The Effect of Temperature and Precipitation on Hydro-electric Power Generation in Vermont

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Abstract

Regression indicates that Vermont (VT) seasonal temperature, precipitation, and hydro-electric power generation (HEPG) have increased during recent years. Regression and correlation indicate that precipitation is the major factor influencing HEPG in summer and precipitation and temperature are both major factors influencing HEPG in winter. The analysis indicates that winter and summer temperature, precipitation, and HEPG will increase during the next ten years as follows:

	Summer		*Winter*	
Temperature	*+0.27F*	*(0.46%)*	*+0.28F*	*(1.01%)*
Precipitation	*+1.88 inches*	*(6.85%)*	*+0.42 inches*	*(2.19%)*
Hydro Generation	*+18,000 MWH*	*(7.2%)*	*+5,200 MWH*	*(1.6%)*

Introduction

Anecdotal evidence indicated that in recent years hydro-electric plants in Vermont have produced an increase in hydro-electric power generation. It was felt that this increase may have been related to increases in temperature and precipitation in VT. To investigate this hypothesis, this study researches the changes in winter and summer temperature, precipitation, and HEPG in VT; the statistical relationships between these three variables; and the future levels of each of these three variables.

Original Data

The original temperature and precipitation data consisted of monthly values of temperature (F) and precipitation (inches) for each of the 20 Co-operative, airport, and National Weather Service reporting stations in VT that observe daily temperature and precipitation. The data was obtained from the NOAA National Climate Data Center for nearly a 27 year period (May 1980 through October 2006).

The original HEPG data consisted of monthly values of energy output (MWH) for each of the 58 hydro-electric generating plants in VT for nearly an 11 year period (May 1996 through

October 2006). The data was obtained from the operators of those plants. Monthly capacity (MW) and off-line periods for each plant were also provided by the plant operators.

Data Preparation

For the temperature and precipitation data, the original data was organized by the NOAA Northeast Regional Climate Center into monthly VT state-wide average temperature and total precipitation values. This was done by averaging the values for all stations in each NOAA Climate Division (three in VT) and then area-weighting these division averages to determine a state average for the month. As part of this study, these values were organized into seasonal temperature averages and seasonal precipitation totals for hydrological summer (May-October) and winter (November-April) from summer 1980 through summer 2006. This created a total of 27 summer values and 26 winter values for VT temperature and precipitation.

For the HEPG data, the monthly station specific off-line periods were used to arrive at values of monthly VT hydro-electric energy capacity. These values were used to yield monthly "plant factored HEPG" data. This is defined as the monthly HEPG produced state-wide expressed as a percent of maximum. These monthly plant factored HEPG values (hereafter denoted as %HEPG) were converted into seasonal totals for a total of 11 summer values and 10 winter values for %HEPG for Vermont.

Data Analysis and Results

1. Regression

Temperature and precipitation data were each regressed against time to establish their long-term trends. Temperature and precipitation data were each regressed against %HEPG to establish the nature of the independent relationship between each variable and %HEPG.

Regression analysis establishes the values for coefficients "a" and "b" in the following equation:

Y = (a)(x) + b, where a = the slope and b = the y-axis intercept.

A positive (negative) regression slope indicates that as values in one data set increase, values in the other data set also increase (decrease), with higher "a" values indicating a more consistent relationship between the changes.

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a.) Temperature/Time Regression

For summer temperature, the regression equation was found to be:

T (F) = (0.0270F/yr) (year) + 4.7594F (note: in all equations presented in this study, the number of significant figures represents the statistical relationships found in the data and do not represent the accuracy of the original data).

For winter temperature, the regression equation was found to be:

T (F) = (0.0280F/yr) (year) – 28.3928F.

The temperature in both summer and winter is shown to be increasing (fig. 1a and 1b). This implies a general warming of Vermont throughout the year throughout the time period studied. The slightly higher winter slope value agrees with many other studies which show that in northern latitudes, winter temperatures are increasing faster than summer temperatures.

Fig. 1a. Thin line – yearly summer temperature values,
thick line – regression line.

Fig. 1b. Thin line – yearly winter values,
thick line – regression line.

b.) Precipitation/Time Regression
For summer precipitation, the regression equation was found to be:

P(in) = (0.1879 inches/yr) (year) – 349.5019 inches.

For winter precipitation, the regression equation was found to be:

P(in) = (0.0415 inches) (year) – 64.2562 inches.

The precipitation in both summer and winter is shown to be increasing (fig. 2a and 2b). The increase in summer precipitation is about 4.89 inches and the increase in winter precipitation is about 1.04 inches. This implies a general wetting of Vermont throughout the year throughout the time period studied, with the increase in summer precipitation about 4 times greater than the increase in winter precipitation. This is reasonable due to summer storms producing more liquid-equivalent precipitation than winter storms (because of the higher summer atmospheric water vapor content).

precipitation (inches)
summer precipitation
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
year

Fig. 2a. Thin line – yearly summer precipitation values,
thick dark line – regression line.

precipitation (inches)
winter precipitation
5
10
15
20
25
30

35
1980
1985
1990
1995
2000
2005
year

Fig. 2b. Thin line – yearly winter precipitation values,
thick line – regression line.

c.) %HEPG/Temperature Regression

For summer temperature, the regression equation was found to be:

%HEPG (MWH) = (-0.0039MWH/F) (T) + 0.5815MWH.

For winter temperature, the regression equation was found to be:

%HEPG (MWH) = (0.0082MWH/F) (T) + 0.2707MWH.

The %HEPG in summer decreases as temperature increases. This implies that, due to increasing temperature alone, warmer summers would result in lower hydro-electric energy production. This is reasonable because warmer summers by themselves result in greater transpiration and evaporation, which lowers river flow and HEPG.

The %HEPG in winter increases as temperature increases. This implies that, due to increasing temperature alone, warmer winters would result in higher hydro-electric energy production. This is reasonable because warmer winters by themselves result in a greater percent of the precipitation occurring as rainfall and more melting of snow on the ground, which increases river flow and HEPG.

d.) %HEPG/Precipitation Regression

For summer total precipitation, the regression equation was found to be:

%HEPG (MWH) = (0.0146MWH/inch) (P) - 0.0375MWH.

For winter precipitation, the regression equation was found to be:

%HEPG (MWH) = (0.0166MWH/inch) (P) + 0.1824MWH.

The average %HEPG in summer increases as precipitation increases. This implies that, due to increasing precipitation alone, wetter summers would result in higher hydro-electric energy production. This is reasonable because wetter summers by themselves result in greater runoff, which increases river flow and HEPG.

The %HEPG in winter decreases as precipitation increases. This implies that, due to increasing precipitation, wetter winters result in lower hydro-electric energy production. This is reasonable because wetter winters, by themselves, result in greater snow accumulation and large, rapid melt-off in the spring. This results in rivers at near base flow and consequent low HEPG throughout most of the winter and loss of HEPG during the rapid spring melt due to increased dam by-pass, dam over-topping, and loss of head.

2. Correlation

Temperature and precipitation were correlated with each other, and temperature and precipitation were each correlated separately with %HEPG, to estimate the strength of the relationships between the variations in data set pairs. A positive (negative) correlation indicates that as the values within one data set vary upward (downward), the values in the other data set also vary upward (downward), with higher values indicating a more consistent relationship between the changes.

a.) Precipitation/Temperature Correlation

The correlation in summer is +0.35 and the correlation in winter is +0.13. This indicates that in each season each year, temperature and precipitation both increase or both decrease, with summer displaying a more consistent relationship.

This is reasonable because there is an increased capacity for the atmosphere to hold water vapor at higher temperatures. The relationship is stronger in summer because higher temperatures and stronger convective activity result in more efficient atmospheric processes for converting water vapor into clouds, creating water droplets within the clouds, and removing water droplets from the clouds as precipitation.

b.) %HEPG/Precipitation Correlation

The correlation between summer precipitation and summer %HEPG is +0.85 and the correlation between winter precipitation and winter %HEPG is +0.39. This indicates that each season these variables vary in the same direction, with the summer relationship stronger than the winter relationship. This is reasonable because more summer precipitation generally means more water flowing through the turbine to increase HEPG (and a smaller amount evapo-transpiring to decrease HEPG) and more winter precipitation generally means more snow laying on the ground to decrease HEPG (and a smaller amount melting to increase HEPG).

3. Extension of Results

a.) Seasonal temperature and precipitation

The regression results were used to estimate the change in temperature and precipitation during the ten year period subsequent to this study.

The regression indicates a 2016 summer temperature of 59.19F, an increase of 0.27F over the 2006 value of 58.92F. In terms of the 2006 summer temperature, this represents an increase of 0.46%. The indicated 2015 winter temperature is 28.03F, an increase of 0.28F over the 2005 value of 27.75F. In terms of the 2005 winter temperature, this represents an increase of 1.01%.

The regression indicates a 2016 summer precipitation of 29.30 inches, an increase of 1.88 inches over the 2006 value of 27.43 inches. In terms of the 2006 summer precipitation, this represents an increase of 6.85%. The indicated 2015 winter precipitation is 19.37 inches, an increase of 0.42 inches over the 2005 value of 18.95 inches. In terms of the 2005 winter precipitation, this represents an increase of 2.19%.

b.) Seasonal hydro-electric power production
To quantitatively estimate future VT seasonal HEPG changes under the combined influence of both temperature and precipitation changes, multiple regression of %HEPG regression on precipitation and temperature was performed.
In summer, the resulting regression equation is:

$$\%HEPG_{sum}(MWH) = (0.017MWH/in)(P_{sum}) - (0.023MWH/F)(T_{sum}) + 1.261MWH$$

As expected, the combined equation shows a positive influence of precipitation and a negative influence of temperature on %HEPG.

The equation indicates a 2016 VT summer %HEPG value of 0.3990, an increase of 0.0267 over the 2006 value of 0.3723. In terms of the 2006 summer %HEPG value, this represents an increase of 7.1545%. This implies that the summer HEPG in 2016 will be 18,000MWH greater than it was in 2006.

In winter, the resulting regression equation is:

$$\%HEPG_{win}(MWH) = (0.150MWH/in)(P_{win}) + (0.005MWH/F)(T_{win}) + 0.060MWH$$

As expected, the equation shows a positive influence of both precipitation and temperature on %HEPG.

The equation indicates a 2015 VT winter %HEPG value of 0.4918, an increase of 0.0076 over the 2005 value of 0.4842. In terms of the 2005 winter %HEPG value, this represents an increase of 1.576%. This implies that the winter HEPG value in winter will be 5,200MWH greater than it was in 2005.

Discussion of Results
Summarizing and interpreting the foregoing results:

- In both winter and summer, the regression results indicate that, in the long term, temperature and precipitation are both increasing.
- In both winter and summer, the positive correlation of precipitation and HEPG indicate that variations in precipitation result in similar variations in HEPG.
- The regression of temperature and precipitation changes on HEPG changes indicate:

  by itself, in summer, as temperature increases, HEPG decreases
  by itself, in summer, as precipitation increases, HEPG increases

by itself, in winter, as temperature increases, HEPG increases
by itself, in winter, as precipitation increases, HEPG increases

That is, although temperature increases and precipitation increases have occurred together, the effects of those changes on HEPG differ in each season.

- Slopes of regression lines:

Summer HEPG/summer temperature	-0.39 %/deg
Summer HEPG/summer precipitation	1.46 %/inch
Winter HEPG/winter temperature	0.82 %/deg
Winter HEPG/winter precipitation	1.66 %/inch

That is, changes in precipitation have the largest effect on changing HEPG and it is positive, changes in winter temperature have a moderate effect on changing HEPG and it is positive, and changes in summer temperature have the smallest effect on changing HEPG and it is negative.

- In summer, the positive effect of increased precipitation (increased run-off and increased river flow) dominate the negative effect of increased temperature (increased evaporation and transpiration, and decreased river flow) to produce a large net increase in HEPG. This increase is reasonable in Vermont where hydro-electric power generation is from "run of river," rather than from reservoirs.

- In winter, the positive effect of increased temperature (increased precipitation falls as rain rather than as snow and increased number of winter thaws) combines with the positive effect of increased precipitation (increased amount of snow on the ground to be melted during mid-winter thaws) to produce only a moderate increase in HEPG. This is reasonable in Vermont where, in spite of the recent warming, the winter climate is still mostly cold and snowy. On the other hand, this implies that with continued winter warming there is the potential for further winter HEPG increases due to further increases in the rain/snow ratio and further declines in snow accumulation on the ground.

Summary

This study indicates that temperature and precipitation in Vermont have increased for nearly 30 years and that the increases in precipitation are statistically related to the increases in temperature. It also indicates that hydro-electric power generation in Vermont has increased for nearly a decade and that this increase is statistically related to the increases in temperature and precipitation during that same time period. In addition, it is indicated that the interaction between temperature and precipitation on HEPG is such that increased HEPG in summer is influenced mostly by increased precipitation and that increased HEPHG in winter is influenced by both increased temperature and increased precipitation.

Since the prevailing scientific thought is that for the foreseeable future temperature and precipitation will continue to increase in northern latitudes in winter and summer, this study implies that there will be a continued increase in annual hydro-electric power generation in Vermont in the foreseeable future.