Appendix 3

Concurrent Flows and Hydrograph Simulations

3.1 Hydrology

Daily streamflow data for the Souhegan River are available from the United States Geological Survey (USGS). One streamflow gage is located in the lower Souhegan before the confluence with the Merrimack River. A second gage is located in Stony Brook. The Milford precipitation gage provided daily precipitation values from 1944 to 2004. Table 1 describes stations characteristics.

Table 1: Available streamflow and precipitation data

Station Number	Station Name	Latitude	Longitude	Drainage Area (mi^2)	Period of Record
USGS 01094000	Souhegan River at Merrimack, NH	42°51´27´´	71°30´24´´ W	171.3	7/13/1909-9/30/1976 and 10/1/2001 to 9/30/2004
USGS 01093800	Stony Brook Tributary near Temple, NH	42°51´36´´	71°50´00´´ W	3.6	10/1/1927-9/30/2004
COOP 275412	Milford	42°49´24´´	71°23´24´´ W	N/A	10/1/1994 to 9/30/2004t

The Souhegan River gaging station was inactive from Water Year 1977 to 2001. For this research, the nearby Stony Brook gage was used to estimate Souhegan flows for the missing time period. The two estimation approaches considered were regression and regional statistical analysis (Maidment, 1993). Both approaches were developed and test using data from periods during which both the Stony Brook and the Souhegan gages were operational (5/1/1963 to 9/30/1976 and 10/1/2001 to 9/30/2004). Relationships were developed between the Souhegan gage and the Stony Brook gage for the first overlap period from (1963 to 1976) and tested using the second overlap period (2002 to 2004).

While both methods provided reasonable estimates, the regression relationships provided better estimates of average daily flow and therefore are used to estimate the missing period. A power equation of the form, $Q_{souhegan} = a\ Q_{stony}^{b}$ where Q is in cfsm, provided the best fit (Table 2). The first regression relationship addressed all flows. The second addressed low flows (< 1 cfsm). The two regression relationships yield identical flow predictions at 1 cfsm. The Stony Brook streamflow data were applied using these regression relationships to estimate flow in the Souhegan River for the missing time period.

Table 2. Regression relationships to estimate Souhegan River streamflow from Stony Brook measured streamflow.

Flow Range	a	b	r^2
All	0.9955	0.8292	0.76
< 1 cfsm	0.9057	0.7807	0.88

3.2 Trend Analysis

The study included a time trend analysis using average discharge, precipitation, and watershed yield (the ratio of precipitation to discharge), and Indicators of Hydrologic Alteration (Richter et al., 1996). Richter et al.'s (1996) *Indicators of Hydrologic Alteration* (IHA) characterize trends in streamflow variability with respect to timing, duration, frequency, and rate of change. IHA statistics were calculated using two periods; water years 1910 to 1976 and water years 1910 to 2004. Results for WY 1910 to 2004 are shown in Table 3.

Linear regression analyses were used to identify trends. Linear regression is a parametric test that quantitatively identifies the presence of a trend. Linear regression of the statistics was used to determine the best-fit line ($y_{fit} = mx + b$) through the data. The slope (m) was used to determine the t_{stat} by

$$t_{stat} = \frac{m}{SE} \tag{1}$$

where the SE is the standard error calculated by

$$SE = \frac{\sqrt{\dfrac{\sum_{i=1}^{N}(y_{fit}(i) - \bar{y})^2}{N-2}}}{\sqrt{\sum_{i=1}^{N}(x(i) - \bar{x})^2}} \tag{2}$$

where N is the number of years, $y_{fit}(i)$ are the values generated from fitted line, $\bar{y}$ is the mean value of the original statistic series, $\bar{x}$ is the average of $x(i)$. A trend is present if the slope of the fitted line is significantly different from zero. A decreasing trend would correspond to a negative slope, while an increasing trend would correspond to a positive slope. Significant trends were identified, using a 95% significance level ($\alpha = 0.05$). Trend results of the flow statistics for each gage are shown in Table 3.

Table 3. Indicators of Hydrologic Alteration (Richter et al. 1996) for the Souhegan River streamflow for water years 1910 to 2004. Note: Day of year count begins on October 1.

Indicator	Means	Coefficient of Variation
Parameter Group #1		
October Q_{ave} (cfs)	177.7	0.9
November Q_{ave} (cfs)	294.9	0.56
December Q_{ave} (cfs)	333.2	0.63
January Q_{ave} (cfs)	286.9	0.71
February Q_{ave} (cfs)	287.8	0.63
March Q_{ave} (cfs)	540.5	0.4
April Q_{ave} (cfs)	700.2	0.42
May Q_{ave} (cfs)	385.9	0.42
June Q_{ave} (cfs)	224.5	0.67
July Q_{ave} (cfs)	92.2	0.64
August Q_{ave} (cfs)	74.6	0.71
September Q_{ave} (cfs)	80.6	0.84
Parameter Group #2		
1-day minimum (cfs)	20.2	0.44
3-day minimum (cfs)	22	0.48
7-day minimum (cfs)	24.4	0.47
30-day minimum (cfs)	36.6	0.47
90-day minimum (cfs)	59	0.43
1-day maximum (cfs)	2955.5	0.45
3-day maximum (cfs)	2142.6	0.4
7-day maximum (cfs)	1530.3	0.35
30-day maximum (cfs)	912.1	0.28
90-day maximum (cfs)	605.4	0.22
Number of zero days	0	0
Base flow	0.09	0.53
Parameter Group #3		
Date of minimum	152.8	0.04
Date of maximum	32.8	0.07
Parameter Group #4		
Low pulse count	7.6	0.53
Low pulse duration (days)	16.9	1.06
High pulse count	9.8	0.39
High pulse duration (days)	4	0.45
Low Pulse Threshold (cfs)	72	
High Pulse Level (cfs)	662.19	
Parameter Group #5		
Rise rate (cfs/day)	146.4	0.4
Fall rate (cfs/day)	-61.6	-0.35
Number of reversals	104.5	0.13

Table 3. Indicators of Hydrologic Alteration (Richter et al. 1996) for the Souhegan River (cont.)

Indicator	Means	Coefficient of Variation
EFC Low Flows		
October Low Flow (cfs)	101.6	0.59
November Low Flow (cfs)	168	0.45
December Low Flow (cfs)	193	0.37
January Low Flow (cfs)	173.3	0.38
February Low Flow (cfs)	168.5	0.38
March Low Flow (cfs)	221.8	0.35
April Low Flow (cfs)	278.5	0.17
May Low Flow (cfs)	229.4	0.25
June Low Flow (cfs)	133.2	0.43
July Low Flow (cfs)	72.4	0.44
August Low Flow (cfs)	64.4	0.33
September Low Flow (cfs)	60.5	0.26
EFC Parameters		
Extreme low peak (cfs)	23.1	0.13
Extreme low duration (days)	6.3	0.69
Extreme low timing	112.8	0.09
Extreme low freq. (per year)	4.1	0.74
High flow peak (cfs)	675.6	0.2
High flow duration (days)	7.5	0.4
High flow timing	331.6	0.98
High flow frequency (per year)	14.6	0.31
High flow rise rate (cfs/day)	247.8	0.34
High flow fall rate (cfs/day)	-86.6	-0.28
Small Flood peak (cfs)	3264.3	0.18
Small Flood duration (days)	33.7	0.41
Small Flood timing	343.2	0.33
Small Flood freq. (per year)	0.7	1.29
Small Flood rise rate (cfs/day)	835.4	1.21
Small Flood fall rate (cfs/day)	-171.8	-0.67
Large flood peak (cfs)	6338.7	0.22
Large flood duration (days)	19.7	0.64
Large flood timing	341	0.48
Large flood freq. (per year)	0.1	3.46
Large flood rise (cfs/day)	1771.2	0.95
Large flood fall (cfs/day)	-477	-0.44

Note: the IHA method calculates 67 different statistics. With the task of testing many paired comparisons there is usually the need to make the effective contrast on a single more conservative comparison. Assuming independent comparisons, the experiment-wise error rate (i.e., the probability of false rejection of at least one of the hypotheses) is given by $\alpha=1-(1-\alpha_p)^r$, where α_p is the selected probability of type I error for a specific comparison and r is the

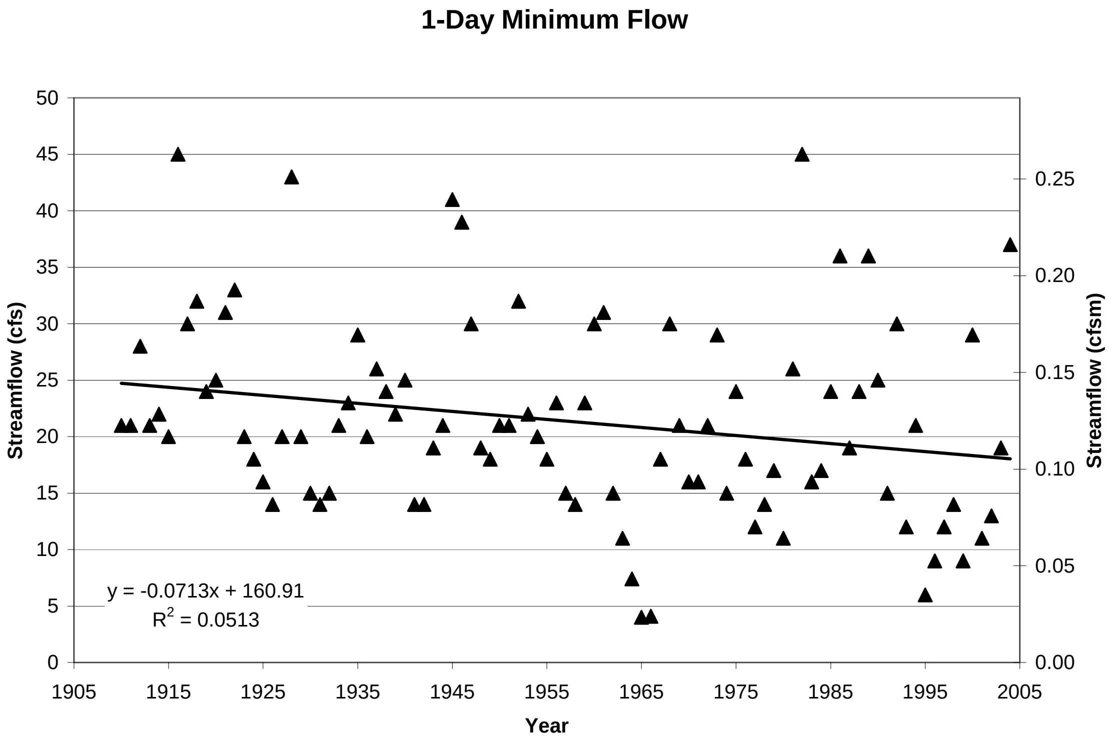
number of comparisons. That is, to accomplish a 95% significance level for the entire series of tests, each individual test should have 99.92% significance level ($\alpha = 0.000765$).
Table 4 summarizes the trend results. Only those IHA statistics having significant trends are shown. The results show no significant trends for annual discharge, precipitation, or yield ratio. Significant decreases in the annual 1 and 3-day minimum values (Figure 1) and the number of reversals (switch from increasing flow to decreasing flow or vice-versa) were found. A trend analysis for the period from 1977 to 2004, showed the magnitude slope for the 1 and 3-day minimum values in the Souhegan River, but no trend was found for Stony Brook during the same period. The day of the year having the 1-day minimum value was consistently within a 3 month period (July 14th to October 17th) and did not change throughout the study period.

Table 4. Trends analysis results

Statistic	**Analysis Period (WY)**	**Significant. Trend**	**Slope**	**Slope p-value**	**r^2**
Average Annual Streamflow	1910-2004	No	0.0335	0.903	0.000
Average Annual Precipitation	1952-2004	No	0.0140	0.821	0.001
Basin Yield (Q/P)	1952-2004	No	-0.0008	0.472	0.010
1-Day Min	1910-2004	Yes	-0.0761	0.027	0.051
3-Day Min	1910-2004	Yes	-0.0761	0.040	0.045
Reversal	1910-2004	Yes	-0.3516	0.000	0.310

3.3 Concurrent Flow Analysis

Concurrent flow measurements were conducted over a range of flows at 10 locations upstream of the USGS gage. Watershed area for each location was determined using ArcGIS. Measured flows were scaled by watershed area to determine flow values in cfsm. These measurements were used to develop regression relationships between the gage data and the flow at each location where $y_{fit} = mx + b$ where m and b are the slope and intercept of the regression relationship, respectively. The relationships will be used to estimate streamflow at the upstream locations. Table 5 summarizes the locations and regression analysis. A result where $m=1$ and $b=0$ would indicate that scaling USGS streamflow data by the watershed area alone is the best relationship. The results indicate that the lower Souhegan is fairly well represented by an area weighting approach, but the Souhegan flow upstream of Milford follows a different relationship.



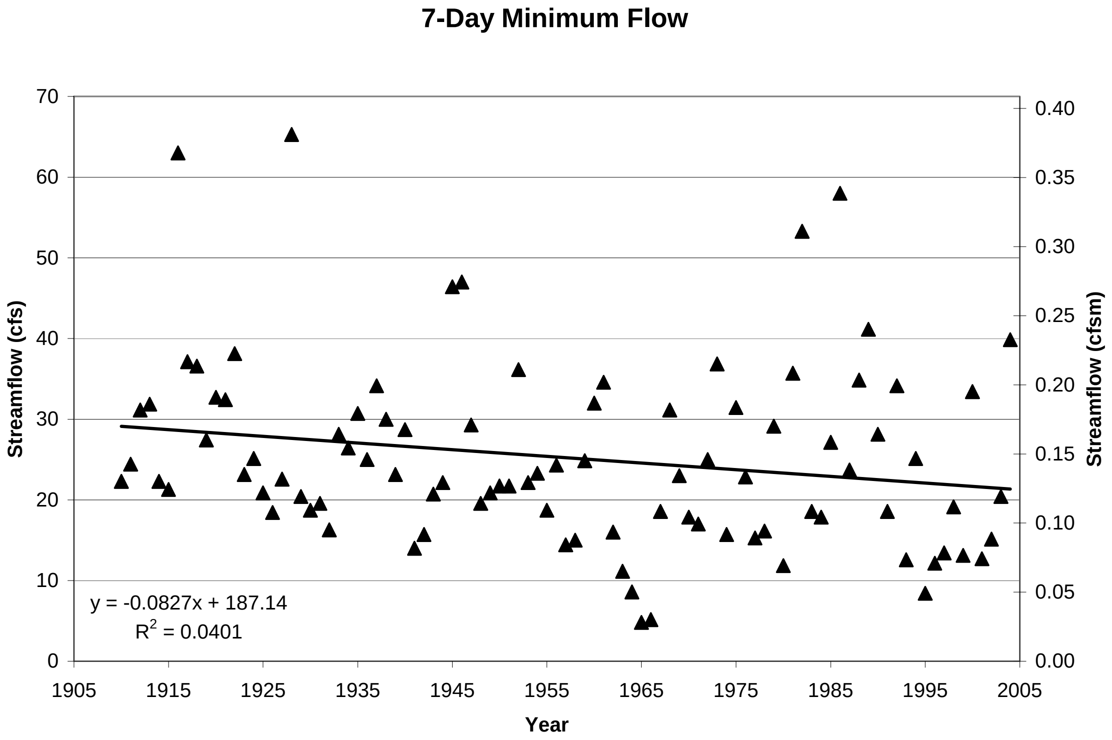


Figure 1. 1- and 7-day annual minimum streamflow values for the Souhegan River from 1910 to 2004. Annual minimum values were determined using the water year.

3.4 Streamflow Time Series

The streamflow record from water years 1910 to 2004 was used to identify 3 year periods having wet, dry, and average conditions. In addition, streamflow values for the last five years and a 30-yr period were identified. 3-yr average streamflow values were determined using a 3-yr moving window. When available, the annual precipitation record was examined to support the selection of 3-yr periods. The maximum average flow (376.0 cfs) occurred from 1951 to 1953 and had a correspondingly high precipitation value of 48.4 in. The minimum average flow (154.4 cfs) occurred from 1964 to 1966 and was preceded by the lowest average annual precipitation (31.8 in) from 1963 to 1965. Average conditions (283.1 cfs) were found from 1994 to 1996. Similar average streamflow also occurred from 1945-1947 (284.8 cfs). The latter will be used as the

1945 to 1947 data were measured while the 1994 to 1996 data were estimated from the Stony Brook gage data. The average streamflow over the last 5 years (262.8 cfs) was slightly below the long-term average conditions. The selected 30-yr period is 1948 to 1977. This period includes historical wet and dry periods and has an average flow (286.5 cfs) that is close to the long-term average. In addition, as the precipitation record began in 1952, all but four years of the record have daily records of precipitation.

Predevelopment hydrographs were estimated using the results from trend analysis and historical dam operation. Here, two factors are noteworthy. First, the 1 and 3-day minimum flow values have decreased steadily over the study period. Selection of the intermediate period to provide a 30 year record provides and intermediate measure of low flow values. Second, dam operations, through short-term management to increase and decrease storage, have historically influenced streamflow records. For the time series identified above, periods having dam management were determined by comparing streamflow hydrographs to daily precipitation values and identifying periods without rainfall that had anomalous increases or decreases. These periods were modified to provide a continuous hydrograph recession curve using the baseflow recession method. The method relates streamflow at two times using an exponential decay function to predict the baseflow recession as follows: $Q_{t+\Delta t} = Q_t e^{-k\Delta t}$ where Q is the streamflow, k is the baseflow recession constant, and Δ t is the time interval between the two measurements. Streamflow values, one day prior to and one day immediately after the anomalous period, were determined and used to calculate the baseflow recession constant. The streamflow values during the anomalous period were estimated using the baseflow recession equation where Q_o was set to the streamflow on the day prior to the anomalous period. These values replaced the measured values. A total of 30 periods that typically lasted less than one week were modified for the 30 year record.

Table 5. Concurrent flow results for locations upstream of the Souhegan River USGS gage using the relationship $Q_{upstream,\ cfsm} = a\ .Q_{USGS,\ cfsm}^{\ b}$

Site	Description	Area (mi^2)	Ratio to USGS gage	Num. of Measures	a	b	R^2
SR6	Handicap Access Fish Ramp - Greenville	33.9	0.198	4	0.6078	0.7774	0.962
SR12	High Energy Bank - Greenville	37.0	0.216	4	0.6307	0.7819	0.731
SR6/SR12				8	0.6189	0.7793	0.830
SR16	Upstream of Monadnock Water	64.6	0.377	3	1.0478	1.599	0.995
SR18	Intervale Road - Wilton	65.0	0.379	2	0.8505	1.2962	1.000
SR16/18				5	0.9437	1.4540	0.984
SR25	Wilton wastewater pumping station	102.3	0.597	4	0.5947	1.0369	0.824
SR31	Shopping Center Mall - Milford	127.2	0.743	3	0.964	1.3287	0.991
SR34	Electric Substation - Milford	139.4	0.814	3	1.0151	1.4825	0.984
SR31/34				6	0.996	1.4159	0.981
SR50	Boston Post Road - Amherst	159.0	0.928	3	0.9573	1.3073	0.979
SR56	Tomalison Farm - Amherst	165.6	0.967	3	0.9726	1.3207	0.996
SR50/56				6	0.9649	1.314	0.987
SR62	Turkey Hill Road - Amherst	169.4	0.989	2	0.8233	1.0098	1.000
USGS	USGS Gage	171.3	1.000	N/A	N/A	N/A	N/A

Appendix 3 References:

Maidment, D. R. 1993. Handbook of Hydrology. United States: McGraw-Hill;

Richter, B. D.; Baumgartner, J. V.; Powell, J., and Braun, D. P. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology. 10(4):1163-1174.