Hydrology, Climate, and Land Use Change in The Winooski River Basin, Vermont

William Redin Hackett

Thesis Defense

Committee:
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Outline

- Statement of Problem
- New England Climate
  - IPCC Predictions
  - Recent Records
- Vermont History
- Study Area
- Methodology
- Results- Weather and Flow records
- Results- Landuse Analysis
- Interpretations and Conclusions
Has discharge in the Winooski River Basin changed over time and if so, why?
Importance of understanding

- Infrastructure designed using stationarity approach
  - More water
  - More storms

- Changing seasonality
  - Agricultural impacts
  - Precipitation timing

Human Population
  - More demand for water

- Ecosystems
Climate in New England

IPCC (2008) predictions for the region:

- Increasing precipitation
- More storms

- Increasing temperatures
- Increasing winter temperatures
- Earlier Spring melt
- More summer drying
New England Climate Records

-Sea Surface Temperatures
  Friedland and Hare, 2007

-New England Temperatures
  Trombulak and Wolfson, 2004

-New England Ice Out Dates
  Hodgkins, 2005
  IPCC, 2008

-New England Storms
  Madsen and Figdor, 2007
Vermont Land Use History

- Post colonial settlement
  - clearing for fuel

- Great Swarming Time
  - Early 1700’s

- Sheep Fever - 1810-1840
  - 75% of New England cleared

- The Decline of Sheep - 1850

- The Age of Dairy
Vermont Land Use History

- Abandonment
  - 50% decrease in farms by 1850

- Reforestation

- Development
Potential Hydrologic Implications

- More Impervious Area
- More runoff
- Flashier discharge - floods
- More Reforestation -> More ET
- Buffered basin response
- Lower baseflows
Winooski River Basin Fly Through
Has discharge in the Winooski River Basin changed over time and if so, why?
<table>
<thead>
<tr>
<th>Weather Station</th>
<th>Years of Coverage</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Essex Junction</td>
<td>1937-1960</td>
<td>104</td>
</tr>
<tr>
<td>Essex Junction</td>
<td>1971-2007</td>
<td>73</td>
</tr>
<tr>
<td>Waterbury 3</td>
<td>1941-1958</td>
<td>143</td>
</tr>
<tr>
<td>Waterbury 2</td>
<td>1958-1992</td>
<td>232</td>
</tr>
<tr>
<td>Montpelier 2</td>
<td>1999-2007</td>
<td>162</td>
</tr>
<tr>
<td>Barre Montpelier AP</td>
<td>1948-2007</td>
<td>343</td>
</tr>
<tr>
<td>Northfield</td>
<td>1923-1974, 1994-2007</td>
<td>204</td>
</tr>
<tr>
<td>Northfield 3</td>
<td>1974-1994</td>
<td>429</td>
</tr>
<tr>
<td>Mt. Mansfield</td>
<td>1954-2007</td>
<td>1204</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Discharge Gage</th>
<th>Years of Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winooski River at Essex Jct.</td>
<td>1929-2005</td>
</tr>
<tr>
<td>Winooski River at Montpelier</td>
<td>1915-1922 &amp; 1929-2005</td>
</tr>
<tr>
<td>Winooski River at Wrightsville</td>
<td>1934-2005</td>
</tr>
<tr>
<td>Little River at Waterbury</td>
<td>1936-2005</td>
</tr>
<tr>
<td>Mad River at Moretown</td>
<td>1929-2005</td>
</tr>
<tr>
<td>Dog River at Northfield Falls</td>
<td>1935-2005</td>
</tr>
</tbody>
</table>
Methods - Weather and Discharge

Annual Precipitation at Waterbury

Annual Discharge at the Mad River

- Linear Spline, lambda=1
- Linear Fit
- Mean
### Results - Annual

<table>
<thead>
<tr>
<th>Trends</th>
<th>Dog River</th>
<th>Mad River</th>
<th>Little River</th>
<th>Winooski River</th>
<th>Winooski River</th>
<th>Winooski River</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Annual Discharge</td>
<td>Northfield</td>
<td>Moretown</td>
<td>Waterbury</td>
<td>Wrightsville</td>
<td>Montpelier</td>
<td>Essex Jct.</td>
</tr>
<tr>
<td></td>
<td>0.124</td>
<td>0.016</td>
<td>0.017</td>
<td>0.166</td>
<td>0.063</td>
<td>0.018</td>
</tr>
<tr>
<td>Total Annual Precipitation</td>
<td>&lt;0.0001</td>
<td>N/A</td>
<td>0.046</td>
<td>N/A</td>
<td>0.046</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Precipitation (in)</th>
<th>Burlington Airport</th>
<th>Montpelier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Mean</td>
<td>0.068</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>Not Significant</td>
<td></td>
</tr>
</tbody>
</table>

![Graphs showing trends in precipitation and discharge over years](image)
### Results - Monthly Precipitation

<table>
<thead>
<tr>
<th>Monthly Precipitation</th>
<th>Dog River Northfield</th>
<th>Little River Waterbury</th>
<th>Winooski River Burlington Airport</th>
<th>Winooski River Montpelier</th>
<th>Winooski River Essex Jet.</th>
<th># UP</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.068</td>
<td>0.145</td>
<td>Not Significant</td>
<td>0.464</td>
<td>0.063</td>
<td>3 of 5</td>
</tr>
<tr>
<td>February</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>0.009</td>
<td>Not Significant</td>
<td>0 of 5</td>
</tr>
<tr>
<td>March</td>
<td>0.037</td>
<td>0.053</td>
<td>Not Significant</td>
<td>0.184</td>
<td>0.016</td>
<td>3 of 4</td>
</tr>
<tr>
<td>April</td>
<td>0.005</td>
<td>Not Significant</td>
<td>0.027</td>
<td>Not Significant</td>
<td>0.125</td>
<td>3 of 5</td>
</tr>
<tr>
<td>May</td>
<td>0.275</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>1 of 5</td>
</tr>
<tr>
<td>June</td>
<td>0.275</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>1 of 5</td>
</tr>
<tr>
<td>July</td>
<td>0.462</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>0.129</td>
<td>2 of 5</td>
</tr>
<tr>
<td>August</td>
<td>0.013</td>
<td>0.028</td>
<td>0.064</td>
<td>0.089</td>
<td>0.162</td>
<td>5 of 5</td>
</tr>
<tr>
<td>September</td>
<td>0.488</td>
<td>0.233</td>
<td>0.190</td>
<td>0.321</td>
<td>0.205</td>
<td>4 of 5</td>
</tr>
<tr>
<td>October</td>
<td>0.021</td>
<td>Not Significant</td>
<td>0.394</td>
<td>0.268</td>
<td>0.088</td>
<td>4 of 5</td>
</tr>
<tr>
<td>November</td>
<td>0.201</td>
<td>0.410</td>
<td>0.071</td>
<td>Not Significant</td>
<td>0.270</td>
<td>3 of 5</td>
</tr>
<tr>
<td>December</td>
<td>0.055</td>
<td>0.280</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>0.400</td>
<td>3 of 5</td>
</tr>
</tbody>
</table>
# Results - Monthly Discharge

<table>
<thead>
<tr>
<th>Monthly Discharge</th>
<th>Dog River Northfield</th>
<th>Dog River Moretown</th>
<th>Little River Waterbury</th>
<th>Winooski River Wrightsville</th>
<th>Winooski River Montpelier</th>
<th>Winooski River Essex Jct.</th>
<th># UP</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>Not Significant</td>
<td>↑ 0.462</td>
<td>↑ 0.037</td>
<td>↑ 0.357</td>
<td>↑ 0.137</td>
<td>↑ 0.232</td>
<td>5 of 6</td>
</tr>
<tr>
<td>February</td>
<td>Not Significant</td>
<td>↑ 0.163</td>
<td>Not Significant</td>
<td>↑ 0.168</td>
<td>↑ 0.050</td>
<td>↑ 0.132</td>
<td>4 of 6</td>
</tr>
<tr>
<td>March</td>
<td>Not Significant</td>
<td>↑ 0.486</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>↓ 0.298</td>
<td>Not Significant</td>
<td>1 of 6</td>
</tr>
<tr>
<td>April</td>
<td>Not Significant</td>
<td>↓ 0.327</td>
<td>↑ 0.061</td>
<td>↓ 0.312</td>
<td>Not Significant</td>
<td>↓ 0.472</td>
<td>1 of 6</td>
</tr>
<tr>
<td>May</td>
<td>↓ 0.417</td>
<td>↓ 0.419</td>
<td>↓ 0.236</td>
<td>↑ 0.061</td>
<td>↑ 0.487</td>
<td>Not Significant</td>
<td>0 of 6</td>
</tr>
<tr>
<td>June</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>↑ 0.247</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>↑ 0.436</td>
<td>2 of 6</td>
</tr>
<tr>
<td>July</td>
<td>↑ 0.070</td>
<td>↑ 0.296</td>
<td>Not Significant</td>
<td>↑ 0.168</td>
<td>↑ 0.158</td>
<td>↑ 0.157</td>
<td>5 of 6</td>
</tr>
<tr>
<td>August</td>
<td>↑ 0.003</td>
<td>↑ 0.008</td>
<td>Not Significant</td>
<td>↑ 0.003</td>
<td>↑ 0.008</td>
<td>↑ 0.006</td>
<td>5 of 6</td>
</tr>
<tr>
<td>September</td>
<td>Not Significant</td>
<td>↑ 0.276</td>
<td>Not Significant</td>
<td>↑ 0.328</td>
<td>↑ 0.223</td>
<td>↑ 0.162</td>
<td>4 of 6</td>
</tr>
<tr>
<td>October</td>
<td>↑ 0.016</td>
<td>↑ 0.005</td>
<td>↑ 0.048</td>
<td>↑ 0.034</td>
<td>↑ 0.077</td>
<td>↑ 0.006</td>
<td>6 of 6</td>
</tr>
<tr>
<td>November</td>
<td>↑ 0.020</td>
<td>↑ 0.012</td>
<td>&lt;0.0001</td>
<td>↑ 0.155</td>
<td>↑ 0.015</td>
<td>↑ 0.008</td>
<td>6 of 6</td>
</tr>
<tr>
<td>December</td>
<td>↑ 0.093</td>
<td>↑ 0.019</td>
<td>↑ 0.003</td>
<td>↑ 0.185</td>
<td>↑ 0.025</td>
<td>↑ 0.006</td>
<td>6 of 6</td>
</tr>
</tbody>
</table>
## Results - Storms and Baseflow

<table>
<thead>
<tr>
<th>Trends</th>
<th>Dog River</th>
<th>Mad River</th>
<th>Little River</th>
<th>Winooski River</th>
<th>Winooski River</th>
<th>Winooski River</th>
</tr>
</thead>
<tbody>
<tr>
<td>First, second, and third highest 24 hour period of discharge per year</td>
<td>0.221</td>
<td>0.344</td>
<td>0.166</td>
<td>0.225</td>
<td>0.014</td>
<td>0.163</td>
</tr>
<tr>
<td>Not Significant</td>
<td>0.395</td>
<td>Not Significant</td>
<td>0.037</td>
<td>0.041</td>
<td>0.036</td>
<td>0.433</td>
</tr>
<tr>
<td>First, second, and third lowest 24 hour period of discharge per year</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.001</td>
<td>0.019</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Not Significant</td>
<td>0.001</td>
<td>&lt;0.0001</td>
<td>0.001</td>
<td>0.017</td>
<td>0.001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Not Significant</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.016</td>
<td>0.005</td>
<td>0.000</td>
</tr>
<tr>
<td>Intensity of largest annual precipitation events</td>
<td>0.183</td>
<td>N/A</td>
<td>Not Significant</td>
<td>N/A</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>Frequency of extreme precipitation</td>
<td>0.004</td>
<td>N/A</td>
<td>0.105</td>
<td>N/A</td>
<td>0.356</td>
<td>0.062</td>
</tr>
<tr>
<td>20 largest precipitation events as a percent of total annual precipitation</td>
<td>0.002</td>
<td>N/A</td>
<td>0.123</td>
<td>N/A</td>
<td>0.230</td>
<td>0.003</td>
</tr>
</tbody>
</table>
## Results - Monthly Temperature

<table>
<thead>
<tr>
<th>Monthly Temperature</th>
<th>Burlington Airport</th>
<th>Montpelier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Low</td>
<td>Mean High</td>
</tr>
<tr>
<td>January</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>February</td>
<td>↑ 0.300</td>
<td>↑ 0.109</td>
</tr>
<tr>
<td>March</td>
<td>↑ 0.314</td>
<td>↑ 0.036</td>
</tr>
<tr>
<td>April</td>
<td>↑ 0.232</td>
<td>↑ 0.032</td>
</tr>
<tr>
<td>May</td>
<td>Not Significant</td>
<td>↑ 0.254</td>
</tr>
<tr>
<td>June</td>
<td>Not Significant</td>
<td>↑ 0.267</td>
</tr>
<tr>
<td>July</td>
<td>↑ 0.208</td>
<td>↑ 0.252</td>
</tr>
<tr>
<td>August</td>
<td>↑ 0.055</td>
<td>↑ 0.121</td>
</tr>
<tr>
<td>September</td>
<td>↑ 0.446</td>
<td>↑ 0.441</td>
</tr>
<tr>
<td>October</td>
<td>↓ 0.484</td>
<td>↓ 0.373</td>
</tr>
<tr>
<td>November</td>
<td>↑ 0.255</td>
<td>↑ 0.182</td>
</tr>
<tr>
<td>December</td>
<td>↑ 0.093</td>
<td>↑ 0.069</td>
</tr>
</tbody>
</table>
Periodicity

A. North Atlantic Oscillation (annual index)

B. Precipitation at Waterbury (in)

C. Annual Discharge at Essex Junction (CFS)

D. Lake Champlain average Cage Height at Burlington (ft)

E. Annual mean high temperature at Burlington (°F)
North Atlantic Oscillation (NAO)

- NAO signal fluctuates and can drastically effect winter weather.
- Difference between Azores High and Icelandic Low.
- More of an effect in Europe, but US winters can be mild and wet during positive NAO winters, and colder during negative winters.
Spectral Analysis

Total Annual Precipitation @ Burlington International Airport

Winooski River @ Essex Jct. Total Annual Flow

7.6 Years
4.5 Years
3.2 Years
2.1 Years

7.7 Years
3.3 Years
2.1 Years

4.5 Years
2.4 Years
Periodicity

![Graph showing periodicity of different locations and variables.
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.

Legend:
- □ Discharge
- ▲ Precipitation
- ○ Lake Level- Champlain
- ● North Atlantic Oscillation

Period (years): 2, 3, 4, 5, 6, 7, 8, 9, 10]
Intro to landuse
Methods - Land Use

The Winooski River Basin

- Landuse Analysis Site

Elevation Categories
Mean = 400m
- Lowlands
- Uplands

0 2.5 5 10 Kilometers
Results - Land Use Change

- 1937/1942
  - Cleared
  - Forested
  - Impermeable

- 1962
  - Cleared
  - Forested
  - Impermeable

- 1974
  - Cleared
  - Forested
  - Impermeable

- 2003
  - Cleared
  - Forested
  - Impermeable
Results - Land Use Change

Basin Average Upland Lowland

A  B  C

- Forested
- Cleared
- Impermeable

% Area


0 20 40 60 80 100
Results—Land Use Change

A. 1937

B. 2003

C. Graph showing percentage area change:
   - Forested
   - Cleared
   - Impermeable

Time:
- 1917/1942
- 1962
- 1974
- 2003
- All eleven quadrats with >10% impervious area are in the lowlands.

- All five unchanged, mainly forested quadrats are in the uplands.
- Five of the seven quadrats within 600 m (Ecological Road Effect Zone) are among those with highest proportions of impervious surfaces.

- Eight of the twelve quadrats within 5km of Interstate have the highest proportions of impervious surface.
Land Use Area Weighted Runoff per 40 inches of precipitation

Hydro Group C

Inches of water

% Area

1937
1962
1974
2003

Cleared
Forest
Impermeable

100
90
80
70
60
50
40
30
20
10
0

1937/1942
1962
1974
2003
$y = -0.0862x + 45.049$

$R^2 = 0.0495$

Evapotranspiration

- Percent Evapotranspiration
- Linear (percent input)

- % Area
  - Cleared
  - Forested
  - Impermeable
So how does it all fit together?

Determine how the individual results relate back to the original question of what has happened within the discharge record.
Interpretations

Changing Seasonality:

- Warmer early spring months
  - less snowpack
  - earlier spring melt

- Less/unchanged precipitation

- More discharge
Interpretations

- Less discharge in early summer months despite more rain
- More ET with reforestation
- Higher base flows despite increased ET
Conclusions

- Precipitation and discharge have increased at all stations in the Winooski Basin over the past seventy years

- Frequency of the largest precipitation events per year has increased

- Baseflow has increased

- Discharge has increased significantly at all stations during fall months along with increased fall precipitation

- Discharge has increased at all stations during early spring months despite decreases in precipitation, the opposite is true for later spring months

- Changing Seasonality- earlier spring, warmer winters

- Land use has changed yielding more forest and impervious surfaces but less cleared land
Conclusions

- Climate drives precipitation, discharge

- Short-term oscillations (NAO) can be detected throughout the system

- Landuse has changed but plays only a subtle role in the system

- Climate is changing and is the main system driver
Acknowledgements

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Paul Bierman

Donna Rizzo, Leslie Morrissey