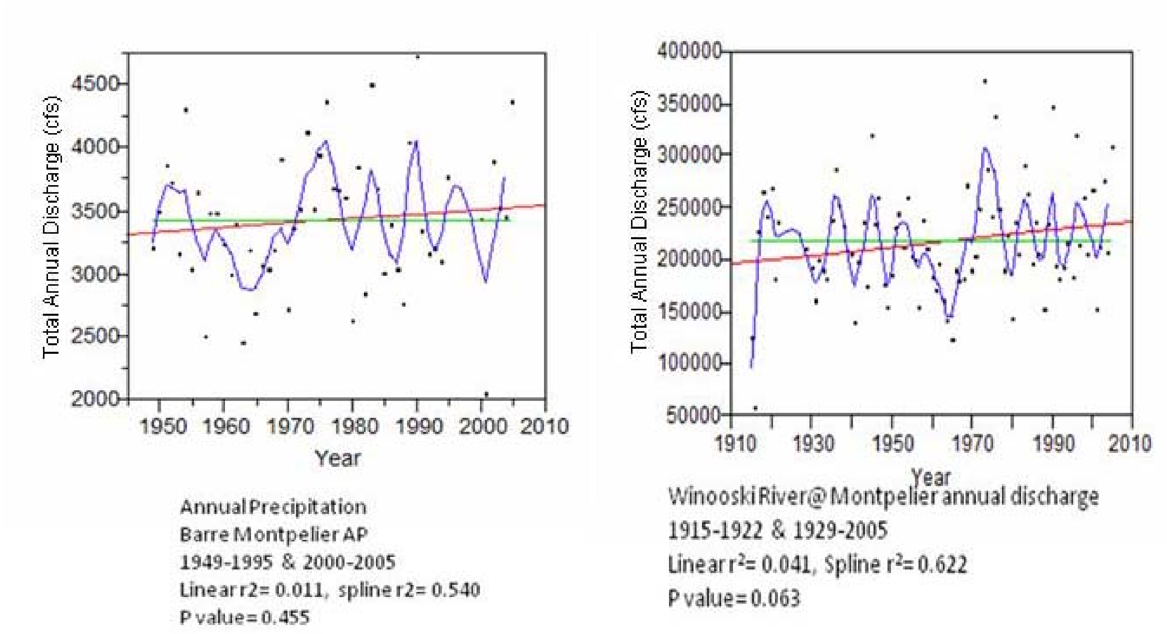
Climate change, both anthropogenic and as a part of natural variability, will likely result in changing precipitation, temperature, and evapotranspiration patterns worldwide (Sato et al.; 2007; Waterson, 2005); but, these changes are not likely to be spatially uniform. Furthermore, microclimate is strongly affected by elevation, which is of importance to this project because headwater stations are located at higher elevations than the stations further downriver. Changes in climate may be compounded by landuse changes, ultimately resulting in complex feedbacks and non-linearities in coupled hydrologic systems such as the Winooski River Basin (Goudie, 2006). The non-stationary nature of the hydrologic system driven by changes in landuse and climate can be detected because consistent long-term records of flow have been collected at several stations in the basin. The challenge is to deconvolve hydrologic changes into those driven by climate and those driven by landuse change (Milly et al., 2008).

5.0 Methods

This project is built on the raw data that already exist: USGS discharge data, NWS/NOAA weather data, and aerial imagery including historical aerial photographs and more recent digital imagery. Organization and a prescribed order to this analysis are key to the success of the project.

5.1 Preliminary Analysis of weather and discharge data

First, I examined the discharge and weather data independently of one another. This included plotting the entire period of record for discharge, precipitation, temperature, and wind direction and speed at each station. I then plotted these data using annual totals, monthly totals, and raw daily data to increase the likelihood of recognizing trends and patterns (Figure 2). Additionally, I examined the magnitude and intensity of storm precipitation and discharge as well as the intensity of dry periods. I then used linear regression to test for the significance of relationships with time of measured variables and to determine the overall trend of the data in each bi-variate plot.



Annual Precipitation
Barre Montpelier AP
1949-1995 & 2000-2005
Linear r2= 0.011, spline r2= 0.540
P value= 0.455

Winooski River@Montpelier annual discharge
1915-1922 & 1929-2005
Linear r^2= 0.041, Spline r^2= 0.622
P value= 0.063

Figure 2. Total annual precipitation and total annual river discharge for the Winooski River at Montpelier, VT. The blue line is a linear spline fit (lambda=1) while the red represents a conventional linear fit. The horizontal green line is the data mean.

Preliminary results show an increase in precipitation and discharge at all stations, though at the annual total levels this relationship was not significant at a 95% confidence level. However, when the same daily data time series is examined using monthly totals, several months at each of the stations show statistically significant changes ($p \leq 0.05$) in precipitation and/or discharge over the period of record. This finding encourages further analysis of more detailed records using monthly, daily, and storm data.

In addition to these basic observations, the general properties of the historical precipitation and discharge records for the Winooski Basin appear to match well with the behavior of the North Atlantic Oscillation over the same period (Hurrell, 1995; *Decade-to-Century-Scale Climate Variability and Change*, 1998). While further analysis is required, simple matching of peaks and valleys in these data provides initial correlation (Figure 3)

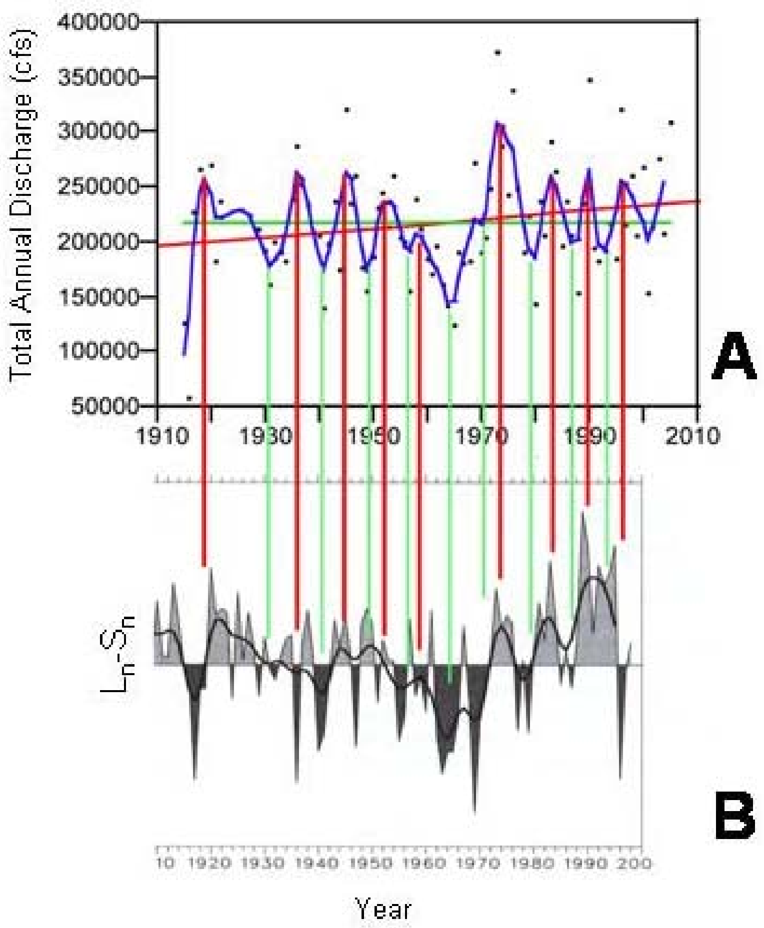


Figure 3. A basic comparison of peaks and valleys in the annual discharge record for the Winooski River at Montpelier (A) to the NAO (B). Figure 3A includes a spline fit (lambda=1) in blue as well as a traditional linear fit in red showing an upward trend in discharge. Figure 3B adapted from *Decade-to-Century-Scale Climate Variability and Change*, 1998.

5.2 Additional Analyses

Over the next six months I will address more complex questions, specifically those related to variability within the data. While the overall trend of any metric I examine may be increasing, patterns within the data, such as cyclical oscillations, provide additional information. The complexity of the data may include oscillations of different amplitudes and frequency as well as “noise”. Spectral analysis, using a mathematical transformation to parse such complex records, allows for a detailed analysis of cyclical patterns and behaviors in a dataset (Fleming et al., 2002). A periodogram is produced, which models the data as a series of sine waves of different frequencies. A spike implies that there is a periodicity within the data beyond the underlying “noise” (Pekarova et al., 2003). Spectral analysis will also serve as a tool to test for correlation of the temporal properties of the precipitation and discharge records.

One visually effective way of analyzing daily data is to use directional statistics (Figure 4). A rose diagram will be employed, assigning each day of the year a place radially on the circle. Using this framework, any number of variables including peak flows, maximum precipitation events, and mass balance calculations can be displayed and compared (Magilligan et al., 1996).

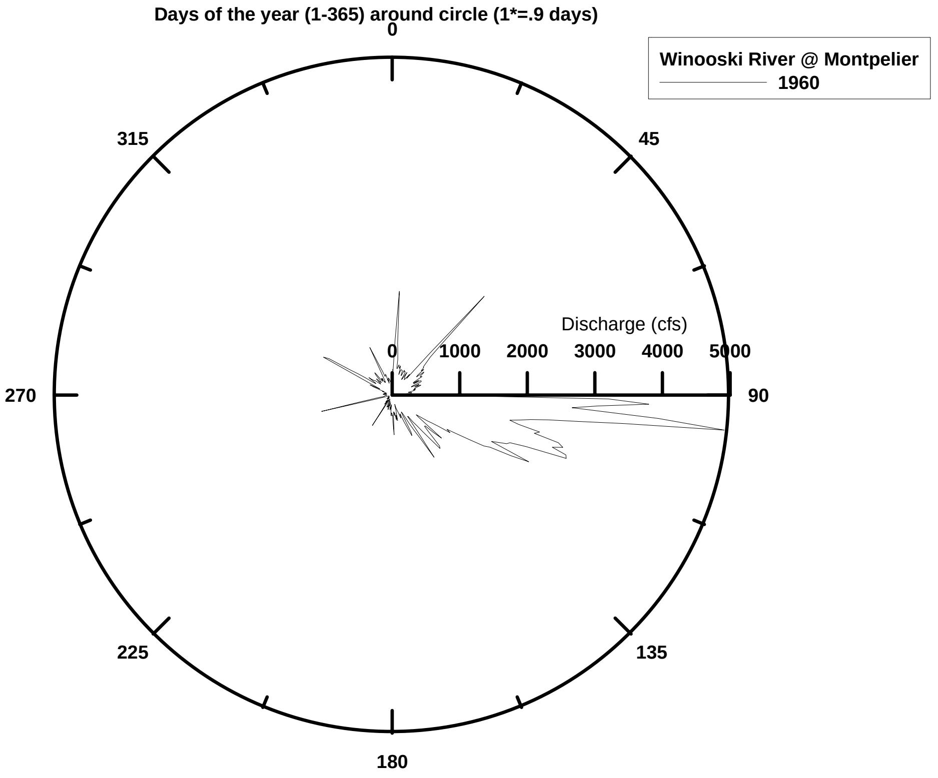


Figure 4. Daily discharge values in cubic feet per second for the Winooski River @ Montpelier gauging station during 1960. Each degree on the circle is equal to ~.9 days for 1/1/60 (day 1) through 12/31/60 (day 365). Here, the high spring flows signifying snowmelt season are clearly shown between days 90 and 120.

5.3 Artificial Neural Network (ANN)

An Artificial Neural Network is an advanced statistical tool that can be used to process and find patterns and relationships in large amounts of data. An ANN is modeled after a biological neural network, which is how the human brain functions (McCulloch and Pitts, 1943). Following design, an ANN is "trained" on a subset of data and relationships are determined. The trained model is then tested on the remaining data to see how well its predictions match reality. If the model replicates the real data well, it can be used to predict future behavior (Ochoa-Rivera, 2008). This is a key advantage to the ANN, as the nodes are able to "learn" and adapt rather than be programmed.

In this way ANNs are data driven and will adapt to properly encompass the nature of large pools of data (Doris, 2007). As a result, ANNs are very useful when working with nonlinear parametric data sets, such as those seen in our time series (Makkeasorn et al., 2008).

For this project, processed data will be analyzed using an ANN with the assistance of Dr. Donna Rizzo and PhD candidate Lance Besaw of the UVM College of Engineering and Mathematical Sciences. A subsample of precipitation, temperature, and discharge data will be used to train our ANN. The training dataset will be a sample of data points, allowing the ANN to learn the trends within the data as well as the regular patterns and oscillations. The ANN is then tested by feeding it the remaining data. Once we have established model veracity, the ANN can be used to predict future behavior as the variables are changed as a result of hypothetical climate or landuse changes (Figure 5).

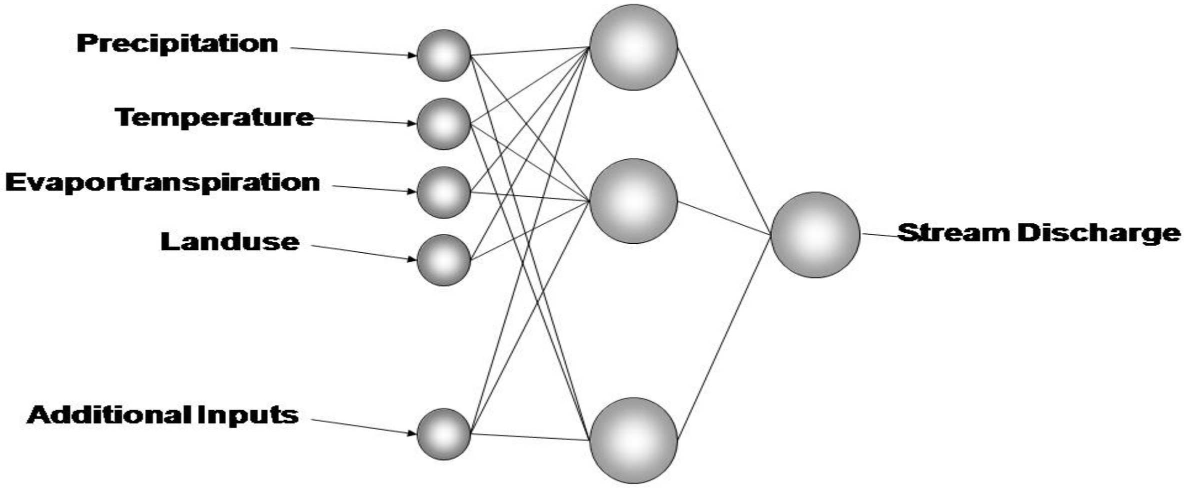


Figure 5. Conceptual model of ANN used in this study (image courtesy of Lance Besaw)

5.4 Analysis of landuse

I will characterize changes in land use and thus permeability over time by analyzing historical aerial imagery for the Winooski Basin that is readily available through the UVM map library. Image dates include: 1937, 1962, 1974, 1999, and 2003. Using Geographic Information Systems (GIS), original aerial photographs will be scanned, geo referenced, and rectified to correct distortion. Then, land surface in each image will be classified into four categories according to their relative permeability: impermeable (pavement, buildings), forest, developed (road shoulders, lawns) or field.

It is impractical to characterize historical landuse from aerial imagery over multiple years for the entire Winooski Basin. Therefore, a random sampling technique will be employed. Initially, a grid will be applied to the whole basin, from which random points will be selected for sampling from two zones: the uplands and the river valleys. For each sampling point, historical imagery will be acquired for a four square kilometer area around that point. Another grid will then be overlain on these images at a frequency of approximately one-hundred intersecting points per square kilometer. At each sample point, the landuse will be manually identified as belonging to one of the four categories (Appendix 1).

I tested this procedure on the Taft Corners area of Williston, Vermont for which I have analyzed historical imagery from 1937, 1962, 1974, and 1999 (Appendix 2). Williston is clearly the most extreme example of land use change within the Winooski Basin and thus ideal to demonstrate my methods. Between 1937 and 1962, forested areas increased by 10% while developed area also saw slight gains. In the 1962, 1974, and 1999 images, there is a clear signal of urbanization with increases in the area covered in road, buildings, and other development from approximately 10% of the landcover to 60% (Figure 6).

At sampling sites across the basin, the changing landuse, as determined by the point-counting method described above, will then be analyzed in relation to the record of precipitation and discharge. Curve numbers (percent of precipitation running off) will be assigned to these basic categories and we will use the well-established TR-55 model to better understand the implications of these landuse shifts ("Urban Hydrology for small watersheds", 1986). Because loss of permeability (the result of development) changes runoff dynamics, the landuse signature, if discernable, should present itself in the discharge data both for peak events and for baseflow once the signal from climate periodicities and any linear climate change are removed.

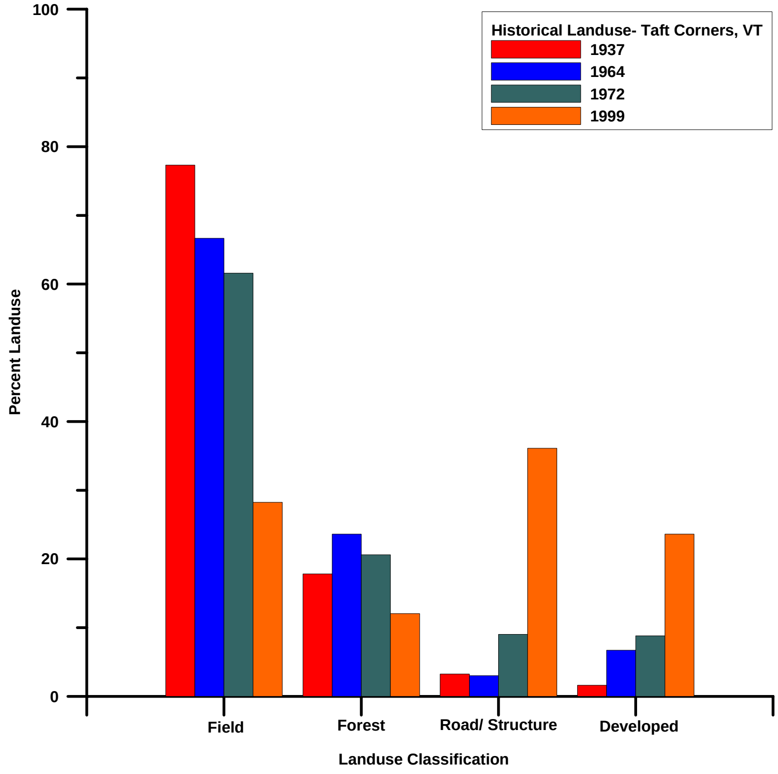


Figure 6. Results of landuse sampling analysis for the Taft Corners area of Williston, VT.

7.0 Timeline

Task	Timing
Discharge and weather data analysis	Spring 2008
Thesis Proposal	Spring 2008
Landuse/historical imagery analysis, paper writing	Summer- Fall 2008
Progress Report, GSA Talk/Poster	Fall 2008
Write Thesis	Spring 2009
Thesis Defense	Spring/Summer 2009

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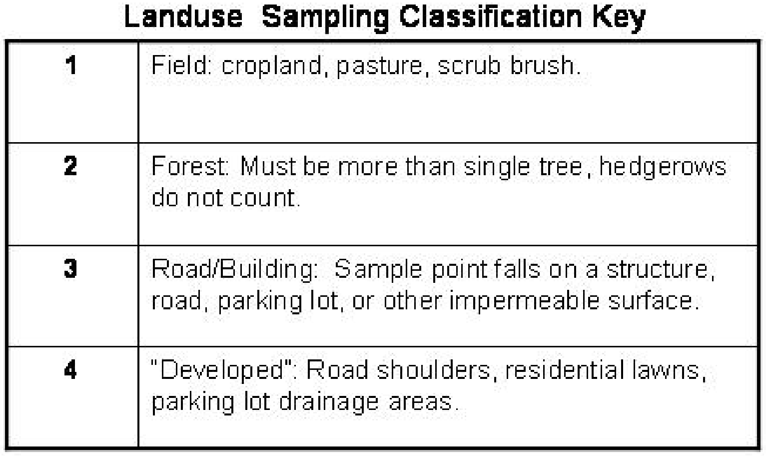
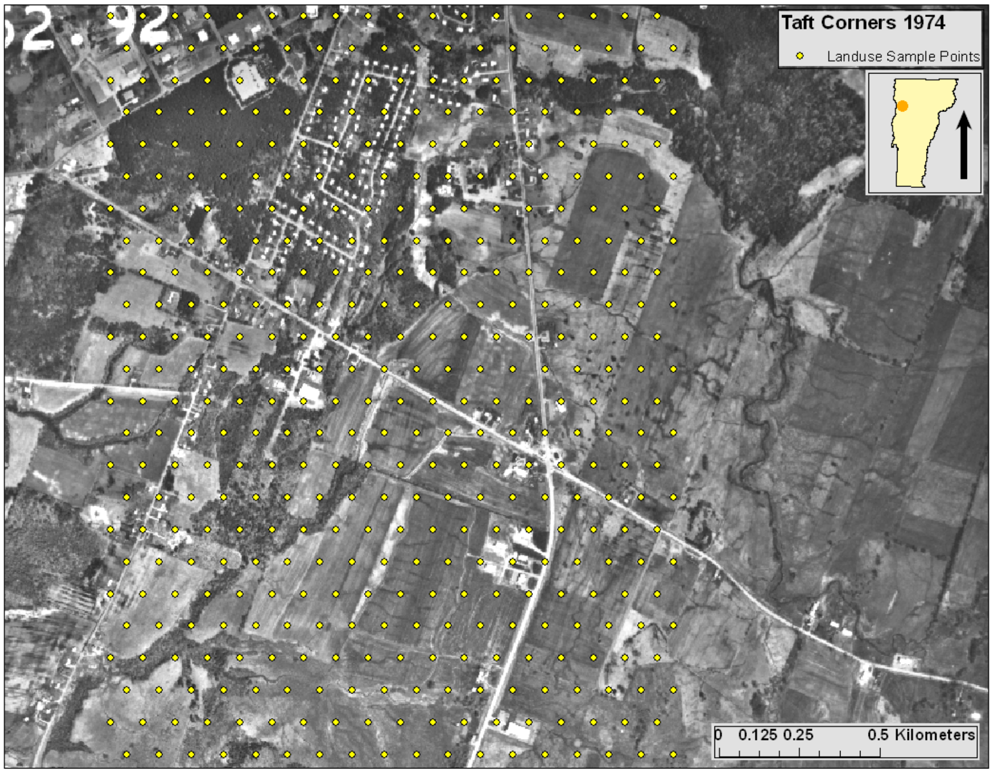
Appendix 1. Classification details for historical aerial imagery sampling



Landuse Sampling Classification Key

1	Field: cropland, pasture, scrub brush.
2	Forest: Must be more than single tree, hedgerows do not count.
3	Road/Building: Sample point falls on a structure, road, parking lot, or other impermeable surface.
4	"Developed": Road shoulders, residential lawns, parking lot drainage areas.

Appendix 2: Historical Imagery Analysis- Taft Corners



52.92
Taft Corners 1974
Landuse Sample Points
0 0.125 0.25 0.5 Kilometers

Taft Corners 1999
Landuse Sample Points
0 0.125 0.25 0.5 Kilometers