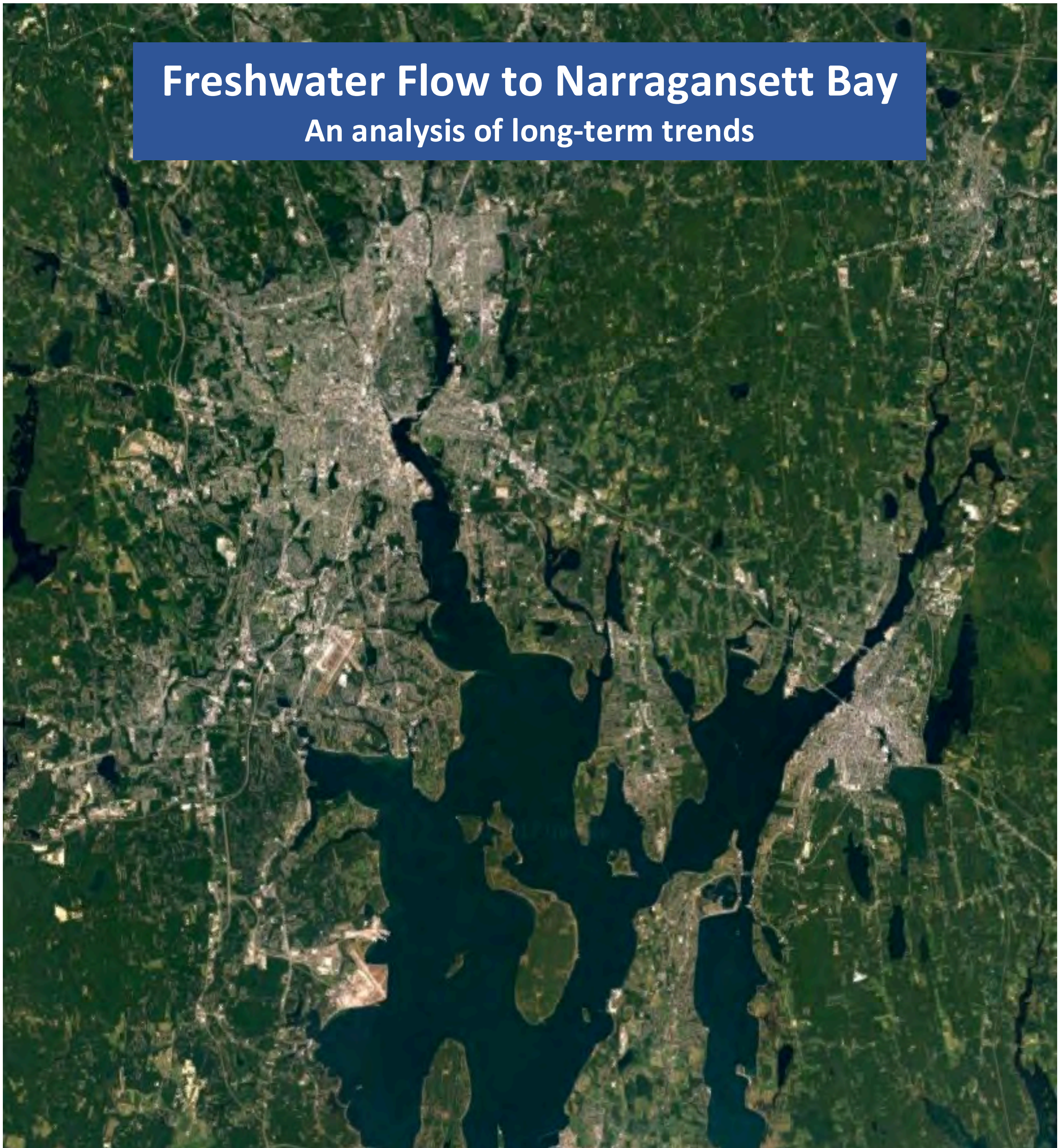
Freshwater Flow to Narragansett Bay

An analysis of long-term trends



State of Rhode Island Department of Environmental Management
Office of Water Resources

University of Rhode Island Coastal Institute

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Acknowledgements

The following individuals generously contributed their time
and expertise in the preparation of this report:

Sue Kiernan (RI DEM), Nicole Rohr (URI CI), Candace Oviatt (URI GSO), Heather Stoffel (URI GSO & RI DEM), Gavino Puggioni (URI Dept. of Statistics), David Vallee (NWS Taunton), and John Mullaney (USGS).

The generation of this report was made possible through funding awarded by the United States Environmental Protection Agency through the Healthy Communities Grant Program in association with the Southeast New England Program.

Although the information in this document has been funded wholly or part by the United States Environmental Protection Agency under assistance agreement 00A00185 to the Rhode Island Department of Environmental Management, it may not necessarily reflect the views of the Agency and no official endorsement should be inferred.

April 2018

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ABSTRACT

Freshwater flow to Narragansett Bay is a key component of bay ecosystem function and has been linked to the development of hypoxia (low dissolved oxygen) in some locations of the bay. Freshwater inputs to Narragansett Bay include contributions from river flow, inputs from wastewater treatment facilities, and precipitation directly on the bay. Among these, river flow dominates, with the three largest river systems being the Blackstone, Pawtuxet and Taunton Rivers. Potential effects in the bay include pollutant transport, particularly nutrients, and localized changes in salinity and water temperature.

We hypothesized that there have been long-term changes in river flow to Narragansett Bay, likely due to changes in land cover within the drainage basin, as well as to changes in precipitation patterns. Our goal was to identify long-term trends to inform analyses of hypoxic events in Narragansett Bay. Observed changes in precipitation patterns since led us to also consider changes in the frequency and magnitude of high flow days since 1970. The long-term records (50 to 90 years) of mean daily flow data from ten USGS river gages located in the Narragansett Bay drainage area were analyzed to identify possible long-term trends in common hydrologic measures of river flow over three time frames: annual, seasonal and June.

The analysis identified a number of significant trends. Most notable were increasing trends in both the brief (1-day) and sustained (30-day) maxima metrics over the annual time frame, and increasing trends in the 1-day maximum over the seasonal time frame. We also observed decreasing trends in the sustained (7- and 30-day) minima over all time frames, suggesting that base flow is decreasing. These observations are consistent with recorded increases in the frequency and magnitude of extreme precipitation events – driving higher maximum flows – and higher summer temperatures, both of which can play a role in lowering groundwater storage and stream base flow. High flow days and events (three or more consecutive high flow days) have become more frequent since 1970, and at some gages, greater in magnitude.

This analysis confirmed a number of long-term trends at stream gages within the Narragansett Bay drainage basin, reflecting continued changes in stream flow contributions to the bay. Given the importance of freshwater inputs to the estuary, monitoring of stream flow is essential and should be maintained. It provides important information needed to understand Narragansett Bay ecology, including assessment of potential changes in the timing and extent of hypoxia in the bay.

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INTRODUCTION

Narragansett Bay is a medium-sized (196 mi^2) temperate estuary located in Rhode Island, USA, with a drainage area of ~ 1700 mi^2, of which about 60% is located in Massachusetts and the remaining 40% in Rhode Island. Land use within the watershed includes roughly 35% urban or urbanizing areas, 6% agriculture, 15% wetlands, with the remaining land in forest, open water or other undeveloped land (NBEP, 2017).

Narragansett Bay is a critically important resource to the region, especially for fisheries, tourism and recreation. Freshwater flow to Narragansett Bay is a key component of bay ecosystem function and has been linked to the development of hypoxia (low dissolved oxygen) in some locations of the bay (e.g., Codiga et al., 2009). Freshwater inputs to Narragansett Bay include contributions from river flow, inputs from wastewater treatment facilities, and precipitation directly on the bay. Among these, river flow dominates, with the three largest river systems being the Blackstone, Pawtuxet and Taunton Rivers. Stream gages that are downstream from wastewater treatment facilities that discharge to rivers (i.e., Pawtuxet and Blackstone Rivers) include freshwater flow contributions from these facilities. Potential effects in the bay include pollutant transport and localized changes in salinity and water temperature.

We hypothesize that there have been long-term changes in river flow to Narragansett Bay, likely due to changes in land cover within the drainage basin, as well as to changes in precipitation patterns (D. Vallee, personal communication) due to climate change. Our goal is not to identify cause but to identify long-term trends to inform analyses of hypoxic events in Narragansett Bay. Freshwater flow to the bay can increase nutrient delivery as well as the tendency for bay stratification by intensifying density differences between the less dense fresher water near the surface and the saltier, colder and denser deep water. Observed changes in precipitation patterns since 1970 (D. Vallee, personal communication) led us to consider changes in the frequency and magnitude of high flow days since 1970. This report is companion to a report on hypoxia in Narragansett Bay (Kellogg, in review) which analyzes data from the Narragansett Bay Fixed Site Monitoring Network over the period 2001 to 2015, focusing on hypoxic events and possible explanatory variables such as freshwater flow, water temperature, chlorophyll concentrations and density differences between surface and bottom sondes at the fixed sites.

METHODS

This section describes the data and statistical methods that were applied to investigate long-term trends in streamflow. All analyses were performed using R (R Core Team, 2016) through the RStudio interface (RStudio Team, 2015). All coding and data are stored at https://github.com/qkellogg/narrbay_flow_hypoxia. R is a free open-source code developed for statistical computing and graphics.

STREAM GAGE DATA

Stream gage data were obtained from the USGS using the R package {dataRetrieval} developed by USGS (Hirsch and De Cicco, 2015). Long-term gages were defined as those gages in the Narragansett Bay watershed with a period of record spanning at least 50 years, excluding any gages with large (multiple year) data gaps (Table 1, Figure 1).

Table 1. USGS stream gages in the Narragansett Bay watershed with a period of record of at least 50 years.

USGS Gage ID	USGS Gage Name	Basin	Latitude	Longitude	Altitude[1] (ft)	Drainage Area (mi2)	POR[2] Start Date
01108000	TAUNTON RIVER NEAR BRIDGEWATER, MA	Taunton	41.9339903	-70.9564307	9.6	261	1-Oct-1929
01109000	WADING RIVER NEAR NORTON, MA	Taunton	41.94760015	-71.1767155	55	43.3	1-Jun-1925
01109060	THREEMILE RIVER AT NORTH DIGHTON, MA	Taunton	41.8662122	-71.12282369	11	84.3	1-Jul-1966
01109070	SEGREGANSET RIVER NEAR DIGHTON, MA	Taunton	41.840379	-71.142824	30	10.6	1-Jul-1966
01110000	QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	Blackstone	42.230372	-71.7109023	335	25.6	1-Oct-1939
01111500	BRANCH RIVER AT FORESTDALE, RI	Blackstone	41.99648716	-71.5625632	180	91.2	24-Jan-1940
01112500	BLACKSTONE RIVER AT WOONSOCKET, RI	Blackstone	42.00620936	-71.5031168	107	416	22-Feb-1929
01114500	WOONASQUATUCKET RIVER AT CENTERDALE, RI	Woonasquatucket	41.8589884	-71.4872823	95	38.3	9-Jul-1941
01116000	SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI	Pawtuxet	41.69010026	-71.5658958	218	62.8	1-Oct-1940
01116500	PAWTUXET RIVER AT CRANSTON, RI	Pawtuxet	41.75093399	-71.4450575	8	200	6-Dec-1939

[1] Datum = NGVD29; [2] POR = Period of record

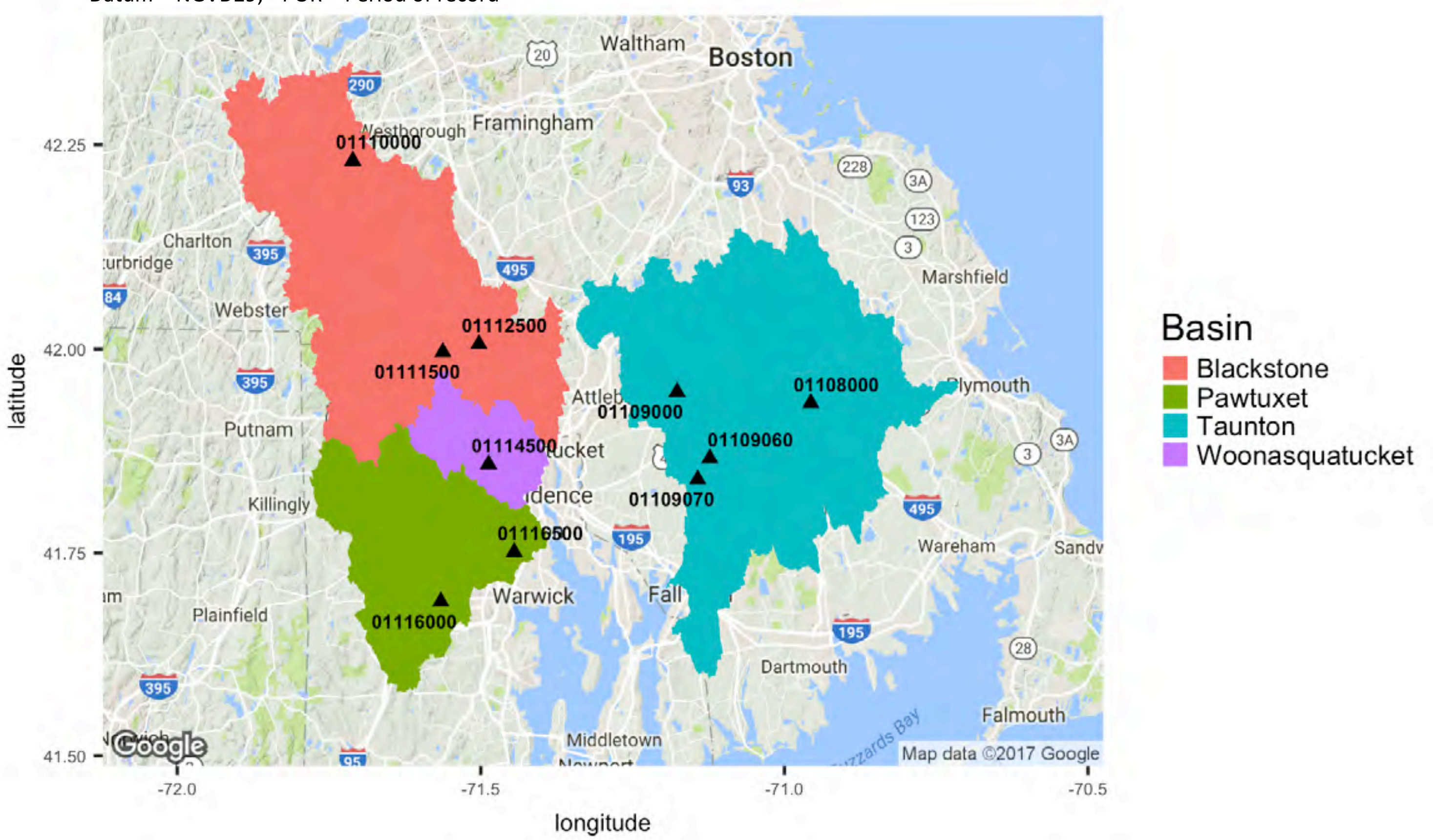


Figure 1. Location of ten long-term USGS stream gages within the Narragansett Bay watershed. Three are located within the Blackstone River basin, two within the Pawtuxet River basin, four within the Taunton River basin, and one within the Woonasquatucket River basin. Map created using {ggmap} R package (Kahle and Wickham, 2013).

Data were retrieved as mean daily discharge in units of ft^3/sec (cfs). The start date for each gage is shown in Table 1, while the end date is the date of retrieval, which for this report is 9/26/17. Four are in the Taunton River basin, three in the Blackstone River basin, one in the Woonasquatucket River basin and two in the Pawtuxet River basin (Figure 1).

Estimating freshwater flow to Narragansett Bay

Existing stream gages account for about 60% of the Narragansett Bay watershed. Ries (1990) used data collected at these gages in combination with other statistical techniques to estimate total freshwater flow to Narragansett Bay, also called the "basin" estimate. Long-term data were analyzed at these gages along with the estimate of total freshwater contributions to the bay, including precipitation and effluent from wastewater treatment plants, on a *monthly* basis. Using these estimates of the *monthly* long-term mean, we derived a monthly factor by taking the estimated monthly long-term mean of total freshwater flow to Narragansett Bay, $\bar{Q}_{\text{Bay}}$, and dividing by the sum of the long-term monthly means of discharge from three of the largest gaged rivers contributing flow to the bay (i.e., Blackstone, Pawtuxet and Taunton Rivers) (Table 2).

$$\text{monthly\_factor} = \bar{Q}_{\text{Bay}} / (\bar{Q}_{\text{Blackstone}} + \bar{Q}_{\text{Pawtuxet}} + \bar{Q}_{\text{Taunton}}),$$

where $\bar{Q}_{\text{Bay}}$, $\bar{Q}_{\text{Blackstone}}$, $\bar{Q}_{\text{Pawtuxet}}$ and $\bar{Q}_{\text{Taunton}}$ are long-term monthly means.

We used these *monthly* factors to estimate freshwater flow to Narragansett Bay on a *daily* basis as follows:

$$Q_{\text{Bay}} = (Q_{\text{Blackstone}} + Q_{\text{Pawtuxet}} + Q_{\text{Taunton}}) * \text{monthly\_factor},$$

where Q_{Bay}, $Q_{\text{Blackstone}}$, Q_{Pawtuxet}, and Q_{Taunton} are daily means and monthly_factor is the calculated monthly factor for the month of the date under consideration.

Table 2. Monthly factors used to estimate freshwater flow to Narragansett Bay using the sum of the mean monthly discharge (cfs) from the Blackstone, Pawtuxet and Taunton Rivers. Data from Ries (1990).

Month	Taunton R near Bridgewater, MA	Blackstone R @ Woonsocket, RI	Pawtuxet R @ Cranston, RI	NB Basin Estimate	monthly_factor
Jan	621	950	450	4590	2.271
Feb	686	993	481	4820	2.231
Mar	948	1540	587	6540	2.127
Apr	853	1440	590	6190	2.147
May	529	871	394	4090	2.280
Jun	315	623	280	2930	2.406
Jul	180	336	171	1820	2.649
Aug	153	300	175	1840	2.930
Sep	180	332	181	1860	2.684
Oct	210	393	185	2120	2.690
Nov	406	631	264	3170	2.437
Dec	559	848	397	4250	2.356
Annual*	470	771	346	3685	

* Long-term annual mean calculated from monthly values; varies slightly from long-term annual means reported in Ries (1990), likely due to loss of significant digits.

Using this method to estimate mean daily flow to the bay gives a long-term annual mean of 3822 cfs, using all complete years of data. Comparing this estimate of long-term mean freshwater flow to Narragansett Bay to estimates reported in the literature shows close agreement. Spaulding and Swanson (2008) estimate annual mean freshwater flow to Narragansett Bay at 104 cms (3673 cfs). Walker and Comeau (2010) estimate 2.4 billion gallons per day (3713 cfs) of freshwater input from all sources. Independent estimates of freshwater flow for specific years are not available, precluding any comparison with estimates for a specified time frame rather than long-term means.

Data Gaps

Data gaps were identified at two of the ten gages (Table 3). The Segreganset River near Dighton, MA gage (#01109070 has relatively short gaps that are not considered substantial enough to warrant removing it the analyses. The Taunton River near Bridgewater, MA gage (#01108000) is missing about twenty years of data (mid-1970s to mid-1990s), but we include this gage in the analyses because it covers a large part of the watershed and is needed to estimate freshwater flow to the bay.

Table 3. Data gaps identified at long-term gages used in analyses.

USGS Gage ID	Name	Data Gap Start	Data Gap End	Number of Days
01108000	Taunton River near Bridgewater, MA	24-Apr-1976 1-Jun-1988	19-Apr-1985 1-Oct-1996	3283 3045
01109070	Segreganset River near Dighton, MA	16-Feb-1992 18-Oct-2016	22-Jul-1992 18-Oct-2016	158 1

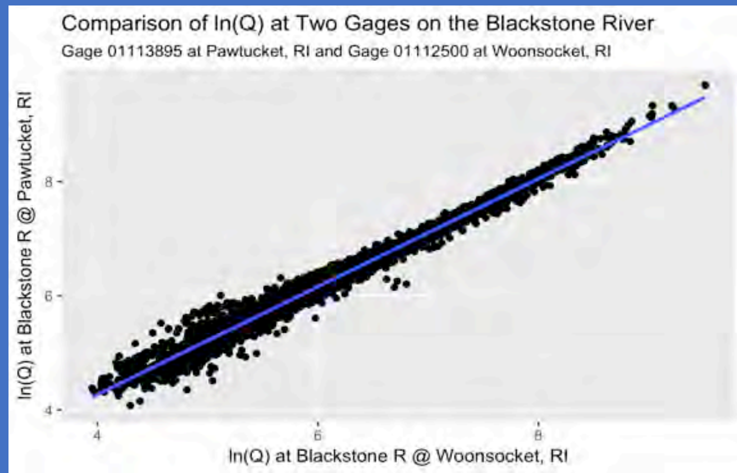
The missing data at the Taunton River gage (#01108000) were estimated using data available at the nearby Three Mile River gage (#01109060), a tributary to the Taunton River with a catchment area comprising about a third of the Taunton River gage (#01108000) catchment area. The mean daily flow at both gages was natural log transformed and a linear regression model was derived in the form

$$\ln(\text{mean daily Q at Taunton}) = \beta_0 + \beta_1 * \ln(\text{mean daily Q at Three Mile})$$

where $\beta_0 = 1.9124295$ and $\beta_1 = 0.8573945$, with an R^2 of 0.93. This relationship was then used to estimate mean daily flow at the Taunton River gage over the two approximately 10-year periods of data gaps (see Appendix A for more details).

Correlation Between Two Gages in the Blackstone River

The USGS gage **Blackstone River at Woonsocket, RI** *(# 01112500) has a period of record starting in 1929, allowing for long-term trend analyses. The USGS gage* **Blackstone River at Roosevelt St. at Pawtucket, RI** *(# 01113895) is closer to the mouth of the river, in the upper bay, but has a period of record starting in 2003, with a gap of about one year from Dec 2005 to Oct 2006. The Woonsocket gage has a drainage area of 416 mi^2 and the gage further down the river in Pawtucket has a drainage area of 474 mi^2. A simple linear regression on the natural log-transformed mean daily discharge produces a model with an R^2 of 0.98 and $p < 0.001$. It is reasonable to assume that the gage in Woonsocket can be used to infer long-term flow trends at the gage in Pawtucket.*



Comparing the ln(Q) at two different gages on the Blackstone River. Linear regression shows that variation at the gage at Woonsocket RI explains 98% of the variation at the gage at Pawtucket, RI.

STATISTICAL ANALYSES

Mean daily flow data at the stream gages, as well as estimates of mean daily flow to Narragansett Bay, were analyzed over three different time frames on an annual basis: annual, seasonal, and June. For this report "seasonal" refers to the time frame considered relevant for hypoxia development in Narragansett Bay, i.e., the months of June through September. Statistics for the month of June were explored because Codiga et al. (2009) found the June mean discharge to be significantly correlated with seasonal hypoxia severity in Narragansett Bay. In each case, only those years where the data are complete for the given time frame are included in the analyses. Data summaries followed methods described in Helsel and Hirsch (2002).

Stream gage data have a lower bound of zero, tend to have outliers that occur infrequently but regularly, and are positively skewed and are therefore non-normally distributed (Helsel and Hirsch, 2002). Some statistical analyses, such as standard deviation, assume the data are normally distributed, requiring a transformation of gage discharge data. This is most often done using the natural log transformation. Hirsch and De Cicco (2015) handle the special case of discharge values that are zero by adding a small constant to all daily discharge values before transforming. The constant is 0.001 times the mean discharge. They recommend using this approach only if a very small fraction of the total days is affected (fewer than 0.1%). We analyzed the data for zero values, identifying two gages where this occurs. The Quinsigamond River (#01110000) had 10 zeros out of more than 28,000 days, which was considered acceptable and we therefore used the recommended adjustment before transforming. The Segreganset River (#01109070) had 570 zeros out of about 18,000 days, which was considered too high, and was therefore omitted from any analyses that required normally distributed data.

Data summaries include "location" (i.e., mean and median) and "spread" (i.e., standard deviation). The mean is sensitive to extremes while the median is "resistant" to extremes, i.e., the mean would not be a reliable descriptor of "location" if the data are skewed, the median being considered a better descriptor of location when dealing with skewed data. Standard deviation is a measure of "spread" and is most readily interpreted when data are normally distributed. To that end, the mean daily discharge data were log transformed before calculating the standard deviation. As an illustration, Figure 2 shows the distribution of the estimated mean daily discharge to Narragansett Bay before and after natural log transformation.

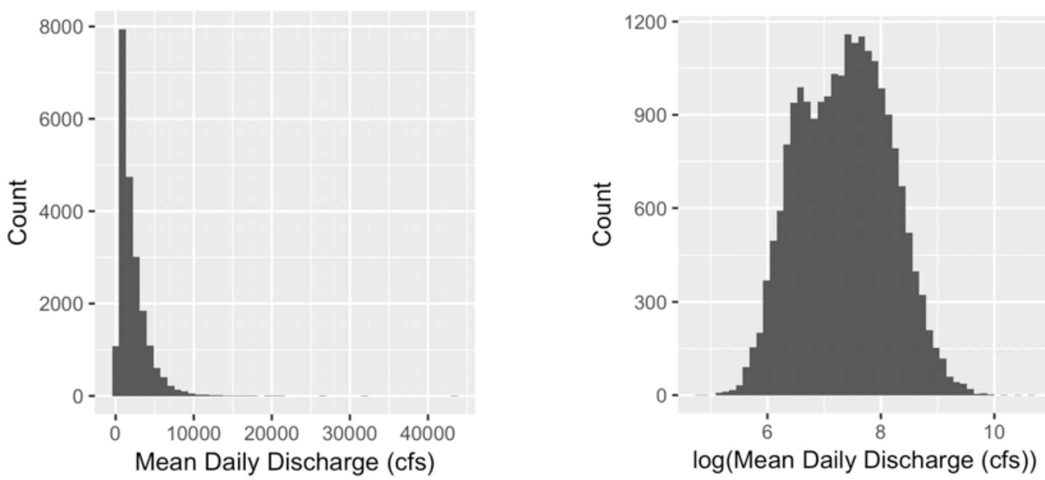


Figure 2. Histograms showing the distribution of estimated mean daily discharge (cfs) to Narragansett Bay before and after natural log transformation. Before transformation the data distribution is skewed while after transformation the data distribution approaches normalcy.

Trends Analyses

Long-term changes in common hydrologic measures of flow

We investigated changes in common hydrologic measures during each time frame (annual, seasonal, June) over the entire period of record for each gage using the tableFlowChange() function in {EGRET}, an R package developed by USGS specifically for this type of stream gage data analysis. Significant trends were identified using the Mann-Kendall test, a non-parametric test that is commonly used to identify trends in hydrologic data. The null hypothesis, H_0, assumes there is no trend. H_0 was rejected at the 90% confidence level, or $p < 0.1$ (Burn and Hag Elnur, 2002). Because the periods of record vary across gages we also investigated trends for the time period common to eight of the ten gages (1943 to 2016) to allow us to directly compare gages. The Start Year is the minimum year in the period of record + 2, because the algorithm is accounting for "edge effects." The two gages that have a period of record starting in 1966 were excluded from these analyses: Three Mile River at North Dighton (# 01109060) and Segreganset River near Dighton, MA (# 01109070).

Long-term changes in high flow days

Of particular interest is the occurrence of high flow days that contribute pulses of freshwater and nutrients to upper Narragansett Bay. When these high flow days occur during the spring and summer months, the likelihood of seasonal hypoxia increases (Codiga et al., 2009; Deacutis, 2008). We explored whether the frequency and/or magnitude of high flow days within the three time frames of interest (annual, seasonal, June) has changed over time. We compared pre- and post-1970 because the National Weather Service has observed statistically significant changes in precipitation patterns in southern New England starting around 1970 (D. Vallee, personal communication). We defined "high flow" days as mean daily flow falling within the highest 5% of all mean daily flows within the period of record at each gage and for the bay, excluding partial years that fall on either end of the record. The threshold for the highest 5% of mean daily flows is known as Q5. We then calculated the mean, median, number of high flow days, and number of high flow events (defined as three or more consecutive high flow days) over each of the time frames of interest.

We investigated long-term trends in the four metrics (mean, median, number of days, and number of events) using the non-parametric Kendall Tau test, which is commonly used to investigate monotonic long-term trends in climate variables and stream flow. We rejected the null hypothesis at the 90% confidence level, or $p < 0.1$. This was done for the entire period of record as well as for the periods pre- and post-1970. When investigating trends in means and medians, only non-zero means and medians were included so as to focus only on high flow means and medians. Count data that were zeros (# of days, # of events) were included as they constitute actual count data.

We also compared pre- and post-1970 means and medians by comparing the estimated slopes and intercepts of linear models for the two time periods. The null hypotheses assume there is no difference between slopes or between intercepts pre- and post-1970, and were rejected at the 90% confidence level, or $p < 0.1$.

We compared the frequency of high flow days (number of days over total time period) pre- and post-1970 by a simple comparison of proportions ($p < 0.1$). This method assumes that the two groups being compared are independent. We recognize that this assumption is not met because we are comparing data from the same gage, but the test is a preliminary look at these data. Future work will continue to refine the statistical analyses of these data, focusing on dynamic modeling, an effort that will require additional time and coding. While the frequency of high flow events is of great interest they are more difficult to analyze using this method because they are of variable length, precluding the use of the comparison of proportions because we are unable to tally a total number of potential events. We do, however, provide graphs for the number of events before and after 1970 to allow insight into potential trends.

RESULTS

DATA SUMMARIES – ANNUAL, SEASONAL AND JUNE

Summary "location" (mean and median) statistics for normalized mean daily flow (mean daily flow divided by drainage area; units of $ft^3/s/mi^2$, or cfsm) at the ten gages are shown annually (Figure 3), seasonally (June 1 to September 30; Figure 4) and in June (Figure 5). Estimates of normalized mean daily freshwater flow to the bay were also analyzed (Figure 6) over the same time frames. Note that means are higher than medians, reflecting the positive skew of gage discharge data. June means and medians are substantially higher than seasonal measures, suggesting that a large proportion of seasonal flow occurs during the first month (June) of the season. Plots of the means and medians of the mean daily flow (not normalized) and standard deviations of the ln(daily Q) over the three time frames for the gages and for the estimated flow to Narragansett Bay are provided in Appendix B.

Long-term means and medians were also calculated over each of the three time frames and are provided in Table 4.

Table 4. Long-term means and medians for the entire period of record at each gage and for Narragansett Bay (cfs). Periods of record for each gage are in Table 1.

Site	Annual		Seasonal		June	
	Mean	Median	Mean	Median	Mean	Median
Taunton R near Bridgewater, MA	496	367	231	140	378	257
Wading R near Norton, MA	74	51	31	15	57	34
Three Mile R at N. Dighton, MA	167	113	76	41	145	81
Segreganset R near Dighton, MA	22	12	8	2	17	6
Quinsigamond R at N Grafton, MA	42	31	23	14	40	29
Branch R at Forestdale, RI	175	120	79	42	141	86
Blackstone R at Woonsocket, RI	786	544	403	245	651	429
Woonasquatucket R at Centerdale, RI	75	52	37	27	62	43
So. Branch Pawtuxet at Washington, RI	132	102	76	59	115	91
Pawtuxet R at Cranston, RI	352	244	208	151	299	204
Narragansett Bay	3822	2806	2191	1470	3237	2192

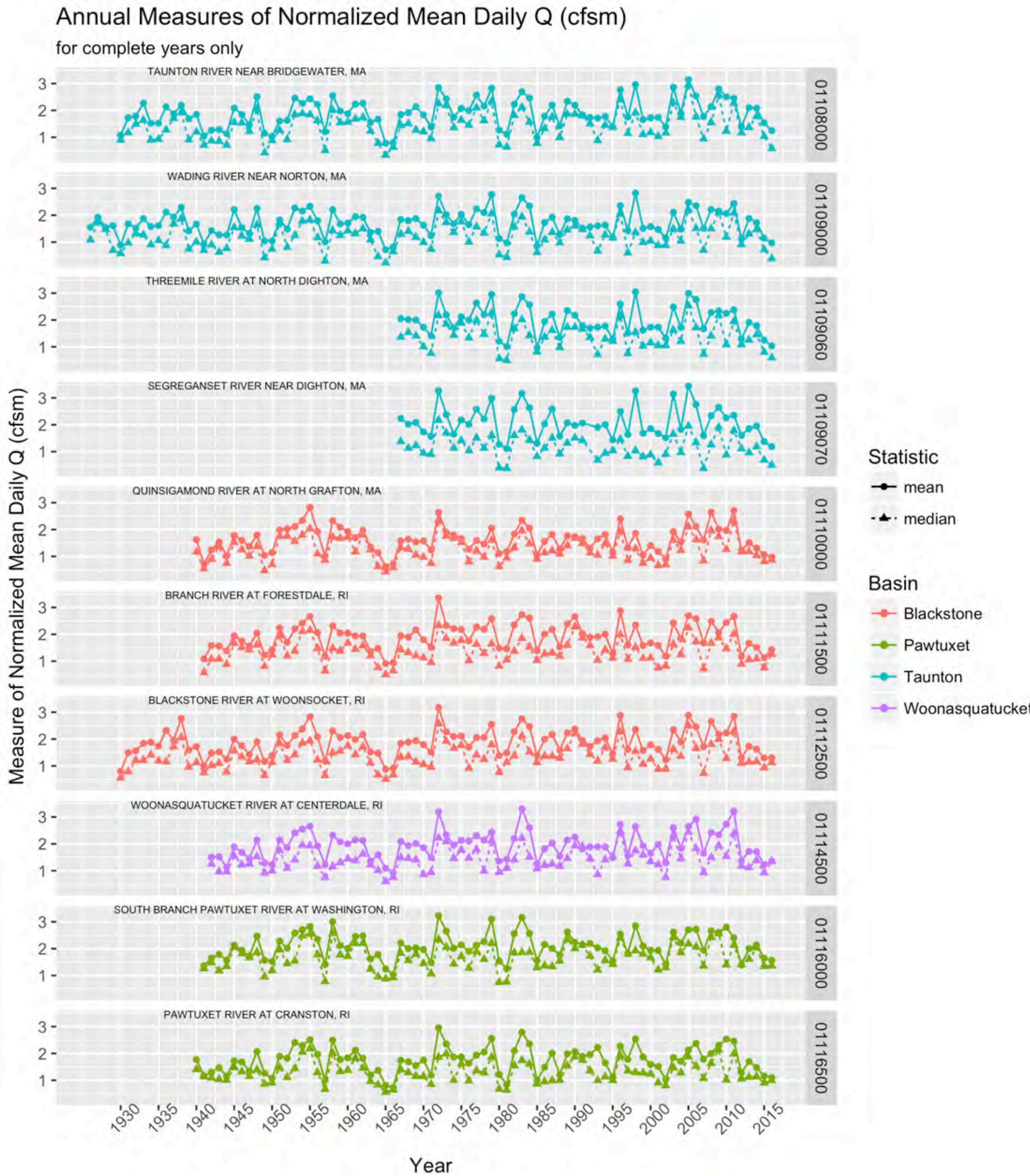


Figure 3. Annual mean and median of normalized mean daily discharge (cfsm) at the ten long-term USGS gages within the Narragansett Bay watershed. Annual means tend to be higher than medians, reflecting the influence of high flow events. Inter-annual variability is high. Taunton River data gaps were handled by estimating missing mean daily flow using mean daily flow from Three Mile River. Years affected are 1976—1985 and 1988—1996. Mean daily flows (cfs) are normalized by dividing by drainage area (mi^2).

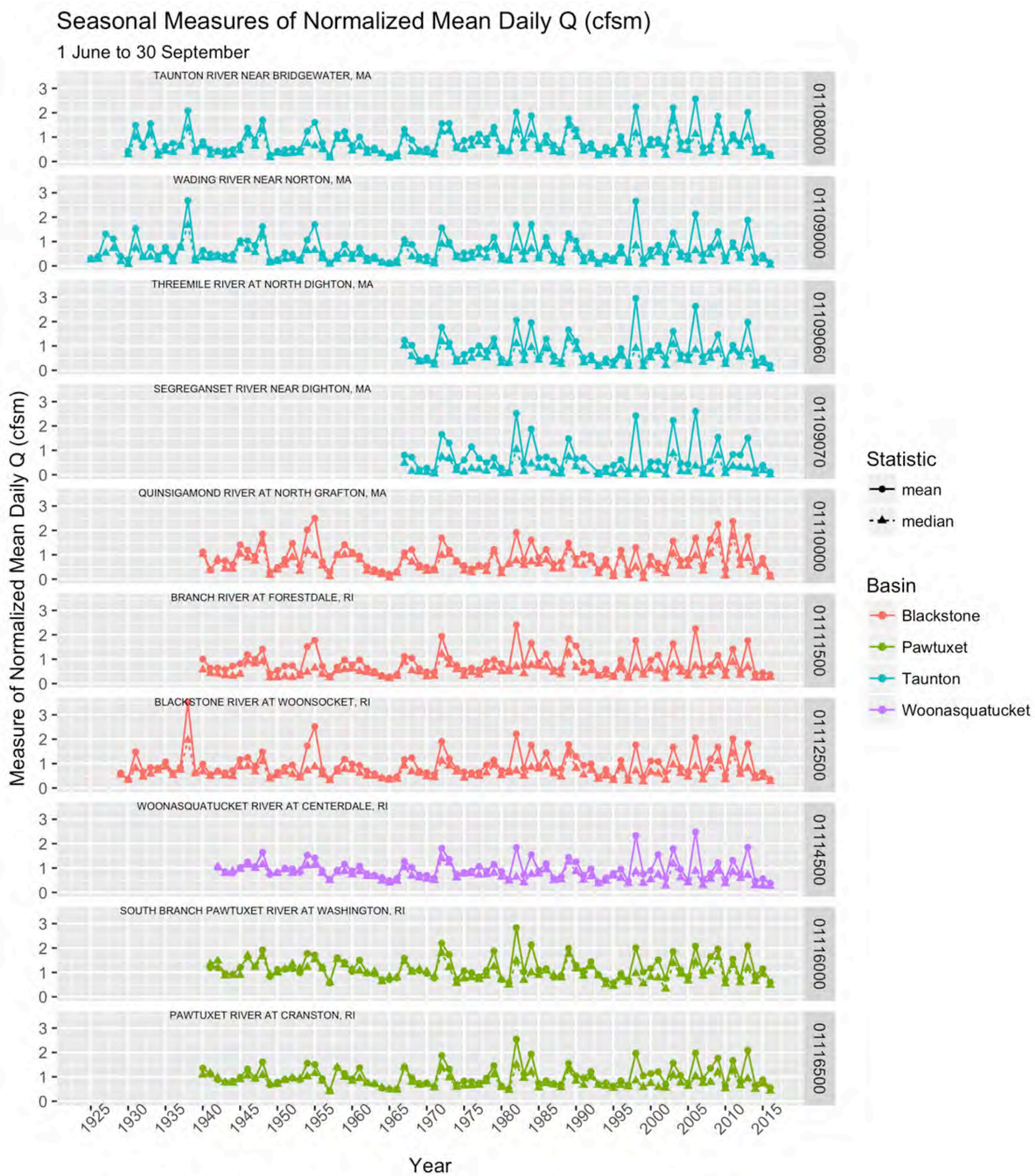


Figure 4. Seasonal (June through September) mean and median of normalized mean daily discharge (cfsm) at the ten long-term USGS gages within the Narragansett Bay watershed. Seasonal means tend to be higher than medians, reflecting the influence of high flow events. Inter-annual variability is high. Taunton River data gaps were handled by estimating missing mean daily flow using mean daily flow from Three Mile River. Years affected are 1976—1985 and 1988—1996. Mean daily flows (cfs) are normalized by dividing by drainage area (mi^2).

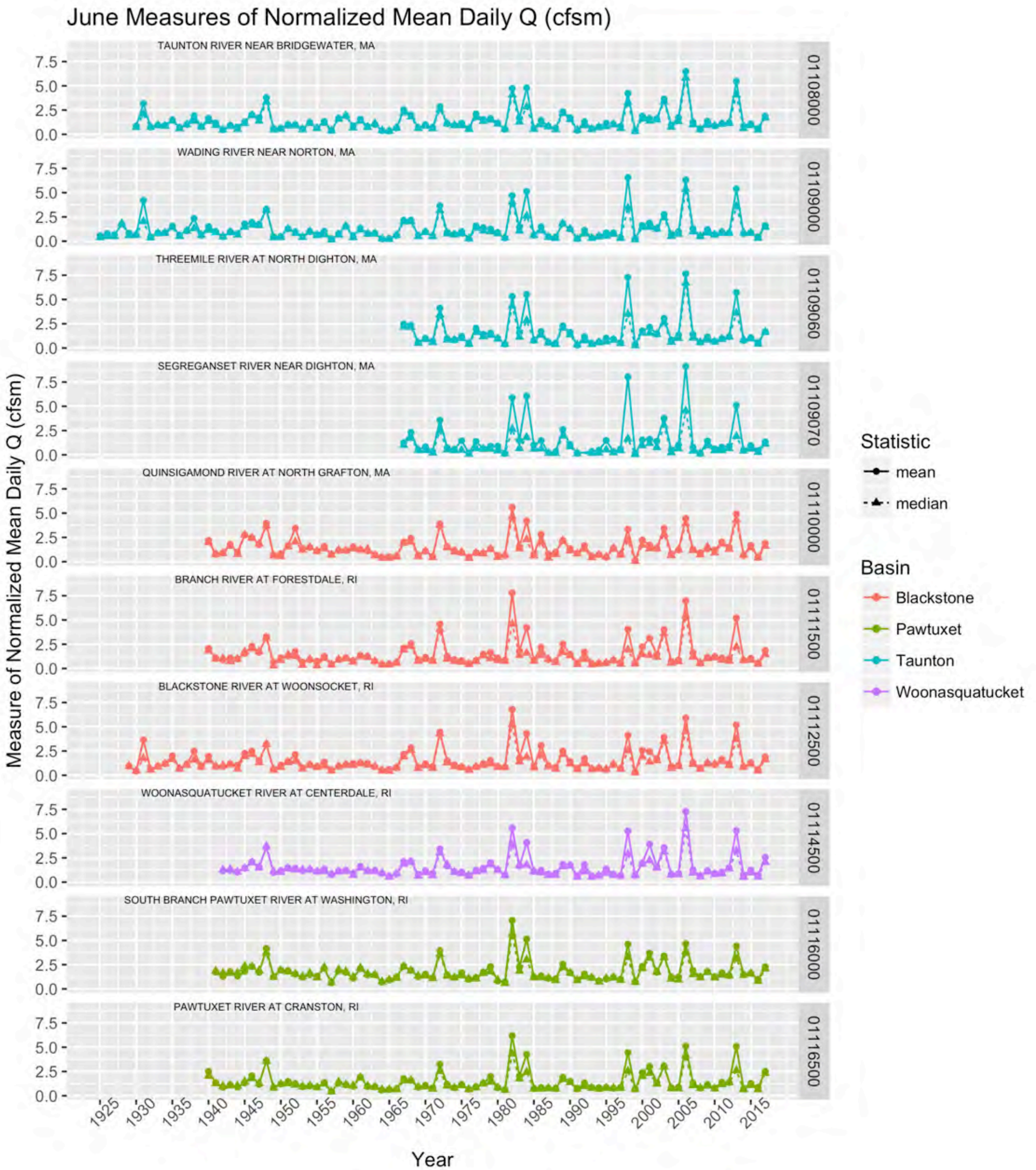


Figure 5. June mean and median of normalized mean daily discharge (cfsm) at the ten long-term USGS gages within the Narragansett Bay watershed. June means are occasionally higher than medians, reflecting the influence of high flow events. Inter-annual variability is high. Taunton River data gaps were handled by estimating missing mean daily flow using mean daily flow from Three Mile River. Years affected are 1976—1985 and 1988—1996. Mean daily flows (cfs) are normalized by dividing by drainage area (mi^2).

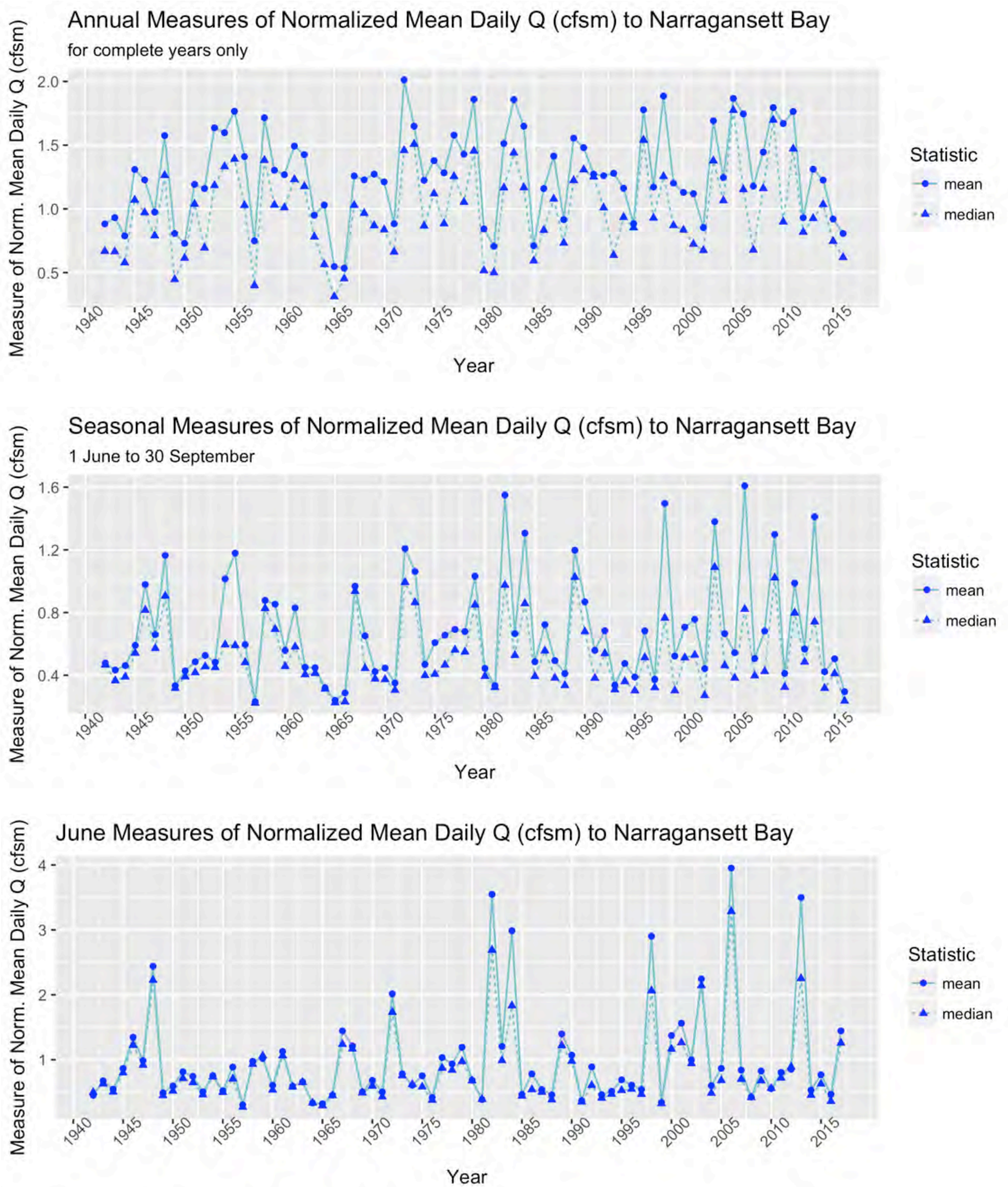


Figure 6. Annual, seasonal and June mean and median of estimates of normalized mean daily freshwater flow to Narragansett Bay. Means are generally higher than medians, reflecting the influence of high flow events. Taunton River data gaps were handled by estimating missing mean daily flow using mean daily flow from Three Mile River. Years affected are 1976—1985 and 1988—1996. Mean daily flows (cfs) are normalized by dividing by the estimated drainage area of 1820 mi^2.

The Narragansett Bay Fixed-Site Monitoring Network (NBFSMN) covers the time period from 2001 to present (RI DEM, 2017). There is interest in using either the seasonal median or mean as a point of comparison for determining whether a particular season is "dry" or "wet." The 15-year time period from 2001 to 2015 is the time period of the most extensive hypoxia monitoring efforts using the NBFSMN. Researchers considering the effects of river flow on the development of hypoxia in the bay are therefore particularly interested in seasonal median and mean freshwater flow to Narragansett Bay from 2001 to 2015. To this end, Figure 7 shows the seasonal medians and means of the estimated flow to Narragansett Bay, along with the long-term seasonal median/mean for the entire period of record and the seasonal median/mean for the period from 2001 to 2015. Note that the mean and median for 2001 to 2015 is higher than the long-term mean and median for 1940 to 2016.

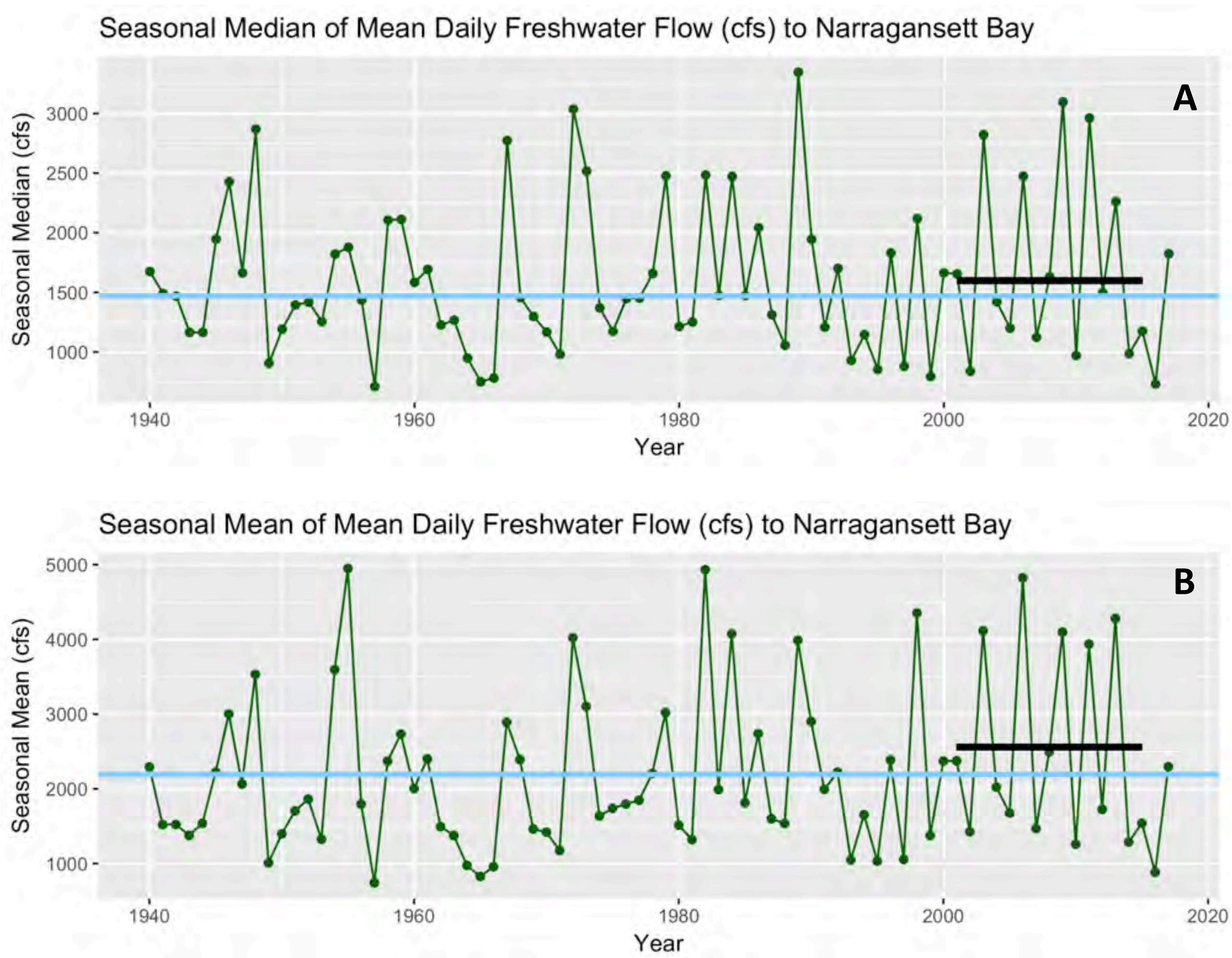


Figure 7. Seasonal medians (A) and means (B) of estimated flow (cfs) to Narragansett Bay. The blue horizontal line denotes the long-term seasonal median or mean for the entire period of record; the black line denotes the median or mean for seasons from 2001 to 2015. Note that this more recent 15-year median (and mean) is higher than that for the entire period of record.

LONG-TERM TRENDS ANALYSES

Trends in Common Hydrologic Measures

Some significant long-term changes (%) in common hydrologic measures were identified for the annual (Tables 5), seasonal (Table 6) and June (Table 7) time frames over the period of record (Start Year to 2016) and over the period 1943 to 2016. Because these analyses were performed using the EGRET package in R, it was not possible to analyze the estimated mean daily flow to Narragansett Bay in the same way because EGRET functions read gage data directly from the USGS website to perform the analyses. To facilitate an understanding of likely trends, however, the three gages that were used to estimate freshwater flow to the bay are boxed in Tables 5 through 7, while significant trends are shaded. When the entire period of record was considered for each gage, a slightly different picture emerged when compared to the period 1943 to 2016. In general, more trends were significant when the entire period of record was considered.

Overall, metrics that represent extremes (high or low flow conditions) are tending to become more extreme, with the exception of the 1-day minimum flows (Tables 5 to 7). The 1-day maximum, which represents a short-term high flow, likely reflecting an extreme precipitation event, is increasing at as many as six of the gages for both the seasonal and annual time frames, though not during June. The mean, 7- and 30-day maxima, representing more sustained high flows, show no significant trends either seasonally or for June. When considered annually, the significant trends are all in the positive direction, suggesting significant increases in base river flow during the other eight months of the year (October through May). The annual median is increasing at several of the gages, while the seasonal and June medians are decreasing at many of those same gages, also suggesting that higher base flow is occurring between October and May while lower base flow is occurring during the seasonal and June time frames. The 7- and

30-day minima reflect more sustained low flows that tend to occur during periods of low rainfall and high evapotranspiration, reducing base flow. These metrics are generally in the negative direction for all time frames and over both periods of analyses, with the exception of the Taunton River gage (#01108000) where the trend is in the positive direction for the annual and seasonal time frames, with no significant trend during June. Similar to many of the gages on these large river systems in New England, the flow at this gage is “affected by diversions to and from basin for municipal supplies. Flow regulated by reservoirs and, prior to about 1975, by powerplants upstream.” (USGS, 2017). It is possible that the long-term trend in the positive direction of the low-flow metrics is the result of changes in these diversions and regulations and not reflective of broader changes in precipitation patterns.

Any changes in stream flow identified over a period of analysis are the result of a combination of factors that include changes in land cover, such as urbanization, changes in diversions and reservoir storage for municipal water supplies, changes in groundwater withdrawals that would affect base flows, as well as changes in precipitation patterns over the specified period of analysis. The goal here is to identify trends, while the specific causes of any trends are outside this analysis.

Trends in Annual Measures of Streamflow

Significant trends in annual means (two of ten gages), medians (three of ten gages), 1-day (four of ten gages), 7-day (two of ten gages), and 30-day (six of ten gages) maxima were all in the positive direction when looking at the entire period of record, with some of the same gages showing significant trends over both time periods (Table 5). For the entire period of record all significant trends in the 30-day minimum were negative (five of the ten gages), and significant trends of the 7-day minimum were negative at six of the ten gages, with one positive trend (Taunton R. near Bridgewater). Four of the six significant trends in the 1-day minimum were positive, while two were in the negative direction.

For the period 1943 to 2016 the trends are similar with the exception of the 30-day minimum where a positive trend was identified at the Taunton River gage (#01108000). Interestingly, the same trend is identified over the entire period of record but was not statistically significant. There were other instances of trends being significant over the period 1943 to 2016 that were not significant when the entire period of record was considered. This was true for both the Blackstone River gage (#01112500) and the Taunton River gage (#01108000). These are rivers that are significantly altered due to dams and diversions, alteration which may be contributing to these discrepancies. Savoie et al. (2017) also analyzed flow data on an annual basis over the period 1979 to 2015 at the Blackstone River gage (#01112500), the Branch River at Forestdale, RI (#01111500) and the Pawtuxet River at Cranston, RI (#01116500), focusing on the mean, median, 1-day maximum and 7-day minimum. They found significantly negative trends in the 7-day minimum at the Blackstone River and Branch River gages, with no significant trends in the 1-day maximum, the mean or the medians over this period of analyses. They also found no significant trends at the Pawtuxet River gage in any of these metrics. The significant trends that they did identify are consistent with those we identified, though we also saw other significant trends that were not picked up during their shorter period of analysis.

Trends in Seasonal Measures of Streamflow

Similar to annual measures, there are several additional significant seasonal trends identified using the entire period of record (Table 6). Over both analysis periods there were no significant trends in the 7- and 30-day maxima, nor the means. All significant trends in the 1-day maximum were in the positive direction (four of ten gages). The significant trends in the median were all in the negative direction (three of ten gages). Most significant trends in the 7-day (eight of ten gages) and 30-day (five of ten gages) minima were negative, with the exception of the Taunton River gage (#01108000), where the trends were positive. The three gages that showed a positive trend in the seasonal 1-day minimum for both periods of analysis also showed a positive trend in the annual 1-day minimum.

Trends in June Measures of Streamflow

There were fewer trends identified when considering only June, but those that were significant showed decreases in the median (two of ten gages), 7-day (three of ten gages) and 30-day (one of ten gages) minimum over both periods of analysis (Table 7). The significant trends in the 1-day minimum (four of ten gages) were all in the positive direction, suggesting that short-term low flows are increasing while sustained low flows, represented by the 7- and 30-day minima, are decreasing. There were no trends identified in the mean, 1-day, 7-day, and 30-day maxima for the month of June over either analysis period.

Table 5. Change (%) over the available period of record (Start Year to 2016) and for 1943 to 2016 in ANNUAL hydrologic measures. The Start Year is the minimum year of record + 2 because the calculations are accounting for "edge effects". Values are shaded when $p < 0.1$. The Taunton, Blackstone and Pawtuxet are boxed because they are used to estimate freshwater flow to Narragansett Bay.

USGS Gage Name	USGS Gage ID	Start Year	1-day Min	7-day Min	30-day Min	Median	Mean	30-day Max	7-day Max	1-day Max
ANNUAL – START YEAR to 2016										
TAUNTON RIVER NEAR BRIDGEWATER, MA	01108000	1931	74	58	29	18	20	20	5.4	-1.1
WADING RIVER NEAR NORTON, MA	01109000	1927	-29	-50	-43	2.1	4.7	20	17	14
THREEMILE RIVER AT NORTH DIGHTON, MA	01109060	1968	-59	-58	-49	-17	-13	-12	-20	-17
SEGREGANSET RIVER NEAR DIGHTON, MA	01109070	1968	-61	-73	-79	-23	-10	-12	-23	-30
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	01110000	1941	-80	-69	-17	16	11	33	39	78
BRANCH RIVER AT FORESTDALE, RI	01111500	1941	-29	-52	-48	-0.043	4.5	29	32	44
BLACKSTONE RIVER AT WOONSOCKET, RI	01112500	1930	98	-25	-18	28	17	20	8.8	11
WOONASQUATUCKET RIVER AT CENTERDALE, RI	01114500	1943	1.7	-58	-58	15	16	54	57	84
SO. BRANCH PAWTUXET RIVER AT WASHINGTON, RI	01116000	1942	173	-17	-20	13	12	22	30	32
PAWTUXET RIVER AT CRANSTON, RI	01116500	1941	102	-39	-26	0.17	8.8	30	62	57
ANNUAL – 1943 to 2016										
TAUNTON RIVER NEAR BRIDGEWATER, MA	01108000		60	49	31	14	15	20	8.5	5
WADING RIVER NEAR NORTON, MA	01109000		-56	-60	-46	5.5	3.6	14	9.7	16
THREEMILE RIVER AT NORTH DIGHTON, MA	01109060		Excluded because Period of Record starts in 1966							
SEGREGANSET RIVER NEAR DIGHTON, MA	01109070									
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	01110000		-79	-69	-21	14	8.9	30	33	69
BRANCH RIVER AT FORESTDALE, RI	01111500		-29	-51	-48	-1.2	3.2	27	30	42
BLACKSTONE RIVER AT WOONSOCKET, RI	01112500		25	-34	-22	8.8	4.9	20	12	21
WOONASQUATUCKET RIVER AT CENTERDALE, RI	01114500		1.7	-58	-58	15	16	54	57	84
SO. BRANCH PAWTUXET RIVER AT WASHINGTON, RI	01116000		170	-17	-20	13	12	21	29	31
PAWTUXET RIVER AT CRANSTON, RI	01116500		90	-38	-25	-0.003	7.6	28	58	56

Table 6. Change (%) over the available period of record (Start Year to 2016) and for 1943 to 2016 in SEASONAL hydrologic measures. The Start Year is the minimum year of record + 2 because the calculations are accounting for “edge effects”. Values are shaded when $p < 0.1$. The Taunton, Blackstone and Pawtuxet are boxed because they are used to estimate freshwater flow to Narragansett Bay.

USGS Gage Name	USGS Gage ID	Start Year	1-day Min	7-day Min	30-day Min	Median	Mean	30-day Max	7-day Max	1-day Max
SEASONAL – START YEAR to 2016										
TAUNTON RIVER NEAR BRIDGEWATER, MA	01108000	1931	62	35	13	-2.4	5.2	16	-6.1	3.3
WADING RIVER NEAR NORTON, MA	01109000	1926	-35	-56	-46	-19	-2.4	19	4.8	11
THREEMILE RIVER AT NORTH DIGHTON, MA	01109060	1968	-60	-57	-49	-36	-14	-17	-17	13
SEGREGANSET RIVER NEAR DIGHTON, MA	01109070	1968	-62	-74	-76	-67	-8.2	-14	-6.4	66
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	01110000	1941	-86	-78	-44	-31	-10	8.9	3.4	30
BRANCH RIVER AT FORESTDALE, RI	01111500	1941	-37	-54	-47	-13	-16	-1.3	-8	-10
BLACKSTONE RIVER AT WOONSOCKET, RI	01112500	1930	59	-35	-25	-15	5.6	34	14	22
WOONASQUATUCKET RIVER AT CENTERDALE, RI	01114500	1943	-6.4	-64	-64	-57	-25	2.8	31	54
SO. BRANCH PAWTUXET RIVER AT WASHINGTON, RI	01116000	1942	148	-24	-33	-33	-6.5	4.2	37	32
PAWTUXET RIVER AT CRANSTON, RI	01116500	1941	62	-41	-27	-27	-0.64	7.2	26	34
SEASONAL – 1943 to 2016										
TAUNTON RIVER NEAR BRIDGEWATER, MA	01108000		57	41	27	8.1	12	5.6	-4.9	15
WADING RIVER NEAR NORTON, MA	01109000		-61	-64	-48	-26	-1.7	-1.2	-3.3	10
THREEMILE RIVER AT NORTH DIGHTON, MA	01109060		Excluded because Period of Record starts in 1966							
SEGREGANSET RIVER NEAR DIGHTON, MA	01109070									
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	01110000		-85	-77	-44	-28	-8.4	8.6	3	29
BRANCH RIVER AT FORESTDALE, RI	01111500		-37	-53	-46	-13	-15	-0.69	-6.2	-7.5
BLACKSTONE RIVER AT WOONSOCKET, RI	01112500		11	-39	-26	-15	-1.7	11	1.4	11
WOONASQUATUCKET RIVER AT CENTERDALE, RI	01114500		-6.4	-64	-64	-57	-25	2.8	31	54
SO. BRANCH PAWTUXET RIVER AT WASHINGTON, RI	01116000		147	-24	-33	-33	-6	4.4	37	32
PAWTUXET RIVER AT CRANSTON, RI	01116500		54	-40	-27	-26	1.1	8.1	29	38

Table 7. Change (%) over the available period of record (Start Year to 2016) and for 1943 to 2016 in JUNE hydrologic measures. The Start Year is the minimum year of record + 2 because the calculations are accounting for "edge effects". Values are shaded when $p < 0.1$. The Taunton, Blackstone and Pawtuxet are boxed because they are used to estimate freshwater flow to Narragansett Bay.

USGS Gage Name	USGS Gage ID	Start Year	1-day Min	7-day Min	30-day Min	Median	Mean	30-day Max	7-day Max	1-day Max
JUNE – START YEAR to 2016										
TAUNTON RIVER NEAR BRIDGEWATER, MA	01108000	1930	22	-9.9	-6.5	6.5	9	26	8.5	3.7
WADING RIVER NEAR NORTON, MA	01109000	1925	-8.6	-18	-2	44	25	37	25	20
THREEMILE RIVER AT NORTH DIGHTON, MA	01109060	1967	-31	-26	-25	-9	-6	-22	-26	3.6
SEGREGANSET RIVER NEAR DIGHTON, MA	01109070	1967	-49	-27	-17	-3.9	0.11	-15	-21	23
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	01110000	1940	-42	-41	-34	-15	-16	-9.7	-11	-0.86
BRANCH RIVER AT FORESTDALE, RI	01111500	1940	92	-16	-26	-14	-6.5	-7.8	-10	-11
BLACKSTONE RIVER AT WOONSOCKET, RI	01112500	1929	96	-2.1	9.7	27	24	21	30	37
WOONASQUATUCKET RIVER AT CENTERDALE, RI	01114500	1942	11	-49	-28	-26	-6	-1.3	19	50
SO. BRANCH PAWTUXET RIVER AT WASHINGTON, RI	01116000	1941	264	-29	-15	-18	0.32	-1.7	12	5.6
PAWTUXET RIVER AT CRANSTON, RI	01116500	1940	152	-27	-22	-19	-2.1	-3.6	6.3	12
JUNE – 1943 to 2016										
TAUNTON RIVER NEAR BRIDGEWATER, MA	01108000		16	-0.91	-1.2	13	18	12	2.8	15
WADING RIVER NEAR NORTON, MA	01109000		-9.4	-17	-7.7	20	18	2.3	7.1	19
THREEMILE RIVER AT NORTH DIGHTON, MA	01109060		Excluded because Period of Record starts in 1966							
SEGREGANSET RIVER NEAR DIGHTON, MA	01109070									
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	01110000		-38	-37	-31	-9.9	-12	-8.8	-7.2	3.8
BRANCH RIVER AT FORESTDALE, RI	01111500		86	-12	-22	-8.1	-0.91	-6.2	-5.6	-3.3
BLACKSTONE RIVER AT WOONSOCKET, RI	01112500		28	-9.2	-5.8	17	15	4.4	10	24
WOONASQUATUCKET RIVER AT CENTERDALE, RI	01114500		8.3	-48	-27	-25	-5	-1.1	20	51
SO. BRANCH PAWTUXET RIVER AT WASHINGTON, RI	01116000		250	-26	-14	-16	2.6	-0.94	13	8.6
PAWTUXET RIVER AT CRANSTON, RI	01116500		129	-24	-18	-15	2.9	-1.6	11	20

Trends in High Flow Days

The Kendall Tau trend test ($p < 0.1$) identified possible trends in high flow events over the entire period of record (Table 8).

Table 8. Statistically significant results of the Kendall Tau trend test on high flow days over the entire period of record. τ indicates the direction of the trend and is similar to a correlation coefficient.

Site	Time Frame	Metric	p value	τ	n
Quinsigamond River at North Grafton, MA	Annual	mean	0.039	0.17	70
USGS gage # 01110000	Annual	median	0.056	0.16	70
	Seasonal	# days	0.068	0.12	78
Branch River at Forestdale, RI	Seasonal	# events	0.086	0.08	78
USGS gage # 01111500	June	median	0.023	0.41	17
	June	# events	0.038	0.07	78
Woonasquatucket River at Centerdale, RI	Annual	# days	0.057	0.15	75
USGS gage # 01114500	Seasonal	# days	0.007	0.16	76
	Seasonal	# events	0.016	0.10	76
	June	# days	0.030	0.10	76
	June	# events	0.018	0.09	76
So. Branch Pawtuxet River at Washington, RI	Annual	mean	0.067	0.15	66
USGS gage # 01116000	Seasonal	# days	0.038	0.13	77
	Seasonal	# events	0.094	0.09	77
Pawtuxet River at Cranston, RI	Annual	mean	0.030	0.18	66
USGS gage # 01116500	Annual	# days	0.048	0.15	77
	Annual	# events	0.014	0.19	77
	Seasonal	# days	0.030	0.15	78
	Annual	mean	0.049	0.16	71
Narragansett Bay	Annual	# days	0.053	0.15	77
	Seasonal	# days	0.082	0.12	78
	Seasonal	# events	0.099	0.09	78
	June	mean	0.077	0.38	13
	June	median	0.024	0.49	13

Table 8 suggests increasing trends in high flow magnitude and/or frequency in high flow days at several stream gages (Quinsigamond R at North Grafton, MA; Branch R at Forestdale, RI; Woonasquatucket R at Centerdale, RI; So. Branch Pawtuxet R at Washington, RI; Pawtuxet R at Cranston, RI; and when considering total estimated flow to Narragansett Bay. It is worth noting that these are the same rivers, with the exception of the Blackstone, that had statistically significant positive trends in the 1-day maximum over annual and seasonal time frames (Tables 5 and 6).

Comparing the frequency of high flow days pre- and post-1970 yielded a significant difference between the two time periods at all gages and over all time frames. The simple test on proportions assumes that the two groups are independent, an assumption which is violated because we are comparing data from the same gage, over different time periods. Therefore, this result should be considered a preliminary, exploratory result.

Figures 8 through 10 show the annual, seasonal and June median, respectively, of high flow days pre- and post-1970. The same plots for the mean, number of high flow days and number of high flow events are provided in Appendix C. Linear models were estimated for the pre- and post- 1970 time periods and compared for significant differences in intercept and/or slope, after log transforming the means and medians. This approach aimed to investigate differences in trends during these two time periods. Statistically significant differences in slope and/or intercept were rare, which is not surprising given the confidence intervals of the linear models. Again, this is a preliminary analysis and further investigation will require more complex statistical approaches.

Implications for Environmental Indicators

Environmental indicators help track changes in Narragansett Bay and its drainage basin and can inform management decisions as trends are detected. Changes in freshwater flow to Narragansett Bay are important in their own right as they relate to freshwater habitats and drinking water quality and quantity, but they are also important in the context of better understanding the development of hypoxia in the bay and how that might change over time as the magnitude and timing of freshwater inputs change over time.

Changes in freshwater flow to Narragansett Bay as measured at USGS gages throughout the drainage basin could be tracked using some of the relevant metrics identified here as showing statistically significant long-term trends, such as the annual and seasonal (June through September) 1-day maximum, and 7- and 30-day minima. The 1-day maximum is showing an increasing trend, suggesting more intense precipitation events. The 7- and 30-day minima are both showing decreasing trends, indicating dryer periods of base flow. These trends are consistent with observed increases in mean and extreme precipitation, as well as increases in temperature in Rhode Island (Runkle et al., 2017). These trends will need to be considered when assessing freshwater flow as a potential driver of bay hypoxia.

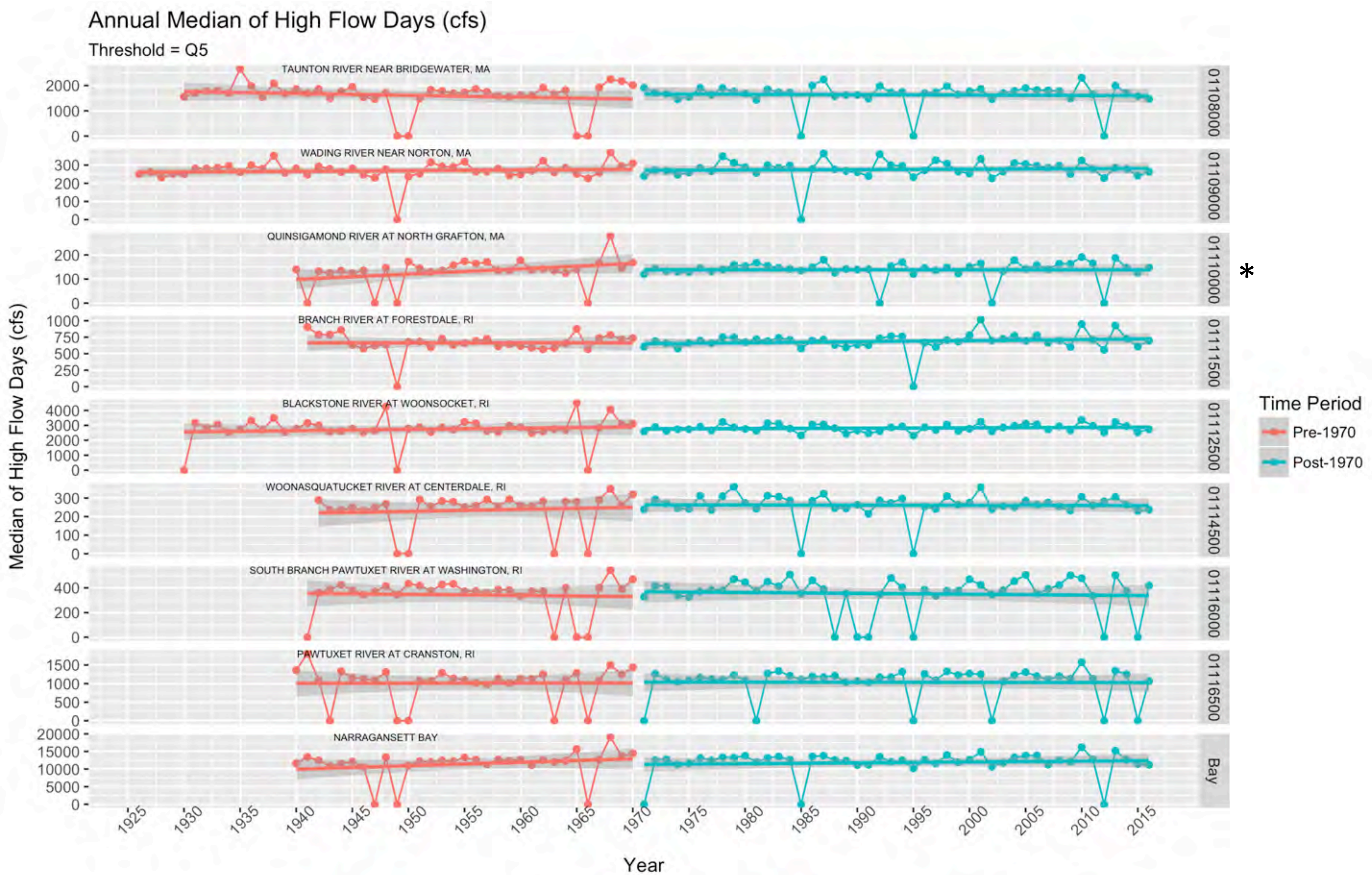


Figure 8. Annual median of high flow days. A median of zero indicates there were no high flow days during that year. Linear models were derived for pre- and post-1970 and tested for statistically significant differences in intercept and/or slope at $p < 0.1$. Using this method only one gage showed a statistically significant difference in intercept (Quinsigamond River, #0111000) and none showed a difference in slope.

* statistically significant difference in intercept + statistically significant difference in slope

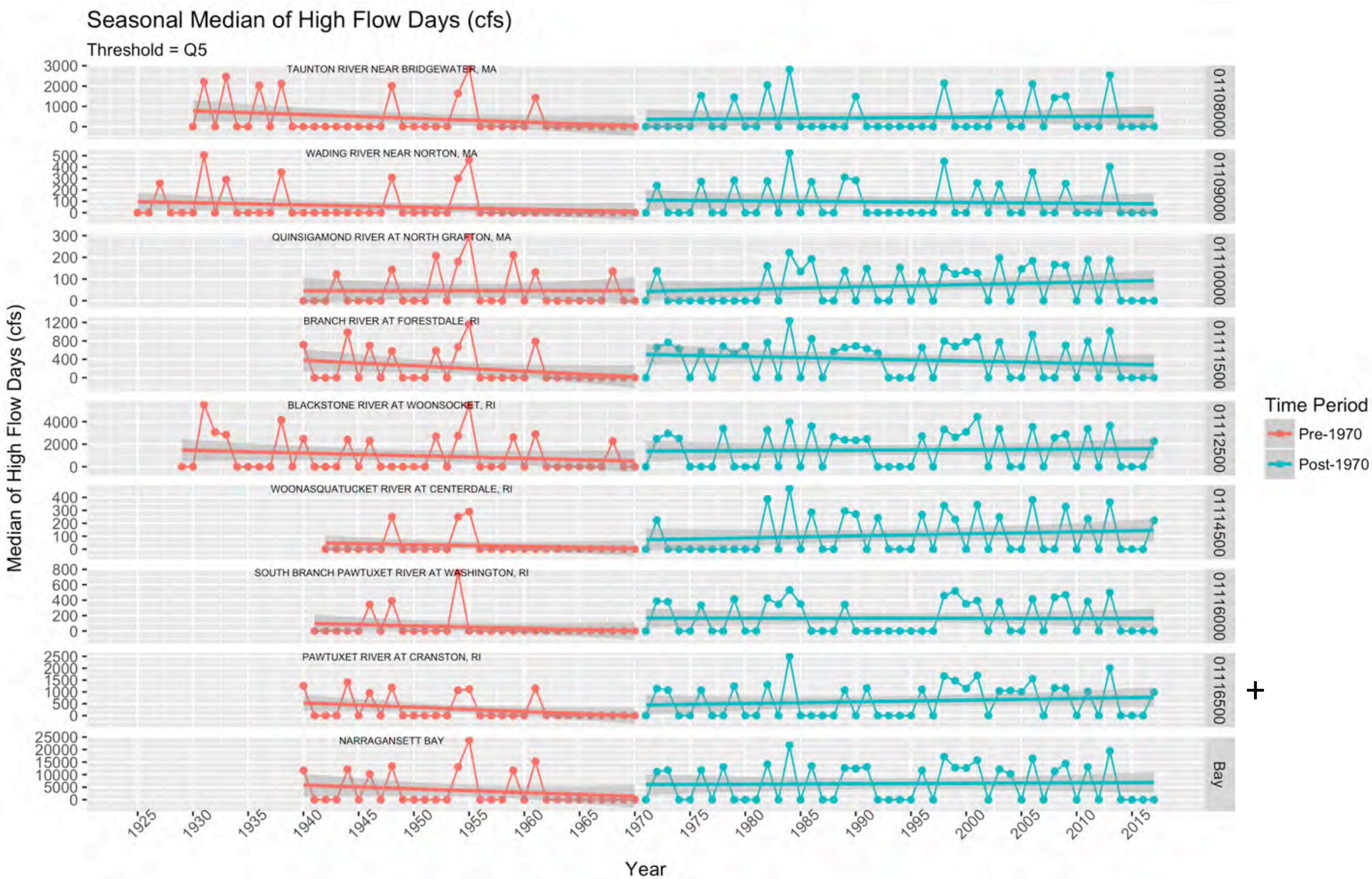


Figure 9. Seasonal median of high flow days. A median of zero indicates there were no high flow days during the season of that year. Linear models were derived for pre- and post-1970 and tested for statistically significant differences in intercept and/or slope at $p < 0.1$. Using this method only one gage showed a statistically significant difference in slope (Pawtuxet River, #0116500) and none showed a difference in intercept.

* statistically significant difference in intercept + statistically significant difference in slope

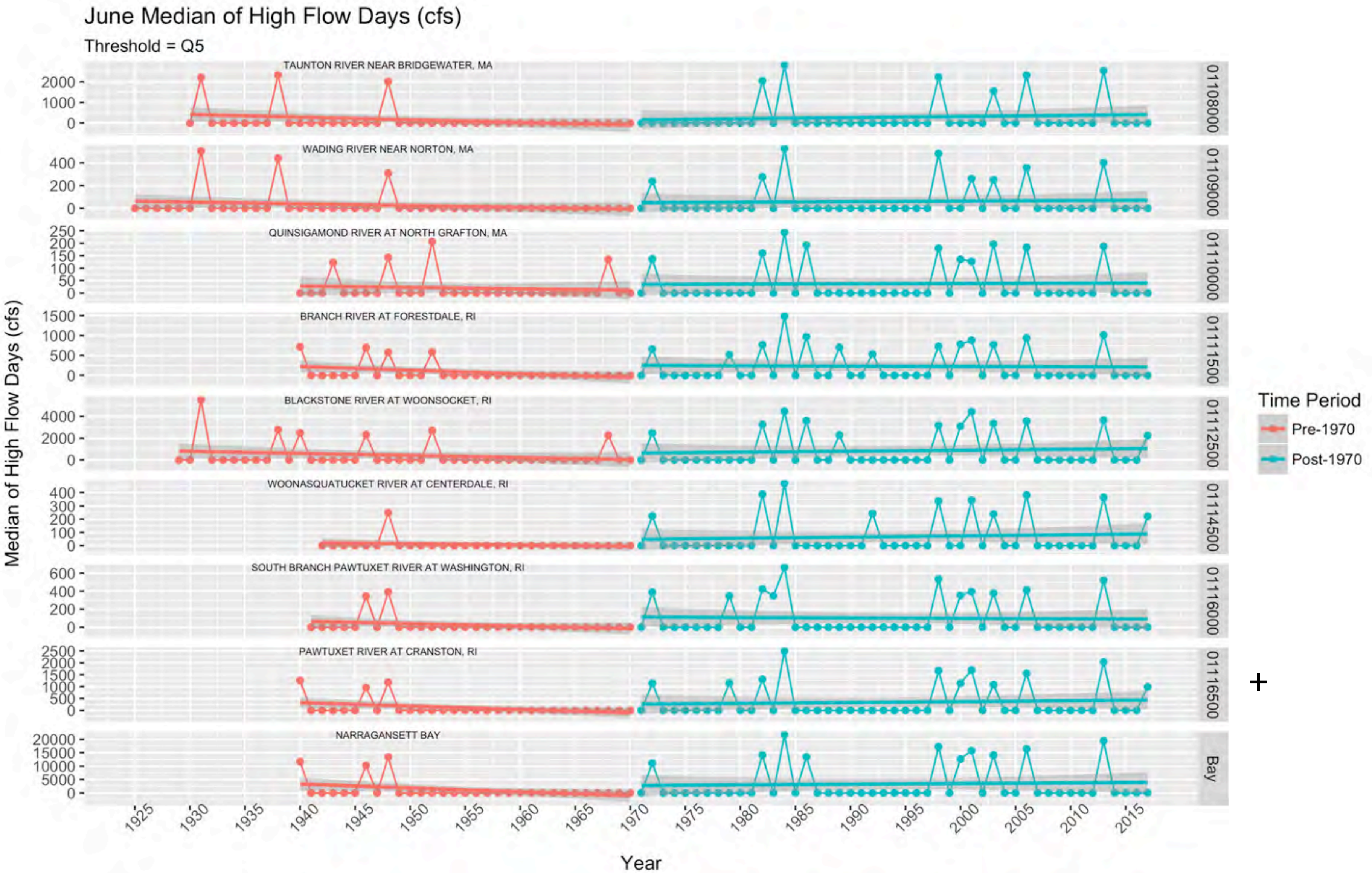


Figure 10. June median of high flow days. A median of zero indicates there were no high flow days during the season of that year. Linear models were derived for pre- and post-1970 and tested for statistically significant differences in intercept and/or slope at *p* < 0.1. Using this method only one gage showed a statistically significant difference in slope (Pawtuxet River, #0116500) and none showed a difference in intercept.

* statistically significant difference in intercept + statistically significant difference in slope

SUMMARY AND NEXT STEPS

The long-term records (50 to 90 years) of mean daily flow data from ten USGS river gages located in the Narragansett Bay drainage area were analyzed to identify possible long-term trends in river flow over three time frames: annual, seasonal and June. A variety of approaches was used to analyze trends in common hydrologic measures as well as trends in high flow days and events.

The analysis identified a number of significant trends. Most notable were increasing trends in both the brief (1-day) and sustained (30-day) maxima metrics over the annual time frame, and increasing trends in the 1-day maximum over the seasonal time frame. We also observed decreasing trends in the sustained (7- and 30-day) minima over all time frames, suggesting that base flow is decreasing. These observations are consistent with recorded increases in the frequency and magnitude of extreme precipitation events – driving higher maximum flows – and higher summer temperatures, both of which can play a role in lowering groundwater storage and stream base flow. High intensity events tend to produce more surface runoff and less groundwater storage, and higher summer temperatures increase groundwater losses due to evapotranspiration.

There were a few exceptions to these general trends. The 1-day minimum showed both positive and negative trends across gages over the annual and seasonal time frames, and positive trends over the June time frame. The annual means and medians at the Taunton and Blackstone Rivers showed increasing trends, along with the annual median at the Woonasquatucket (Table 5), while the only significant trends in seasonal means and medians were negative (Woonasquatucket, S. Branch of the Pawtuxet, and the Pawtuxet River at Cranston, RI) (Table 6), suggesting drier summers on average even as annual flow is increasing.

High flow days and events (three or more consecutive high flow days) have become more frequent since 1970, and at some gages, greater in magnitude. Based on previous research, we would expect that an increase in the number of high flow days or events occurring in June may presage more severe or frequent hypoxia events in Upper Narragansett Bay later in the season (Codiga et al., 2009).

Causes for these observed trends in freshwater flow to Narraganset Bay are outside the purview of this report, but likely include a combination of changes in land cover, diversion and storage for municipal drinking water supplies and powerplants, as well as changes in precipitation patterns. Because causes have not been identified, confident prediction of future freshwater flow patterns to Narragansett Bay is not currently possible (Serinaldi et al., 2017); however, based on the data available it is reasonable to assume that freshwater flow to Narragansett Bay will continue along these trends when compared to 30 years ago.

This analysis confirmed a number of long-term trends at stream gages within the Narragansett Bay drainage basin, reflecting continued changes in stream flow contributions to the bay. Given the importance of freshwater inputs to the estuary, monitoring of stream flow is essential and should be maintained. It provides important information needed to understand Narragansett Bay ecology, including assessment of potential changes in the timing and extent of hypoxia in the bay.

Possible future work to build on these analyses includes identifying a reliable and consistent method for characterizing “normal”, “wet”, and “dry” seasonal freshwater inputs to the bay as they relate to seasonal hypoxia extent and severity. Additionally, the characterization and tracking of high flow days could be refined. Continued tracking of a suite of indicators characterizing freshwater flow within the Narragansett Bay watershed could be used to identify trends and assess possible consequences related to bay ecosystem function.

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APPENDIX A. Estimating mean daily flow at the Taunton River near Bridgewater, MA gage (#01108000) using mean daily flow data at the Three Mile River gage (#01109060).

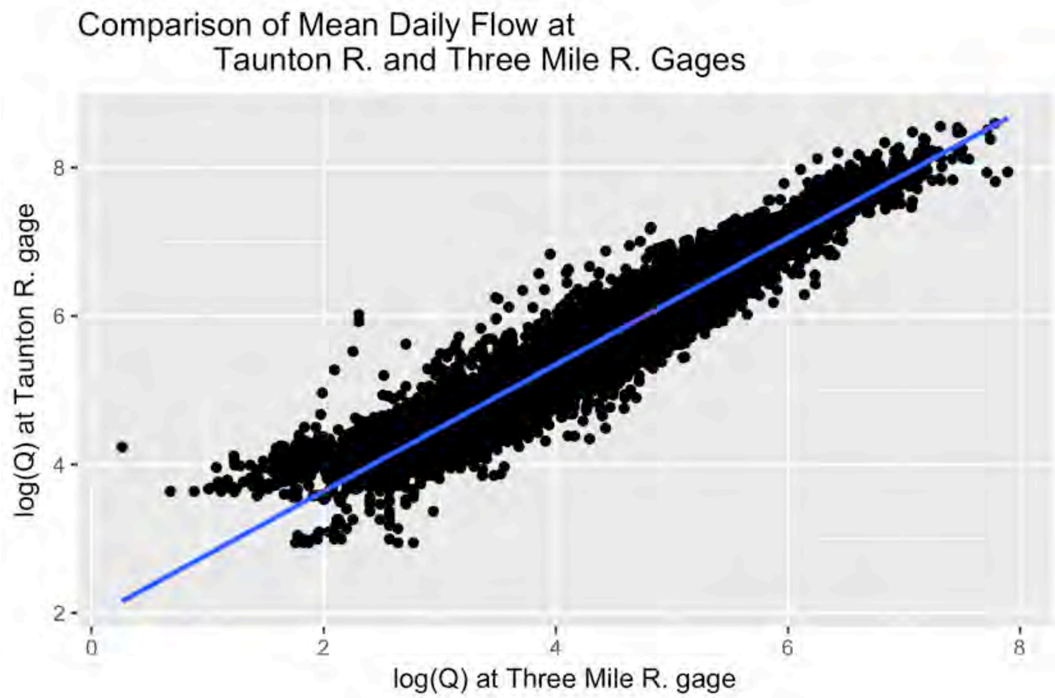


Figure A1. Linear regression of log normalized mean daily discharge (cfs) at Taunton River near Bridgewater, MA (#01108000) with Three Mile River (#01109060). $R^2 = 0.93$.

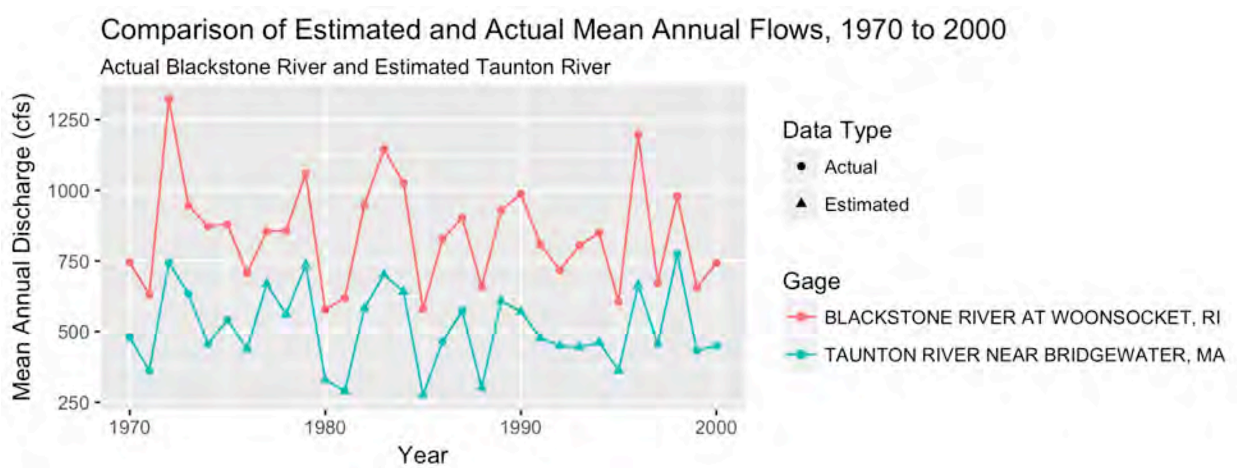
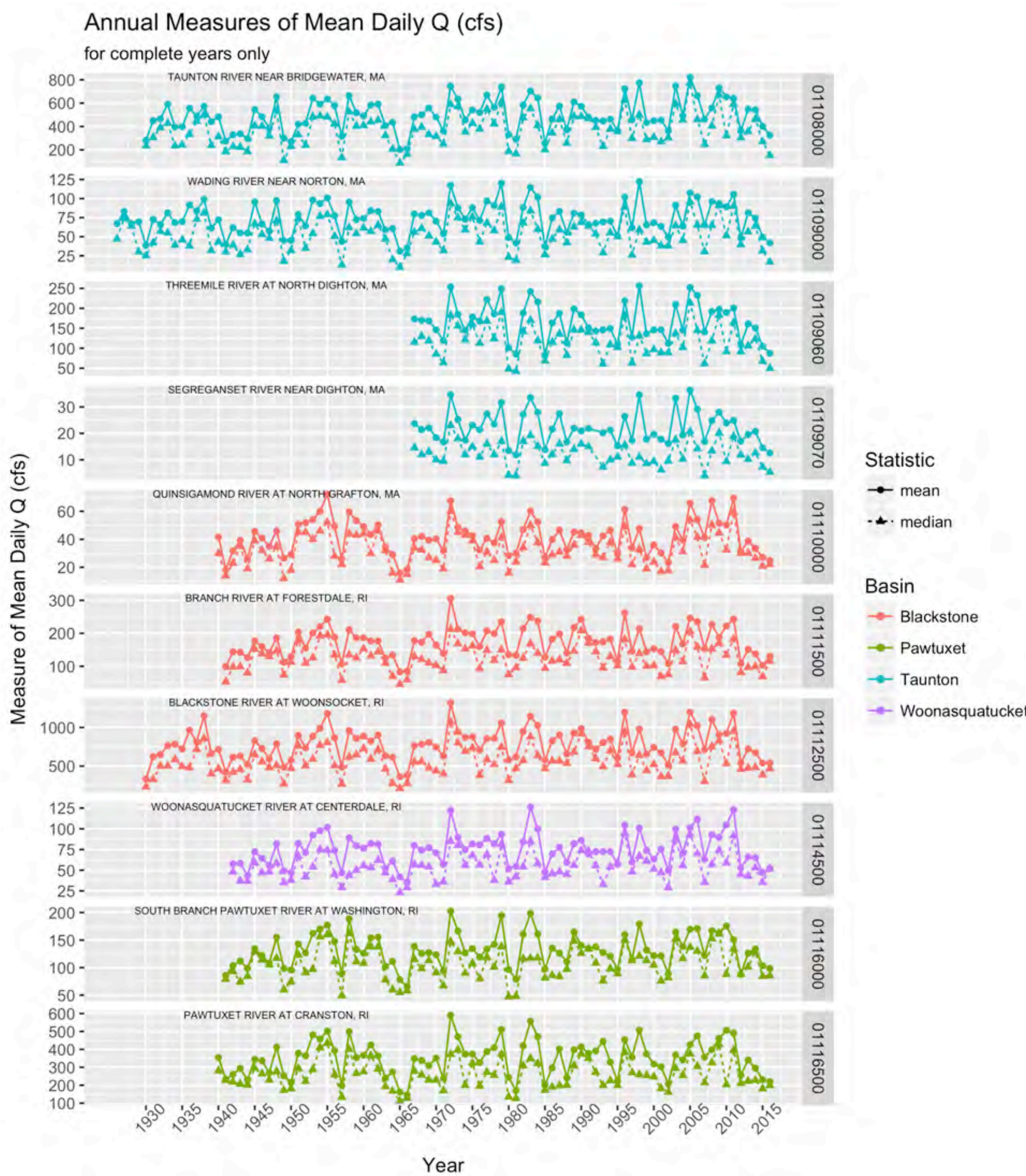
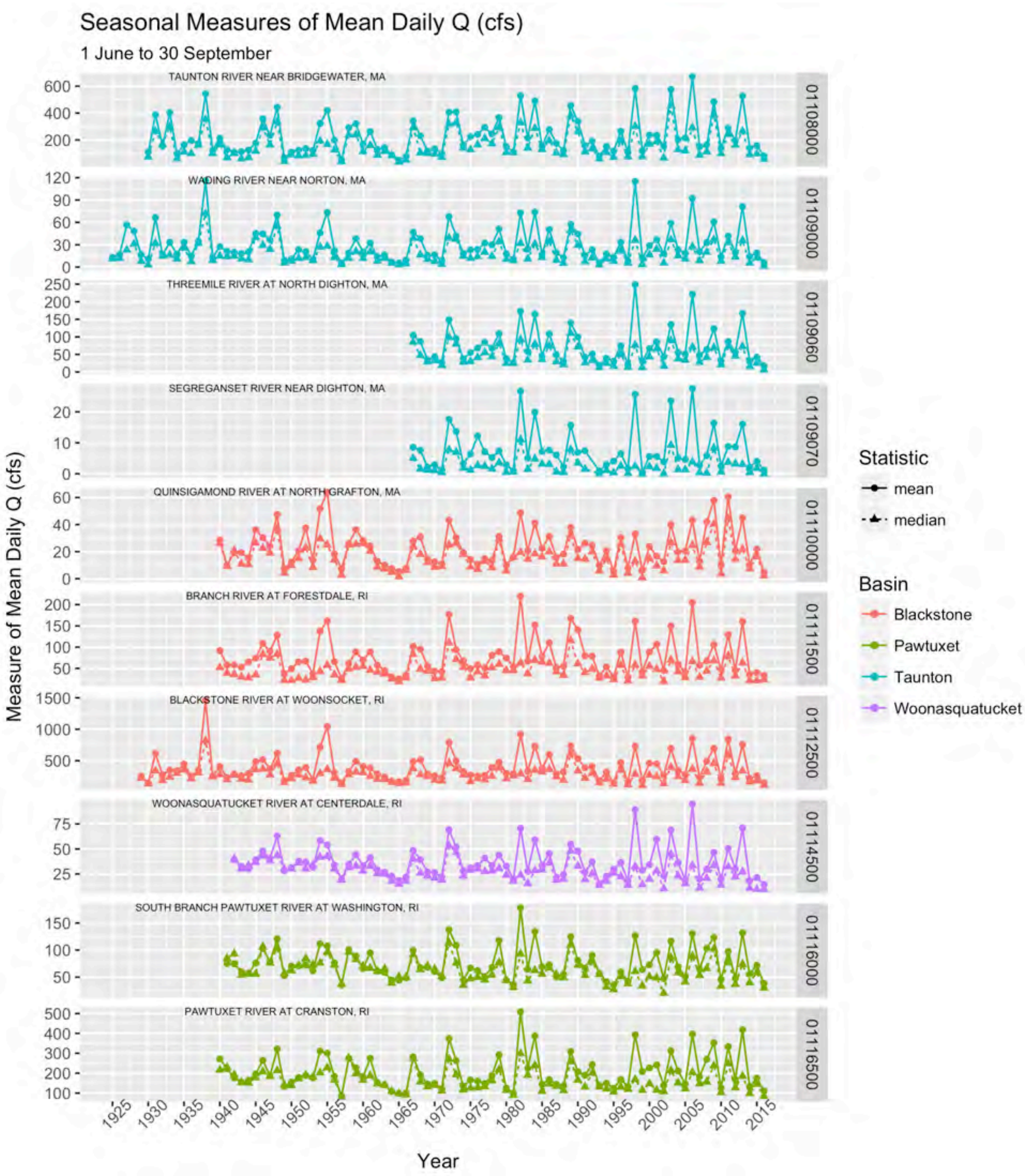
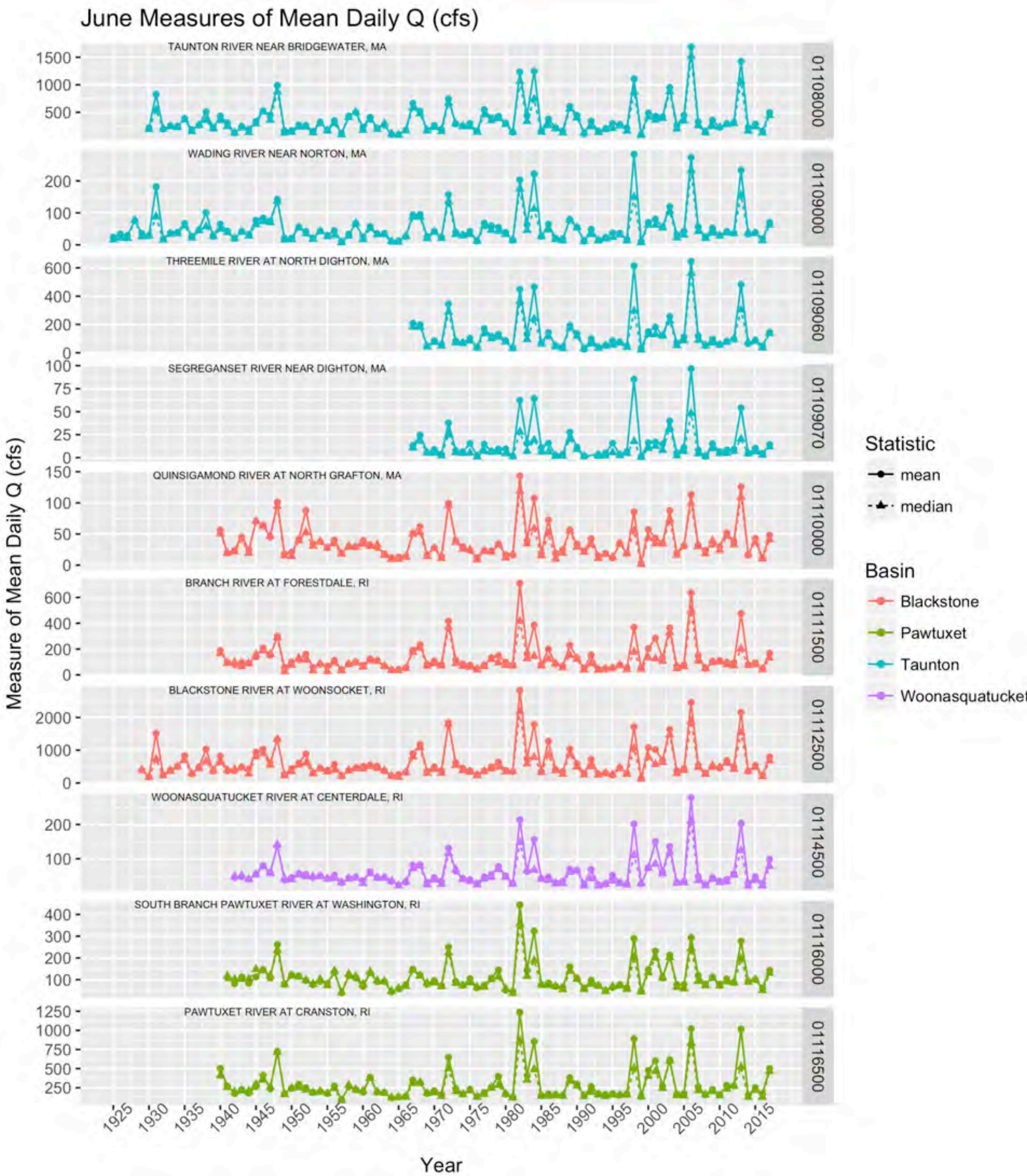


Figure A2. Comparison of actual mean annual discharge data recorded at the Blackstone River at Woonsocket, RI gage (#01112500) with estimated data used to fill data gaps at the Taunton River near Bridgewater, MA gage (#01108000).

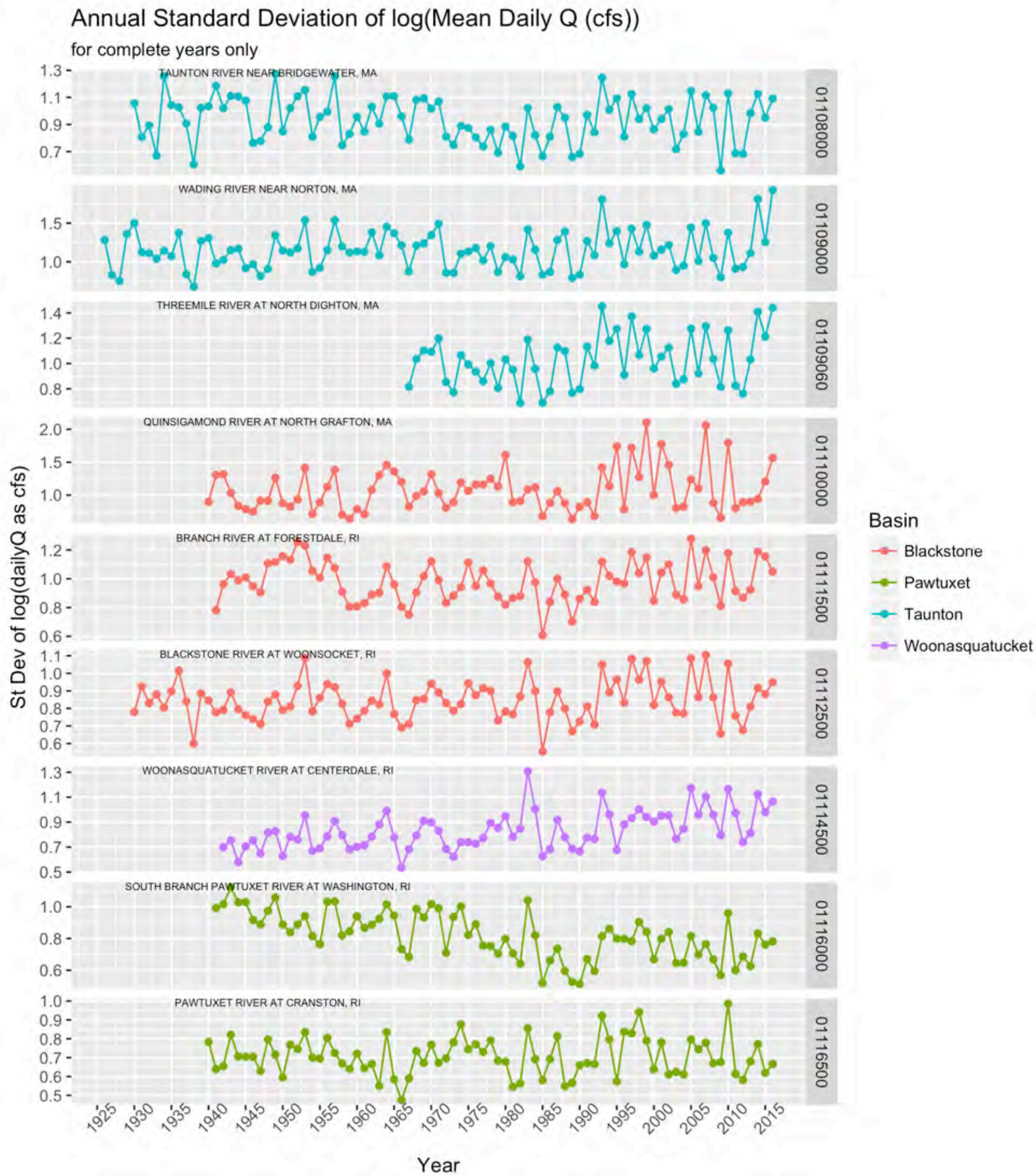
APPENDIX B. Supplementary Plots of Summary Statistics



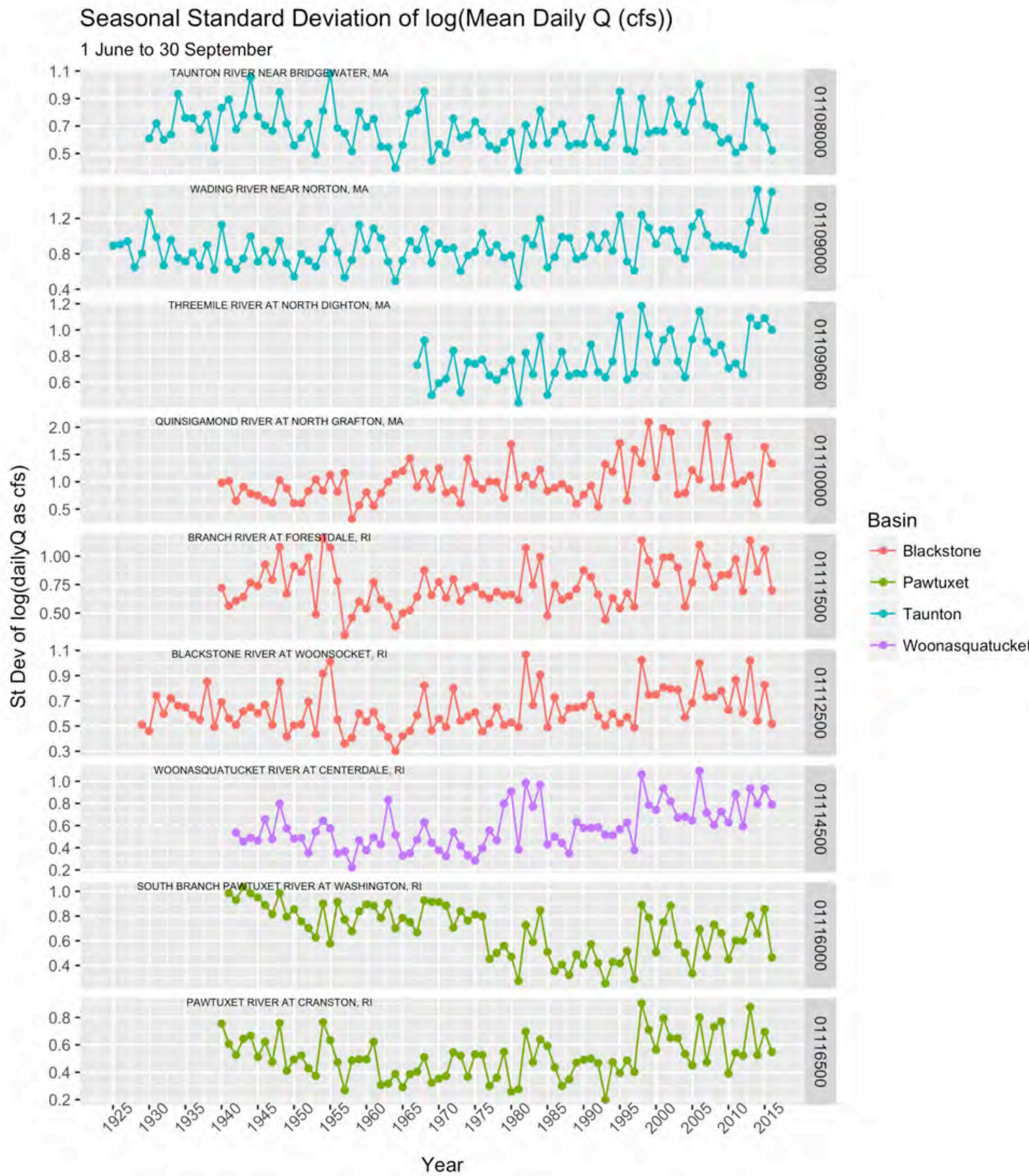

Seasonal Measures of Mean Daily Q (cfs)
1 June to 30 September
TAUNTON RIVER NEAR BRIDGEWATER, MA
01108000
WADING RIVER NEAR NORTON, MA
01109000
THREEMILE RIVER AT NORTH DIGHTON, MA
01109060
SEGREGANSET RIVER NEAR DIGHTON, MA
01109070
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
01110000
BRANCH RIVER AT FORESTDALE, RI
01111500
BLACKSTONE RIVER AT WOONSOCKET, RI
01112500
WOONASQUATUCKET RIVER AT CENTERDALE, RI
01114500
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
01116000
PAWTUXET RIVER AT CRANSTON, RI
01116500
Measure of Mean Daily Q (cfs)
Year
Statistic
mean
median
Basin
Blackstone
Pawtuxet
Taunton
Woonasquatucket

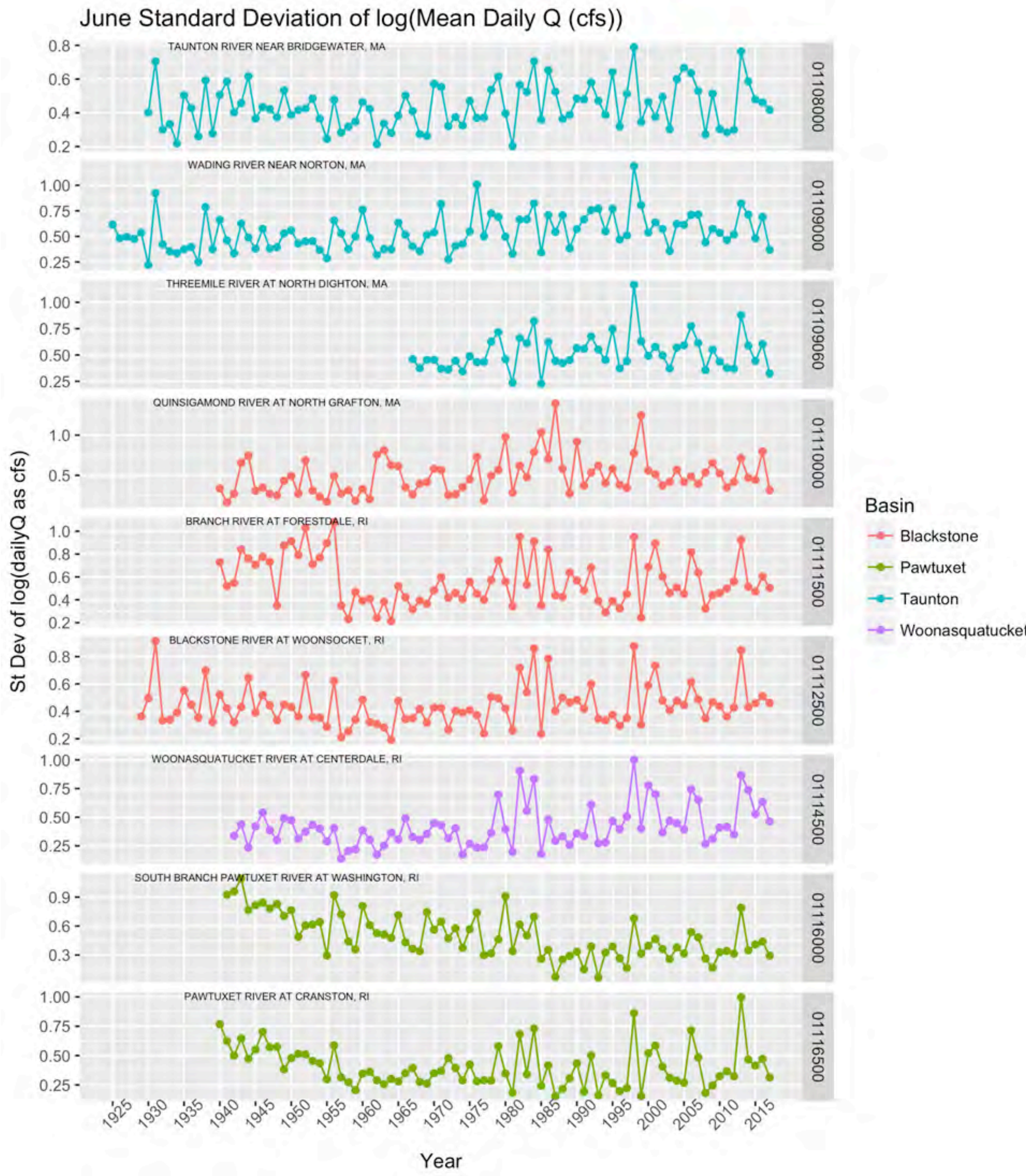


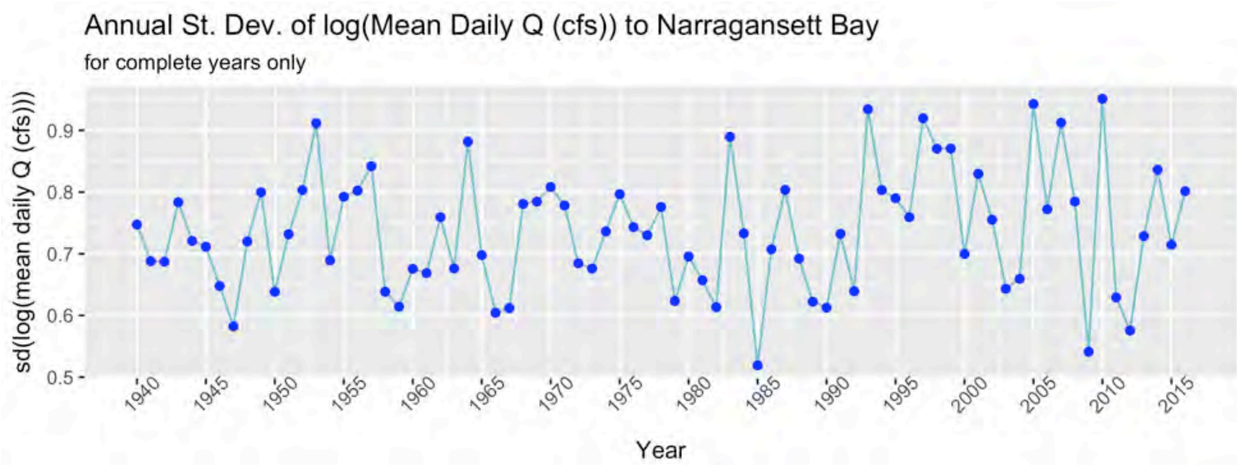
June Measures of Mean Daily Q (cfs)
TAUNTON RIVER NEAR BRIDGEWATER, MA
01108000
WADING RIVER NEAR NORTON, MA
01109000
THREEMILE RIVER AT NORTH DIGHTON, MA
01109060
SEGREGANSET RIVER NEAR DIGHTON, MA
01109070
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
01110000
BRANCH RIVER AT FORESTDALE, RI
01111500
BLACKSTONE RIVER AT WOONSOCKET, RI
01112500
WOONASQUATUCKET RIVER AT CENTERDALE, RI
01114500
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
01116000
PAWTUXET RIVER AT CRANSTON, RI
01116500
Measure of Mean Daily Q (cfs)
Year
Statistic
mean
median
Basin
Blackstone
Pawtuxet
Taunton
Woonasquatucket

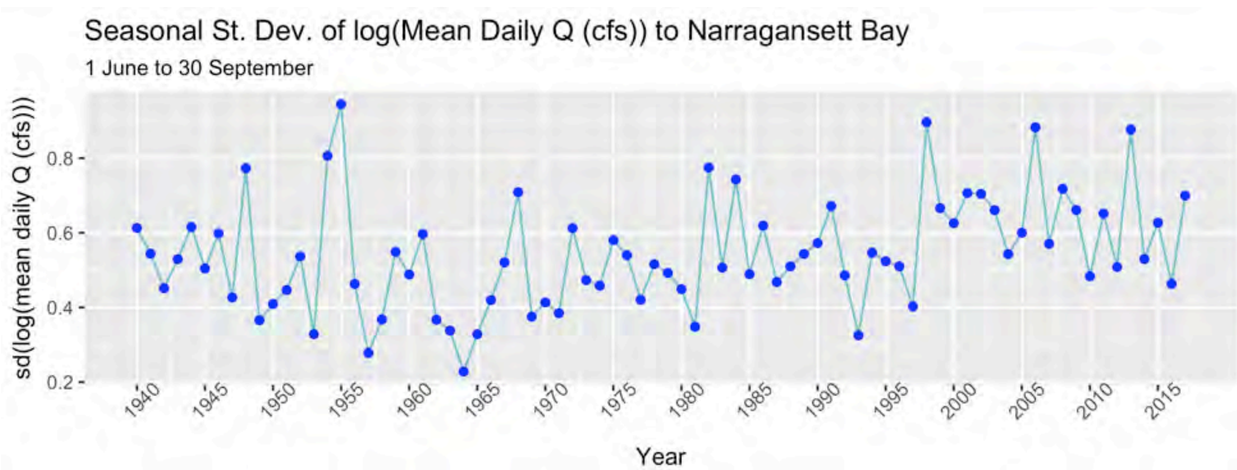


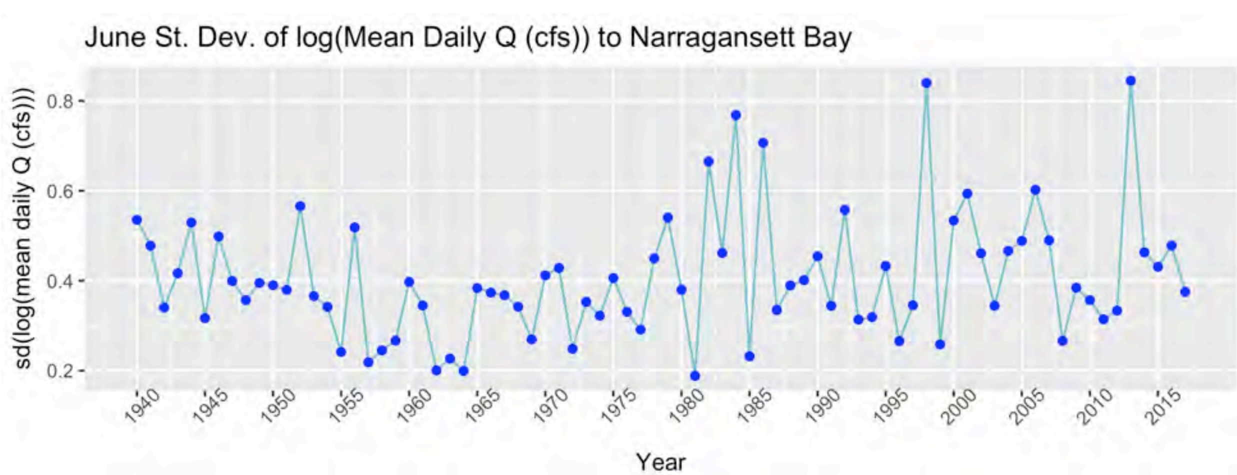
Annual Standard Deviation of log(Mean Daily Q (cfs))
for complete years only
TAUNTON RIVER NEAR BRIDGEWATER, MA
01108000
WADING RIVER NEAR NORTON, MA
01109000
THREEMILE RIVER AT NORTH DIGHTON, MA
01109060
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
01110000
BRANCH RIVER AT FORESTDALE, RI
01111500
BLACKSTONE RIVER AT WOONSOCKET, RI
01112500
WOONASQUATUCKET RIVER AT CENTERDALE, RI
01114500
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
01116000
PAWTUXET RIVER AT CRANSTON, RI
01116500
St Dev of log(dailyQ as cfs)
Year
Basin
Blackstone
Pawtuxet
Taunton
Woonasquatucket


Seasonal Standard Deviation of log(Mean Daily Q (cfs))
1 June to 30 September
TAUNTON RIVER NEAR BRIDGEWATER, MA
01108000
WADING RIVER NEAR NORTON, MA
01109000
THREEMILE RIVER AT NORTH DIGHTON, MA
01109060
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
01110000
BRANCH RIVER AT FORESTDALE, RI
01111500
BLACKSTONE RIVER AT WOONSOCKET, RI
01112500
WOONASQUATUCKET RIVER AT CENTERDALE, RI
01114500
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
01116000
PAWTUXET RIVER AT CRANSTON, RI
01116500
St Dev of log(dailyQ as cfs)
Year
Basin
Blackstone
Pawtuxet
Taunton
Woonasquatucket

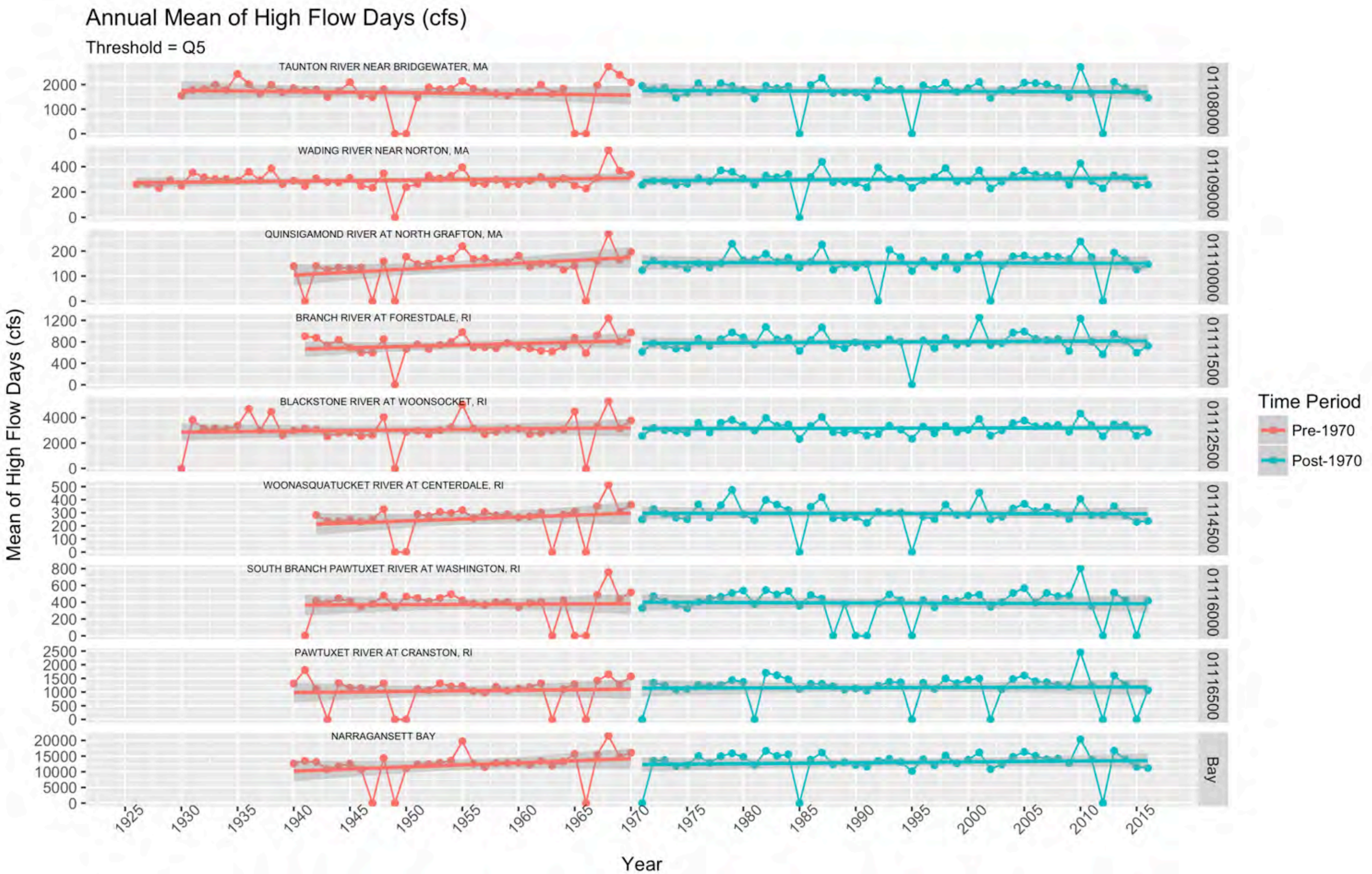

June Standard Deviation of log(Mean Daily Q (cfs))
TAUNTON RIVER NEAR BRIDGEWATER, MA
01108000
WADING RIVER NEAR NORTON, MA
01109000
THREEMILE RIVER AT NORTH DIGHTON, MA
01109060
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
01110000
BRANCH RIVER AT FORESTDALE, RI
01111500
BLACKSTONE RIVER AT WOONSOCKET, RI
01112500
WOONASQUATUCKET RIVER AT CENTERDALE, RI
01114500
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
01116000
PAWTUXET RIVER AT CRANSTON, RI
01116500
St Dev of log(dailyQ as cfs)
Year
Basin
Blackstone
Pawtuxet
Taunton
Woonasquatucket

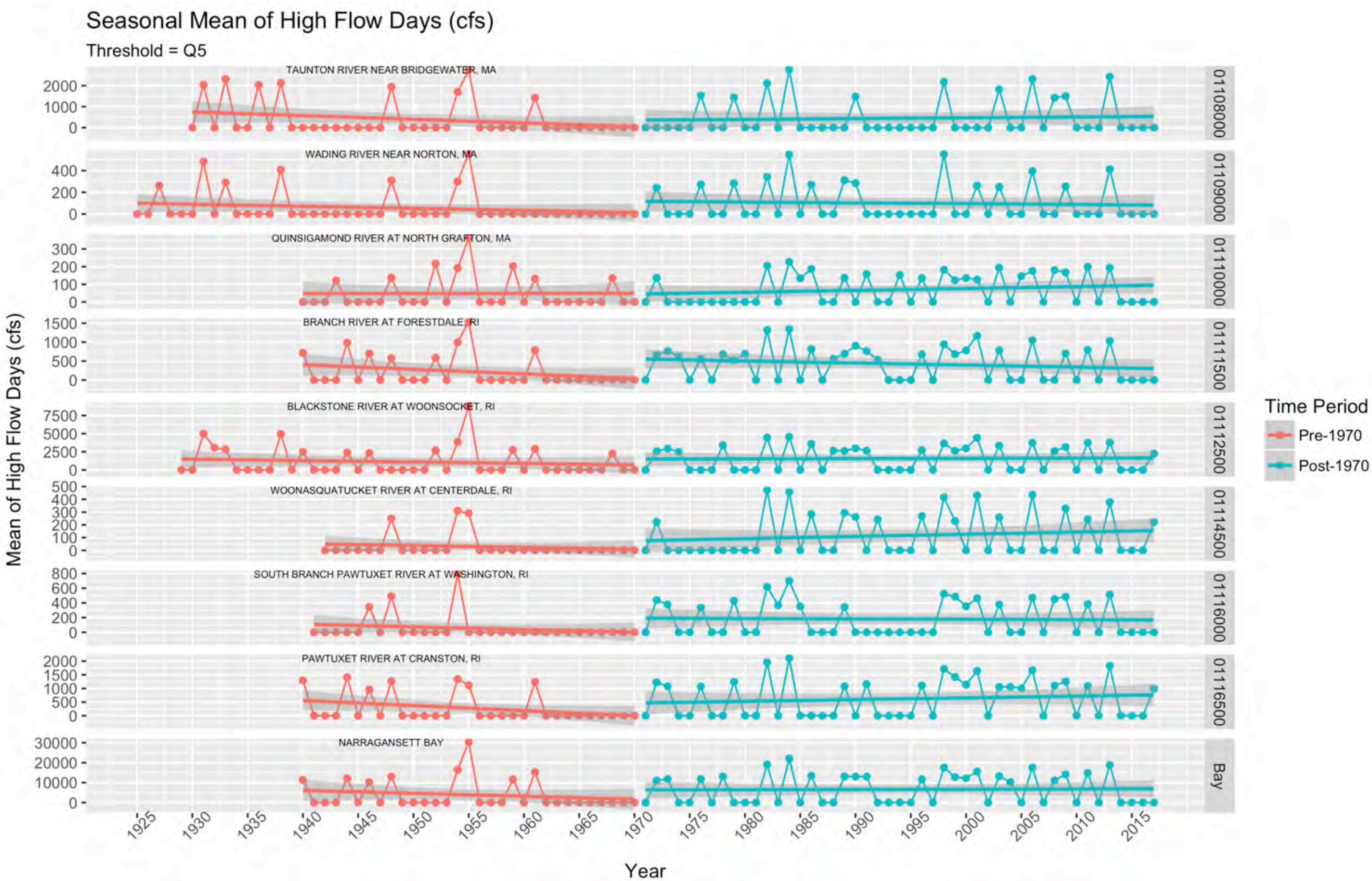

Annual St. Dev. of log(Mean Daily Q (cfs)) to Narragansett Bay
for complete years only
sd(log(mean daily Q (cfs)))
0.5
0.6
0.7
0.8
0.9
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

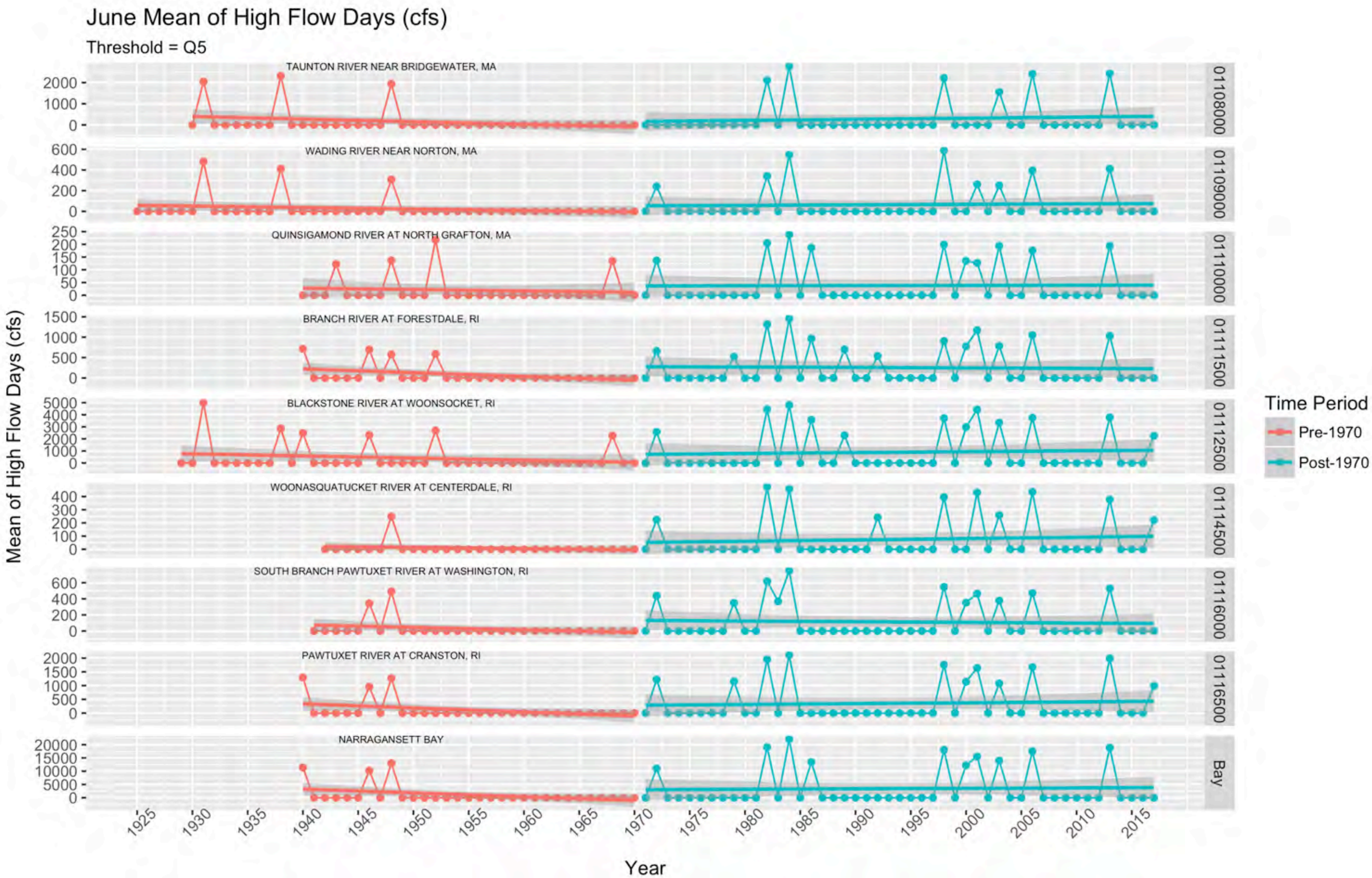

Seasonal St. Dev. of log(Mean Daily Q (cfs)) to Narragansett Bay
1 June to 30 September
sd(log(mean daily Q (cfs)))
0.2
0.4
0.6
0.8
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year


June St. Dev. of log(Mean Daily Q (cfs)) to Narragansett Bay
sd(log(mean daily Q (cfs)))
0.2
0.4
0.6
0.8
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

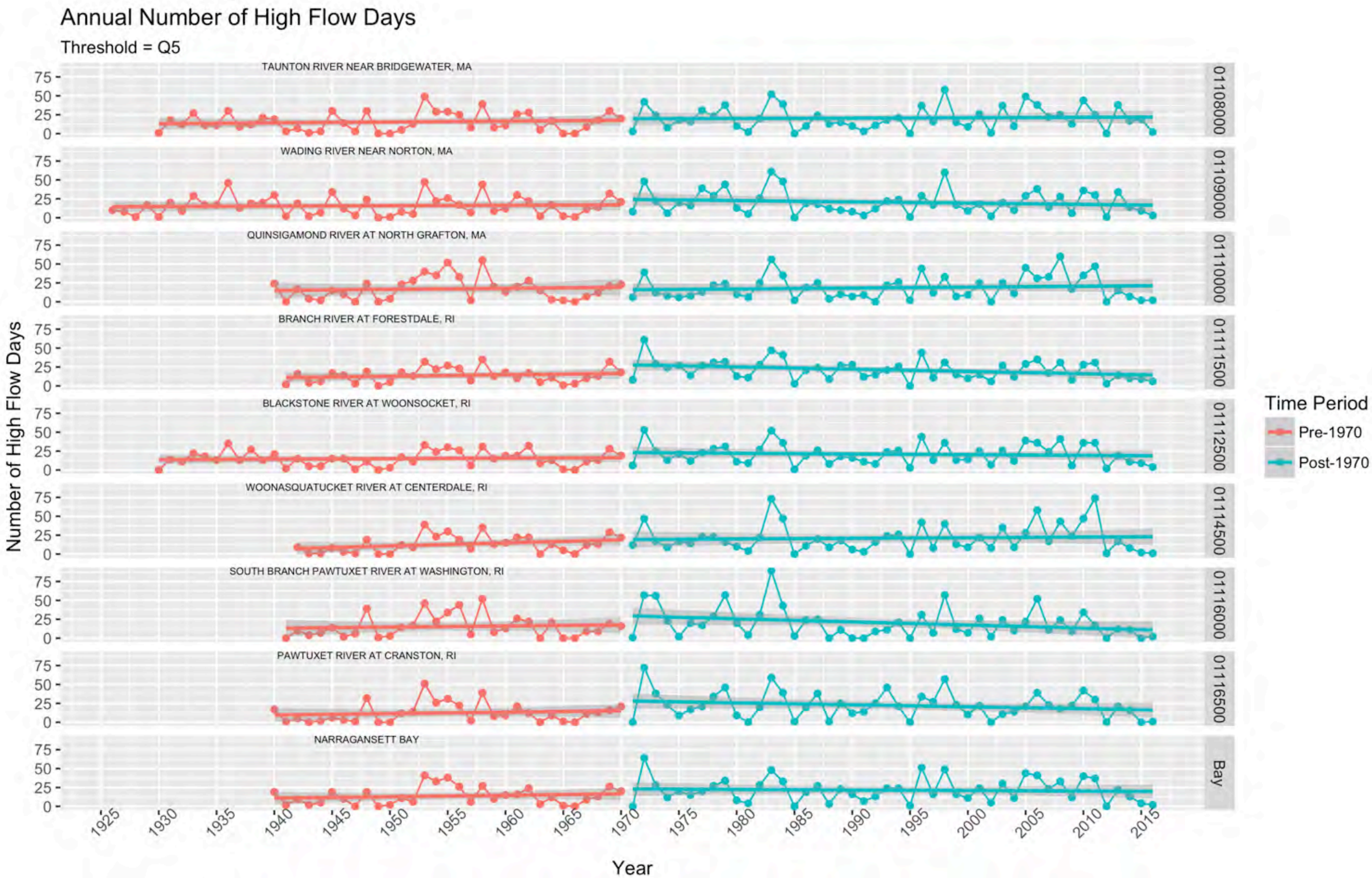
APPENDIX C. Pre- and Post- 1970 annual, seasonal and June means of high flow days, number of high flow days, and number of high flow events.

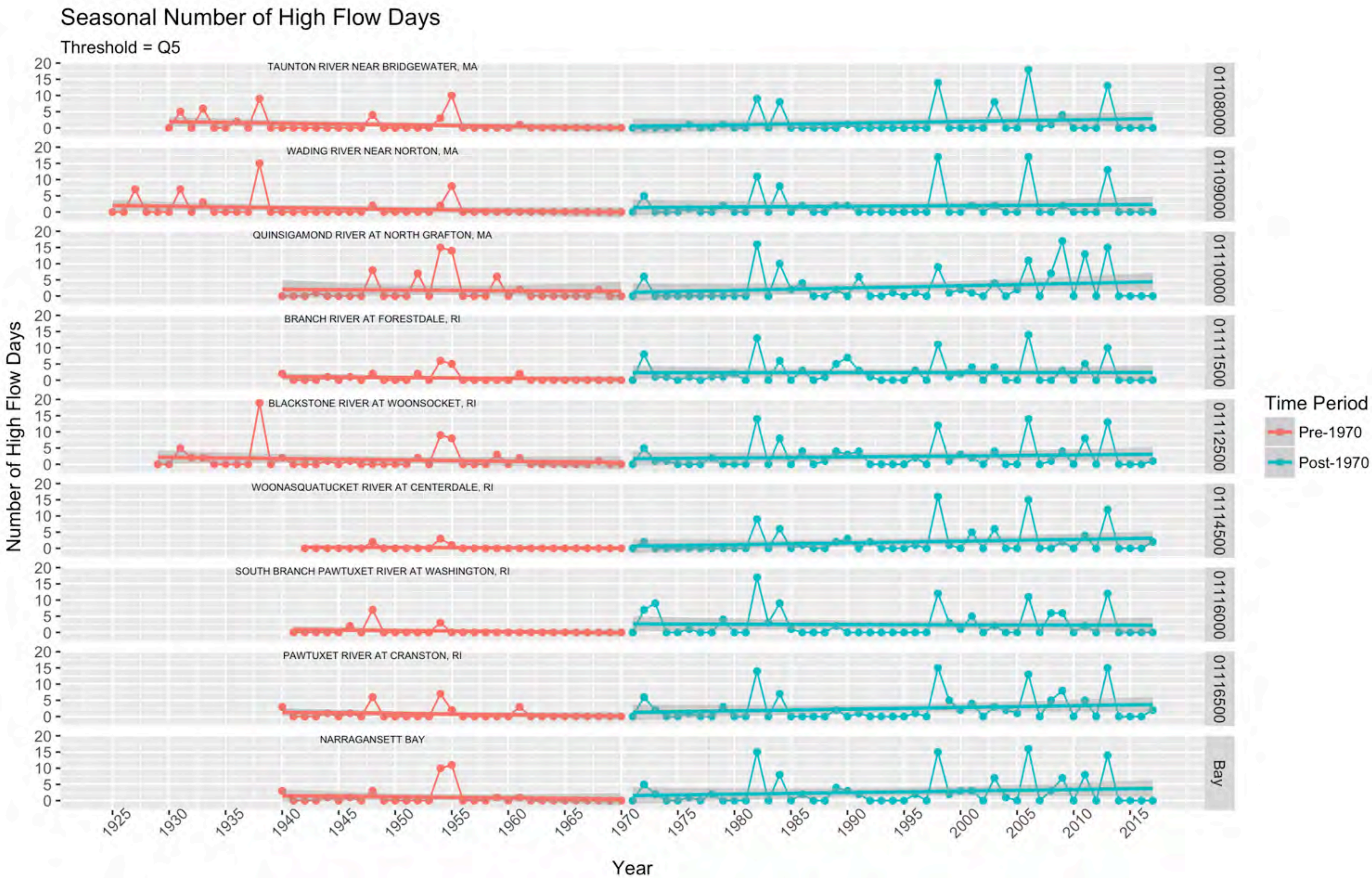


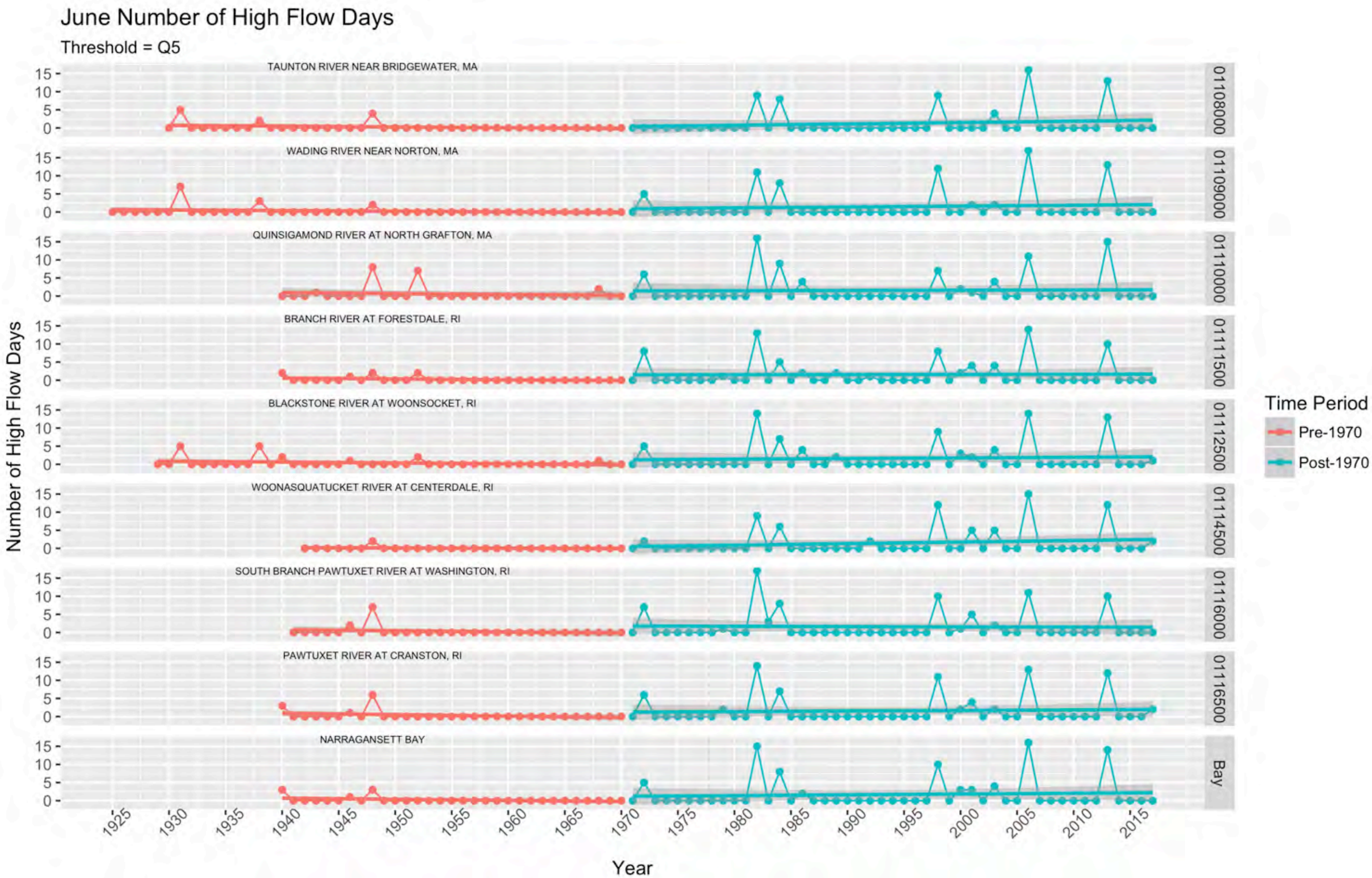

Seasonal Mean of High Flow Days (cfs)
Threshold = Q5
TAUNTON RIVER NEAR BRIDGEWATER, MA
WADING RIVER NEAR NORTON, MA
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
BRANCH RIVER AT FORESTDALE, RI
BLACKSTONE RIVER AT WOONSOCKET, RI
WOONASQUATUCKET RIVER AT CENTERDALE, RI
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
PAWTUXET RIVER AT CRANSTON, RI
NARRAGANSETT BAY
01108000
01109000
01110000
01111500
01112500
01114500
01116000
01116500
Bay
Mean of High Flow Days (cfs)
Year
Time Period
Pre-1970
Post-1970



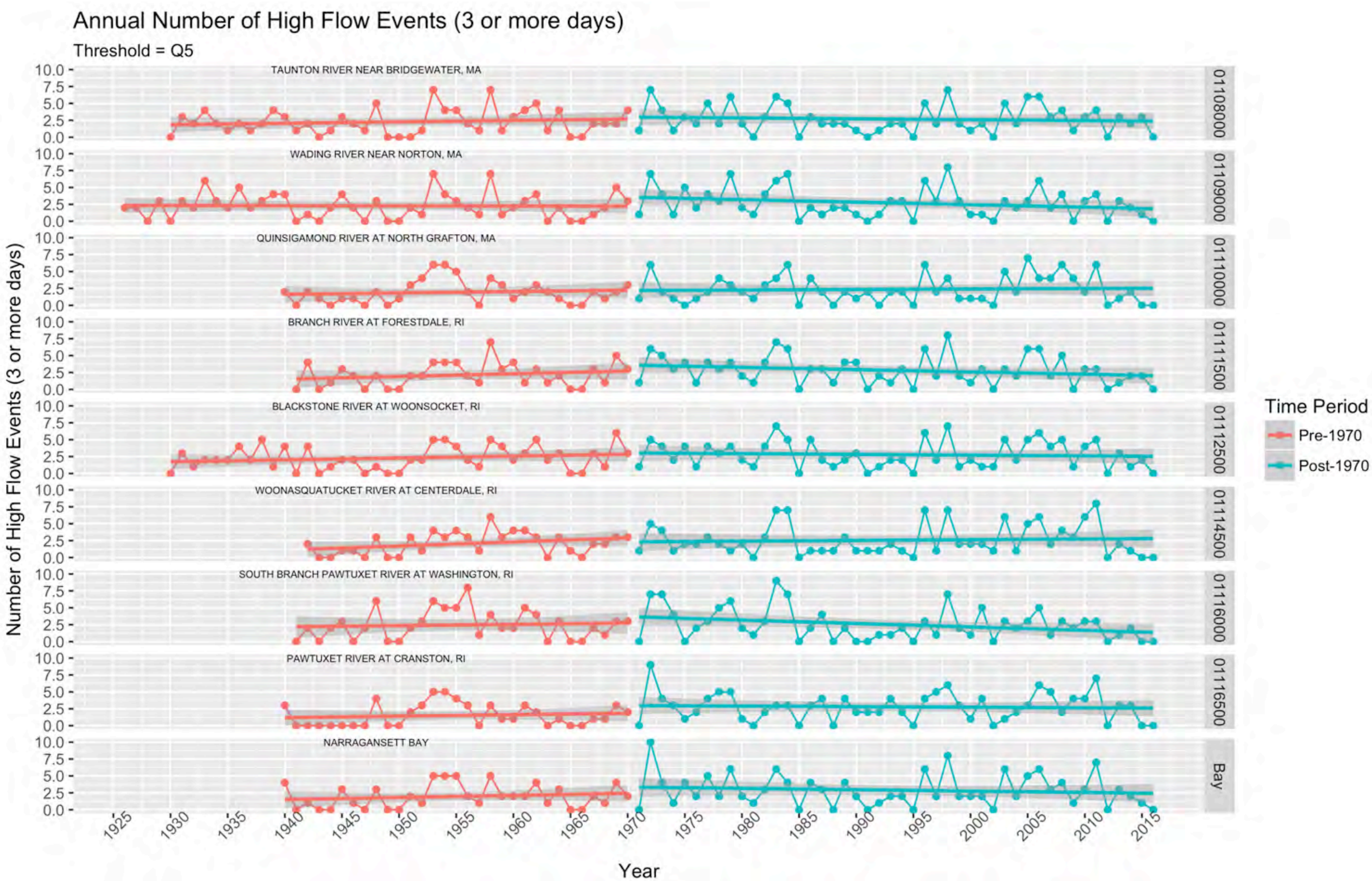
June Mean of High Flow Days (cfs)
Threshold = Q5
TAUNTON RIVER NEAR BRIDGEWATER, MA
WADING RIVER NEAR NORTON, MA
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
BRANCH RIVER AT FORESTDALE, RI
BLACKSTONE RIVER AT WOONSOCKET, RI
WOONASQUATUCKET RIVER AT CENTERDALE, RI
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
PAWTUXET RIVER AT CRANSTON, RI
NARRAGANSETT BAY
01108000
01109000
01110000
01111500
01112500
01114500
01116000
01116500
Bay
Mean of High Flow Days (cfs)
Year
Time Period
Pre-1970
Post-1970


Annual Number of High Flow Days
Threshold = Q5
TAUNTON RIVER NEAR BRIDGEWATER, MA
01108000
WADING RIVER NEAR NORTON, MA
01109000
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
01110000
BRANCH RIVER AT FORESTDALE, RI
01111500
BLACKSTONE RIVER AT WOONSOCKET, RI
01112500
WOONASQUATUCKET RIVER AT CENTERDALE, RI
01114500
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
01116000
PAWTUXET RIVER AT CRANSTON, RI
01116500
NARRAGANSETT BAY
Bay
Number of High Flow Days
Year
Time Period
Pre-1970
Post-1970

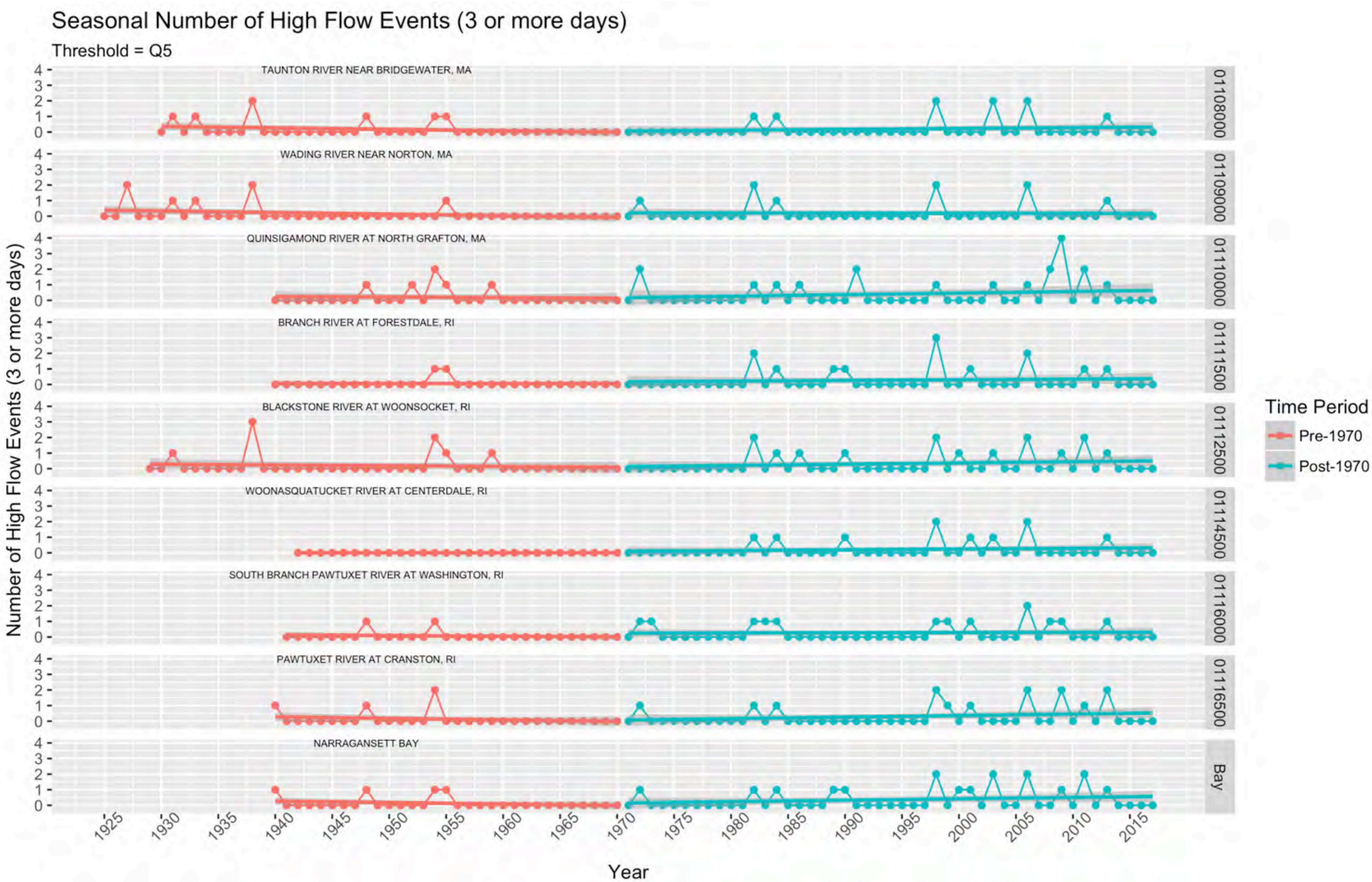

Seasonal Number of High Flow Days
Threshold = Q5
TAUNTON RIVER NEAR BRIDGEWATER, MA
WADING RIVER NEAR NORTON, MA
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
BRANCH RIVER AT FORESTDALE, RI
BLACKSTONE RIVER AT WOONSOCKET, RI
WOONASQUATUCKET RIVER AT CENTERDALE, RI
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
PAWTUXET RIVER AT CRANSTON, RI
NARRAGANSETT BAY
01108000
01109000
01110000
01111500
01112500
01114500
01116000
01116500
Bay
Number of High Flow Days
Year
Time Period
Pre-1970
Post-1970



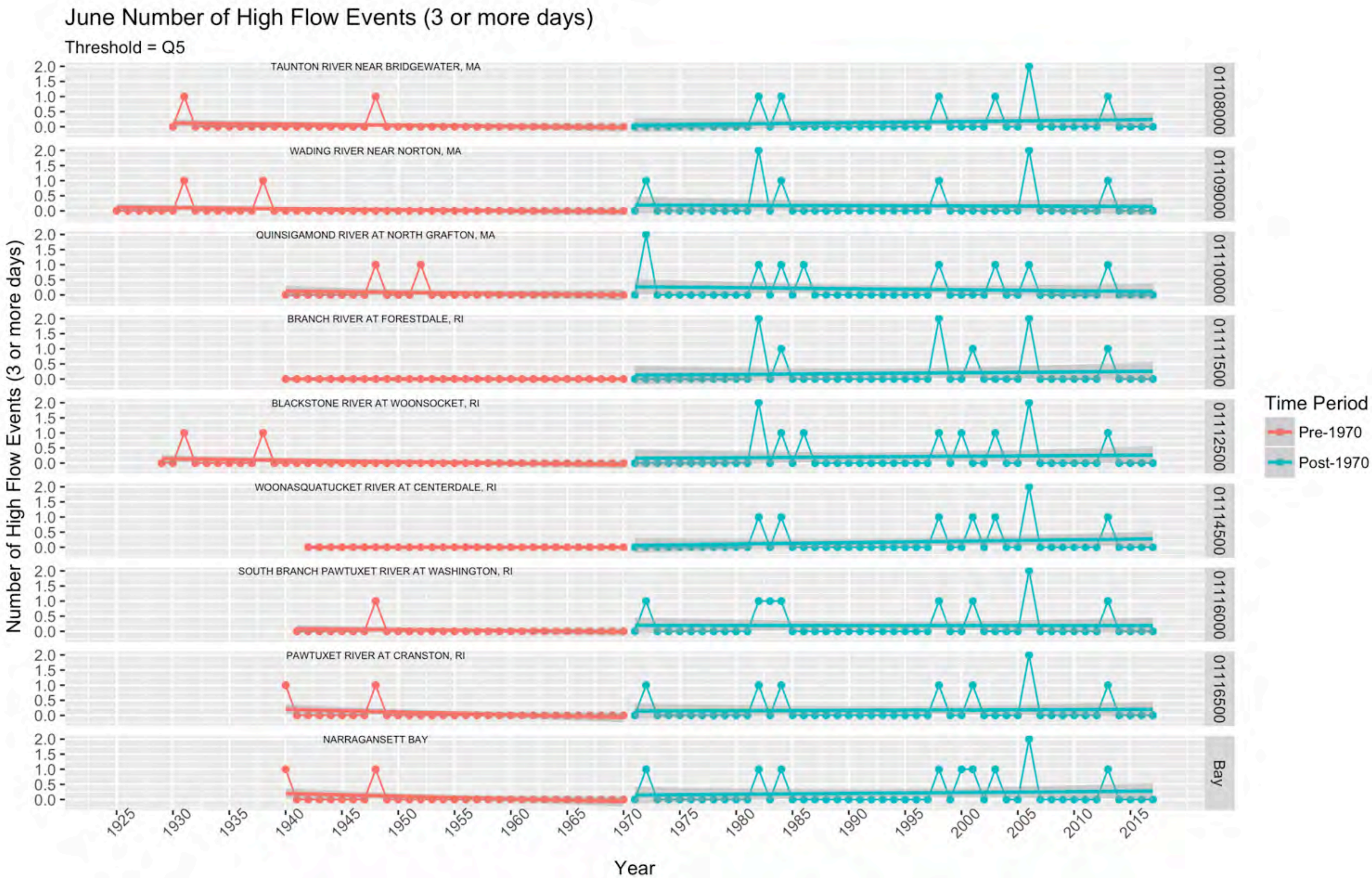
June Number of High Flow Days
Threshold = Q5
TAUNTON RIVER NEAR BRIDGEWATER, MA
WADING RIVER NEAR NORTON, MA
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
BRANCH RIVER AT FORESTDALE, RI
BLACKSTONE RIVER AT WOONSOCKET, RI
WOONASQUATUCKET RIVER AT CENTERDALE, RI
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
PAWTUXET RIVER AT CRANSTON, RI
NARRAGANSETT BAY
01108000
01109000
01110000
01111500
01112500
01114500
01116000
01116500
Bay
Number of High Flow Days
Year
Time Period
Pre-1970
Post-1970



Annual Number of High Flow Events (3 or more days)
Threshold = Q5
TAUNTON RIVER NEAR BRIDGEWATER, MA
WADING RIVER NEAR NORTON, MA
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
BRANCH RIVER AT FORESTDALE, RI
BLACKSTONE RIVER AT WOONSOCKET, RI
WOONASQUATUCKET RIVER AT CENTERDALE, RI
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
PAWTUXET RIVER AT CRANSTON, RI
NARRAGANSETT BAY
01108000
01109000
01110000
01111500
01112500
01114500
01116000
01116500
Bay
Number of High Flow Events (3 or more days)
Year
Time Period
Pre-1970
Post-1970



Seasonal Number of High Flow Events (3 or more days)
Threshold = Q5
TAUNTON RIVER NEAR BRIDGEWATER, MA
01108000
WADING RIVER NEAR NORTON, MA
01109000
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
01110000
BRANCH RIVER AT FORESTDALE, RI
01111500
BLACKSTONE RIVER AT WOONSOCKET, RI
01112500
WOONASQUATUCKET RIVER AT CENTERDALE, RI
01114500
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
01116000
PAWTUXET RIVER AT CRANSTON, RI
01116500
NARRAGANSETT BAY
Bay
Number of High Flow Events (3 or more days)
Year
Time Period
Pre-1970
Post-1970


June Number of High Flow Events (3 or more days)
Threshold = Q5
TAUNTON RIVER NEAR BRIDGEWATER, MA
WADING RIVER NEAR NORTON, MA
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA
BRANCH RIVER AT FORESTDALE, RI
BLACKSTONE RIVER AT WOONSOCKET, RI
WOONASQUATUCKET RIVER AT CENTERDALE, RI
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI
PAWTUXET RIVER AT CRANSTON, RI
NARRAGANSETT BAY
01108000
01109000
01110000
01111500
01112500
01114500
01116000
01116500
Bay
Number of High Flow Events (3 or more days)
Year
Time Period
Pre-1970
Post-1970