LONG-TERM CHANGES IN REGIONAL HYDROLOGIC REGIME FOLLOWING IMPOUNDMENT IN A HUMID-CLIMATE WATERSHED

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ABSTRACT

We analyzed the type of hydrologic adjustments resulting from flow regulation across a range of dam types, distributed throughout the Connecticut River watershed, using two approaches: 1) the Index of Hydrologic Alteration (IHA) and 2) log-Pearson Type III flood frequency analysis. We applied these analyses to seven rivers that have extensive pre- and post-disturbance flow records and to six rivers that have only long post-regulation flow records. Lastly, we analyzed six unregulated streams to establish the regional natural flow regime and to test whether it has changed significantly over time in the context of an increase in forest cover from < 20 % historically to > 80% at present. We found significant hydrologic adjustments associated with both impoundments and land use change. On average, maximum peak flows decrease by 32% in impounded rivers, but the effect decreases with increasing flow duration. 1-day minimum low flows increase following regulation, except for the hydro-electric facility on the mainstem. Hydrograph reversals occur more commonly now on the mainstem, but the tributary flood control structures experience diminished reversals. Major shifts in flood frequency occur, with the largest effect occurring downstream of tributary flood control impoundments, and less so downstream of the mainstem's hydro-electric facility. These overall results indicate that the hydrologic impacts of dams in humid environments can be as significant as those for large, multiple-purpose reservoirs in more arid environments.

KEYWORDS: dams, floods, low flow, watershed management, aquatic ecosystems.

INTRODUCTION

Reservoirs, dams, irrigation flow diversions, and flood control structures have been common developments over the past five decades to the extent that relatively few large rivers are unaffected by these alterations (Benke, 1990; Graf, 1999). Reservoirs vary in size and function, so generalizations are difficult (Power et al., 1996). Dams, though, generate significant hydro-geomorphic alterations with impacts occurring both upstream and downstream of reservoirs (Williams and Wolman, 1984; Collier et al., 1996; Hadley and Emmett, 1998), and these hydro-geomorphic impacts have profoundly altered and degraded river ecosystems (cf. Ward and Stanford, 1995; Bovee, 1986; Ligon et. al., 1995; Power et al., 1996). In order to mitigate the environmental consequences of flow regulation, numerous instream flow measures have been suggested to sustain and maintain ecological integrity along a stream reach. These measures include establishing and maintaining minimum flow releases (Colby, 1990) or permitting controlled "flushing" releases that establish the necessary high flows for sediment transport (Williams, 1996; Collier et al., 1996; Stanford et al., 1996; Collier et al., 1997; Rubin et al., 1998). However, controlled flushing flows may not serve to enhance the entire spectrum of ecological or geomorphological conditions and therefore may not be a system-wide solution (Kondolf and Wilcox, 1996; Wu, 2000). Instead of tailoring flows for particular species or flow requirements, Power et al. (1996) suggest that ecological integrity is best preserved by regulation structures and management schemes that approximate the natural flow regime inherent prior to flow management and disturbance (cf. Stanford et al., 1996; Poff et al., 1997). Determining the effects of impoundments on this natural regime is therefore critical for restoration and conservation of aquatic ecosystems.

While previous studies have documented significant changes in hydrologic and sediment regimes before and after impoundment (Graf, 1980; Williams and Wolman, 1984; Chien, 1985; Andrews, 1986; Elliott and Parker, 1997; Hadley and Emmett, 1998; and Van Steeter and Pitlick, 1998), this literature has some important limitations. Specifically, most previous research efforts have examined single case-studies of pre- and post-impoundment conditions in large, water storage reservoirs in semi-arid Western United States watersheds. Impoundment effects under these conditions are likely to differ significantly from effects of other reservoir types (for example flood-control dams), and for other, more mesic geographic regions. Focus on single case-studies also precludes integrated assessment of impoundment effects on drainage-wide or region-wide scales, where a range of reservoirs types exist. Finally, focusing on single case studies of pre-and post impoundment often lacks appropriate spatial controls (i.e. physically comparable, unimpounded rivers). Without these controls, long-term changes in flow regimes caused by land use or climate change may be incorrectly singularly attributed to impoundment.

This paper details the hydro-geomorphic adjustments occurring within the Upper Connecticut River watershed as a function of long-standing and widespread flow regulation. Our basic goal is to determine the pre-impact and on-going "natural" flow regime for the Upper Connecticut River watershed across a range of basin sizes, and to determine what hydrologic features have been most affected by flow regulation. The wide range and magnitude of flow regulation, and the dense network of stream gages with long periods of record, make the Connecticut basin an excellent study system to evaluate these goals. We applied two techniques, the Index of Hydrologic Alteration (Richter et al., 1996) and log-Pearson Type III flood frequency analysis, to nineteen gages with daily discharge data having an average length of record of ~ 50 years. We applied these methods to determine if reservoirs have significantly altered the hydrologic regime, and if so, what hydrologic index best captures and expresses that disturbance. Secondly, in order to determine if post-reservoir changes resulted singularly from the impacts of reservoirs, we examined the hydrologic characteristics for undisturbed streams to ascertain the "natural" background conditions of those site-specific and regional changes.

STUDY AREA

For the purposes of this study, we are describing the Upper Connecticut River watershed as the section upstream of the Vermont/Massachusetts border and continuing upstream to North Stratford, NH (Fig. 1). This section is an ecologically sensitive region. Three federally-listed endangered species occur along a 15 km reach downstream of Wilder Dam in West Lebanon, NH to approximately Hart Island, VT: the dwarf wedge mussel (*Alasmidonta heterodon*), Jesup's milk vetch (*Astragalus robinsii* var. *jessupi*), and the cobblestone tiger beetle (*Cincindela marginipennis*). Furthermore, floodplain forests have declined in quality and extent in part due to several centuries of agricultural disturbance, but also due to reductions in overbank flooding resulting from flow regulation (Bechtel and Sperduto, 1998). Those remaining floodplain forests generally consist of single-age stands with few young trees (Bechtel, pers. comm.), a pattern strongly associated in other regions with diminished magnitude and frequency of large floods (Molles et al., 1998).

The area is lithologically diverse, and in the West Lebanon, NH section it consists primarily of intensely folded meta-sedimentary and meta-volcanic rocks ranging in metamorphic grade. Low temperature biotite-garnet zones occur along the mainstem of the Connecticut River with progressively higher grade metamorphics trending westward from the Connecticut River (Lyons, 1958). Granitic intrusions also commonly exist, and most of the region is mantled by a relatively thick till cover except at the higher elevations or along the steep hillsides. The region is highly dissected with most of the incision occurring prior to Quaternary glaciation (Denny, 1982). The main valley of the Connecticut River is relatively narrow, and the narrowing is exacerbated by a series of late-Pleistocene and Holocene terraces inset within the already constrained valleys.

The region possesses a continental humid climate with precipitation averaging approximately 900 mm/yr with a relatively even distribution throughout the year. The even precipitation pattern, however, does not manifest in an even flood distribution. New England possesses a mixed population flood regime with several flood producing mechanisms present: rain (sometimes as hurricanes), rain-on-snow/frozen ground, and snowmelt (Magilligan and Graber, 1996). Large floods have ravaged New England throughout the early to mid-twentieth century with catastrophic floods occurring in 1927, 1936, 1938, 1954, 1955, 1969, and 1987 (Jahns, 1947; Patton, 1988).

Because of the intensity and frequency of floods in the region, a series of flood-control dams were constructed in the 1950s and 1960s on some of the major tributaries of the Connecticut River. Conversely, most of the large dams on the mainstem of the Connecticut River are hydropower dams that were constructed in the early and middle part of the century. These hydropower dams are operated by various public and private utilities and contain a mixture of storage reservoirs and run-of-the river power generation facilities (cf. Fallon-Lambert, 1998). The region possesses one of the highest frequencies of dams per area in the United States; however, the storage impacts are not as great as other regions where larger structures exist and where climates are more arid (Graf, 1999).

USGS stream monitoring began early in New England with numerous gages having records beginning in the 1910s. This lengthy record coincides with other changes in the New England landscape, primarily the shift away from agriculture and grazing (both cattle and sheep). The peak of land clearing occurred in the late 1800s and has declined dramatically over the 20th Century, with many parts of the region currently at their highest levels of forest cover in well over one hundred years (Fig. 2). Despite this widespread reforestation, on-going urbanization and scattered agricultural activity, combined with lag effects of basin recovery (cf. Magilligan and Stamp, 1997), certainly limit pre-disturbance characteristics from being completely attained. However, modern flow characteristics for unregulated and regulated streams differ considerably from their early 20th Century counterparts due to this regionally extensive reforestation. In some instances, the modern regime in many unregulated streams may approximate their pre-historical flow conditions.

METHODOLOGY

The dominant focus of this study is to document the impacts of flow regulation by dams, and we have accomplished this primarily by analyzing stream gage data for seven rivers that have lengthy pre-impoundment flow data combined with extensive post-impoundment data. One of these dams, the Wilder Dam at West Lebanon, NH, is a hydro-electric facility on the mainstem Connecticut River, while the remaining six sites occur on the tributaries and are primarily flood-control structures (Fig. 1, Table 1). In order to broaden the scope of impoundment impacts, we also analyzed six sites that have USGS monitoring over the period of impoundment, but that lack a comparative pre-impoundment flow record. These sites cannot be compared to a pre-disturbance flow regime but can be used as replicates of post-impoundment impacts. These sites generally have long gaging records that capture long-standing hydrologic changes typical of flow regulation and include a broader range of dam types and contributing basin area. Two more hydro-electric dams on the mainstem of the Connecticut river are included: one 60 km upstream of the Wilder Dam at West Lebanon (the Connecticut River at Wells River), and the Bellows Falls Dam at North Walpole, NH approximately 60 km downstream of the Wilder Dam. Lastly, in an attempt to characterize long-term hydrologic changes occurring throughout the 20th Century by climatic and land use controls, we analyzed the gage data for six unregulated tributary sites. The main site for this part of the analysis is the White River, VT, which is the largest free flowing monitored river in the Upper Connecticut River basin (1,757 km^2) and also possesses one of the longest USGS gage records, dating back to 1915. It drains the southern and eastern flanks of the Green Mountains and empties directly into the Connecticut River, less than 4 km downstream of the Wilder Dam in West Lebanon, NH. We have analyzed these records for all gaged sites using two distinct methodologies: The Index of Hydrologic Alteration and log-Pearson Type III flood frequency analysis.

Index of Hydrologic Alteration

Flow regulation can affect the timing, magnitude, duration, and frequency of flows. We have used the Index of Hydrologic Alteration developed by Richter et al. (1996) to quantify these potential impacts and applied it to nineteen stream gage records throughout the Upper Connecticut River watershed. This model uses mean daily discharges and calculates 32 indices that describe the hydrologic regime for that station (Table 2). The thirty-two indices generated by IHA consist of five major categories : (1) magnitude; (2) magnitude and duration of annual extreme conditions; (3) timing of annual extreme conditions; (4) frequency and duration of high and low pulses; and (5) rate and frequency of changes in conditions. In essence, the model evaluates changes in both minima and maxima, and also synthesizes and groups these two extremes over several temporal scales (1-day, 3-day, 7-day, 30-day, and 90-day). The method does not characterize the storm hydrograph per se, but instead calculates the hydrograph rise and fall based on the mean daily discharges, and determines the number of rises and falls for a given year. The IHA expresses hydrologic variability within the year by calculating the number of times the sequence of daily discharges changes from a rising hydrograph to a falling hydrograph, and vice versa. These reversals can occur on daily, weekly, or seasonal scales and depend upon broad hydro-climatological conditions reflecting regional flood-producing mechanisms and basin characteristics. For large basins where snowmelt floods dominate the hydrologic regime, spring runoff will be a long continuous hydrograph rise with little fluctuation. In smaller streams or in situations where an interrupted sequence of frontal storms drives runoff, the number of hydrograph rises and falls will be maximized. The model also expresses the duration of high and low events and determines, for a given year, the number of times (i.e. “pulses”) that the 75th percentile is exceeded and the number of times that the 25th percentile is not attained. It also characterizes the length of the pulses exceeding the representative quartiles. All of the indices of the IHA were also regressed against time (in years) to determine if any significant serial trends exist due to climatic or land use impacts. Precipitation data came from the Hanover, NH gage which has a lengthy series that covers the entire record of streamflow data.

Flood Frequency Analysis

Most of the attention on hydrologic parameters generally addresses in-channel flows (1-day minimum, hydrograph reversals, etc.), yet many other ecological parameters within the riparian zone depend upon the occurrence of annual maximum events. For lowland sites in the Connecticut River basin, the condition and maintenance of floodplain forests is a critical issue. Many of the floodplain forests have been disturbed or destroyed by logging, agriculture, or urbanization throughout the 19^{th} and 20^{th} Century; however, less direct causes may also explain their demise and/or degradation. Many of the floral and faunal species in these riparian-to-terrace environments require some modicum of disturbance to keep out competitors, to bring in nutrients, or to enhance seed dispersal (Bayley, 1995; Hughes, 1997). Floods are the usual mechanism to effect these conditions, and flow management by impoundments has greatly reduced the magnitude and frequency of floods in the Upper Connecticut River basin. In order to isolate the changes in flood frequency due to flow regulation, we used a log-Pearson Type III analysis for the annual maximum flood series for each gage and calculated the estimated 2-yr, 5-yr, 10-yr, 20-yr, 100-yr, and 200-yr discharges for all nineteen gages (U.S. Water Resources Council, 1976). If the station had a pre- and post-disturbance flow record, we calculated these estimated flood frequencies for the pre- and post-disturbance record to show the hydrologic shifts in out-of-bank discharges as a function of regulation. These comparisons demonstrate, in a probabilistic sense, the changes that occur in a stream's ability to inundate overbank areas as well as indicating the shifts in the bankfull discharge, which is the dominant discharge associated with channel formation and sediment transport and strongly corresponds to the 2-yr flood (Wolman and Miller, 1960; Andrews, 1980). In addition to these comparisons, data from the flood frequency analysis were used to establish a regional bankfull flood frequency curve for unregulated rivers (Fig. 3). This curve was the basis for establishing a critical aspect of the natural flow regime, and was subsequently used to compare bankfull flood frequencies of impounded rivers.

RESULTS

Hydrologic impacts following impoundment

Discharge Variation for High Flows

For the Upper Connecticut River basin the dominant impact of regulation appears to manifest in the magnitude and duration of extreme conditions. The lack of importance of the other IHA parameters may be a function of the humid climate of the northeastern US and/or result from the types of dams present in the region. For example, alterations in the timing of high flows have not necessarily occurred following impoundment in the Upper Connecticut River basin (Fig. 4). This lack of effect contrasts strongly with impoundment impacts in the arid and semi-arid southwestern US where snowmelt from the mountains is stored for subsequent later release. Furthermore, in five of the seven basins, the date of the annual maximum flow is somewhat earlier (2-26 days earlier), but because of the large range in the standard deviations, the trend is not statistically significant.

The most significant changes emerged in the magnitude of high flows following impoundment. On average, 1-day maximum flows decrease by approximately 32% following flow regulation. Six of the seven sites are flood control structures on major tributaries and are therefore designed to contain high flows. However, the difference in high flows decreases as the temporal window expands (Fig. 5). At the temporal scale of the month to the seasonal (i.e. 90-day), no significant differences exist following impoundment. The average range in the annual maximum flood decreases by approximately 32% and is fairly consistent across dam type and contributing basin size, except for the Ompompanoosuc River in Vermont which experienced only a 20% reduction (Fig. 6). This river has one of the smallest drainage areas (326 km^2) of all our sites and also has a different management operation. The dam operates as a run-of-the-river facility from May to November, but maintains a 6 m pool elevation from November to May. Conversely, the North

Hartland Dam on the Ottaquechee River is a combined flood control and recreational facility. It has a similar contributing watershed size (570 km^2) as the Ompompanoosuc River, yet it has a greater reduction in the average of the annual maximum floods. Because of its recreational function, it maintains a constant 10.6 m pool elevation throughout the year.

Discharge Variation for Low Flows

The magnitude, duration, and timing of low flows control an array of ecological functions (Poff et al., 1996), and changes in low flows following impoundment can be as severe as changes in high flows (Hadley and Emmett, 1998). Many of the trends evident in high flows, though, do not extend to differences in low flow conditions for the same time steps, as strong differences exist in the response of tributary rivers and the mainstem Connecticut River. Tributaries generally experienced increases in 1-day minimum flows following impoundment (Fig. 7), while 1-day minimum flows strongly decreased following impoundment in the mainstem Connecticut (Fig. 7). These differences in response likely result from differences in dam type and management, and/or basin size. The reduced 1-day minimum flows may also reflect the lack of government control on minimum releases in the early part of the post-impoundment record. Government-mandated minimum flow releases did not occur until the later 1970s, and the severely dry years of the late 1950s and early 1960s corresponded with unusually low releases from the Wilder Dam in West Lebanon, NH (Fig. 8). The need to store water for hydropower generation and the occurrence of an unusually dry climate of the 1960s explain the differing pattern for the Connecticut River at West Lebanon although the extensive low flows pre-date the regional drought. For the tributaries, increased 1-day minimum flows following impoundment may correspond to the natural changes tending to occur over time in unregulated streams. Thus, for minimum flows, the impact of flow regulation on the tributaries appears to mimic currently occurring conditions in free flowing streams (see subsequent section "Hydrologic regime in unregulated rivers").

No trend exists in the average date of minimum flows as four of the seven basins have average minimum flows occurring earlier in the year (Fig. 4). The wide range in the standard deviations precludes any statistical significance. However, the magnitude of the extreme low flow minima (i.e. 1-day) tends to increase following impoundment (Fig. 7), but the trends are less decisive as the duration (e.g. 3-day, 7-day, etc.) increases. For the mainstem Connecticut River, low flows for all durations decrease following impoundment, which may either reflect its basin size, operation function (i.e. hydropower), and/or management history. Post-impoundment low flows increased for all durations for the Black River and West River, but the effect is only statistically significant for the 90-day duration for the Black River and for the 3-day minimum flow for the West River. In general, low flows for all tributary streams tend to increase for all durations following impoundment, but the large variance over the time series limits any definitive conclusions. For the Connecticut River, low flows decrease following impoundment for all durations, but the decrease is only statistically significant for the 1-day and 3-day low flow durations.

Hydrograph Changes

For impoundments within the Upper Connecticut River watershed, hydrograph reversals tend to decline, except for the Wilder Dam on the Connecticut River which has a 30% average increase in the number of hydrograph reversals (Fig. 9). Trends evident across the sites again probably reflect dam type and perhaps, to a lesser degree, contributing watershed area. The summer run-of-the-river management operation of the Union Village Dam on the Ompompanoosuc River shows the least change in hydrograph reversals. This management perhaps best mimics the regional natural flow regime as it permits more reversals in the summer (typical of rain-induced runoff punctuating summer streamflow drawdown) and less reversals in the late spring (typically a long hydrograph rise season) Conversely, the Connecticut River below Wilder Dam has become more "flashy" following impoundment due to its management as a hydropower facility (with some flood control). Prior to impoundment the Connecticut River at West Lebanon had a typical large watershed, snowmelt-dominated hydrologic regime averaging 108 reversals per year (Fig. 9). Subsequent to impoundment, the number of reversals has increased to approximately 160 per year.

Hydrologic Adjustments at Other Impounded Sites

Hydrologic impacts for the two additional hydro-electric sites on the Connecticut River (Table 1) correspond to the magnitude, type, and direction of shifts that exist for the post-impoundment data for the Wilder Dam on the Connecticut River. Even though the Bellow Falls Site is 60 km downstream of the Wilder Dam with an additional 5,000 km^2 of contributing basin area, its average post-impoundment 1-day and 3-day minimum flows (Table 3) are well below that of the pre-impoundment 1-day and 3-day minimum flows for the Wilder Dam. The trend reverses for low flow durations of 7-days or greater. Also, if the magnitudes and shifts following impoundment of the Wilder Dam are accurate, then the low flows at the two additional sites on the Connecticut River are probably less than their pre-impoundment natural low flows. The post-impoundment Julian dates for the minimum and maximum flows agree fairly closely amongst the three sites on the Connecticut River, with the dates for the Connecticut River at Wells River being almost identical with those at the downstream Wilder Dam (Table 3 and Fig. 4). Furthermore, flow regulation for these hydropower facilities generates the same number of reversals evident at the Wilder Dam suggesting that the post-impoundment "flashiness" of the hydrograph is a mainstem phenomenon.

Results from the tributary impoundments are slightly more difficult to interpret as they lack specific analogs and/or pre-impoundment flow records. However, when compared to pre- and post-impoundment flow data for similar size basins, generally similar impacts result. The discharge changes do not necessarily vary sequentially with changes in drainage area, which may reflect differences in dam management operation. The minimum flows for the West River for the 1-day through the 30-day flow durations are lower than the releases for the Mascoma River which has a smaller contributing drainage area. The Mascoma River reservoir is a combined water supply and recreation facility while the reservoir on the West River is a U.S. Army Corps of Engineers flood control structure which maintains a constant pool elevation. Furthermore, the flood control structure on the Ashuelot River has unusually low releases for all low flow durations.

Mean 1-day maximum flows following impoundment for these sites generally correspond to post-impoundment changes for those sites with a pre- and post-impoundment flow records. The sites in Table 3 do not have pre-impoundment records for comparison, however data for free-flowing rivers can be used as surrogates of pre-impoundment flows if differences in drainage area can be adjusted for. The quotient of peak flows and drainage area (i.e. specific discharge) for free-flowing rivers and for post-impoundment 1-day maximum flows (Fig. 10) resembles the same pattern for those sites with extensive pre- and post impoundment records, indicating that peak discharges per square kilometer have been reduced on the order of nine percent.

Impoundment Impacts on Flood Frequency

The reduction in the peak discharges due to flow regulation (Fig. 6) can be expressed by adjustments in the probability of achieving a flow of a specific magnitude. Dam type, location, and management can significantly modify the natural magnitude-frequency relationships. For alluvial surfaces containing floodplain forests, these shifts in magnitude-frequency relationships manifest in a decreased occurrence (in a probabilistic sense) of inundation. Most of the alluvial surfaces containing floodplain forests occur within the main valley of the Connecticut River, and may exist as bars and islands, and/or may be on low-lying late Pleistocene and Holocene terraces. Flow regulation by Wilder Dam on the mainstem of the Connecticut River has greatly modified the natural magnitude-frequency relationship which hinders the frequency of inundation of these riparian surfaces. Log-Pearson Type III analyses for the pre-impoundment flow record generates a 2-yr bankfull discharge of 1,370 m^3/s which correlates perfectly with the regional flood frequency analysis for bankfull discharges for free-flowing rivers (Fig. 3). Comparison of pre- and post-impoundment flood frequencies indicates that major reductions have occurred with the impacts becoming especially acute for floods with a 10-yr or greater recurrence interval (Fig. 11A). The pre- and post-impoundment 2-yr bankfull discharges are relatively close indicating that the flow release strategies currently in use have not affected the magnitude of the bankfull discharge. The discharge differences become progressively larger as the recurrence intervals increase. Many of the floodplain forest communities exist beyond the 10-yr floodplain, and these surfaces have a post-impoundment frequency of inundation that would require the post-impoundment 100-yr flood.

The shifts in magnitude-frequency relationships are even more dramatic for smaller watersheds, irrespective of management style. Flow regulation on the Black River in southern Vermont has so significantly altered the flood frequency relationships that the pre-impoundment 2-yr bankfull discharge of 158 m^3/s exceeds the post-impoundment 200-yr flood (Fig. 11B). Moreover, the largest discharge released following impoundment (117 m^3/s) would have only corresponded to the pre-impoundment 2-yr flood. The Union Village Dam on the Ompompanoosuc River operates as a run-of the-river facility during the summer months and permits some larger flows released. However, the impact of regulation on flood frequency for this management style (Fig. 11C) mimics management where a constant pool elevation is maintained (Fig. 11B). As is true for the Black River, the largest recorded outflow for the Union Village Dam on the Ompompanoosuc River (65 m^3/s) is below that of the pre-impoundment bankfull discharge.

Besides major changes in flood frequencies, examination of actual releases following impoundment reveals significant reductions in out-of-bank discharges. The 2-yr channel forming discharge rarely occurs, especially on the tributaries with flood-control structures (Table 4). The one major exception is the Wilder Dam at West Lebanon. This hydro-electric facility has a maximum operating range of 1.5 m with minimal reservoir storage which results in numerous large releases especially during spring runoff (Fallon-Lambert, 1998). The peak discharge of 2,230 m^3/s during the 1973 flood generated an event corresponding to the pre-dam 10-yr flood. Generally, however, post-dam maximum releases barely achieve pre-dam bankfull discharges. The data for this analysis can be enhanced by including those gages with only post-impoundment records. Although these sites lack pre-impoundment flow data, it is possible to estimate the shifts in out-of-bank occurrences. The regional drainage area-bankfull discharge relationship (Fig. 3) for unregulated rivers was used to estimate the natural 2-yr flood at each site based on its drainage area. The inclusion of these sites shows that mainstem releases from the hydro-electric facilities commonly achieve pre-dam bankfull discharges (Table 4). The tributary sites exhibiting similar relationships to pre-dam channel-forming discharges are those where flood control is not the sole nor dominant function.

Hydrologic Regime in Unregulated Rivers

Hydrologic shifts have occurred throughout the 20th Century in all the gaged, unregulated streams in the region (Table 5) and are best demonstrated by the gage record of the White River in east-central Vermont (Fig. 1). Peak flows decline over time, but the trend is not statistically significant ($0.10 > \alpha > 0.05$). The early part of the flood series was characterized by extremely large floods, in part due to the moderately high levels of agriculture still present in the watershed, but also due to the occurrence of an unusual series of climatic events. The three largest floods in an eighty-year record occurred within an eleven year period at the beginning of the record. An informal crest-stage recorder on the Connecticut River in Hartford, Connecticut shows that three of the largest four floods in a 200-yr record all occurred in a ten year window in the early to middle part of the 20th Century (Patton, 1988).

The changes in land use for the White River watershed show up more strongly in low flow characteristics than in high flows. Low flow minima have steadily risen over the period of record ($\alpha < 0.05$), as shown by the changes in the 1-day minimum flow (Fig. 12), although all low flow durations (3-day, 7-day, etc.) show the same increasing trend (Table 5). The increased low flow over time probably reflects the increased re-forestation occurring in Vermont over the 20th Century, and corresponds to the type of hydrologic changes that occur following land use change (Potter, 1991). This re-forestation also influences the timing of low flows. At the early part of the record, the Julian date of the 1-day minimum flow was, on average, on the 266th day of the year (September 23rd); whereas, the date of the 1-day minimum flow has become progressively earlier over the gage record, with the 1-day minimum flow now occurring, on average, on the 223rd day (August 11th) of the year (Fig. 13). This late summer/early fall timing of the minimum more closely approximates the pre-disturbance hydrologic regime that biota have evolved to expect for this region. The decrease in the date of the minimum flow reveals the increased regional recharge in conjunction with landscape re-vegetation.

Comparison of the mean annual hydrographs for the beginning and end of the record shows the different shapes of the recharge limb during the autumnal recharge, and also the different magnitudes of the snowmelt signal (Fig. 14). Baseflow begins earlier in the fall and also remains higher than in the beginning of the record through the fall and into the winter runoff, in part due to increases in soil infiltration. The rising limb of the snowmelt runoff peaks earlier and larger in the 1920s, potentially due to a greater exposure of the snowpack to direct insolation. This early and larger rise occurs even though the average March precipitation for the 1920s is smaller than the 1990s.

Trends expressed by the White River data typify the other five non-regulated streams although their shorter gage records limit statistical significance. The trends, however, are generally in the same direction. The low flow shifts are especially evident throughout the region with all sites showing an increase in low flow over time, with three of the six sites displaying significant increases (Table 5). As with the White River, basin wide recharge during the late summer and early fall also occurs in these unregulated rivers with mean monthly runoff for August and September flows increasing, with five of the six unregulated streams possessing a significant increase in either August or September flows over time. The date of the minimum 1-day low flow similarly decreases over time. Hydrograph reversals all show significant changes over time, but not all the basins behaved similarly. Basin size may explain the differences. For basins greater than 25 km^2 hydrograph reversals decreased significantly over time indicating that their daily flows are less flashy. Conversely, smaller basins (Ayers Brook and Mink Brook) have become more flashy over time. The differences result in part because basins of differing size respond differently to either snowmelt or rainfall induced events.

DISCUSSION OF RESULTS

These results portray a comprehensive pattern of hydrologic responses across dam type, function, and contributing basin size. The hydrologic responses show up in changes in both low flows and high flows. Thus, for the Upper Connecticut River watershed disturbance of the natural flow regime manifests most significantly in the shifts in the extremes. In situations where pre-impoundment and post-impoundment flow records exist, the post-impoundment changes vary as a function of dam type and watershed scale with post-disturbance high flows greatly reduced in size and variance. The average reduction of 32% in the 1-day peak flow corresponds with peak reductions noted elsewhere. Van Steeter and Pitlick (1998) noted a 28-39% decrease in the average peak discharge of the Colorado River and its major tributary, the Gunnison River. Williams and Wolman (1984) provided mean pre- and post-impoundment peak discharges for 48 sites, with all but one west of the Mississippi River. A calculation of their mean differences generates a mean reduction of peak discharges of 36% following impoundment (standard deviation = 70%), although some sites actually increased in mean peak discharge following impoundment. The wide range for their analysis results in part from their incorporation of a wide array of dam types. Other problems emerged as their gages had variable flow records and were sometimes located long distances from the impoundment. However, the comparison of our results with those of others indicates that, on average, mean peak discharges tend to decrease by approximately 30-35%

following impoundment. For our sites, the change also depended on dam management, with a diminished change for the seasonal run-of-the-river operation of the Union Village Dam.

Ecological Implications

Impoundment impacts on peak discharges are probably best represented by changes in flow frequency. These frequency changes have important ecological implications in our study reach as the maintenance of floodplain forests depends greatly on some intermediate scale of disturbance. While decline and extirpation of riparian communities following the elimination of flooding has been demonstrated in river systems throughout North America (Ward and Stanford, 1995; Molles et al., 1998), almost nothing is known about the effects of hydrologic alteration on these communities in New England. Part of the problem is that floristic differences between upland and riparian forests are much less well defined in Northeastern mesic temperate zones than they are in the arid and semi-arid west. For example, sugar maple (*Acer saccharum*) may be an important component of both forest types (Bechtel and Sperduto, 1998). Also, the long history of intensive land use, often particularly concentrated along river corridors, makes it difficult to determine the actual composition and spatial extent of riparian communities in the absence of intense human disturbance.

In spite of these uncertainties, our results point to several areas of concern. Differences in flood magnitude and frequency associated with impoundment mean that a given floodplain surface will be inundated less frequently, and that the total spatial extent of inundated floodplain will be less for an event of a given post-impoundment recurrence interval. The first effect is likely to have a major impact on riparian communities in New England via effects on competitive interactions between species. The dominant tree species on Connecticut River floodplains, silver maple (*Acer saccharinum*) is tolerant of indundation, but intolerant of shading, suggesting that the species would be highly vulnerable to replacement by shade tolerant species if flooding was eliminated (Peterson and Bazzaz, 1984). However, Bechtel and Sperduto (1998), in a floodplain forest survey, found that silver maple-dominated forests were found largely on the mainstem Connecticut River, within the 1-2 year post-impoundment floodplain while Metzler and Damman (1985) found silver maple forests within the 1-11 year floodplain in the lower Connecticut River. We found that impoundment on the Connecticut River mainstem in the vicinity of the West Lebanon, NH stream gage, while having a major effect on large (greater than or equal to 5-year) floods, had little effect on the magnitude of the 2-year discharge. This suggests relatively little effect of hydrologic alteration in the Connecticut basin on this dominant riparian tree species. However, the extent to which silver maple formerly occurred along higher river terraces, or along major tributaries, is unclear at the present time, making this conclusion tentative. Decreased frequency of inundation is also likely to strongly affect herbaceous plant communities (Barnes, 1978) which include a number of rare, threatened, and endangered species (Bechtel and Sperduto, 1998). Many upland herbaceous species in New England are introduced species which would be expected to thrive in the high light open canopy conditions of river floodplains in the absence of frequent flooding. In fact, the abundance of these species has been increasing, and has been suggested to be a major threat to existing populations of native floodplain plants (Bechtel, pers.comm). In addition to changes in flood frequency, reduction in flooded area is likely to have a major influence on floodplain communities already fragmented and reduced in size as a result of land use and development. Increased reduction and fragmentation, and reduced habitat connectivity, makes remaining floodplain communities more vulnerable to invasion and random extinction.

Changes in the natural flow regime can occur in other metrics besides changes in peak flows, and for some ecological parameters, shifts in low flows, timing of high and low flows, or changes across different flow durations can be even more significant. For the Upper Connecticut River, changes in the timing of either low or high flows do not appear to be significant, but this influence may be region specific. Elliott and Parker (1997) found that monthly mean discharge during the April-July snowmelt season decreased 63% following impoundment, while mean monthly flows for the remainder of the year increased 170%. This marked shift for semi-arid regions results because of broader hydroclimatological controls on flood timings and on dam management where considerable volumes of water are stored for subsequent release (Graf, 1999). For New England, these shifts are less dramatic because of high annual precipitation totals, combined with the lack of a seasonal precipitation signal, and the minimal water storage behind impoundments.

Geomorphic Implications

Although this work has focused primarily on the hydrologic shifts due to flow regulation, these results point to an array of potential geomorphic adjustments occurring in the Upper Connecticut River watershed. We did not analyze any of the geomorphic impacts following impoundment due more to a lack of available data rather than to a lack of impacts. Most studies on geomorphic impacts chronicle changes in stream channel cross-sectional morphology over time (Petts and Pratts, 1983; Hadley and Emmet, 1998); changes in channel planform or bed elevation downstream of reservoirs (Chien, 1985); or sedimentological changes downstream of a dam (Graf, 1980; Petts, 1984; Chien, 1985; Andrews, 1986; ASCE, 1992; Schmidt et al., 1995; Pitlick and van Steeter, 1998; Brandt, 2000). Unfortunately, the Upper Connecticut River basin lacks the necessary data sources to appropriately evaluate geomorphic changes. Although New England has one of the densest networks of USGS stream gages, the distribution of sediment gages is chronically limited. Similarly, it lacks the critical pre-impoundment channel surveys necessary for comparison to post-impoundment channel changes.

Because of regional geologic conditions, many of the potential geomorphic shifts that tend to occur following impoundment may not necessarily affect the mainstem of the Connecticut River, or affect it minimally. Bed degradation generally occurs immediately downstream of dams (cf. Williams and Wolman, 1984), yet conditions present in the Connecticut River basin may act to diminish the role of channel incision. Significant Holocene isostatic rebound following deglaciation (Koteff and Larson, 1989) initiated an incisional episode, and the mainstem flows on, or near, bedrock throughout the study reach. Furthermore, the geologic history and setting of the mainstem also limits other geomorphic adjustments. Changes in channel planform and/or sinuosity may also occur following impoundment (Williams and Wolman, 1984). However, the Connecticut River flows down strike of a narrow belt of resistant meta-volcanic and meta-sedimentary rocks. This structural and lithologic control generates a constrained valley throughout most of the Vermont and New Hampshire border, thereby inhibiting significant lateral channel migration. Geomorphic adjustments of the tributaries may not be as limited as those on the mainstem as the tributaries included in this analysis flow across a diverse array of lithologic and structural environments.

The greatest potential adjustments appear to be associated with sedimentological differences or channel narrowing. The flux of suspended sediments from the tributaries combined with diminished magnitude of large floods, especially in the impounded tributaries, may lead to enhanced fine-grained deposition and embeddedness (cf. Andrews 1986). Also, because of the abundant coarse-grained till throughout the region and the locally available coarse-grained bed material on the mainstem, impacts on bedload could be significant. Thus impoundment is likely to have strong, but complex, effects on substratum composition, an important determinant of instream benthic invertebrate community structure (Minshall, 1984). Channel bed particle size distributions tend to change significantly immediately downstream of dams (Williams and Wolman, 1984). In the Connecticut River, where threatened habitats and species frequently occur on low-lying islands formed and maintained by river-transported sediments, this effect may be significant. Because the abundance and diversity of benthic organisms generally increases with increasing particle size, changes in substrate size may negatively impact these communities.

CONCLUSIONS

Our analysis provides a framework for anticipating potential ecological consequences of hydrologic alteration in the region, and can also help set priorities for conservation and research. Lack of strong effects on discharge seasonality, or on total discharge volume provide a major contrast to the effects of large dams in western semi-arid regions (Graf, 1980; Williams and Wolman, 1984; Chien, 1985; Andrews, 1986; Elliott and Parker, 1997; Hadley and Emmet, 1998; and Van Steeter and Pitlick, 1998). As a consequence, we do not expect ecological consequences arising from reductions in total instream habitat area (Bovee 1986), major shifts in water temperature regime (Ward and Stanford, 1995), or mismatch between the timing of flow events and life history events (Montgomery et al., 1983; Puckridge et al., 1998), to be major factors in the Connecticut River Basin. However, impoundment in the Connecticut basin has significantly altered the natural flow regime by eliminating extreme flows and changing hydrograph variability. These alterations have previously been associated with major ecological change in other systems, affecting both instream and riparian habitats.

The effects of hydrologic alteration on ecological communities must be put in the context of other sources of long-term change in both the physical and biotic environment of the New England region. We found that long-term gage records revealed significant change over time unrelated to the effects of impoundment, particularly in the increased low flow and baseflow over time and the earlier timing of 1-day minimum flows. Without this knowledge, we could have mistakenly attributed these phenomena to the effects of impoundment. Similarly, we caution that the use of “snapshot” associations between ecological and physical characteristics in such a dynamic environment may be misleading. We suggest that better understanding of both the mechanisms of interaction between ecological communities and hydrologic alteration, along with more data on historical ecological characteristics and channel morphology, are necessary to adequately assess the ecological and geomorphic impacts of hydrologic alteration in the Connecticut River basin.

FIGURE CAPTIONS

Figure 1 Map of Study Area (adopted from Fallon-Lambert, 1998)

Figure 2. Time Series of Vermont Agricultural Activity (data from the Vermont County Census).

Figure 3. Regional bankfull discharge (m^3/s) vs. drainage area (km^2). The point for the largest drainage area is for the pre-impoundment West Lebanon gage. We have included this datum to extend this relationship to larger watersheds. Neither the trend line nor the explained variance is affected by the inclusion of the West Lebanon datum. Additional data for unregulated streams comes from Magilligan and Graber (1996)

Figure 4. Mean Julian date for daily minimum flows (upper diagram) and maximum flows (lower diagram) for pre- and post-impoundment conditions. The bars represent the standard deviation.

Figure 5. Mean difference in discharge following impoundment for different flow durations.

Figure 6. Pre- and post-impoundment magnitudes of 1-day peak flow for all sites. The bars represent the standard deviation.

Figure 7. Mean pre- and post-impoundment 1-day low flow minima for all sites. The bars represent the standard deviation.

Figure 8. Time series of the Connecticut River at West Lebanon, NH 1-day minimum flows.

Figure 9. Mean number of hydrograph reversals following impoundment. The bars represent the standard deviation.

Figure 10. Mean 1-day maximum specific discharge (per km^2) for unregulated streams vs. streams with only a post-impoundment record (streams listed in Table 1).

Figure 11. Results of log-Pearson Type III flood frequency analysis for (A) the Connecticut River at the Wilder Dam, (B) for the Black River, VT, and (C) the Ompompanoosuc River at the Union Village Dam. The dashed upper line in each plot is for the pre-dam flood frequency analysis and the solid lower line is for the post-impoundment record.

Figure 12. Time series of 1-day minimum over time for the White River, VT

Figure 13. White River: Time Series of the Julian Date of the 1-day minimum flow.

Figure 14. Mean annual hydrograph for the White River, VT. The dashed line is for the period 1920-29, and the solid line is for the most recent ten years (1988-1997).

TABLE CAPTIONS

Table 1: Basins included for the analysis showing dam name, function, date of dam, drainage area upstream of gage, the beginning date of the gage record, and the gage ID number. For dam function, "f" represents flood control, "p" represents hydro-electric power generation, and "r" represents recreation. Dam function information from Fallon-Lambert (1998).

Table 2: Indices for Index of Hydrologic Alteration. Adapted from Richter et al. (1996)

Table 3: Results from the IHA analysis for rivers with only a post-impoundment flow record.

Table 4: Frequency counts of number of flows released after impoundment that equal or exceed the 2-yr bankfull discharge, and the recurrence interval following impoundment. For those gages lacking pre-impoundment flow data, the 2-yr bankfull discharge was estimated from the regional relationship in Figure 3.

Table 5: Results from the IHA analysis for unregulated rivers (** indicates significant correlation (at $\alpha < 0.05$) for regression trend against time (yrs)).

LITERATURE CITED

Andrews, E. D., 1980. Effective and Bankfull Discharges of Streams in the Yampa River Basin, Colorado and Wyoming. Journal of Hydrology 46(3-4):311-330.

Andrews, E. D., 1986. Downstream Effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. Geological Society of America Bulletin 97(8):1012-1023.

ASCE, 1992. Sediment and Aquatic Habitat in River Systems. Journal of Hydraulic Engineering, American Society of Civil Engineers 118(5):669-687.

Barnes, W. J., 1978. The Distribution of Floodplain Herbs as Influenced by an Annual Flood Elevation. Wisconsin Academy of Sciences, Arts and Letters 66():255-265.

Bechtel, D. A. and D. D. Sperduto, 1998. Floodplain Forest Natural Communities Along Major Rivers in New Hampshire. New Hampshire Natural Heritage Inventory. Concord, NH, 56 pp.

Benke, A., 1990. Perspective on America's Vanishing Streams. Journal of the North American Benthological Society 9(1):77-88.

Bovee, K. D., 1986. Development and Evaluation of Habitat Suitability Criteria For Use in the Instream Incremental Methodology. U.S. Fish & Wildlife Service Biological Report. 86(7).

Brandt, S. A., 2000. Classification of Geomorphological Effects Downstream of Dams. Catena 40 (2000): 375-401.

Chien, N., 1985. Changes in River Regime After the Construction of Upstream Reservoirs. Earth Surface Processes and Landforms 10(2):143-159.

Colby, B. G., 1990. Enhancing Instream Flow Benefits in an Era of Water Marketing. Water Resources Research 26(6):1113-1120.

Collier, M. P., R. H. Webb, and J. C. Schmidt, 1996. Dams and Rivers. U.S. Geological Survey Circular 1126, 94 pp.

Collier, M. P., R. H. Webb, and E. D. Andrews, 1997. Experimental Flooding in the Grand Canyon, Scientific American 276(1):82-89.

Denny, C. A., 1982. The Geomorphology of New England. U.S. Geological Survey Professional Paper 1208, 18 pp.

Elliott, J. G. and R. S. Parker, 1997. Altered Streamflow and Sediment Entrainment in the Gunnison Gorge. Journal of the American Water Resources Association 33(5):1041-1054.

Fallon-Lambert, K., 1998. Instream Flow Uses, Values and Policies in the Upper Connecticut River Watershed. Connecticut River Joint Commissions Report, 178 pp.

Graf, W. L., 1980. The Effect of Dam Closure on Downstream Rapids. Water Resources Research 16(1):129-136.

Graf, W. L., 1999. Dam Nation: A Geographic Census of American Dams and Their Large-Scale Hydrologic Impacts. Water Resources Research 35(4):1305-1311.

Hadley, R. F. and W. W. Emmett, 1998. Channel Changes Downstream from a Dam. Journal of the American Water Resources Association 34(3):629-637.

Jahns, R. H., 1947. Geological Features of the Connecticut River Valley, Massachusetts as Related to Recent Floods. U.S. Geological Survey Water Supply Paper 996, 158 pp.

Kondolf, G. M. and P. R. Wilcock, 1996. The Flushing Flow Problem: Defining and Evaluating Objectives. Water Resources Research 32(8):2589-2599.

Koteff, C. and F. D. Larsen, 1989. Postglacial Uplift in Western New England: Geologic Evidence for Delayed Rebound. *In*: Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound, S. Gregersen and P.W. Basham (Editors). Kluwer Academic Publishers, pp. 105-123.

Ligon, F. K., W. E. Dietrich, and W. J. Trush, 1995. Downstream Ecological Effects of Dams BioScience 45(3):183-192.

Lyons, J. B., 1958. Geology of the Hanover Quadrangle. New Hampshire State Planning and Development Commission 43 pp.

Magilligan, F. J. and B. E. Graber, 1996. Hydroclimatological and Geomorphic Controls on the Timing and Spatial Variability of Floods in New England, USA. Journal of Hydrology 178(1-4):159-180.

Magilligan, F. J and M. Stamp, 1997. Historical Land-cover Changes and Hydrogeomorphic Adjustment in a Small Georgia Watershed. Annals of the Association of American Geographers 87(4):614-635.

Metzler, K. J. and A. W. H. Damman, 1985. Vegetation Patterns in the Connecticut River Flood Plain in Relation to Frequency and Duration of Flooding. Naturaliste Canadien 112(4):535-547.

Minshall, G. W., 1984. Aquatic Insect - Substratum Relationships. *In:* The Ecology of Aquatic Insects, V. H. Resh and D. M. Rosengerg (Editors) Praeger Publishers, New York, New York, pp. 358-401.

Molles, M. C., C. S. Crawford, L, M. Ellis, H. M. Valett, and C. N. Dahm, 1998. Managed Flooding for Riparian Ecosystem Restoration - Managed Flooding Reorganizes Riparian Forest Ecosystems Along the Middle Rio Grande in New Mexico. BioScience 48(9):749-756.

Montgomery, W. L., S. D. McCormick, R. J. Naiman, F. G. Whoriskey, and G. A. Black, 1983. Spring Migratory Synchrony of Salmonid, Catostomid, and Cyprinid Fishes in Rivière à la Truite, Québec. Canadian Journal of Zoology. 61(11): 2495-2502.

Patton. P. C., 1988. Geomorphic Response of Streams to Floods in the Glaciated Terrain of Southern New England. *In*: Flood Geomorphology, V. R. Baker, G. Kochel, and P. C. Patton (Editors). John Wiley and Sons, New York, New York, pp. 261-277.

Peterson, D. L., and F. A. Bazzaz, 1984. Photosynthetic and Growth-responses of Silver Maple (*Acer-saccharinum*) Seedlings to Flooding. American Midland Naturalist 112(2):261-272.

Petts, G. E., 1984. Sedimentation Within a Regulated River. Earth Surface Processes and Landforms 9(2):125-134.

Petts, G. E. and J. D. Pratts, 1983. Channel Changes Following Reservoir Construction on a Lowland River. Catena 10(1-2):77-85.

Pitlick J. and M. M. Van Steeter, 1998. Geomorphology and Endangered Fish Habitats of the Upper Colorado River 2. Linking Sediment Transport to Habitat Maintenance. Water Resources Research 34(2):303-316.

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(11):769-784.

Potter, K. W., 1991. Hydrological Impacts of Changing Land Management Practices in a Moderate-Sized Agricultural Catchment. Water Resources Research 27(4):845-855.

Power, M. E., W. E. Dietrich, and J. C. Finlay, 1996. Dams and Downstream Aquatic Biodiversity: Potential Food Web Consequences of Hydrologic and Geomorphic Change. Environmental Management 20(6):887-895.

Puckridge, J. T., F. Sheldon, K. F. Walker, and A. J. Boulton, 1998. Flow Variability and the Ecology of Large Rivers. Marine and Freshwater Research 49(1):55-72.

Richter, B. D., J. V. Baumgartner, J. Powell, and D. P. Braun, 1996. A Method for Assessing Hydrologic Alteration Within Ecosystems. Conservation Biology 10(4):1163-1174.

Rubin, D. M., J. M. Nelson, and D. J. Topping, 1998. Relation of Inversely Graded Deposits to Suspended-sediment Grain-size Evolution During the 1996 Flood Experiment in Grand Canyon, Geology 26(2):99-102.

Schmidt, J. C., P. E. Grams, and R. H. Webb, 1995. Comparison of the Magnitude of Erosion Along 2 Large Regulated Rivers. Water Resources Bulletin 31(4):617-631.

Stanford, J. A., J. V. Ward, W. J. Liss, C. A. Frissell, R. N. Williams, J. A. Lichatowich, and C. C. Coutant, 1996. A General Protocol for Restoration of Regulated Rivers. Regulated Rivers: Research and Management 12(4-5):391-413.

U.S. Water Resources Council, 1976. Guidelines for Determining Flood Flow Frequency. Bulletin 17, United States Government Printing Office, Washington, D.C., 77 pp.

Van Steeter, M. M. and J. Pitlick, 1998. Geomorphology and Endangered Fish Habitats of the Upper Colorado River 1. Historic Changes in Streamflow, Sediment Load, and Channel Morphology. Water Resources Research 34(2):287-302.

Ward, J.V. and J.A. Stanford, 1995. The Serial Discontinuity Concept - Extending The Model To Floodplain Rivers. Regulated Rivers Research & Management 10 (2-4): 159-168.

Wiele, S. M., J. B. Graf, and J. D. Smith, 1996. Sand Deposition in the Colorado River in the Grand Canyon from Flooding of the Little Colorado River. Water Resources Research 32(12):3579-3596.

Williams, C. W., 1996. Flooding the Colorado River. Geotimes 41(8):6-7.

Williams, G. P. and M. G. Wolman, 1984, Downstream Effects of Dams on Alluvial Rivers. U.S. Geological Survey Professional Paper 1286, 83 pp.

Wolman M. G. and J. P. Miller, 1960. Magnitude and Frequency of Forces in Geomorphic Processes. Journal of Geology 68(1):54-74.

Wooton, J. T., M. S. Parker, M. E. Power, 1996. Effects of Disturbance on River Food Webs. Science 273(5281):1558-1561.

Wu, F. C., 2000. Modeling Embryo Survival Affected By Sediment Deposition Into Salmonid Spawning Gravels: Application To Flushing Flow Prescriptions. Water Resources Research 36(6): 1595-1603.

Figure 1:

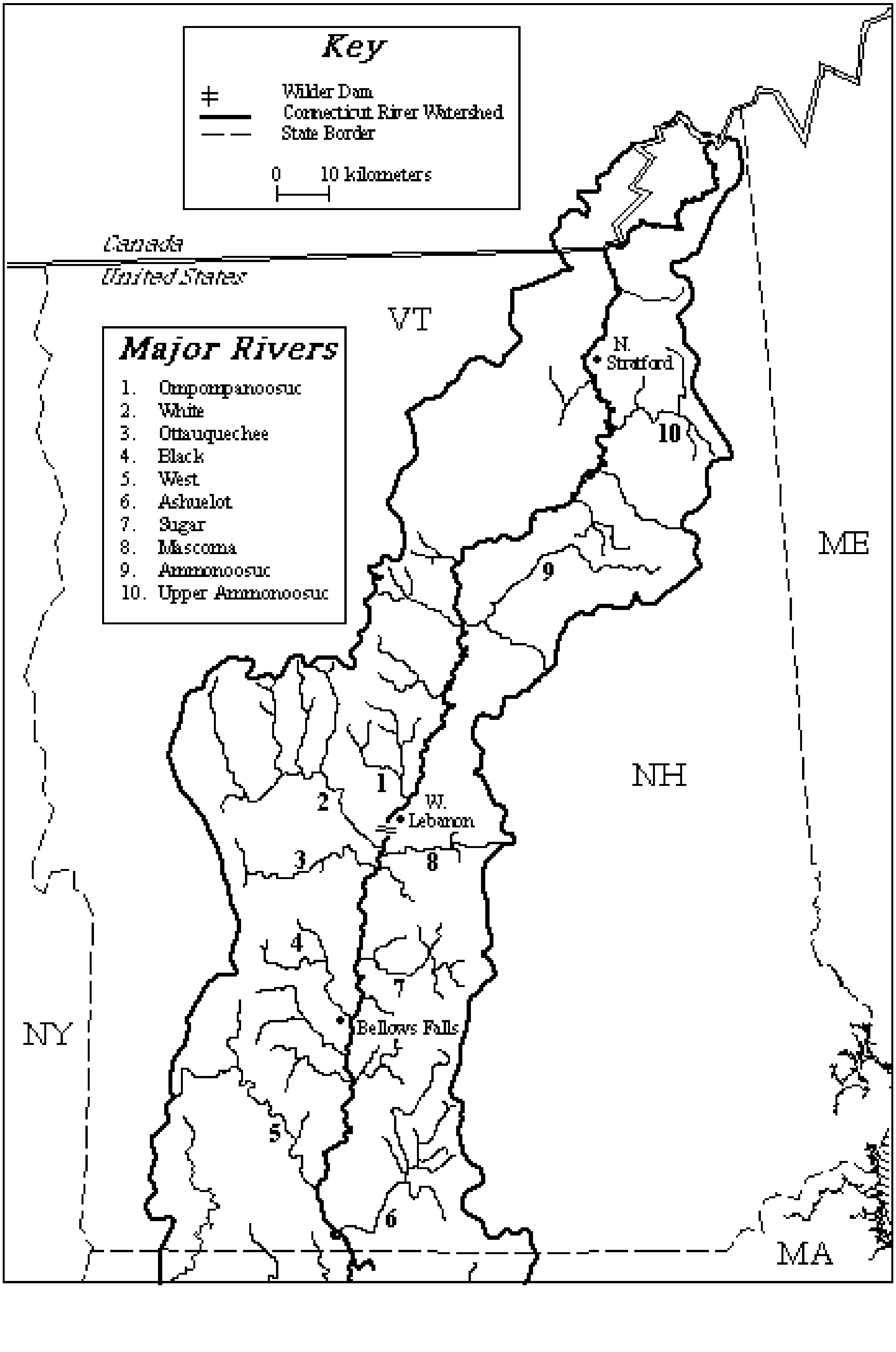

Key
Wilder Dam
Connecticut River Watershed
State Border
0
10 kilometers
Canada
United States
VT
Major Rivers
1. Ompompanoosuc
2. White
3. Ottauquechee
4. Black
5. West
6. Ashuelot
7. Sugar
8. Mascoma
9. Ammonoosuc
10. Upper Ammonoosuc
N. Stratford
10
9
ME
NH
1
2
W. Lebanon
3
8
4
7
Bellows Falls
NY
5
6
MA

Figure 2:

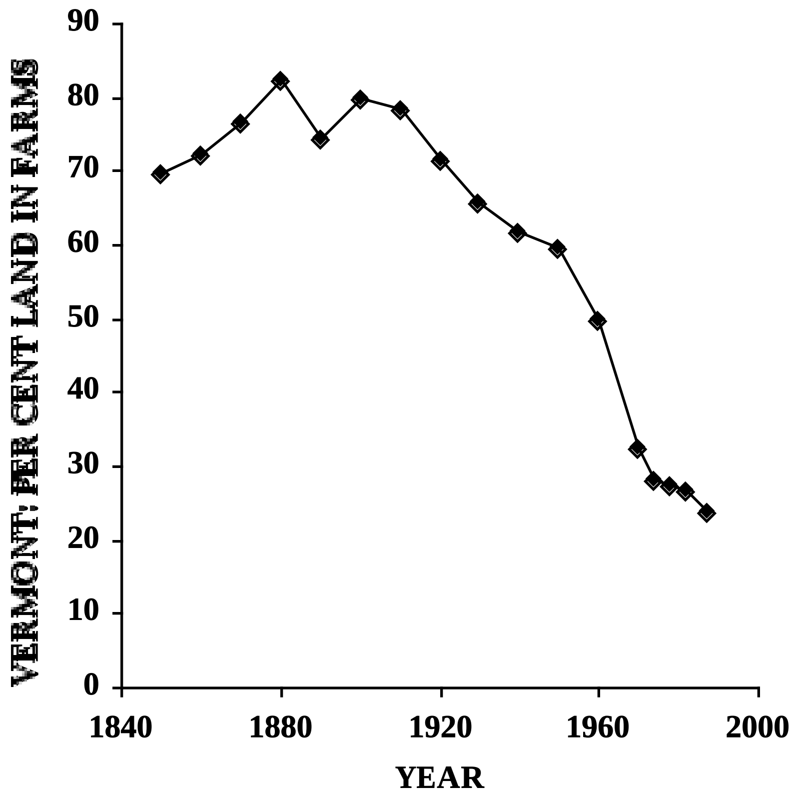
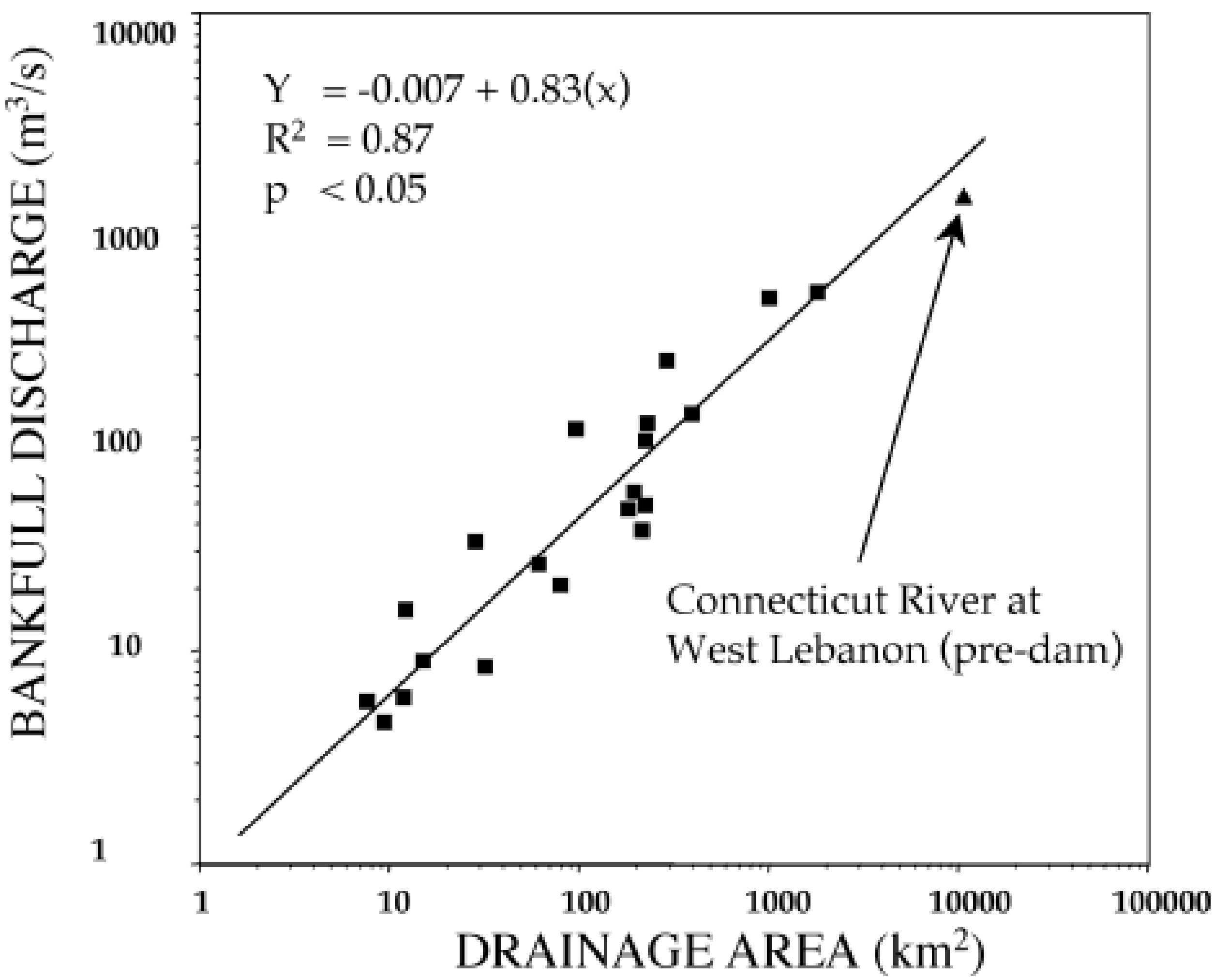
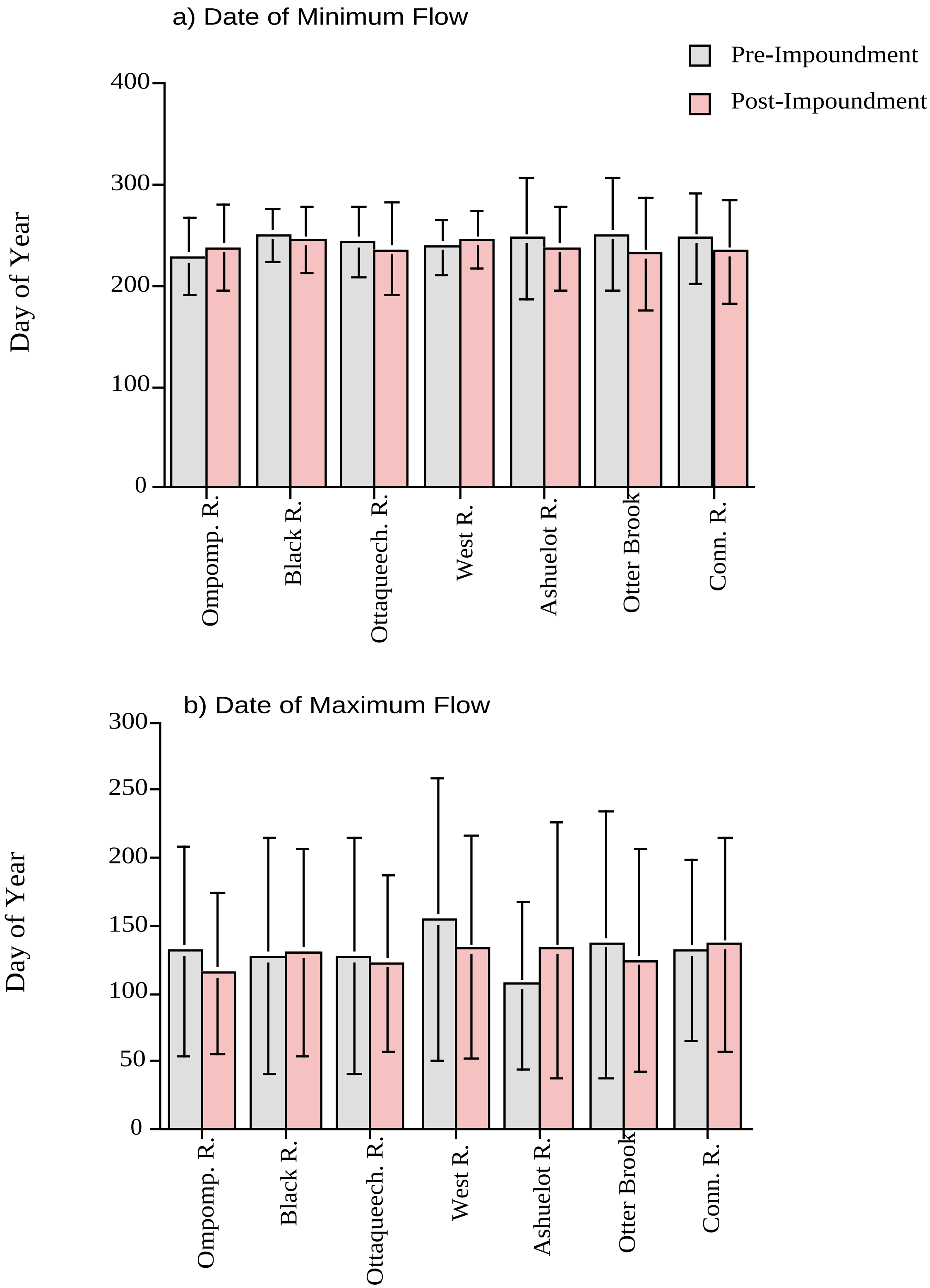

VERMONT: PER CENT LAND IN FARMS
0
10
20
30
40
50
60
70
80
90
1840
1880
1920
1960
2000
YEAR

Figure 3:



Y = -0.007 + 0.83(x)
R² = 0.87
p < 0.05
Connecticut River at
West Lebanon (pre-dam)
BANKFULL DISCHARGE (m³/s)
DRAINAGE AREA (km²)
1
10
100
1000
10000
100000

Figure 4:


a) Date of Minimum Flow
Pre-Impoundment
Post-Impoundment
Day of Year
400
300
200
100
0
Ompomp. R.
Black R.
Ottaqueech. R.
West R.
Ashuelot R.
Otter Brook
Conn. R.
b) Date of Maximum Flow
Day of Year
300
250
200
150
100
50
0
Ompomp. R.
Black R.
Ottaqueech. R.
West R.
Ashuelot R.
Otter Brook
Conn. R.

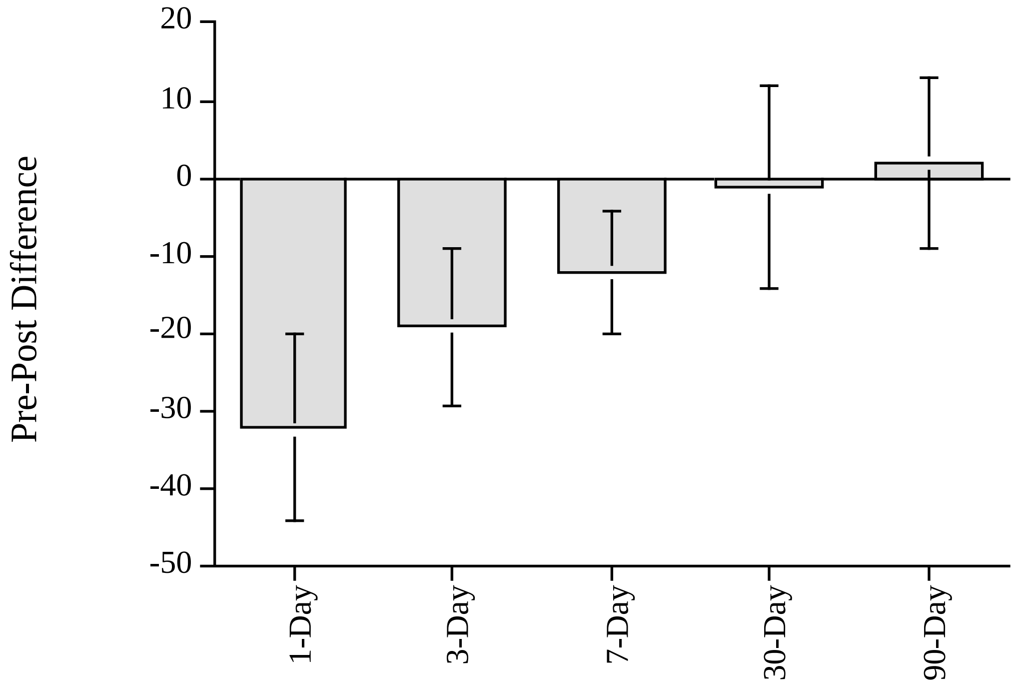

Pre-Post Difference
20
10
0
-10
-20
-30
-40
-50
1-Day
3-Day
7-Day
30-Day
90-Day

Figure 5:

Figure 6:

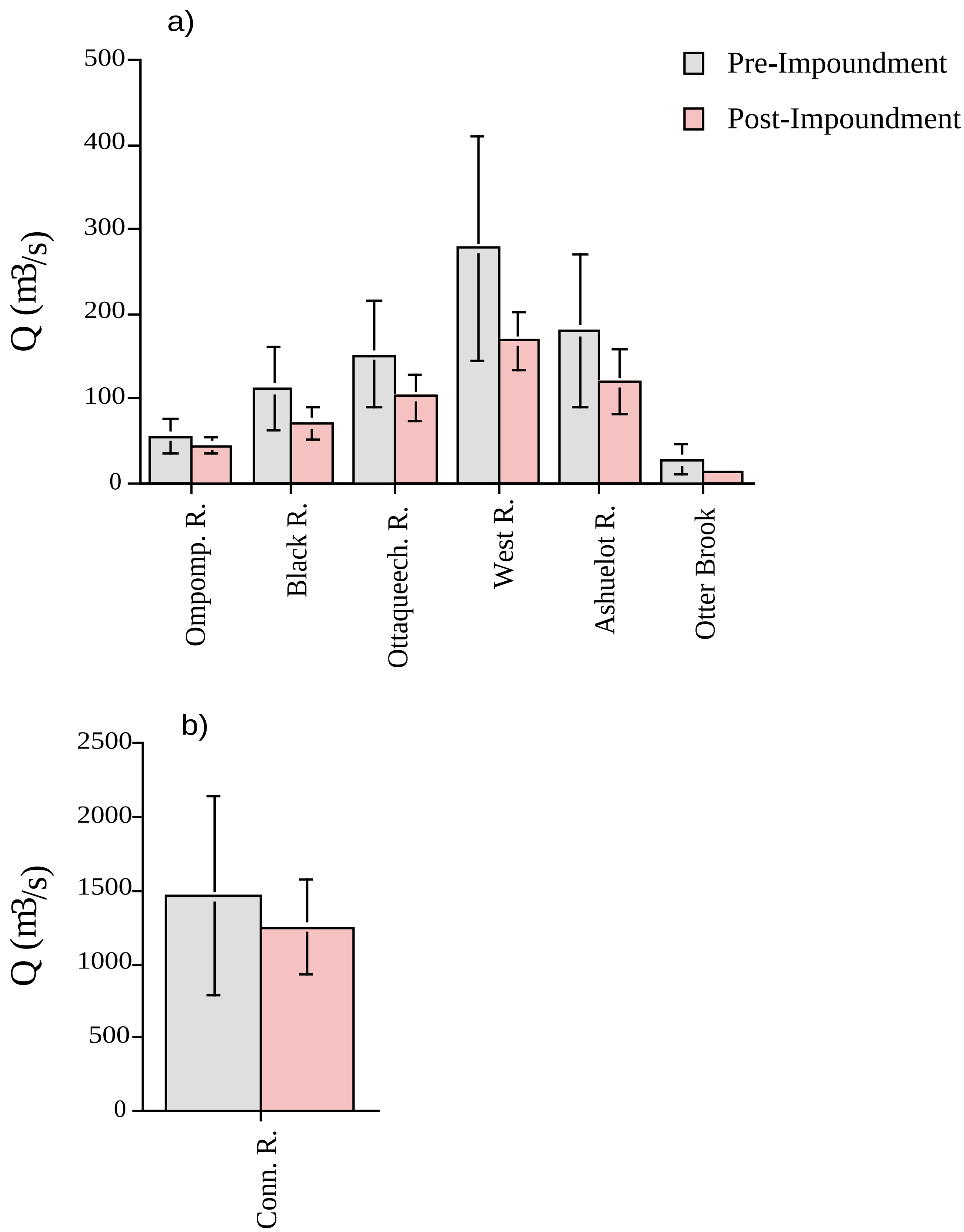
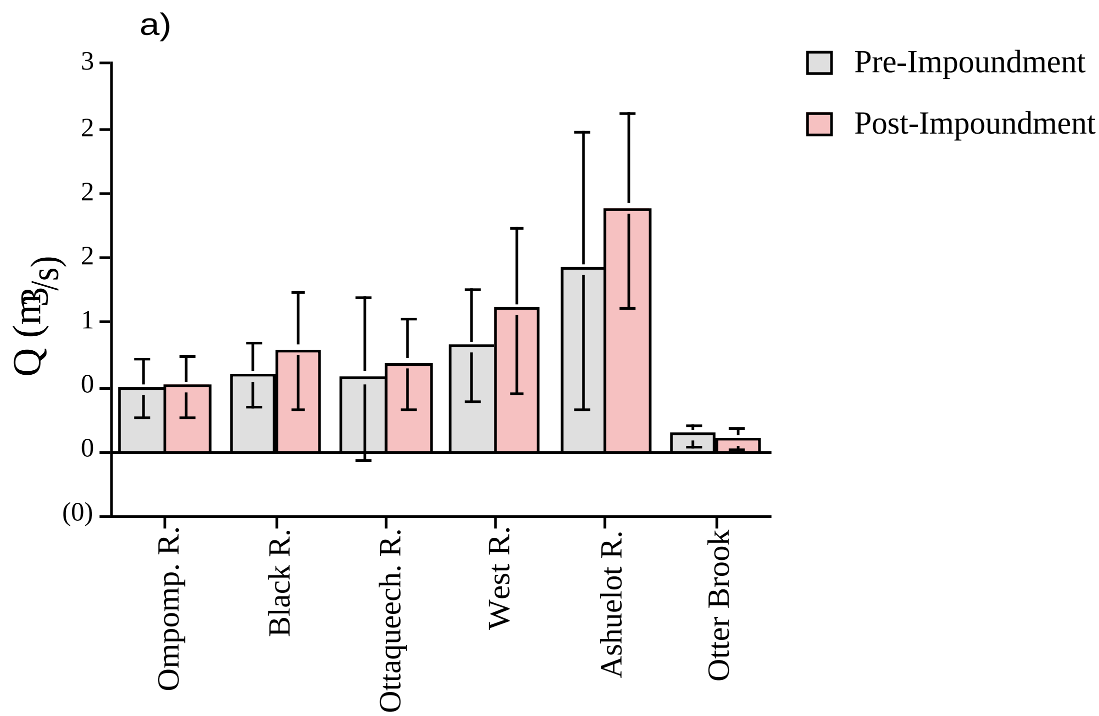

a)
Pre-Impoundment
Post-Impoundment
Q (m^3/s)
0
100
200
300
400
500
Ompomp. R.
Black R.
Ottaqueech. R.
West R.
Ashuelot R.
Otter Brook
b)
Q (m^3/s)
0
500
1000
1500
2000
2500
Conn. R.

Figure 7:


a)
Pre-Impoundment
Post-Impoundment
3
2
2
2
1
0
0
(0)
Q (m3/s)
Ompomp. R.
Black R.
Ottaqueech. R.
West R.
Ashuelot R.
Otter Brook

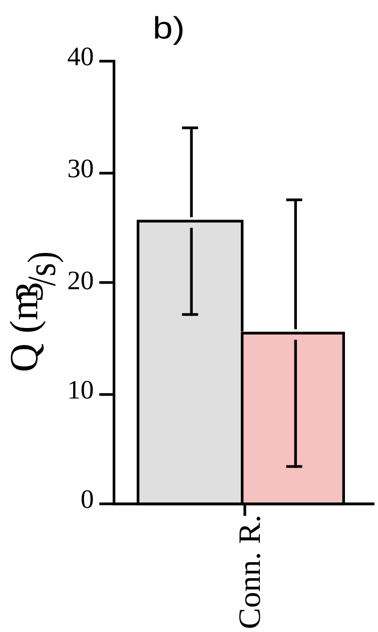
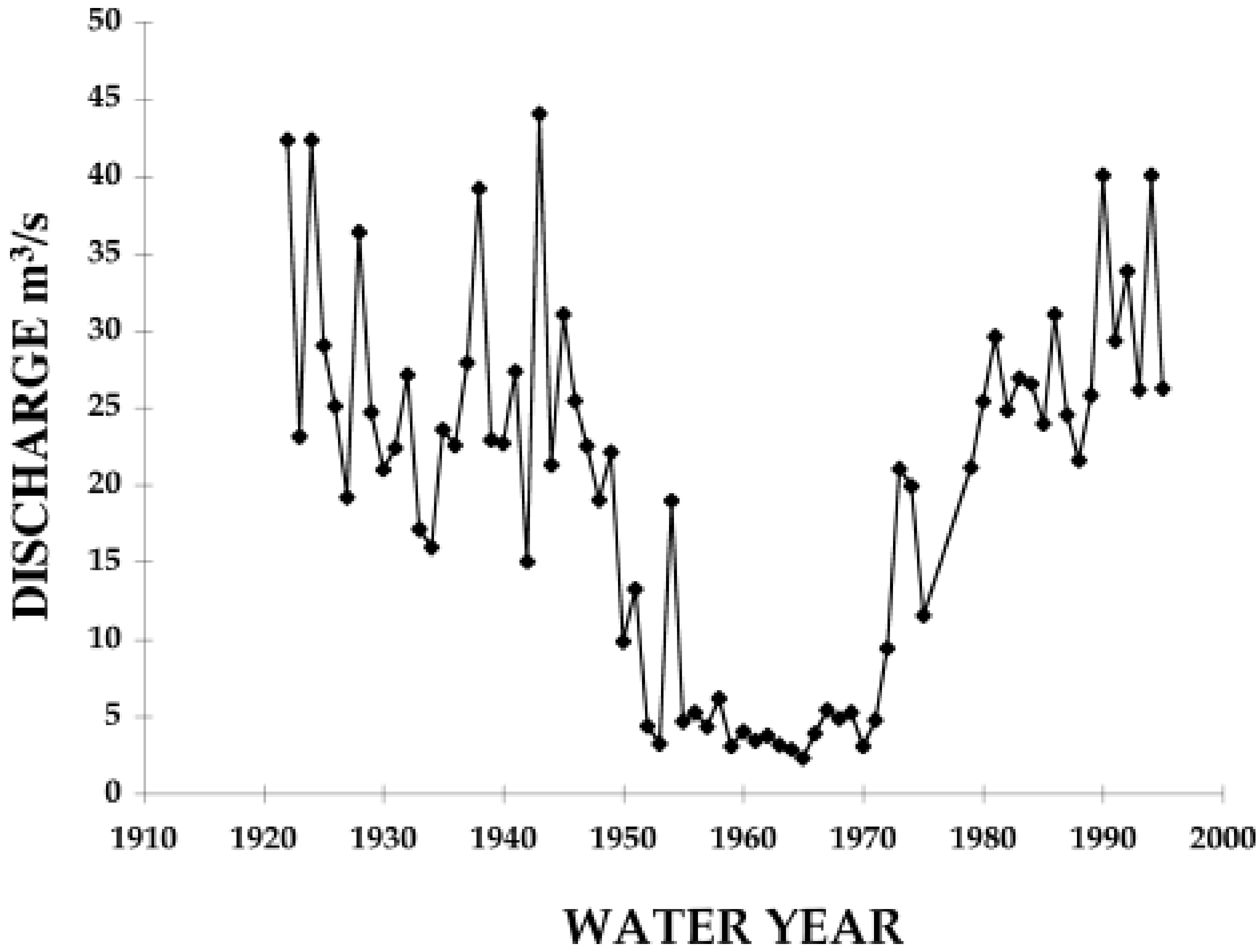

b)
40
30
20
10
0
Q (m3/s)
Conn. R.

Figure 8:



50
45
40
35
30
25
20
15
10
5
0
DISCHARGE m3/s
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
WATER YEAR

Figure 9:

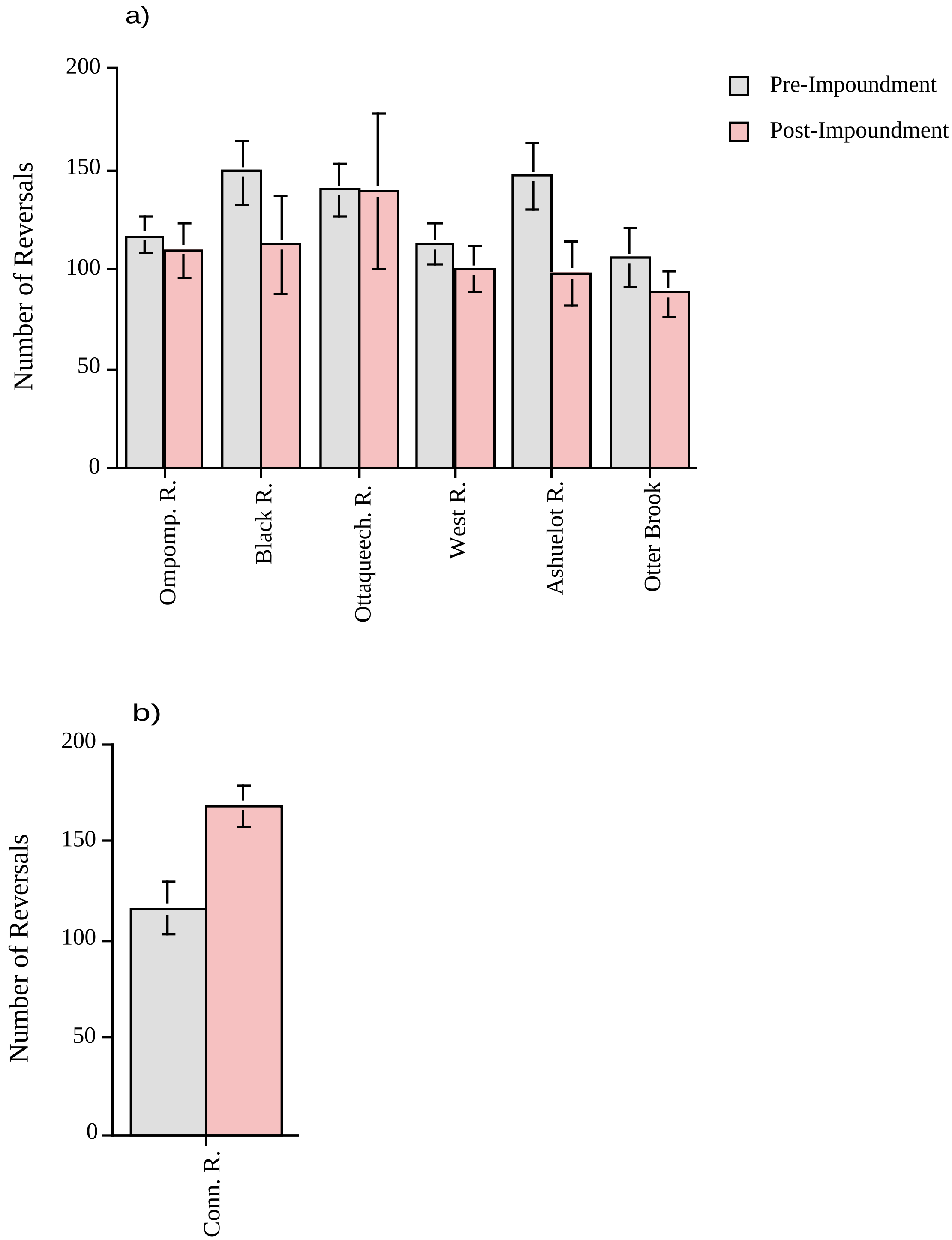

a)
Pre-Impoundment
Post-Impoundment
Number of Reversals
200
150
100
50
0
Ompomp. R.
Black R.
Ottaqueech. R.
West R.
Ashuelot R.
Otter Brook
b)
Number of Reversals
200
150
100
50
0
Conn. R.

Figure 10:

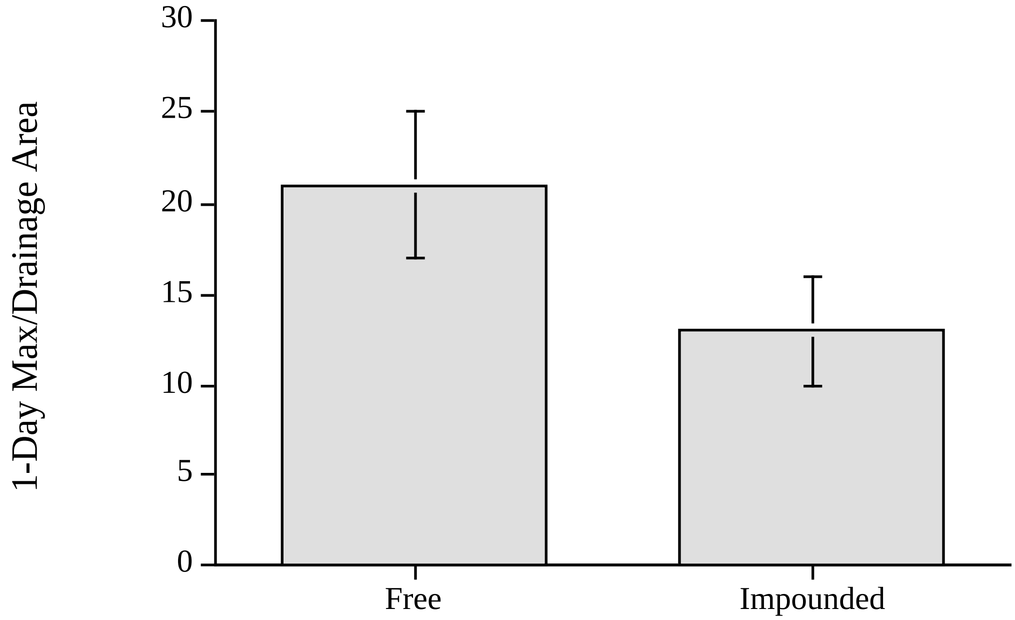


Figure 11:

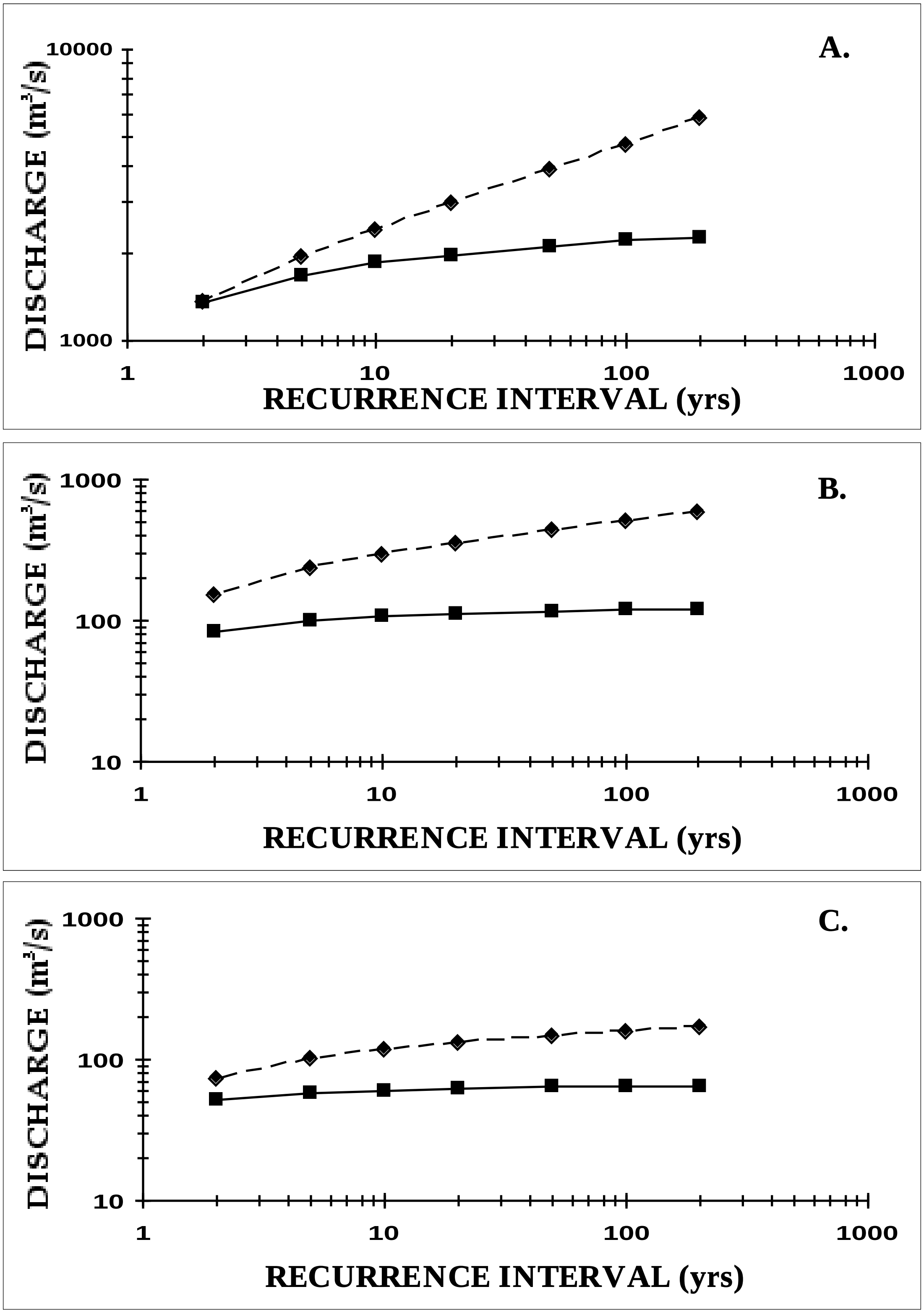
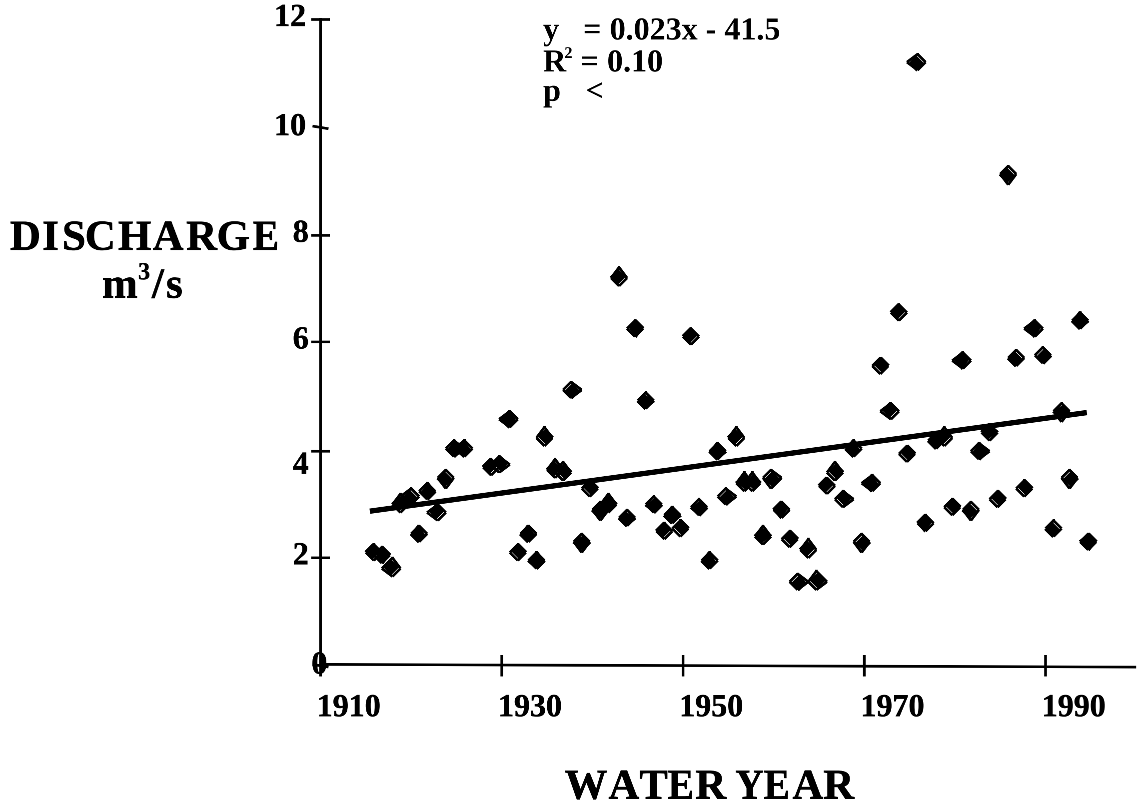
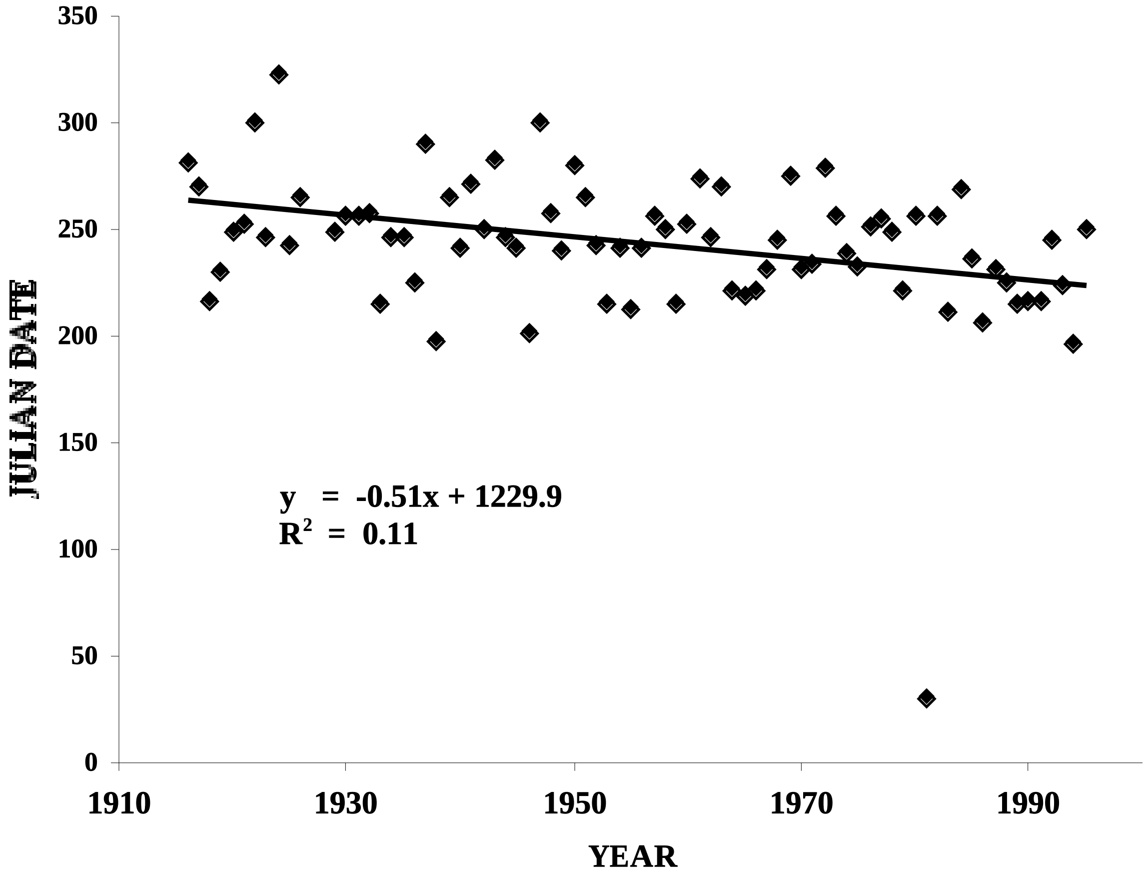

A.
DISCHARGE (m³/s)
10000
1000
1
10
100
1000
RECURRENCE INTERVAL (yrs)
B.
DISCHARGE (m³/s)
1000
100
10
1
10
100
1000
RECURRENCE INTERVAL (yrs)
C.
DISCHARGE (m³/s)
1000
100
10
1
10
100
1000
RECURRENCE INTERVAL (yrs)

Figure 12:



y = 0.023x - 41.5
R2 = 0.10
p <
12
10
8
6
4
2
0
DISCHARGE
m3/s
1910
1930
1950
1970
1990
WATER YEAR

Figure 13:



350
300
250
200
150
100
50
0
JULIAN DATE
y = -0.51x + 1229.9
R2 = 0.11
1910
1930
1950
1970
1990
YEAR

Figure 14:

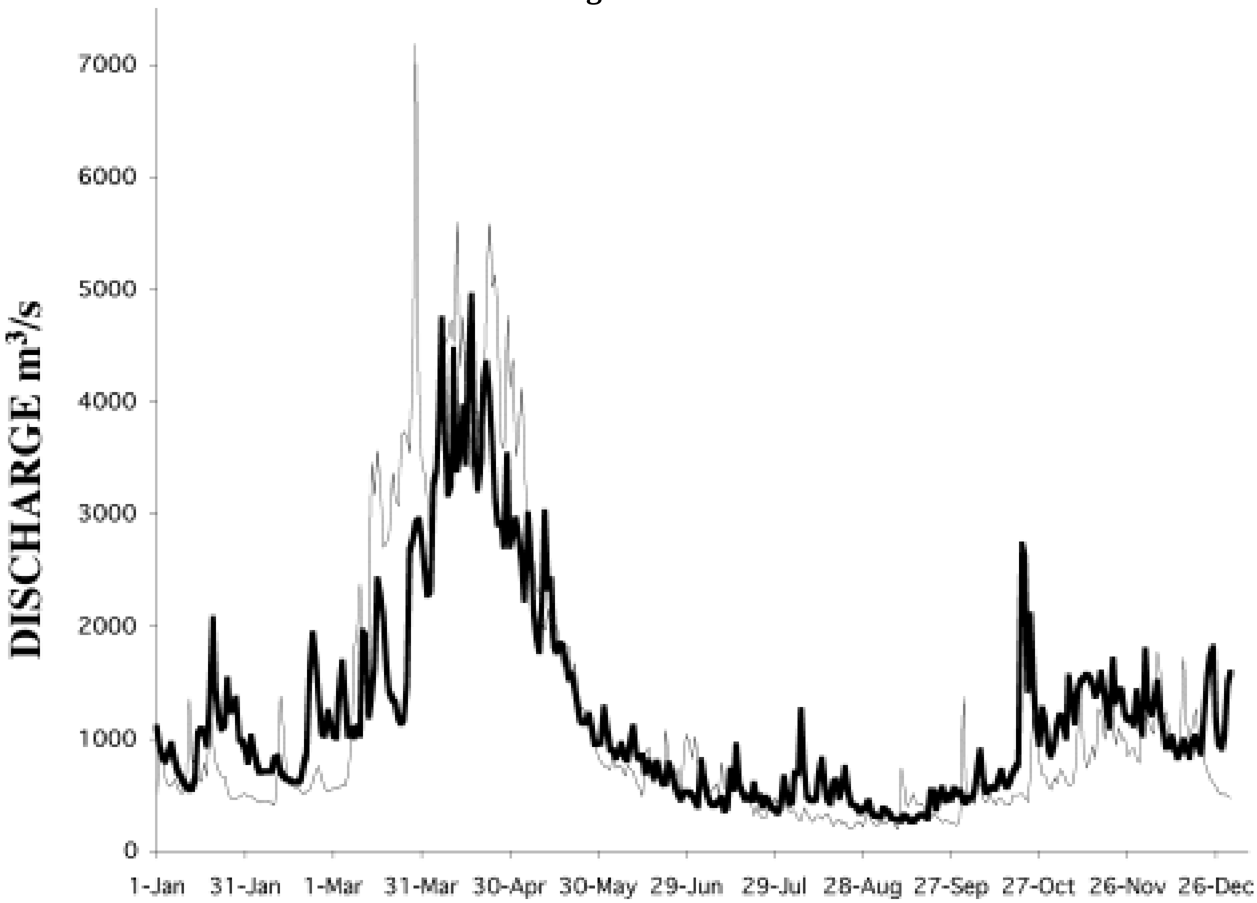

DISCHARGE m^3/s
0
1000
2000
3000
4000
5000
6000
7000
1-Jan
31-Jan
1-Mar
31-Mar
30-Apr
30-May
29-Jun
29-Jul
28-Aug
27-Sep
27-Oct
26-Nov
26-Dec

Table 1:

STATION	MAJOR DAM(S) OF INFLUENCE AND FUNCTION(S)	DATE OF DAM	GAGE DRAINAGE AREA (km^2)	GAGE START DATE	GAGING STATION ID #
I. IMPOUNDED R.S WITH PRE- AND POST IMPOUNDMENT DATA					
Connecticut R. @ West Lebanon, NH	Wilder Dam: p, f	1951	10598.3	1911	1144500
Ashuelot R.@ Hinsdale, NH	Surry Mt. Dam: f, r	1942	1087.8	1914	1161000
West R.@ Newfane, VT	Townshend Dam: f, r	1961	797.7	1928	1156000
Ottaqueechee R. @ N. Hartland, VT	N. Hartland Dam: f, r	1961	572.4	1930	1151500
Black R. @ N. Springfield, VT	N. Springfield Dam: f	1960	409.2	1929	1153000
Ompomp. R. @ Union Village, VT	Union Village Dam: f	1949	336.7	1940	1141500
Otter Brook near Keene, NH	Otter Brook Dam: f, r	1958	122.2	1923	(pre-dam) 1158500 (post-dam)1158600
IMPOUNDED R.S WITH POST-IMPOUNDMENT DATA ONLY					
Connecticut R. @ N. Walpole, NH	Bellows Falls Dam: p, r	1928	14226.9	1942	1154500
Connecticut R. @ Wells R., VT	Comerford Dam: p, r	1931	6848.0	1949	1138500
McIndoes Falls Dam: p		1931			
Moore Dam: p, r, f		1957			
Sugar R. @ West Claremont, NH	Sunapee Dam: p	1920s	696.7	1928	1152500
West R. @ Jamaica, VT	Ball Mt . Dam: f, r	1961	463.6	1946	1155500
Mascoma R. @ Mascoma, NH	Lake Mascoma Dam:	1920s	396.3	1923	1150500
Ashuelot R. nr. Keene, NH	Surry Mt. Dam: f, r	1942	261.6	1945	1158000
UNIMPOUNDED R.S:					
White R. @ West Hartford, VT	N/A	N/A	1787.1	1915	1144000
Williams R. nr. Rockingham, VT	N/A	N/A	290.1	1940	1153500 & 1153550
Wells R. @ Wells R., VT	N/A	N/A	254.9	1942	1139000
Ayers Brook @ Randolph, VT	N/A	N/A	79.0	1939	1142500
East Orange Branch @ E. Orange VT	N/A	N/A	23.1	1959	1139800
Mink Brook nr. Etna, NH	N/A	N/A	11.9	1962	1141800

Table 2:

IHA statistics	*Regime characteristics*	*Hydrologic parameters*
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual maxima 7-day means Annual minima 7-day means Annual maxima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1 day maximum Julian date of each annual 1-day minimum
Group 4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year
Group 5: Rate and frequency of water consecutive daily means condition consecutive daily values	Frequency Rate of Change	Means of all positive differences between Means of all negative differences between change No. of rises No. of falls

Table 3:

	1-day min. (m^3/s)	3-day min. (m^3/s)	7-day min. (m^3/s)	30-day min. (m^3/s)	90-day min. (m^3/s)	1-day max. (m^3/s)	3-day max. (m^3/s)	7-day max. (m^3/s)	30-day max. (m^3/s)	90-day max. (m^3/s)	Base-flow	Date min.	Date max.	# of Rev.
1. **Connecticut River** @N. Walpole	21.0	32.8	47.8	63.2	94.4	1689.4	1546.5	1343.6	914.7	567.0	0.18	223	120	163
2. **Connecticut River** @Wells River	13.5	21.3	30.8	41.0	60.4	866.7	772.7	641.2	423.7	266.8	0.22	221	136	158
3. **Sugar River** @West Claremont	1.4	1.5	1.6	2.0	3.1	117.4	92.8	71.9	44.1	26.2	0.14	253	125	113
4. **West River** @Jamaica	0.6	0.6	0.7	1.0	2.3	123.6	96.1	73.4	43.7	24.2	0.06	240	145	103
5. **Mascoma River** @Mascoma	0.9	1.3	1.5	1.6	2.1	54.6	47.8	37.6	21.8	12.9	0.25	241	134	72
6. **Ashuelot River** near Keene	0.2	0.2	0.3	0.4	0.9	28.2	27.3	25.4	18.6	11.2	0.05	239	115	85

Table 4:

IMPOUNDED R.S WITH PRE- AND POST-IMPOUNDMENT DATA

	Drainage Area (km^2)	Calculated 2-yr Q (m^3/s)	Number of Times that Calculated Pre-Dam 2-yr Q is Exceeded by Post-Impoundment Outflow	Pre-Dam Frequency of Largest Post-Dam Even
Connecticut R. @ West Lebanon, NH	10598.3	1376.4	18	5-10 yr flood
Ashuelot R. @ Hinsdale, NH	1087.8	180.1	3	10 yr flood
West R. @ Newfane, VT	797.7	356.8	0	~ 2-yr flood
Ottaqueechee R. @ N. Hartland, VT	572.4	145.9	7	2-5 yr flood
Black R. @ N. Springfield, VT	409.2	156.6	0	< 2 yr flood
Ompompanoosuc R. @ Union Village, VT	336.7	76.2	0	2 yr flood
Otter Brook near Keene, NH	122.2	32.3	0	< 2 yr flood

MPOUNDED R.S WITH POST-IMPOUNDMENT DATA ONLY

	Drainage Area (km^2)	Calculated 2-yr Q (m^3/s)	Number of Times that Calculated Pre-Dam 2-yr Q is exceeded By Post-Impoundment Outflow	Pre-Dam Frequency of Largest Post-Dam Event
Connecticut R. @ N. Walpole, NH	14226.9	2519.7	8	N/A
Connecticut R. @ Wells R., VT	6848.0	1393.6	9	N/A
Sugar R. @ West Claremont, NH	696.7	218.9	9	N/A
West R. @ Jamaica, VT	463.6	157.4	16	N/A
Mascoma R. @ Mascoma, NH	396.3	138.6	6	N/A
Ashuelot R. nr. Keene, NH	261.6	99.0	0	N/A

Table 5:

	1-day min. m^3/s	3-day min. m^3/s	7-day min. m^3/s	30-day min. m^3/s	90-day min. m^3/s	1-day max. m^3/s	3-day max. m^3/s	7-day max. m^3/s	30-day max. m^3/s	90-day max. m^3/s	Baseflow	Date min.	Date max.	Number of Reversals
1. **Mink Brook** (Drainage Area = 11.9 km^2; n = 33)														
Mean	0.20	0.23	0.31	0.60	1.34	115.03	80.94	56.96	30.60	17.32	0.04	229	116	99
Std. Dev.	0.01	0.01	0.01	0.02	0.03	1.72	1.05	0.65	0.33	0.16	0.00	23.11	69.16	12.62
Corr. Coeff.	0.24	0.24	0.22	0.34**	0.34**	0.22	0.20	0.06	-0.04	-0.04	0.27	-0.20	-0.02	0.41**
2. **East Orange River** (Drainage Area = 23.1 km^2; n = 37)														
Mean	0.04	0.05	0.05	0.08	0.12	3.95	3.06	2.56	1.72	1.02	0.00	237	139	115
Std. Dev.	0.03	0.04	0.04	0.05	0.07	1.62	1.22	0.98	0.52	0.25	0.00	43.89	80.01	10.67
Corr. Coeff.	0.49**	0.46**	0.45**	0.44**	0.41**	-0.11	-0.21	-0.25	-0.28	-0.09	0.55**	-0.06	0.08	0.36**
3. **Ayers Brook** (Drainage Area = 78.9 km^2; n = 54)														
Mean	0.13	0.14	0.15	0.20	0.33	14.54	10.79	8.39	5.36	3.13	0.00	231	131	115
Std. Dev.	0.09	0.09	0.10	0.13	0.20	5.35	3.39	2.47	1.50	0.76	0.00	45.35	78.71	11.15
Corr. Coeff.	0.18	0.22	0.28**	0.25	0.24	-0.07	-0.05	-0.04	-0.05	0.03	0.29**	-0.37**	-0.08	-0.39**
4. **Wells River** (Drainage Area = 259.4 km^2; n = 54)														
Mean	0.57	0.61	0.67	0.91	1.37	38.92	30.90	24.04	14.99	8.95	0.00	223	135	113
Std. Dev.	0.21	0.23	0.26	0.42	0.59	13.11	9.49	6.91	3.94	2.13	0.00	62.99	73.71	11.80
Corr. Coeff.	0.12	0.11	0.17	0.28**	0.29**	0.19	0.15	0.03	-0.11	-0.05	0.02	-0.13	-0.05	-0.51**
5. **Williams River** (Drainage Area = 290.1 km^2; n = 54)														
Mean	0.35	0.37	0.40	0.55	1.00	77.65	52.81	38.37	21.91	12.49	0.00	242	130	108
Std. Dev.	0.19	0.20	0.23	0.34	0.65	33.31	20.26	13.36	6.73	3.09	0.00	37.34	84.96	10.70
Corr. Coeff.	0.38**	0.40**	0.39**	0.35**	0.36**	0.47**	0.45**	0.35**	0.28**	0.33**	0.32**	-0.06	-0.04	-0.14
6. **White River** (Drainage Area = 1787.1 km^2; n = 78)														
Mean	3.71	3.96	4.31	5.64	8.95	394.84	287.39	217.02	132.94	76.85	0.00	244	128	118
Std. Dev.	1.66	1.69	1.88	2.82	4.75	142.06	97.38	68.60	36.29	16.58	0.00	34.77	80.28	12.94
Corr. Coeff.	0.32**	0.24**	0.24**	0.30**	0.23**	-0.14	-0.13	-0.12	-0.19	-0.17	0.27**	-0.33**	0.03	-0.62**