Hydrologic Alteration *in the* Connecticut River Watershed

TNC Mission Statement: The Nature Conservancy's mission is to preserve the plants, animals and natural communities that represent the diversity of life on Earth by protecting the lands and waters they need to survive.

CT River Program Goal: To ensure the long-term conservation and viability of the Connecticut River and its most important tributaries.

Acknowledgments: The Conservancy would like to thanks the U.S Army Corps, New England District and the US Army Corps Hydrologic Engineering Center; U.S. Forest Service, Northern Forest Research Station; U.S. Geological Survey, Conte Anadromous Fish Laboratory for their support of this work.

draft

abstract

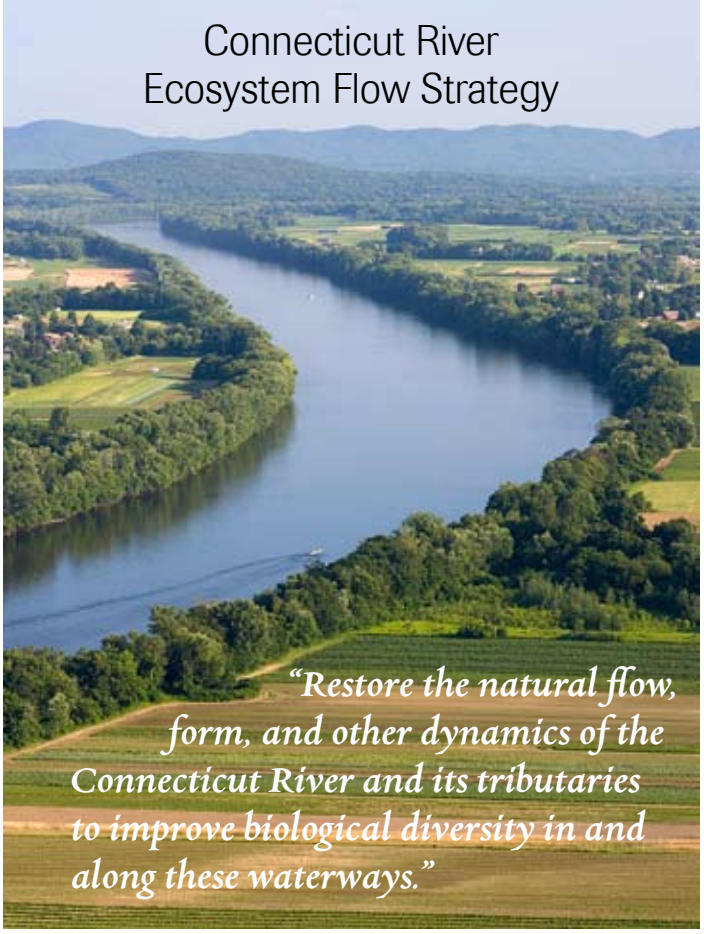
Restoring Ecosystem Flows

Managing water for people and nature

The Connecticut River and its tributaries have been integral to human settlement of the region. People have relied on these rivers as sources of food, water, and energy; as settlement and transportation corridors; as a means of diluting pollutants; and for recreation. With this close relationship came the need to quell damaging floods and provide dependable river flows. The taming of rivers in the Connecticut River watershed began soon after Europeans settled the region, intensified after catastrophic floods in the late 1930s, and continues to this day. Hydrologic control was accomplished primarily by the construction of flood control, water storage, and hydropower dams.

There are 65 major dams on the mainstem of the Connecticut River and its tributaries, with a major dam defined as a structure capable of storing at least 10% of total annual runoff at its location. Mainstem dams in the upper Connecticut River (in Vermont and New Hampshire) impound approximately 54% of the river's length. Overall, the watershed contains 16 flood-control reservoirs and at least 125 reservoirs used for power generation. Using the National Inventory of Dams database and state dam lists, The Nature Conservancy estimates there are 2,722 dams in the Connecticut River watershed.

Dams and impoundments are a primary cause of flow alteration in the Connecticut River watershed. On average, individual dams in the watershed store a lower proportion of annual runoff than do individual dams in other regions of the United States. However, the density of dams in the watershed is among the highest in North America, Europe, and the former Soviet Union (Dynesius and Nilsson 1994, Graf 1999). Therefore hydrologic alteration from the cumulative effects of dams may be as great in the Connecticut River watershed as elsewhere in North America. Altered hydrology is a primary stressor to The Nature Conservancy's conservation targets in the Connecticut River watershed.



© Jerry and Marcy Monkman/EcoPhotography.com

RESTORING ECOSYSTEM FLOWS

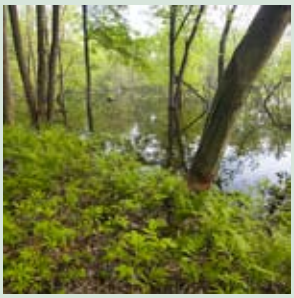
The Nature Conservancy is developing a **Connecticut River Ecosystem Flow Strategy**. Its goal is to restore the natural flow, form, and other dynamics of the Connecticut

Ecosystem flow includes the quality, quantity and timing of water flow required to maintain the components, functions, processes, and resilience of aquatic ecosystems that provide goods and services to people.

The Nature Conservancy's Conservation Targets

Floodplain Ecosystems

The watershed's floodplain ecosystems and riparian zones, which include the once magnificent floodplain forests, are important conservation targets. Floodplain forests are one of the most endangered natural communities in the Northeast. Loss of bankfull and overbank flows has contributed to the widespread loss or degradation of floodplain communities. Human development and agriculture was historically concentrated along river corridors, and many floodplain forests were cleared for farms, roadways, railways, homes, and cities. Several floodplain-dependent species are considered regionally or globally rare.



floodplain forest

Estuarine Ecosystems

The tidal wetlands and estuary in the lower Connecticut River were recognized as Wetlands of International Importance under the 1994 Ramsar Convention. This conservation target includes an extensive system of high quality freshwater and brackish tidal marshes. Salinity concentrations determine the types and distribution of tidal wetlands in the lower Connecticut River; these concentrations depend largely on river discharge and tidal fluctuations. Changes in the magnitude, frequency, and duration of freshwater discharge may alter plant and animal communities in these habitats.

tidal wetland

Migratory and Resident Fish

Ten diadromous fish—species that migrate between freshwater and saltwater to spawn—are native to the Connecticut River watershed. In addition, resident freshwater fish migrate within freshwater environments during their lives. Dams have contributed to the extirpation, range reduction, or decline of diadromous species by blocking migration routes and by altering flow-related migration cues and habitat within accessible river reaches. Hydrologic alteration has contributed to the widespread shift in freshwater fish communities from fluvial specialists to habitat generalists, loss of shallow and near-shore habitats in many rivers, and the proliferation of non-native species.

alewife

Aquatic and Floodplain Invertebrates

yellow lampmussels

Freshwater mussels and tiger beetles are important conservation targets because they are sensitive to environmental degradation and because several species are rare. Seven of 12 freshwater mussel species in the watershed are listed as Endangered, Threatened, or Special Concern by one or more states, including the federally endangered dwarf wedgemussel. Among the key threats to these species are the declines of native fish, altered hydrology, altered fluvial geomorphology, and pollution. The puritan tiger beetle and cobblestone beetle are also very rare and are sensitive to altered hydrology.

River and its tributaries to improve biological diversity in and along these waterways.

Why focus on flow? Restoring the natural flow regime is a long-term solution to restoring rivers and native biodiversity (Poff *et al.* 1997, Richter *et al.* 2003). Restoration efforts have historically focused on water quality and minimum flow requirements, which have improved conditions for aquatic life and ensured consistent flows. During the last decade, however, a cadre of scientists began to advocate a new approach to water management that recognized the importance of natural flow regimes. Key aspects of the natural flow regime could be maintained or restored by designing ways to divert or store water for human needs. Many scientists and resource managers support this approach.

The Nature Conservancy is working with cities around the world from Quito Ecuador to New York City and most recently the Yangtze River in China to identify ways to meet growing water needs while maintaining the ecosystems that supply this water. Building on proven global leadership, the Connecticut River Program of The Nature Conservancy has begun work to restore the ecologically necessary flows of the Connecticut River and its tributaries. In many instances, it is neither socially acceptable nor attainable to restore presettlement flows. The Nature Conservancy's goals are more realistic: to identify aspects of the altered flow regime that are most important to conservation targets and seek restoration strategies that balance ecological and human needs.

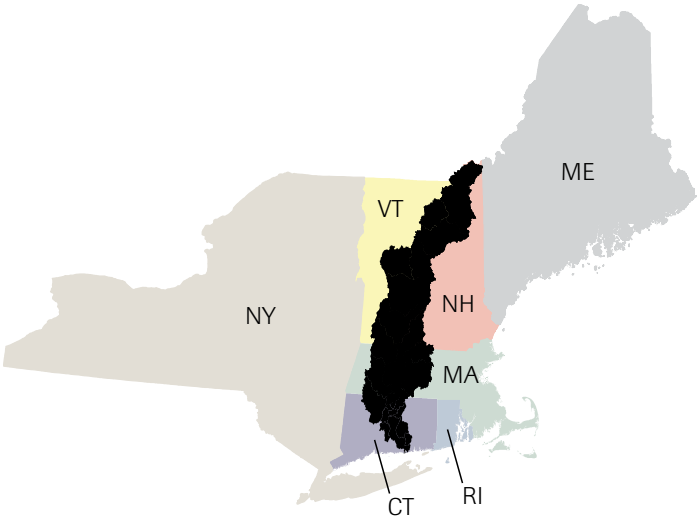


Figure 1. Location of the Connecticut River basin (black) in relation to northeastern states. See Figure 2 or 3 for tributary locations.

COLLABORATION AND ADAPTIVE MANAGEMENT

Collaboration and adaptive management are essential for flow restoration in the Connecticut River watershed (Richter *et al.* 2003, 2006; Rogers 2006). Dam operators are particularly important partners because they can exert a high degree of control over flow regimes. The Nature Conservancy has a strong tradition of working with dam operators—both private hydropower companies and the US Army Corps of Engineers—to develop creative solutions to managing flows that are based on sound science. Other stakeholders include public and private interests that use water for irrigation, consumption, waste treatment, industry, and recreation. An important challenge is addressing the constraints that traditional valuation and management of river resources place on contemporary ecosystem management. It is imperative to nurture broad awareness of, and support for, river restoration (Wohl *et al.* 2005, Rogers 2006).

The Nature Conservancy and its partners are developing a dynamic dialogue to understand and prescribe flow scenarios. The Conservancy has taken the first two steps of a five-step process for restoring environmental flows in the Connecticut River watershed. These steps included an initial meeting to discuss data needs and limitations, and a comprehensive review of the scope of hydrologic alteration and its potential effects on biota and ecological processes. The next three steps are to work with partners to develop flow recommendations, implement these changes in dam operations, measure ecosystem response, and then modify flow recommendations as new information emerges.

Figure 2. Tributaries and dam locations in the Connecticut River watershed. Only major tributaries (with drainage areas exceeding 30 square miles) are labeled. All dams are shown regardless of size. Dam location data from NID database and state lists, and were compiled by The Nature Conservancy.

Assessing Hydrologic Alteration

Using hydrologic analysis to assess ecosystem threats and conservation opportunities

In 2004, a group of nearly 50 experts representing all four states, federal and state natural resource staff, academics, non-profit organizations, and TNC staff from each state met for a series of planning meetings. Using the Conservancy's conservation planning process, participants identified the important elements of biodiversity in the Connecticut River Basin, called conservation targets, threats to these conservation targets, and specific strategies that will help to protect and restore conservation targets. Experts identified altered flow regimes as a primary threat to all of the conservation targets.

During that meeting and others since, participants examined the causes of hydrologic alteration and the effects of altered hydrology on conservation targets. It was clear that an understanding of the effects of hydrologic alteration should not be based solely on a conceptual understanding of the effects of dams or empirical studies conducted outside of the region. New England is unique due to its geology, glacial history, climate, and its nearly 400-year history of intensive landscape alteration by humans. Therefore, watershed-specific studies were needed to provide a more precise understanding of the distribution, types, and magnitude of hydrologic alteration in the Connecticut River and its tributaries.

The Nature Conservancy invested in two years (2005-2007) of research into understanding the extent and effects of hydrologic alteration in the watershed, collaborating with the US Geological Survey, US Forest Service, and the US Army Corps of Engineers. Studies included a review of the biological and ecological effects of altered hydrology (Zimmerman 2006a), a floodplain analysis (Anderson *et al.* 2007), and five hydrologic analyses (Zimmerman 2006b, 2006c; Zimmerman and Lester 2006, Gannon 2007). Hydrologic analyses are described herein, followed by a summary of hydrologic alteration and its ecological consequences.

> Flow regimes vary within and among rivers, as do the effects of altered flow regimes. It is important to recognize this individuality when assessing hydrologic alteration and prescribing restoration.

1. HYDROLOGIC ANALYSES

ESTIMATES OF EXISTING FLOW ALTERATIONS

(*see* Zimmerman and Lester 2006)

Objective: To determine the spatial distribution of dams and assess the potential for dams to alter flows in 44 major tributaries of the Connecticut River, which were defined as watersheds with drainage areas exceeding 30 square miles.

Data Sources: NID database and USGS stream gage data. The NID database provided information on the location and maximum storage capacity of each dam. USGS data were used to calculate mean annual runoff for each gaged tributary by summing daily mean flows. The stream gage closest to the confluence with the Connecticut River was used to compute mean annual runoff. For ungaged streams or for streams without a gage near the confluence, mean annual runoff was estimated using the relationship between basin area and mean annual runoff derived from gaged tributaries; this coefficient was 0.19. Thus, mean annual runoff in ungaged tributaries was estimated as 0.19 x basin area.

Analysis: Computed the ratio of total dam storage to mean annual runoff. This yielded a flow index for each tributary; the potential for hydrologic alteration was categorized as Low (<10), Moderate (10-30), High (31-50), and Severe (>50).

Major Results

- Of the more than 2,700 dams in the watershed, only 65 are able to store at least 10% of mean annual runoff. Most of the high capacity dams are in tributaries.
- Of the 44 major tributaries, the potential for hydrologic alteration was Low in 27 (61.4%), Moderate in 7 (15.9%),

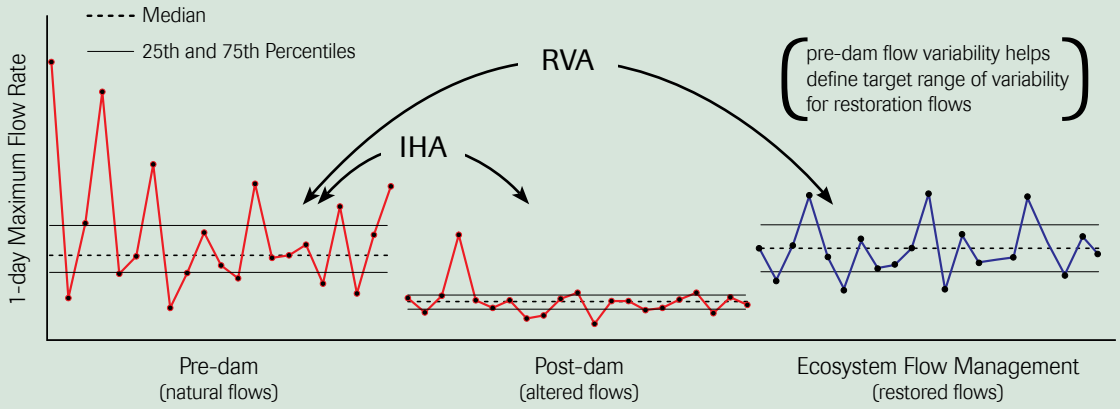
IHA and RVA

The Indicators of Hydrologic Alteration (IHA) software is widely used to assess the effects of dams, diversions, and other human influences on hydrologic regimes (Richter *et al.* 1996). IHA analysis characterizes variation in the magnitude, duration, and timing of water conditions and five groups of environmental flow components (The Nature Conservancy 2006). IHA works in the following way:

- Computes values for each parameter for each year in the pre-disturbance and post-disturbance time series
- Computes the central tendency and dispersion of each parameter for the entire pre-disturbance and post-disturbance time series (134 statistics per time series: 67 for central tendency and 67 for dispersion)
- Compares the 134 statistics between the pre-disturbance and post-disturbance time series and presents results as a percentage deviation from one time series to another

IHA results are expressed statistically or graphically. Graphs commonly show variability for a given parameter (or group of parameters) for the pre- and post-disturbance time series.

The Range of Variability Approach (RVA) is intended to help select flow management targets based on the range of variation in 33 IHA parameters (parameters for environmental flow components are not included in the RVA analysis), particularly from a pre-disturbance time series (Richter *et al.* 1997). A management target—usually expressed as a range, dispersion from the mean, or percentiles—is expressed for each of the 33 IHA parameters. A management team, comprised of regulatory agencies, conservation groups, and dam operators, selects specific management targets and a system to ensure that targets are reached. RVA lends itself to adaptive management: RVA targets should be adjusted to accommodate new research, monitoring, and stakeholder needs.



Representation of IHA analysis for one of the flow parameters and how the natural range of variability is used to select management targets.

High in 7 (15.9%), and Severe in 3 (6.8%) (Figure 4).

- Rivers with Low or Moderate potential for hydrologic alteration were primarily located in the northern parts of the watershed or had small basin areas.
- Seven of ten rivers with a High or Severe potential for hydrologic alteration had ACOE flood control dams, and two rivers with flood control dams were classified as Moderate.
- Potential for flow alteration is highest in the Upper Connecticut River, Deerfield River, and Chicopee River .

Scope of the Analysis: The analysis only considers maximum dam storage capacity; actual storage capacity, flow management, water withdrawals, or other types of hydrologic alteration were not considered. Flow index categories do not consider site-specific hydrologic analyses or potential effects of altered hydrology on natural communities or ecosystems. The flow index should be one of several tools to assess hydrologic alteration and can help identify rivers that warrant more detailed analysis. The analysis only considered tributaries and not the mainstem Connecticut River.

HYDROLOGIC ANALYSIS OF TRIBUTARIES

(*see* Zimmerman and Lester 2006)

Objective: To determine the types and degree of hydrologic alteration caused by dams among tributaries with sufficient USGS stream gage records, and to determine if there were region-wide patterns of hydrologic alteration.

Data Sources: USGS stream gage data. Only gages with at least 20 years of flow data before and after construction of

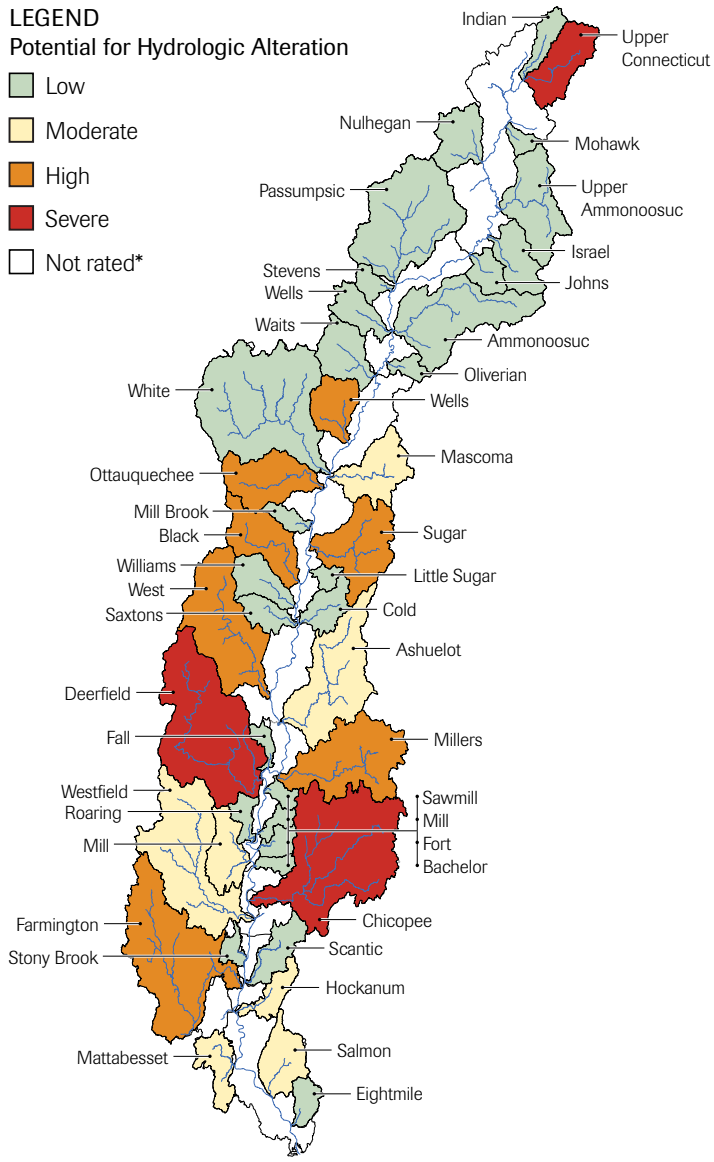


Figure 4. Potential for hydrologic alteration in Connecticut River tributaries, based on the number and storage capacity of dams within each watershed. Only major tributaries (those with a drainage area exceeding 30 square miles), are included in this analysis. See Zimmerman and Lester (2006).

an upstream dam (or dams) were eligible for the analysis.

Analysis: IHA software was used to examine changes in the magnitude, duration, frequency, timing, and rate of change of components of the hydrograph. A total of 67 hydrologic parameters were computed but only nine were considered for assessment of hydrologic alteration. Only nine gages in seven tributary watersheds qualified for the analysis.

Major Results (Table 1)

- Seven of nine stream gages showed a large decrease (80-94%) in the frequency of floods with a 2-year and greater return interval.
- Six of nine stream gauges showed moderate decreases (8-91%) in the magnitude of the 3-day maximum flow.
- Low flow duration increased and the Q90 frequency (the flow exceeded 90% of the time) tended to decrease.
- Variable results and results inconsistent with general trends highlight the need for more detailed analysis.

Scope of the Analysis: Only nine gages in seven tributary basins (out of 74 gages and 44 basins) had sufficient data for the IHA analysis, and of those, seven gages were located downstream of ACOE flood control dams. None were located in Connecticut. Prevalent flow alterations described in the analysis (particularly the reduced frequency and magnitude of floods) may apply mainly to river reaches downstream of flood control dams: tributaries with flood control dams that were not included in this analysis include the Millers River (MA), Farmington River (CT), and Ompompanoosuc (VT). The only tributary (Wells River) in the analysis that showed an increase (71%) in the 2-year flood frequency was also the only tributary that did not have a flood control dam. Hydrologic analyses of a more representative set of tributaries will likely result in different conclusions with respect to the types and intensity of flow alteration.

HYDROLOGIC EFFECTS OF FLOOD CONTROL DAMS IN THE ASHUELOT RIVER AND WEST RIVER

(*see* Zimmerman 2006b)

Objective: To examine the types and spatial extent of hydrologic alteration in the Ashuelot River and West River due to four ACOE flood control dams: Surry Mountain and Otter Brook dams in the Ashuelot River, and Ball Mountain and Townshend Dams in the West River.

Data Sources: Mean daily streamflow records from USGS stream gages and ACOE records of inflows and outflows from reservoirs (used to simulate natural flows). The analysis used four gages from the Ashuelot River (below Otter Brook Dam and Surry Mountain Dam, West Swanzey, and Hinsdale) and three gages from the West River (below Ball Mountain Dam and Townshend Dam, and Newfane).

Analysis: IHA software was used to compare simulated natural mean daily flows to observed mean daily flows be-

Table 1. Results of IHA analyses for stream gages on Connecticut River tributaries with at least 20 years of daily flow data pre- and post-construction of an upstream dam. Results represent percent deviation from natural flow conditions after dam construction. See Zimmerman and Lester (2006).

Tributary	Summer/ Fall Central Tendency	Winter Central Tendency	Spring Central Tendency	Low Flow Frequency	Low Flow Duration	Low Flow Magnitude	High Flow Magnitude	2-year Flood Frequency	2-year Flood Duration
Ashuelot River	11	18	20	-69	233	-5	-21	-83	34
Black River	34	79	85	-53	50	21	-12	-80	-24
Chicopee (Swift River)	15	31	4	43	8	-39	-91	-93	61
Chicopee (Ware River)	24	23	16	-33	33	5	1	2	0
Ottauquechee River	16	34	18	37	0	-29	-18	-81	-56
Wells River	29	27	10	-40	-25	21	9	71	3
West River	17	30	11	-80	100	47	-12	-89	4
Westfield River	20	22	15	-30	0	5	-1	-94	21
Westfield (Middle Branch)	8	18	20	-60	-10	4	-8	-87	-23

low each dam and at the mouth of each river for the period 1984-2004. The RVA of simulated versus observed flows was compared to describe changes in the annual distribution of flow statistics. The analysis used simulated natural flows rather than actual pre-dam flows for two reasons: (1) adequate pre-dam stream gage data were only available for one of the flood control dams, and (2) a comparison of natural and regulated flows over the same time period reduces confounding effects of changes in climate or precipitation. Methods for computing simulated flows are described in Zimmerman (2006b). Simulated natural flow data were considered unaltered (natural) and actual stream gage data were considered altered (regulated) for the analysis.

Major Results

- Flood control dams increased flow stability by reducing or eliminating extreme high and low flows and decreasing day-to-day variability (Table 2). Figures 5 and 6 show the effect of dams on the frequency of small floods and 1-day maximum flow rates.
- In the Ashuelot River, the magnitude of low-flow alterations are dampened further downstream due to inflow from tributaries, but bankfull and overbank flows are nearly nonexistent 30 miles downstream near the confluence with the Connecticut River.
- In the West River, the magnitude of high and low flow events were reduced further downstream but high and low flow duration, low flow frequency, flow variability, and rate of change were not significantly different between natural and regulated flows at the river mouth.

Scope of the Analysis: This study provides compelling examples of the scope of hydrologic alteration downstream of flood control dams, and results generally agree with the hydrologic analyses of several tributaries that also looked mainly at rivers with flood control dams. Use of simulated natural flows was the best possible solution to the problem of limited stream gage data. Within-day flow variation caused by dam operations (e.g., ramping rates with ramping periods < 24 hours) were not captured in this analysis, nor were changes in dam operations made late in the study period (e.g., ramping rates and minimum flow agreements).

Table 2. Results of IHA analyses for stream gages downstream of Army Corps of Engineers flood control dams on the Ashuelot River (NH) and West River (VT). All results represent percent deviation from natural flow conditions. See Figure 3-4. Results from Zimmerman (2006b).

	Ashuelot River Flood Control Dams		West River Flood Control Dams	
Flow Parameter	Surry Mountain	Otter Brook	Ball Mountain	Townshend
Frequency of 2-year flood events	-94	-100	-75	-90
Magnitude of 1-day maximum flows	-44	-39	-17	-25
Frequency of extreme low flows	-67	-60	-80	-60
Magnitude of 1-day minimum flows	161	186	83	36
Duration of low flow pulses	160	40	60	13
Daily hydrograph reversals	-53	-40	-38	-27

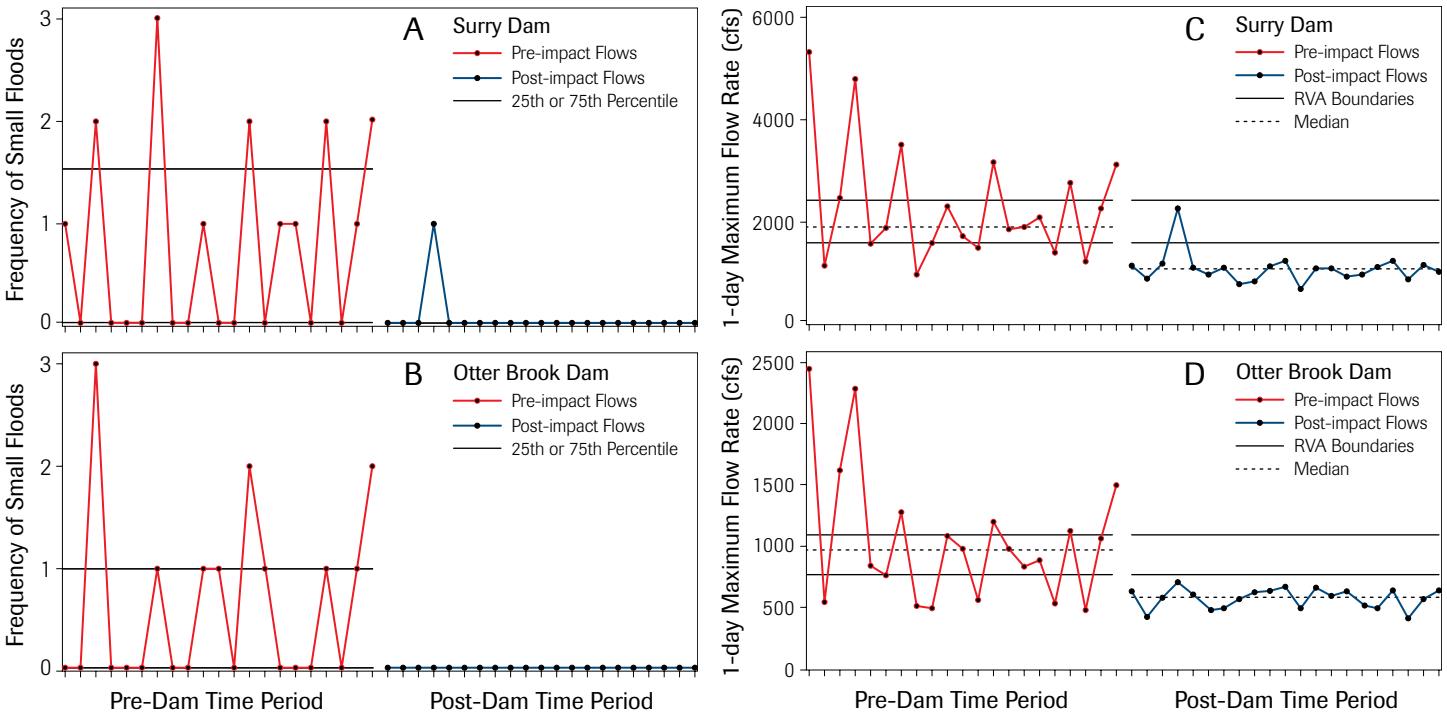


Figure 5. Alteration of high flow parameters downstream of the Surry and Otter Brook Dams in the Ashuelot River watershed. A and B: Frequency of bankfull and overbank flows (≥2-year recurrence interval). C and D: Magnitude of 1-day maximum flows. See Zimmerman (2006b).

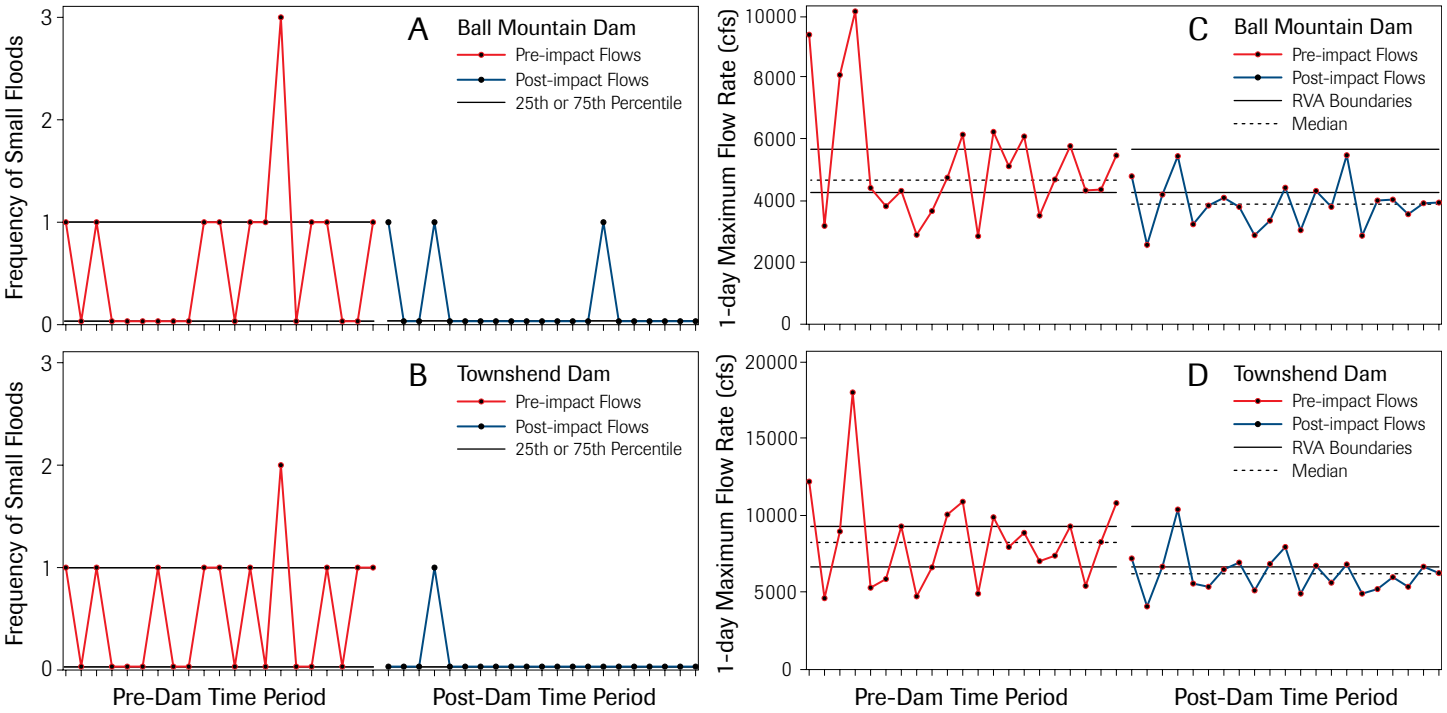


Figure 6. Alteration of high flow parameters downstream of the Ball Mountain and Townshend Dams in the West River watershed. A and B: Frequency of bankfull and overbank flows (≥2-year recurrence interval). C and D: Magnitude of 1-day maximum flows. See Zimmerman (2006b).

One of the ten hydroelectric dams on the Connecticut River's mainstem.

EFFECTS OF HYDROPOWER AND FLOOD CONTROL DAM OPERATIONS ON HOURLY FLOW VARIATION

(*see* Zimmerman 2006c)

Objective: To determine the frequency and magnitude of hourly flow fluctuations at stream gages downstream of hydropower and flood control dams and at reference sites.

Data Sources: Hourly flow data from USGS stream gages at hydropower (peaking and run-of-river), flood control, and reference sites. For hydropower and flood control sites, gages had to be located directly downstream of a hydropower dam, without other dams or major tributaries in between, and the gages needed to record hourly flow data for an adequate period (9 years). Reference sites were chosen from among a set of gages on the least altered rivers in the basin.

Analysis: Hourly flow data were used to calculate four metrics of diurnal flow fluctuations for all stream gages for each 24-hour period. Three of the metrics—the Richards-Baker (R-B) flashiness index, the ratio of the range of the diurnal cycle to total daily discharge (% of total), and coefficient of diel variation (SD/mean)—represented fluctuations in flow volume at a site. The fourth metric—the number of reversals—represented overall flow variability without information about the amount of water added or removed with each flow reversal. Frequency histograms of each metric were used to determine thresholds of diurnal flow fluctuations above which flows would be considered flashy, and these thresholds were used to calculate the number of days with flashy flows at hydropower versus reference sites.

Major Results (Table 3)

- Peaking hydropower sites had more than six times as many days per year with high values for the R-B Index, more than four times as many days per year with a high ratio of the range of the diurnal cycle to total daily discharge, and three times as many days per year with a high coefficient of diel variation than reference sites. These sites had a higher (but not statistically different) number of days with a high number of reversals.
- There were no strong and consistent differences in the magnitude of flow metrics at hydropower or flood control dams versus reference sites.
- Overall, reference sites had diurnal flow fluctuations similar in magnitude to hydropower sites, but the degree of flashiness occurred significantly less often at reference sites.
- Areas of greatest concern for effects of high diurnal flow variation from among sites included in this analysis include the Deerfield River, Connecticut River near Montague, Chicopee River, and West River. Conservation targets and potential restoration benefits should be

Table 3. Mean number of days per year (range in parentheses is 95% confidence interval) at gages (reference sites and downstream of flood-control, run-of-river hydropower, and peaking hydropower dams) with high values for diurnal flow fluctuations. See text for explanation of the metrics. Flashiness thresholds for each metric were determined from histograms and days with values above the thresholds were considered flashy. Values in bold were significantly ($p<0.01$) different from reference sites. See Zimmerman (2006c).

Metric	Flashiness Threshold	Days Per Year Above Threshold			
		Reference	Flood control	Run-of-river	Peaking
R-B index	≥0.05	32 (3-62)	31 (5-57)	67 (44-89)	**202** (147-256)
Reversals	≥9.00	12 (0-58)	60 (20-101)	73 (38-108)	27 (0-112)
% of total	≥0.03	38 (17-59)	41 (23-60)	45 (29-60)	**166** (128-205)
SD/mean	≥0.15	69 (42-97)	82 (58-106)	80 (59-100)	**221** (170-271)

assessed in these and other rivers or river reaches with unnaturally high diurnal flow variation.

Scope of the Analysis: A limited number stream gages could be used in this analysis because of their location, lack of hourly flow data, and lack of suitable references sites (especially on the mainstem Connecticut River). The number of sites in the analysis is sufficient to assess differences in the frequency of days with flashy flows between reference and hydropower sites and the magnitude of each metric under natural versus altered conditions. The analysis can help guide decisions on flow restoration and to assess if restoration should involve the volume or variability in flows (or both). In addition, the analysis can help identify sites with dams that are operated in a manner inconsistent with their designation (i.e., hydropower dams that are designated as run-of-river but operated as peaking).

ANALYSIS OF WATER WITHDRAWALS/DIVERSIONS IN CONNECTICUT AND MASSACHUSETTS

(*see* Gannon 2007)

Objective: Examine authorized water withdrawals and discharges in the Connecticut and Massachusetts portions of the Connecticut River watershed, and describe each state's water resource management policies with regard to withdrawals and discharges.

Data Sources: Information on authorized water withdrawals were obtained from the Massachusetts Department of Environmental Protection and the Connecticut Department of Environmental Protection. Information on authorized discharges were obtained through the US Environmental Protection Agency's National Pollutant Discharge and Elimination System (NPDES) permit program. Massachusetts's Water Management Act (WMA) and the Connecticut Water Diversion Policy Act (CWDPA) were reviewed for relevant water resource management policies.

Analysis: Analysis focused on the total amount of authorized water withdrawals and discharges in each state, the types and proportion of water withdrawals and discharges subject to environmental review, and how withdrawals and discharges compare to natural streamflows in the Connecticut River and its major tributaries.

Major Results

- Massachusetts and Connecticut authorize the withdrawal or diversion of 6,676.5 million gallons per day (MGD) from the Connecticut River watershed, including 315 MGD of withdrawals in Massachusetts and 6,361.5 MGD of withdrawals and diversions in Connecticut.
- Of the authorized water withdrawals in Massachusetts (in the Connecticut, Deerfield, Chicopee, Millers, and Westfield Rivers), only 5.4 percent are subject to the permitting process created by the WMA. The remaining 94.5 percent are grandfathered and not subject to environmental review.
- In Massachusetts, non-consumptive withdrawals and withdrawals that do not exceed the threshold that triggers regulatory review under the WMA are unknown, but probably constitute a significant amount of water.
- As of 2007, 122 NPDES permits exist in the Massachusetts portion of the Connecticut River watershed, authorizing the discharge of 313.5 MGD.
- Of the authorized water withdrawals in Connecticut, only 15 percent are subject to the permitting process created by the CWDPA, and 85 percent are grandfathered and not subject to environmental review.
- In Connecticut, several types of withdrawals are exempt from CWDPA requirements but the total amount of water is unknown.
- As of 2007, Connecticut granted 94 NPDES permits within the Connecticut River watershed, authorizing the discharge of 845.4 MGD.
- Despite comprehensive permitting processes for water withdrawals mandated by the CWA and CWDPA, only 14.6 percent of the withdrawals or diversions were subject to environmental review under those programs.

Scope of the Analysis: The analysis only considered the Massachusetts and Connecticut portions of the watershed, but since 84 percent of the watershed's human population lives in these two states, this bias is appropriate. Results raise questions about how each state's water resource policies are protecting natural streamflow and biota, especially considering all forms of hydrologic alteration, natural variability in streamflows, and long-term effects of climate change. Further inquiry should characterize and quantify all withdrawals and diversions exempt from environmental review, relate results to instream flow and ecosystem health, and develop environmentally sound water resource policies.

SUMMARY OF STUDIES

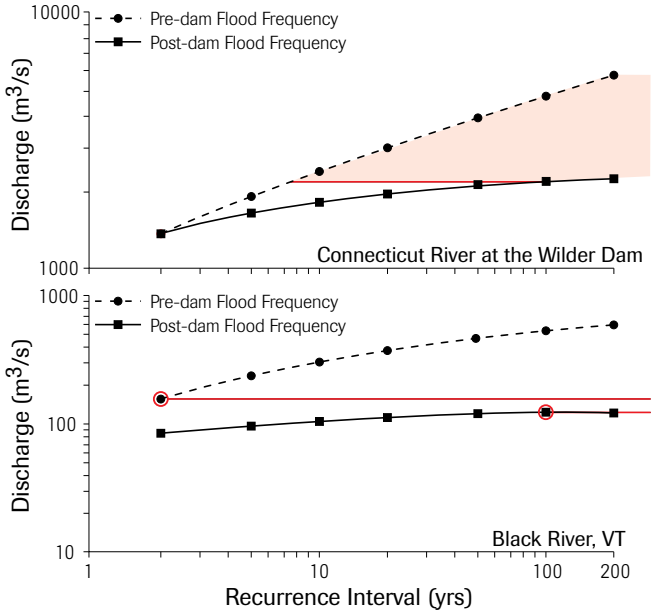
Major conclusions from the five hydrologic analyses are as follows:

1. Based on the storage capacity and number of dams, 17 of 44 major tributaries are likely to experience moderate to severe hydrologic alteration; these occur mainly in the southern half of the Connecticut River watershed. However, flow regimes depend on actual dam storage, flow management, other forms of hydrologic alteration, and watershed characteristics. Thus, the flow ratings index is most useful for directing detailed analyses.
2. Flood control dams have dramatically stabilized flow regimes in several tributaries via the following effects:
   a. Large decreases in the frequency and magnitude of high flow events
   b. Moderate to large decreases in the frequency of extreme low flow periods
   c. Moderate to large increases in the magnitude of low flows and duration of low-flow pulses

   These effects are most pronounced in river reaches near flood control dams, although the reduced frequency and magnitude of high flow events may affect longer reaches and the mainstem Connecticut River.
3. The frequency and magnitude of hourly flow fluctuations is high downstream of peaking hydropower dams.
4. The analyses described above are biased toward rivers with flood control dams because of availability of stream gage data. Hydrologic alteration is also evident in rivers without flood control dams but there are little data available to assess specific effects.
5. Only 14.6 percent of the 6,676.5 MGD of streamflows that are authorized to be withdrawn or diverted from the watershed in Massachusetts and Connecticut are subject to environmental review under each state's water resource management policies. The remaining 85.4 percent are grandfathered and exempt from review.
6. It is important to characterize and quantify all withdrawals and diversions currently exempt from environmental review, relate results to instream flow and ecosystem health, and integrate these results into water resource policies.

The reduced frequency and magnitude of high flow events is of greatest concern to The Nature Conservancy because of the importance of bankfull flows and floods to riparian communities and channel geomorphology. High within-day flow variability is also a concern for reaches downstream of peaking hydropower dams.

Results of these studies are consistent with the findings of Magilligan and Nislow (2001) that flow regulation has primarily reduced the magnitude and duration of extreme conditions, particularly floods. In the mainstem Connecticut River, dams had acute effects on the frequency of large floods (>10-year recurrence interval) and relatively minor effects on the frequency of bankfull discharges (Figure 7a). However, flow regulation in smaller watersheds had dramatic effects on bankfull discharges. For the Black River (Vermont), the pre-impoundment bankfull discharge of 158m³/s exceeded the post-impoundment 200-year flood (Figure 7b) (Magilligan and Nislow 2001). So while bankfull discharge events still occur in the mainstem Connecticut River, they have been greatly reduced or eliminated in most tributaries that have flood control dams.



7A. In the mainstem Connecticut River at West Lebanon, NH, dams have little effect on bankfull flows (< 2 years recurrence interval), but have major effect on larger flows with longer recurrence intervals. Riparian areas that flooded every 8-10 years pre-dam are now expected to flood only once in a hundred years; higher floodplain terraces may never experience flooding again.

7B. In the Black River, a tributary of the Connecticut near Springfield, VT, dams have affected both large, infrequent and small, frequent floods. On average flood levels that occurred every two years during the pre-dam period are now predicted to occur less than once every two *hundred* years.

Figure 7. Flood frequency analysis for: (A) the Connecticut River at Wilder Dam, and (B) the Black River (Vermont). Redrawn with permission from Magilligan and Nislow (2001).

The West River in Vermont. © Jerry and Marcy Monkman/EcoPhotography.com

2. ECOLOGICAL EFFECTS OF ALTERED HYDROLOGY

(*see* Zimmerman 2006a)

Hydrologic alteration can affect aquatic and riparian species and communities directly, through changes in water availability and flow events linked to life history strategies, and indirectly, through changes in habitat, water temperature, water quality, and ecological processes (Poff *et al.* 1997, Bunn and Arthington 2002). In fact, one would hard-pressed to describe important instream and riparian processes or species that are independent of the flow regime.

Given the connection between the flow regime and fluvial geomorphology, it is not surprising that the physical structure of rivers change dramatically when the natural flow regime is altered (Poff *et al.* 1997). In some cases, persistent hydrologic alteration over several decades has caused geomorphic changes that are essentially irreversible without massive intervention or reintroduction of large floods. The most significant geomorphic changes are channel restriction, channel incision (downcutting), sediment accumulation due to loss of flushing flows, and armoring due to reduced or lost sediment sources, and loss of riparian wetlands (Rosgen 1996). Geomorphic effects are highly variable due to different river types and flow regimes. There is no comprehensive geomorphic assessment of the Connecticut River or its tributaries that fully assess geomorphic response to altered hydrology, although erosion and channel instability are prevalent in some areas (Field Geology Services 2004).

The physical presence of dams and altered flow regimes strongly influence temperature regimes (Ward and Stanford 1979, Lessard and Hayes 2003). Most dams in the Connecticut River watershed create shallow impoundments and release water from the surface; thus, the primary effect is to elevate downstream water temperatures in the summer. The location, density, and storage capacity of impoundments determine the degree of thermal alteration and effects on fish and invertebrate assemblages. Even small surface-release impoundments may warm waters enough to affect species that were already near the upper limit of their thermal range, such as Atlantic salmon in many tributaries to the Connecticut River. Through myriad effects on channel morphology, habitat diversity, and loss of hydrologic connections with floodplains and groundwater, altered flow regimes may compound thermal impacts that result from the physical presence of a dam.

Hydrologic alteration specifically affects The Nature Conservancy's key conservation targets within the Connecticut River watershed, including floodplain forests, estuarine communities, migratory and resident fish, and aquatic invertebrates. These ecological targets should be considered when assessing hydrologic alteration, prescribing flow regimes, and monitoring effects of flow restoration.

The Natural Flow Regime

A flow regime describes the full range of a river's natural flow variability. It includes seasonal flow patterns; the timing, magnitude, and duration of extreme conditions; temporal variability (hourly, daily, seasonally, and yearly), and rates of change (Richter *et al.* 1996, Poff *et al.* 1997). The five critical elements of the flow regime are as follows:

- Magnitude is the amount of water moving past a fixed location per unit time.
- Frequency is the number of times a flow of a certain magnitude occurs within a specified time interval.
- Duration is the length of time that a flow of a certain magnitude lasts.
- Timing is the regularity and seasonality with which flows of a certain magnitude occur.
- Rate of change is the rate at which flows change from one magnitude to another.

The flow regime is the primary driving force within river ecosystems (Poff *et al.* 1997). The importance of the natural flow regime, and ecological consequences of hydrologic alteration, are described in the lists below. Healthy rivers exhibit a constantly shifting mosaic of habitats largely maintained by hydrologic variability, and native species are adapted to exploit new opportunities as they arise.

The flow regime is influenced by river size, climate, geology, elevation, groundwater, position within a watershed, nature of upland and riparian areas, and channel form. Rivers draining the Eastern and Western Highlands of the Connecticut River valley tend to have non-alluvial channels that are underlain by bedrock and sediments that resist erosion. These rivers often have more variable flows and may be particularly sensitive to low flows. In contrast, larger rivers and low-gradient rivers in the Connecticut Valley Lowlands tend to have alluvial channels that are more dynamic, with frequent changes in channel morphology through erosion and sedimentation. Thus, flow regimes vary within and among rivers, as do the effects of altered flow regimes. Recognition of this individuality is important when assessing alteration and prescribing restoration.

IMPORTANCE OF NATURAL FLOW REGIMES

Large and Small Floods (>2 year recurrence interval)

- Induce meandering, scouring, and filling of channel
- Create and maintain floodplain landforms such as side channels, oxbows, wetlands, deposition bars, and beaches
- Scour riparian vegetation, deposit alluvial soils on the floodplain, and transport nutrients from the floodplain to the channel
- Supply a diverse seed bank to floodplains and enhance recruitment and diversity of riparian species (when timed with seed drop of riparian species)
- Develop and maintain floodplain forest communities and discourage non-adapted species from encroaching on the floodplain
- Create spawning and rearing habitat for river herring on floodplains when timed with spawning, provided that flood duration is sufficient to allow eggs to hatch and juveniles to escape
- Increase invertebrate production by connecting floodplain habitat to the main channel

Bankfull Flows (1.5-2 year recurrence interval)

- Define and maintain channel shape and prevent vegetation growth in the channel
- Effective discharge for sediment transport
- Provide migration and spawning cues for many native stream fish
- Provide maximum area of channel and riverbank habitat for fish and invertebrates, thereby increasing productivity

Seasonal Low Flows

- Create variable water availability and water chemistry conditions in instream, riparian, and hyporheic habitats
- Provide foraging opportunities for invertebrates, fish, birds, and mammals
- Create bottlenecks for species that become abundant and dominant at high and stable flows; regulate community structure
- Increase habitat for some riparian species, such as cobblestone tiger beetle and puritan tiger beetle

CONSEQUENCES OF ALTERED FLOW REGIMES

Reducing high flow events…

- Disrupts physical processes (e.g., sediment transport, scouring and erosion) of channels and floodplains
- Degrades and destroys floodplain forests
- Encourages encroachment of non-riparian and non-native species
- Decreases the export of terrestrial nutrients to aquatic systems
- Decreases the size and hydroperiod of floodplain wetlands, with impacts on invertebrate communities and higher trophic levels
- Reduces spawning and foraging habitat, and migratory and spawning cues, for stream fishes
- Reduces the availability and quality of instream and bank habitat for invertebrates, fish, amphibians, and reptiles

Increasing the duration and lowering the magnitude of low flows…

- Increases water temperature and decreases dissolved oxygen
- Reduces available habitat for different species and life stages
- Favors habitat generalists over fluvial specialists
- Reduces the diversity and abundance of fishes and freshwater mussels, especially those species that rely on habitats dewatered or isolated during low flow periods

Increasing short-term flow fluctuations…

- May result in bank erosion, increased water temperatures at stream margins, and dewatering and desiccation of channel margins
- Strands and displaces fish and aquatic invertebrates that depend on stream margin habitat, which may eliminate some species and result in lower species diversity and abundance
- Reduces or eliminates stable beach habitat for puritan tiger beetle and cobblestone tiger beetle

© Jerry and Marcy Monkman/EcoPhotography.com

Flooding the Floodplain

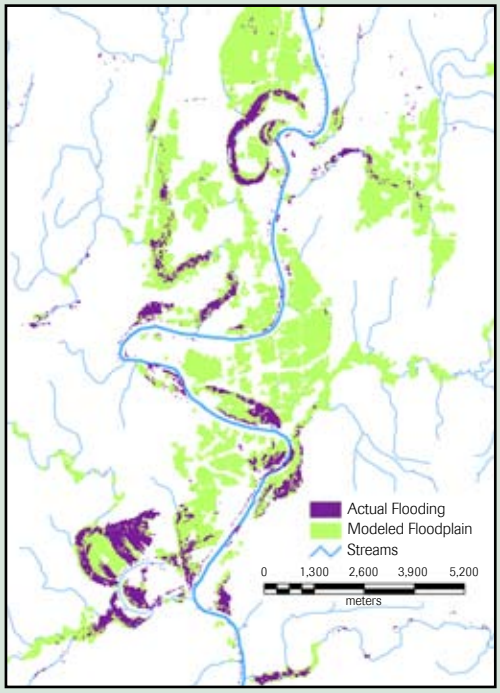
Floodplain forests, open wetlands, and open riparian communities occur along river channels and in portions of valleys prone to periodic river flooding. Plant species that occur in these habitats have widely varying tolerances to inundation, dry periods, and physical disturbance (e.g., ice scour, soil erosion and deposition, etc.). Variation in the availability of water, physical disturbance, and environmental tolerance of floodplain species leads to highly structured and diverse communities, from low-elevation herbaceous communities adapted to anoxic soils and almost continuous inundation during the growing season, to high terrace riparian forests that naturally flood only a few times per century.

Floodplain forests are one of the most endangered natural communities in the Northeast. Human development and agriculture was historically concentrated along river corridors, and many floodplain forests were cleared for farms, roadways, railways, homes, and cities. Concurrently, alteration of channels, banks, and river flows greatly altered the natural flood regime, essentially starving remnant floodplain forests from their most essential element.

Nislow *et al*. (2002) studied the effects of hydrologic alteration on floodplain habitats along the mainstem Connecticut River in an area downstream of the Wilder Dam. They found that high terrace floodplain forests that flooded every 10-100 years before impoundment of the upper Connecticut River were predicted to flood at >100 year intervals following impoundment. Thus, dams essentially isolated high terrace floodplain forests from river influence. Lower elevation floodplain communities—such as silver maple forests—experienced smaller changes in flood frequency but significant changes in flood duration. Impoundment did not alter the frequency or duration of floods in the <2-year floodplain communities. However, results of Magilligan and Nislow (2001) suggest that hydrologic alteration in tributaries might have more pronounced effects on low-elevation floodplain communities by dramatically increasing the recurrence interval of small floods (<10-year recurrence interval).

Ecologists have mapped and evaluated more than 50 remaining floodplain forests in the Connecticut River watershed—more than any other watershed in the Northeast. The Nature Conservancy is working toward a floodplain assessment for the entire watershed to give context to the remnant forests, highlight broad-scale patterns, identify restoration areas, and suggest conservation strategies. Toward that goal, The Nature Conservancy developed a floodplain analysis tool to identify existing high-quality floodplain forests and potential restoration sites (Anderson *et al*. 2007). This involved a five-step procedure:

1. Develop a model to predict locations in the watershed where geomorphic characteristics favored the development of riparian communities.
2. Determine riparian forests that were still experiencing some level of spring flooding.
3. Distinguish floodplain forests from other riparian wetlands such as alluvial marshes or conifer swamps.
4. Characterize each floodplain forest according to its size, condition, and landscape context.
5. Determine conservation priorities and identify candidates for restoration.



Modeled floodplains versus actual flooding in a portion of the Connecticut River watershed near Northampton, Massachusetts. Floodplain analysis revealed the following basin-wide statistics:

- Modeled floodplains and riparian areas = 378,107 acres
- Actual land inundated in April 2001 flood = 48,957 acres
- Average size of floodplain occurrences = 26 acres

Source: Anderson *et al*. 2007

Challenges For Flow Restoration

The environmental history—and future—of the watershed poses challenges to aquatic conservation and will require creative solutions to restore ecosystems

Hydrologic alteration is prevalent throughout the Connecticut River and its tributaries. Dams are not the only cause of hydrologic alteration in the Connecticut River watershed, and therefore flow restoration cannot focus solely on dams. Water consumption, urbanization and other land-use changes, historic straightening of channels, and climate change have important consequences. The dramatic transformation of the New England landscape from virgin forests to croplands and grazing lands strongly affected the hydrology and geomorphology of streams and rivers. Recovery was more likely in rivers with minimal hydrologic alteration. A legacy of historic habitat degradation was the disruption of ecological processes—notably hydrologic regimes—that impeded the ability of rivers to heal themselves.

Water withdrawal for water supply, irrigation, snowmaking, and other uses may affect river flow throughout the watershed, with effects most pronounced in tributaries (Trout Unlimited 2006). Urbanization and an increase in impervious surfaces (roadways, parking lots, rooftops, etc.) have affected flows in some Connecticut River tributaries. Urbanization commonly results in an increased frequency and magnitude of high flows, redistribution of water from base flow to storm flow, increased daily variation in flows, and reduced low flows (Roy *et al.* 2005). Pollution in urban watersheds compounds the adverse effects of altered hydrology (Walsh *et al.* 2005).

The human population will continue to increase in the watershed. The demand for freshwater—for domestic, industrial, and agriculture use—will put enormous strain on regional water supplies. One of the greatest challenges in decades ahead is developing water resource policies that provide drinking water and quality of life while sustaining healthy aquatic ecosystems (Trout Unlimited 2006).

Climate change is expected to have important consequences on streamflows by dampening and changing the timing of spring peak flows (via reduced snowfall), and reducing streamflows by warming temperatures and increasing evaporation and transpiration (Moore *et al.* 1997). The frequency and intensity of large storms are expected to increase (New England Regional Assessment 2001) and cause large but erratic floods.

CONCLUSION

Aspects of the natural flow regime must be restored to allow rivers to recover and native species to flourish. Based on concepts and studies outlined in this document, The Nature Conservancy seeks tools to assess and prescribe flow strategies that address the following:

1. Loss of bankfull and overbank flows in the Connecticut River and its tributaries, especially downstream of flood control dams.

   Goal: Where it is possible, restore the timing and magnitude of high-flow events to increase floodplain inundation and restore channel processes.

2. High within-day flow variability downstream of hydropower dams (i.e., hydropeaking).

   Goal: Reduce within-day flow variability to improve the quality and quantity of aquatic habitat.

3. Large water withdrawals.

   Goal: In rivers with human-induced chronic low flows, seek ways to ameliorate the effects of large water withdrawals and maintain healthy ecosystems.

It is neither economically acceptable nor attainable to restore pre-settlement flows. The Nature Conservancy's goals are more realistic: to identify aspects of the altered flow regime that are most important to conservation targets and to seek restoration strategies that balance ecological and human needs. A sustainable balance can be attained if people understand the costs and benefits of ecosystem flow strategies. Success will only be achieved through collaboration, careful planning, and adaptive management (Richter *et al.* 2006). The Nature Conservancy challenges stakeholders to engage in this process.

REFERENCES

Anderson....(riparian analysis)

Bunn, S.E. and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30:492-507.

Dynesius, M. and C. Nilsson. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. *Science* 266:753-762.

Field Geology Services. 2004. Fluvial geomorphology assessment of the northern Connecticut River, Vermont and New Hampshire. Connecticut River Joint Commissions, Charlestown, New Hampshire.

Graf, W.L. 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* 35:1305-1311.

Lessard, J.L., and D.B. Hayes. 2003. Effects of elevated water temperature on fish and macroinvertebrate communities below small dams. *River Research and Applications* 19:721-732.

Magilligan, F.J., and K.H. Nislow. 2001. Long-term changes in regional hydrologic regime following impoundment in a humid-climate watershed. *Journal of the American Water Resources Association* 37:1551-1569.

Moore, M.V., M.L. Pace, J.R. Mather, P.S. Murdoch, R.W. Howarth, C.L. Folt, C.Y. Chen, H.F. Hemond, P. Flebbe, and C.T. Driscoll. 1997. Potential effects of climate change on freshwater ecosystems of the New England/Mid-Atlantic region. *Hydrological Processes* 11:925-947.

NERA (New England Regional Assessment). 2001. Preparing for a Changing Climate. The New England Regional Assessment Overview. U.S. Global Change Research Program, University of New Hampshire, Durham, NH.

Nislow, K.H., F.J. Magilligan, H. Fassnacht, D. Bechtel, and A. Ruesink. 2002. Effects of dam impoundment on the flood regime of natural floodplain communities in the upper Connecticut River. *Journal of the American Water Resources Association* 38:1533-1548.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime. *Bioscience* 47:769-784.

Richter, B.D., A.T. Warner, J.L. Meyer, and K. Lutz. 2006. A collaborative and adaptive process for developing environmental flow recommendations. *River Research and Applications* 22:297-318.

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

Richter, B.D., J.V. Baumgartner, R. Wigington, and D.P. Braun. 1997. How much water does a river need? *Freshwater Biology* 37:231-249.

Richter, B.D., R. Mathews, D.L. Harrison, and R. Wigington. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* 13:206-224.

Rogers, K.H. 2006. The real river management challenge: integrating scientists, stakeholders and service agencies. *River Research and Applications* 22:269-280.

Rosgen, D. 1996. *Applied River Morphology*. Wildland Hydrology, Colorado, USA.

Roy, A.H., M.C. Freeman, B.J. Freeman, S.J. Wenger, W.E. Ensign, and J.L. Meyer. 2005. Investigating hydrologic alteration as a mechanism of fish assemblage shifts in urbanizing streams. *Journal of the North American Benthological Society* 24:656-678.

The Nature Conservancy. 2006. Indicators of Hydrologic Alteration software. Version 7.0.

Trout Unlimited. 2006. A Glass Half Full: The Future of Water in New England.

Walsh, C.J., A.H. Roy, J.W. Feminella, P.D. Cottingham, P.M. Groffman, and R.P. Morgan. 2005. The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society* 24:706-723.

Ward, J.V., and J.A. Stanford. 1979. Ecological factors controlling stream zoobenthos with emphasis on thermal modification of regulated streams. Pages 35-55 in: *The Ecology of Regulated Streams* (J.V. Ward and J.A. Stanford, editors). Plenum Press, New York, NY.

Wohl, E., P.L. Angermeier, B. Bledsoe, G.M. Kondolf, L. MacDonnell, D.M. Merritt, M.A. Palmer, N.L. Poff, and D. Tarboton. 2005. River restoration. *Water Resources Research* 41:W10301.

Zimmerman, J.K.H. 2006a. Response of physical processes and ecological targets to altered hydrology in the Connecticut River basin. The Nature Conservancy, Connecticut River Program, Northampton, MA.

Zimmerman, J.K.H. 2006b. Hydrologic effects of flood control dams in the Ashuelot River, New Hampshire, and West River, Vermont. The Nature Conservancy, Connecticut River Program, Northampton, MA.

Zimmerman, J.K.H. 2006c. Hourly variation in river flow downstream of hydropower and flood control dams in the Connecticut River basin: comparison with unregulated sites. The Nature Conservancy, Connecticut River Program, Northampton, MA.

Zimmerman, J.K.H., and A. Lester. 2006. Spatial distribution of hydrologic alteration and fragmentation among tributaries of the Connecticut River. The Nature Conservancy, Connecticut River Program, Northampton, MA.