Hydrologic effects of flood control dams in the Ashuelot River, New Hampshire, and West River, Vermont

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Connecticut River Program
and
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The vision of the Connecticut River Program is to improve the health of New England's largest river system by restoring the following characteristics: flow patterns with natural variations in magnitude, frequency duration, timing and rate of change, that transport appropriate loads of sediment and nutrients and that maintain productive and diverse habitats supporting numerous species. We further envision the Connecticut River Program as a center of scientific excellence, actively exporting knowledge in environmental flow management, solutions to stream fragmentation and floodplain restoration.

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Executive Summary

The objective of this analysis was to examine the effects of flood control dams on the hydrographs of the Ashuelot River in New Hampshire and the West River in Vermont, two tributaries to the Connecticut River. Each river basin has two flood control dams owned by the Army Cops of Engineers: Surry Mountain and Otter Brook dams in the Ashuelot basin, and Ball Mountain and Townshend dams on the West River. I examined the effects of the dams on river flows by comparing the natural and regulated hydrographs of each river downstream of each dam. I also examined the extent to which flood control dams altered flows at the confluence of each tributary and the mainstem Connecticut River to determine the spatial extent of hydrologic alteration for each river. I used simulated data of unimpaired daily mean flows over a 20-year time period to characterize the unimpaired hydrograph of each river, and I compared these flow regimes to observed daily mean streamflows recorded during the same time period.

Flow regulation had similar effects on streamflows in both rivers. The main effects of the dams included:

- Near elimination of overbank flows (2 year or greater recurrence interval) in both rivers
- Decreased magnitude of maximum flows in both rivers
- Decreased frequency of low flow pulses (Q90) in the West River
- Increased magnitude of minimum flows (i.e., higher minimum flows) in both rivers
- Increased duration of both high (Q10) and low (Q90) flow pulses in the Ashuelot, but only high flow pulses in the West
- Increased diurnal (sub-daily) flow fluctuations in the West River below Ball Mountain Dam

Overall, flood control dams on the Ashuelot and West rivers have altered the magnitude, duration, and frequency of both high and low flows, and variability and rate of change of the hydrograph. Although specific changes to stream flows varied for each river and below each dam, in general the dams reduced or eliminated extreme low and high flows (calculated using mean daily flows), but may have increased short-term variability. The reduction in the magnitude and frequency of high flows has likely decreased the spatial extent of floodplain inundation, scour of vegetation and debris from floodplain sites, and deposition of alluvial soils.

Overall, this has likely resulted in a reduction in regeneration of floodplain forest communities along both rivers. In addition, short-term flow fluctuations in the West River may have led to shifts in fish and invertebrate composition, favoring habitat generalists over fluvial specialist species and eliminating or reducing abundance of species dependent on stream margin habitat. I recommend flow restoration scenarios that reintroduce high flows that inundate floodplains and maintain river and floodplain landforms, as well as elimination of unnatural short-term flow fluctuations.

Introduction

I compared the natural and regulated hydrographs of two major tributaries to the Connecticut River: the Ashuelot River in New Hampshire and the West River in Vermont. Specifically, I examined the effects of four flood control dams owned by the Army Corps of Engineers (Surry Mountain and Otter Brook dams in the Ashuelot basin and Ball Mountain and Townshend dams on the West River) on river flows by comparing simulated natural flows to flows recorded at U.S. Geological Survey stream gages downstream of each reservoir. In addition, I examined the extent to which flood control dams altered flows at the confluence of each tributary and the mainstem Connecticut River to determine the spatial extent of hydrologic alteration for each river.

I used simulated data of unimpaired daily mean flows over a 20-year time period to characterize the unimpaired hydrograph of each river, and I compared these flow regimes to observed daily mean streamflows recorded during the same time period. I used simulated natural flows for this analysis, instead of stream gage records from time periods before the dams were built, for two reasons: (1) a record of pre-impact (i.e., before dams were constructed) stream gage data over a time period sufficient for capturing inter-annual variation in the hydrograph (≥20 years) was only available downstream of one of the four flood control dams, and (2) a comparison of natural and regulated streamflows over the same time period allows for hydrologic analyses that are not potentially confounded with changes in climate, precipitation, or land use. I present the methods that were used to calculate simulated natural flows, analyses comparing the natural and regulated hydrographs, and potential ecological implications for the Ashuelot and West Rivers.

Methods

Flow simulations

Simulated natural flow data sets were created for the Ashuelot and West rivers by John Hickey, hydraulic engineer at the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE). Simulated natural mean flows were calculated on a daily basis for locations on each stream that had either active or historical stream gages. In total, natural flows were calculated for four stream gage sites in the Ashuelot River basin (on Otter Brook below Otter Brook Dam and on the Ashuelot River below Surry Mountain Dam, at West Swanzey, and at Hinsdale) and four sites on the West River (below Ball Mountain dam, below Townshend dam, at Newfane, and at the mouth of the West). Mean daily streamflow records were collected from USGS stream gages on both rivers (Table 1).

Data were missing from stream gage records below Surry Mountain dam, Otter Brook dam, and Ball Mountain Dam from 1989 to 1995, and from gage records below Townshend dam from 1983 to 1994 and 2000 to 2004. Average daily streamflow for these dates was estimated from instantaneous values of reservoir releases available from USACE archives (USACE in press). Daily mean flow values below Surry Mountain, Otter Brook, and Ball Mountain dams were estimated using multiple instantaneous observations of reservoir releases for each day.

Daily mean flows below Townshend dam had to be estimated from one daily instantaneous observation (taken at 7:00am) for a number of years (USACE in press). Using one instantaneous observation per day does not introduce systematic bias in flow calculations, because flow releases may occur at any time during a 24-hour period. However, use of one observation per day may result in estimates that are lower or higher than actual mean daily flows, depending on whether conditions changed before the subsequent 7am observation. Thus, mean daily streamflow values for the West River are more accurate for the location below Ball Mountain dam than below Townshend dam.

Daily reservoir release and pool elevation data for Surry Mountain, Otter Brook, Ball Mountain, and Townshend dams were collected from the New England District of USACE. Hardcopies of daily data were available for 1983 – 2001 and electronic records were available from 1997 to the present. Data prior to 1983 were available as annual plots. These plots did not have sufficient detail for accurate estimations of daily data; therefore, only data from 1983 to 2004 were used in natural flow simulations.

Simulated natural flows were calculated on a daily basis by adjusting mean daily streamflow from gage records to remove the influence of upstream reservoirs, using stream gage data, reservoir releases, and reservoir pool elevations. Change in water stored in each reservoir over a 24-hour period (referred to as a “holdout”) was calculated as the difference between reservoir pool elevations at the beginning and end of each day (midnight to midnight) and translating this value to storage using elevation-storage rating tables available from the New England District of USACE and the formula:

$$\text{Inflow}_t = \text{Outflow}_t + (\text{Storage}_t - \text{Storage}_{t-1})*0.50417 \text{ cfs-day/acft-day}$$

Instantaneous observations taken at 7am were treated as occurring at 12am of the same day. Checks on the data were performed to determine that no water was created or lost in the calculations, and data were adjusted so that reservoir inflow patterns reflected precipitation and streamflow trends. However, this data adjustment was not completed for the stream gage below Townshend dam because of the long period of missing mean daily stream gage data (USACE in press).

Holdouts were routed from each dam to downstream gages and added to local flows calculated at each gage (adjusting for the time it would take for a holdout to travel to a downstream gage). Local flows were calculated by subtracting flows from the upstream gage (or outflows from the upstream reservoir) from flows recorded at each gage. There was no stream gage at the mouth of the West River; therefore, local flows at the mouth were estimated by multiplying inflows to the Ball Mountain reservoir by the ratio (64.2%) of the drainage area between the mouth and the Newfane gage and the drainage area above Ball Mountain.

To calculate natural flows at the Hinsdale stream gage, holdouts from both reservoirs were transformed to 3-hour time steps. The Ashuelot River between each reservoir and Hinsdale was divided into routing reaches, and the number of time steps that should be considered in calculations of both moving averages (controlling the degree of attenuation, or flattening of peak flows) and travel time (the number of time steps required to get from the start of a reach to the end) were assigned to each reach (USACE in press). Natural flows were calculated by routing the holdouts as 3-hour time steps to the confluence of the Ashuelot and Otter Brook at Keene, adding the holdouts from Surry Mountain and Otter Brook together, routing the combined holdouts to West Swanzey, adding holdouts to gaged flows at West Swanzey, routing the combined holdouts to Hinsdale, transforming the 3-hour time series to daily mean values, and adding to gaged flows at Hinsdale.

Natural flows at Townshend dam were calculated by adding outflows from Ball Mountain to the local flows calculated for Townshend. No routing was applied for the Townshend gage. Natural flows from Townshend were transformed to 3-hour time steps and routed to the Newfane gage. Newfane natural flows were calculated by transforming the 3-hour time series to daily mean values and adding local flows for the Newfane gage. Natural flows from the Newfane gage were converted to 3-hour time intervals and routed to the mouth of the West. Natural flows for the Mouth were calculated by transforming the 3-hour intervals to mean daily flows, and adding local flows estimated at the mouth (see USACE in press for a more detailed description of flow simulations).

IHA analyses

I compared simulated natural mean daily flows for water years 1984 – 2004 to observed mean daily flows from stream gage data for the same time period for stream gages below each dam (Surry Mountain and Otter Brook on the Ashuelot; Ball Mountain and Townshend on the West) and at the mouth of each river (the Hinsdale gage on the Ashuelot; the river mouth on the West). I used the Indicators of Hydrologic Alteration (IHA) Software (The Nature Conservancy 2005) for all hydrologic analyses. IHA allows comparisons of pre-impact and post-impact hydrologic data, usually from a dataset of mean daily stream gage data collected at the same location both before and after the construction of a dam or other water project. Because I analyzed two datasets from the same time period, I converted the data to a continuous time series for the IHA analyses. The simulated natural flow data for each location were assigned dates from water year 1984 to 2004 (both Julian day and year were preserved from the original data) and the stream gage data were assigned dates from water year 2005 – 2025 (Julian day was preserved but year was changed from the original data). Thus, simulated natural flow data were considered pre-impact and stream gage data were considered post-impact for these analyses.

I used IHA to investigate changes in the magnitude, duration, frequency, timing, and rate of change of flows in the Ashuelot and the West below each dam and for the combined effects of both dams near the mouth of each river. IHA analyses for most metrics were non-parametric because the hydrologic data were not normally distributed. Therefore, I examined differences in natural and gaged flows based on changes to median and quartile values of hydrologic parameters calculated by IHA (67 parameters total; Richter et al. 1996; The Nature Conservancy 2005). The only metric that was calculated using parametric statistics was the frequency of small and large floods, because parametric statistics allow the calculation of a flow that has a 50% probability of occurring in any year (equivalent to flows with ≥2-year recurrence interval). In addition, I compared the Range of Variability (RVA; Richter et al. 1997) of each hydrologic parameter calculated using natural streamflows with variability of regulated streamflows to examine changes in the annual distributions of flow statistics over the study period.

Because of the large number of parameters calculated by IHA, I only present results for the one parameter that showed the greatest difference between natural and gaged flows from each highly correlated parameter group (e.g., 1-day, 3-day, and 7-day maximum flow; Table 2). I examined changes in variation of parameters using RVA boundaries for a sub-set of IHA parameters (32 original IHA parameters listed in Richter et al. 1996; RVA boundaries are set at 33 and 67 percentiles). RVA boundaries are set at the 33 and 67 percentiles for the unimpaired flow data (i.e., 33% of the total annual observations for the unimpaired hydrograph should fall into each RVA category), and change in variability is assessed by examining the proportion of annual observations from the impaired hydrograph that fall in each RVA category (i.e., deviation from 33%). I examined changes in 25 and 75 percentiles for the unimpaired and impaired hydrographs for the remaining IHA parameters (metrics that represent Environmental Flow Components, or EFCs). All p-values presented in this analysis were "significance counts" calculated using IHA. IHA determines significance counts by performing a randomization test for each metric. All years of data are randomly re-arranged 1000 times, and the significance count is calculated as the percent of all simulations (out of 1000) that resulted in a deviation factor (percent change between pre-impact and post-impact medians and CVs) greater than the observed data. Significant counts were calculated for all IHA variables presented in this report, with the exception of flood frequency.

Principal Component Analysis

I used Principal Component Analysis (PCA) to examine correlations among hydrologic parameters calculated by IHA, and to identify groups of parameters that best explained annual variation in natural and gaged streamflows. I used annual median values of all IHA parameters calculated over the 20-year simulation period and 20-year period of stream gage data (40 observations total). I removed 12 variables from the analysis (peak, duration, timing, frequency, rise rate, and fall rate of large floods; peak, duration, timing, rise rate, and fall rate of small floods; number of days with zero flow) because there were few years with observations of these flow parameters. The remaining 55 variables were entered into the PCA analysis. I used loadings of the IHA parameters on the first two Principal Component axes (i.e., the two linear combinations of variables that explained the most variation in annual streamflow) to identify flow parameters that best explained annual variation in flow. These results were used to assist with selection of a subset of IHA variables to focus on in the analysis. In addition, I examined annual observations plotted with respect to the first two Principal Component axes for potential differences in variation of natural and gaged flows.

Results

Ashuelot River

The Ashuelot River and tributaries have a total of 15 impoundments listed in the National Inventory of Dams (Table 3). The total potential water storage from these impoundments is equal to 78,369 acre feet. Two flood control dams, Surry Mountain and Otter Brook, account for 88% of the total storage capacity of all impoundments in the Ashuelot basin. All impoundments in the Ashuelot basin combined are capable of storing up to 16% of the total annual water yield at the Hinsdale stream gage. All dams are operated as run-of-river except for Surry Mountain and Otter Brook. Surry Mountain and Otter Brook dams are generally operated as run-of-river except during flood control, although the dams may still have significant deviations from instantaneous run of river flow when they are not in flood control operations.

Comparisons of simulated natural flows and flows recorded by USGS stream gages below Surry Mountain and Otter Brook dams indicate changes in the frequency, magnitude, and duration of both low and high flows as a result of the impoundments, as well as changes in overall variability of the hydrograph. The frequency of floods (≥2 year recurrence interval based on natural flow simulations) has been nearly eliminated below both dams (Figure 1). Flows with a 2-year recurrence interval are roughly equivalent to bankfull flows, although the actual recurrence interval of bankfull discharge varies with geomorphology and hydrologic variability of the river (Gordon et al. 2004). Flows of a larger magnitude generally flow overbank and begin to inundate areas of the floodplain. Stream gage data indicated that these flood events occurred once below Surry Mountain Dam (a 94% decrease in frequency) and never occurred below Otter Brook Dam in the period between 1984 and 2004. The magnitude of the 1-day maximum flow for each river decreased by 44% ($p=0.01$) below Surry Mountain dam and 39% ($p<0.01$) below Otter Brook (Figure 2). However, the median duration of high flow pulses (the highest 10% of flows over the study period) increased below both impoundments, by 43% (from 3.5 to 5 days; $p<0.01$) below Surry Mountain and 17% (from 3 to 3.5 days; $p=0.02$) below Otter Brook (Figure 3), possibly due to extended water releases from flood control operations.

Minimum flows had greater proportional changes as a result of impoundment than maximum flows below both dams, although the magnitude of changes in minimum flows was comparatively small. The frequency of low flow pulses, defined as the lowest 10% of all flows over the study period, decreased by 50% ($p=0.08$) below Surry Mountain and 33% ($p=0.20$) below Otter Brook after impoundment (Figure 4). The magnitude of 1-day minimum flows increased (i.e., higher minimum flows) by 160% ($p=0.02$) below Surry Mountain dam and 186% ($p<0.01$) below Otter Brook (Figure 5). However, the duration of low flow pulses increased by 85% (from 3.25 to 6 days; $p<0.01$) below Surry Mountain and 100% (from 3 to 6 days; $p<0.01$) below Otter Brook (Figure 6).

The variability of the mean daily flow values for the Ashuelot below Surry Mountain and Otter Brook below Otter Brook dam generally decreased. Daily hydrograph reversals (the frequency of changes in flow between a rising and a falling period) declined by 53% ($p=0.28$) below Surry Mountain and 40% ($p<0.01$) below Otter Brook (Figure 7). Rate of change in flow did not increase below the dams, with median fall rate (the difference in flow between consecutive daily values during a falling period) decreasing by 43% below Surry Mountain ($p=0.02$; Figure 8) and 5% below Otter Brook ($p=0.58$; Figure 8). Timing of the 1-day maximum flow did not change downstream of either Surry Mountain (1% change; $p=0.81$; Figure 9) or Otter Brook (2% change; $p=0.80$; Figure 9).

The overall pattern of decreased magnitude and frequency of maximum flows and frequency of minimum flows, increased magnitude of minimum flows, and decreased hydrograph reversals suggests lower flashiness and variability in flows below both dams. However, we only analyzed variability and rate of change using mean daily flows. The use of daily means may mask shorter-term flow fluctuations that could potentially be examined using hourly or 15-minute flow data. Although diurnal flow fluctuations outside of natural variation have not been observed for the Ashuelot River, such flow fluctuations have been observed on the West River below Ball Mountain Dam (Figure 10). We did not examine flow variability on a sub-daily basis because (1) sub-daily data cannot be analyzed using IHA, and (2) we did not have sub-daily data that represented natural flow conditions (either simulated or from USGS stream gages).

Changes to high flows and flow variability in the Ashuelot River as a result of both Surry Mountain and Otter Brook Dam persist downstream. The magnitude of most other changes is dampened, particularly alterations of low flows, likely due to inflow from tributaries. Bankfull and overbank flows are still nearly nonexistent approximately 30 river miles downstream from both dams at the Hinsdale gage, near the confluence with the Connecticut River. Flood events with a 2-year return interval under natural conditions occurred twice during the 20 year period (an 88% decrease in frequency) based on stream gage observations (Figure 1). The median magnitude of 1-day maximum flows decreased by 24% (p=0.10; Figure 2) and the duration of high flow pulses increased by 14% (p=0.32; Figure 3). The median magnitude of 1-day minimum flows increased by 5% (p=0.68) as a result of the dams (Figure 5). There was no significant change in either the median frequency of low flow pulses (0% change; p=0.87; Figure 4) or the duration of low flow pulses (31% change; p=0.59; Figure 6). The number of hydrograph reversals decreased by 14% (p=0.01; Figure 7). Fall rate (6% decrease; p=0.80; Figure 8) and timing of the 1-day maximum flow (2% change; p=0.80; Figure 9) were relatively unchanged.

PCA analyses indicated that the largest proportion of variation in annual median values of IHA parameters below Surry Mountain and Otter Brook Dams was explained by magnitude of maximum flows, magnitude of minimum flows, and frequency of low flow pulses (i.e. these variables had the highest loadings on the first two Principal Component axes). Annual median values for simulated natural flows and regulated flows were clearly separated when flow observations were plotted on the first two Principal Component axes for Surry Mountain Dam, indicating that hydrologic variables explaining annual variation in natural flows were different from variables explaining variation in regulated flows (Figure 11). A separation between regulated and natural flows was less clear for Otter Brook Dam (Figure 11). Most of the variation in natural flows below Surry Mountain was explained by magnitude of maximum and minimum flows, whereas natural flow variability below Otter Brook was explained by magnitude of maximum flows. Variation in annual median values for regulated flows below Surry was not related to variables with high factor loadings. Variation in regulated flows below Otter Brook was best explained by magnitude of minimum flows, frequency of low flow pulses, and fall rate. I used the variables with high factor loadings in the PCA analyses to help choose which variables to analyze more closely using IHA. In addition, the PCA analysis helped to identify which IHA variables were highly correlated.

West River

The West River and tributaries have a total of 13 major impoundments (Army Corps of Engineers National Inventory of Dams; Table 4) and total potential water storage equal to

144,773 acre feet. Two flood control dams, Ball Mountain and Townshend, account for 96% of the total storage capacity of all impoundments in the West River basin. The combined maximum storage for all impoundments in the West basin is 31% of the total annual water yield at the Newfane stream gage. All dams are operated as run-of-river except for Ball Mountain and Townshend. Ball Mountain and Townshend are generally operated as run-of-river except during flood control, although the dams may still have significant deviations from instantaneous run of river flow when they are not in flood control operations. Because of difficulties calculating simulated natural flows below Townshend dam (USACE in press), results for hydrologic analyses below Ball Mountain dam should be considered more accurate.

Differences between simulated natural and regulated daily flows for stream gages below Ball Mountain and Townshend dams on the West River are similar to flow alterations below impoundments on the Ashuelot River. Impoundments on the West River have resulted in changes to the frequency, magnitude, and duration of both high and low flows. In addition, my analysis suggests changes in overall flow variability and rate of change of the hydrograph. Similar to the Ashuelot River, bankfull and overbank flows have been nearly eliminated below both impoundments (Figure 1). Flow events with a 2-year return interval based on natural flow simulations occurred three times below Ball Mountain Dam (a 77% decrease in 2-year flood frequency) and once below Townshend dam (a 92% decrease) over the 21-year analysis period. The magnitude of the median annual 1-day maximum flow decreased by 17% ($p=0.01$) below Ball Mountain and 25% ($p=0.01$) below Townshend (Figure 2). Median high pulse duration increased below Ball Mountain (2 days for natural flows and 2.5 for regulated flows; $p=0.06$; Figure 3) and Townshend (2 days for natural flows and 3 days for regulated flows; $p<0.01$; Figure 3).

Minimum flows increased below both dams relative to natural flow simulations. Similar to the results for the Ashuelot River, the magnitude of changes in minimum flows were small compared with changes in maximum flows, although proportional changes in minimum flows were large. The median frequency of low flow pulses (the lowest 10% of all flows during the study period) decreased by 57% (from 7 to 3 annually; $p=0.03$) below Ball Mountain dam and by 38% (from 8 to 5 annually; $p=0.23$) below Townshend dam (Figure 4). The magnitude of the median annual 1-day minimum flow increased by 83% ($p<0.01$) below Ball Mountain and 36% ($p=0.15$) below Townshend. The median duration of low flow pulses generally stayed constant below Ball Mountain (11% increase; $p=0.77$; Figure 6) and Townshend dams (0% increase; $p=0.28$; Figure 6).

Variability of daily median flows has decreased below both dams on the West River. Hydrograph reversals have decreased by 38% ($p<0.01$) below Ball Mountain and 27% ($p<0.01$) below Townshend (Figure 7). In contrast to the Ashuelot River, the rate of change in flows has increased. Fall rate increased by 29% ($p=0.02$) below Ball Mountain and 34% ($p=0.02$) below Townshend (Figure 8). Timing of the 1-day maximum flow did not change downstream of either Ball Mountain (1% change; $p=0.82$; Figure 9) or Townshend (1% change; $p=0.86$; Figure 9).

The overall pattern of changes in flows below Ball Mountain and Townshend dams is similar to the pattern below the flood control dams on the Ashuelot. Generally, extreme high and low flows do not occur or occur less frequently below the impoundments. The decrease in hydrograph reversals suggests that flows are more stable. However, the analysis of reversals and fall rate only examine changes in daily mean values. Daily means may mask substantial sub-daily flow fluctuations, such as fluctuations observed below Ball Mountain Dam (Figure 10).

The effects of Ball Mountain and Townshend dams on the magnitude of maximum and minimum flows persisted 20 miles downstream from Townshend dam at the mouth of the West River. However, high and low flow duration, low flow frequency, flow variability, rate of change, and timing of maximum flows were not significantly different between natural and regulated flows at the river mouth. Bankfull and overbank flows were still rare, with two flow events equivalent to a flood with a 2-year return interval occurring during the study period (a decrease of 83%; Figure 1). The median magnitude of annual 1-day maximum flows decreased by 27% (p=0.02; Figure 2) at the mouth compared to a natural hydrograph, although the duration of high pulses did not change (3 days for both natural and regulated flows; p=0.26; Figure 3). The magnitude of 1-day minimum flows increased by 64% (p=0.01; Figure 5). The frequency of low flow pulses (6 per year for both natural and regulated flows; p=0.53; Figure 4) and duration of low flow pulses (3-day duration for natural and 3.75 for regulated flows; p=0.19; Figure 6) did not change. Hydrograph reversals decreased by 8% (p=0.32; Figure 7) and median fall rate decreased by 22% (p=0.25; Figure 8) compared with natural flows, although these changes were not significant. Timing of 1-day maximum flows did not change (0% change; p=0.94; Figure 9).

PCA analyses for flows below Ball Mountain and Townshend dams indicated that the largest proportion of variation in annual median values of IHA parameters was explained by magnitude of maximum flows, magnitude of minimum flows, and frequency of low flow pulses. These IHA parameters were the same that explained variation in flows in the Ashuelot River. Median values for natural and regulated flows were not clearly separated for either dam when annual flow statistics were plotted on the first two Principal Component axes, although some separation was evident with respect to magnitude of maximum flows (Figure 11). Thus, variation in natural flows was explained by the magnitude of high flow events, whereas variation in both natural and regulated flows was explained by the magnitude of low flows, frequency of extreme low flows, and magnitude, frequency, and duration of high pulses. As with the Ashuelot analysis, PCA results were used to help guide selection of variables to examine closely using IHA.

Discussion

Hydrologic change

The most dramatic change in the hydrographs for both rivers was the near elimination of bankfull and overbank flows, measured by the lack of floods with a 2-year or greater recurrence interval and a decrease in the magnitude of maximum flows. Likewise, the magnitude of minimum flows increased in both rivers (i.e. low flows were not as low after regulation), although the frequency of low flow pulses (Q90) only decreased below Ball Mountain Dam on the West River. These trends were matched by increased duration of both high (Q10) and low flow pulses in the Ashuelot, whereas the West River only showed increased duration of high flow pulses. Although flow variability (measured by daily flow reversals, or the frequency of changes in flow from a rising to a falling period, and vice versa) decreased for both rivers and rate of change in flow (measured by fall rate, or the median difference in flow between consecutive daily values during a falling period) increased in the West River, these results are based on daily mean flows and may be misleading. In fact, flow variability and rate of change apparently increased for the West River below Ball Mountain Dam, based on a comparison of hourly flows in the West River and a neighboring unregulated river (Saxtons River). Overall, flood control dams on the Ashuelot and West rivers have altered the magnitude, duration, and frequency of both high and low flows, and likely the variability and rate of change of the hydrograph. Although the degree and spatial extent of specific changes to stream flows varied for each river and below each dam, the general effect of the dams in both basins was the reduction or elimination of extreme high and low flows.

Ecological implications

The most dramatic hydrologic alteration in both the Ashuelot and West Rivers was the reduction of high flows that would typically inundate floodplains. Thus, species and communities found in floodplains are likely to be impacted by flow alterations in both rivers. A report synthesizing published literature that linked hydrologic alteration and ecosystem response in the Connecticut River and its tributaries discussed potential effects of reductions in high flows on floodplain ecosystems (Zimmerman 2006). Flow needs of floodplain communities based on Zimmerman's (2006) report are outlined below. Most of the literature addressing flow needs of floodplain communities examines timing and frequency of flooding. However, historical patterns of flood frequency can be used to determine flood magnitude at various recurrence intervals.

Timing of floods

- Good conditions for germination occur when fuitfall and seed dispersal coincide with receding spring floods (Dixon 2003).
- The length of a species' dispersal period is likely related to its sensitivity to the timing and duration of floods (Dixon 2003). The relatively short dispersal period for maples suggests that timing of flows may be more critical for maple recruitment than species with longer dispersal periods (see Zimmerman 2006, Table 4 for periods of seed dispersal for tree species commonly found on floodplains).
- High flows that occur after seed germination may cause erosion or anoxic conditions, leading to reductions in seedling densities (Dixon 2003).

Flood frequency, magnitude, and duration

- Riparian communities in areas that receive mechanical damage from frequent flooding, erosion, and scour tend to be dominated by seedlings and herbaceous species, whereas higher floodplain sites are dominated by mature trees (Metzler and Damman 1985). Areas that are currently dominated by seedlings may eventually become mature floodplain forest because of the dynamic nature of river channels and changing geomorphology.
- The silver maple-sensitive fern riverine floodplain forest is the wettest floodplain forest type and is adapted to annual flooding of relatively long duration (Eric Sorenson, Vermont Agency of Natural Resources, personal communication).

- The silver maple-ostrich fern riverine floodplain forest has more sandy soils with better drainage and may only flood once every few years, or for shorter periods each year (Eric Sorenson, Vermont Agency of Natural Resources, personal communication).
- The sugar maple-ostrich fern riverine floodplain forest is flooded infrequently, possibly once every few years or more (Eric Sorenson, Vermont Agency of Natural Resources, personal communication).
- A study conducted on a tributary to Lake Champlain in Vermont indicated that large floods (> 5 year recurrence interval) are crucial for recruitment of floodplain species whereas smaller floods (e.g., 2-year recurrence interval) are important for maintenance of existing communities (Hughes and Cass 1997). Periodic recruitment events, in addition to maintenance of existing communities, are needed for long-term persistence of floodplain forests.

The above flow needs of floodplain communities suggest that the lack of overbank flows along both the Ashuelot and West Rivers will result in a net loss of the extent of floodplain forests and a potential change in species composition. Although the above hydrologic analysis indicates that overbank flows are rare or have been eliminated along both rivers, site-specific surveys are needed to determine whether low-lying areas along either river continue to flood, and the frequency of flooding in these locations. However, the lack of flooding indicates that the spatial extent of flood-prone areas has greatly decreased, and the flood frequency, magnitude, and duration have likely decreased in areas that do still flood. These patterns may result in shifts in floodplain communities to species more tolerant of drier conditions and species that are better competitors for space and light. It is likely that mature floodplain forests exist in areas that no longer flood or have had a shift in the flood regime; however, regeneration may not occur in these areas if conditions required for germination are not met.

In addition to floodplain forests, overbank flows are required to maintain habitat for the cobblestone tiger beetle, a species listed as threatened in Vermont and New Hampshire. Habitat for the cobblestone tiger beetle is primarily cobble and sand beaches (New Hampshire Fish and Game Department 2005), and the species is found along the West River. Habitat for the cobblestone tiger beetle is flooded regularly, with floods and ice scour maintaining substrate texture on beaches and removing encroaching vegetation. Flood control dams have inundated potential habitat and decreased the frequency and duration of floods that scour vegetation and maintain cobble and sand beaches (Leonard and Bell 1999; New Hampshire Fish and Game Department 2005). Potential elimination of ice jams by the Army Corps of Engineers is another possible threat because ice jams also scour vegetation from cobble shores (New Hampshire Fish and Game Department 2005).

Short-term flow fluctuations are another potential threat to both riparian and aquatic species in the West River. Short-term flow fluctuations below dams may periodically inundate cobble and sand beaches during natural low-flow periods and may decrease survival of adult and larval cobblestone tiger beetle (New Hampshire Fish and Game Department 2005). Periodic inundation of beaches reduces the availability of stable beach habitat for foraging adults during normal low-flow periods. A study by Bain et al. (1988) found that the magnitude and frequency of within-day flow variation below a dam also affects the structure of the fish community. The habitat types used by most fish species in the West River were shallow- and slow-water habitats found along the river margin. Within-day flow fluctuations essentially eliminate river shorelines as functional habitat for the species that used these areas. Species that used habitat along the river's edge were often seen stranded in small, isolated pools after rapid decreases in discharge. Increased within-day flow variability may also lead to stranding of mussels or high water temperatures near the river's edge that decrease mussel abundance or reproductive potential (Vaughn and Taylor 1999). In addition to direct effects of flow variability on mussels, host fish species necessary for reproduction of mussels are usually found in these shallow water zones, and abundance of these species may be greatly decreased due to stranding or elimination of shallow- and slow-water habitats.

Increased magnitude of low flows (i.e., higher 1-day minimum flow) was also identified as a change in the flow regime that has occurred below dams on both rivers. This pattern suggests that mean 1-day minimum flows are higher than they would be if the dams were not present; however, it is possible that shorter-term low flows (i.e., instantaneous or hourly minimum flows) are lower below dams on the Ashuelot and/or West and these trends are not detectable with mean daily flow data. For example, flows may be reduced well below natural low flow discharge for periodic tunnel inspections at Ball Mountain dam. These tunnel inspections may only last one or two hours, after which flows may increase dramatically. Such short-term low flows may not be detectable in mean daily flow data but have the potential to adversely affect aquatic species, mainly by stranding fish and invertebrates that inhabit shallow areas near stream margins.

I am not aware of any studies that have examined the effects of increased low flows on stream communities in the northeast U.S. However, species that depend on habitat that is primarily available during summer low flow periods may be adversely affected by increased low flows. For example, adult cobblestone tiger beetles forage in cobble beach habitat that is maintained by spring high flows and exposed during low flow periods in the summer. Less cobble beach habitat may be available if the increased magnitude of low flows also increases water level in these areas. However, mean flows for the summer months did not change significantly with the dams in place. Thus, lows flows may not have changed enough to decrease availability of beach habitat throughout the summer. It is likely that decreased magnitude and frequency of high flows has a greater impact on availability of beach habitat because the lack of inundation and scour may lead to vegetation encroachment on beaches. Site-specific hydraulic and/or habitat modeling and geomorphic assessment would be needed to determine the amount of beach habitat available under different flow scenarios.

Recommendations

Based on the results of the hydrologic analysis and the ecological implications of these changes in hydrology, I recommend that any plans for flow restoration focus on reintroducing flows that inundate floodplain areas along both rivers, and eliminating unnatural diurnal flow fluctuations in the West River below Ball Mountain dam. In addition, I recommend that instantaneous inflows to reservoirs should be equal to outflows (i.e., run-of-river) when the dams are not in flood control operations to ensure that short-term reductions (i.e., shorter than one day) or fluctuations in flow do not result in stranding of fish or invertebrates.

The Ashuelot and West Rivers are excellent sites for experimental flow releases and associated research on links between flow and ecological response. The following hypotheses may be addressed by modifying dam operations and combining experimental releases with site-specific field research:

- Releases of high flows designed to inundate floodplain sites in early spring will result in increased germination of floodplain forest species (e.g., silver maple). For target species with periods of fruitfall in the spring, releases should be timed so that floods are receding as species begin seed drop.
- Controlled flood releases will help maintain river and floodplain landforms, thus providing or enhancing habitat for aquatic and riparian species. For example, high flows will scour vegetation from sandy beaches and deposit alluvial soils at some floodplain sites.
- Decreased short-term flow fluctuations will increase abundance of mussels and fish species that prefer stream margin habitat.
- Decreased short-term flow fluctuations will result in a fish community with a higher proportion of fluvial specialists and a lower proportion of habitat generalists.
- Flood releases and decreased short-term flow fluctuations will increase the amount of habitat available for the cobblestone tiger beetle.

Monitoring of geomorphic and ecological response to experimental flow releases or occasional natural floods will allow for assessment and refinement of the above hypotheses. Little information is available linking hydrologic alteration with ecological response for the northeast compared with other areas of the U.S. (Zimmerman 2006). Research and monitoring on the Ashuelot and West rivers will likely develop relationships between changes in river flow and riparian and aquatic communities that will be applicable to other rivers in the Connecticut River basin, and potentially to other river basins in the eastern U.S.

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Table 1. USGS stream gage locations for the Ashuelot River, New Hampshire and West River, Vermont.

River basin	*Gage ID*	*Location*	*Drainage area (mi^2)*	*Period of Record*
Ashuelot	1158000	Ashuelot below Surry Mtn. dam	100.0	1945-2003
Ashuelot	1158500	Otter Book near Keene	42.3	1923-1958
Ashuelot	1158600	Otter Brook below Otter Brook dam	47.2	1958-2003
Ashuelot	1160350	Ashuelot at West Swanzey	316.0	1994-2003
Ashuelot	1161000	Ashuelot at Hinsdale	420.0	1907-2003
West	1155500	West at Jamaica	179.0	1946-2003
West	1155910	West below Townshend dam	278.0	1994-2000
West	1156000	West at Newfane	308.0	1919-1989

Table 2. Individual flow metrics chosen for analysis of hydrologic alteration within each parameter group calculated by the Indicators of Hydrologic Alteration (IHA) software. Principal Components Analysis (PCA) indicated that flow metrics within each parameter group were highly correlated. Therefore, one metric (with the largest difference between natural and regulated flow conditions) was chosen from each group to represent changes in hydrology. All metrics were calculated using non-parametric statistics except where noted.

IHA parameter group	*Flow metric*	*Description*
Maximum flow frequency	Frequency of small and large floods	Count of flows with ≥ 2 year recurrence interval over the period of record (flows with a 50% probability of occurring each year, calculated using parametric statistics)
Maximum flow magnitude	1-day maximum flow	Maximum daily flow recorded, on an annual basis
Maximum flow duration	High pulse duration	Median flow plus 40%, equivalent to Q10
Minimum flow frequency	Low pulse duration	Median flow minus 40%, equivalent to Q90
Minimum flow magnitude	1-day minimum flow	Minimum daily flow recorded, on an annual basis
Minimum flow duration	Low pulse duration	Median flow minus 40%, equivalent to Q90
Variability (among-day)	Reversals	Count of daily changes between a rising and a falling limb of the hydrograph
Rate of change (among-day)	Fall rate	Difference in flow between consecutive daily values during a falling period
Timing	Timing of maximum flows	Median date of the 1-day maximum flow

Table 3. Major dams on the Ashuelot River and tributaries. Data from the National Inventory of Dams and New Hampshire Fish and Game Department.

Dam name	*River*	*City*	*Date of completion*	*Max Storage (acre feet)*	*Drainage area (mi^2)*	*Owner*	*Purpose*
May Pond (aka Butterfiels)	Ashuelot	Washington	1934	590	7.1	DRED	Recreation
Ashuelot Pond	Ashuelot	Washington	1872	4000	27	LAE Association	Recreation
Village Pond	Ashuelot	Marlow	1922	275	35	Audio Accessories Inc.	Recreation
Surry Mountain	Ashuelot	Surry	1941	44000	100	Army Corps of Engineers	Flood control and recreation
Ashuelot River	Ashuelot	Keene	1919	280	113	City of Keene	Recreation
Homestead Woolen Mill[a]	Ashuelot	Swanzey	1910	270	316	Homestead Woolen Mills	Other
Ashuelot Paper	Ashuelot	Hinsdale	1905	220	410	HDI Associates III	Hydroelectric
Lower Robertson	Ashuelot	Hinsdale	1905	100	406	HDI Associates III	Hydroelectric
Fiske Mill Hydro	Ashuelot	Hinsdale	1922	90	418	Fisk Mill Hydro	Hydroelectric
Otter Brook Dam	Otter Brook	Keene	1958	24800	47	Army Corps of Engineers	Flood control and recreation
Goose Pond	Unnamed tributary	Keene	1946	606	2	City of Keene	Recreation
Millen Lake	Unnamed tributary	Washington	1970	1348	1	Millen Lake Association	Recreation
Long Pond	Unnamed tributary	Lempster	1922	637	1	Town of Lempster	Recreation
Forest Lake	Unnamed tributary	Winchester	1925	378	7	Forest Lake Improvement Association	Recreation
Sand Pond	Unnamed tributary	Marlow	1925	775	1	Sand Pond Association	Recreation

[a] In the process of being removed

Table 4. Major dams on the West River and tributaries. Data from the National Inventory of Dams and Vermont Agency of Natural Resources, Department of Environmental Conservation.

Dam name	*River*	*City*	*Date of completion*	*Max Storage (acre feet)*	*Drainage Area (mi^2)*	*Owner*	*Purpose*
Weston Mill	West	Weston				Weston Community Club	Fire protection, stock, or farm pond
Williams	West	Londonderry	1900	75	44	Town of Londonderry	Other
Ball Mountain	West	Jamaica	1961	84240	172	Army Corps of Engineers	Flood control
Townshend	West	Townshend	1961	54300	278	Army Corps of Engineers	Flood control, recreation
Lowell Lake	Unnamed tributary	Londonderry	1850	1475	2	State of Vermont - FPR	Recreation
Wantastiquet Lake	Unnamed tributary	Weston	1880	530	17	Wantastiquet Trout Club	Recreation
Gale Meadows	Mill Brook	Londonderry	1965	2942	10	State of Vermont - DFW	Recreation
Hapgood Pond	Flood Brook	Peru	1939	86	4	USDA Forest Service	Recreation
Burbee Pond	Turkey Mountain Brook	Windham	1920	220	4	Ernest K. Friedli	Recreation
Sunset Lake	Stickney Brook	Marlboro	1910	680	1	Town of Brattleboro	Water supply
Stickney Brook Diversion	Stickney Brook	Dummerston					Water supply
Stratton Mountain Lake	North Branch Brook tributary	Winhall	1977	300	2	Stratton Corporation	Recreation
Gulf Brook Reservoir	Gulf Brook	Stratton	1975	120	0.25	Stratton Corporation	Other

Figure 1. Annual frequency of bankfull and overbank flows (≥2-year recurrence interval). Note that flood frequency was the only metric calculated using parametric statistics.

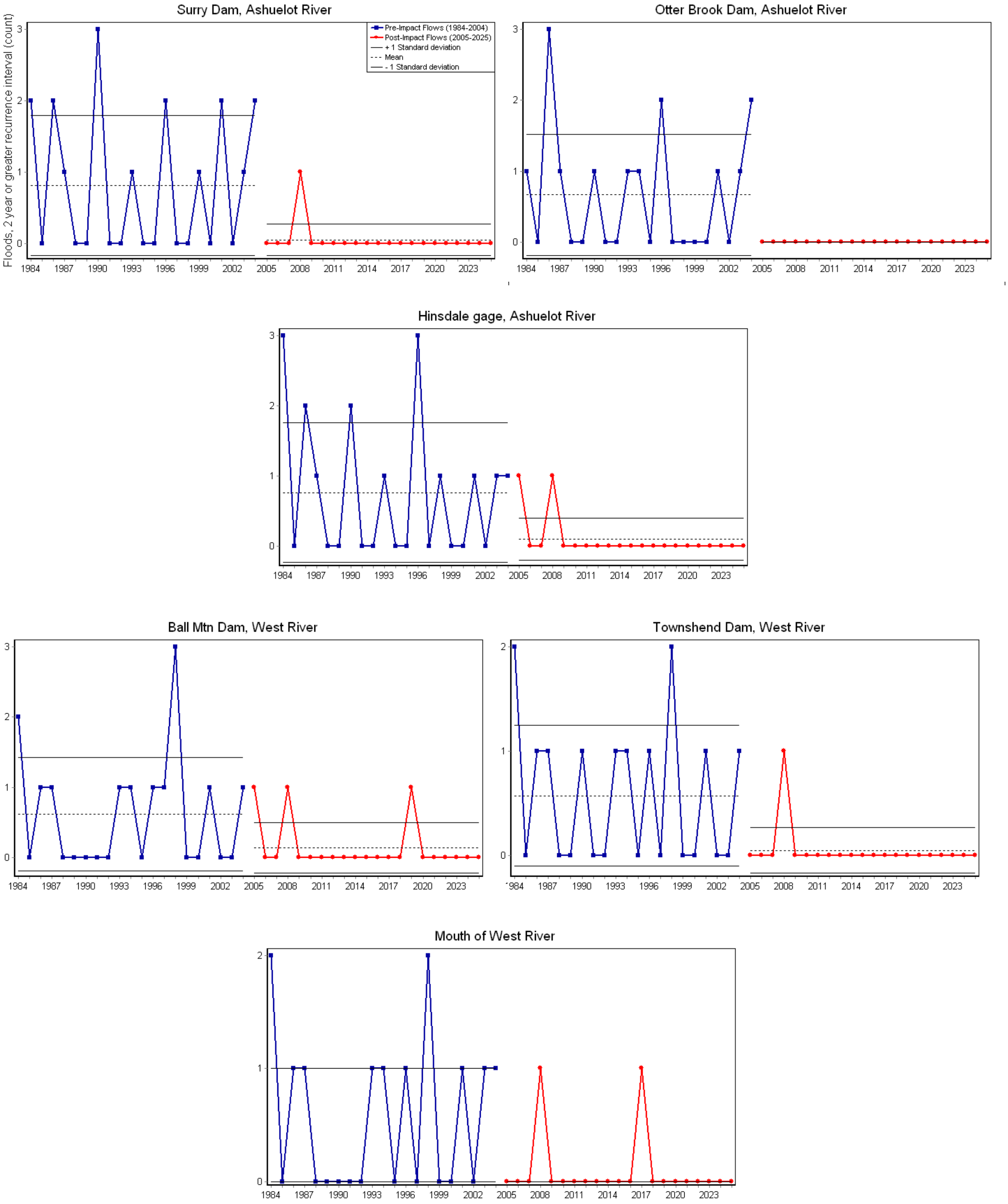
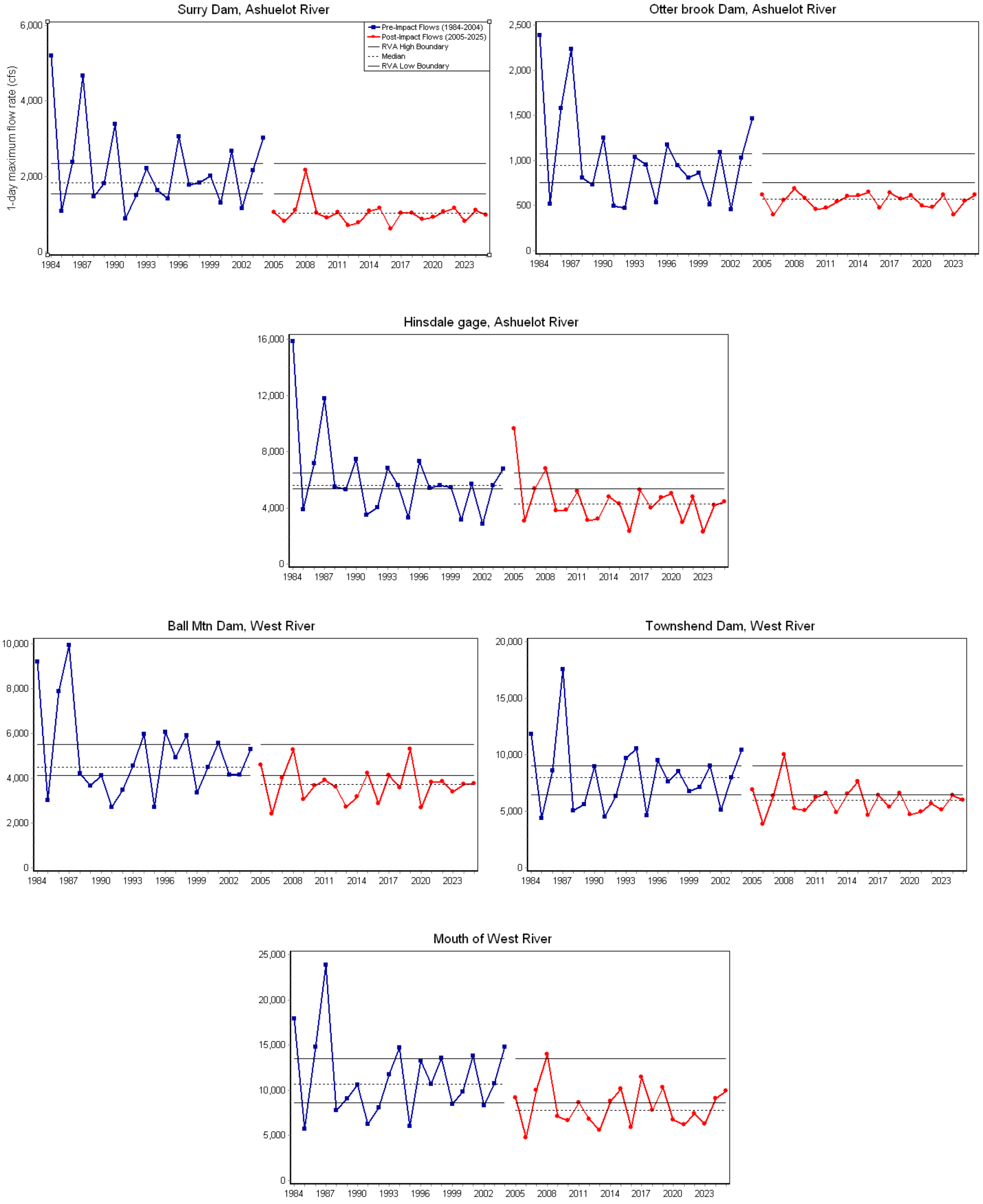


Figure 2. Magnitude of high flows (1-day maximum).



Surry Dam, Ashuelot River

Otter brook Dam, Ashuelot River

Hinsdale gage, Ashuelot River

Ball Mtn Dam, West River

Townshend Dam, West River

Mouth of West River

Figure 3. Duration of high flow pulses. High flow pulses were calculated as 40% above the median and are equivalent to the Q10, or the flow magnitude that is exceeded 10% of the time.

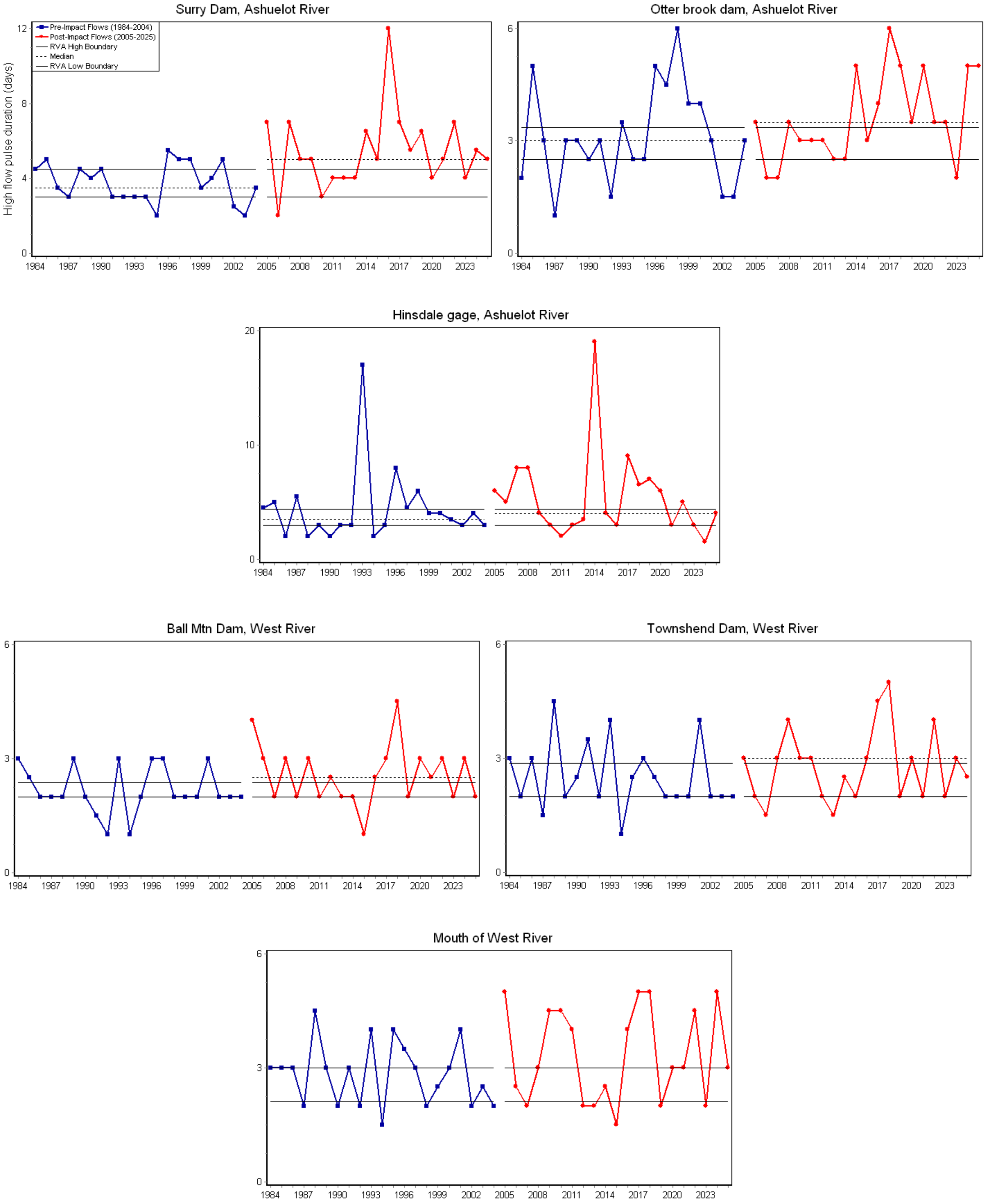
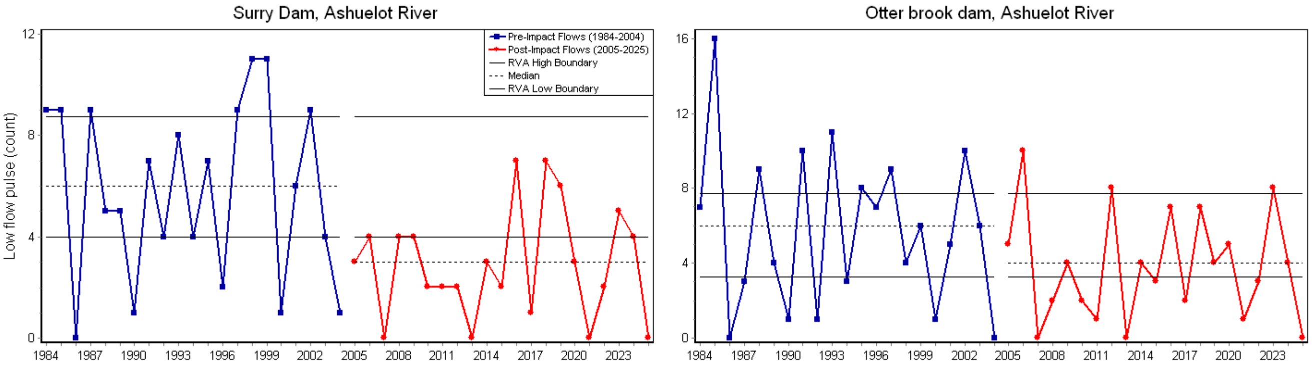
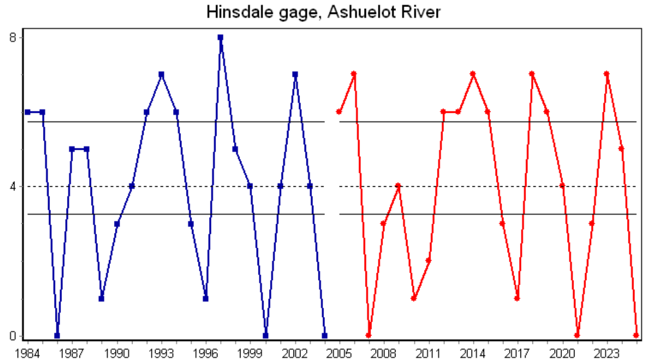
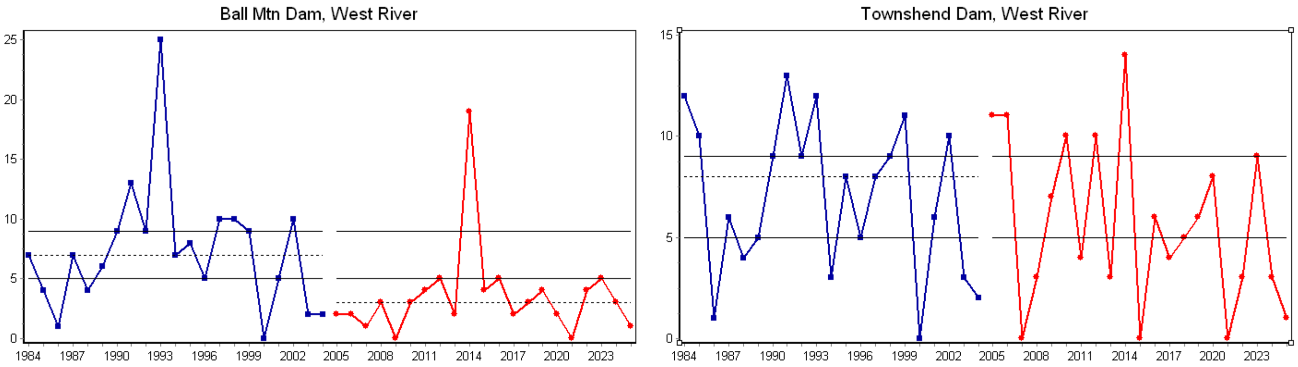


Figure 4. Frequency of low flow pulses. Low flow pulses were calculated as 40% below the median and are equivalent to the Q90, or the flow magnitude that is exceeded 90% of the time.


Surry Dam, Ashuelot River

Otter brook dam, Ashuelot River


Hinsdale gage, Ashuelot River


Ball Mtn Dam, West River

Townshend Dam, West River

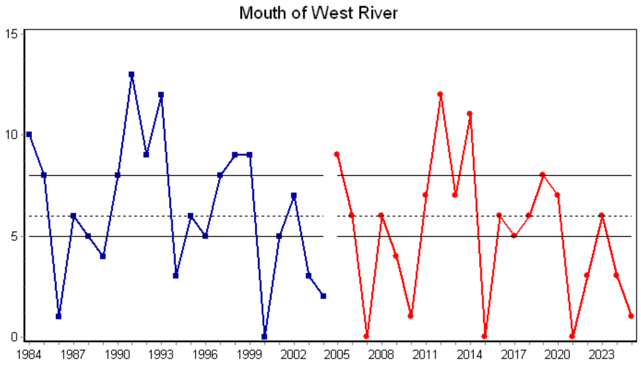

Mouth of West River

Figure 5. Magnitude of low flows (1-day minimum).

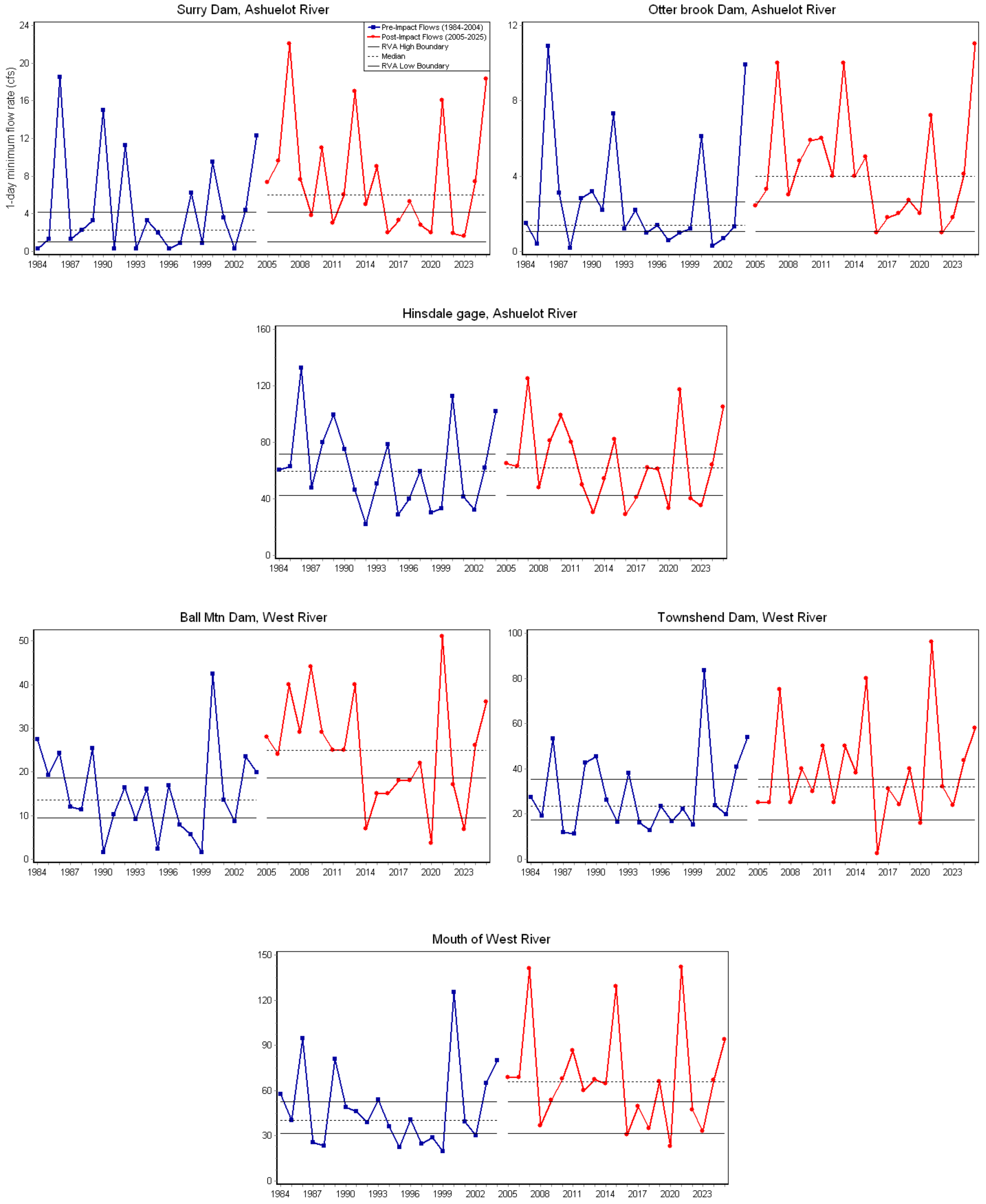
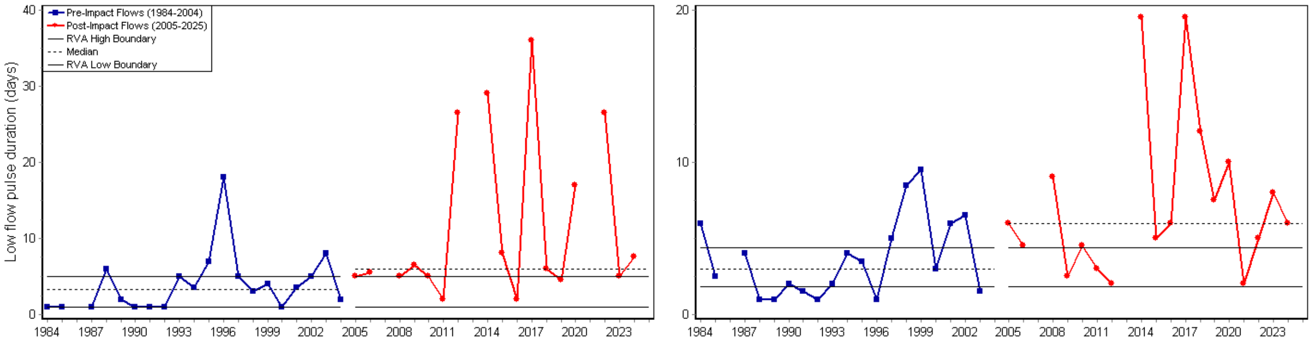


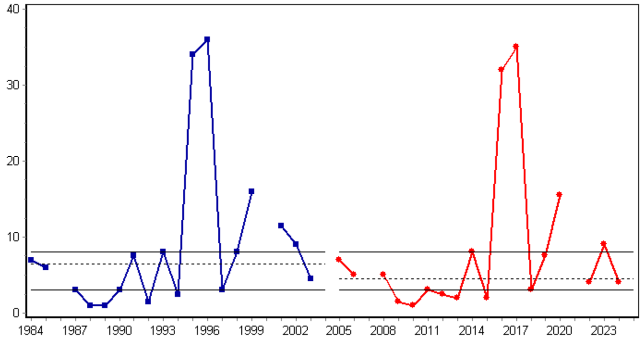
Figure 6. Duration of low flow pulses. Low flow pulses were calculated as 40% below the median and are equivalent to the Q90, or the flow magnitude that is exceeded 90% of the time. Years with missing values did not have any flows classified as low flow pulses.

Surry Dam, Ashuelot River

Otter brook dam, Ashuelot River

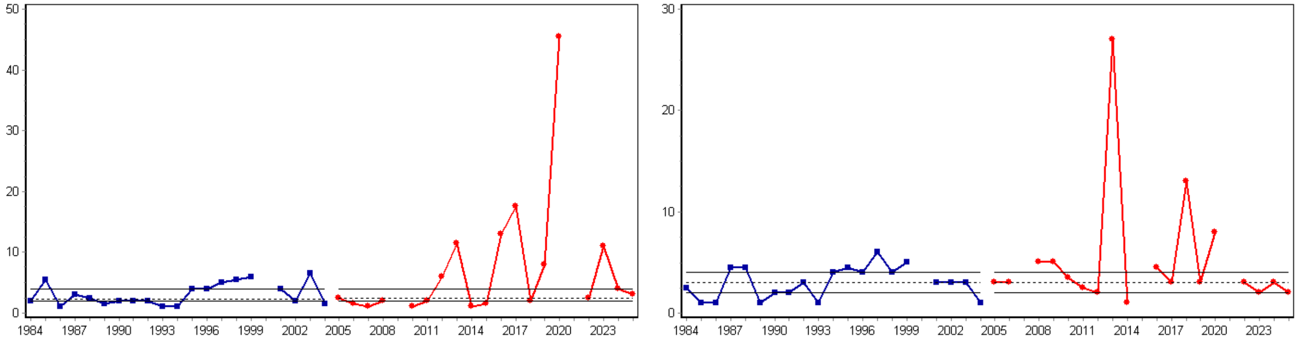


Hinsdale gage, Ashuelot River



Ball Mtn Dam, West River

Townshend Dam, West River



Mouth of West River

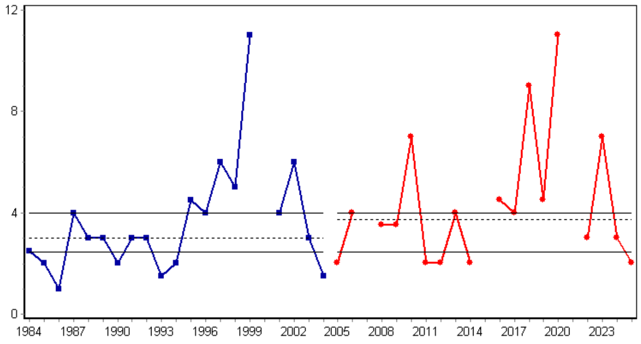


Figure 7. Variability among days (reversals).

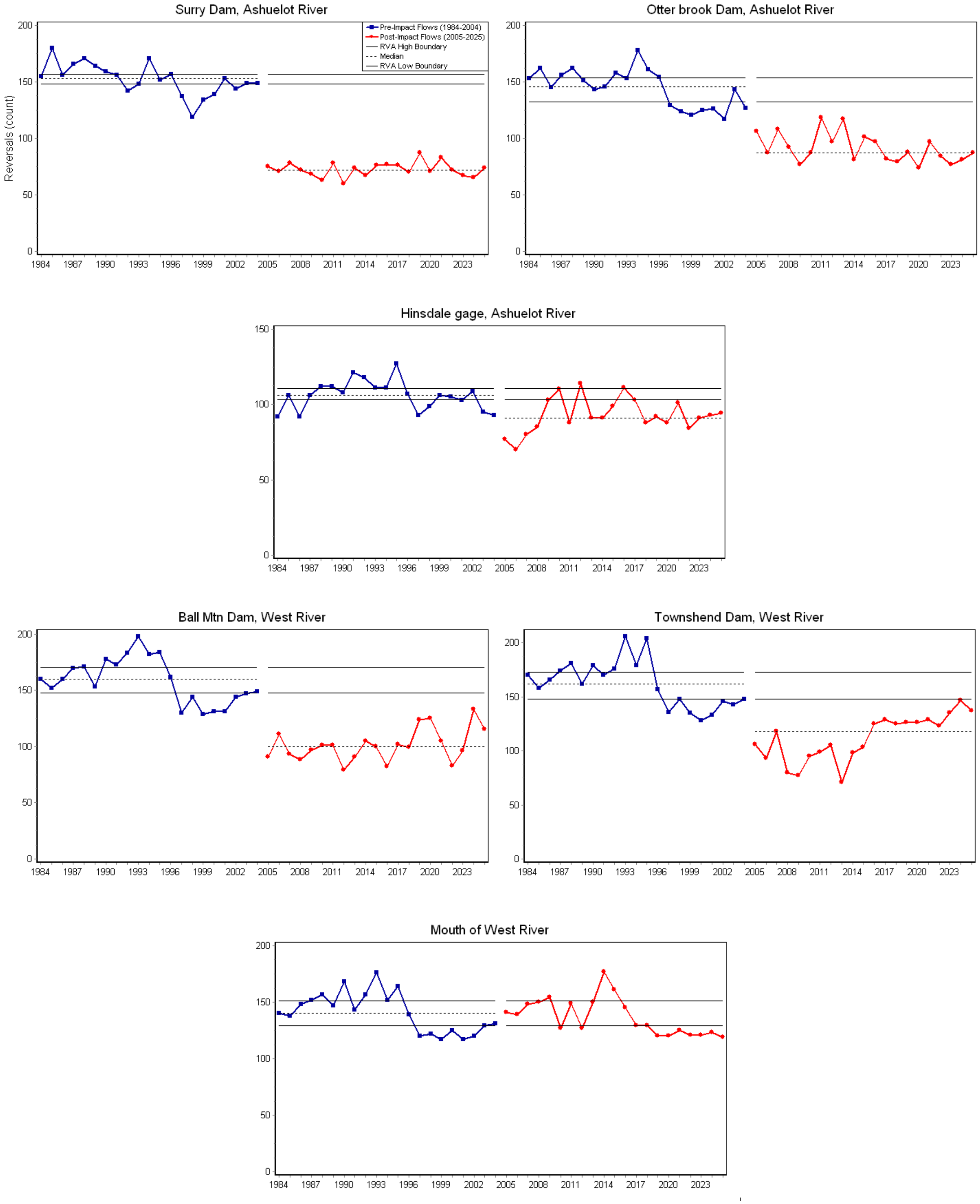


Figure 8. Rate of change among days (fall rate).

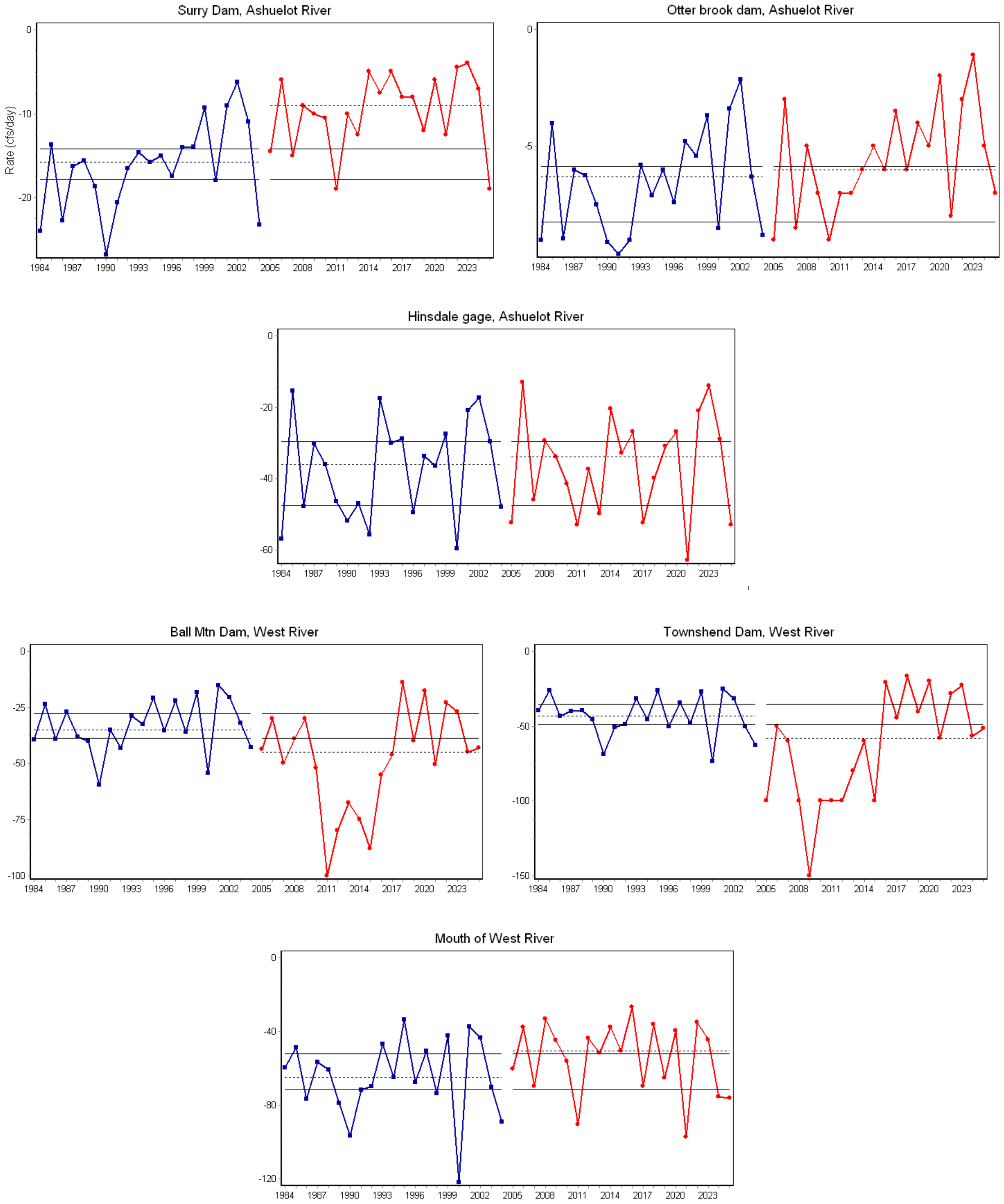
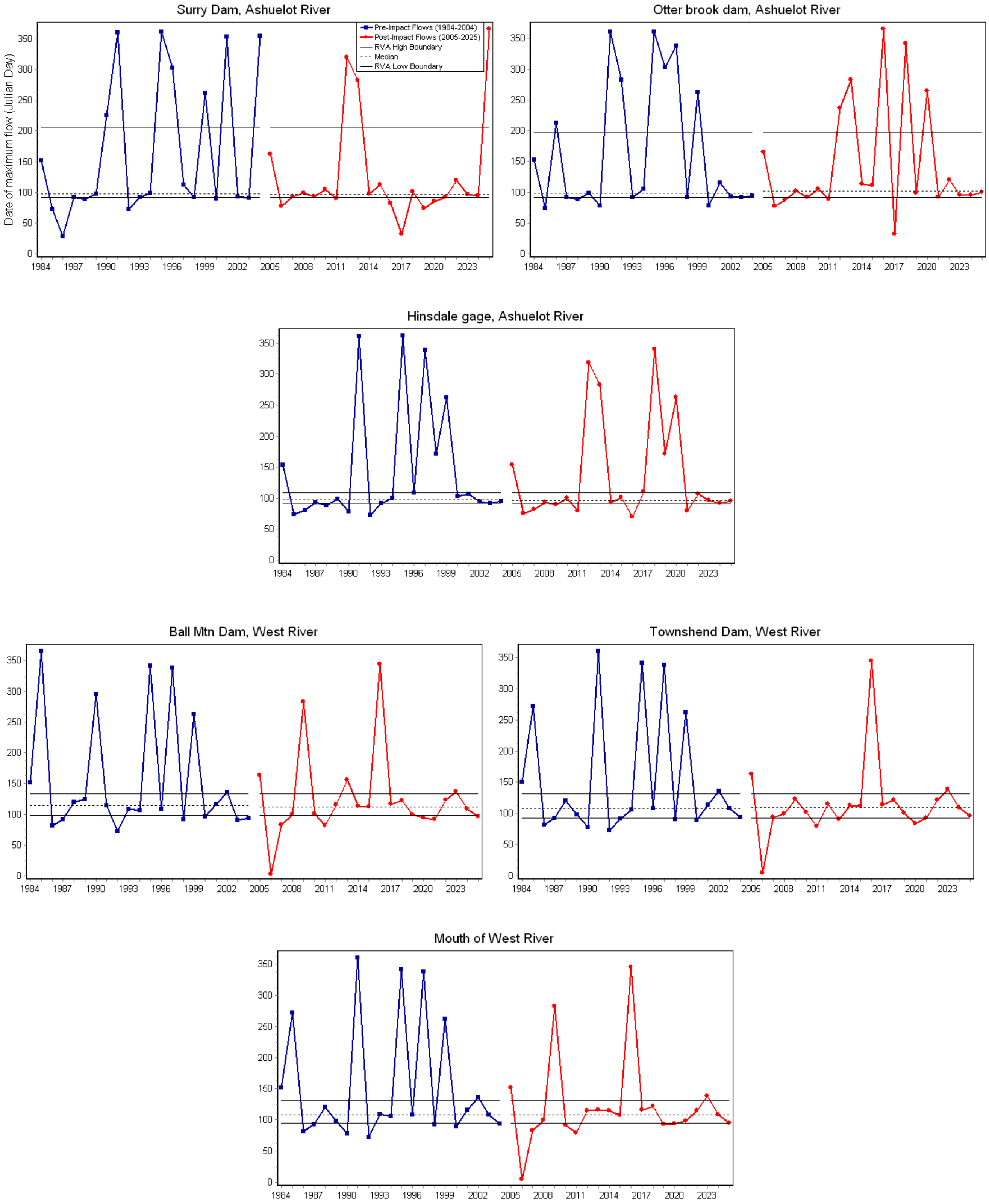


Figure 9. Timing of maximum flow (median Julian date of 1-day maximum).


Surry Dam, Ashuelot River

Otter brook dam, Ashuelot River

Hinsdale gage, Ashuelot River

Ball Mtn Dam, West River

Townshend Dam, West River

Mouth of West River

Figure 10. Example of diurnal flow fluctuations for the West River below Ball Mountain Dam, compared with the Saxtons River, a neighboring unregulated watershed to the north. Discharge for both rivers has been adjusted for basin area (csm = cubic feet per second per square mile). Data are from Brian Fitzgerald, Vermont Agency of Natural Resources.

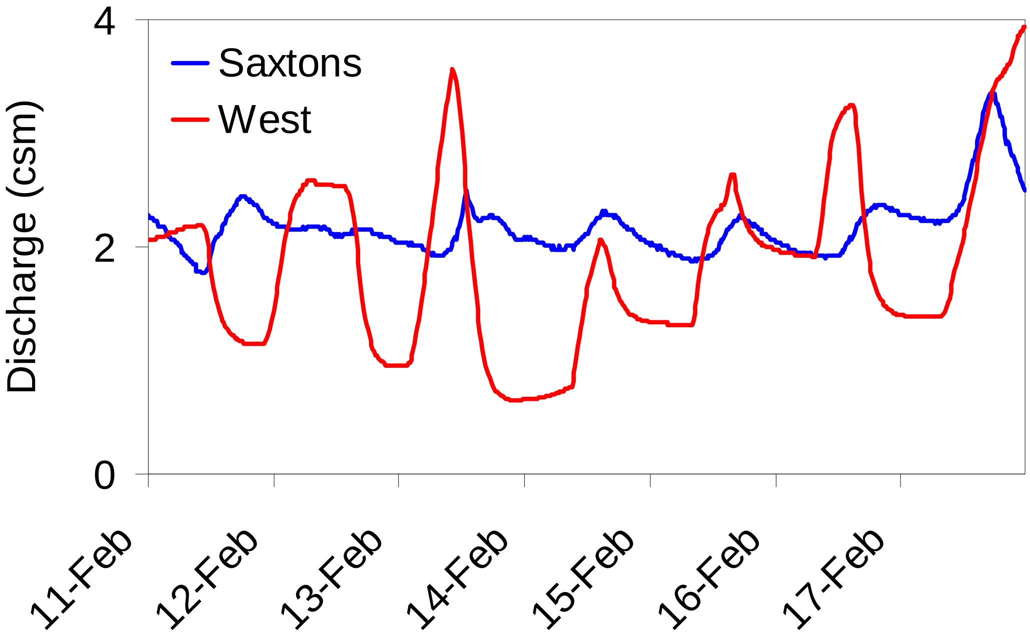


Figure 11. PCA analysis of IHA parameters; N = simulated natural flows, R = regulated flows observed from stream gage data. Plot labels represent variables with highest loadings on each axis.