

## **Appendix 13**

### **Hydrographs**

## **1.0 Introduction**

This appendix presents the methods used in the development of the hydrographs (streamflow time series) for the Lamprey River Protected Instream Flow Study. Dr. Jennifer Jacobs of the University of New Hampshire performed the hydrologic analysis for the development of the hydrographs used in this study. These hydrographs were used primarily in the MesoHABSIM analysis of aquatic life and fish as discussed in Part One of the report and in the assessment of the Protected Instream Flows as discussed in Part Two of the report.

For the MesoHABSIM modeling a representative 30-year hydrograph was developed for the Lamprey River for the evaluation of existing conditions. The development of this hydrograph was based on the Lamprey River streamflow recorded at the USGS Packers Fall gage. The MesoHABSIM modeling also included an analysis of baseline conditions that required the development of a “naturalized” 30-year hydrograph. This naturalized hydrograph was based on the 30-year recorded hydrograph that was then adjusted to correct for water use and lake management (Pawtuckaway Lake).

For the assessment of the Protected Instream Flows five different representative hydrographs were developed based on the Lamprey River streamflow recorded at the USGS Packers Falls gage. These included representative hydrographs for that last five years (during the study), the three wet year period, three dry year period and three average year period.

The following sections discuss the methods used for the development of the different hydrographs mentioned above and the data sets for these analyses are provided at the end of this appendix.

### **1.1 Hydrologic Data**

The first step in the development of the hydrographs was the collection of pertinent streamflow and precipitation data for the analysis. For the development of the representative hydrographs streamflow data for both the Lamprey River and its neighboring watershed the Oyster River were obtained and reviewed. Daily streamflow data for the Lamprey River at the Packers Falls gage (#01073500) near Newmarket, New Hampshire are available from the United States Geological Survey (USGS). This streamflow gage is located towards the end of the Lamprey Designated River. Daily streamflow data are also available for the neighboring Oyster River as recorded at the USGS gage (#01073000) near Durham, New Hampshire. The location and period of record for these gages are presented in Table 1.

Precipitation data are available from the National Oceanic and Atmospheric Administration (NOAA) precipitation gage located in Durham, New Hampshire. The Durham gage has recorded daily precipitation values from 1939 to present. This is the longest, continuously operating NOAA station in the region. The location and period of record for the Durham precipitation gage are presented in Table 1.

**Table 1 - Available streamflow and precipitation data reviewed for this study.**

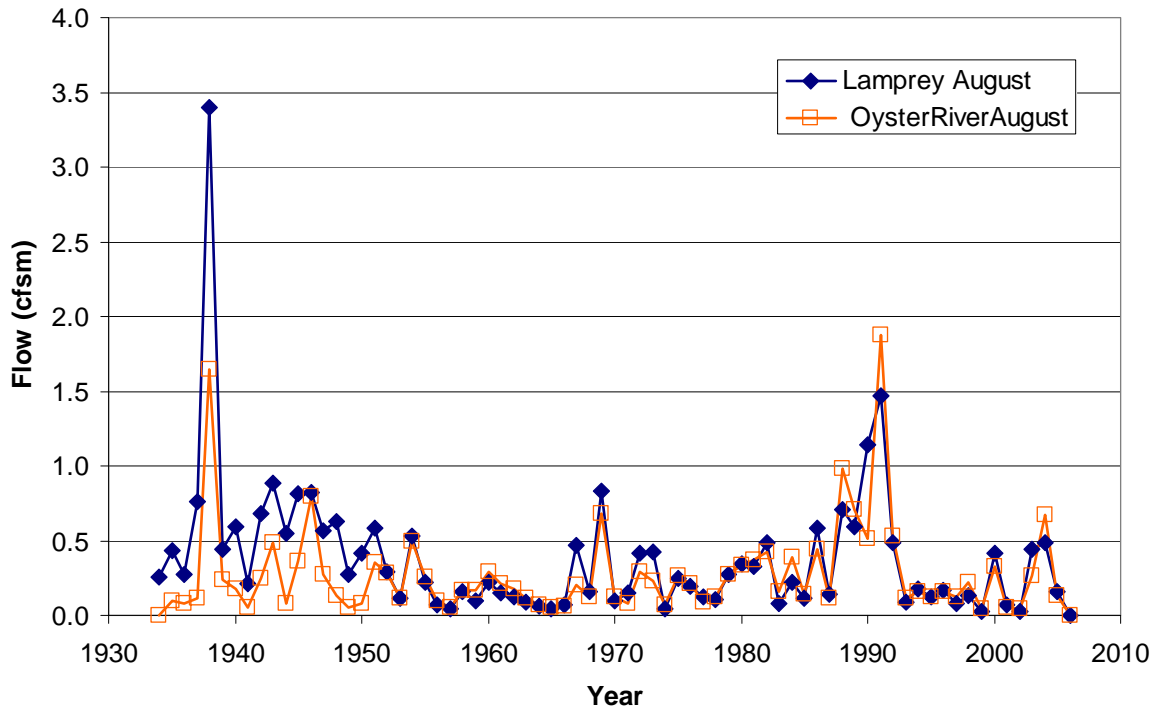
<b>Station Number</b>	<b>Station Name</b>	<b>Latitude NAD27</b>	<b>Longitude NAD27</b>	<b>Drainage Area (mi<sup>2</sup>)</b>	<b>Period of Record</b>
USGS 01073500	Lamprey River near Newmarket, NH	43°06'09'	70°57'11'' W	183	7/24/1934 to present
USGS 01073000	Oyster River near Durham, NH	43°08'55'	70°57'56'' W	12.1	12/15/1934 to present
COOP 272174	Durham	43°09'	71°57' W	N/A	12/1/1939 to present

## **1.2 Historical Trend Analysis**

The second step in the development of the representative hydrographs was a historical trend analysis of streamflow. The purpose of this trend analysis was to identify any significant changes in flow over time. Those periods where significant changes in flow were documented, due to water use or water management, were excluded from the period of record used for the development of the representative hydrographs.

The historical trends of average discharge, precipitation, and watershed yield (the ratio of precipitation to discharge) were analyzed graphically and using linear regression, while mean daily streamflow for the period of record was analyzed using the Nature Conservancy's Indicators of Hydrologic Alteration software (Richter et al. 1996). Richter et al.'s (1996) *Indicators of Hydrologic Alteration* (IHA) used linear regression analyses to identify trends in streamflow variability with respect to timing, duration, frequency, and rate of change. IHA statistics were initially calculated for water years 1934 to 2007.

For the period of record, significant trends were identified for average and low flow conditions in many fall months, using a 95% significance level ( $\alpha = 0.05$ ). To confirm this trend, the mean flow values for the Lamprey and Oyster Rivers for August were compared. The results of this comparison (Figure 1), shows a distinct change in the flow regime in early 1950s. Previous researchers including Stephen Roy (DES), Brandon Kernen (DES), Tom Mack (USGS), and Rob Flynn (USGS) have also noted these differences.



**Figure 1 - Mean August streamflow values (cfsm) for the Lamprey River and the Oyster River from 1934 to 2006.**

Rob Flynn of the USGS, investigated the historical record and found:

*“Beginning in the early to mid-1950's, there is a downward shift in the hydrograph at the USGS Lamprey River gage for the months of July and August and an upward shift in the hydrograph for the months of October and November. The downward shift of the hydrograph for July and August and the reversal of this shift in the hydrograph for October and November, indicates that the Lamprey River flow may be impacted by impoundment and management of that impoundment. Last week, I stopped by the NHDES Dam bureau and took a look at the files for the Dolloff Dam on Pawtuckaway Lake in Nottingham, NH as Pawtuckaway Lake flows into the North River which empties into the Lamprey River above Wadleigh Falls (and the USGS gage at Packers Falls). The Pawtuckaway drainage area is 20.66 sq. mi. The New Hampshire Resources Board took over operation of the Dolloff Dam in 1955. Prior to this, the structure was operated by New Hampshire Electric as a storage reservoir for power generation. On August 14, 1950, an agreement was made between the State of NH and NH Electric to maintain the lake at 10 feet in the winter and 18 feet in the summer with summer defined as the period of June 1 to October 1. Prior to this agreement, New Hampshire Electric would draw down the lake all summer. After this agreement, drawdown occurred in the fall (beginning October 1) and a constant level was maintained throughout the summer. I believe that the management practices of New Hampshire Electric beginning in 1951 and of the New Hampshire Resources board beginning in 1955 are the cause of the shift in the hydrograph for the Lamprey River. In addition, it was noted in the file that the Dolloff Dam was repaired and the gate was repaired and closed in 1950 and that prior to this repair, there was "excess leakage" at the gate.” (personal communication from R. Flynn, USGS to T. Mack, USGS, November 27, 2006).*

Based on the findings of the historical trend analysis (IHA) and the documented change in the management of the water levels of Pawtuckaway Lake in the mid 1950s, the streamflow data for the Lamprey River for the period prior to 1955 was not considered when identifying three-year periods having wet, dry, and average conditions as well as the representative 30-yr period.

### **1.3 Concurrent Flow Analysis**

A series of concurrent flow measurements was performed on the Lamprey River by Dr. Tom Ballestero of the University of New Hampshire during 2005, 2006 and 2007. Instantaneous discharge was measured at two locations on the Lamprey Designated River (downstream of Wadleigh Falls and upstream of Lee Hook Road) that are located upstream of the USGS Packers Falls gage. The purpose of these measurements was to obtain streamflow data at multiple locations along the Lamprey Designated River so that a streamflow time series (hydrograph) could be developed for each of these ungaged locations based on the streamflow records at the USGS Packers Falls gage. In addition, the results of the concurrent flow measurements were used to determine if streamflow could be estimated for points along the Lamprey Designated River using a ratio of watershed area.

The concurrent flow measurements were conducted for flows ranging from 7.4 to 300 cfs (0.04 to 1.64 cfs<sub>m</sub>) as measured at the USGS Packers Falls gage (Table 2). The flows recorded at Lee Hook Road and Wadleigh Falls were compared with the flows recorded at the USGS Packers Falls gage using linear regression methods. The results of the linear regressions of the concurrent streamflows measured at the two ungaged locations with the flows recorded at the USGS Packers Fall gage are summarized in Table 3.

**Table 2 - Summary of concurrent flow measurements recorded at Wadleigh Falls and Lee Hook Road along with flows recorded at the USGS Packers Falls gage near Newmarket.**

<b>Measurement Location</b>	<b>Date</b>	<b>Lamprey R. USGS Gage Discharge (cfs)</b>	<b>Lamprey R. USGS Gage Discharge per unit Area (cfs/sq. mi.)</b>	<b>Measured Discharge (cfs)</b>	<b>Measured Discharge per unit Area (cfs/sq. mi.)</b>
Wadleigh Falls	3-Aug-05	39.00	0.21	33.82	0.25
	10-Aug-05	21.00	0.11	15.14	0.11
	11-Sep-06	11.00	0.06	7.10	0.05
	24-Sep-05	11.00	0.06	11.06	0.08
	9-Sep-06	89.00	0.49	68.90	0.51
	13-Sep-06	51.00	0.28	36.69	0.27
	8-Oct-06	62.00	0.34	49.33	0.37
	13-Oct-06	80.00	0.44	60.34	0.45
	17-Dec-06	300.00	1.64	231.74	1.72
	9-May-07	238.00	1.30	193.60	1.43
	23-Jun-07	105.00	0.57	83.24	0.62
Lee Hook Road	3-Aug-05	38.00	0.21	36.69	0.23
	10-Aug-05	21.00	0.11	18.55	0.12
	11-Sep-06	11.00	0.06	10.30	0.06
	24-Sep-05	11.00	0.06	13.93	0.09
	9-Sep-06	87.00	0.48	83.40	0.52
	13-Sep-06	51.00	0.28	42.53	0.26
	8-Oct-06	62.00	0.34	57.96	0.36
	13-Oct-06	80.00	0.44	73.78	0.46
	18-Dec-06	285.00	1.56	234.67	1.46
	9-May-07	238.00	1.30	227.28	1.41
	23-Jun-07	105.00	0.57	86.55	0.54

**Note:**

Drainage area upstream of Wadleigh Falls = 135 square miles.

Drainage area upstream of Lee Hook Road = 161 square miles.

Drainage area upstream of USGS Packers Falls gage = 183 square miles.

**Table 3 - Concurrent flow results for locations upstream of the Lamprey River USGS gage using the relationship  $Q_{\text{upstream}} = a \cdot Q_{\text{USGS}}$ .**

Site Description	Area (mi <sup>2</sup> )	Ratio to USGS gage	Number of Measures	a	R <sup>2</sup>
Wadleigh Falls	135	0.738	16	0.7849	0.998
Lee Hook Road	161	0.880	16	0.8813	0.9902
USGS Gage	183	1.000	N/A	N/A	N/A

Using the results of the regression analyses, streamflow at Wadleigh Falls and Lee Hook Road can be estimated, based on recorded flows at the USGS Packers Falls gage, using the following two equations:

$$1) \quad Q_{\text{WF}} = 0.7849 * Q_{\text{PF}}$$

$$2) \quad Q_{\text{LHR}} = 0.8813 * Q_{\text{PF}}$$

Where:

$Q_{\text{WF}}$  = Discharge at Wadleigh Falls

$Q_{\text{LHR}}$  = Discharge at Lee Hook Road

$Q_{\text{PF}}$  = Discharge at USGS Packers Falls gage

The flows at these two locations can also be estimated using the watershed area ratio method, where the flows recorded at the USGS Packers Falls gage are multiplied by the ratio of the watershed area for the concurrent flow measurement location and the watershed area of the USGS Packers Falls gage (183 square miles). When the watershed ratios are compared with the regression results for the two sites, the area downstream of Lee Hook Road is fairly well represented by the watershed area ratio approach (both ratio and regression values similar). While the estimated flows for the Wadleigh Falls site based on the regression analysis would be slightly greater than those derived using the watershed area ratio approach.

#### 1.4 Streamflow Time Series

Streamflow time series were developed for five representative periods under existing conditions. Representative hydrographs were identified to document the hydrologic conditions experienced over a 30 year period, the last five years, and for three year periods representing dry, wet and average hydrologic conditions. The three year and five year representative hydrographs were used in the assessment of the protected instream flows, while the 30-year hydrograph was used in the MesoHABSIM modeling. In addition, a 30-year hydrograph for naturalized conditions was developed for use in the MesoHABSIM modeling.

## Representative Hydrographs

The streamflow record for water years 1955 to 2007 was examined to identify three-year periods having wet, dry and average conditions. In addition, streamflow values for the last five years (2003 to 2007) and a typical 30-year period were also identified. The three-year average streamflow values were determined using a three-year moving window. When available, the annual precipitation record was also examined to support the selection of the three-year periods.

The maximum annual average flow (452.6 cfs) occurred from 2005 to 2007 and had a correspondingly high precipitation value of 54.2 inches, so this period of record was identified to represent the three-year wet condition. The minimum average flow (179.5 cfs) occurred from 1964 to 1966 with a very low average annual precipitation (35.7 inches), so this period of record was identified to represent the three-year dry condition. Average conditions for streamflow (286.4 cfs) and precipitation (43.5 inches) occurred from 1990 to 1992 and this period was identified as being representative of the three-year average condition. Over the last five years (2003 to 2007), the average streamflow (386.2 cfs) was well above the long-term average conditions. The selected 30-year period is 1976 to 2005. This period includes historically wet and dry periods and has an average flow (287.0 cfs) that is close to the long-term average. An IHA analysis performed on the 30-year period showed no trends for any month's average, maximum or minimum values.

## Naturalized Hydrograph

A naturalized hydrograph for 1976 to 2005 was developed by removing the Affected Water User (AWU) net withdrawals net of return flow and historical dam operation at the Dolloff Dam on Pawtuckaway Lake in Nottingham, New Hampshire. The AWUs included in this analysis are listed in Table 4.

**Table 4 – Affected Water Users in the Lamprey River Water Management Planning Area.**

<b>Name</b>	<b>Water Use ID</b>	<b>Type</b>
SEVERINO TRUCKING COMPANY INC	20751 20751-S03	SW
SCENIC NURSERY INC	20747 20747-S03	SW
SCENIC NURSERY INC	20747 20747-S02	GW
SCENIC NURSERY INC	20747 20747-S01	GW
LEISURE VILLAGE	20783 20783-S01	GW
LEISURE VILLAGE	20784 20783-S01	GW
LEISURE VILLAGE	20785 20783-S02	GW
FERNALD LUMBER INC	20557 20557-S03	SW
FERNALD LUMBER INC	20557 20557-D01	GW
EPPING WWTF	20389 20389-D01	SW
PENNICHUCK WATER WORKS	20351 20061-S01	TW
RAYMOND WATER DEPARTMENT	20061 20061-S01	GW

EPPING WATER WORKS	20045 20045-S04	GW
EPPING WATER WORKS	20045 20045-S02	GW
PENNICHUCK WATER WORKS	20018 20018-S01	GW
NEWMARKET WATER WORKS	20057 20057-S02	GW
CHIKALLA GERALD*	20126 20126-S01	SW
UNIVERSITY OF NH	20066 20066-S02	SW
EPPING WATER WORKS	20045 20045-S01	GW
DELUGE INCORPORATED	20679 20679-S01	GW
NEWMARKET WATER WORKS	20057 20057-S05	SW
NEWMARKET WATER WORKS	20057 20057-S04	SW
NEWMARKET WATER WORKS	20057 20057-S03	GW
NEWMARKET WATER WORKS	20057 20057-S01	SW
EPPING WATER WORKS	20045 20045-S03	GW

**Note:**

SW - Surface water

GW - Groundwater

TW - Transfer of water from Raymond to Pennichuck Water Works

\* - Nottingham Lake Dam

To consider the impact of AWU withdrawals, a monthly record of net withdrawals was created for each year that water records were available. All long term water use data records from AWUs, not just those having direct and induced recharge, were considered. The withdrawal records were developed from the quarterly water use reports on file with DES from the fourth quarter of 1988 through 2005. Prior to quarterly reporting, the 1976 to 1988 period, monthly withdrawals were estimated from historical data with input from the AWUs. AWUs having permitted withdrawals in 1988 and 1989 were contacted regarding historic water use location and quantity. Net water use (equivalently consumptive water use) was estimated by multiplying the gross use by a consumptive loss rate.

The University of New Hampshire/Town of Durham Water System (UDWS, Water Use ID 20066) is the largest consumptive users of water from the Lamprey River. The UDWS has a pump station located in the impoundment upstream of Wiswall Dam and periodically transfers water out of the Lamprey River watershed (and upstream of the Lamprey USGS gage) to the Oyster River watershed (but downstream of the Oyster River USGS gage). Since this transfer is between drainage basins, it is considered to be 100 percent consumptive and therefore yields no return flow. In contrast to most other AWUs, this water use is intermittent and using monthly average values to estimate daily water use is not reasonable. Instead, a daily time series for the 30-year period was created from daily records obtained from Mr. Wesley East of the University of New Hampshire Water Works.

These daily records covered all but four of the years of the 30-year period. Periodic differences were identified between the monthly totals from the plant's daily records and the quarterly water user report values on file with DES. Additional records were reviewed with Mr. East of the UNH Water Works prior to establishing the daily values for this study. For 1997, 1999, 2000, and

2001, only monthly records were available. Based on input from Mr. East, a pumpage rate of 800,000 gallons per day (gpd) was applied to the number of days necessary to match the monthly totals. An odd pumpage rate was used on one day each month, as necessary, to match the reported monthly values. The streamflow records were reviewed and work days (Monday to Saturday) having the lowest flow values were assumed to be the dates on which pumping occurred. The remaining days had no withdrawal.

The resulting consumptive withdrawal rates were added to the daily flows in the measured 30-year hydrograph (1976 to 2005) to generate streamflow records without the impact of AWUs withdrawals also referred to as the naturalized hydrograph. These values are presented in Table 5.

**Table 5 – Average daily consumptive loss (cfs), including all water losses in and upstream of the Lamprey Designated Reach.**

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
pre '85	0.080	0.071	0.068	0.068	0.075	0.080	0.075	0.075	0.071	0.066	0.061	0.065
85	0.112	0.102	0.101	0.099	0.109	0.116	0.111	0.110	0.104	0.098	0.094	0.096
86	0.112	0.102	0.101	0.099	0.109	0.116	0.111	0.110	0.104	0.098	0.094	0.096
87	0.112	0.102	0.101	0.099	0.109	0.116	0.111	0.110	0.104	0.098	0.094	0.096
88	0.112	0.102	0.101	0.099	0.109	0.116	0.111	0.110	0.104	0.098	0.094	0.096
89	0.116	0.110	0.102	0.103	0.107	0.126	0.108	0.110	0.112	0.102	0.083	0.085
90	0.109	0.104	0.095	0.098	0.107	0.116	0.105	0.097	0.103	0.098	0.095	0.089
91	0.107	0.109	0.106	0.097	0.106	0.119	0.125	0.126	0.117	0.108	0.095	0.091
92	0.100	0.106	0.111	0.114	0.158	0.144	0.138	0.133	0.133	0.110	0.106	0.113
93	0.112	0.118	0.116	0.113	0.146	0.154	0.370	0.338	0.139	0.115	0.119	0.117
94	0.113	0.125	0.120	0.149	0.150	0.171	0.170	0.158	0.156	0.125	0.125	0.125
95	0.125	0.126	0.124	0.148	0.156	0.167	0.171	0.376	0.778	0.140	0.129	0.126
96	0.118	0.136	0.140	0.161	0.171	0.181	0.146	0.152	0.137	0.147	0.129	0.131
97	0.140	0.157	0.151	0.161	0.158	0.253	0.235	0.473	0.145	0.237	0.177	0.150
98	0.130	0.131	0.125	0.154	0.167	0.169	0.181	0.178	0.166	0.151	0.131	0.118
99	0.151	0.159	0.182	0.193	0.220	0.264	0.259	0.354	0.291	0.138	0.135	0.144
00	0.119	0.132	0.145	0.158	0.203	0.179	0.205	0.184	0.199	0.130	0.112	0.117
01	0.124	0.151	0.150	0.179	0.201	0.472	0.200	0.237	0.264	0.174	0.221	0.163
02	0.208	0.213	0.362	0.363	0.315	0.356	0.614	0.918	1.012	1.614	1.176	0.496
03	0.285	0.306	0.298	0.271	1.177	1.053	1.171	1.158	1.168	1.292	0.882	0.131
04	0.177	0.163	0.240	0.211	0.296	0.290	0.450	0.586	1.217	1.054	0.851	0.528
05	0.157	0.151	0.165	0.159	0.215	0.225	0.273	0.274	0.245	0.183	0.168	0.156

The naturalized hydrograph was also corrected for the historical dam operation at the Dolloff Dam on Pawtuckaway Lake in Nottingham, New Hampshire. Historic operation records for the Dolloff Dam were obtained from the DES Dam Bureau. The dam levels are routinely raised

seven feet in the spring and lowered seven feet in the fall. The levels are controlled by a series of stop logs that may be inserted or removed. Typically, the dam levels are lowered by incrementally removing stop logs from October to December. Levels are typically raised in February and March to within 2 to 3 feet of the recreational pool. The remainder of the pool is filled by early May.

Sixteen years of historic operation records for the Dolloff dam were reviewed to determine typical operations including fill and release start and end dates and fill and release volume. The median drawdown period begins on October 12 and ends on December 19, a 67.5 day period, during which the Pawtuckaway Lake levels typically drop from 24.73 ft to 19.35 ft (staff gage height). The volume released from storage was estimated, using a storage area relationship, to be 3,938 acre-ft over the 67.5 day release period or equivalently 29.29 cfs. 1,535 acre-ft of this release volume is typically refilled at a rate of 20.8 cfs from February 21st to March 29<sup>th</sup>. The remaining 2,403 acre-ft is filled from March 30<sup>th</sup> to May 5<sup>th</sup> at a rate of 33 cfs. It should be noted that while the stop logs are typically removed by December 19<sup>th</sup>, additional outflow continues to lower lake levels somewhat during the remainder of January and February. In early February the first stop logs are placed to begin to the refill process.

The existing dam operations at Pawtuckaway Lake result in somewhat augmented flows in the fall during the release period and reduced flows in the spring during the filling period. In light of this management scenario, the historical streamflow time series was adjusted by subtracting the releases in the fall and adding the fill rates in the spring. A daily time series was created to adjust for dam operation where negative values correspond to corrections for the fall release and positive values to corrections for the spring fill. The resulting time series were added to the daily flows in the measured 30-year hydrograph to generate streamflow records without the dam management. This 30-year naturalized hydrograph was then used in the MesoHABSIM modeling of baseline conditions for aquatic life and fish (see Part One of main report).

As a supplement to this appendix (see enclosed CD), the daily recorded streamflows for the USGS Packers Falls gage for the period of 1976 to 2005 and the watershed weighted flows for the Lee Hook Road and Wadleigh Falls concurrent measurement sites are tabulated. This table also includes the naturalized daily mean flows for the same period of record and at the same locations.

#### **References:**

Richter, B.D., Baumgartner, J.V., Powell, J., and D.P. Braun. 1997. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* **10**: 1,163-1,174.