Spatial distribution of hydrologic alteration and fragmentation among tributaries of the Connecticut River

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September 2006

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Connecticut River Program Vision

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

We examined the spatial distribution of hydrologic alteration and river fragmentation among the 44 major tributaries of the Connecticut River as a tool for watershed-scale conservation planning and to assist in development of strategies for mitigating threats to aquatic ecosystems in the Connecticut basin. Our objectives were to:

1. Examine the spatial extent and distribution of hydrologic alteration and fragmentation for tributaries to the Connecticut River by developing indices of potential flow alteration and fragmentation from dams for individual watersheds
2. Develop maps of the entire Connecticut River basin that illustrate relative threats to river flows and connectivity among tributaries, as well as patterns of land use among tributary basins
3. Analyze data from US Geological Survey (USGS) stream gages with sufficient periods of record (i.e., at least 20-years pre- and post- dam construction) to determine the types and degree of hydrologic alteration among tributaries.

Hydrologic alteration

- 27 tributaries had dam storage capacity that was less than 10% of mean annual runoff at the confluence with the Connecticut River. These rivers were considered low risk for hydrologic alteration.
- 7 rivers were classified as having moderate flow risk (dam storage 10-30% of mean annual runoff).
- 7 rivers had high risk of flow alteration (dam storage 31-50% of mean annual runoff).
- 3 rivers had dam storage capacity greater than 50% of mean annual runoff and were considered to be severely impacted with respect to flow (the Upper Connecticut, Deerfield, and Chicopee).
- Out of the 10 rivers classified as high risk or severely impacted, 7 had flood control dams owned by the Army Corps of Engineers (no flood control dams were located on rivers in the low or moderate risk categories).

Fragmentation

- 18 tributaries had low fragmentation from dams (0.00-0.06 dams/mi^2).
- 15 were moderately fragmented (0.07-0.12 dams/mi^{2-}).
- 6 were highly fragmented (0.13-0.18 dams/mi^2).
- 5 were very highly fragmented (0.19-0.24 dams/mi^2; the Bachelor, Hockanum, Mill/Manhan, Millers, and Sawmill Rivers).
- Rivers with low fragmentation values were mostly located in northern Vermont and New Hampshire, whereas rivers with high or very high fragmentation values were found mainly in Massachusetts and Connecticut. Rivers with high or very high fragmentation values also tended to be smaller watersheds (lower watershed area).
- More accurate assessments of dams in each tributary basin and fragmentation from other sources, such as culverts, will likely increase the fragmentation index for most tributaries.

Site-specific hydrologic analyses

- 7 of 44 tributary basins had sufficient data for site-specific analyses.
- The most dramatic change in flows was the reduction in the frequency of floods and the magnitude of high flows (9 of 11 stream gages).
- Low flows only decreased on two rivers (the Swift River in the Chicopee watershed and the Ottauquechee River).
- Low flow duration tended to increase and the frequency of the Q90 (the flow exceeded 90% of the time) tended to decrease across tributaries.
- 6 of the 7 tributary basins in the analysis had Army Corps of Engineers or state-owned flood control dams, potentially biasing the analysis to detect effects on flood flows rather than other types of hydrologic alteration.

The Connecticut River Program can use these data for basin-scale planning, either to protect areas with low risk for hydrologic alteration and high river connectivity, or to develop strategies to mitigate threats in higher-risk watersheds. This analysis should be used to target tributary basins that are of conservation interest, and eligible for more detailed site-specific studies. In particular, detailed hydrologic analyses of effects of dams, land use, and water withdrawals on mean daily flows should be conducted to determine the scope of hydrologic alteration in specific locations and potential effects on aquatic and riparian species, communities, and ecosystems. Dams for flood control, hydroelectric power generation, and water supply have all contributed to altered flows in tributaries to the Connecticut River basin; however, effects of flood control dams on overbank flows seem to be the most prevalent threats to natural communities among tributaries in this analysis.

Introduction

The goal of The Nature Conservancy's Connecticut River Program is to restore and maintain the health of the Connecticut River and its tributaries. The program aims to use a watershed-planning approach to design and implement strategies to mitigate hydrologic alteration and river fragmentation throughout the basin. To achieve this goal, it is necessary to understand the spatial extent, distribution, and scope of hydrologic alteration and fragmentation in the Connecticut River watershed. Although the ideal hydrologic analysis would be a comparison of current hydrologic conditions to historic unaltered hydrology (without any dams, water withdrawals, or urban or agricultural land use), daily time series of natural (unaltered) flows are not available for the majority of tributaries in the basin, as well as the mainstem of the Connecticut River.

Our objectives were to 1) examine the spatial extent and distribution of hydrologic alteration and fragmentation for tributaries to the Connecticut River by developing indices of potential flow alteration and fragmentation from dams for individual watersheds; 2) develop maps of the entire Connecticut River basin that illustrate relative threats to river flows and connectivity among tributaries, as well as patterns of land use among tributary basins; and 3) analyze data from US Geological Survey (USGS) stream gages with sufficient periods of record (i.e., at least 20-years pre- and post- dam construction) to determine the types and degree of hydrologic alteration among tributaries. We intend that the Connecticut River Program can use these data for basin-scale planning, both to examine where threats overlap with stream reaches targeted for conservation action and to determine primary categories of hydrologic alteration in the basin (e.g., lack of overbank flows, decreased low flows) and how these types of alteration may impact particular species, natural communities, or ecosystems.

In addition to this analysis, other reports are available that address hydrologic alteration in the Connecticut River basin and potential ecological effects. A detailed hydrologic analysis was conducted for the West and Ashuelot Rivers (Zimmerman 2006a), two tributaries to the Connecticut River, that used simulated natural flow data to examine the effects of flood-control dams owned by the U.S. Army Corps of Engineers (ACOE) on the hydrographs of each tributary. An extensive literature review was also completed that examines links between hydrology, physical processes, and ecological targets (species, natural communities, or ecosystems targeted for conservation by The Nature Conservancy) for the Connecticut River (Zimmerman 2006b).

Methods

Individual tributary calculations

To examine the spatial extent and distribution of hydrologic alteration and fragmentation among tributaries to the Connecticut River, we developed indices of 1) the potential for dams to store water in each basin (flow index) and 2) the number of dams divided by the drainage area (fragmentation index) for each major tributary. The number of tributaries to the Connecticut River depends on the definition used to determine a major tributary. We defined a major tributary to have a drainage basin of at least 30mi^2 (corresponding with The Nature Conservancy's classification of streams that are size 2 or greater, or all rivers that are not classified as headwater streams). Using this definition, there are 44 major tributaries to the Connecticut River (Table 1).

The ratio of total dam storage to mean annual runoff is a useful indicator of the potential impact of dams on river flows (Graf 1999), particularly in absence of an analysis of site-specific flow data. Because we do not have adequate stream gage data to examine site-specific hydrologic impacts for every tributary in the Connecticut basin, we calculated total maximum dam storage as a percent of mean annual runoff (flow index) as a means to compare the potential of hydrologic alteration due to dams among tributaries. For each tributary, we calculated mean annual runoff by gathering mean daily flow data for each day of the year (averaged over the period of record; available on the USGS website) recorded at the stream gage closest to the confluence with the mainstem Connecticut River. We multiplied each value of mean daily flow (measured in cfs) by the number of seconds in a day (86,400), and summed these values over the year (resulting in a calculation of mean cubic feet per year). For tributaries without gages (or without gages near the confluence) we estimated mean annual runoff using the relationship between basin area and mean annual runoff calculated for gaged tributaries. The mean coefficient for this relationship was 0.19 (standard deviation = 0.03). Thus, we multiplied the basin area by 0.19 to estimate mean annual runoff in ungaged tributaries. Total dam storage for each watershed was calculated by summing the maximum storage value for each dam listed in the National Inventory of Dams (NID) database (US Army Corps of Engineers 2006) for each tributary basin.

The ratio of dams per watershed area is a useful indicator of fragmentation in a watershed, although it does not take into account spatial distribution of dams, fish passage, or fragmentation from barriers other than dams, such as culverts. We divided the number of dams identified in the NID database (US Army Corps of Engineers 2006) for each tributary basin by basin area (in square miles) to calculate an index of dams/mi^2 (fragmentation index). Ratios of dam storage to mean annual runoff and dam fragmentation have been used to estimate the potential for hydrologic alteration in major rivers of North America and Eurasia (Dynesius and Nilsson 1994; Graf 1999).

In addition to the flow and fragmentation indices, we calculated percent of basin area in forested/shrub, wetland, agricultural, or developed land use. Basin area, stream drainage networks, and land use data were obtained from the EPA National Land Cover data set, image date 1992-1993. Land use as percent of basin area was calculated by Arlene Olivero (The Nature Conservancy, Eastern Regional Office) using ArcView GIS software. In addition to land cover data, we used ArcView to create maps of each tributary basin that included locations of dams and USGS stream gages. Dams and stream gages were added using coordinates of latitude and longitude from the NID (US Army Corps of Engineers 2006) and the USGS website.

Among-tributary comparisons

We examined the spatial distribution of threats to river flows and connectivity among tributaries by developing maps of the entire Connecticut River basin that rated tributaries according to their flow and fragmentation indices and illustrated basin-wide patterns in land use. We classified each tributary according to the risk for hydrologic alteration and fragmentation relative to other tributaries in the basin. Tributaries with maximum dam storage <10% of mean annual runoff were classified as “low flow risk”, and tributaries with storage >50% of runoff were classified as “severely impacted”. The remaining tributaries were split into two categories: a flow index between 10 and 30% was classified as “moderate flow risk” and an index between 31 and 50% was classified as “high flow risk”. We divided the range of fragmentation values for all tributaries into four equal bins and classified each tributary as “low fragmentation” (0-0.06 dams/mi^2), “moderate” (0.07-0.12 dams/m^2), “high” (0.13-0.18 dams/mi^2), or “very high” (0.19-0.24 dams/mi^2). We created individual basin-scale maps that illustrated 1) flow index; 2) fragmentation index; 3) % forest cover; 4) % wetlands; 5) % agriculture; and 6) % developed land.

Site-specific hydrologic analyses

Although the USGS operates 74 stream gages throughout the Connecticut River watershed, many of these gages were installed after the construction of upstream dams and do not have data available that characterize natural streamflows before dams were present. However, we analyzed the effects of dams on mean daily streamflows for a subset of tributary stream gages that had at least 20 years of flow data both before and after construction of an upstream dam (or dams). The purpose of these site-specific analyses was to examine changes in magnitude, duration, frequency, timing, and rate of change of components of the hydrograph (low flows, high flow pulses, and overbank flows) at individual locations, and determine if common changes in flows were occurring at multiple sites (e.g., the most dramatic changes to flow regimes basin-wide were decreases in the magnitude of low flows).

We 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, using mean daily stream gage data collected at the same location both before and after the construction of a dam or other water project. IHA calculates a total of 67 parameters (Richter et al. 1996; The Nature Conservancy 2005) that quantify the magnitude, frequency, duration, timing, and rate of change of components of the hydrograph, including low flows, high flow pulses, and small and large floods. We calculated all IHA parameters for each stream gage that had a sufficient period of record to incorporate inter-annual hydrologic variability (i.e., 20 years) pre- and post-dam construction. However, we only examined nine IHA parameters for each stream gage that we felt were the most useful for assessing hydrologic change, while minimizing the number of parameters reported for each site (Table 2).

Results

Tributary characteristics and comparisons

There are over 1000 dams listed in the National Inventory of Dams for the Connecticut River basin (US Army Corps of Engineers 2006) and approximately 2500 dams listed in state dam databases (Arlene Olivero, personal communication), although most dams do not have the storage capacity to have a large effect on hydrology. Of all the dams throughout the Connecticut River watershed, we estimated that 65 dams had the capacity to store at least 10% of local mean annual runoff. However, we could not estimate local mean annual runoff at all dam sites, thus our estimate of the number of dams with a ratio of maximum storage capacity to mean annual runoff of at least 10% is likely conservative. Although some of these dams are located on the mainstem Connecticut River, most are found in tributary basins.

Out of the 44 major tributaries to the Connecticut River, 27 had dam storage capacity (all dam storage in the tributary basin, combined) that was less than 10% of mean annual runoff at the confluence with the Connecticut River (Table 1). We considered these rivers to be at low risk for hydrologic alteration. We considered rivers with dam storage capacity greater than 50% of mean annual runoff to be severely impacted with respect to flow. Three tributaries were in this category (the Upper Connecticut, Deerfield, and Chicopee). Seven rivers were classified as having moderate flow risk (dam storage 10-30% of mean annual runoff), and seven rivers had high risk of flow alteration (dam storage 31-50% of mean annual runoff). Out of the ten rivers classified as high risk or severely impacted, seven had flood control dams owned by the Army Corps of Engineers (no flood control dams were located on rivers in the low risk category; flood control dams were located on two rivers in the moderate risk categories). Tributaries with a “low risk” rating were primarily located in the northern Connecticut River basin (northern Vermont and New Hampshire) or have a small drainage basin (Table 1). Figure A-1 (appendix) illustrates flow risk among tributary basins.

Fragmentation of tributaries ranged from 0 to 0.24 dams/mi^2. We divided this range of fragmentation values into four equal categories to assign a “fragmentation risk” to each tributary that was relative to other tributaries in the Connecticut River basin. Eighteen tributaries had low fragmentation (0.00-0.06 dams/mi^2), 15 were moderately fragmented (0.07-0.12 dams/mi^{2-}), 6 were highly fragmented (0.13-0.18 dams/mi^2), and 5 were very highly fragmented (0.19-0.24 dams/mi^2; the Bachelor, Hockanum, Mill/Manhan, Millers, and Sawmill Rivers). Rivers with low fragmentation values were mostly located in northern Vermont and New Hampshire, whereas rivers with high or very high fragmentation values were found mainly in Massachusetts and Connecticut. The fragmentation index was only based on the number of dams for each basin that was listed in the NID database (US Army Corps of Engineers 2006). The NID often does not list small dams that may not store much water but may still add to fragmentation of aquatic habitat. Therefore, more accurate assessments of dams in each tributary basin and fragmentation from other sources, such as culverts, will likely increase the fragmentation index for most tributaries. We assumed that smaller dams and culverts would likely be proportional to the number of NID dams in a watershed. Thus, although the fragmentation index would likely increase for most basins with the inclusion of additional data on stream barriers, the relative degree of fragmentation among tributaries would likely be similar. Figure A-2 (appendix) illustrates fragmentation from dams among tributary basins.

Comparisons of dominant land use among tributary basins tended to follow a north-south gradient throughout the Connecticut River watershed. Northern tributaries in Vermont and New Hampshire tended to be heavily forested, whereas southern tributaries in Connecticut tended to be more developed. The percent forest in tributary basins ranged from 37% in the Stony Brook watershed (Connecticut) to 91% in the Upper Ammonoosuc (New Hampshire), whereas percent developed land ranged from 1% in the Upper Ammonoosuc to 37% in the Stony Brook basin. Agriculture tended to be a low percent of total land use in tributary basins in Vermont, New Hampshire, and Massachusetts, but was more dominant in tributaries in Connecticut. The four tributaries with the largest percentage of agriculture in the basin (the Hockanum, Mattabesset, Stony Brook, and Farmington) and five of the eight tributaries with agriculture comprising over 10% of basin land use were located in Connecticut. Percent wetland in a basin tended to be constrained more by watershed geomorphology than human land use. Northern tributary basins, particularly in Vermont, tended to drain high gradient areas of the Green Mountains, thus did not have large areas of wetlands. In contrast, tributaries in Massachusetts and Connecticut tended to drain lower-gradient valleys and had more wetland areas. Figures A-3 through A-5 (appendix) illustrate land use trends among tributary basins.

Site-specific hydrologic analyses

Out of the 74 stream gages in the Connecticut River watershed, 11 gages had at least 20 years of data both before and after construction of an upstream dam. Of these 11 gages, two were on the mainstem Connecticut River and were not included in this analysis (no gages on the mainstem Connecticut River had 20 years of data before construction of all upstream dams). Therefore, we used IHA to examine changes in hydrology after dam construction for nine stream gages in seven tributary basins.

Overall, the most dramatic change in flows for all stream gages was the reduction in the frequency of floods (flows with 2-year or greater recurrence interval) and the magnitude of high flows (Table 3). Nine of eleven stream gages recorded a large decrease in flood frequency (ranging from 80 to 94%) and a more moderate decrease in the magnitude of the 3-day maximum flow (ranging from 1 to 94%). In contrast, the gage on the Ware River (Chicopee watershed) showed no change in high flows, whereas the Wells River had a 71% increase in the frequency of floods and a 9% increase in the 3-day maximum flow.

Low flows only decreased on two rivers, the Swift (in the Chicopee watershed) and the Ottauquechee. The 3-day minimum flow decreased by 39% in the Swift River and by 29% in the Ottauquechee River. The 3-day minimum flow remained relatively constant in the Ashuelot, Ware (Chicopee watershed), Westfield, and Middle Branch of the Westfield, and increased in the Black, Wells, and West Rivers. Low flow duration tended to increase and the frequency of the Q90 (the flow exceeded 90% of the time) tended to decrease across tributaries, although a few tributaries did not exhibit this pattern. Changes in central tendency (monthly median flows) tended to be greatest in the winter and lowest in the summer/fall, although not all rivers followed this trend.

Conclusions

Overall, dams for flood control, hydroelectric power generation, and water supply have all contributed to altered flows in tributaries to the Connecticut River basin. The three tributaries with a flow index classification of “severely altered”, the Upper Connecticut River, Deerfield River, and Chicopee River, all have large numbers of dams, but the dams with the largest storage capacities (thus, the greatest potential to alter river hydrology) fall into at least one of these three categories. The Upper Connecticut River has one flood control dam (owned by the state of New Hampshire), two hydroelectric dams, and one dam for recreation that all have large storage capacities. The Deerfield River has two hydroelectric dams with large storage potentials, as well as several smaller hydroelectric dams. The Chicopee Watershed has three dams that store a large volume of water in the Quabbin Reservoir, a water supply reservoir that mainly supplies communities in Eastern Massachusetts, outside of the Connecticut River basin. The Swift River (a tributary to the Ware River, which in turn is a tributary to the Chicopee) has been largely flooded to create the Quabbin, and two tributaries to the Chicopee (the Ware River and Conant Brook) have flood control dams owned by the Army Corps of Engineers. Our calculated flow index is useful for examining relative flow alteration among tributaries; thus, we can determine that the Upper Connecticut, Deerfield, and Chicopee likely have the most severely altered flow regimes of all the tributaries in the basin. However, our flow risk categories (severely altered, high risk, moderate risk, and low risk) are based on the distribution of dam storage to runoff ratios among tributaries, and are not based on site-specific hydrologic analyses or potential effects of altered hydrology on natural communities or ecosystems. In addition, we did not include water withdrawal data in this analysis (except as a component of dam storage in the case of water supply reservoirs), and the potential for hydrologic alteration in some rivers may increase if water withdrawals are considered. Thus, these indices should be used as a tool to determine rivers that require more detailed hydrologic and ecological analyses.

Fragmentation indices were based on the number of all dams per basin area, without emphasizing the size of a dam (or storage potential) or whether a dam had some type of fish passage. We were interested in estimating fragmentation to multiple aquatic and riparian species and communities as well as for stream processes, thus the lack of emphasis on fish passage. Not surprisingly, tributaries with large fragmentation values were those with relatively large numbers of small dams or with small basin area (thus affecting the dam to basin area ratio). Although this index is useful for examining relative fragmentation among tributaries, it does not provide information about average or maximum connected stream lengths, spatial distribution of dams, or fragmentation from other sources (such as culverts).

Indices of flow alteration and fragmentation are useful in illustrating the spatial extent and distribution of potential threats to freshwater ecosystems in the Connecticut River watershed, identifying sources of these threats, and selecting areas for more detailed analyses. Site-specific hydrologic analyses are necessary to quantify the degree and types (i.e., reduced overbank flows, lower low flows) of flow alteration in a river after a dam was constructed. However, these analyses cannot be performed for most gages in the Connecticut River basin because the period of record of flow data is insufficient. The Connecticut River basin has good coverage of stream gages and long records of flow data compared with other areas of the country. However, many dams in tributaries to the Connecticut River (dams for sawmills and gristmills) were built in the 1700's and the first dam across the mainstem Connecticut was constructed in 1798. Although many of these dams have since been removed or replaced by more modern structures built in the first half of the twentieth century, most stream gages do not have an adequate period of record before dam construction to be useful for an analysis of hydrologic alteration without some modeling of simulated natural flow conditions.

Site-specific hydrologic analyses in areas where sufficient data were available suggested that the main types of hydrologic alteration in tributaries to the Connecticut River were (1) reduced frequency of overbank flows (flows with 2-year or greater recurrence interval, (2) reduced magnitude of maximum flows, and (3) increased duration and decreased frequency of low flows. Reductions in magnitude of low flows were only observed in two tributaries (the Swift River of the Chicopee basin, site of the Quabbin Reservior, and the Ottauquechee River, a tributary containing a flood control dam). However, site-specific hydrologic analyses were only conducted for 7 of 44 tributary watersheds. In addition, none of the watersheds analyzed were in the southern Connecticut basin in the state of Connecticut. Based on land-use patterns, basins in Connecticut had higher percent developed land and likely had higher human population densities than tributaries in Massachusetts, Vermont, or New Hampshire. Higher population densities could result in higher rates of water withdrawals relative to other areas of the basin, leading to reduced magnitude of low flows, and relatively high proportion of impervious surfaces could lead to flashier storm flows and higher maximum flows. Out of the nine stream gages used in the site-specific analyses, seven gages were on tributaries with flood control dams owned by the Army Corps of Engineers, which may explain why reductions in maximum flows and flood frequency were the prevalent flow alterations in our analyses. The only tributary that showed an increase in the 2-year flood frequency (Wells River) was also the only tributary without an ACOE or state-owned flood control dam in the basin. Thus, analyses of a broader and more representative set of tributaries may result in different conclusions with respect to the types of flow alteration present in tributaries throughout the basin.

In conclusion, our spatial analysis of flow alteration and fragmentation among tributaries to the Connecticut River should be useful in conservation planning, either to protect areas with low risk for hydrologic alteration and high river connectivity, or to develop strategies to mitigate threats in higher-risk watersheds. This analysis should be used to target tributary basins that are of conservation interest, and eligible for more detailed site-specific studies. In particular, detailed hydrologic analyses of effects of dams, land use, and water withdrawals on mean daily flows should be conducted to determine the scope of hydrologic alteration in specific locations and potential effects on aquatic and riparian species, communities, and ecosystems. Finally, even most detailed hydrologic analyses only examine effects of water projects on mean daily flows. Many hydropower dams in the Connecticut River basin (both in the mainstem and tributaries) may cause substantial changes in hourly flows that are not measurable with daily flow analyses. Short-term flow fluctuations (within a 24-hour period) may have adverse effects on many aquatic and riparian species that use river margins or riparian habitat only available during summer low-flow periods (Zimmerman 2006b).

Table 1. Major tributaries (drainage basin >30mi^2) to the Connecticut River and watershed characteristics, including index of potential flow alteration, fragmentation by dams (using all dams included in the National Inventory of Dams database), and land use. "*" indicates tributaries with flood control dams owned by the Army Corps of Engineers.

Tributary	Drainage area (mi^2)	Flow index (%)[1]	Fragmentation index (dams/mi^2)	% Forest	% Wetland	% Agricultural	% Developed
Ammonoosuc	403	1.0	0.04	88.5	3.6	1.2	4.1
Ashuelot*	419	21.8	0.11	82.7	4.6	3.8	6.3
Bachelor	32	5.6	0.22	63.6	12.4	8.9	12.5
Black*	203	36.9	0.10	83.5	0.7	2.3	12.0
Chicopee*	724	850.0	0.17	66.6	8.4	6.4	10.3
Cold	97	1.7	0.03	84.5	3.2	1.5	9.6
Deerfield	663	73.7	0.08	83.6	4.4	2.4	7.4
Eightmile	61	0.5	0.10	79.6	6.1	2.2	9.7
Fall	35	1.5	0.17	73.5	5.7	6.8	13.1
Farmington*	606	46.2	0.14	70.6	6.3	10.2	8.9
Fort	49	0.6	0.12	59.2	8.1	12.6	19.1
Hockanum	80	16.6	0.20	39.3	6.8	38.1	13.5
Indian	71	0.4	0.01	90.8	6.8	0.1	1.0
Israel	138	0.0	0.00	85.1	5.8	0.8	5.5
Johns	73	6.1	0.07	76.7	11.5	1.2	5.7
Little Sugar	30	0.4	0.03	87.2	3.5	0.9	7.7
Mascoma	195	21.7	0.08	80.9	4.8	3.3	7.5
Mattabesset	109	12.4	0.18	42.1	5.9	28.2	20.7
Mill (Amherst)	35	5.3	0.14	64.4	5.3	11.6	17.0
Mill Brook	44	2.9	0.14	80.0	0.2	1.1	18.4
Mill/Manhan	145	22.2	0.20	69.1	7.1	10.1	11.8
Millers*	393	38.5	0.19	72.9	10.4	6.0	6.2
Mohawk	35	0.3	0.03	88.2	4.7	0.8	4.6
Nulhegan	146	0.0	0.00	88.3	8.7	0.2	0.7
Oliverian	39	5.9	0.05	88.1	2.2	0.2	6.7
Ompompanoosuc*	136	39.9	0.07	85.4	1.8	0.3	10.8
Ottaquechee*	224	34.5	0.09	85.6	0.5	0.6	11.7

Tributary	Drainage area (mi^2)	Flow index (%)[1]	Fragmentation index (dams/mi^2)	% Forest	% Wetland	% Agricultural	% Developed
Passumpsic	505	4.5	0.03	80.5	4.3	2.0	10.4
Roaring Brook	49	7.4	0.12	66.2	9.3	5.8	17.4
Salmon	150	26.1	0.09	68.8	8.4	6.0	13.1
Sawmill	33	6.1	0.24	75.0	11.6	4.5	7.2
Saxtons	78	0.1	0.01	89.6	2.2	1.3	6.4
Scantic	113	1.0	0.10	55.5	5.2	11.6	26.6
Stevens	47	7.6	0.06	74.1	2.7	1.1	19.0
Stony Brook	37	2.2	0.08	35.6	8.1	18.2	36.5
Sugar	283	32.4	0.12	78.3	4.8	3.3	9.3
Upper Ammonoosuc	253	0.8	0.04	91.0	3.9	0.8	1.1
Upper Connecticut	183	176.5	0.05	86.9	4.9	0.2	0.7
Waits	154	0.4	0.03	86.1	2.9	0.8	9.2
Wells	100	6.0	0.04	83.2	3.6	0.9	8.2
West*	420	30.5	0.04	89.8	2.4	1.1	5.8
Westfield*	517	23.8	0.12	78.3	5.1	6.3	7.7
White	710	0.6	0.03	83.5	1.6	0.9	12.9
Williams	116	0.0	0.01	88.1	1.6	1.3	8.3

[1]Flow index is calculated as the maximum dam storage in a basin divided by the mean annual runoff (multiplied by 100)

Table 2. Flow metrics used to examine hydrologic alteration at stream gage sites on tributaries to the Connecticut River. All parameters were reported as % change pre- and post-dam (post dam - pre-dam/pre-dam). List of parameters is from Colin Apse (The Nature Conservancy, Eastern Region Freshwater Program).

Flow characteristic	IHA parameter	Definition
Summer/fall central tendency (magnitude)	July-October median flow	Sum of the % change (absolute value) of monthly median flows
Winter central tendency	November-February medians	Sum of the % change (absolute value) of monthly median flows
Spring central tendency	March-June medians	Sum of the % change (absolute value) of monthly median flows
Low flow frequency	Low pulse count	% change in the median annual frequency of low flows that are exceeded 90% of the time (Q90)
Low flow duration	Low pulse duration	% change in the median annual duration of low flows (Q90)
Low flow magnitude	7-day minimum flow	% change in the magnitude of the median 7-day low flow
High flow frequency	Flood frequency (2-year and greater recurrence interval)	% change in the mean annual frequency of floods with at least a 2-year recurrence interval
High flow duration	Flood duration (2-year and greater recurrence interval)	% change in the mean annual duration of floods with at least a 2-year recurrence interval
High flow magnitude	3-day maximum flow	% change in the magnitude of the median 3-day high flow

Table 3. Results of hydrologic analyses for stream gages on tributaries to the Connecticut River with at least 20 years of daily flow data pre- and post-construction of an upstream dam. All results represent % deviation from natural flow conditions (i.e., conditions pre-dam) after dam construction. Seasonal columns (summer/fall, winter, and spring) represent the absolute value of the sum of % deviation between pre- and post-dam for median monthly flows in that season (e.g., the summer/fall column represents the summed % deviation of median monthly flows for July-October, typically a period of low flows). For all other columns, negative values represent a % decrease compared to pre-dam flows, whereas positive values represent an increase. Out of all the tributaries represented, only the Wells River was at a low risk for hydrologic alteration based on our flow index.

Tributary	Gage number	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	1161000	11	18	20	-69	233	-05	-21	-83	34
Black	1153000	34	79	85	-53	50	21	-12	-80	-24
Chicopee (Swift River)	1175500	15	31	4	43	8	-39	-91	-93	61
Chicopee (Ware River)	1173000	24	23	16	-33	33	5	1	2	0
Ottauquechee	1151500	16	34	18	37	0	-29	-18	-81	-56
Wells	1139000	29	27	10	-40	-25	21	9	71	3
West	1156000	17	30	11	-80	100	47	-12	-89	4
Westfield	1179500	20	22	15	-30	0	5	-1	-94	21
Westfield (Middle branch)	1180500	8	18	20	-60	-10	4	-8	-87	-23

Literature Cited

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

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

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.

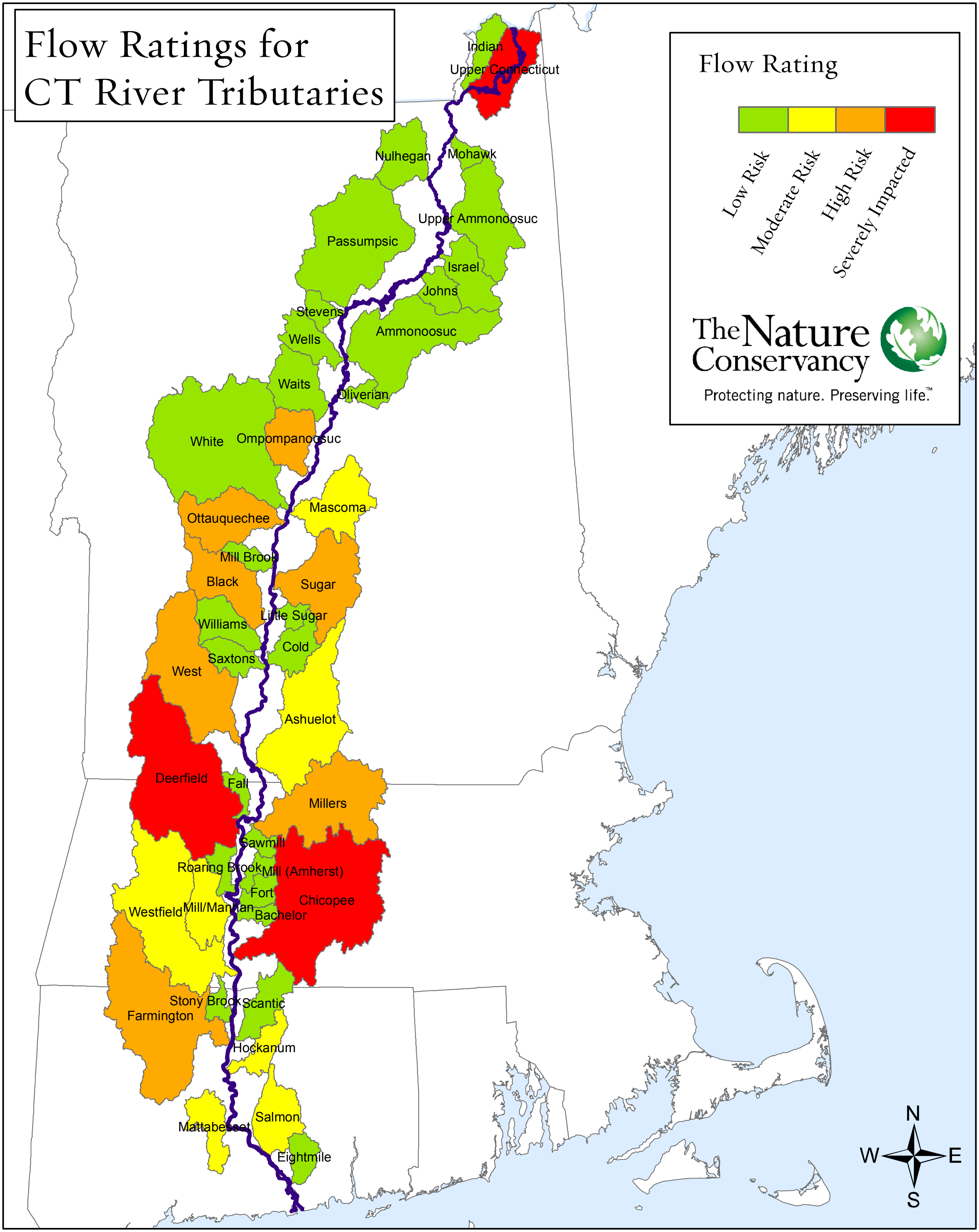
The Nature Conservancy. 2005. Indicators of Hydrologic Alteration. Version 7.0.

US Army Corps of Engineers. National Inventory of Dams. http://crunch.tec.army.mil/nid/webpages/nid.cfm U.S. Army Topographic Engineering Center, Alexandria, VA.

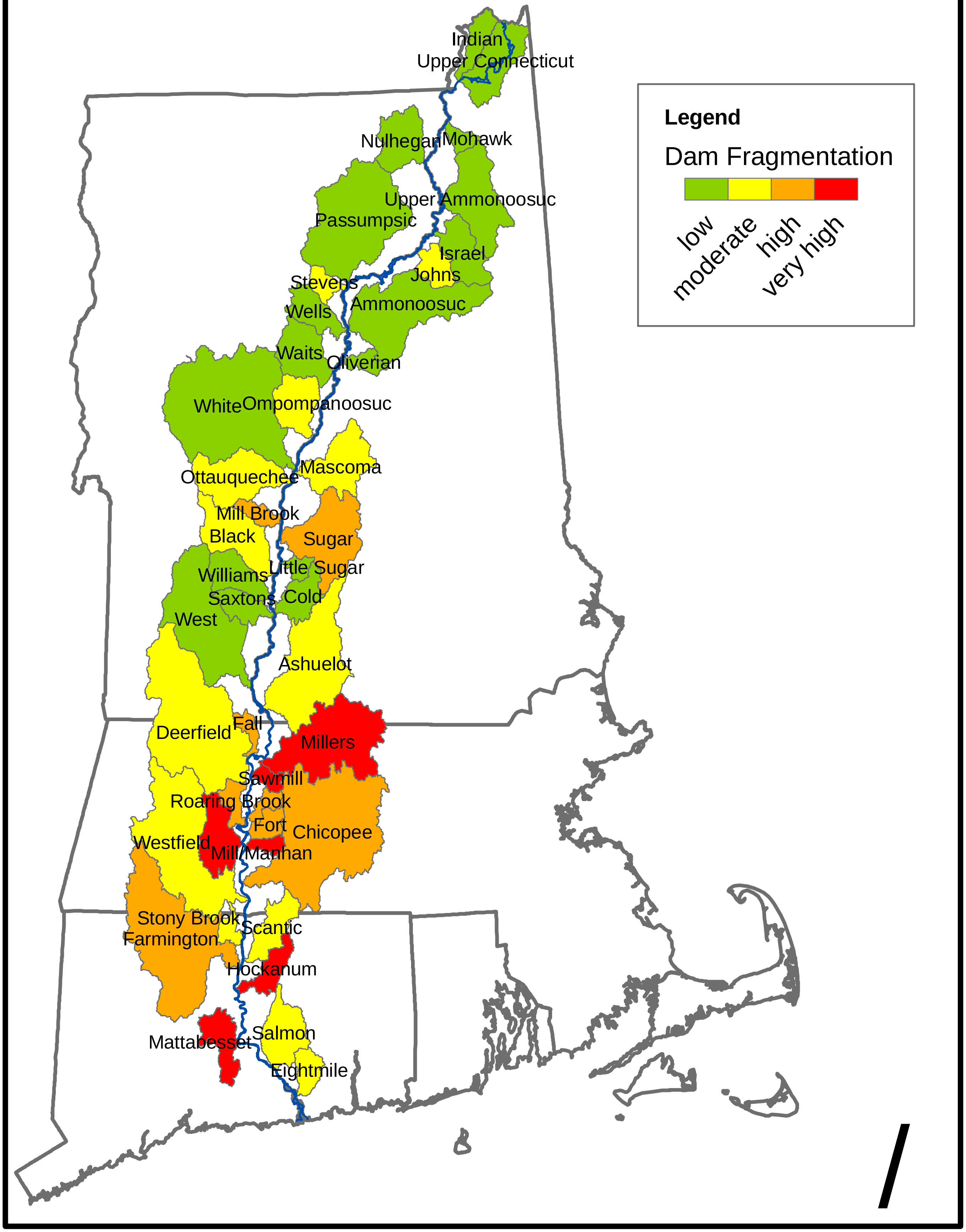
Zimmerman, J. K. H. 2006a. Hydrologic effects of flood control dams in the Ashuelot River, New Hampshire, and West River, Vermont. The Nature Conservancy, Connecticut River Program, Northampton, MA.

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

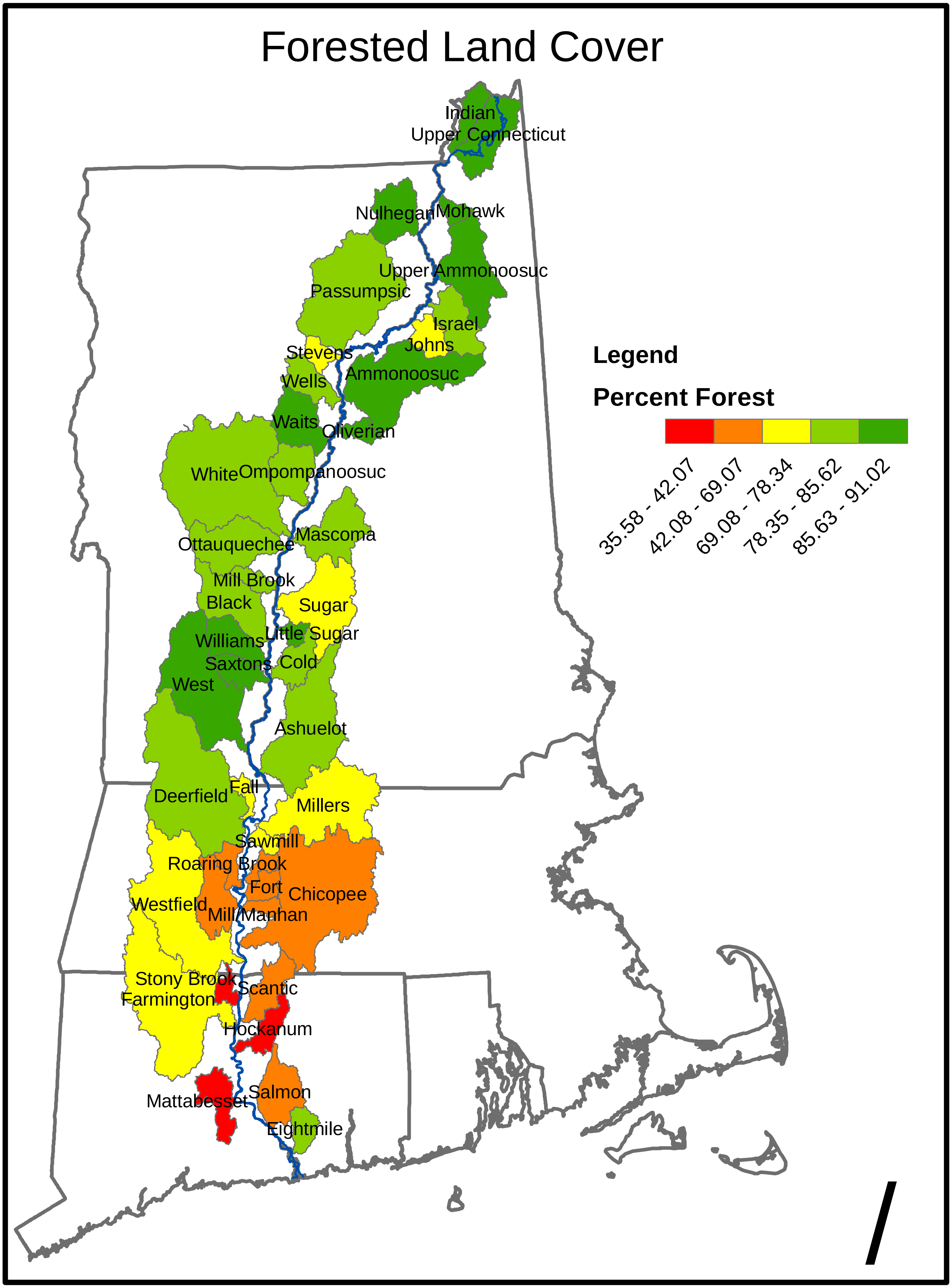
Flow Ratings for CT River Tributaries



Dam Fragmentation for CT River Tributaries



Forested Land Cover



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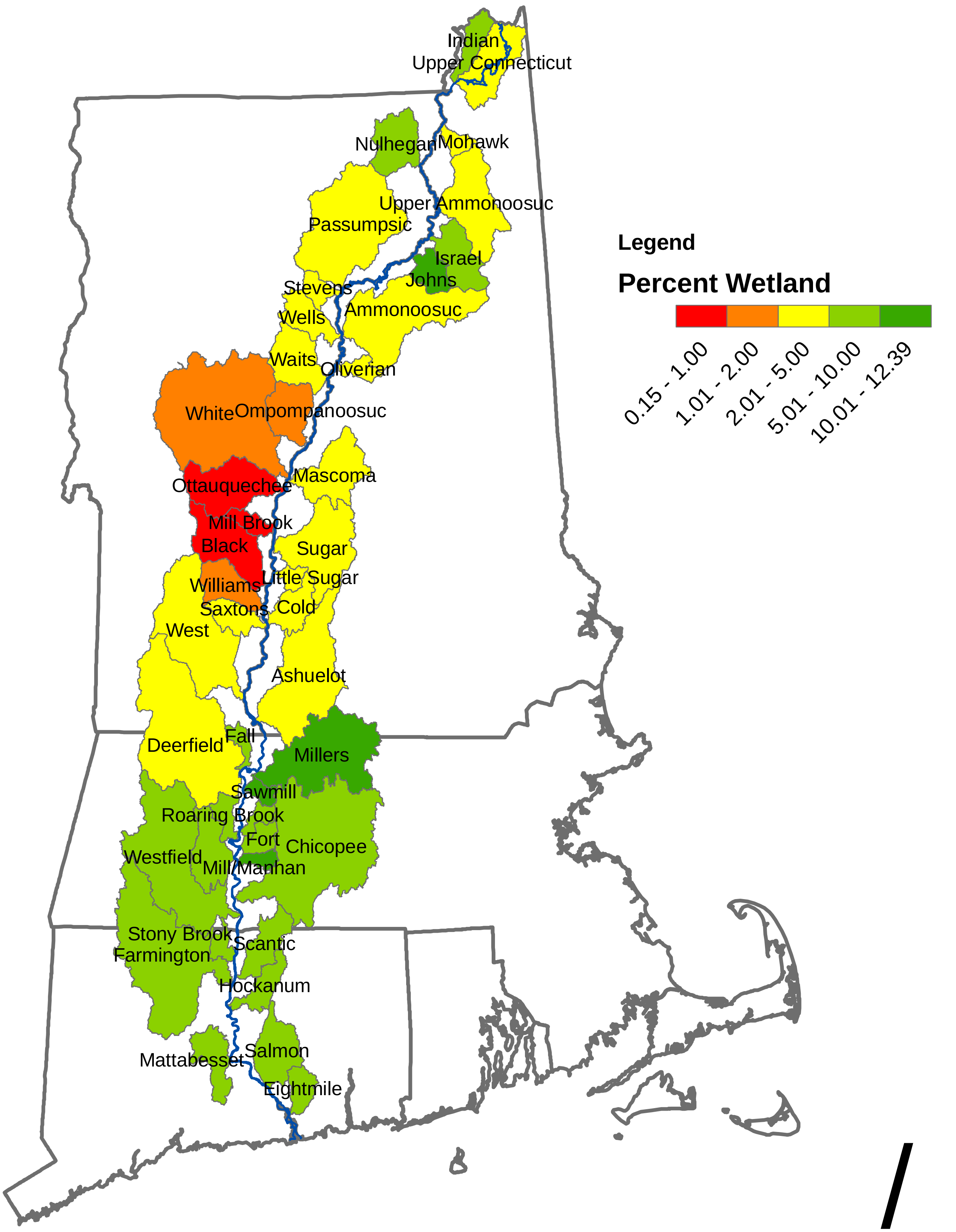
Percent Wetland



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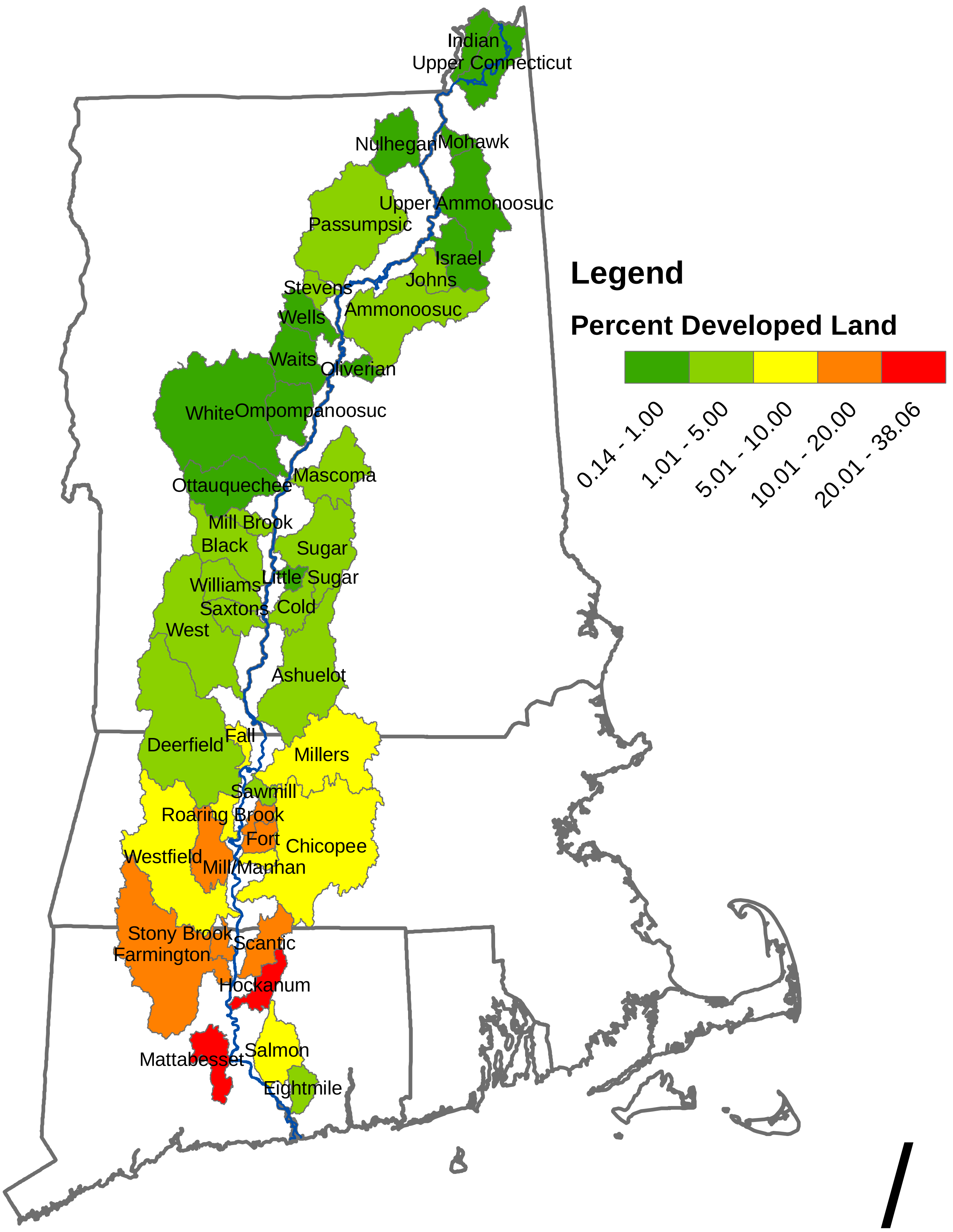
Percent Developed Land



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