A CUSUM Analysis of Discharge Patterns by a Hydroelectric Dam and Discussion of Potential Effects on the Upstream Migration of American Eel Elvers

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2003

Canadian Technical Report of Fisheries and Aquatic Sciences No. 2454

Fisheries and Oceans Canada
Pêches et Océans Canada

Canadian Technical Report of
Fisheries and Aquatic Sciences No. 2454

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Cat. No. FS 97-6/2454 ISSN 0706-6457

Correct citation for this publication:
Jessop, B. M., and C. J. Harvie. 2003. A CUSUM analysis of discharge patterns from a hydroelectric dam and discussion of potential effects on the upstream migration of American eel elvers. Can. Tech. Rep. Fish. Aquat. Sci. No. 2454. 28 p. + *v*

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Abstract

Temporal changes in the seasonal and daily pattern and volume of discharge from the Mactaquac Dam, Saint John River, were examined for possible relationship with the abrupt cessation in 1980 of the annual arrival of elvers of the American eel (*Anguilla rostrata*) to the fish lift at the dam. Cumulative sum (CUSUM) analysis of the variability in magnitude, duration, timing, frequency and rate of change of the hourly and daily seasonal (May 15-July 15, 1970-1992) mean discharges from the hydroelectric dam showed significant changes that coincide with the installation of the final two (of six) turbines in the fall and winter of 1979-1980 and with the raising by 0.9 m of the headpond water level in 1984. American eel elvers are weak swimmers that, after a period of active upstream migration, settle into a bottom-dwelling, less-migratory mode. Changes in the pattern and volume of discharge from the dam may have sufficiently delayed upstream elver migration, via the creation of velocity barriers or other discharge conditions within a higher-gradient zone of about 11 km, such that reaching the Mactaquac Dam was no longer achievable during the window of active migration.

Although suggestive, the correlation between the timing of the cessation of annual elver appearance at the Mactaquac Dam fishway and the installation of the final two turbines at the dam is weakened by the absence of a well-designed before-after-control environmental impact study. Unlooked-for and unanticipated environmental impacts do occur even if their exact cause cannot be easily established afterward. Fishery managers anticipating large man-made changes to the natural flow regime of a river should consider the possibility of an effect on the upstream migration of eel elvers.

Resumé

Nous avons examiné les changements dans le temps des régimes saisonnier et quotidien du débit au barrage de Mactaquac, sur la rivière Saint-Jean, afin d'en déterminer les liens possibles avec la disparition soudaine en 1980 de la remonte annuelle des civelles d'anguille d'Amérique (*Anguilla rostrata*) à l'élévateur à poissons du barrage. L'analyse, par la méthode des sommes cumulées, de la variabilité de l'ampleur, de la durée, du moment, de la fréquence et du taux de changement des rejets moyens horaires, quotidiens et saisonniers (du 15 mai au 15 juillet, de 1970 à 1992) du barrage hydroélectrique a révélé des modifications importantes qui coïncident avec l'installation des deux dernières turbines (pour un total de six) à l'automne 1979 et à l'hiver 1980 et avec l'élévation du niveau de l'eau du bassin de retenue de 0,9 m en 1984. Les civelles d'anguille d'Amérique sont de faibles nageurs qui, après une période de remonte, adoptent un mode de vie plus sédentaire au fond de l'eau. Les changements dans les régimes du barrage et le volume d'eau qu'il rejette peuvent avoir suffisamment retardé la remonte des civelles, en créant des barrières hydrodynamiques ou en modifiant les conditions de rejet de l'eau dans un tronçon à forte pente d'environ 11 km, pour qu'elles ne puissent plus atteindre le barrage Mactaquac au cours de leur période de migration.

Bien que suggestive, la corrélation entre le moment de la disparition des civelles dans l'élévateur à poissons du barrage de Mactaquac et l'installation des deux dernières turbines est affaiblie par l'absence d'une étude d'impact environnemental bien conçue et fondée sur une comparaison avant-après. Des impacts environnementaux imprévus se produisent, même si leur cause exacte est difficile à déterminer par la suite. Les gestionnaires des pêches qui prévoient que les activités humaines entraîneront des modifications importantes du régime naturel d'une rivière devraient envisager la possibilité d'un effet sur la remonte des civelles.

Introduction

Naturally variable flows are critical to the ecosystem function and native biodiversity of unregulated rivers (Poff et al. 1997). Regulated rivers, such as those with hydroelectric dams, are subject to a wide variety of hydrological and ecological effects, many of which negatively affect the native biota (Cushman 1985; Moog 1993; Poff et al. 1997). The critical components of flow variation that affect ecological processes are the magnitude, frequency, duration, timing, and rate of change (Moog 1993; Poff et al. 1997). Instream migrations of diadromous fishes evolved under the timing and pattern of natural flow regimes. The rapid, short-term fluctuations in discharge characteristic of peaking operations at hydroelectric dams may seriously affect life cycle transitions of resident and diadromous fishes such as upstream and downstream migration and spawning as well as their abundance, diversity, and productivity (Cushman 1985; Zincone and Rulifson 1991; Moog 1993; Auer 1996; Stalnaker et al. 1996; Poff et al. 1997). Young and small fish may be highly susceptible to downstream displacement and mortality during high flows, depending upon the species (Harvey 1987). The loss or reduction of shallow water, low flow habitat may also alter the fish community (Bain et al. 1988).

American eels (*Anguilla rostrata*) are one of several diadromous fishes native to the Saint John River, New Brunswick, that have been affected by the construction of hydroelectric dams (Ruggles and Watt 1975). American eel elvers (freshwater age-0) juvenile eels recently arrived from the sea, typically 55-65 mm TL) typically enter rivers in southwestern New Brunswick annually between early May and late June (Groom 1975; Jessop 1998). Prior to 1980, large numbers of elvers, often forming ribbons along the outer walls of the fishway at the Mactaquac Dam, could be observed during their upstream migration between mid-June and early July (LeBlanc 1973; B. Jessop, personal observation). In 1980, the presence of elvers at the fishway abruptly ceased and they have not been observed since (B. Jessop; R. Price, Supervisor, Mactaquac Dam fishway, personal observations). In this study, we provide a possible explanation for the abrupt disappearance of elvers at the Mactaquac Dam; specifically, the increased daily and seasonal variability, and seasonal mean level of water discharge associated with the installation of the final two of six turbines in late 1979 and early 1980.

Study Site

The Saint John River is 678 km long, drains an area of 54,930 km^2 and enters the lower Bay of Fundy at Saint John, New Brunswick (Ruggles and Watt 1975). The lower 120 km is tidal with a saline wedge penetrating about 70 km upstream during low flow periods (Carter and Dadswell 1983). Tidehead is at about river kilometer (rkm) 120, downstream of Fredericton (rkm 129), but the tidal influence is difficult to measure much beyond rkm 90 because of the effect on water levels of the operation of the Mactaquac Dam hydroelectric station, located about rkm 148. The river bed gradient between the Reversing Falls at the river mouth (created by a sill 5 m below the Bay of Fundy mean high tide level; Carter and Dadswell 1983) and the Mactaquac Dam is about 0.019 $m \cdot km^{-1}$ and may be divided into two segments - Reversing Falls to Fredericton (129 km) with a riverbed gradient of 0.0048 $m \cdot km^{-1}$ and Fredericton to Mactaquac Dam tailrace (18 km) with a gradient of 0.119 $m \cdot km^{-1}$. The river surface gradient between the Mactaquac Dam and the head of tide varies with the lagged (1 h) discharge from the dam, from about 0.09 $m \cdot km^{-1}$ at 80 $m^3 \cdot s^{-1}$ discharge to 0.16 $m \cdot km^{-1}$ at 1,100 $m^3 \cdot s^{-1}$ (Randall 1975). Within the steeper river bed gradient zone, a 9-km section of braided channels, bars, and islands with riffles, runs, and pools begins about 5 km downstream of the Mactaquac Dam.

The Mactaquac Dam (Figure 1) was constructed in 1968 as a combination of "run of the river" and peak load hydroelectric plant, with generation largely controlled by the natural river flow but with a peak-load cycle imposed by daily demand that produces rapid alterations in downstream flow (Ruggles and Watt 1975). The generating station is operated as a peak-load plant during low flows and as a base-load plant during high flows. A typical daily generating pattern is as follows: multiple unit discharge commences about 0600 h, rises sharply to about 150 MW by 0700 h then rises steadily until 1200 h when an average load of 245-255 MW is reached and maintained until about 2200 h when the decline to the overnight low of 10-15 MW begins and is reached by 0100 h where it remains until the cycle begins again. The duration of the minimum load period varies with seasonal and daily demand.

The first three turbines were installed during 1968 and the fourth was installed in 1972. Installation of the final two of six turbines in October of 1979 and February of 1980 achieved a rated generating capacity of 660 megawatts. The headpond was raised by 0.9 m during June of 1984 following work that raised the dam height, which effectively increased potential power generation by 3%. Each turbine has a maximum discharge of about 396 $m^3 \cdot s^{-1}$; the maximum total discharge for six turbines is 2,380 $m^3 \cdot s^{-1}$. Prior to 1980, flows exceeding about 1,500 $m^3 \cdot s^{-1}$ were spilled; after 1980, flows exceeding 2,380 $m^3 \cdot s^{-1}$ were spilled. At low flows (minimum allowable discharge of 65.1 $m^3 \cdot s^{-1}$), all discharge is typically through the turbine nearest the fishway collection gallery. There is presently an approximately 10:1 maximum (about 650 $m^3 \cdot s^{-1}$):minimum (65 $m^3 \cdot s^{-1}$) discharge ratio during normal conditions, during which the tailrace can range from about 3 m to 4.8 m above datum (personal communication, F. Harriman, Manager, Mactaquac Generating Station).

Upstream passage for Atlantic salmon (*Salmo salar*) and river herring (*Alosa pseudoharengus, A. aestivalis*) at the 55 m high dam is provided by a trap-and-truck facility (Ruggles and Watt 1975). This facility is not designed for, or suited to, the passage of American eel elvers or juveniles due to the high water velocities through the collection gallery and associated crowder, brail, and hopper pools and the spacing of the floorboards in the brail pool. However, small numbers (typically less than 100 eels; personal observation B. Jessop) of larger (exceeding 300 mm TL) yellow eels may get passed upstream during the run of river herring. The Atlantic salmon brail pool has a hydraulic jump at the entrance, which deters eels, and the salmon are trucked to a nearby fish culture facility for sorting before transfer upstream. Eels and other species transported to the culture facility are released downstream of the dam.

Methods

Mean daily discharge measurements ($m \cdot s^{-1}$) for the period May 15-July 15, which brackets the period of historic elver appearance at the Mactaquac Dam, were obtained for the years 1970-1992 (Environment Canada 1994). Measurements were taken at the Environment Canada, Water Survey Branch, McKinley Ferry gauging station located about 1 km downstream of the Mactaquac Dam. Hourly measurements of river discharge ($m \cdot s^{-1}$) were obtained for the period May 15 to July 15 for the years 1975 to 1992 because the annual data for this period were most complete (Environment Canada, Environmental Monitoring Division, Fredericton, NB). Hourly values that were missing, occasionally extending for several days, were excluded from further consideration. Thirteen of the 18 years contained missing hourly values, representing from 0.07% to 66.2% of the seasonal data (Table 1). The high correlation ($r = 0.91$, $P < 0.001$, $N = 18$) between the annual seasonal (May 15-July 15) mean discharges estimated from the hourly discharge data and the mean May 15-July 15 daily discharges supports the reliability of annual trends based upon the hourly discharge data.

Richter et al. (1996) define 32 hydrologic parameters for the Indicators of Hydrologic Alteration method (IHA) to assess the change in a hydrologic regime before and after the system has been altered by human activities. These parameters reflect the magnitude, duration, timing, frequency and rate of change of discharge within a river system. We have selected many of these parameters, along with several more based primarily on hourly discharge values, to provide a biologically relevant flow profile of the Saint John River below the Mactaquac Dam (Table 2).

Thirty seasonal (May 15 to July 15) hydrologic parameter values were calculated for each year between 1970 and 1992. A shorter, more focused season interval (May 15 to June 15) was also examined, providing a second set of values for 24 of the hydrologic parameters. The shorter season defines a time interval that is thought to have the strongest influence on the movement of elvers. The set of annual values for each hydrologic parameter is defined in this analysis as a data series.

The cumulative sum (CUSUM) method of analysis (Woodward and Goldsmith 1964) was applied to all 54 data series (long and short season) to assess changes in annual seasonal discharge over the years of the data series. The CUSUM method is a technique for detecting the magnitude and location of changes in mean level within a time series. A constant target value (c, usually the data series average, as used in this analysis) is subtracted from each value in the data series (x_j) and the differences are accumulated over each successive series value, forming cumulative sums (S_i):

$$S_i = \sum_{j=1}^{i}(x_j - c)$$

The cumulative sums are plotted in a CUSUM chart on the original time scale (i). A change in the underlying mean of the data series will be revealed as a simultaneous change in the slope of the CUSUM chart. When the data series mean corresponds to the target value, the path of the CUSUM is roughly horizontal. When the local average of the series is greater than the target value, the CUSUM slopes upwards. Conversely, when the local average is less than the target value, the CUSUM slopes downwards. The greater the difference between the local average of the series and the target value, the steeper the slope of the CUSUM path. Therefore, relatively small changes in the mean level of a data series will appear as noticeably different slopes in the CUSUM chart. The point at which the slope of the CUSUM chart changes is a "turning point", corresponding to the point in the data series just before the change in mean level took place. Turning points are tested for significance in this analysis by the Span test.

The Span test uses an estimate of the data series variation to determine whether a turning point on the CUSUM chart corresponds to a real change in the mean level of the data series or just random fluctuation. The test assumes the data to be independent, normally distributed and with constant variance. The ends of any segment of the CUSUM path, within which a single change in the mean of the data series is suspected, are joined and the maximum vertical distance (V_{max}) between the CUSUM path and this line is measured. The test statistic (V_{max}/s) is the maximum vertical distance standardized by dividing it by an estimate of the data series variation (s)

$$s = \sqrt{\sum(x_{i+1} - x_i)^2 / 2(n-1)}$$

where n is the number of data series values. The test statistic is referred to the nomogram of critical values (BSI 1980) for the appropriate span (m) to obtain the probability of exceeding $|Vmax/s|$ in a sequence of length m from a series of independent, approximately normal observations. Critical values at the $\alpha = 0.05$ level were used in this analysis.

The CUSUM chart can be dissected into shorter spans and each span treated in the manner as described above, with the basis for segmentation the occurrence of local maxima or minima in the CUSUM chart. Each span must start or end on either end of the CUSUM path or on a significant turning point, straddle the turning point being analysed, and have its other end on any point which looks as if it might possibly be a significant turning point. The test is carried out at the $m\alpha/n\%$ level to provide a significance level for the whole series of approximately $\alpha\%$.

The CUSUM method is widely applied in industrial quality control (Woodward and Goldsmith 1964; van Dobben de Bruyen 1968; BSI 1980). Nicholson (1984) examined time series for sei whale percent female maturity and current meter velocity data, Jessop and Anderson (1989) examined longitudinal trends in juvenile fish CPUE, Manly (1994) applied the method to time series of various environmental variables and Hurst (1954) examined annual discharge to determine reservoir storage capacity requirements. We are unaware of any previous application of the CUSUM method to examine temporal trends in the discharge parameters of a hydroelectric dam.

Results

Between 1967 and 1992, annual discharges at the Mactaquac Dam, measured at McKinley Ferry gauging station, ranged from 581 to 1170 $m^3 \cdot s^{-1}$ (Environment Canada 1993). Annual discharge did not differ significantly between the years before 1980 and 1980 and beyond ($F = 0.14$, df = 1,24, $P = 0.72$). The maximum monthly mean discharge occurred either in April (56% of years) or May as a consequence of spring runoff while minimum mean monthly discharges usually occurred between July and March.

Group 1: Magnitude of Seasonal and Biweekly Daily Mean Discharge

The daily mean discharge typically is high during May and declines through the spring and summer (Figure 2). Mean seasonal (May 15-July 15) daily discharge varied annually between 366 and 1735 $m^3 \cdot s^{-1}$ (Figure 3a), and between 357 and 2698 $m^3 \cdot s^{-1}$ in the short season (May 15-June 15). Based on the CUSUM chart of the longer season data series, potential turning points were identified at 1971, 1979, 1982, and 1984 (Figure 3b). The Span test indicated that only 1979 was significant at $\alpha = 0.05$ (Table 3). The mean daily discharge during the period 1980-1992 was 34% lower than during the period 1970-1979 (Figure 3a). The shorter season data series also indicated 1979 as a significant turning point (Table 3).

CUSUM charts for the 4 biweekly data series of mean daily discharge indicated that, under the Span test, 1978 was a significant turning point in the May 15-31 data series, with the mean of the period 1979-1992 49% lower than that of 1970-1978 (Table 3; Figure 4a). The years 1982 and 1984 were identified as significant turning points in the June 1-15 data series, with the mean of the period 1985-1992 43% lower than that of 1970-1982, and both much lower than that of 1983-1984 (Table 3; Figure 4b). Neither of the June 16-30 or July 1-15 data series provided significant turning points (Table 3).

Group 2: Magnitude and Duration of Seasonal Extremes in Daily Mean Discharge

Seasonal 1-day maximum daily mean discharges varied annually between 1159 and 6120 $m^3 \cdot s^{-1}$ while 1-day minimum values typically remained about 100 to 200 $m^3 \cdot s^{-1}$. A potential turning point in the data series of maximum discharges occurred in 1979, but was only marginally non-significant at $P = 0.059$ (Table 3; Figure 5a). The high maximum discharge in 1984 likely contributed to a higher p-value than expected.

Seasonal 3-day, 7-day and 30-day maximum daily mean discharge series were all similar in appearance and gave similar results. The Span test indicated that 1979 was a significant turning point in all 3 data series, with the mean of the period 1980-1992 38-42% lower than that of 1970-1979 in each series (Table 3; Figure 5b). None of the potential turning points in the 1-day, 3-day, 7-day or 30-day minimum daily mean discharge series were found to be significant at $\alpha = 0.05$.

The shorter seasonal 1-day, 3-day and 7-day maximum data series showed similar results to the longer seasonal data series, with all 3 series indicating significant turning points at 1979. The shorter seasonal 1-day and 3-day minimum data series also had significant turning points at 1979 (Figure 6a-b), but the 7-day minimum data series indicated that 1984 was the significant turning point (Figure 6c). Visually, the data series drops to a lower average after 1979, but high values in 1983 and 1984 obscure the effect. In all data series, the mean of the post-turning point period was lower (range 37-63%) than that of the pre-turning point period (Table 3).

The range between the seasonal 1-day minimum and 1-day maximum daily mean discharge values varied annually between 1063 and 5992 $m^3 \cdot s^{-1}$. The CUSUM chart was very similar to that of the seasonal 1-day maximum daily mean discharge series (Figure 5a), though the Span test indicated that 1979 was a marginally more significant turning point. The mean range of the period 1980-1992 was 36% lower than that of 1970-1979. The shorter seasonal range series did not indicate any significant turning points (Table 3).

Group 3: Timing of Seasonal Extremes in Daily Mean Discharge

The timing of the seasonal 1-day minimum generally occurred after day 26 of the season. The CUSUM chart and the Span test for the minimum data series indicated that a significant turning point occurred in 1983, with the mean timing of the period 1984-1992 28% lower than that of 1970-1983. The 1-day maximum generally occurred before day 19, but no potential turning points were found to be significant. The timing of the 1-day minimum and maximum in the shorter season showed no significant turning points (Table 3).

Group 4: Frequency and Duration of High and Low Daily Mean Discharge Pulses

The low pulse threshold is defined as the 25th percentile of all daily mean discharge values in the period 1970-1979. The high pulse threshold is likewise defined as the 75th percentile of all such values. The count of low daily mean discharge pulses varied annually between 0 and 10 and the count of high daily mean discharge pulses varied between 0 and 4 (Figure 7a-b). The CUSUM charts of both data series indicated a potential turning point at 1984, significant at $\alpha = 0.05$. In addition, 1982 was found to be a significant turning point in the high pulse data series. The mean count of low pulses of the 1985-1992 period was 100% higher than that of 1970-1984. The mean count of high pulses was similar between the periods 1970-1982 and 1985-1992, but about 65% lower than that of 1983-1984 (Table 3).

The mean duration of the low pulses varied annually between 0 and 10.5 days, with 1971 a noticeably high value. There were no significant turning points found in the data series. The mean duration of the high pulses varied between 0 and 20 days (Figure 7c). The only significant turning point was 1979, the mean of the period 1980-1992 dropping 68% from that of 1970-1979 (Table 3).

For the shorter season, the CUSUM chart of the low pulse count data series showed 1978, 1979 or 1980 as almost equally likely turning points. Due to the discrete nature of the count data, the most appropriate turning point could not be determined from the CUSUM chart, so the mid-point year, 1979, was chosen. The mean count of low pulses of the 1980-1992 period was 77% higher than that of 1970-1979. The CUSUM chart of the high pulse count data series showed a potential turning point at 1979, which was significant at $\alpha = 0.05$. The mean high pulse count for the period 1980-1992 was 65% lower than that of 1970-1979 (Table 3).

The shorter season low and high pulse duration data series showed results similar to the longer season, with the mean high pulse duration of the period 1980-1992 67% lower than that of 1970-1979 (Table 3).

Group 5: Rate and Frequency of Change of Daily Mean Discharge

The mean of all positive differences between consecutive daily discharge values (rise rate) generally ranged between 100 and 200 $m^3 \cdot s^{-1}$ per day. The mean fall rate data series varied annually between 115 and 292 $m^3 \cdot s^{-1}$ per day. No significant turning points were found either data series. The same data series for the shorter season indicated significant turning points at 1982 and 1985 for the fall rate data series, but none for the rise rate data series. The mean fall rates were similar for the periods 1970-1982 and 1986-1992, but about 40% lower than that of 1983-1985 (Table 3).

The number of times daily mean discharge changed from rising to falling or falling to rising during the season varied annually between 20 and 38, but showed a steady increase over time. The CUSUM chart showed a gradual change in slope between 1977 and 1984, with 1977 being the most significant turning point. The mean number of flow changes of the 1978-1992 period was only 19% higher than that of 1970-1977. The same data series for the shorter season showed a more marked 88% increase after a significant 1974 turning point (Table 3).

Group 6: Magnitude of Daily Range of Hourly Discharge

The daily range (maximum – minimum) of the hourly discharge values, highlighting the amount of discharge variation found within each day of the season, was plotted in Figure 8. The mean seasonal daily range varied annually between 468 and 1272 $m^3 \cdot s^{-1}$. The CUSUM chart indicated significant turning points at 1980 and 1986. The mean daily range of the period 1987-1992 was slightly higher than that of 1975-1980, and both were 25-35% lower than that of the period 1981-1986. The data series for the shorter season was similar, but with a turning point at 1985 instead of 1986 (Table 3).

A minimum level of discharge flow was observed in most years, usually starting in late June, which reduced the daily range. The mean seasonal daily range was recalculated, excluding those days when the discharge "bottomed out". The data series for both the full and shorter seasons increased steadily from 1975 to 1985, dropped sharply over the next year or two, then leveled off. The steady increase in the daily range contributed to CUSUM charts with rounded paths instead of sharp turning points. However, significant turning points were found at 1979, 1982 and 1985 in both the full and shorter seasons. The mean daily range for the period 1986-1992 was close to that of 1980-1982, about 26% lower than that of 1983-1985, and about 51% higher than that of 1975-1979 (Table 3).

Group 7: Magnitude of Extremes of Hourly Mean Discharge

The hourly discharge values were averaged, over the season, for each hour of the day (0100-2400 h) and plotted by year. The discharge slowly descends from 0100 h to the daily minimum at 0500 h, quickly rises to the daily maximum at 1100 h, slowly falls until 2100 h or 2200 h, then falls quickly to 2400 h (Figure 9). The seasonal minimums, maximums and ranges of these values vary annually. The seasonal minimum hourly mean discharge data series varied between 117 and 988 $m^3 \cdot s^{-1}$. A significant turning point was found at 1979, resulting in the mean of the period 1980-1992 being 56% lower than that of 1975-1979. The seasonal maximum hourly mean discharge varied between 588 and 1658 $m^3 \cdot s^{-1}$. The CUSUM of the data series indicated a significant turning point at 1986, giving a mean level 31% lower after 1986 than for the period 1975-1986. The shorter season data series gave similar results, except that a turning point was found in 1985, instead of 1986, for the seasonal maximum data series (Table 3).

The seasonal range of hourly mean discharge varied between 252 and 1039 $m^3 \cdot s^{-1}$ (Figure 10a). The years 1980 and 1986 were found to be significant turning points in the data series. The means of the periods 1975-1980 and 1987-1992 were similar, but both were about 40% lower than that of the period 1981-1986. The range of hourly mean discharge between 1100 h and 2200 h was calculated as an indication of the length of time the flow remained constantly high during the daily cycle. The CUSUM chart showed 1979 as a significant turning point, resulting in the mean level of the 1980-1992 period being 175% higher than that of 1975-1979 (Figure 10b). The shorter season data series gave similar results (Table 3).

Group 8: Rate of Change of Hourly Mean Discharge

The rate of change between minimum and maximum hourly mean discharge within the daily cycle, or "ramp up" rate to full discharge, was estimated by the average slope of the line between the minimum and maximum hourly discharges. Significant turning points in the CUSUM chart of the data series occurred in 1979 and 1986 (Figure 10c). The seasonal mean rate of change was similar between the periods 1975-1979 and 1987-1992, but both were about 40% lower than that of 1980-1986. The shorter season data series indicated significant turning points at 1979 and 1985 (Table 3).

Discussion

Annual variability in seasonal (May 15-July 15) mean daily discharge at a "run of the river" hydroelectric station depends mainly upon seasonal precipitation and the timing of the spring snow melt relative to the period examined, less so on operating procedures. Thus, the high seasonal mean discharges in 1972 and 1984 resulted from unusually heavy spring precipitation coupled with a later than usual runoff. The 1972 flood will not be further discussed because it had no influence on the post-1979 failure of elvers to reach the Mactaquac Dam. The effects of the 1984 extended (May-July) high water levels on various CUSUM analyses are particularly noticeable in the analysis, e.g., Figure 3. The high water effectively masked the reduction in mean level after 1979 of the June 1-15 daily mean discharge (Figure 4b), the seasonal 1-day, 3-day, 7-day and 30-day minimum daily discharge, and the 1-day maximum daily discharge (Figure 5a).

The installation of the last two turbines at the Mactaquac Dam in 1979-1980 coincides with the first group of significant CUSUM turning points in the analysis of daily and hourly seasonal discharge. The increase in generating capacity from four to six turbines and changes to operating procedures reduced the seasonal daily mean discharge relative to the pre-1980 period (Figure 3), decreased the seasonal 3-day, 7-day and 30-day maximum daily discharge (Table 3; Figure 5b), decreased the shorter seasonal 1-day and 3-day minimum daily discharge (Figure 6), decreased the range of the daily mean discharge (Table 3), increased the shorter seasonal count of low daily mean discharge pulses (Table 3), decreased the shorter seasonal count of high daily mean discharge pulses (Table 3), decreased the duration of high discharge pulses (Figure 7c), increased the daily range of hourly discharge (Table 3), decreased the minimum hourly mean discharge (Table 3), increased the range of the hourly mean discharge and of the hourly mean discharge between 1100-2200 h (Figure 10a-b), and increased the rate of change of the hourly mean discharge during the daily ramping up of power generation (Figure 10c).

The second group of significant CUSUM turning points occurring in 1984, 1985 and 1986 is coincident, on a lagged or cumulative-effect basis, with the raising of the Mactaquac Lake water level in the spring of 1984, which became fully effective with respect to the elver run in 1985. This group can be divided into two subgroups: those data series with the significant turning point apparently based only on the effect of the extended high water level in 1984 and/or the extended low water level in 1987 and 1988 (Figure 2), and those data series where the change in mean level does not appear to rely primarily on these water level extremes, but likely is affected by the raising of the headpond water level in 1984. The June 1-15 daily mean discharge (Figure 4b), shorter seasonal 7-day minimum daily discharge (Figure 6c), seasonal count of low discharge pulses (Figure 7a), and seasonal count of high discharge pulses (Figure 7b) data series appear to all have had significant 1984 turning points affected only by the extreme water levels, based on the abrupt and short-lived change in the data series at these years. Without such extremes in the data series, there would likely have been no significant change in mean level for the two pulse counts series, and only one significant change after 1979 for the June 1-15 daily mean discharge and the 7-day minimum daily discharge series. The raising of the headpond appears to have significantly reduced the data series mean level for the seasonal maximum (Table 3), seasonal range (Figure 10a), and rate of change (Figure 10c) of the hourly mean discharge; the seasonal mean of the daily range of hourly discharge (Table 3); and the seasonal mean of the daily range of hourly discharge above minimum flow (Table 3). The additional water storage provided by raising the headpond level also extended the period during which higher power generation levels could be maintained by reducing the rate of seasonal drawdown of the headpond.

Although the CUSUM approach may not have been previously used to examine temporal trends in river discharge parameters for significant change, the CUSUM results were largely similar (Jessop and Harvie, unpublished data) to those of the recently described IHA method (Richter et al. 1996). As an alternative to the IHA method, the CUSUM method offers some advantages, including its well-developed methodology (Woodward and Goldsmith 1964; van Dobben de Bruyn 1968), graphical presentation, and lack of any *a priori* presumptions about locations of turning points (or critical events) in the data series, as is required by the IHA method.

Hydroelectric dams are major modifiers of river flow and ecology (Cushman 1985; Moog 1993; Stalnaker et al. 1996; Poff et al. 1997). Operation of the Mactaquac Dam, largely as a "run of the river" hydroelectric station, has not greatly altered the seasonal flow pattern of the spring flood that serves to cue the spawning migrations of anadromous fishes such as the Atlantic salmon, river herring and elvers of the catadromous American eel. However, superimposition of a daily peak-load generation cycle can have serious ecological effects that increase in magnitude with an increasing ratio of maximum: minimum discharge and rate of change in discharge (Moog 1993; Poff et al. 1997). An abrupt cessation of the annual appearance of American eel elvers at the Mactaquac Dam in 1980 coincided with the installation of the final two turbines at the dam in fall and winter of 1979-1980. The changes to daily and hourly discharge patterns indicated by the first group of CUSUM turning points can plausibly account for the failure of elvers to migrate to the Mactaquac Dam after 1979 and implies a threshold set of generating conditions beyond which elver migration is prevented.

Alternative explanations may exist. For example, larval production in the Sargasso Sea may have declined after 1979, or oceanic conditions may have altered their distribution patterns, with consequent effect on the availability and distribution of glass eels/elvers to the Maritime Provinces and specifically the Saint John River. Unfortunately, no good data exists to convincingly support such hypotheses for the relevant time period, except perhaps for oceanographic conditions represented by the North Atlantic Oscillation (NAO) index, assuming that the trends in North American elver abundance follow those of Europe (ICES 2001). No extended time series of elver abundance exist for North America; the longest available index (for the East River, Sheet Harbour, Nova Scotia) covers only the period between 1989-1999 and shows no trend in abundance (Jessop in press). Even if elver run size to the Saint John River has declined since 1979, a failure of elvers to appear at the Mactaquac Dam might presuppose a major effect of elver density on the strength of upstream migration rather than an innate urge for upstream migration and expansion into available habitat. Our understanding of the nature of elver migration does not permit a definitive answer.

In the low gradient, slower flowing, tidal section of the Saint John River downstream of Fredericton, American eel elvers likely use selective tidal stream transport to move rapidly upstream (McCleave and Kleckner 1982) but active swimming is required as the river gradient increases upstream of Fredericton. Prior to 1980, elvers are estimated to have taken about 62 d (assuming mean elver entrance to the river during mid April and the first substantial appearance of elvers at the Mactaquac Dam in mid June) to migrate the 148 km from the river mouth to the dam at an average speed of 2.4 $km \cdot d^{-1}$, with progress most rapid in the tidal zone. An 11-km section of braided channels, gravel bars, and islands begins about 5 km downstream of the Mactaquac Dam.

A detailed understanding does not exist of the interaction of stream velocity/discharge and stream morphology on the upstream migration of eel elvers. However, elvers are weak swimmers and move along the stream edge where water velocities are reduced and shore irregularities provide resting areas. Jessop (2002a) concluded that river discharge, with its associated effect on water velocity, was the primary instream factor controlling the rate of elver upstream movement. At water velocities exceeding 35-40 cm·s^{-1}, elvers have difficulty swimming or cannot maintain position and most will not swim at water velocities exceeding 25 cm·s^{-1}, tending instead to rest in the stream substrate (McCleave 1980; Barbin and Krueger 1994). Velocity barriers need only act along a relatively short shoreline length (centimeters to tens of meters depending upon water velocity) to seriously delay or prevent upstream movement by elvers. At a discharge of 1,120 m^3·s^{-1}, near-shore (2-3 m) water velocities in a downstream braided channel were measured at 12 cm·s^{-1} at the shallow-slope stream bank and 26 cm·s^{-1} at the steep-slope stream bank (Randall 1975). Water velocity measurements made inshore (about 0.3 m from shore and 10 cm depth) at 15 sites located from just downstream of the Mactaquac Dam to 7.5 km downstream averaged 10.0 cm·s^{-1} (range 1.5-27.4 cm·s^{-1}) at a discharge of 1,540 m^3·s^{-1}. At hourly discharges ranging from 300 m^3·s^{-1} to 1,500 m^3·s^{-1} or more the potential exists for velocity barriers to elver upstream migration over several kilometers. Depending upon seasonal water levels, elvers migrated upstream in the East River, Chester, at 15.3-38.2 m·d^{-1} over a distance of 1.3 km with an average gradient of 1.3%, within which were two small (about 2.4 m) falls (Jessop 2002b). In a high (2.2%) gradient zone of the Annaquatucket River, Haro and Krueger (1988) reported upstream movement by elvers of slightly more than 6 m·d^{-1}.

Although power generation and high discharges occur primarily during daylight when elver migratory activity is less than at night, low nighttime discharge may also reduce migration success. At night, the reduced discharge withdraws the water flow into the steeper-sided main stream channel, greatly reducing the wetted area and the shallow, slower-flowing areas at the stream edge (Heede and Rinne 1990), thereby maintaining effective velocity barriers to elver migration. Elvers left at the high-water stream edge may also experience higher mortality under these more hazardous environmental conditions. If sufficient cumulative delay is provided by higher and more variable hydroelectric discharge cycles, elvers may cease their visibly-migrating phase and enter their bottom-dwelling phase before reaching a previously attainable stream location. A declining proportion of juvenile eels continue upstream migration for a number of years, unless prevented by obstructions (Tesch 1977; Moriarty 1986). Prior to construction of the Mactaquac Dam, juvenile eels migrated as far as Grand Falls, about 220 km upstream of the Mactaquac Dam.

Larger and older eels are abundant downstream of the Mactaquac Dam, as is evident by the commercial fishery that occurs there. A preliminary study into the feasibility of trapping and trucking small juvenile eels upstream of the Mactaquac Dam evaluated the abundance of small juvenile eels at a site about 0.5 km downstream of the Mactaquac Dam fish-lift (Jessop, unpublished data). Between June 19 and August 13, 1992, almost 1,900 juvenile eels were collected by a shoreline eel trap similar in general design to that used to collect elvers at other sites (Jessop 2000). The juvenile eels averaged 100.4 mm long (range 74-133 mm); none were considered elvers (Jessop 1998).

The absence of quantitative measurements of elver abundance prior to 1980 limits some conclusions but the issue is presence and absence and not annual variability in numbers greater than zero. This study retrospectively analyzes a fortuitously observed, unanticipated perturbation that, by its nature, is not readily duplicated or manipulated in a more traditional scientific manner. Since 1973, fishway staff have regularly, but casually, observed the occurrence or non-occurrence of elvers as has one of the authors (Jessop) during regular visits to the fishway when sampling river herring 1-3 days per week during their upstream migration and while monitoring the commercial fishery at the dam (Jessop 1990). The obvious presence of elvers prior to 1980 and a scarcity of information on their biology at that time prompted preparation of a sampling program for elvers to be implemented during the spring of 1980. The absence of elvers at the fishway that spring and thereafter have since prevented such a sampling program.

The possibility exists that changing discharge conditions at the Mactaquac Dam simply changed the hydrodynamics of the tailrace and nearby area, including the fish-lift zone, as opposed to areas further downstream. The turbine nearest the entrance to the fish-lift collection gallery is operated at a much lower generation level than the more distant turbines to improve the attraction of the fish-lift for Atlantic salmon and gaspereau. The addition of the new turbines in 1980 at the upstream end of the turbine row did not change this operational practice. Elvers are unlikely to bypass the fish-lift zone and gather in the large back-eddy (when the spillways are not in use) at the base of the dam upstream of the fish-lift. The turbulent main discharge plume exits the dam upstream of the fish-lift area and flows across the river to impact the far side of the river (true right bank) as it flows downstream. The flow along the bank nearest the fish-lift (true left bank) is relatively less turbulent in the area of, and immediately downstream of, the fish-lift and is likely to be the bank where elver migration is easiest. Thus, upstream migrant elvers are likely to be contained in the fish-lift area rather than to move beyond it if they do reach the fish-lift. The flow does not attain a pattern dictated by bed geomorphology for several kilometers downstream. A downstream blockage could, of course, prevent elvers from even reaching the fish-lift area. The question of just how far downstream such an area might be is not readily answered, although exclusion from the fish-lift zone might be considered an important effect in itself if one were planning to collect elvers at the fish-lift for upstream transport. If the discharge conditions in 1992, when the juvenile survey downstream of the dam found no elvers, are compared with those of other years since 1980, the great majority of years had discharge conditions that could mostly be considered less favourable to elver migration. Some years, such as 1986-1988 had certain conditions that might be considered favourable to elver migration relative to the other years. Why elvers were not observed at the fish-lift in those years is not readily explainable given our poor understanding of the detailed effects of hydrodynamic change on elver migration. It is unlikely that any single condition is decisive, except in extreme situations and that the cumulative effect of several conditions is most important.

Interest in the response of biological systems to anthropogenic change is typically focused on problems and species regarded as important. Thus, on the Saint John River, the impact of the construction and operation of the Mactaquac Dam on diadromous fish stocks migrating upstream was largely focused on the Atlantic salmon, with no evident consideration given to other diadromous species such as the American eel. (Ruggles and Watt 1975). Environmental impact considerations were largely limited to determining how best to provide fish passage for Atlantic salmon as required by the Minister of Fisheries under the Federal Fisheries Act and how to mitigate the anticipated losses to salmon production via construction of the Mactaquac Fish Culture Station. The fish-passage facility was designed specifically for Atlantic salmon but fortuitously proved able to handle large numbers of river herring (Ruggles and Watt 1975; Jessop 1990). No passage for American eels was provided. The presence of the Mactaquac Dam has largely destroyed the run of American shad *A. sapidissima* that once migrated further upstream (Ruggles and Watt 1975). The dam is also believed responsible for extirpation of the striped bass that once spawned a short distance downstream of the dam site (Jessop 1995), although feeding, migrant striped bass are common in the vicinity of the dam and frequently enter the fishway. Successful spawning by striped bass is dependant upon discharge patterns typical of natural-flow rivers and may be severely affected by hydroelectric dam discharge patterns set for economic reasons (Rulifson and Manooch 1990; Zincone and Rulifson 1991). A risk assessment was done for the planned raising of the Mactaquac Dam headpond water level in 1984 (Anon. 1980) but no assessment was done of the actual impact. The possibility of an effect on elver upstream migration was not foreseen or considered when the environmental impact of constructing the dam was evaluated, when the number of turbines was increased, or when the headpond level was raised (Ruggles and Watt 1975; Anon. 1980).

In summary, the association between the failure of elvers of the American eel to reach the Mactaquac Dam from 1980 onwards and the installation of the last two turbines at the dam and subsequent changes in discharge pattern is suggestive, but not proof, of a direct cause and effect.

A hypothesis examining this relationship could be experimentally tested by active manipulation of seasonal discharge patterns, although active manipulation may be impractical for economic reasons. The role of the 1984 increase in headpond elevation is less clear but it likely contributed further to preventing the upstream migration of elvers to the Mactaquac Dam. The fortuitous observation reported here should be notice that, where eel elvers are present, any planned study of the environmental impact of the potential effects of changing the hydrological regime of a regulated river should consider the possible effects on the upstream movement of elvers.

Acknowledgements

We thank P. Amiro, L. Marshall, J. Gibson and D. Cairns for their comments on earlier versions of the manuscript.

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Table 1. Number and dates of missing hourly discharge values and their percentage of the May 15 – July 15 seasonal data.

Year	Dates	Number of hours	Percentage of seasonal data
1975	May 15 - 20	144	9.68
1976	June 10, hour 8	1	0.07
1977	June 22 - July 15	576	38.7
1978	May 15	24	1.61
1979	July 12, hours 6 - 7	2	0.13
1980	none		
1981	July 15	24	1.61
1982	none		
1983	none		
1984	May 15 - 20; June 2 - 7	288	19.4
1985	July 11 - 15	120	8.07
1986	June 15 - 27	312	21.0
1987	none		
1988	none		
1989	May 15 - 19; July 8 - 15	312	21.0
1990	May 15 - 24; May 27, hour 24; May 28 - June 27	985	66.2
1991	May 15 - 16	48	3.23
1992	June 3 - 4; June 6, hour 24; June 7 - 30; July 3 - 9	793	53.3

Table 2. Description of the 30 hydrologic parameters used in the analysis. Source: Richter et al. (1996).

Group characteristics	Hydrologic parameters (number)
Group 1: Magnitude of seasonal and biweekly daily mean discharge	Mean of daily discharge for season (1). Mean of daily discharge for each biweekly period (4): May 15-31, June 1-15, June 16-30, July 1-15.
Group 2: Magnitude and duration of seasonal extremes in daily mean discharge	1-day, 3-day, 7-day and 30-day average minimums and maximums of daily discharge (8). Seasonal range (1-day max - 1-day min) of daily discharge (1).
Group 3: Timing of seasonal extremes in daily mean discharge	Season day number of 1-day maximum and minimum (2).
Group 4: Frequency and duration of high and low daily mean discharge pulses	Number and average duration of high (> 25th percentile) and low (< 25th percentile) daily discharge pulses (4).
Group 5: Rate and frequency of change of daily mean discharge	Mean of all positive and negative differences between consecutive daily discharge values (2). Number of discharge flow reversals (1).
Group 6: Magnitude of daily range of hourly discharge	Mean of daily range of hourly discharge (1). Mean of daily range of hourly discharge for days when discharge stayed above minimum flow (1).
Group 7: Magnitude of extremes of hourly mean discharge	Minimum, maximum and range of hourly mean discharge (3). Range of hourly mean discharge between 1100 and 2200 hours (1).
Group 8: Rate of change of hourly mean discharge	Rate of change from minimum to maximum hourly mean discharge - "ramp-up" (1).

Table 3. Results of the cumulative sums (CUSUM) analyses. Bold values indicate significance at the α = 0.05 level. If more than one potential turning point for a hydrological parameter was tested for significance, only those with a p-value less than 0.200 are included in the table. Note that the biological relevance of the turning points should be considered in relation to the years 1980, when the absence of elvers at the Mactaquac Dam fish-lift first occurred, and 1984, when the headpond level was raised. Turning points occur in the year prior to the event effects.

	Full season (May 15 - July 15)					Short season (May 15 - June 15)				
Hydrologic parameter	Potential turning point	Within the series	p-value	Series segment	Segment mean	Potential turning point	Within the series	p-value	Series segment	Segment mean
Group 1: Magnitude of seasonal and biweekly daily mean discharge										
Season	**1979**	1970 - 1992	**0.002**	1970 - 1979	1151	**1979**	1970 - 1992	**<0.001**	1970 - 1979	1698
	1971	1970 - 1974	0.195	1980 - 1992	754	1982	1980 - 1984	0.176	1980 - 1992	990
	1982	1980 - 1984	0.198			1984	1983 - 1992	0.126		
	1984	1983 - 1992	0.187							
May 15-31	**1978**	1970 - 1992	**<0.001**	1970 - 1978	2354					
				1979 - 1992	1189					
June 1-15	**1984**	1970 - 1992	**0.040**	1970 - 1982	968					
	1982	1980 - 1984	**0.031**	1983 - 1984	1919					
				1985 - 1992	549					
June 16-30	1985	1970 - 1992	>0.500	1970 - 1992	583					
July 1-15	1991	1970 - 1992	>0.500	1970 - 1992	479					
Group 2: Magnitude and duration of seasonal extremes in daily mean discharge										
1-day minimum	1984	1984 - 1992	0.111	1970 - 1992	150	**1979**	1970 - 1992	**0.001**	1970 - 1979	660
									1980 - 1992	242
3-day minimum	1984	1970 - 1992	0.109	1970 - 1992	216	**1979**	1970 - 1992	**0.002**	1970 - 1979	762
									1980 - 1992	377
7-day minimum	1984	1970 - 1992	0.261	1970 - 1992	304	**1984**	1970 - 1992	**0.017**	1970 - 1984	791
									1985 - 1992	411
30-day minimum	1984	1972 - 1992	0.110	1970 - 1992	490					
1-day maximum	1979	1970 - 1992	0.059	1970 - 1992	3051	**1979**	1970 - 1992	**0.049**	1970 - 1979	3824
									1980 - 1992	2409
3-day maximum	**1979**	1970 - 1992	**0.031**	1970 - 1979	3525	**1979**	1970 - 1992	**0.029**	1970 - 1979	3525
				1980 - 1992	2178				1980 - 1992	2157
7-day maximum	**1979**	1970 - 1992	**0.005**	1970 - 1979	3035	**1979**	1970 - 1992	**0.005**	1970 - 1979	3035
				1980 - 1992	1753				1980 - 1992	1742
30-day maximum	**1979**	1970 - 1992	**<0.001**	1970 - 1979	1754					
	1982	1980 - 1984	0.179	1980 - 1992	1041					
	1984	1983 - 1992	0.158							
1-day range	**1979**	1970 - 1992	**0.047**	1970 - 1979	3653	1978	1970 - 1992	0.192	1970 - 1992	2600
				1980 - 1992	2322					
Group 3: Timing of seasonal extremes in daily mean discharge										
Day # of minimum	**1983**	1970 - 1992	**0.039**	1970 - 1983	50	1974	1970 - 1992	>0.500	1970 - 1992	26
	1986	1984 - 1992	0.145	1984 - 1992	36					
Day # of maximum	1982	1970 - 1987	0.055	1970 - 1992	7.3	1986	1983 - 1992	0.193	1970 - 1992	5.5
	1987	1987 - 1992	0.062							
Group 4: Frequency and duration of high and low daily mean discharge pulses										
Low pulse count	**1984**	1970 - 1992	**<0.001**	1970 - 1984	3.4	**1979**	1970 - 1992	**0.010**	1970 - 1979	1.3
				1985 - 1992	6.8				1980 - 1992	2.3
High pulse count	**1982**	1970 - 1984	**0.040**	1970 - 1982	1.5	**1979**	1970 - 1992	**<0.001**	1970 - 1979	1.7
	1984	1983 - 1990	**<0.001**	1983 - 1984	4.0				1980 - 1992	0.6
				1985 - 1992	1.3					
Low pulse duration	1971	1970 - 1992	0.285	1970 - 1992	5.1	1986	1970 - 1992	0.294	1970 - 1992	8.7
High pulse duration	**1979**	1970 - 1992	**<0.001**	1970 - 1979	10.9	**1979**	1970 - 1992	**<0.001**	1970 - 1979	4.9
				1980 - 1992	3.5				1980 - 1992	1.6
Group 5: Rate and frequency of change of daily mean discharge										
Rise rate	1982	1970 - 1987	0.098	1970 - 1992	166	1984	1984 - 1992	0.085	1970 - 1992	205
	1987	1983 - 1992	0.099							
Fall rate	1982	1970 - 1992	0.059	1970 - 1992	-185	1982	1970 - 1992	0.145	1970 - 1982	-192
	1971	1970 - 1974	0.156			**1982**	1970 - 1985	**0.012**	1983 - 1985	-336
	1985	1983 - 1992	0.158			**1985**	1983 - 1992	**0.022**	1986 - 1992	-203
Count of flow changes	**1977**	1970 - 1992	**0.038**	1970 - 1977	26	**1974**	1970 - 1992	**<0.001**	1970 - 1974	8
				1978 - 1992	31				1975 - 1992	15

Table 3 (cont.). *Results of the cumulative sums* (CUSUM) analyses. Bold values indicate significance at the $\alpha = 0.05$ level. If more than one potential turning point for a hydrologic parameter was tested for significance, only those with a p-value less than 0.200 are included in the table.

	Full season (May 15 - July 15)					Short season (May 15 - June 15)				
Hydrologic parameter	Potential turning point	Within the series	p-value	Series segment	Segment mean	Potential turning point	Within the series	p-value	Series segment	Segment mean
Group 6: Magnitude of daily range of hourly discharge										
Range	**1980**	1975 - 1992	**0.021**	1975 - 1980	609	**1980**	1975 - 1992	**<0.001**	1975 - 1980	636
	1983	1981 - 1985	0.160	1981 - 1986	939	**1985**	1981 - 1992	**0.007**	1981 - 1985	1108
	1986	1981 - 1992	**0.040**	1987 - 1992	707				1986 - 1992	822
Range above minimum										
	1979	1975 - 1992	**<0.001**	1975 - 1979	612	**1979**	1975 - 1992	**<0.001**	1975 - 1979	597
	1982	1980 - 1985	**<0.001**	1980 - 1982	931	**1982**	1980 - 1985	**0.006**	1980 - 1982	927
	1985	1983 - 1992	**<0.001**	1983 - 1985	1245	**1985**	1983 - 1992	**<0.001**	1983 - 1985	1263
				1986 - 1992	921				1986 - 1992	887
Group 7: Magnitude of *extremes of hourly mean discharge*										
Minimum	**1979**	1975 - 1992	**<0.001**	1975 - 1979	812	**1979**	1975 - 1992	**<0.001**	1975 - 1979	1236
				1980 - 1992	357				1980 - 1992	554
Maximum	**1986**	1975 - 1992	**0.018**	1975 - 1986	1176	**1985**	1975 - 1992	**0.018**	1975 - 1985	1522
				1987 - 1992	816	1988	1986 - 1990	0.113	1986 - 1992	1122
Range	**1980**	1975 - 1992	**0.036**	1975 - 1980	439	**1979**	1975 - 1992	**<0.001**	1975 - 1979	360
	1986	1981 - 1992	**0.006**	1981 - 1986	784	**1986**	1980 - 1992	**0.004**	1980 - 1986	846
				1987 - 1992	495				1987 - 1992	581
1100-2200 Range	**1979**	1975 - 1992	**0.019**	1975 - 1979	76	**1979**	1975 - 1992	**0.008**	1975 - 1979	58
	1986	1980 - 1992	0.195	1980 - 1992	209				1980 - 1992	239
Group 8: *Rate of change of hourly mean discharge*										
Ramp-up rate	1979	1975 - 1992	0.132	1975 - 1979	66	**1979**	1975 - 1992	**0.002**	1975 - 1979	55
	1979	1975 - 1986	**0.009**	1980 - 1986	118	**1985**	1980 - 1992	**0.040**	1980 - 1985	130
	1986	1980 - 1992	**0.037**	1987 - 1992	77				1986 - 1992	90

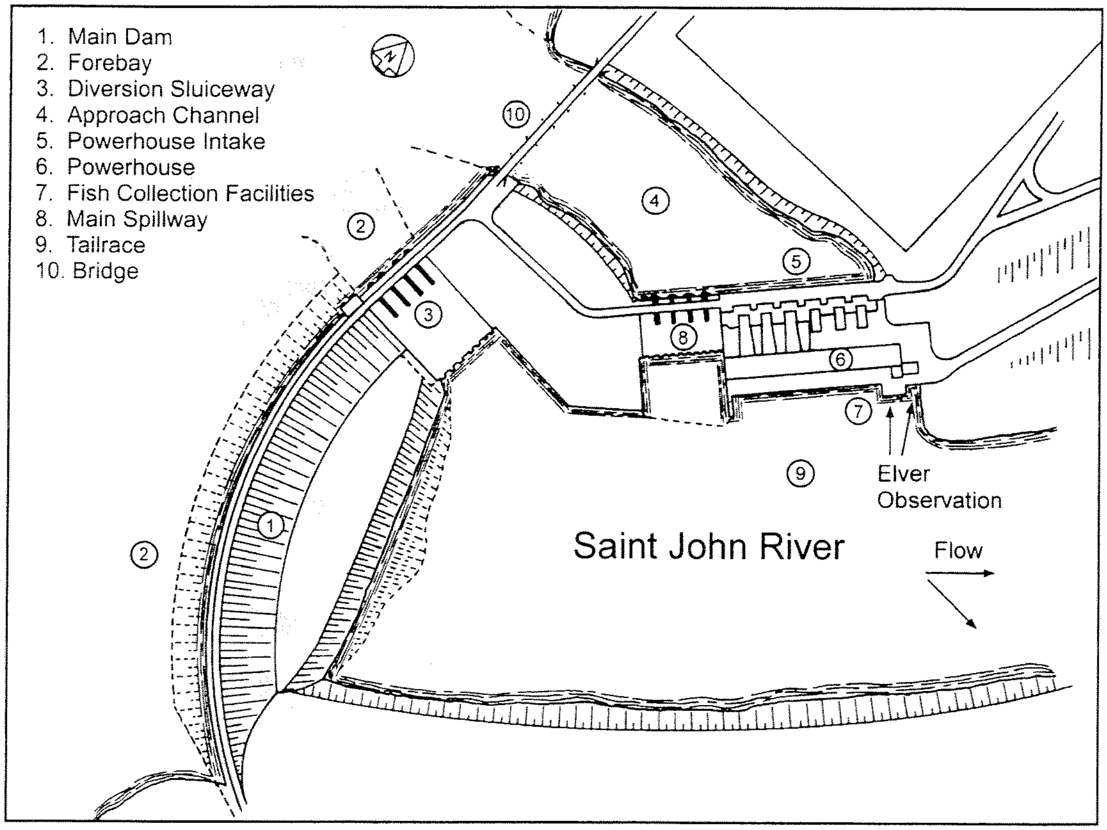


Figure 1. Study site map.

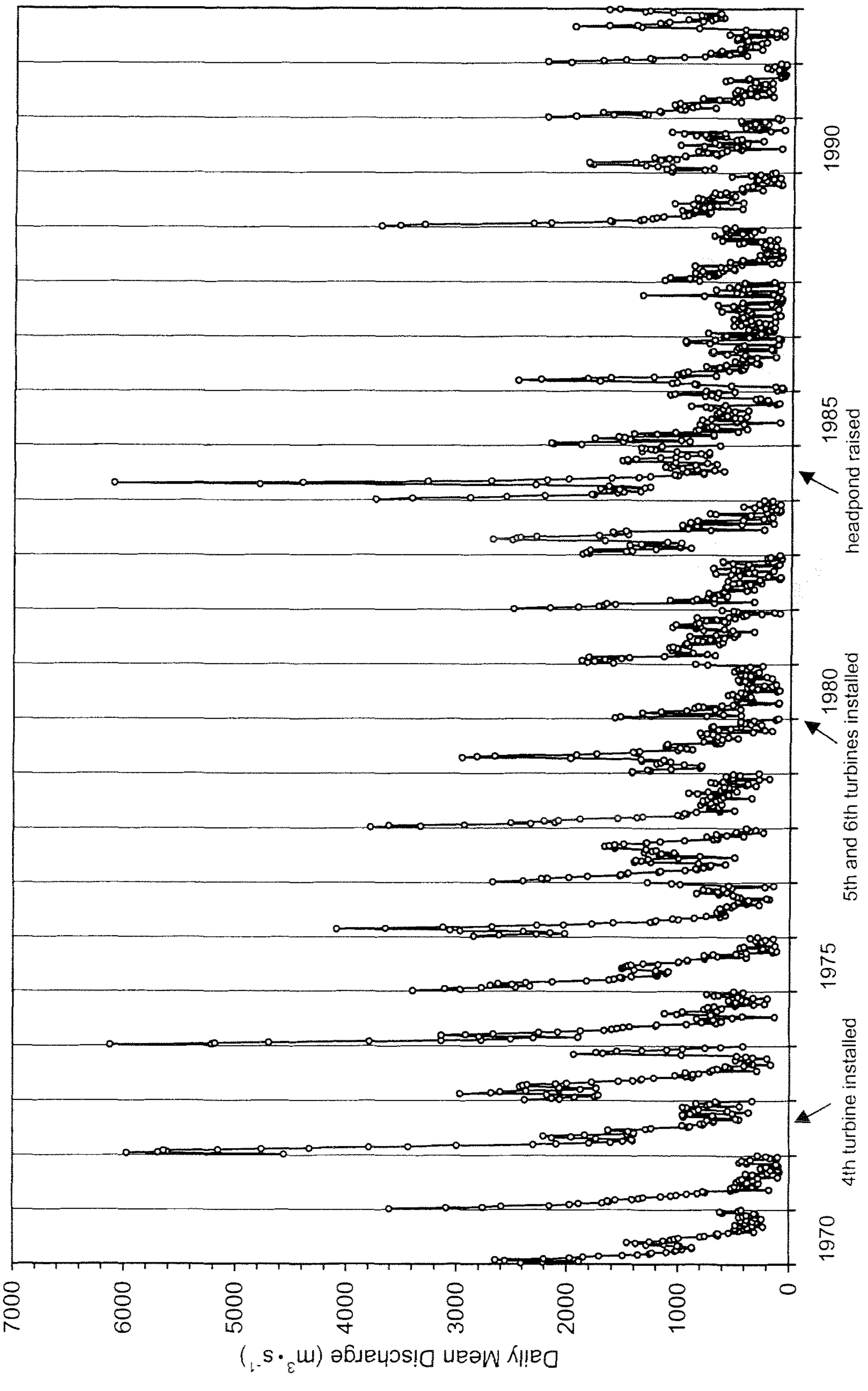


Figure 2. Daily mean discharge from May 15 to July 15, 1970 to 1992.

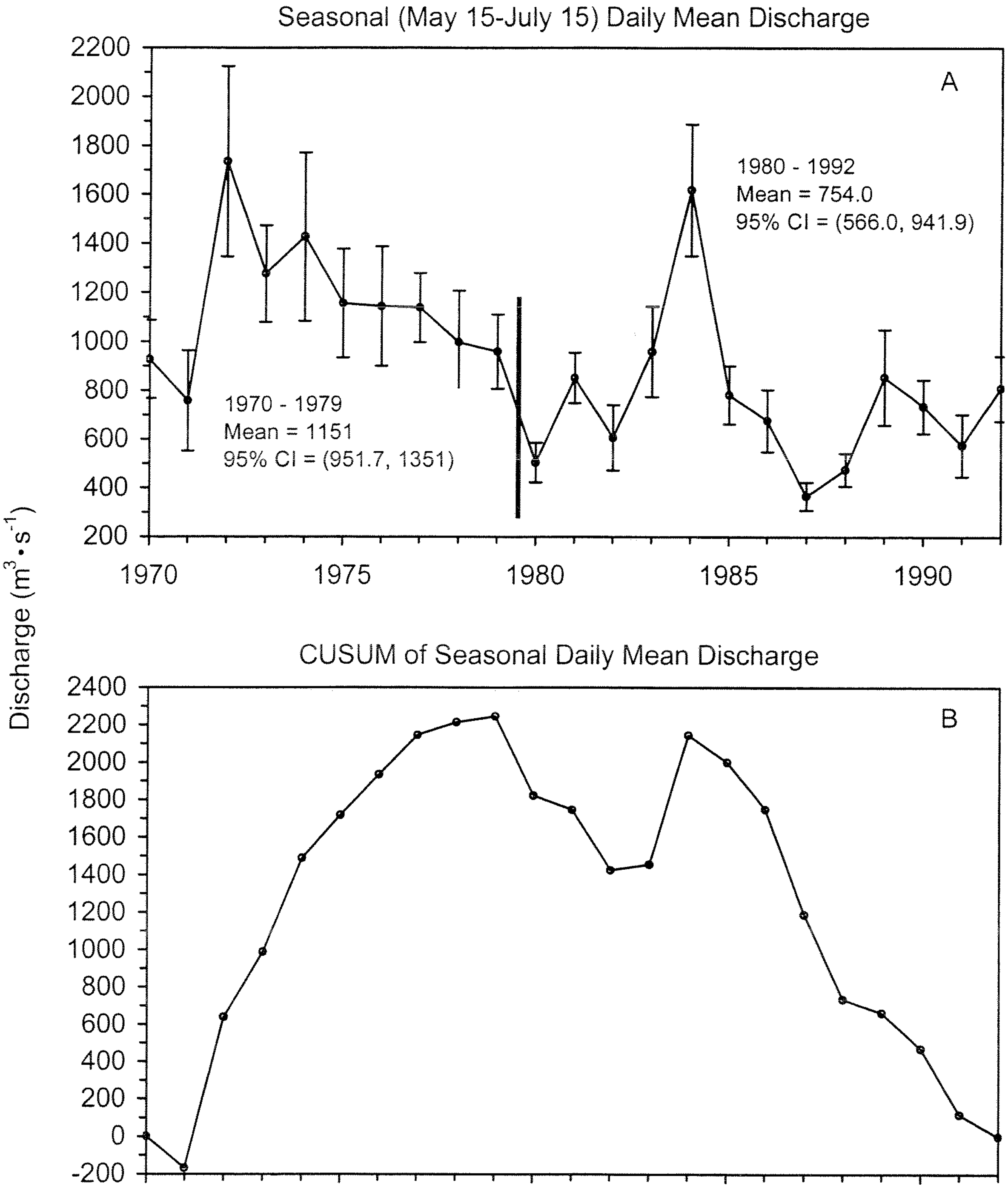


Figure 3. Seasonal (May 15 – July 15) daily mean discharge with 95% confidence intervals (A) and CUSUM values (B), 1970 to 1992. Bold vertical lines divide the series into sections with significantly different mean levels. The turning point is the year prior to the dividing line.

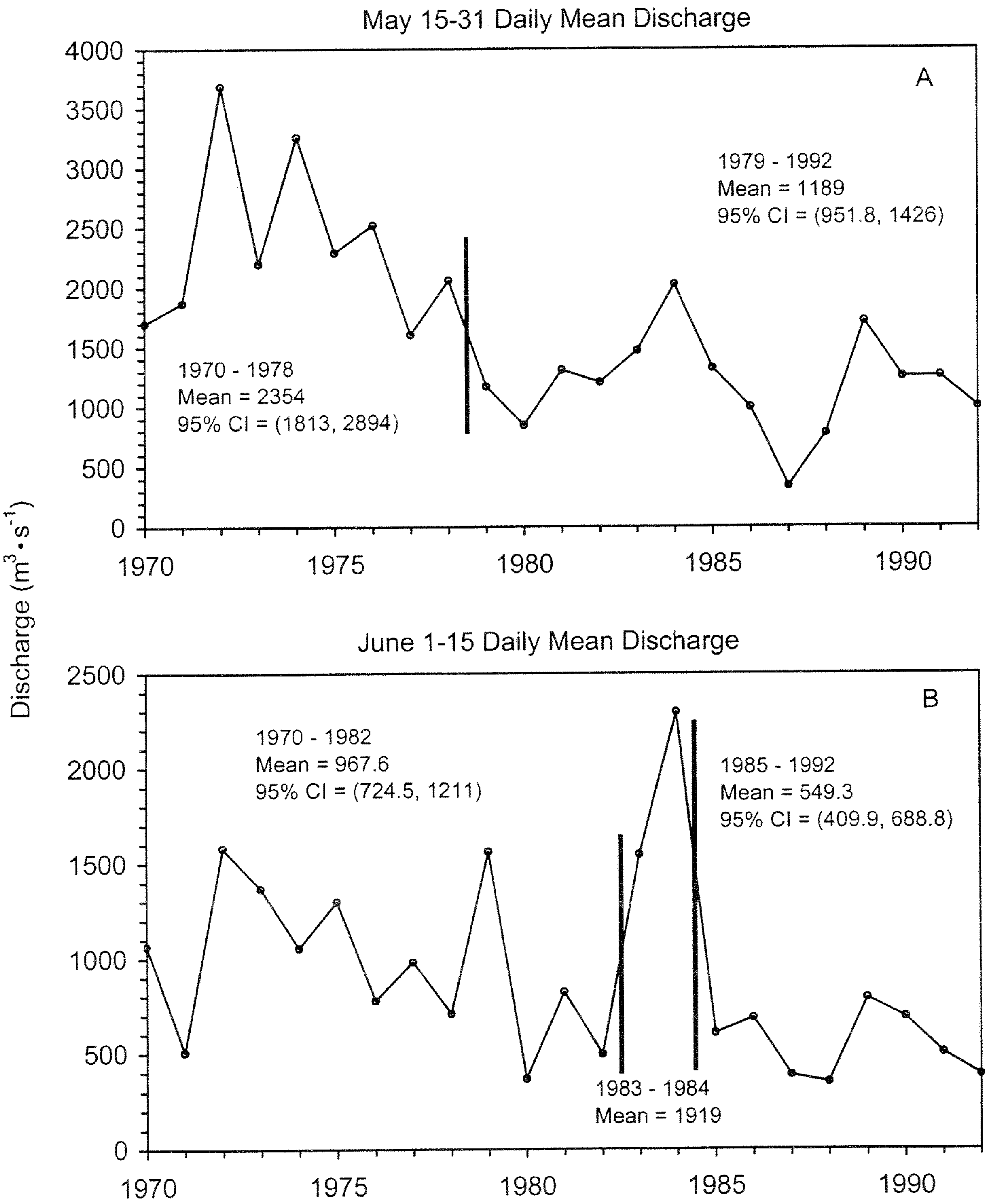
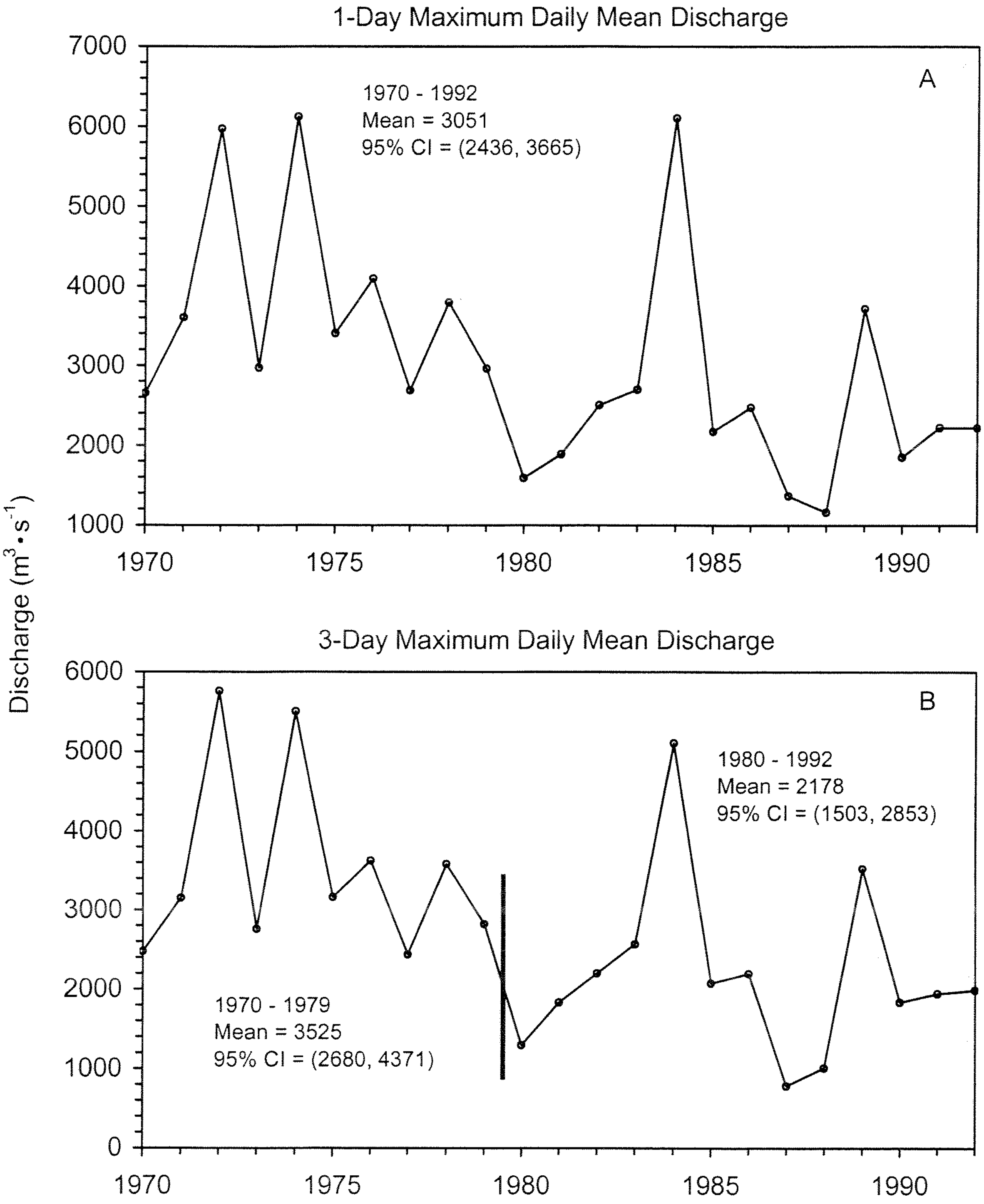


Figure 4. Biweekly May 15 – 31 (A) and June 1 - 15 (B) daily mean discharge, 1970 to 1992. Bold vertical lines divide the series into sections with significantly different mean levels. The turning point is the year prior to the dividing line.


1-Day Maximum Daily Mean Discharge

1970 - 1992
Mean = 3051
95% CI = (2436, 3665)

3-Day Maximum Daily Mean Discharge

1980 - 1992
Mean = 2178
95% CI = (1503, 2853)

1970 - 1979
Mean = 3525
95% CI = (2680, 4371)

Figure 5. Seasonal (May 15 - July 15) 1-day (A) and 3-day (B) maximum daily mean discharge, 1970 to 1992. Bold vertical lines divide the series into sections with significantly different mean levels. The turning point is the year prior to the dividing line.

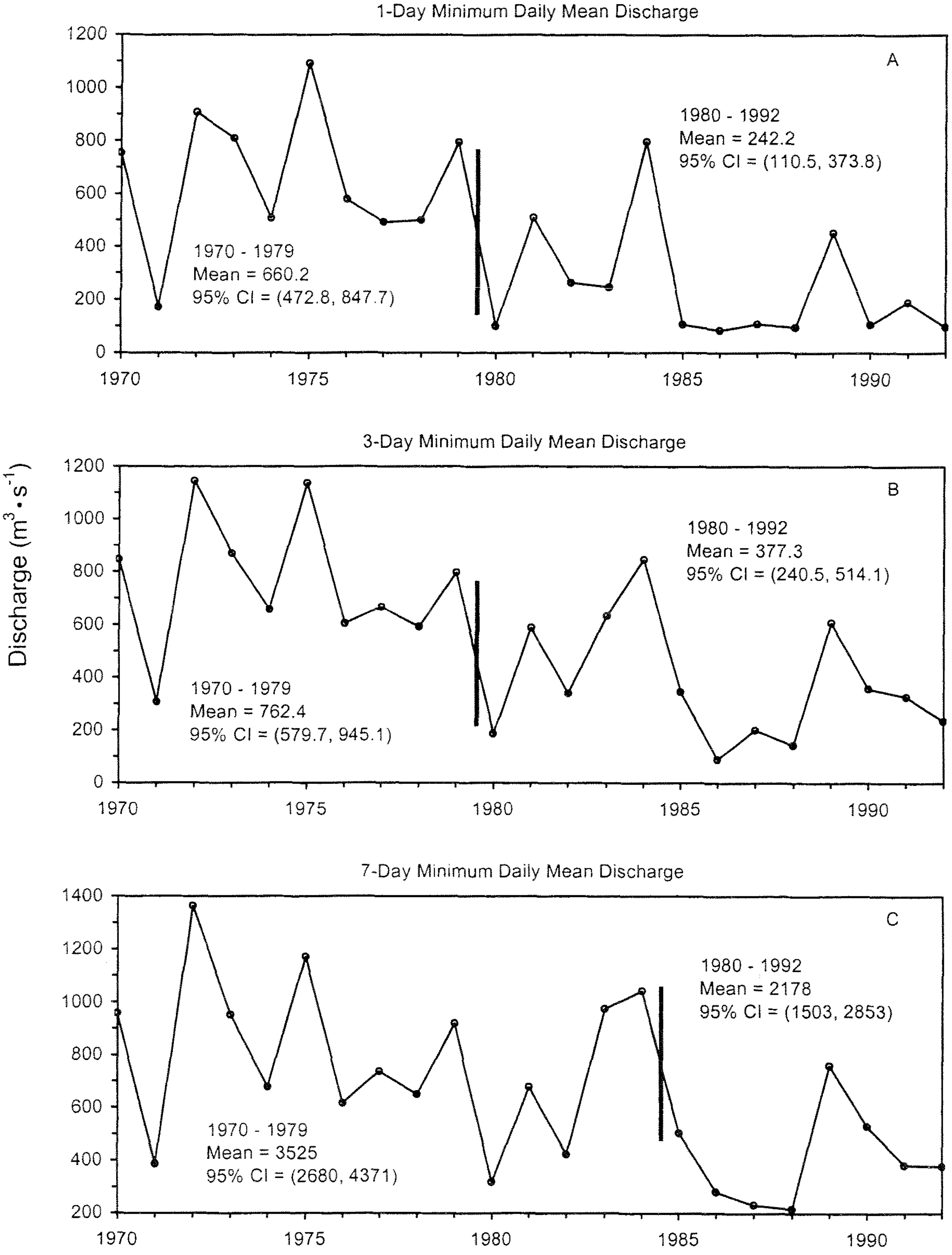


Figure 6. Shorter seasonal (May 15 - June 15) 1-day (A), 3-day (B), and 7-day (C) minimum daily mean discharge, 1970 to 1992. Bold vertical lines divide the series into sections with significantly different mean levels. The turning point is the year prior to the dividing line.

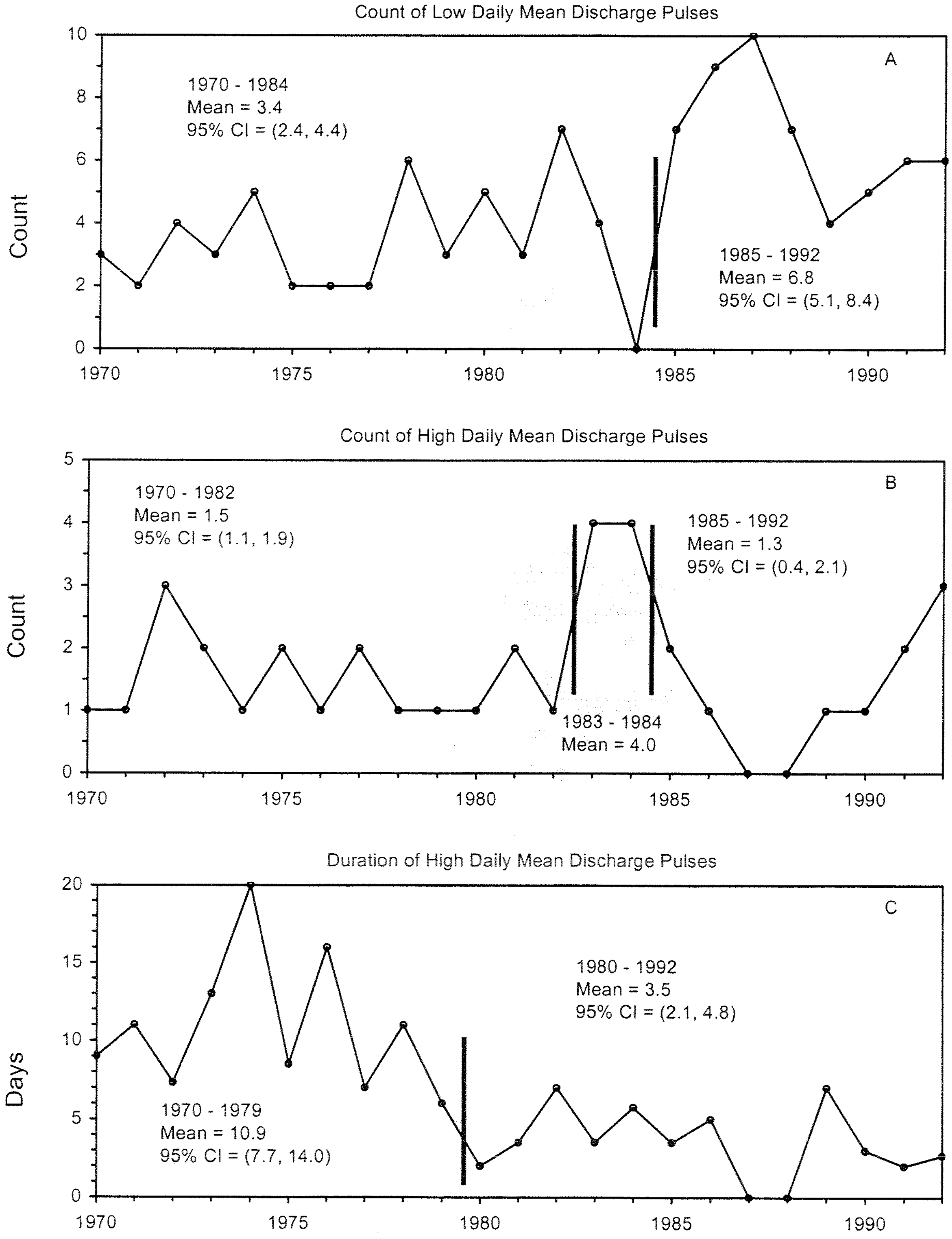


Figure 7. Seasonal (May 15 - June 15) count of low (A), count of high (B) and duration of high (C) daily mean discharge pulses, 1970 to 1992. Bold vertical lines divide the series into sections with significantly different mean levels. The turning point is the year prior to the dividing line.

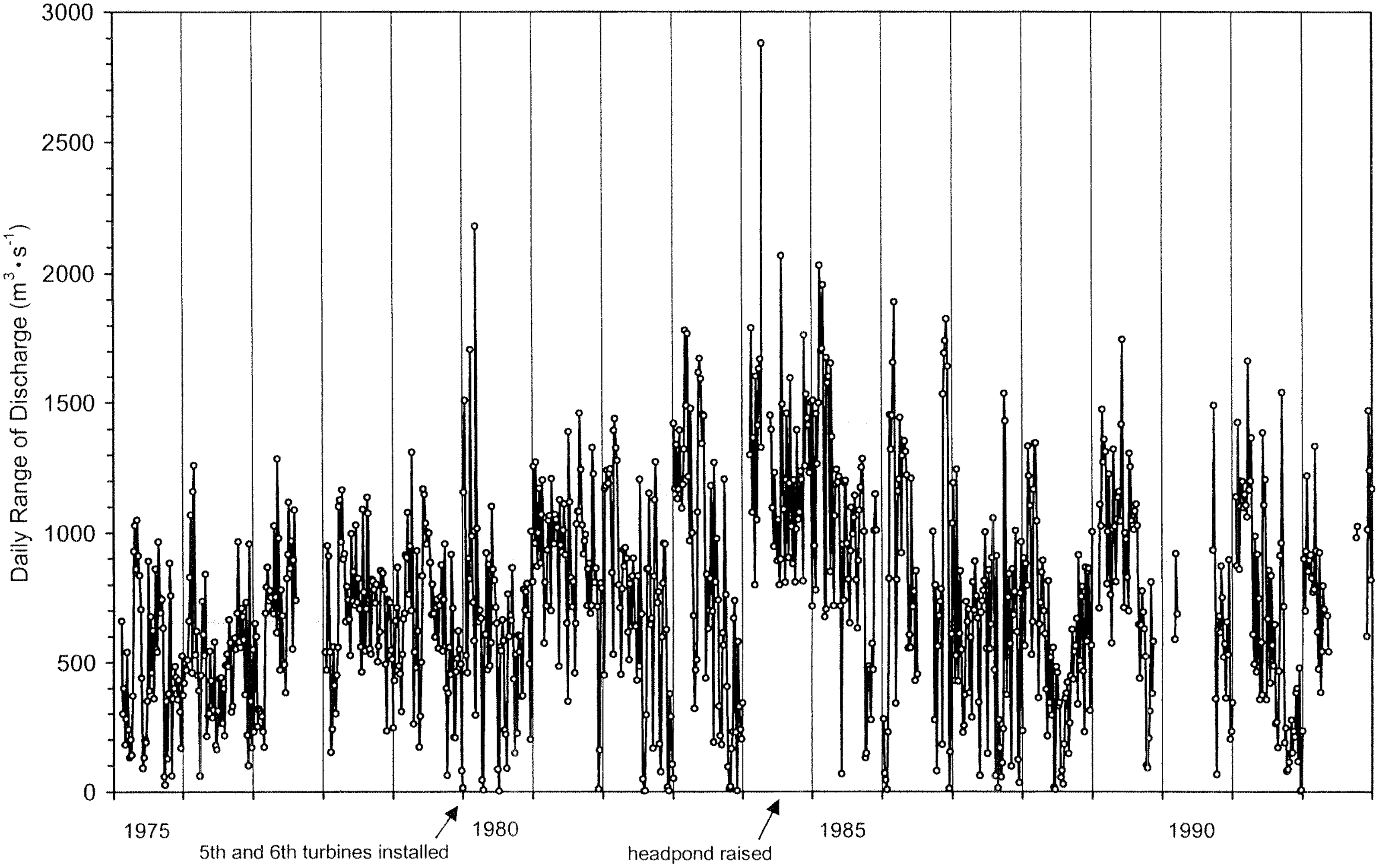


Figure 8. Daily range of discharge from May 15 to July 15, 1975 to 1992.

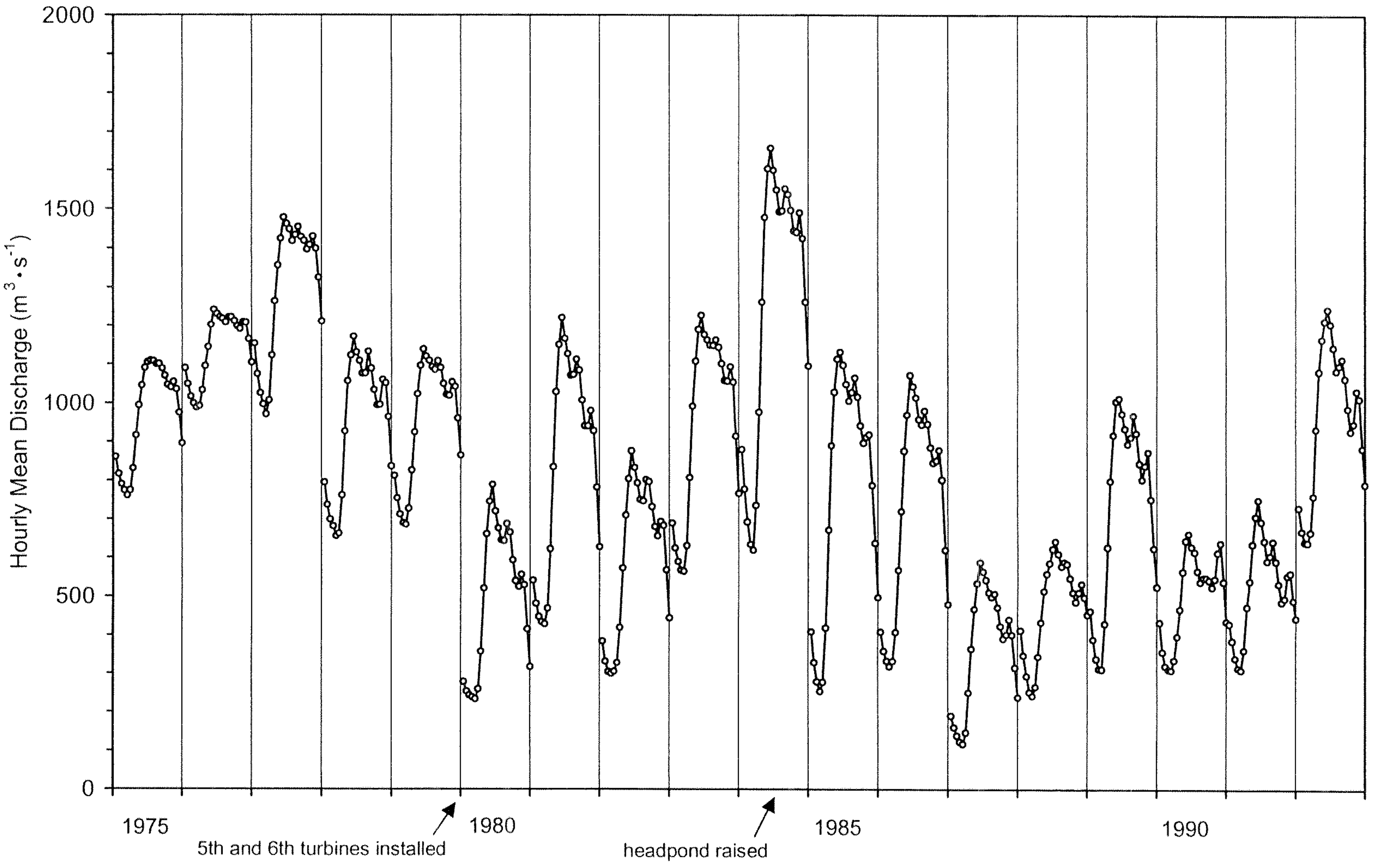


Figure 9. Hourly mean discharge from 0100 h to 2400 h, 1975 to 1992.

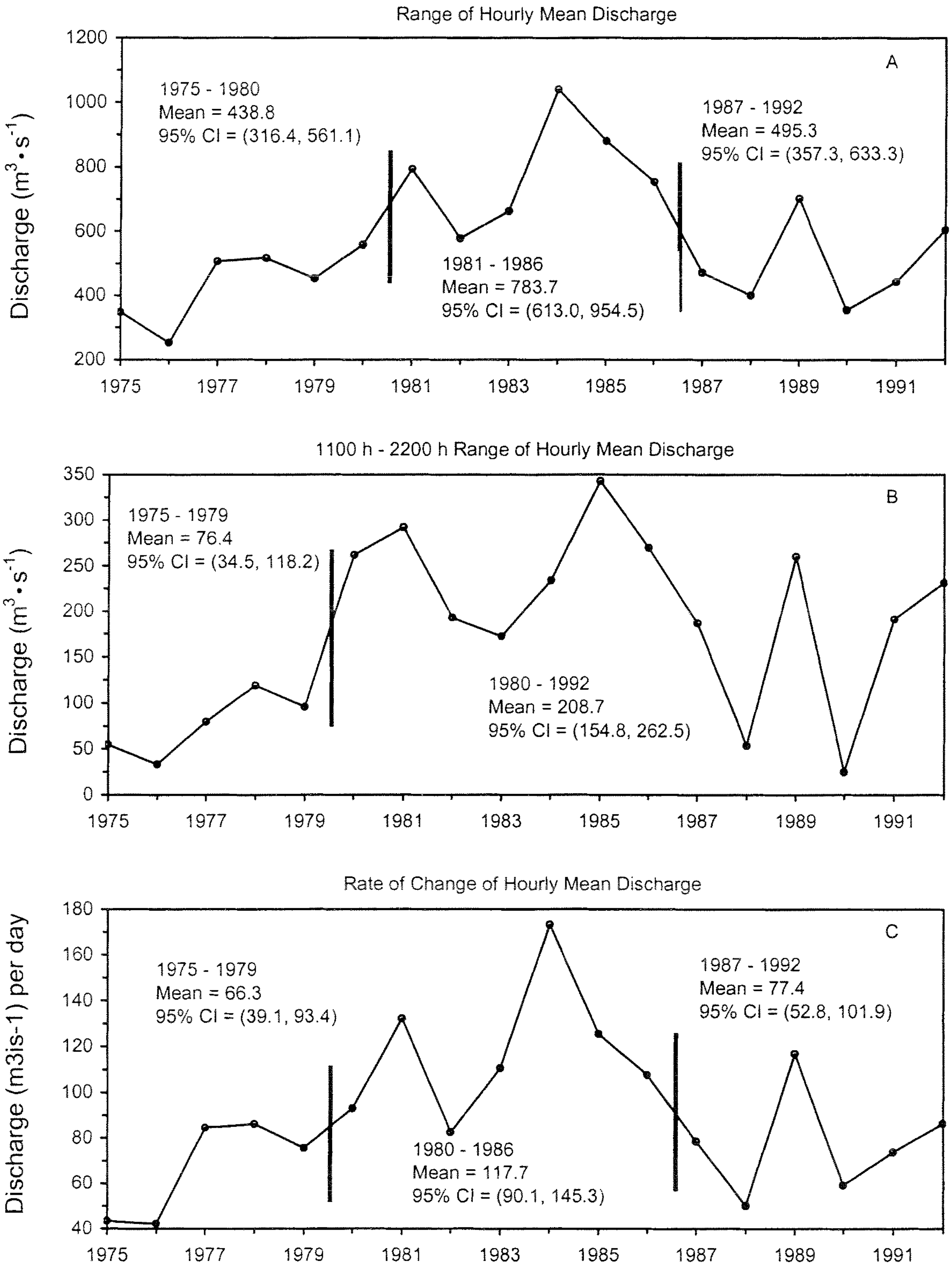


Figure 10. Seasonal (May 15 - July 15) range (A), range between 1100 h and 2200 h (B) and rate of change (C) of hourly mean discharge, 1975 to 1992. Bold vertical lines divide the series into sections with significantly different mean levels. The turning point is the year prior to the dividing line.