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

A Progress Report Presented

by

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to

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of

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1.0 Introduction

Watershed systems are dynamic and complex requiring the investigation of many variables to achieve a thorough understanding of process, the effect of external forcings, and the intensity and pattern of watershed response. The Winooski River Basin of Northern Vermont has undergone significant changes in landuse over the past seventy years (Albers, 2000) while also experiencing various climatic changes (Bradbury et al., 2002). Human-induced landuse change has altered hydrologic behavior by changing the nature and flowpaths of runoff (Hooke, 2000) while climate change (both human induced and as part of natural periodicity) has altered the amount and type of precipitation (Sato et al., 2007; Waterson, 2005). While each of these factors independently affects the hydrologic response of the basin, there also complex interactions causing additional, unforeseen responses.

This study's goal is to understand the hydrologic response of the Winooski River Basin to changes in landuse and climate over the past seventy years (Figure 1). National Weather Service stations supply daily weather data, including precipitation which is the hydrologic input to the system. Aerial photographs of the same sites over multiple different years since the 1930's allow analysis of landuse, which determines in large part the behavior of precipitation that enters the system (Harden, 2006; Sahagian, 2000; Burton, 1997). U.S. Geological Survey discharge records from six stations on the Winooski River and its major tributaries provide output data in the form of water running off through the fluvial network.

The statistical analysis of each of these datasets, including overall trends, seasonality, and identification of natural periodicity allows for a fuller overall understanding of the Winooski River system and its behavior over time and space.

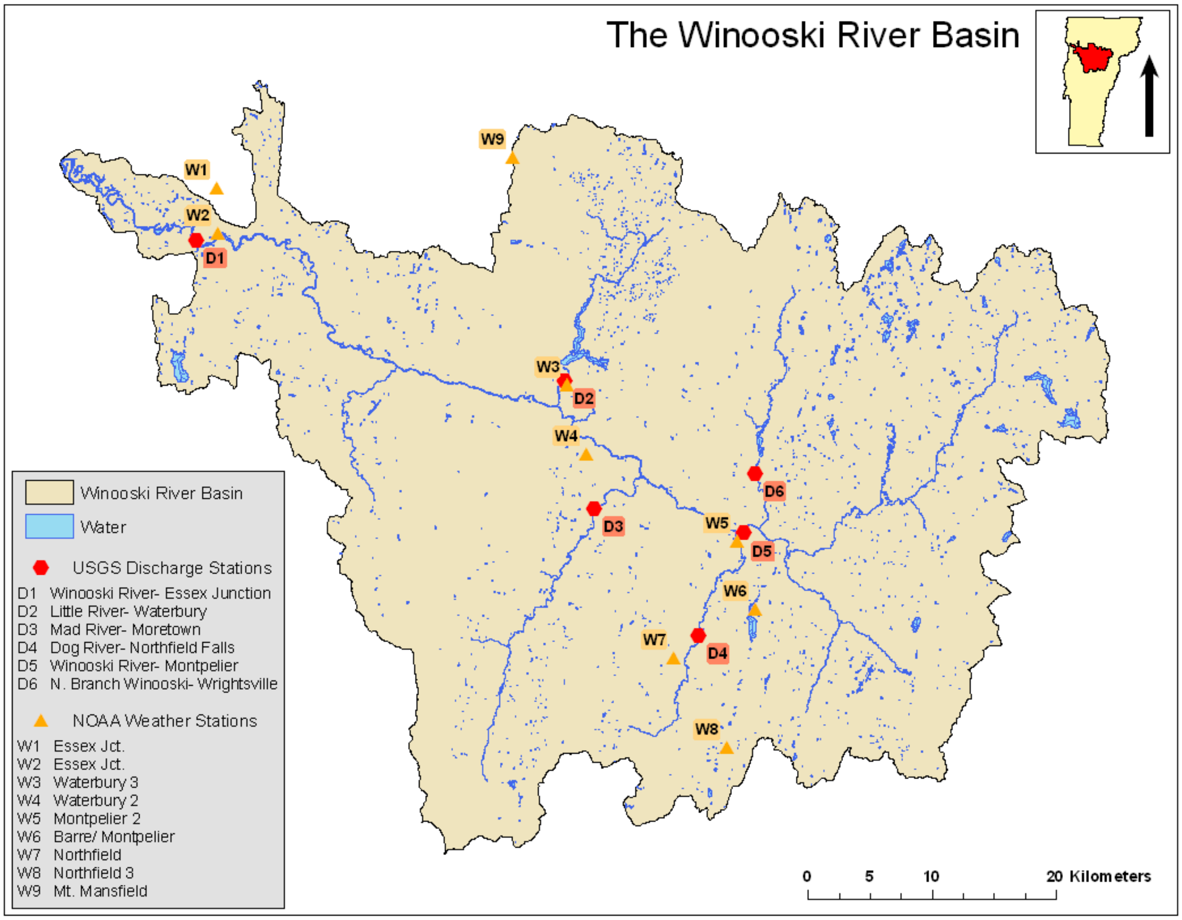

Figure 1. The Winooski River Basin with USGS discharge and NOAA weather stations as well as the Mt. Mansfield weather station (W9) for data reference at elevation. Station locations are taken from USGS and NOAA station listings. Hydrography base map is from The Vermont Center for Geographic Information.

2.0 Work Completed to Date

This study has progressed substantially over the past six months. Work that I have completed falls into two categories: analysis of Winooski River Basin discharge and weather records and analysis of landuse over time.

2.1 Analysis of Discharge and Weather Data - Methods

To establish long term (multi-decadal) trends in the data, I plotted the entire period of record for discharge, precipitation, and temperature (~1930-2005) using annual totals. Then, I repeated this process using monthly data to allow for investigation of changes in seasonality. Additionally, I examined the magnitude and intensity of storm precipitation and discharge as well as the intensity of dry periods. I also used linear regression to test for the significance of broad trend relationships over time of measured variables and to determine the overall trend of the data in each bi-variate plot.

During my proposal, I discussed the possibility of a correlated periodicity between the precipitation and discharge records and the North Atlantic Oscillation (NAO). The NAO is traditionally defined as the difference in sea level pressures between the Azores high and Icelandic low and since the NAO is most active in the winter, it is usually calculated as being the mean difference in these pressures during the winter months (Hurrell and Van Loon, 1997; Solow, 2002). Regionally, NAO activity can bring wetter winters when the index is positive or dryer winters when the index is negative. To investigate whether precipitation, runoff, and the NAO share similar periodicity, I used spectral analysis to deconstruct the datasets into noise and signal. Using a program called "Auto Signal", I conducted a Fast Fourier Transformation on these data, which filters out the red noise from the periodic signals within the data. Red noise needs to be removed to expose the signal because spectral power increases with decreasing frequency as a result of the noise. Geophysical and atmospherically forced data must be adjusted for red noise because it has a "memory" component while traditional white noise does not (Overland et al., 2006; Shulz and Mudelsee, 2002).

2.2 Analysis of Discharge and Weather Data- Preliminary Results

Using total annual data, results show an increase in precipitation and discharge at all stations, though all are not significant at the 95% confidence level (Table 1). When the same record 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. Of particular interest are some months where the relationship between precipitation and discharge has changed. An example of this can be seen at the Dog River site, where precipitation has increased at a statistically significant level while discharge is on a downward trend (Tables 2 and 3). Additionally, when the three lowest 24 hour flow days were analyzed, all stations showed a statistically significant increase in magnitude of low flows (the days with the least flow each year are seeing more flow). The intensity (amount of precipitation in a 24 hour period) of the highest precipitation days per year has also increased.

Table 1. Summary table of results for statistical analysis of discharge and precipitation records as described in the first column.

Category:		Dog River Northfield	Mad River Moretown	Little River Waterbury	Winooski River Wrightsville	Winooski River Montpelier	Winooski River 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	↑ 0.455	↑ <0.0001
First, second, and third highest 24 hour period of discharge per year	1	↓ 0.221	↓ 0.344	↓ 0.166	↑ 0.225	↓ 0.014	↓ 0.163
	2	↓ 0.395	↑ 0.753	↓ 0.037	↑ 0.041	↓ 0.036	↓ 0.433
	3	↓ 0.851	↑ 0.494	↓ 0.006	↑ 0.009	↓ 0.105	■ 0.936
First, second, and third lowest 24 hour period of discharge per year	1	↑ <0.0001	↑ <0.0001	↑ 0.0006	↑ 0.019	↑ <0.0001	↑ <0.0001
	2	↑ 0.0005	↑ <0.0001	↑ 0.0006	↑ 0.017	↑ 0.001	↑ <0.0001
	3	↑ 0.0006	↑ 0.0002	↑ 0.0005	↑ 0.016	↑ 0.005	↑ 0.0002
Intensity of largest annual precipitation in 24 hour period		↑ 0.183	N/A	↑ 0.884	N/A	↑ 0.793	↑ 0.589
Frequency of extreme precipitation events		↑ 0.004	N/A	↑ 0.105	N/A	↑ 0.356	↑ 0.062
20 largest precipitation events as a % of total annual precipitation		↓ 0.002	N/A	↓ 0.123	N/A	↑ 0.23	↓ 0.003

Note: Sheet contains p values for each variable at each station (red indicates a significant p value at the 95% confidence level) and trend arrows, which when pointing up show an increasing trend over the period of record, down showing a decreasing trend, and a black box indicating no change.

Table 2. Summary table of results for statistical analysis of discharge records by month as described in the first column.

P Values Category: Monthly Discharge	Dog River Northfield	Mad River Moretown	Little River Waterbury	Winooski River Wrightsville	Winooski River Montpelier	Winooski River 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	↑ *0.05*	↑ 0.132	5 of 6
March	↓ 0.707	↑ 0.486	↓ 0.912	↑ 0.575	↓ 0.298	↑ 0.73	3 of 6
April	↓ 0.61	↓ 0.327	↑ 0.061	↓ 0.312	↓ 0.561	↓ 0.472	3 of 6
May	↓ 0.417	↓ 0.419	↓ 0.236	↓ 0.061	↑ 0.487	↓ 0.52	3 of 6
June	↑ 0.657	↑ 0.563	↑ 0.247	↑ 0.518	↑ 0.514	↑ 0.436	6 of 6
July	↑ 0.07	↑ 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*	6 of 6
September	↑ 0.63	↑ 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	↑ *0.02*	↑ *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

Note: Sheet contains p values for each variable at each station (red indicates a significant p value at the 95% confidence level) and trend arrows, which when pointing up show an increasing trend over the period of record, down showing a decreasing trend, and a black box indicating no change.

Table 3. Summary table of results for statistical analysis of precipitation by month records as described in the first column.

P Values Category: Monthly Precipitation	Dog River Northfield	Mad River Moretown	Little River Waterbury	Winooski River Wrightsville	Winooski River Montpelier	Winooski River Essex Jct.	# UP
January	↑ 0.068	N/A	↑ 0.145	N/A	↓ 0.464	↑ 0.063	3 of 4
February	↑ 0.54	N/A	■ 0.991	N/A	↓ *0.009*	↓ 0.874	1 of 4
March	↑ *0.037*	N/A	↑ *0.053*	N/A	↓ 0.184	↑ *0.016*	2 of 4
April	↑ *0.005*	N/A	↓ 0.77	N/A	↑ 0.802	↑ 0.125	3 of 4
May	↑ 0.275	N/A	↓ 0.921	N/A	↑ 0.583	↑ 0.714	3 of 4
June	↑ 0.275	N/A	↓ 0.787	N/A	↑ 0.715	↑ 0.519	3 of 4
July	↑ 0.462	N/A	↓ 0.875	N/A	↑ 0.718	↑ 0.129	3 of 4
August	↑ *0.013*	N/A	↑ *0.028*	N/A	↑ 0.089	↑ 0.162	3 of 4
September	↑ 0.488	N/A	↑ 0.233	N/A	↑ 0.321	↑ 0.205	4 of 4
October	↑ *0.021*	N/A	↑ 0.816	N/A	↑ 0.268	↑ 0.088	4 of 4
November	↑ 0.201	N/A	↑ 0.41	N/A	↑ 0.635	↑ 0.27	4 of 4
December	↑ *0.055*	N/A	↑ 0.28	N/A	↑ 0.881	↑ 0.4	4 of 4
	12 of 12		7 of 12		9 of 12	12 of 12	# UP

Note: Sheet contains p values for each variable at each station (red indicates a significant p value at the 95% confidence level) and trend arrows, which when pointing up show an increasing trend over the period of record, down showing a decreasing trend, and a black box indicating no change.

Spectral Analysis revealed a series of statistically significant (at the 99% confidence level) periodicities in each of the weather and discharge datasets at periods of 2.2, 2.4, 4.5 and 7.6 years. For example, spectral analysis of the Winooski River discharge record at Essex Jct. has the same periodicity as the annual precipitation record at Burlington International Airport (Figures 2 and 3). Additionally, when the annual discharge and precipitation records are plotted and compared, they are clearly in phase with one another (Figure 4). This relationship is logical, as an increase in precipitation should yield an increase in runoff and river discharge and therefore any climatic forcing of precipitation would be expected to appear in the discharge record.

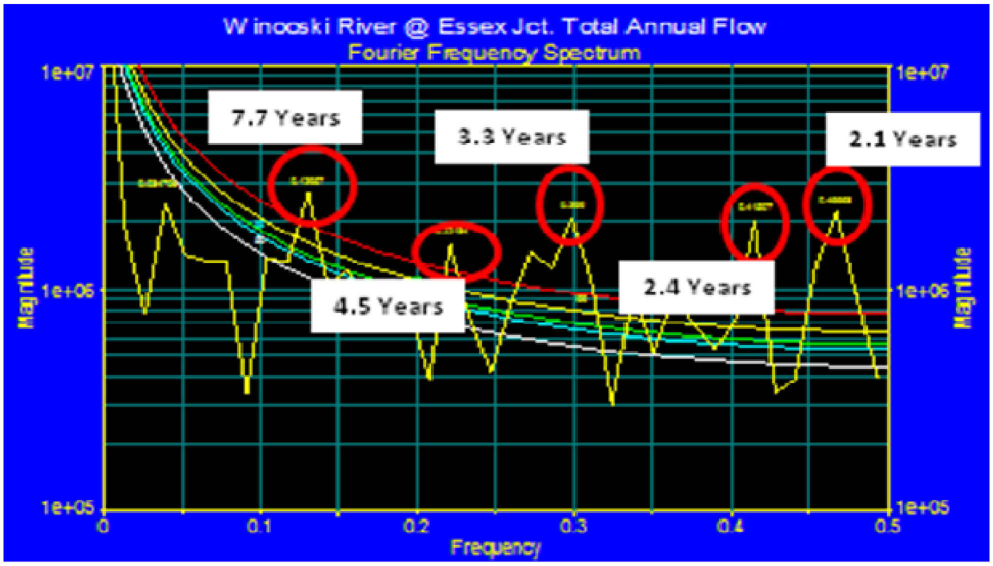

Figure 2. Auto Signal output showing periodic signals after noise has been removed within the record of discharge at the Winooski River at Essex Junction station. Amplitude of peaks indicates spectral power, and curved lines are labeled with confidence levels indicating the significance of spectral peaks.

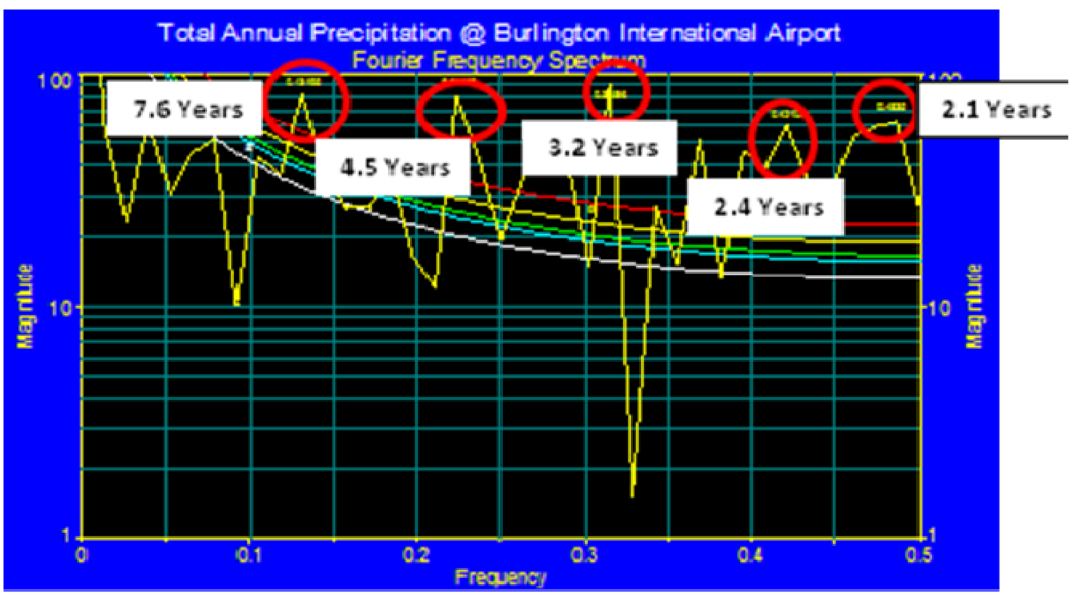

Figure 3. Auto Signal output showing periodic signals after noise has been removed within the record of precipitation at the Burlington International Airport. Amplitude of peaks indicates spectral power, and curved lines are labeled with confidence levels indicating the significance of spectral peaks.

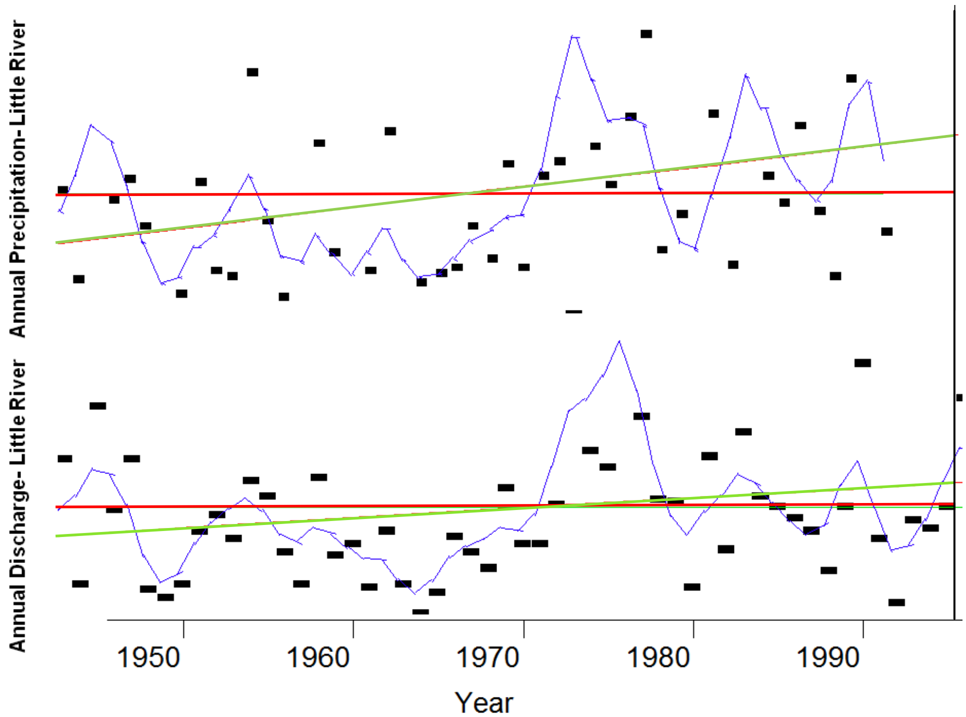

Figure 4. Annual precipitation values (top) taken from National Weather Service plotted by year are in phase with annual discharge values from the Essex Junction, VT Winooski River gauging station (discharge from USGS water). Red line is the mean, green line is a linear fit, and blue line is a spline fit.

Annual values for the NAO reveal its strongest spectral peak at 7.6 years, which is one of the strongest peaks produced by the precipitation and discharge data. Furthermore, the NAO is clearly in phase with the discharge data (Figures 5 and 6). The similarity of spectral peaks and phase between the North Atlantic Oscillation, precipitation, discharge, and the Lake Champlain gage height data over the past 70 years strongly suggests that the NAO influences the hydrology of northern Vermont (Figure 7).

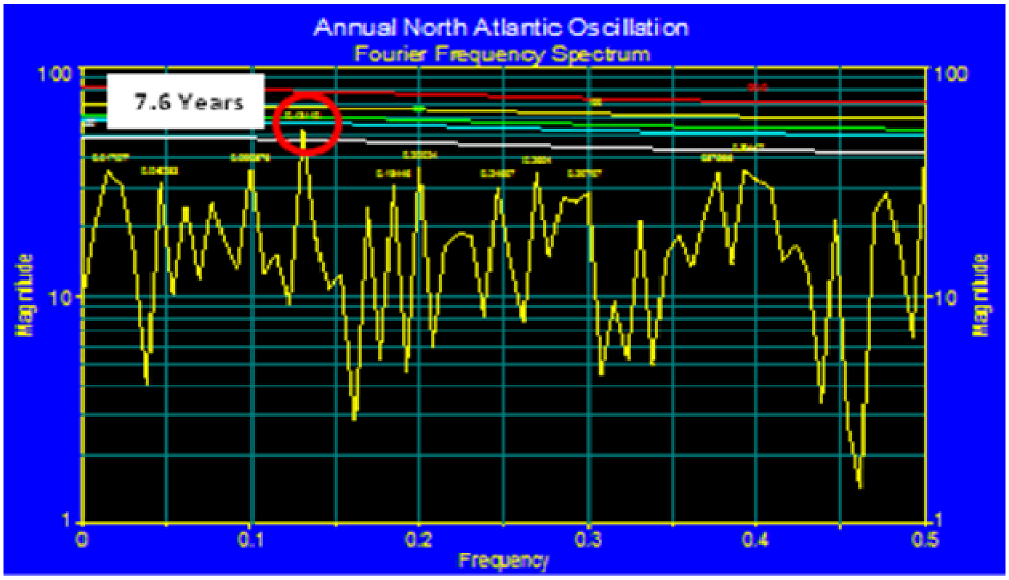

Figure 5. Auto Signal output showing periodic signals after noise has been removed within the record of annual values of the North Atlantic Oscillation. Amplitude of peaks indicates spectral power, and curved lines are labeled with confidence levels indicating the significance of spectral peaks. NAO annual values from NOAA Physical Science Division.

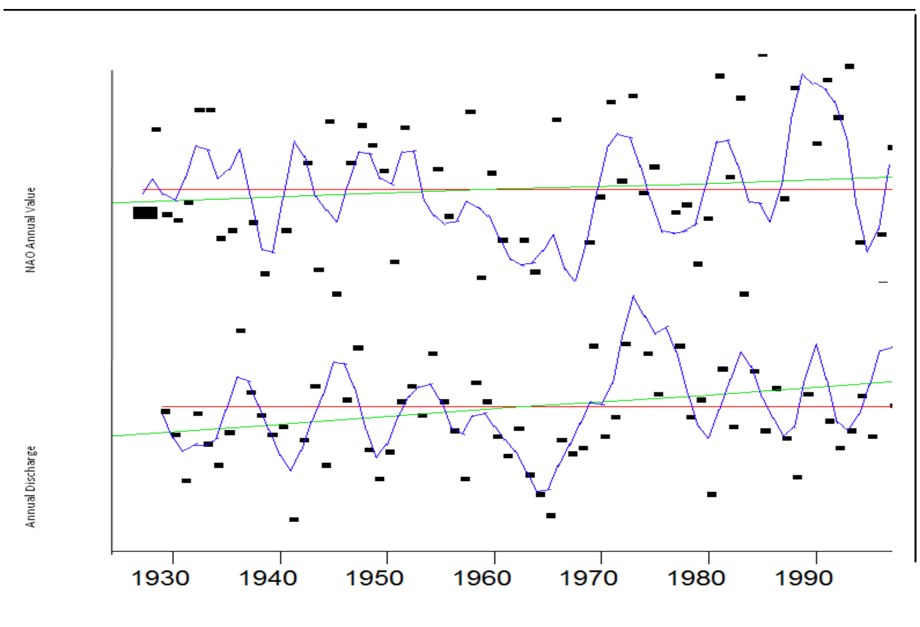

Figure 6. NAO annual values (top) taken from NOAA Physical Science Division plotted by year are in phase with annual discharge values from the Essex Junction, VT Winooski River gauging station (discharge from USGS water). Red line is the mean for each record, green line is a linear fit, and blue line is a spline fit.

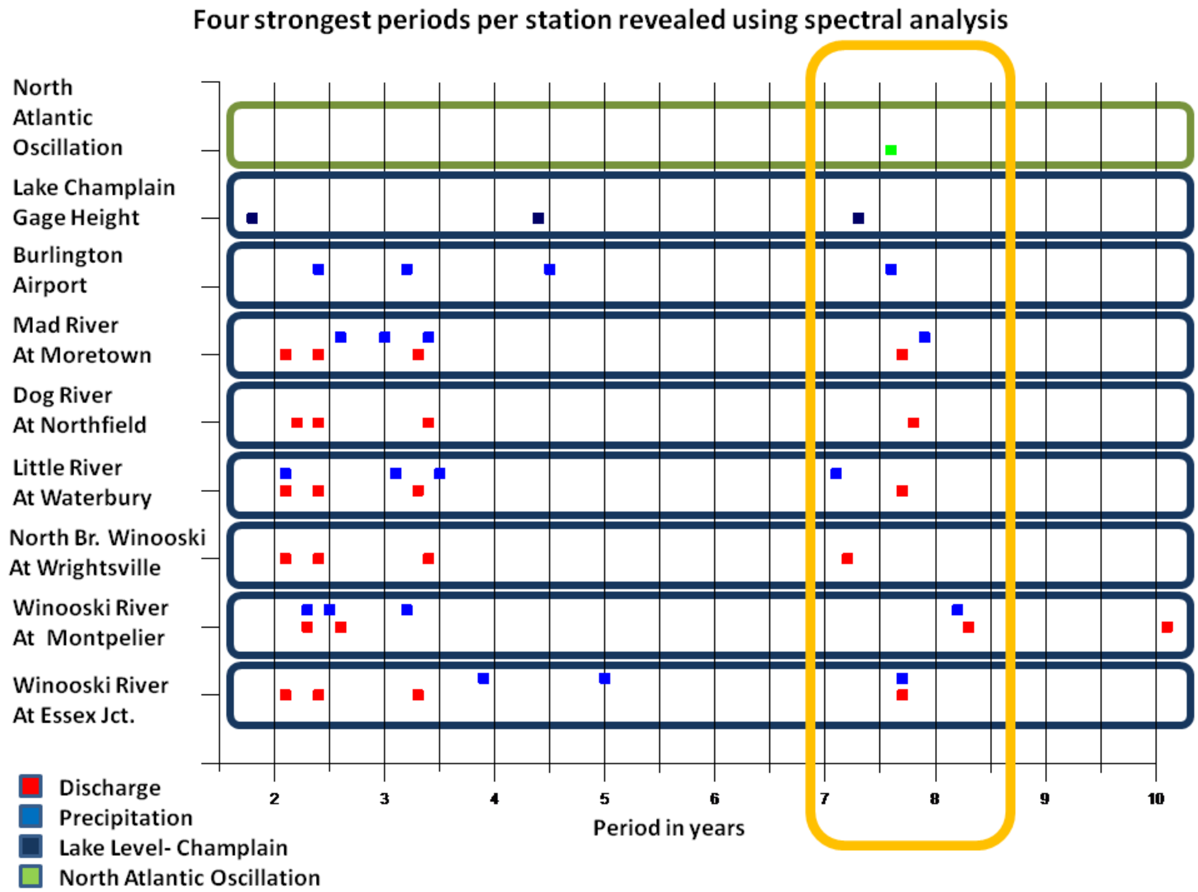

Figure 7. Top four spectral peaks for each station are marked by their period in years. Red marks indicate discharge peaks and blue marks indicate precipitation. The North Atlantic Oscillation period is marked with a green symbol, and the similarity of this to the other records is shown in the orange box. (weather data from National Weather Service, discharge data from USGS water and NAO data from NOAA Physical Science)

2.3 Analysis of Landuse- Methods

I analyzed aerial photographs at thirty random sample locations within the Winooski Basin to determine land use changes over the past seventy years. Since these data have a propensity to be fairly normal and well structured around the “average” landuse, a sample size of thirty was used to represent the basin (Janke and Tinsley, 2005). Sample sites were generated randomly using the “random point generation” tool in the Hawths Tools toolbar in ARC GIS. Hawths Tools derives a specified number of random locations within a given area (the Winooski River Basin) where 3 km X 3 km squares are placed. Within each of these random boxes lie 300 random sampling points with a forced minimum distance of 50 meters between them; these internal points were generated using the same technique used to generate the sample boxes. Three hundred sample points were chosen as a sample size based on significance as defined by sampling procedure in pollen grain research (Velez et al., 2008; Lupo et al., 2006; Liu et al., 2007).

Each box was established with its own unique arrangement of 300 sample points and these data were all saved in GIS as layers (Figure 8). Then, using the resources of the digital aerial imagery and hard copy aerial photos of Vermont housed in the University of Vermont Map Library, imagery over time (1937- where available, 1962, 1974 and 2003) was acquired for fifteen of the thirty sample boxes (Figure 9). Hard copy photos were scanned into ARC GIS and georeferenced to correct distortion; applying specific coordinates to the standard image format. With a constant set of random points for each sample box, the imagery for each timestep was overlain on the map (Figure 10).

Using the sample points within each nine square kilometer site, landuse/landcover at each point was classified into one of four categories. Manual classification of sites was chosen over automated software-driven methods due to the varying quality/clarity of the older images. In doing the analysis manually, the limited number of categories and the ability of an individual to use surrounding context to help accurately classify a problematic point on the images offsets the worries of bias (Munro et al., 2008). "Actively cultivated/ vegetation repressed" land consists of lawns, agricultural fields, grazed pastures, or any environment where tree growth is prevented. "Forested" defines any area where unrestricted tree 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 roads, parking lots, buildings, or any other impermeable surface. Lastly, water describes any body of water. Using these guidelines, manual identification of each point allows for a tally of each category in each sample box, leading to proportions by site which can then be extrapolated across the basin.

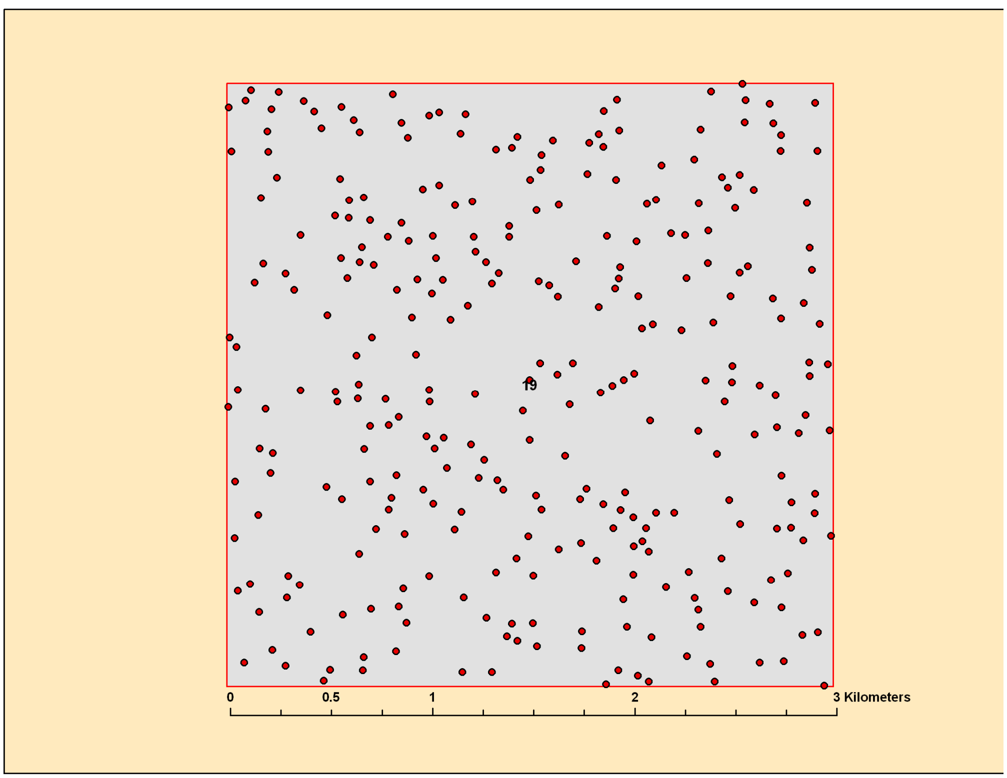

Figure 8. A 9 km^2 sample box with 300 randomly generated sample points contained within its bounds.

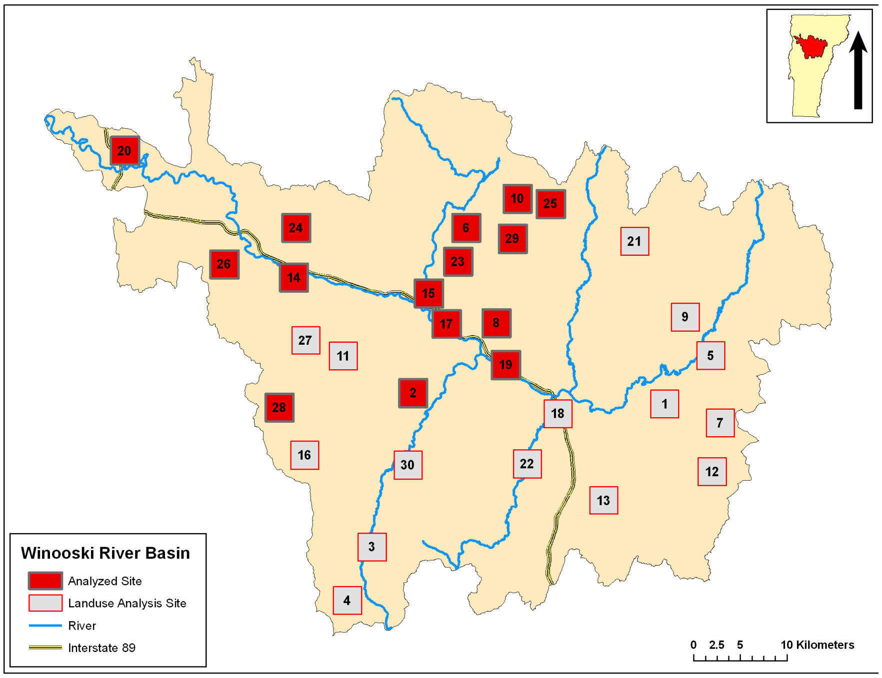

Figure 9. The Winooski River Basin with randomly generated landuse sample boxes shown throughout the basin. Red boxes indicate boxes which have been sampled, gray boxes remain to be analyzed. Hydrography base map is from The Vermont Center for Geographic Information.

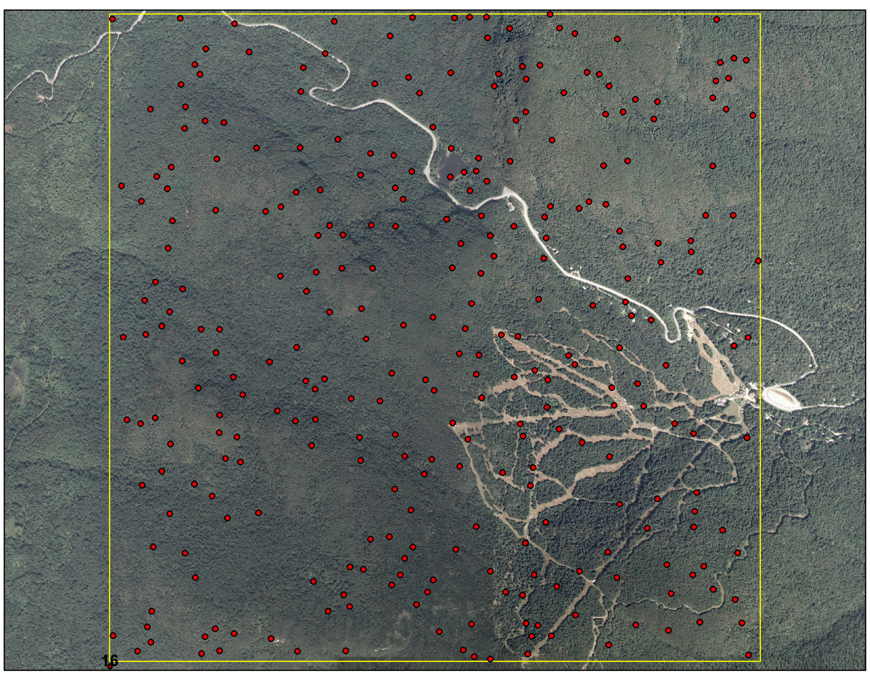

Figure 10. 2003 Imagery now underlies the sample box and the 300 sample points at the Mad River Glen ski area.

2.4 Analysis of Landuse- Preliminary Results

At present, half of the thirty sample boxes have been processed using this technique. Results reveal a general trend of increasing development at 12 of the 15 sites, with varying degrees of magnitude. Aside from that general trend, there are three different but classifiable scenarios that describe land use change over time at subsets of these fifteen sites. The first trajectory involves an increase in developed land and a decrease in cultivated area which corresponds to an increase in forested area. As time goes on, the percentage of cultivated land remains the same or continues to decline while forest begins to decline again in response to increased development (Site 20, Figure 11). The second path is similar to the first except that the forested proportion sees continual growth instead of a late period decrease (Site 26, Figure 11). The third trajectory is common only to three sites that are nearly dominated by forested land, and have been throughout all sampled timesteps

Despite varying settings for the sample sites which range from completely forested upland sites to developed areas along the Winooski River, the overall trend in the Winooski River Basin is one of increasing forest land, decreasing cultivated land, and increasing impermeable surfaces (Figure 12). The minimal increase in average percentage of impermeable surfaces is believed to be as a result of the influence of the nearly completely forested sites. To demonstrate this effect, I recalculated the average percentages after eliminating all sites that at any timestep had more than 80% of its points classified as forested. The results show a more consistent progression of increasing impermeable surfaces and decreasing cultivated area (Figure 13).

Figure 11. Landuse analysis histograms for six sites within the Winooski Basin. Each bar represents a timestep with the percent of total landuse shown for each of three categories.

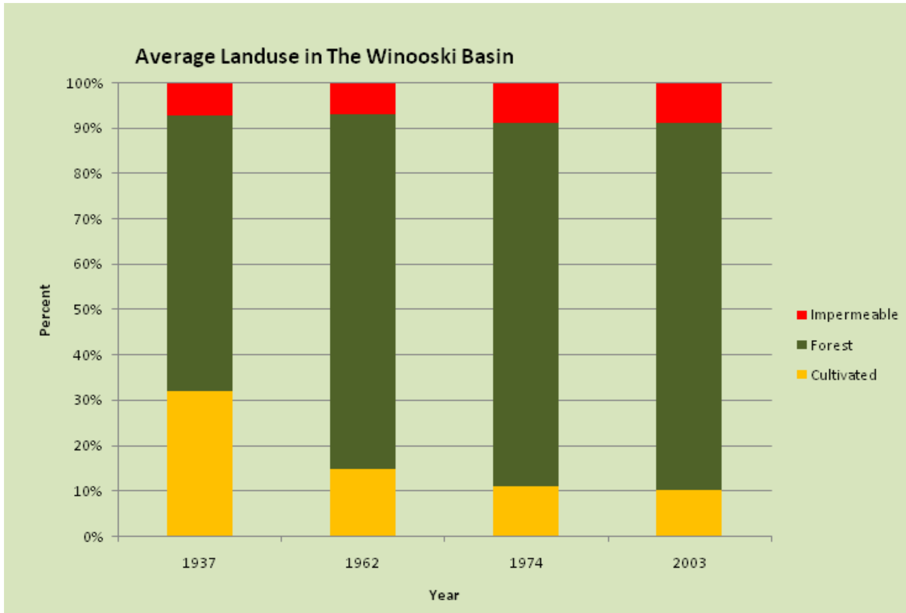

Figure 12. Average landuse analysis resulting histogram for the first fifteen sampled sites within the Winooski Basin. Each bar represents a timestep with the percent of total landuse shown for each of three categories.

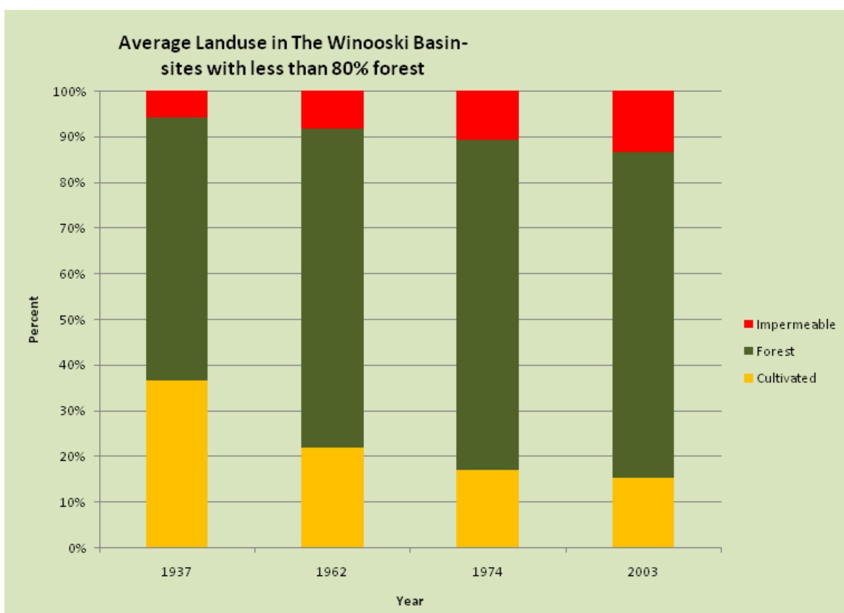

Figure 13. Average landuse analysis resulting histogram for the first seven sampled sites within the Winooski Basin that at no point had more than 80% of points counted as forest. Each bar represents a timestep with the percent of total landuse shown for each of three categories.

In addition to quantifying landuse change with aerial photos, I also reshot historical oblique aerial imagery as a visual means of documenting land-use change. Figure 14 shows an example of an image taken in 1959 and the current image, taken in July of 2008 at a site near the Interstate 89 Richmond exit. While not used for quantification of landuse change, the collection of over 40,000 negatives archived by the state of Vermont provides an immense wealth of historical context which covers the period of highway construction statewide. Additionally, these images serve to corroborate the data collected from the aerial photographs in this study. Figure 14 shows that over several decades the area along the Winooski River near Richmond, VT gained a highway and other impermeable development while also seeing reforestation of pasture land on the hill slopes and in the riparian zone. This is the same trend that I have quantified at 12 of the 15 sites analyzed so far in the Winooski Basin.

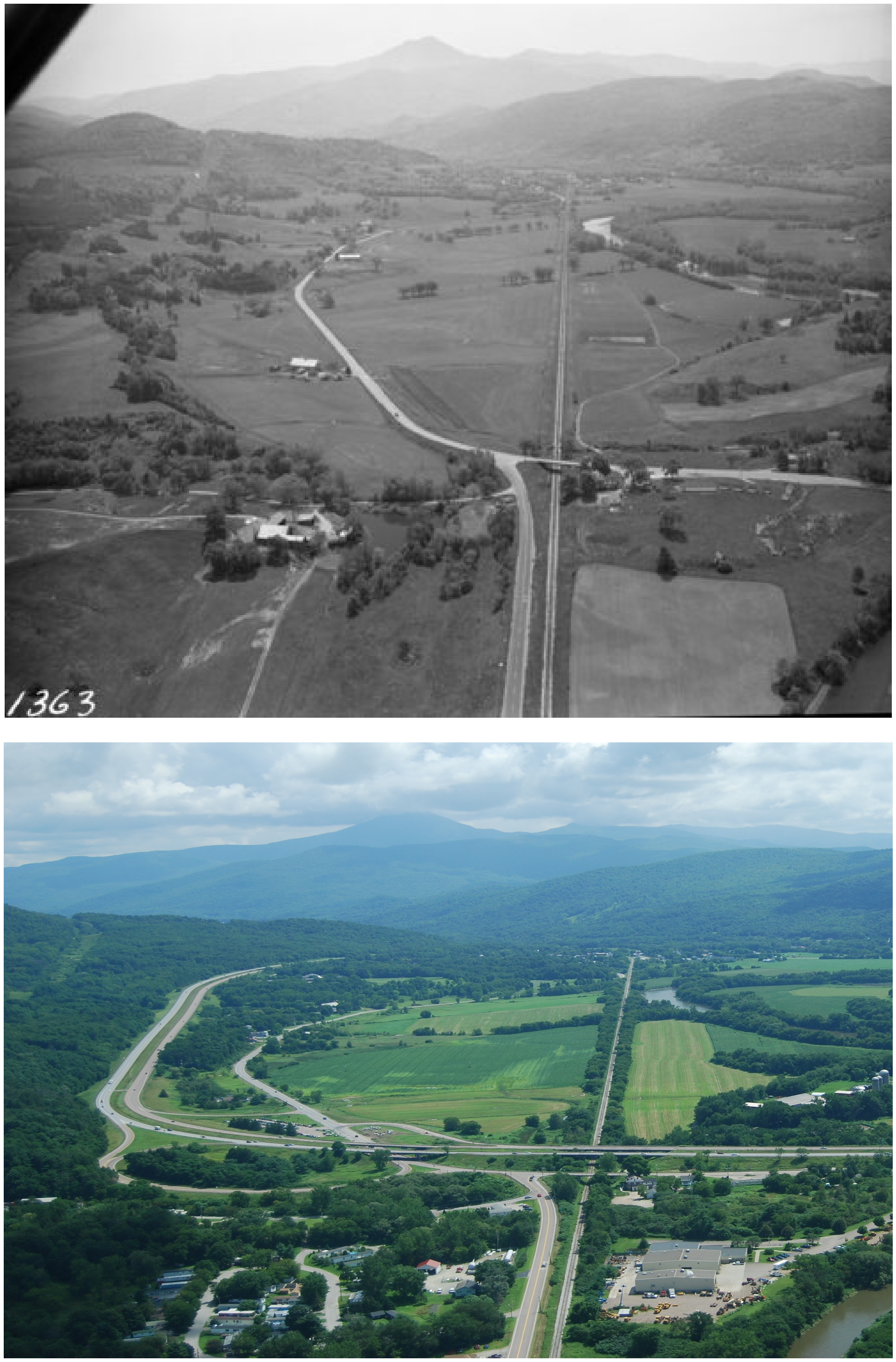

Figure 14. A 1959 image (top) and 2008 image taken obliquely from an aircraft near the Richmond exit from Interstate 89. Notice the highway is not present in the upper image as well as the additional construction in the lower portion of the 2008 image. Also, substantial reforestation has taken place in the 2008 image on the hillsopes as well as along the railroad tracks and riparian zone.

3.0 Remaining Work

3.1 Discharge and Weather Data Statistics

Analysis of these data is nearing completion. Remaining analysis includes additional basic statistics on the air temperature, lake level and the Mt. Mansfield weather data. Additional analysis of all weather and discharge data includes a more intensive analysis of the changes in the relationship between precipitation and discharge.

3.2 Analysis of Landuse

I will analyze landuse change at the remaining fifteen sites using the same techniques, yielding a total of 9,000 points at 30 sites. Additionally, I will acquire aerial imagery for all thirty sites from the 1940's and the 1980's. The addition of these two timesteps will allow for a more even interval between each sample year.

Following the completion of categorization at each sample site, I will conduct basic statistics of landuse change at each site, and then extrapolate that information across the basin as well as to look at the uplands vs. lowlands for different trends. After collecting all the landuse data, I will use a simple run-off model (TR-55, curve number approach) to understand what effect landuse shifts may have on runoff within the basin. These results will then be used to attempt to identify any potential correlation between landuse changes and the temporally changing relationship between precipitation and discharge as previously discussed.

4.0 Timeline for Completion

12/1/08	Progress Report
12/25/08	All point counting complete
1/1/09	Landuse statistics complete
1/15/08	All statistics complete
2/20/09	Full draft of thesis due
3/6/09	Record/ Format Check
3/late/09	Thesis Defense
4/10/09	Final Draft Due to UVM

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