Effects of Climate Nonstationarity on Low-Flow Models for Southern New England

Author: Benjamin Daniels

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EFFECTS OF CLIMATE NONSTATIONARITY ON LOW-FLOW MODELS FOR SOUTHERN NEW ENGLAND

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BENJAMIN JUDAH DANIELS

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Abstract

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for Southern New England

Benjamin J. Daniels

Advisor: Dr. Noah Snyder

Increasing attention has been drawn to the need for reliable streamflow estimates at ungaged locations under a range of climatic and hydrologic conditions. Climate projections for the northeastern United States over the 21st century—which include significant increases in temperature and precipitation—could have broad impacts on streamflows, potentially reducing the accuracies of existing streamflow models for the region. This thesis investigates recent changes in daily flow-durations in southern New England, and examines their influence on the reliability of the low-flow models for Massachusetts presented by Ries and Friesz (2000). An analysis of discharge data collected at gaging sites through water year 2012 revealed increases in nearly all flow durations at sites across southern New England since the mid-20th century, whereas very low flows (quantiles at or above the 95-percent exceedance probability) generally showed decreases, especially since the 1990s.

Twenty-year moving streamflow quantiles at each of ten selected exceedance probabilities were examined for the periods of record of 16 streamflow-gaging stations in southern New England. The beginning of water year 1992 appeared to mark an inflection point in low-flow quantiles, before which very low flows were steady or increasing, and after which these flows showed near-universal decreases. While the observed peak in 20-year low-flow quantiles around 1992 may be due to the statistical method used to calculate the quantile trends,

the inflection point could also be an indicator of when increasing evapotranspiration surpassed increasing precipitation as the principal climatic driver of changes in low flows in southern New England. The general upward translation of the flow-duration curve observed over the last 60 years is very likely linked to increases in annual precipitation during this period, while the decreases in very low flows are likely due to changes in climatic variables (increasing summer temperatures and evapotranspiration rates), and amplified by anthropogenic factors (greater areas of impervious surfaces and increasing rates of surface- and ground-water withdrawal).

The data suggest that increasing precipitation rates have already caused the Ries and Friesz (2000) equations for the median low flows (Q50 to Q75) to become biased towards underestimation, and decreases in very low flows threaten to render the models for these flows biased towards overestimation in the coming decades. The streamflow quantile trends (for both the entire period of record of the gaging stations and just the post-1992 period) for each of the ten flow-durations of interest were extended into the future to the point where the corresponding Ries and Friesz (2000) model would fail (when actual flow durations would be outside the 90-percent prediction intervals for the estimated flows for greater than 10% of sites). The models for the lowest streamflows are estimated to lose validity by as early as 2018. Climate change is predicted to have significant effects on streamflow characteristics in southern New England over the 21st century, and the results of this study indicate that the Ries and Freisz (2000) low-flow models should be reformulated using more recent streamflow data within the next decade, and validated every 20 years thereafter to ensure their accuracies are maintained despite the effects of regional nonstationarity.

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Introduction

The development of methods for estimating streamflows in ungaged catchments has been an active area of research in hydrology for several decades (Dingman, 1972; Cervione et al., 1982; Fennessey and Vogel, 1990; Ries and Friesz, 2000; Ahearn, 2010). The transfer of streamflow statistics from gaged to ungaged stream sites facilitates effective water resources management, flood protection, pollution control, land-use planning, and environmental conservation. Attention has recently been drawn to the need for streamflow estimates at ungaged locations under a variety of climatic and hydrologic conditions. In 2003, the International Association of Hydrological Sciences launched the Predictions in Ungauged Basins Initiative to encourage collaborative research toward reducing uncertainty in hydrological predictions (Sivapalan et al., 2003). The Hydrology Laboratory of the National Weather Service recently established the Distributed Model Intercomparison Project to compare hydrologic models and improve river forecasting methods (Smith et al., 2004). Growing demands on global surface-water resources and the vulnerability of those resources to the impacts of climate change have brought increasing attention to the need for reliable streamflow models in the 21st century (Vörösmarty et al., 2000; IPCC, 2007; Kundzewicz et al., 2008).

Water resource managers have traditionally operated under the assumption of stationarity, the idea that natural systems fluctuate within an unchanging range of variability (Milly et al., 2008). Under stationarity, model estimation errors are assumed to be reducible by additional observations or more accurate estimators (Milly et al., 2008). Global climate change has rendered the stationarity assumption false by applying external forcing on naturally climate-integrated systems, pushing their envelopes of variability (IPCC, 2007). Changes in Earth's climate—including alterations in the means and extremes of precipitation, temperature, evapotranspiration, and humidity—are having substantial impacts on the runoff rates of unregulated watersheds, leading to greater frequency and severity of flood and low-flow events (Hayhoe et al., 2007; IPCC, 2007; USGCRP, 2009). These hydroclimatic changes will pose new challenges to water managers as they design and implement plans that incorporate nonstationarity, now recognized as a fundamental characteristic of our planet's climate system.

Numerous studies have shown trends in regional climate indicators that signal future changes in climate in the northeastern US (Schwartz et al., 2006; Frumhoff et al., 2007; Hayhoe et al., 2007; Hayhoe et al., 2008; Guerra and Boutt, 2009; USGCRP, 2009). Increases in temperature and precipitation in the region over the last century have been directly measured, and are evidenced by changes in many natural climate indicators, including last-frost dates, snow depth, bloom dates, snow-rain ratios, growing season durations, and lake ice-out dates (e.g., Hodgkins et al., 2003; Hodgkins et al., 2005; Hayhoe et al., 2007; Dudley et al., 2010). Hydroclimatic projections for New England over the 21st century indicate higher annual precipitation but relatively unchanged summer rainfall, increases in the magnitude and frequency of flood flows, increases in temperature during all seasons, and longer periods of drought between rainfall events (Hayhoe et al., 2007; Hayhoe et al., 2008; Collins, 2009; USGCRP, 2009; Dudley et al., 2010; Betts, 2011; Campbell et al., 2011; Armstrong et al., 2012; Armstrong et al., 2013). Because the dynamics of hydrologic systems are driven by climate variables, nonstationarity will be directly reflected by changes in the flow regimes of unregulated streams, with far-reaching consequences for aquatic biota and for people who live near or exploit surface waters (Hodgkins and Dudley, 2005). Evidence of a hydroclimatic shift around 1970 has been found by Armstrong et al (2012) and others, who examined flood flows in New England and found a significant increase their magnitudes and frequency around 1970.

Conflicts between water supply and demand are most likely to occur during periods of prolonged dry weather, when the flow of water in streams is at its lowest (Smakhtin, 2001). Low-flow statistics describe the relationship between low flow magnitude and frequency at a location on a stream, e.g., the 7-day, 10-year low flow (the 7-day low flow with a 10-year return period) or the 95-percent duration flow (the daily streamflow equaled or exceeded 95% of the time). These statistics are needed by federal, state, and local agencies for a range of water-use planning, management, and regulatory activities, including (1) developing environmentally sound watershed management plans, (2) siting and permitting new water withdrawals, interbasin transfers, and effluent discharges, (3) determining minimum streamflow thresholds to maintain aquatic habitats, and (4) land-use planning and regulation (Ries and Friesz, 2000). Low-flow statistics are also needed by commercial and industrial facilities to determine availability of water for water supply, wastewater returns, and hydropower generation.

Low-flow statistics can be computed from streamflow data collected at gaging stations with sufficiently long periods of record, but statistics are often needed at locations where no such data exist. As a result, a number of methods have been developed to estimate streamflow statistics at ungaged sites, the most common of which is regional regression analysis. In a U.S. Geological Survey (USGS) Water-Resources Investigations Report, Ries and Friesz (2000) presented regression equations for estimating flow-duration and low-flow frequency statistics for ungaged, natural-flow streams in Massachusetts, based on measurements of daily streamflow made at gaging stations prior to climatic year 1996. The resulting equations are currently used by the USGS to estimate low-flow statistics for ungaged stream reaches in Massachusetts, and have been incorporated into StreamStats, a GIS-based Web application developed by the USGS for obtaining streamflow estimates for user-selected sites. Nonstationarity threatens to decrease the accuracies of the Ries and Friesz (2000) regression models as southern New England watersheds respond to potentially significant changes in precipitation and temperature over the 21^{st} century, thus making the models obsolete.

Purpose and Scope

This thesis investigates changes in low flow-durations (quantiles of daily streamflow) in southern New England watersheds, and examines their effects on the accuracies of the Ries and Friesz (2000) regression models for natural, long-term streamflows in Massachusetts. Historical daily streamflow time series from gaging stations in Massachusetts and adjacent states are analyzed, and the Ries and Friesz (RF) estimation equations are tested using observed flow-duration curves (FDCs) from selected periods of record. Potential trends in flow-durations in southern New England catchments are evaluated towards projecting the future reliability of the RF models.

Five research questions are addressed by this work:

1. How well do the RF regression methods estimate streamflow for the period since 1995, when they were developed, both within Massachusetts and in adjacent states?
2. How do the pre- and post-1996 flow-duration curves compare for unregulated streams in southern New England?
3. Following on the work of Armstrong et al. (2012), how do low-flow quantiles compare for the periods before 1970, after 1970, between 1970 and 1996, and after 1996?
4. What are the trends in low-flow quantiles for gages with more than 60 years of record, and what do they suggest about future streamflows in southern New England?
5. Given the observed trends in low-flow quantiles, when can the RF equations expected to no longer be valid?

The answers to these research questions are pursued in four parts:

- Part I is an analysis of 15 streamflow-gaging stations used in the RF regression analyses, and is divided into two subsections: a comparison of pre- and post-1996 FDCs, and an evaluation of model performance at the 15 sites for the post-1996 period.
- Part II is an analysis of 21 streamflow-gaging stations in southern New England not used in the RF regressions, and is similarly divided into two subsections: a comparison of pre- and post-1996 FDCs, and an evaluation of model performance at the 21 sites for the post-1996 period.
- Part III is an examination of changes in flow-durations over time at 17 stations in southern New England with more than 60 years of record, using 1970 and 1996 as cut dates to divide the periods used to compute the FDCs.
- Part IV is an analysis of trends in 20-year streamflow quantiles for 16 stations in southern New England with more than 60 years of continuous record, with the intention of projecting trends in streamflow quantiles and estimating future accuracies for the RF models.

In addition to evaluating the effects of nonstationarity on the RF regression equations, this thesis explores an expanded geographic applicability for the models by applying them to a set of streamflow-gaging stations in states bordering Massachusetts, primarily Connecticut and Rhode Island. An assessment of the RF models is warranted because these methods are used by the USGS and other public and private entities for a range of design and planning applications, and because projected climate trends suggest that the streamflow models will grow increasingly less accurate in the 21st century as New England watersheds respond to changes in climate variables.

Background

The Flow-Duration Curve

Streamflow—or discharge (Q)—is defined as the volume rate of flow of water in a channel, including any sediment or other solids suspended or dissolved in it (Buchanan and Somers, 1969). Streamflow is typically expressed in cubic feet per second (cfs), cubic meters per second, or million gallons per day[1] (Buchanan and Somers, 1969). Continuous measurements of daily mean streamflow at a gaging site can be assembled into a flow-duration curve (FDC), which represents the relationship between the magnitude and frequency of streamflows over a specified period (Figure 1). An FDC is the complement of the cumulative

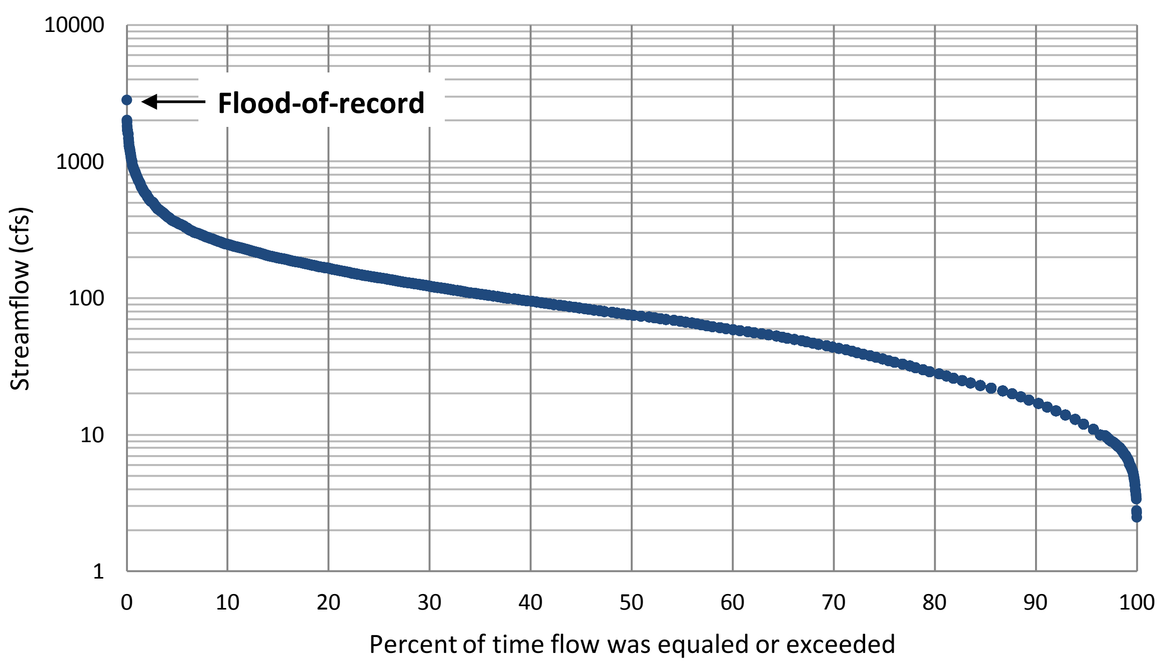

Figure 1. Daily flow-duration curve for the USGS streamgage on the North Nashua River at Fitchburg, MA, for water years 1981-2005. (A water year begins October 1 and ends September 30 of the year specified.)

[1] Because the USGS measures streamflow in units of cfs, and because the streamflow estimation equations investigated in this thesis use United States customary units as inputs and outputs, streamflows in this thesis are given in units of cfs. 1 cfs is 0.0283 cubic meters per second.

distribution function of daily streamflow. When the period of record used to construct an FDC is sufficiently long (typically at least 10 years), the points along the curve are used as an indicator of the long-term exceedance probabilities of the specified discharges (Searcy, 1959). An FDC provides a simple, yet comprehensive graphical view of the overall historical variability of streamflow at a site, without regard to sequence of occurrence (Fennessey, 1994).

The points along an FDC are flow-durations, or exceedance quantiles. For example, the 95-percent duration flow (Q95) is the daily mean streamflow that is equaled or exceeded 95-percent of the time. Flow durations are calculated by first sorting the observed daily mean streamflows for a period of record from largest to smallest and assigning each streamflow value a rank, starting with 1 for the largest value (Ahearn, 2008). The frequency of exceedance for each flow value is then computed using the Weibull plotting position formula (Helsel and Hirsch, 2002):

$$P = 100 * [M/(n+1)] \ , \qquad (1)$$

where P is the percent of time that a given flow was equaled or exceeded at the site, M is the ranked position of the streamflow value, and n is the number of observed streamflows for the period of record. If a sufficiently long period of record is used to construct the FDC, then the value P for a specified streamflow represents the long-term exceedance probability for that flow (Searcy, 1959).

The first use of an FDC is commonly attributed to Clemens Herschel in about 1880 (Foster, 1934). Their widespread use in the early 20th century is evidenced by Foster's (1934) description of FDCs as one of the most important graphical tools available to the hydrologist. The characteristics of FDCs in North Carolina and Ohio were summarized by Saville and Watson (1933) and Cross and Bernhagen (1949), respectively. Perhaps the most comprehensive manual on the construction, interpretation, and application of FDCs was written by Searcy (1959). Numerous studies have developed regional procedures for estimating daily FDCs at ungaged locations in southern New England (Dingman, 1978; Male and Ogawa, 1982; Fennessey and Vogel, 1990; Ries, 1994a, 1994b; Dingman and Lawlor, 1995; Ries and Friesz, 2000; Flynn, 2003; Archfield et al., 2007; Ahearn, 2010). The FDC has a wide range of regulatory, planning, and design applications and remains an extremely important tool in hydrologic research.

Regional Regression Analysis

Regional regression modeling is one of the most widely used techniques for estimating streamflow statistics at ungaged sites (Smakhtin, 2001). In multiple linear regression analysis (regression analysis), a streamflow statistic (the dependent variable) for a group of streamflow-gaging stations is statistically related to one or more physical or climatic characteristics of the upstream drainage basins for those stations (the independent variables). The resulting equations enable the transfer of streamflow statistics from gaged to ungaged sites by determining the basin characteristics for the ungaged site used as explanatory variables in the regression equations, and solving the equations based on these input values. The USGS has used regression analysis to develop equations for estimating streamflow statistics at ungaged sites for every state, Puerto Rico, and the island of Tutuila, American Samoa (Ries, 2007).

Equations can be developed by use of several different regression analysis algorithms (Ries and Friesz, 2000). The various algorithms use different methods for minimizing the differences between the values of the dependent variable for the stations used in the analysis (the observed values) and the corresponding values given by the resulting regression equation (the estimated or fitted values) (Ries and Friesz, 2000). The choice of one algorithm over another depends on the characteristics of the data used in the analysis and on the underlying assumptions for use of the algorithm (Ries and Friesz, 2000).

Equations obtained by use of regression analysis take the general form

$$Y_i = b_0 + b_1X_1 + b_2X_2 + \cdots + b_nX_n + \varepsilon_i \ , \tag{2}$$

where Y_i is the estimate of the dependent variable for site i, X_1 to X_n are the n independent variables, b_0 to b_n are the n + 1 regression model coefficients, and ε_i is the residual error (the difference between the observed and estimated value of the dependent variable) for site i. Assumptions for the use of regression analysis are (1) the mean of the ε_i is zero, (2) the ε_i are normally distributed, (3) the variance of the ε_i is constant and independent of the values of X_n, and (4) the ε_i are independent of each other (Ries and Friesz, 2000).

Measured streamflow and basin characteristics used in hydrologic regression are typically log-normally distributed (Ries, 1994b). Logarithmic transformation of the variables is therefore necessary to linearize the relations between the dependent and independent variables and to normalize the distributions of the residual errors, satisfying assumptions 1 and 2. Logarithmic (base 10) transformation results in an equation of the form

$$\log Y_i = b_0 + b_1 \log X_1 + b_2 \log X_2 + \cdots + b_n \log b_n + \varepsilon_i \ , \tag{3}$$

or, after retransforming by taking antilogs to obtain the algebraically equivalent form

$$Y_i = 10^{b_0}\left({X_1}^{b_1}\right)\left({X_2}^{b_2}\right) \ldots \left({X_n}^{b_n}\right)10^{\varepsilon_i} \ . \tag{4}$$

In the early 1970s, the USGS began using ordinary least squares (OLS) regression to estimate the parameters of regional low-flow regression models (Thomas and Benson, 1970). However, hydrologic data commonly violate the assumption that the residual errors associated with the streamflow observations are constant and independently distributed (assumption 3), and regional streamflow data from a group of gaging stations will typically vary in length of record and may be spatially correlated for concurrent flows (violating assumption 4) (Stedinger and Tasker, 1985). To address these deficiencies, Tasker (1980) proposed the use of weighted least squares (WLS) regression for regionalization of streamflow statistics, in which weights are assigned proportional to record length and inversely proportional to the variances of the observed streamflow statistics for the gaging stations. WLS regression accounts for differences in record lengths among the stations used in the analysis, and has been shown to yield greater accuracy in results when compared to OLS procedures for hydrologic regression (Tasker and Stedinger, 1986).

Both OLS and WLS regression do not compensate for possible cross-correlation of concurrent streamflow records between sites; the spatial correlation of streamflows causes bias in the estimated coefficients of the parameters and in the estimated variance of the regression equations (Ries, 2007). The problem is particularly significant where streamgages are located on the same stream, or in similar or adjacent watersheds (Jennings et al., 1994). Generalized least squares (GLS) regression was proposed by Stedinger and Tasker (1985, 1986) to account for both the differences in record length and the possible correlation of streamflow statistics among gaging stations used in the analysis. GLS analysis allows the prediction error for ungaged sites to be partitioned into model error and sampling error, and has been demonstrated to provide more accurate estimates of regression coefficients and better estimates of model error than OLS procedures (Stedinger and Tasker, 1985). Because GLS was developed specifically for regression with flow-frequency statistics, however, it requires substantial extra effort for use with flow-duration statistics (Ries and Friesz, 2000).

GLS regression is theoretically the most appropriate for use in streamflow regionalization, but its superiority compared to WLS is marginal under certain circumstances, depending on the characteristics of the streamflow data used (Tasker and Stedinger, 1989). Stedinger and Tasker (1985) concluded that the WLS procedure performs nearly as well as GLS analysis when cross-correlations are modest and when standard errors are high. In a study to develop regional regression equations for estimating low-flow frequencies in Massachusetts, Vogel and Kroll (1990) found that cross-correlation of the data they used in their analysis was only 0.35, and therefore equations for predicting low-flow statistics for Massachusetts streams using WLS should have model precision that is nearly the same as equations developed using GLS. Moreover, the weights assigned to stations used in WLS analysis can be easily adjusted if necessary to compensate for non-constant variance of the regression residuals (Ries and Friesz, 2000). The current USGS state streamflow estimation equations are based on either WLS or GLS regression, although the GLS technique is the more popular of the two (Ries, 2007).

Low-Flow Hydrology in Southern New England

In 2005, an average of 3.5 billon liters per day of freshwater was withdrawn from streams and rivers in Massachusetts for various uses, including public water-supply, irrigation, and industrial activities (Kenny et al., 2009). The eastern one-third of the state, where about 75 percent of the population resides, is particularly vulnerable to water-supply shortages during droughts (Ries, 1994a). Estimates of low-flow indices are used by state agencies, consultants, local planners, and engineers for planning and management of activities related to water resources, such as waste-load allocation, aquatic habitat protection, water-supply management, and siting of treatment plants and sanitary landfills (Wandle and Randall, 1994). Low-flow estimates are also used to make decisions regarding interbasin transfers, withdrawals for water supply, and minimum downstream-release requirements for hydropower, irrigation, and cooling-plant facilities (Risley, 1994).

The lowest streamflows in Massachusetts typically occur in July, August, and September because of the combined effects of evapotranspiration and aquifer depletion (Simcox, 1992; Armstrong et al., 2008). Except during and for a short time after storm events, summertime streamflows in Massachusetts are derived from groundwater discharged by aquifers in unconsolidated deposits adjacent to streams (baseflow) (Ries and Friesz, 2000). Numerous regression studies in New England have found drainage area to be the variable most highly correlated with low-flow statistics (Fennessey and Vogel, 1990; Vogel and Kroll, 1990; Risely, 1994; Ries and Friesz, 2000; Archfield et al., 2007; Ahearn, 2010). Differences in the magnitude of streamflow per unit basin area in southern New England have been found to be a function of differences in various geologic and topographic characteristics of the drainage basin, including area of stratified drift deposits (Ries, 1994a, 1994b; Archfield et al., 2007; Ahearn, 2010), area of lakes and swamps (Wandle and Randall, 1994), area of forest land (Hornbeck et al., 1993, 1997), mean basin slope (Vogel and Kroll, 1992; Ries and Friesz, 2000), and basin relief (Fennessey and Vogel, 1990; Vogel and Kroll, 1990; Risely, 1994).

Methods for Estimating Low-Flow Statistics for Massachusetts Streams

The USGS report by Ries and Friesz (2000) entitled "Methods for Estimating Low-Flow Statistics for Massachusetts Streams" is the last of six reports in the Basin Yield study series. The Basin Yield studies, begun in 1988 in cooperation with the Massachusetts Department of Environmental Management, Office of Water Resources, were carried out to develop and evaluate methods for estimating low-flow statistics for ungaged stream sites in Massachusetts. The first three reports describe the development of equations for estimating low-flow statistics for ungaged sites (Ries, 1994a; Ries, 1994b; Ries, 1997). The forth report describes and provides data for the network of 148 low-flow partial-record (LFPR) stations that was operated in Massachusetts during the summers of 1989 through 1996 (Ries, 1999). The fifth report is a USGS Fact Sheet that describes Massachusetts StreamStats, a Web application for obtaining basin characteristics and streamflow estimates for user-selected sites in the state (Ries et al., 2000).

In the final Basin Yield studies report, Ries and Friesz (2000) describe methods for estimating flow-durations, low-flow frequency statistics, and August median flows for unregulated Massachusetts streams. Regression equations were developed to estimate the natural, long-term 99-, 98-, 95-, 90-, 85-, 80-, 75-, 70-, 60-, and 50-percent duration flows; the 7-day, 2-year (7Q2) and 7-day, 10-year (7Q10) low flows; and the median August flow for ungaged sites in Massachusetts. These equations have been incorporated into Massachusetts StreamStats, a GIS-based Web application for obtaining streamflow estimates for user-selected sites in Massachusetts, available online (http://streamstats.usgs.gov/massachusetts.html). This thesis focuses on the regression models developed by Ries and Friesz (2000) to estimate ten streamflow quantiles on the lower half of the flow-duration curve at ungaged sites (Table 1).

Statistic	Equation
Q_{50}	$0.955(DA)^{1.020}$
Q_{60}	$0.763(DA)^{1.050}(DR/ST+0.1)^{0.123}$
Q_{70}	$0.607(DA)^{1.070}(DR/ST+0.1)^{0.357}10^{0.121(REG)}$
Q_{75}	$0.509(DA)^{1.080}(DR/ST+0.1)^{0.432}10^{0.158(REG)}$
Q_{80}	$0.507(DA)^{1.060}(SL)^{0.191}(DR/ST+0.1)^{0.693}10^{0.145(REG)}$
Q_{85}	$0.365(DA)^{1.080}(SL)^{0.255}(DR/ST+0.1)^{0.746}10^{0.159(REG)}$
Q_{90}	$0.329(DA)^{1.080}(SL)^{0.396}(DR/ST+0.1)^{0.985}10^{0.160(REG)}$
Q_{95}	$0.171(DA)^{1.120}(SL)^{0.457}(DR/ST+0.1)^{0.999}10^{0.190(REG)}$
Q_{98}	$0.116(DA)^{1.130}(SL)^{0.412}(DR/ST+0.1)^{1.030}10^{0.247(REG)}$
Q_{99}	$0.082(DA)^{1.160}(SL)^{0.427}(DR/ST+0.1)^{1.050}10^{0.255(REG)}$

Table 1. Regression equations developed by Ries and Friesz (2000) to estimate ten flow-durations at ungaged sites in Massachusetts. Q_{xx} is the xx-percent duration flow in cubic feet per second; *DA* is drainage area (square miles); *SL* is mean basin slope (percent); *DR/ST* is area of stratified drift per unit of total stream length (square miles per mile); and *REG* is hydrologic region (0 for eastern, 1 for western).

These flow-durations were regressed against measured basin characteristics at continuous-record streamflow-gaging and LFPR stations in Massachusetts and adjacent states in southern New England. The basin characteristics that were statistically significant in most or all of the final regression equations were drainage area, area of stratified drift deposits per unit stream length plus 0.1, mean basin slope, and an indicator variable that was 0 in the eastern region and 1 in the western region of Massachusetts. These selected explanatory variables are essentially unchanging physical basin attributes, and do not include climate indices that could account for the effects of nonstationarity.

The independent variables used in a regression analysis are typically chosen using a variable-selection algorithm that determines which combination of independent variables provides the best estimates of the dependent variable. Ries and Friesz (2000) used an algorithm that considers all possible combinations of the independent variables and ranks them with minimization of Mallows' C_p as the selection criterion. Mallows' C_p is a statistic used to assess the fit of a regression model and select predictor variables for which the amount of model overfitting and/or underfitting is minimized (Mallows, 1973). The selected subsets of independent variables were then analyzed by use of weighted least squares regression analysis, with weights assigned proportional to the years of record and inversely proportional to the variances of the computed streamflow statistics for the stations (Ries and Friesz, 2000).

In a regression analysis, equation 3 above provides unbiased estimates of the mean response of the dependent variable, meaning that the expected value of ε_i is zero (Ries and Friesz, 2000). However, retransformation of logarithm-base 10 estimates to estimates in their original units of measure using equation 4 predicts the median rather than the mean response of the dependent variable, and thus is biased. For streamflow data, the median tends to be lower than the mean (Ries and Friesz, 2000). A bias-correction factor (BCF) developed by Bradu and Mundlak (1970) has been shown to be optimal when the residual errors are normally distributed (Cohn et al., 1989). This BCF provides minimum variance unbiased estimates (MVUE) of the dependent variable, and has the advantage of being unbiased regardless of the number of stations used in the analysis (Ries and Friesz, 2000). Ries and Friesz (2000) employed the MVUE BCF in their final regression equations.

The independent variables selected for the final equations were required to be statistically significant at the 95-percent confidence level, and the signs and magnitudes of the coefficients had to be hydrologically reasonable (for example, larger drainage areas would be expected to produce higher streamflows; Ries and Friesz, 2000). The basin characteristics considered in the regression analyses were selected based on their theoretical relation to differences in streamflow magnitudes, results of previous hydrologic studies in southern New England, and on the ability to measure them (Ries and Friesz, 2000). Only physical basin characteristics were considered in the regressions, resulting in models that could be employed without reference to rainfall or other climate data. The characteristics measured for use in the regressions were drainage area; area of stratified drift, wetlands, and water bodies; total stream length; maximum, minimum, and mean basin elevation; maximum, minimum, and mean elevation in stratified drift; and mean basin slope. Several additional basin characteristics were determined using combinations of the measured characteristics. For example, drainage density was considered as a potentially significant explanatory variable in the analyses, computed by dividing the total stream length by the drainage area (Ries and Friesz, 2000).

Ries and Friesz (2000) determined flow-duration statistics and basin characteristics for 37 continuous-record streamflow-gaging stations and 107 LFPR stations for use in the regression analyses (Figure 2). The stations included in the analyses monitored streamflows that were considered to be essentially unregulated during low streamflow periods. Discharge records through climatic year 1995 were used to compute the flow durations for the gaging stations. (A climatic year is the 12-month period beginning April 1st of the year specified.) Basin characteristics were determined from USGS and Massachusetts Office of Geographic Information (MassGIS) digital map data using an automated GIS procedure developed for the Basin Yield studies.

The regression models developed by Ries and Friesz (2000) are not applicable to the southeast coastal region of the state, including the eastern part of the Buzzards Bay basin, Cape Cod, and the islands of Martha's Vineyard and Nantucket (Figure 2). These areas, which are

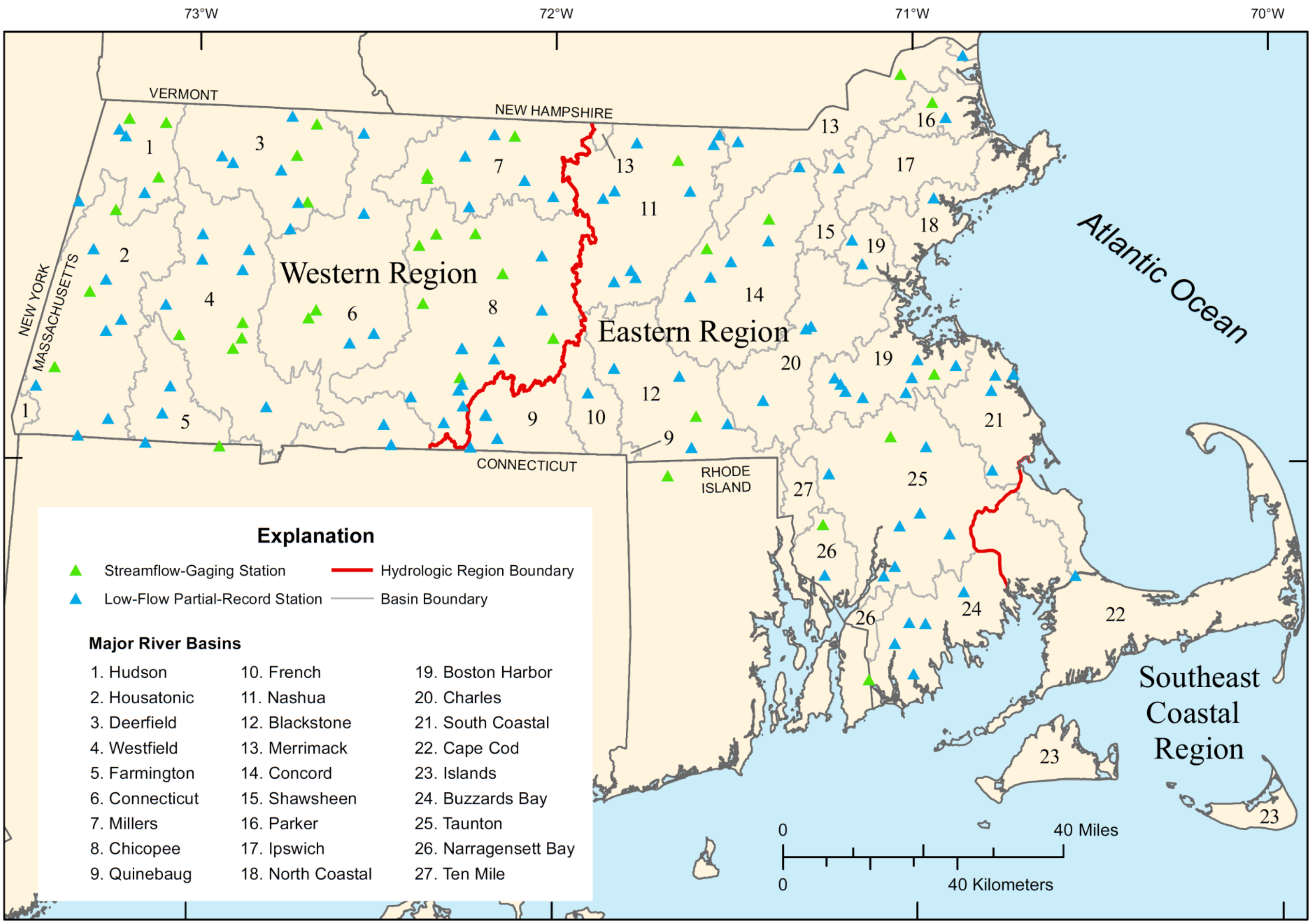

Figure 2. Locations of streamflow-gaging stations and low-flow partial-record stations used by Ries and Friesz (2000) to develop regression equations for estimating low-flow statistics for ungaged Massachusetts streams, and boundaries of the 27 major river basins and three hydrologic regions in the state.

almost entirely underlain by coarse-grained stratified drift deposits, commonly have groundwater and surface-water divides that are not coincident (Archfield et al., 2010). Additionally, flows for most streams in these areas are highly affected by regulation, diversions, or controls by cranberry bogs (Ries et al., 2000). The Ries and Friesz (2000) equations apply only to locations with natural flow conditions; appropriate adjustments of streamflow estimates should be made for human influences if the equations are applied to regulated sites. The models' applicability is further limited by the ranges of basin characteristics used to develop them (Table 2). Extrapolation of the equations to sites with basin characteristics outside the ranges of those used to develop the equations will produce streamflow estimates with unknown and possibly very large errors (Ries et al., 2008).

Basin Characteristic	Minimum	Mean	Maximum
Drainage area (mi^2)	1.61	14.9	149
Total basin stream length (mi)	1.79	27.9	319
Mean basin slope (percent)	0.32	5.28	24.6
Area of stratified drift per unit stream length (mi^2/mi)	0.00	0.144	1.29
Region	0	--	1

Table 2. Ranges of basin characteristics used by Ries and Friesz (2000) to develop equations for estimating low-flow statistics for ungaged Massachusetts streams.
[mi, miles; mi^2, square miles; --, not applicable]

Previous Low-Flow Estimation Methods for New England

Numerous regional regression models incorporating physical and climatic basin characteristics as independent variables have been developed for estimating low-flows at ungaged sites in New England. Johnson (1970) estimated low flows for sites in Massachusetts, New Hampshire, Rhode Island, and Vermont, using drainage area, mean annual precipitation, and January minimum temperature as predictor variables. Tasker (1972) developed a low-flow regression model for southeastern Massachusetts using drainage area and a groundwater factor, related to the transmissivity and availability of water in the basin aquifers. Dingman (1978) used drainage areas and mean basin elevations to synthesize flow-duration curves for unregulated streams in New Hampshire. Cervione and others (1982) developed regionalization methods for Connecticut in which the area of coarse-grained stratified drift and the area of till were used as explanatory variables to estimate the 7-day, 10-year low flow (7Q10). Male and Ogawa (1982) used a suite of basin geomorphic and climatic characteristics—including drainage area, mean annual precipitation, area of swamps and lakes, and a groundwater factor—to estimate low-flow duration discharges in Massachusetts.

Vogel and Kroll (1990) used drainage area and basin relief to regionalize low-flow frequencies in Massachusetts, and Fennessey and Vogel (1990) used the same parameters to synthesize the lower half of the flow-duration curve for streams in the state. In another study, Vogel and Kroll (1992) developed improved regression equations for estimating low-flow statistics in central western Massachusetts. They found that low-flow statistics in this region were highly correlated with the product of drainage area, mean basin slope, and a base flow recession constant, with the recession constant acting as a surrogate for both basin hydraulic conductivity and drainable soil porosity. Cervione and others (1993) described a regression equation relating the 7Q10 flow to the percentage of drainage area underlain by coarse-grained stratified drift and till-covered bedrock in nonurbanized catchments in Rhode Island. Wandle and Randall (1994) applied regression techniques to define the relationship between low flows in central New England watersheds and a suite of basin characteristics, including: drainage area; basin relief; mean basin elevation; main-channel length; and areal extent of till, alluvium, coarse- and fine-grained stratified drift deposits, swamps, and lakes.

Risley (1994) presented a low-flow frequency model for estimating the 7Q2 and 7Q10 flows at stream sites in Massachusetts using drainage area and basin relief as independent variables. Dingman and Lawlor (1995) developed an approach for estimating low-flow quantiles in New Hampshire and Vermont by regression on basin characteristics. They found that drainage area, mean elevation, and fraction of drainage basin underlain by sand and gravel deposits are significant predictors of quantiles of annual minimum seven-day-average flows. Vogel and others (1999) developed regression models for mean annual streamflow in 18 regions of the continental United States and found that the mean and variance of annual streamflow for natural-flow streams in the New England region could be estimated as a function of drainage area, mean basin precipitation, and mean basin temperature.

As discussed above, the report by Ries and Friesz (2000) was the sixth and final in the Massachusetts Basin Yield study series. Reports for the first two Basin Yield studies (Ries, 1994a, 1994b) each provided equations for estimating the natural, long-term 95-, 98-, and 99-percent duration streamflows for ungaged streams in Massachusetts. The two sets of equations were developed by use of WLS (Ries, 1994a) and GLS (Ries, 1994b) regression procedures, and also differed in the number of stations used in the analyses (more stations were used in the GSL analysis). Significant basin characteristics used in both studies were drainage area, area underlain by stratified drift deposits per unit of stream length, and a surrogate for the effective head on the aquifer in the stratified drift deposits, computed by subtracting the minimum basin elevation from the mean basin elevation (Ries, 1994a, 1994b). The methods developed by Ries and Friesz (2000) for estimating low-flow statistics in Massachusetts supersede those from earlier reports.

Effects of Climate Change on Streamflows in New England

Evidence of climate change in the northeastern US has been well documented (Trombulak and Wolfson, 2004; Hayhoe et al., 2007; Huntington et al., 2009; USGCRP, 2009). Analyses of long-term air temperature data show a warming trend of 0.8°C ±0.1°C over the last century (Hayhoe et al., 2007). Precipitation is exhibiting changes in volume, intensity, and form (rain versus snow), and has increased by an average of 95 ±20 mm in the region during the 20th century (Hayhoe et al., 2007). The greatest increases in air temperature have occurred during winter (Hayhoe et al., 2007), with a corresponding decline in the proportion of precipitation falling as snow (Huntington et al., 2004). These changes, as well as climate characteristics that govern evapotranspiration (such as air temperature, air humidity, solar radiation, wind speed, and atmospheric CO_2 concentration), have the potential to alter streamflow regimes in New England in complex ways (Campbell et al., 2011).

Hodgkins and Dudley (2005) found significant increases in various annual percentile streamflows in New England between 1902 and 2002. A reduction in winter snowpack and earlier spring arrival in New England has advanced the timing of spring freshets and caused a more uniform distribution of flow throughout the snowmelt period (Hartley and Dingman, 1993; Hodgkins et al., 2003; Hodgkins and Dudley, 2006; Campbell et al., 2011). Huntington (2003) found that climate warming could significantly reduce runoff in New England due to increased evapotranspiration, but noted uncertainties in mitigating factors, such as increased precipitation and cloudiness, which could offset projected decreases in streamflow. Hayhoe et al. (2007)

found nonstationarity leading to a redistribution of streamflows in the northeastern US over the last century, with a general tendency toward more streamflow in winter and spring, and less in summer and fall. However, the author again noted that increases in precipitation may have compensated for increases in evapotranspiration, masking underlying trend towards decreasing summer low flows (Hayhoe et al., 2007). Projections of 21st century streamflow quantiles point to increasing trends for the 50th quantile and above (higher flows) and decreasing trends for the 25th quantile and below (low flows) (Hayhoe et al., 2007).

Bradbury et al. (2002) examined the relationship between New England drought and large scale atmospheric circulation patterns, including the El Nino/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). The authors found significant positive correlations between the NAO and monthly streamflows at western inland locations (Bradbury et al., 2002). Kingston et al. (2007) also explored the relationship between the NAO and New England river flows, and found streamflows more closely linked to the East Coast trough rather than the Icelandic low or Azores high. Several recent studies have documented evidence of increasing flood frequencies and magnitudes in New England throughout the late 20th and early 21st century, and found a step change for these trends around the end of water year 1970 (Collins, 2009; Armstrong et al., 2012; Armstrong et al., 2013). Collins (2009), Armstrong et al. (2012), and Armstrong et al. (2013) found evidence for a lagged positive relationship between the NAO and flood magnitude and frequency in New England, and Armstrong et al. (2013) found some evidence of greater flooding in the region during ENSO years. These studies suggest that the timing and magnitude of streamflows in New England are to some extent related to cyclic variability in large-scale atmospheric circulation patterns.

Study Area Description

Massachusetts encompasses an area of about 20,961 km^2 (8,961 mi^2) in the northeastern United States (Ries, 1994a). The Massachusetts Office of Water Resources divides the state into 27 major river basins for planning and regulatory purposes (Figure 2). Ries (1997) defined three hydrologic regions in Massachusetts based on differences in August median streamflow per unit area: the western, the eastern, and the southeast coastal regions (Figure 2). The western region is defined by all major basins that drain to the Connecticut River plus those west of the Connecticut River Basin. The eastern region is defined by all basins east of the Western region, except Cape Cod, the islands, the southern part of the South Coastal basin, and the eastern part of the Buzzards Bay basin, which together define the southeast coastal region. Low streamflows per unit drainage area are significantly higher, on average, in the western region than in the eastern region (Ries and Friesz, 2000). These differences are likely due to the combination of lower mean annual temperatures, higher mean elevations, higher basin relief, higher precipitation, lower evapotranspiration, and lower areal percentages of wetlands and water bodies in western Massachusetts than in the eastern part of the state (Ries and Friesz, 2000).

Massachusetts has a humid continental climate. Precipitation in the state, which is distributed fairly evenly throughout the year, averages about 112 cm/yr (Simcox, 1992). However, average annual precipitation can vary by 25 cm or more from year to year and spatially within the state, with the highest precipitation typically occurring in the high-elevation areas of western Massachusetts (Randall, 1996). Average annual temperatures range from 10°C in coastal areas to 7.2°C in the western mountains (Ries, 1994a). Annual evaporation from wetlands and water bodies ranges from 66 cm in the west of the state to 71 cm in the east (Moody et al., 1986).

Topographic relief and mean basin slope, which are highly correlated, tend to increase with increasing elevation in Massachusetts (Ries and Friesz, 2000). Elevations range from sea level along the coast to over 1000 m in the western mountains (Ries, 1994b). Several other basin characteristics vary from east to west in Massachusetts, including areal percentage of lakes, ponds, and wetlands, and areal percentage of coarse-grained stratified drift deposits, which both generally decrease from east to west in the state (Ries and Friesz, 2000).

The surficial geology in much of Massachusetts is characterized by unconsolidated glacial deposits, specifically till and stratified drift (Simcox, 1992). The distribution of these hydrologically distinct glacial sediments greatly influences the flow characteristics of streams and rivers (Armstrong et al., 2008). Glacial till, found primarily in upland areas, is an unstratified and unsorted deposit of material ranging in size from clay particles to large boulders, deposited directly by glaciers with little or no modification by meltwater (Ries and Friesz, 2000). Stratified drift, commonly found in river valleys and lowland areas, generally consists of fine sand, silt, or clay deposited in temporary lakes that formed during glacial retreat, or medium- to coarse-grained sand and gravel deposited by glacial streams (Ries, 1994b). Till and fine-grained stratified drift deposits generally have smaller infiltration capacities and lower hydraulic conductivities than coarse-grained stratified drift deposits, which causes streams in till uplands to have relatively rapid runoff rates and low baseflows (Armstrong et al., 2008). By contrast, rainfall on coarse-grained stratified drift infiltrates rapidly and is stored in aquifers, which causes streams in these areas to have relatively slow runoff rates and high baseflows (Ries, 1994b).

Methodology

This investigation of changes in streamflows in southern New England and their effects on the accuracies of the Ries and Friesz (2000) (RF) regression models was conducted in four parts. Part I examines discharge data from 15 of the 37 continuous-record streamflow-gaging stations that RF used in their regression analyses (Table 3, Figure 3). These 15 stations were selected because, in addition to collecting streamflow data from periods prior to April 1st, 1996 (which were used in the RF regressions), these gages monitored the continuous period of climatic years 1996 to 2011. Two daily flow-duration curves (FDCs) were computed for each streamgage: one for the gage's period of record prior to climatic year 1996, and one for the 16-year period of climatic years 1996 to 2011. The curves were constructed from mean daily streamflow data downloaded from the USGS National Water Information System (NWIS) website (http://waterdata.usgs.gov/nwis). Following construction of the observed FDCs, estimates of ten flow-durations on the lower half of the FDC were calculated for the gaging sites using the regression equations and basin characteristics (explanatory variables) provided in the Ries and Friesz (2000) report. Prediction intervals at the 90-percent confidence level were calculated for the estimates using procedures also provided by RF.

To increase the size of the gaging station sample set, Part II analyzes 21 streamgages in southern New England that were not used in the RF analyses (Table 3, Figure 3). To ensure that the gages analyzed in Part II monitored essentially natural flow conditions, a criterion for their selection was that they were identified by Armstrong et al. (2008) as monitoring least-altered streams in southern New England. The stations were also required to have basin characteristics within the ranges of those used in the RF regressions (Table 2). As in Part I, FDCs were constructed from streamflow data downloaded from the NWIS website for the stations' periods

Station Number	Station Name	Period of Record (water years)	Drainage Area (mi^2)	Hydrologic Region
Part I Gaging Stations				
01096000	Squannacook River near West Groton, MA	1950-2012	64.4	Eastern
01097300	Nashoba Brook near Acton, MA	1964-2012	12.9	Eastern
01101000	Parker River at Byfield, MA	1946-2012	21.4	Eastern
01105600	Old Swamp River near South Weymouth, MA	1966-2012	4.47	Eastern
01111300	Nipmuc River near Harrisville, RI	1996-1990, 1994-2012	16.0	Eastern
01162500	Priest Brook near Winchendon, MA	1919-2012	19.2	Western
01169000	North River at Shattuckville, MA	1940-2012	89.8	Western
01169900	South River near Conway, MA	1967-2012	24.1	Western
01170100	Green River near Colrain, MA	1968-2012	41.3	Western
01171500	Mill River at Northampton, MA	1939-2012	54	Western
01174565	West Branch Swift River near Shutesbury, MA	1984-1985, 1996-2012	12.5	Western
01175670	Sevenmile River near Spencer, MA	1961-2012	8.69	Western
01176000	Quabog River at West Brimfield, MA	1919-2012	149	Western
01181000	West Branch Westfield River at Huntington, MA	1936-2012	94	Western
01333000	Green River at Williamstown, MA	1950-2012	42.6	Western
Part II Gaging Stations				
01073000	Oyster River near Durham, NH	1935-2012	12.21	Eastern
01095220	Stillwater River near Sterling, MA	1994-2012	28.88	Eastern
010965852	Beaver Brook at North Pelham, MA	1987-2012	47.79	Eastern
01105730	Indian Head River at Hanover, MA	1967-2012	30.09	Eastern
01109000	Wading River near Norton, MA	1926-2012	43.58	Eastern
01111500	Branch River at Forestdale, RI	1940-2012	91.21	Eastern
01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	1994-2011	4.95	Eastern
01115187	Ponaganset River at South Foster, RI	1994-2012	14.38	Eastern
01117468	Beaver River near Usqepaug, RI	1975-2012	9.18	Eastern
01117500	Pawcatuck River at Wood River Junction, RI	1941-2012	99.34	Eastern
01117800	Wood River near Arcadia, RI	1964-1980, 1983-2012	35.17	Eastern
01118000	Wood River at Hope Valley, RI	1941-2012	74.17	Eastern
01118300	Pendleton Hill Brook near Clarks Falls, CT	1959-2012	4.01	Eastern
01121000	Mount Hope River near Warrenville, CT	1941-2012	27.12	Eastern
01123000	Little River near Hanover, CT	1952-2012	29.61	Eastern
01184100	Stony Brook near West Suffield, CT	1981-2012	10.53	Western
01187300	Hubbard River near West Hartland, CT	1939-1954, 1957-2012	20.67	Western
01188000	Burlington Brook near Burlington, CT	1932-2012	4.1	Western
01193500	Salmon River near East Hampton, CT	1929-2012	104.74	Western
01195100	Indian River near Clinton, CT	1982-2012	5.62	Western
01199050	Salmon Creek at Lime Rock, CT	1962-2012	29.57	Western

Table 3. Gaging stations analyzed in Parts I and II, their periods of record, drainage areas and hydrologic regions.

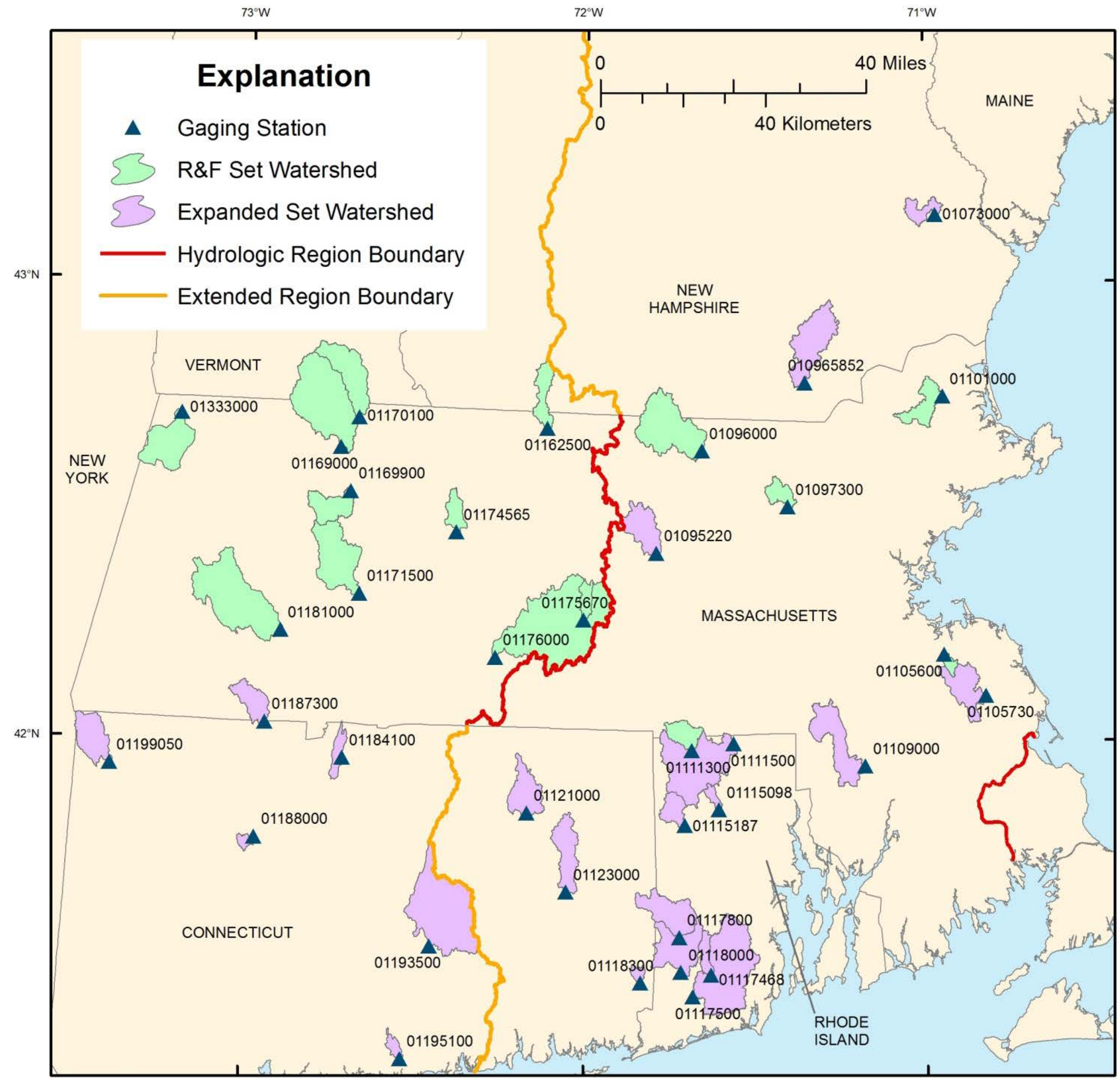

Figure 3. Gaging stations analyzed in Part I (R&F Set) and Part II (Expanded Set), and their upstream watersheds. The boundary separating the eastern and western hydrologic regions of Massachusetts defined by Ries (1997) was extended north and south to identify the hydrologic regions for gaging stations in the expanded set in New Hampshire and Connecticut, respectively.

of record prior to climatic year 1996 and for the period of climatic years 1996 to 2011. Again, ten flow durations were estimated for each gaging location using the RF equations. Basin characteristics for the gages were taken from Armstrong et al. (2008), or, for the case of station 01188000 Burlington Brook near Burlington, CT, from an online USGS data-collection station report (http://streamstatsags.cr.usgs.gov/gagepages/html/01188000.htm). To determine the hydrologic region variable for the stations outside of Massachusetts, the boundary defined by Ries (1997) separating the eastern and western hydrologic regions was extended north and south into New Hampshire and Connecticut, respectively (Figure 3). The boundary was extended using the criteria given by Ries (1997) to define the hydrologic regions of Massachusetts.

Part III of this study further examines changes in daily FDCs in southern New England watersheds over time. In Parts I and II, the end of climatic year 1995 (March 31, 1996) was used as the "cut point," or dividing date between time periods used to plot gaging stations' FDCs. This date was chosen because this was last date for which streamflow data were used in the Ries and Friesz (2000) regression analyses, but different cut points dividing a gaging station's period of record can equally be used to examine changes in the characteristics of a site's FDC between periods. Recent studies (e.g., Collins, 2009; Armstrong et al., 2012; and Armstrong et al., 2013) have found evidence of a hydroclimatic shift in New England around the beginning of water year 1971 (October 1, 1970), which increased flood magnitudes and frequencies in the region. This cut point was used to divide the FDCs of 17 gaging stations used in Parts I or II with more than 60 years of record to investigate the potential effects of the hydroclimatic shift on the region's low-flow characteristics. The periods of record at the 17 stations were divided into two (pre- and post-1970) and three (pre-1970, 1971-1995, and 1996-2012) periods, and FDCs were calculated for each period.

For Part IV of the investigation, “moving quantiles” were computed for 16 of the 17 gaging stations analyzed in Part III. The one station in Part III that was not examined in Part IV (the gage on the Hubbard River near West Hartland, CT) was missing streamflow data for water year 1957 and was therefore not included in Part IV. For each of the 16 stations, the ten daily streamflow quantiles of interest were computed from a 20-year period within the stations' periods of record, beginning with the period of water years 1933 to 1952 (if the station's period of record went back that far). Quantiles were then calculated for the 20-year period beginning one year later (1934 to 1953). In this way, 20-year moving quantiles were calculated for each twenty-year period in the stations' periods of record through the 20-year period of water years 1993 to 2012.

To estimate when the RF regression equations would no longer be valid (i.e., when actual streamflows would be outside of the 90-percent prediction intervals for more than ten percent of stream sites), the 20-year quantiles at the 16 stations were projected into the future using a linear least-squares best fit line. Trend lines for each of the ten flow-durations of interest were applied to the entire period of record at each station, and R^2 and *p*-value measures of fitness were calculated for each trend line. Some quantiles, especially at the highest exceedance probabilities, appeared to have increasing trends prior to water year 1992 and decreasing trends for the period of water years 1992 to 2012. To investigate this, linear lines of best fit were also applied to all ten quantiles of interest for just the 21-year period of 1992 to 2012. Trend lines for the period of record and post-1992 periods at each station were extended into the future to the point where they met the upper or lower bound of the prediction interval for the estimated flow-duration at that site. The water year at which greater than 10% of the 16 stations (2 of 16) exhibited model failures was considered to be the approximate failure date for that flow-duration model.

Results

Part I: Analysis and Validation using Original Stations

Complete pre- and post-1996 (climatic year) flow-duration curves and RF model estimates for the 15 streamgages analyzed in Part I are provided in Appendix A, and an example plot for the Mill River at Northampton, MA gaging station is presented in Figure 4. The sequential FDCs shown in the figure are typical of those observed at the other gaging sites analyzed in Part I. Appendix B contains plots of observed pre- and post-1996 streamflow quantiles at the gaging stations, plotted as percentages of the upper or lower bounds of the 90-percent prediction intervals for the RF estimates for the gaging sites. An example plot for the Q70 flow is presented in Figure 5. Note that the Q70 flow increased between the two periods at all 15 stations analyzed, and that the Q70 RF model underestimated the post-1996 Q70 flows at 14 of the 15 stations. Reference numbers and hydrologic regions for the gaging stations in Figure 5 are given in Table 4. Geographical representations of the RF model performances at the 15 gaging stations when compared to the observed post-1996 streamflows are provided in Appendix C, and an example figure for the Q70 flow is presented in Figure 6.

Observed flow-durations at the 15 streamgages were generally higher for the post-1996 period than for pre-1996, especially for streamflow quantiles between the 60-percent and 80-percent exceedance probabilities. Points on the stations' FDCs increased by 50% or more between the two periods at five of the 15 stations, all of which were in the western hydrologic region. Although similarly large increases were also seen at the gaging station on the West Branch Swift River near Shutesbury, MA (Appendix A, panel 11, or Figure A11), the pre-1996 period of record at this station was only two years long and was therefore inadequate to characterize pre-1996 flow-durations at this site. Some portion of the FDC for the post-1996

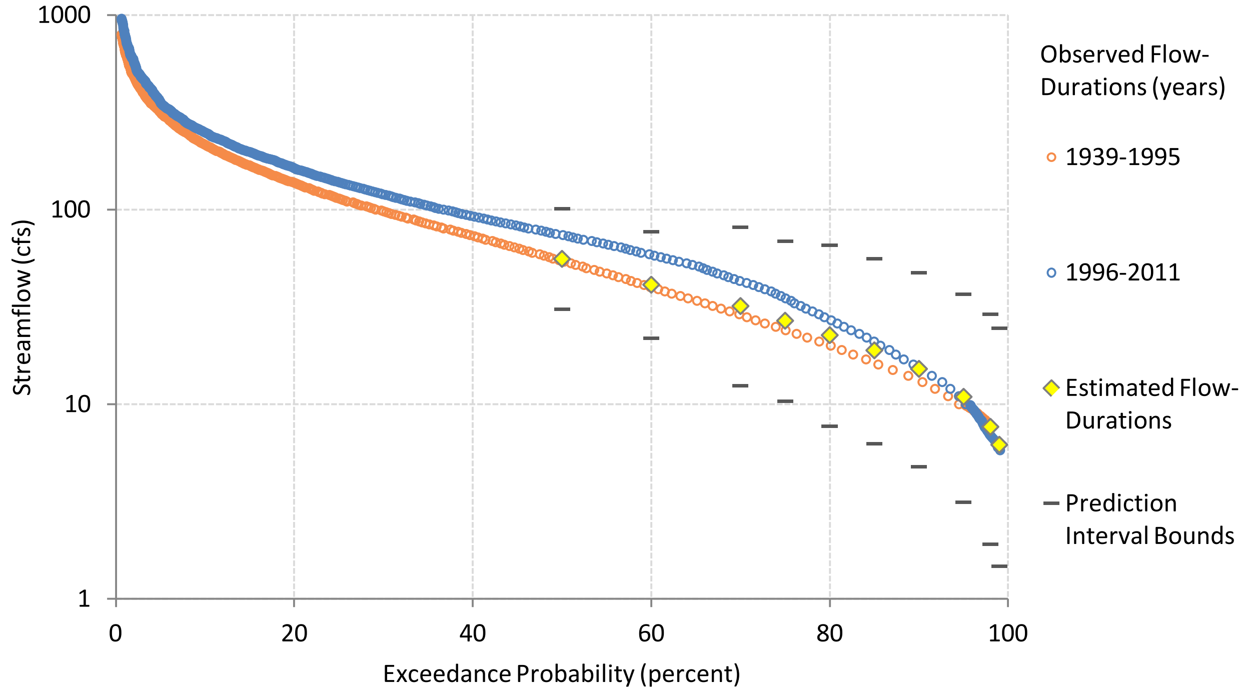

Figure 4. Flow-duration curves for pre- and post-1996 periods of record from the Mill River at Northampton, MA gaging station. Also shown are the RF model estimates and the upper and lower bounds of the 90-percent prediction intervals for the estimates.

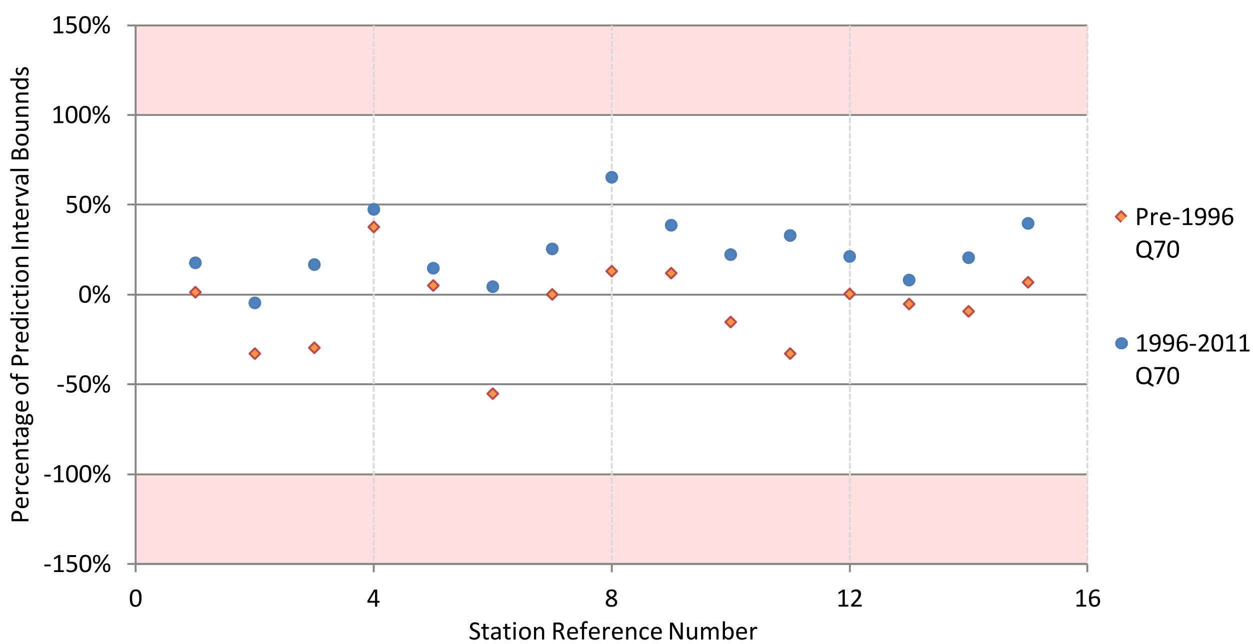

Figure 5. Observed Q70 flows at the 15 gaging stations analyzed in Part I for the pre- and post-1996 periods, plotted as percentages of the upper or lower bounds of the 90-percent prediction intervals for the RF estimates. Model failure regions are shaded pink. Station reference numbers refer to Table 4.

Station Reference Number	USGS Station Number	USGS Station Name	Hydrologic Region
1	01096000	Squannacook River near West Groton, MA	Eastern
2	01097300	Nashoba Brook near Acton, MA	Eastern
3	01101000	Parker River at Byfield, MA	Eastern
4	01105600	Old Swamp River near South Weymouth, MA	Eastern
5	01111300	Nipmuc River near Harrisville, RI	Eastern
6	01162500	Priest Brook near Winchendon, MA	Western
7	01169000	North River at Shattuckville, MA	Western
8	01169900	South River near Conway, MA	Western
9	01170100	Green River near Colrain, MA	Western
10	01171500	Mill River at Northampton, MA	Western
11	01174565	West Branch Swift River near Shutesbury, MA	Western
12	01175670	Sevenmile River near Spencer, MA	Western
13	01176000	Quabog River at West Brimfield, MA	Western
14	01181000	West Branch Westfield River at Huntington, MA	Western
15	01333000	Green River at Williamstown, MA	Western

Table 4. Station reference numbers and hydrologic regions for gaging stations analyzed in Part I, the streamflow data for which are plotted in Figure 5.

period crossed below the pre-1996 curve at eight of the 15 gaging stations in the analysis nearly always for the lowest flows (Appendix A). The decreases in streamflow quantiles between the pre- and post-1996 periods were greater, more common, and extended along a longer length of the FDCs, on average, in the eastern hydrologic region than the western region.

Low-flow quantiles at the 90-percent exceedance probability (Q90) and above decreased between the two time periods at 60% of gaging sites in the eastern hydrologic region, while this was true of only 10% of gages in the western region (Appendix A). At the four gaging sites in the western hydrologic region where post-1996 FDCs crossed below the pre-1996 curves, it was always for the very lowest flows, with the average crossing point being the 94-percent exceedance probability (±2.3%, 1 standard deviation). At the three sites in the eastern hydrologic region where post-1996 FDCs crossed below the pre-1996 curves for the lowest

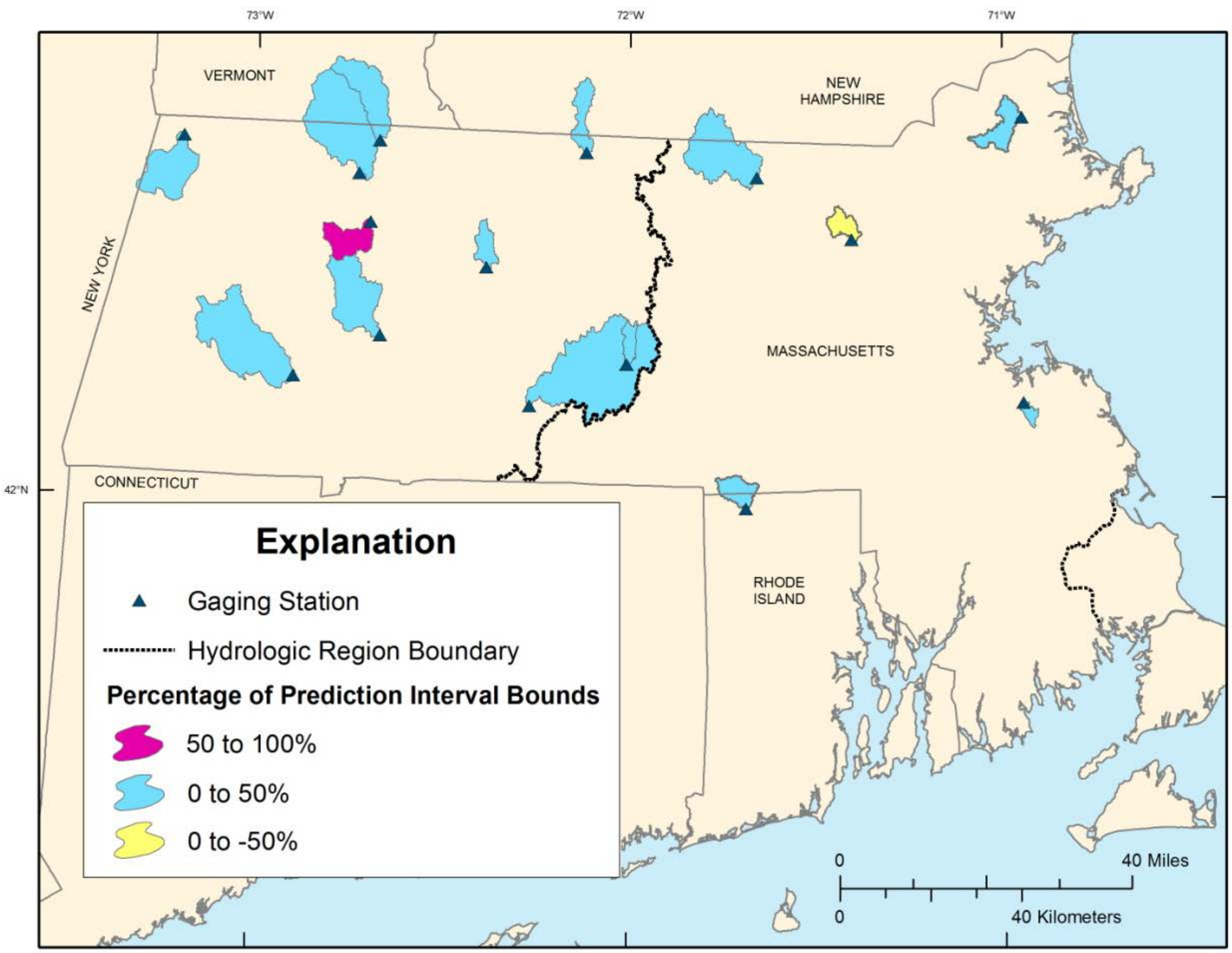

Figure 6. Watersheds for the gaging stations analyzed in Part I, colored according to the values of the observed post-1996 Q70 flows, expressed as a percentage of the upper or lower bounds of the 90-percent prediction intervals for the RF estimates.

flows, the average crossing point was the 84-percent exceedance (±1.9%). Decreases in flow-durations between the two periods were greater on average in the eastern hydrologic region than the western region, with post-1996 streamflow quantiles in the eastern region being as little as 24% of the pre-1996 values (Figure A5).

Observed streamflow quantiles for the 1996 to 2011 period at the 50- to 90-percent exceedance probabilities were within the 90-percent prediction intervals for the estimated quantiles for more than 90% of the streamgages analyzed in Part I. Specifically, the models correctly estimated (within the prediction intervals) the quantiles at all 15 gages (100%) for the 50-, 70-, 75-, and 80-percent duration flows, and at 14 of the 15 gages (93.3%) for the 60- and 85-percent duration flows. Failure rates were 13.3% (2 of 15 gages) for the 95-percent duration flow, and 20% (3 of 15 gages) for the 98- and 99-percent duration flows. However, because of the relatively small size of the sample set (15 gaging stations), none of the models can be rejected as invalid with greater than 95% confidence ($p = 0.184$). All model failures for the 85- to 99-percent duration flows were overestimates (observed flows were below the lower bound of the 90-percent prediction interval for the estimates). In some cases, the models overestimated very low streamflows by more than an order of magnitude, but it should be noted that these gross overestimations were typically for relatively small catchments, where Q99 flows were less than one cfs (i.e., Figures A2, A3, and A5).

While the RF models overestimated a majority of the very low (greater than 95-percent exceedance probability) flows at the 15 gaging sites, they tended to underestimate the more median flows for the post-1996 period. For the 50- to 75-percent exceedances, the models underestimated streamflows at more than 85% of stations, although observed flows were nearly always within the prediction intervals for the estimates (with one exception at the 60-percent exceedance, Figure A8). This tendency of the models towards underestimation of the 50- to 75-percent duration flows is greater than would be expected by chance ($p < 0.05$), suggesting that increasing median and near-median streamflows in Massachusetts have caused the models to become biased towards underestimation of these flows. In the one case where a model failed due to an underestimate (for the Q60 flow at the South River near Conway, MA streamgage, Figure A8), the Q60 flow increased between the pre- and post-1996 periods; in the cases where the RF models failed due to overestimates (for the 85-, 90-, 95-, 98-, and 99-percent exceedance flows), those flows decreased between the pre- and post-1996 periods.

Part II: Analysis and Validation using Additional Stations

Pre- and post-1996 flow-duration curves and RF model estimates for the streamgages analyzed in Part II are provided in Appendix D, and an example plot for the gaging station on the Oyster River near Durham, NH is presented in Figure 7. The sequential FDCs shown in the figure are typical of those observed at the other gaging sites analyzed in Part II. Appendix E contains plots of observed pre- and post-1996 streamflow quantiles at the gaging stations, plotted as percentages of the upper or lower bounds of the 90-percent prediction intervals for the RF estimates for the gaging sites in Part II. An example plot for the Q70 flow is presented in Figure 8. Note that the Q70 flow increased between the two periods at 19 of the 21 stations analyzed, and that the Q70 RF model underestimated the actual post-1996 Q70 flows at 18 of the 21 stations. Reference numbers and RF hydrologic regions for the gaging stations in Figure 8 are given in Table 5. Geographical representations of the RF model performances at the 21 gaging stations when compared to the observed post-1996 streamflows are provided in Appendix F, and an example figure for the Q70 flow is presented in Figure 9.

As at the original gaging stations analyzed in Part I, observed streamflow quantiles for the 21 additional gages in southern New England were generally higher for the post-1996 period than for the period before climatic year 1996, especially for the 60- to 80-percent duration flows. Flow-durations increased between the pre- and post-1996 periods by 50% or more at three of the 21 stations, and the increases were greater in magnitude, on average, and more common in the western hydrologic region than the eastern region. A portion of the post-1996 FDC crossed

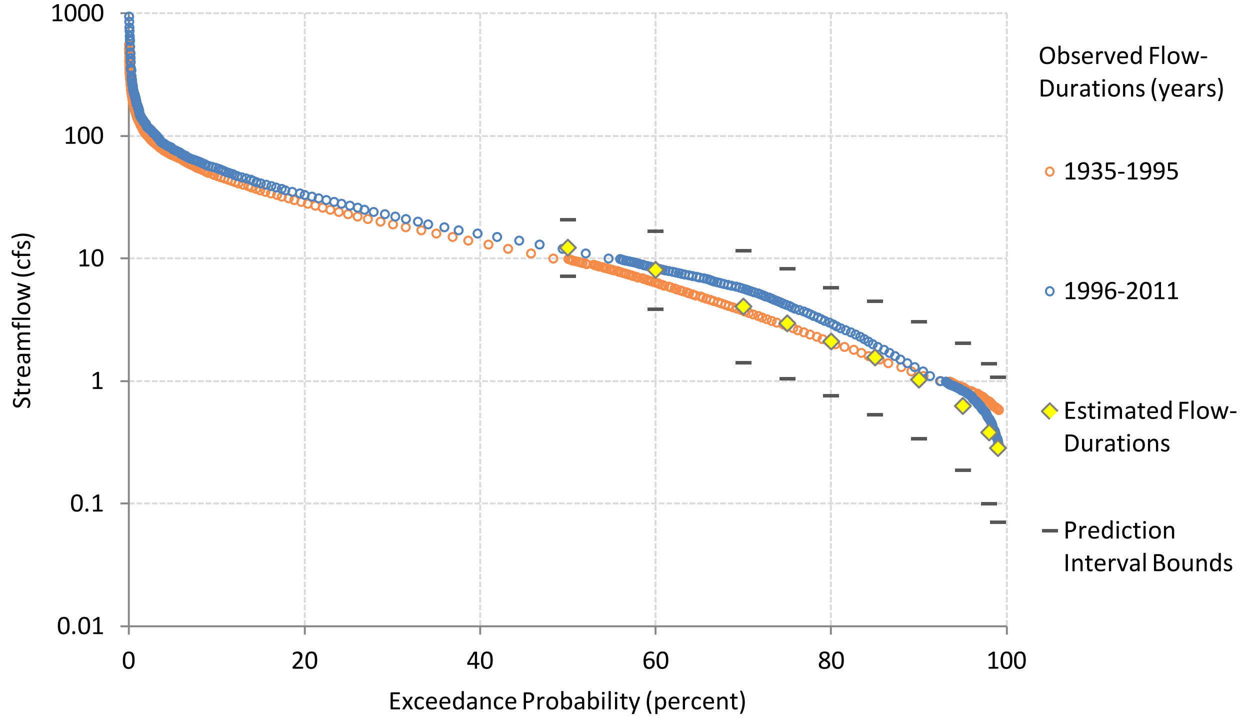

Figure 7. Flow-duration curves for pre- and post-1996 periods of record from the Oyster River near Durham, NH gaging station. Also shown are the RF model estimates and the upper and lower bounds of the 90-percent prediction intervals for the estimates.

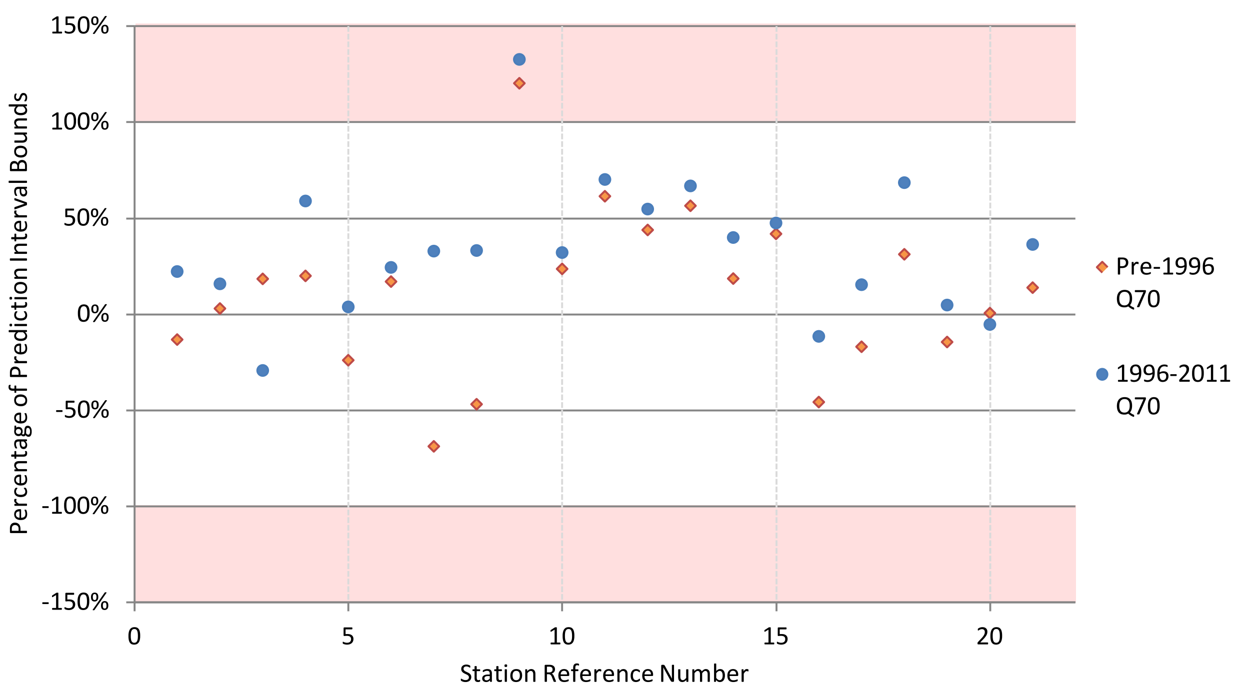

Figure 8. Observed Q70 flows at the 21 gaging stations analyzed in Part II for the pre- and post-1996 periods, plotted as percentages of the upper or lower bounds of the 90-percent prediction intervals for the RF estimates. Model failure regions are shaded pink. Station reference numbers refer to Table 5.

Station Reference Number	Station Number	Station Name	Hydrologic Region
1	01073000	Oyster River near Durham, NH	Eastern
2	01095220	Stillwater River near Sterling, MA	Eastern
3	010965852	Beaver Brook at North Pelham, MA	Eastern
4	01105730	Indian Head River at Hanover, MA	Eastern
5	01109000	Wading River near Norton, MA	Eastern
6	01111500	Branch River at Forestdale, RI	Eastern
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	Eastern
8	01115187	Ponaganset River at South Foster, RI	Eastern
9	01117468	Beaver River near Arcadia, RI	Eastern
10	01117500	Pawcatuck River at Wood River Junction, RI	Eastern
11	01117800	Wood River near Arcadia, RI	Eastern
12	01118000	Wood River at Hope Valley, RI	Eastern
13	01118300	Pendleton Hill Brook near Clarks Falls, CT	Eastern
14	01121000	Mount Hope River near Warrenville, CT	Eastern
15	01123000	Little River near Hanover, CT	Eastern
16	01184100	Stony Brook near West Suffield, CT	Western
17	01187300	Hubbard River near West Hartland, CT	Western
18	01188000	Burlington Brook near Burlington, CT	Western
19	01193500	Salmon River near East Hampton, CT	Western
20	01195100	Indian River near Clinton, CT	Western
21	01199050	Salmon Creek at Lime Rock, CT	Western

Table 5. Station reference numbers and hydrologic regions for gaging stations analyzed in Part II, and whose streamflow data are plotted in Figure 8.

below the pre-1996 curve at 13 of the 21 gaging stations in the analysis, nearly always for the lowest flows (Appendix D).

Low-flow quantiles decreased between the pre- and post-1996 periods at 83% of gages in the eastern hydrologic region, versus 46% of gages in the western region (Appendix D). For the four gaging sites in the western hydrologic region where post-1996 FDCs crossed below the pre-1996 curves, the average crossing point was the 94-percent exceedance probability (±2.3%).

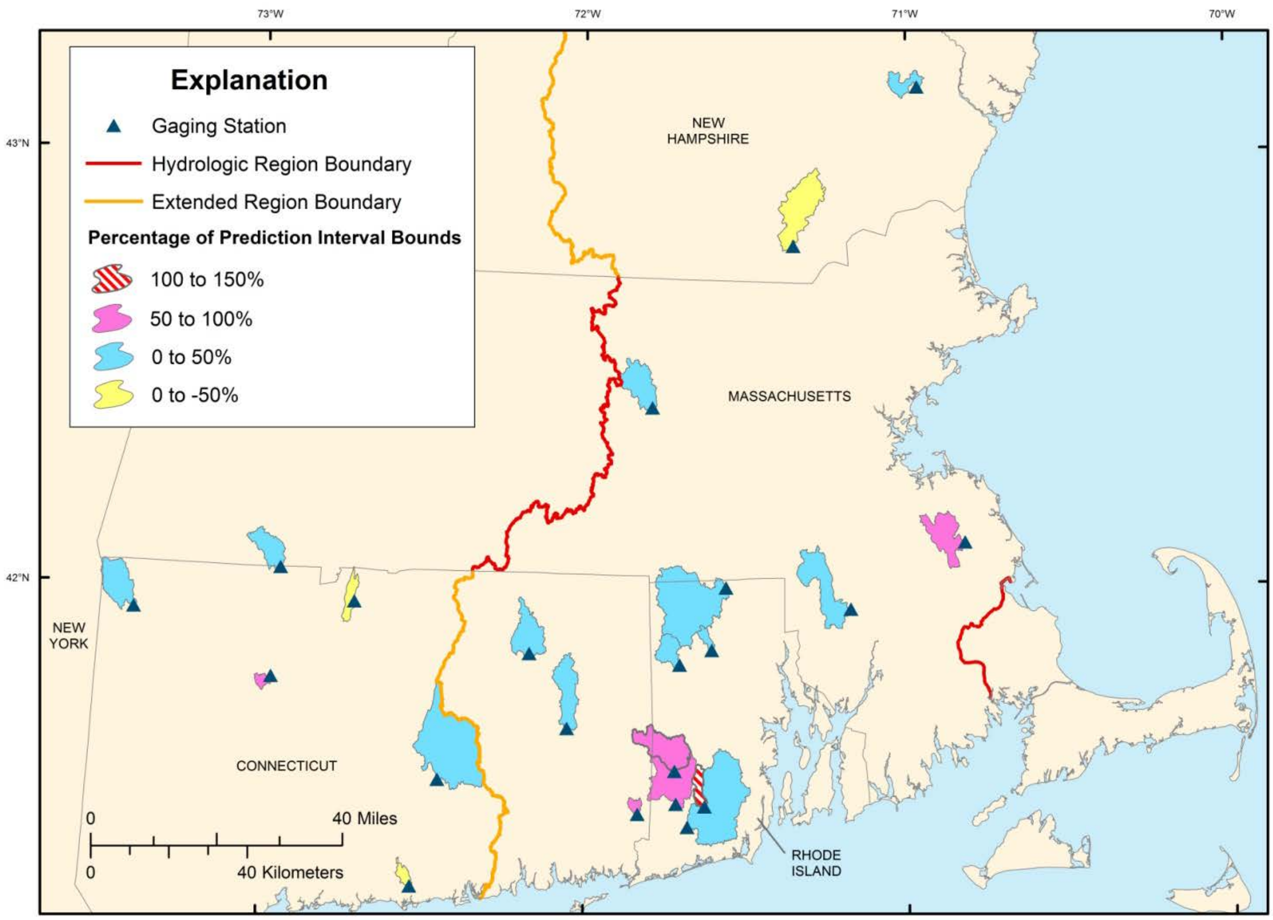

Figure 9. Watersheds for the gaging stations analyzed in Part II, colored according to the values of the observed post-1996 Q70 flows, expressed as a percentage of the upper or lower bounds of the 90-percent prediction intervals for the RF estimates.

For the six gaging sites in the eastern hydrologic region where post-1996 FDCs crossed below the pre-1996 curves at the lowest flows, the average crossing point was the 92-percent exceedance (±4.0%). Decreases in flow-durations between the two periods were greater on average in the eastern hydrologic region than the western region, with post-1996 streamflow quantiles in the eastern region being as little as 54% of the pre-1996 values (Figure D4). The greatest decreases in low-flow quantiles observed in the eastern hydrologic region were generally for smaller catchments, where very low streamflows were less than 1 cfs.

Observed flows for the 1996 to 2011 period were within the 90-percent prediction intervals for the RF estimates at more than 90% of the 21 stations for each of the ten quantiles of interest. Specifically, model success rates were 90.5% (Q50 and Q99), 95.2% (Q60, Q70, Q75, Q95, and Q98), and 100% for the remaining exceedances (Q80, Q85, and Q90). As with the streamgages analyzed in Part I, the models tended to underestimate the median and near-median streamflows. Streamflow quantiles at the 50- to 75-percent exceedance probabilities were underestimated at more than 85% of stations in the sample set, and the models for each of these flow-durations failed due to underestimation at one or more gaging sites. This apparent tendency of the Q50 through Q75 models towards underestimation has a greater than 95% probability of being a true bias ($p < 0.05$), suggesting that increasing median and near-median streamflows are causing the models for these flows to become biased towards underestimation. The regression models did not show a clear bias towards overestimating very low flows for the streamgages in Part II, either overall or in a particular hydrologic region. However, model failures for the 95- to 99-percent duration flows, where they occurred, were always overestimates.

Part III: Flow-Duration Curve Analysis with 1970 and 1996 Cut Dates

Flow-duration curves (FDCs) for the pre-1970, 1971-1995, and post-1996 (water year) periods at each of the 17 stations analyzed in Part III are provided in Appendix G, and an example plot for the gaging station on the North River at Shattuckville, MA is presented in Figure 10. The data showed a general increase in quantiles of daily streamflow at the gaging stations between the pre- and post-1970 periods**.** The greatest increases, on average, were for the 60- to 80-percent flow durations. A decrease in streamflow quantiles between the two periods was observed at four gages in the sample set, always for quantiles at the 95-percent exceedance

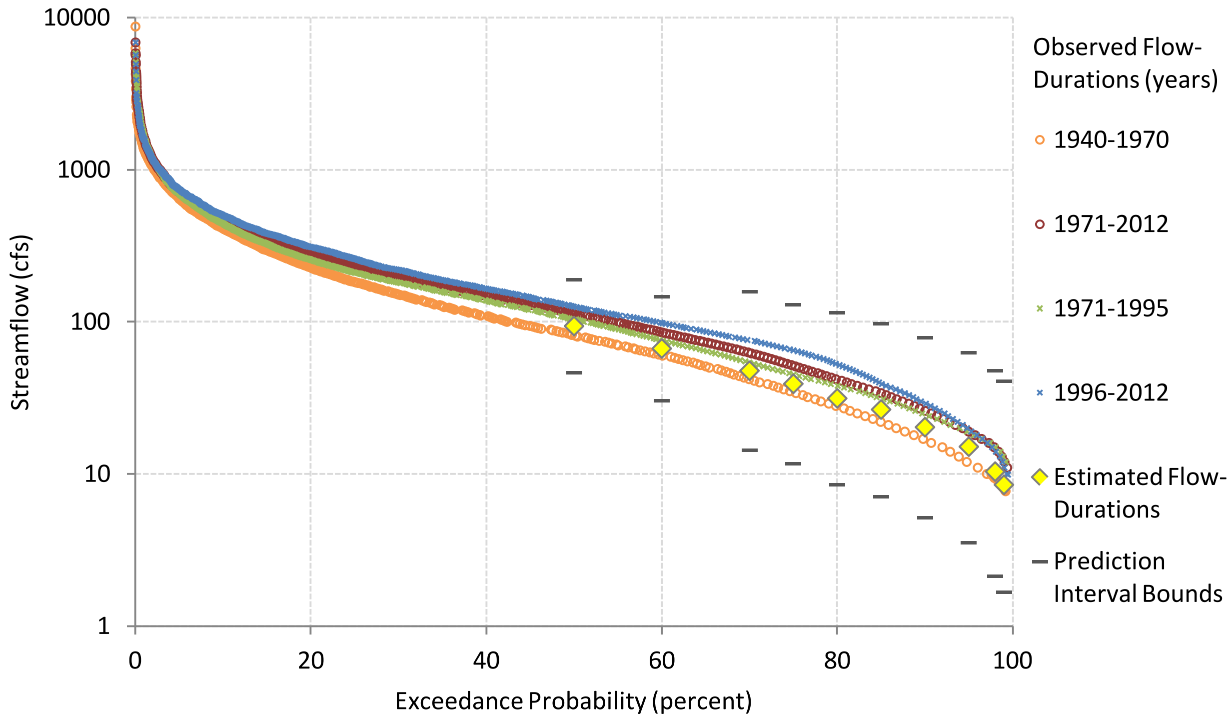

Figure 10. Flow-duration curves for pre-1970, 1971-1995, and post-1996 periods of record from the North River at Shattuckville, MA gaging station. Also shown are the RF model estimates and the upper and lower bounds of the 90-percent prediction intervals for the estimates.

probability and above (the lowest flows). Low-flow quantiles decreased between the two periods at 38% of streamgages (three of eight) in the eastern hydrologic region, while this was true of only 11% of gages (one of nine) in the western region. Where flow-duration curves for the more recent period crossed below that of the older period, the average crossing point was the 96-percent duration flow (±1.5%).

When two cut dates were used to divide the gaging stations' periods of record, there was, on average, a consecutive increase in streamflow quantiles between the three periods (pre-1970, 1971-1995, and 1996-2012; Appendix G). Again, the greatest increases between the three periods were seen in the 60- to 80-percent duration flows. Despite the general increase in most streamflow quantiles, a portion of the FDC for the most recent period crossed below one or both of the older curves at 16 of the 17 stations, nearly always for the lowest flows. The low-flow quantile at which the FDC for the most recent period crossed below the 1971-1995 curve varied, with the average being about the 87-percent exceedance (±6.0%). (This does not include gages where all or almost all of the post-1996 FDC was below the 1971-1995 curve, such as the Branch River at Forestdale, RI gage [Figure G4] and the Little River near Hanover, CT gage [Figure G8].) At more than a quarter of gaging sites, the FDC for the most recent period was nearly indistinguishable from the 1971-1995 curve for most flow-durations other than very low flows, although both curves were generally higher than the pre-1970 FDCs.

Part IV: Trend Analysis of 20-Year Quantiles

Plots of 20-year moving streamflow quantiles for each of the 16 gaging stations analyzed in Part IV are provided in Appendix H, and an example plot for the gaging station on the Squannacook River near West Groton, MA is presented in Figure 11. Figure 12 shows period-of-record and post-1992 trend lines for 20-year quantiles at the Squannacook River near West Groton, MA streamgage. R^2 and *p* values, failure years, and slope direction (positive or negative) for all trend lines are provided in Appendix I, where *p* values <0.05 are shown in boldface. A summary of the period-of-record and post-1992 quantile trend extension analyses is provided in Table 6.

Trends in 20-year quantiles at the 50- to 99-percent exceedances varied in strength and direction at the gaging stations for their periods of record up to 2012 (last water year of the 20-year period analyzed). Linear best-fit lines for 20-year quantiles over this period were strongest for the more median flows, and had positive slopes for the vast majority of significant ($p < 0.05$) trends at the 50- through 90-percent exceedance probabilities (Appendix I). Trend lines had positive slopes for 92.9 % of significant trends in the Q50 flow, and 100% of significant trends

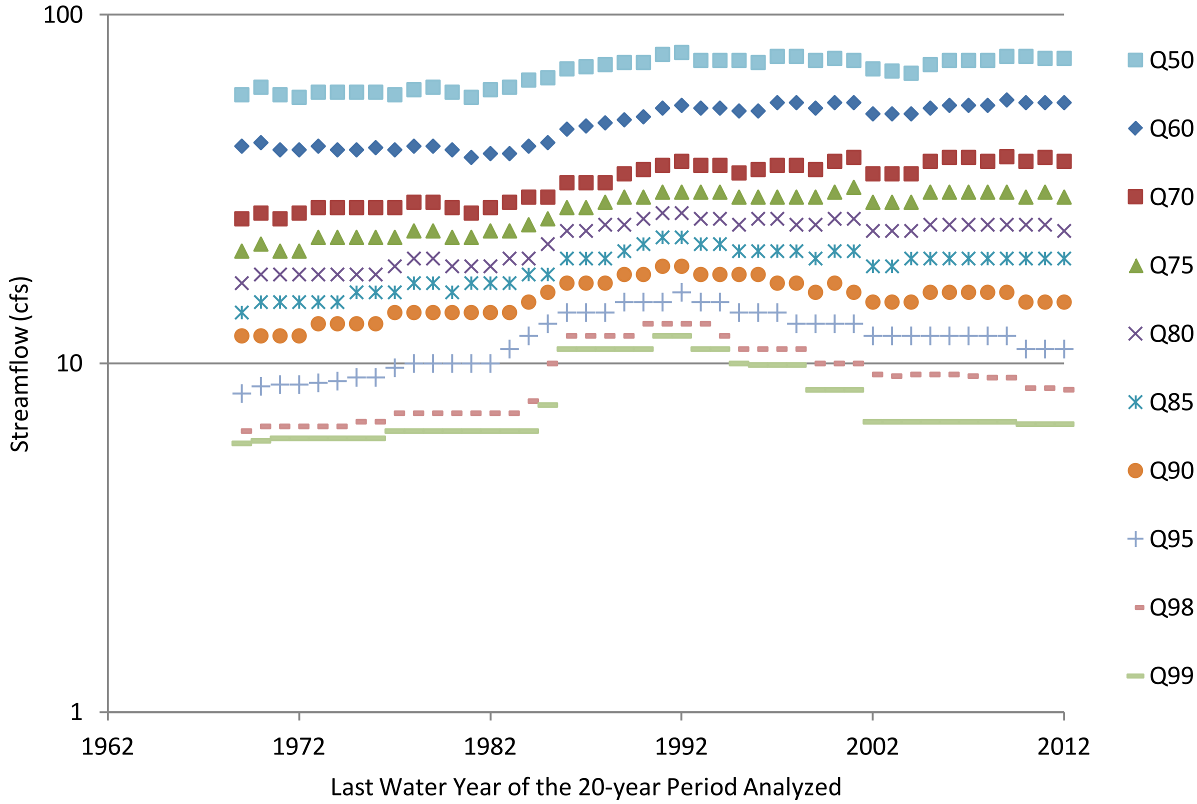

Figure 11. Plot of 20-year streamflow quantiles for the gaging station on the Squannacook River near West Groton, MA over the station's entire period of record through water year 2012.

in the Q60 through Q90 flows. Trends were weaker for the Q95 through Q99 flows (fewer stations showed significant trends for these flows than for the more median flows), and a greater proportion of stations showed downward trends in 20-year quantiles for these flows. Significant trends, upward or downward, were present at only 68.8% of stations for the Q95 and Q99 flows, and 62.5% of stations for the Q98 flow.

Between 1992 and 2012, the trends flattened or became downward trends for many of the higher exceedance probability quantiles (lower flows), with downward trends being greatest for the lowest flows (Figure 12; Appendices H and I). Trends were stronger for the post-1992 than for the stations' periods of record for the Q85 through Q99 flows—a greater proportion of

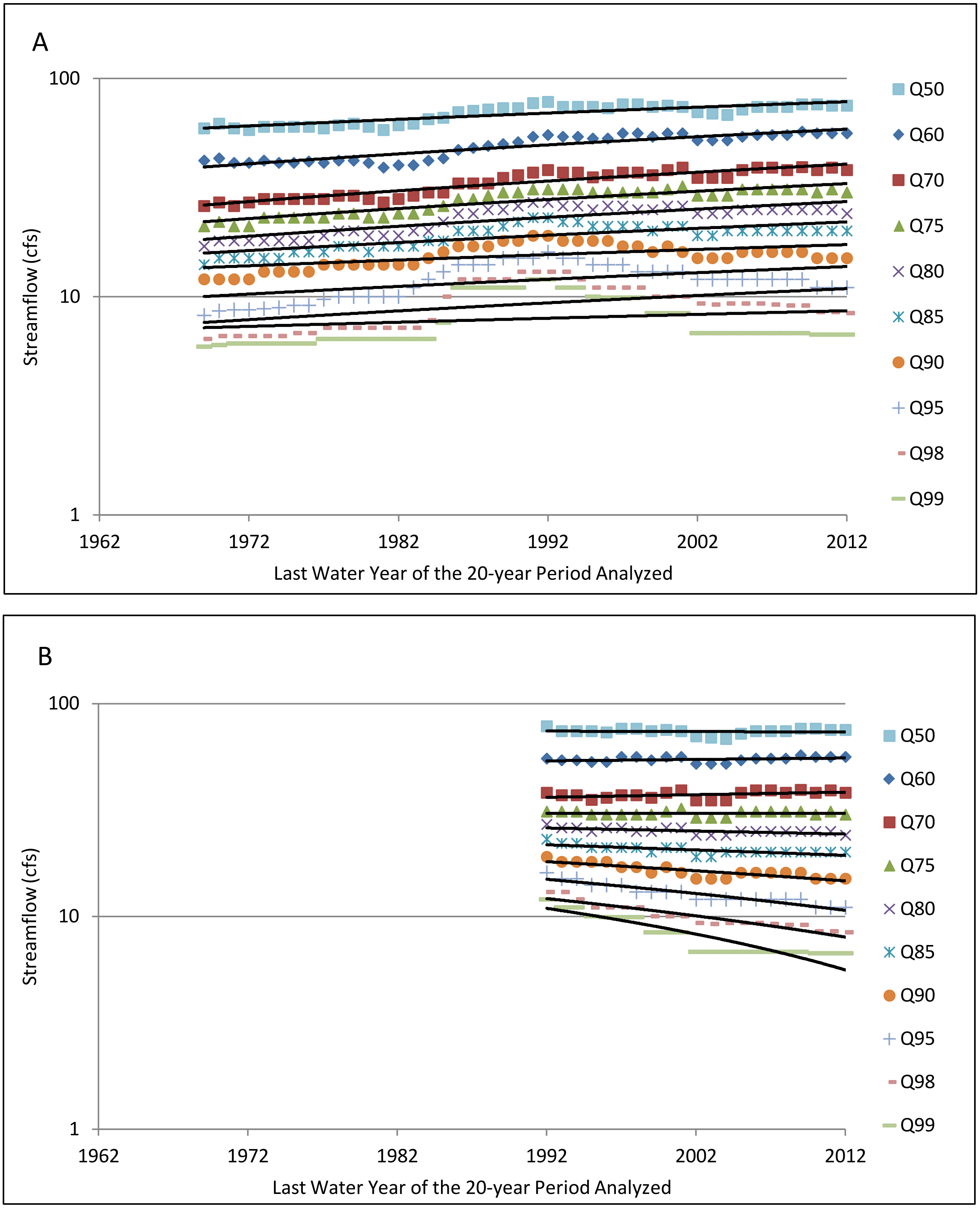

Figure 12. Linear least-squares trend lines fitted to 20-year streamflow quantiles over the entire period of record (panel A) and just the post-1992 period (panel B) for the gaging station on the Squannacook River near West Groton, MA.

Streamflow Model	Failure year (Period of Record trend)	Percent of Trends with *p* <0.05	Overestimate (O) or Underestimate (U)	Failure year (Post-1992 trend)	Percent of Trends with *p* <0.05	Overestimate (O) or Underestimate (U)
Q50	2081	87.5	U	2067	56.3	U
Q60	2081	87.5	U	2041	75.0	U
Q70	2118	87.5	U	2071	75.0	U
Q75	2092	93.8	U	2070	81.3	U
Q80	2158	93.8	U	2066	93.8	O
Q85	2159	81.3	U	2052	93.8	O
Q90	2155	75.0	U	2044	81.3	O
Q95	2159	68.8	O	2032	81.3	O
Q98	2126	62.5	O	2027	81.3	O
Q99	2114	68.8	O	2018	87.5	O

Table 6. Estimated failure years, percent of trends with *p*-values <0.05, and types of failure (overestimate or underestimate) for the Ries and Friesz (2000) streamflow models, calculated from period-of-record and post-1992 trend analyses. Best estimates of years at which the models will no longer be valid are highlighted.

stations showed trends with $p < 0.05$ for the post-1992 period for these flow-durations. An equal number of stations (15 of 16) showed trends in the Q80 flow with $p < 0.05$ for the post-1992 period as for the gages' entire periods of record. Of significant trends ($p < 0.05$) for the post-1992 period, over 92% were downward for the Q95, Q98, and Q99 flows. Specifically, best-fit lines had negative slopes for 92.3% of significant trends in the Q95 flow, 100% of significant trends in the Q98 flow, and 92.9% of significant trends in the Q99 flow. The water years at which projected streamflow quantiles will be outside the RF model 90-percent prediction intervals for more than 10% of gaging sites in the sample set (the failure years) for the period-of-record and post-1992 trend analyses are presented in Table 6.

Discussion

The general upward translation of FDCs between the pre- and post-1996 (climatic year) periods observed at the original and additional gaging stations (Appendices A and D) is consistent with increasing mean precipitation in southern New England during these periods. Increasing streamflows are what would be expected in a region where historical records show a long-term trend in annual precipitation of about +9.5 millimeters per decade over the last century (Hayhoe et al., 2007). The greater and more widespread increases in streamflow observed in the western hydrologic region (e.g., Figures A7, A8, A10, and D17) are consistent with a greater increase in precipitation in that region, which includes all watersheds to the west of and including the Connecticut River valley. An analysis of monthly rainfall data from six precipitation-gaging stations in Massachusetts (three in each hydrologic region) for the period of calendar years 1950 to 2011 showed a greater average increase in monthly precipitation in the western region between the pre- and post-1996 periods (Massachusetts DCR, 2014). A more rigorous statistical analysis of precipitation data is needed, but it is likely that the greater average increases in streamflow quantiles observed in the western hydrologic region are linked to greater increases in precipitation in that region between the pre- and post-1996 periods.

The general increases in flow-durations between the two periods were lessened or reversed—becoming decreases—at the highest exceedances probabilities for gaging stations both within and adjacent to Massachusetts. Very low flows showed smaller increases or decreases between the pre- and post-1996 periods, with the largest decreases observed for the lowest flows (e.g., Figures A2, A5, D1, and D6). Very low daily streamflows in southern New England occur during the late summer months, when groundwater storage is depleted by the effects of evapotranspiration. Steady increases in mean annual and summer temperatures (and corresponding evapotranspiration), combined with little change or decreases in summer rainfall in the northeastern US since the mid-20th century (Hayhoe et al., 2007; USGCRP, 2009), are likely causing decreasing summer baseflows in watersheds across southern New England (Figures 13 and 14). Forecasted increases in summer temperatures, combined with more frequent and more severe drought periods (Hayhoe et al., 2007; USGCRP, 2009), could have a significant impact on very low streamflows in southern New England, and pose a serious threat to aquatic ecosystems and water supplies in the region.

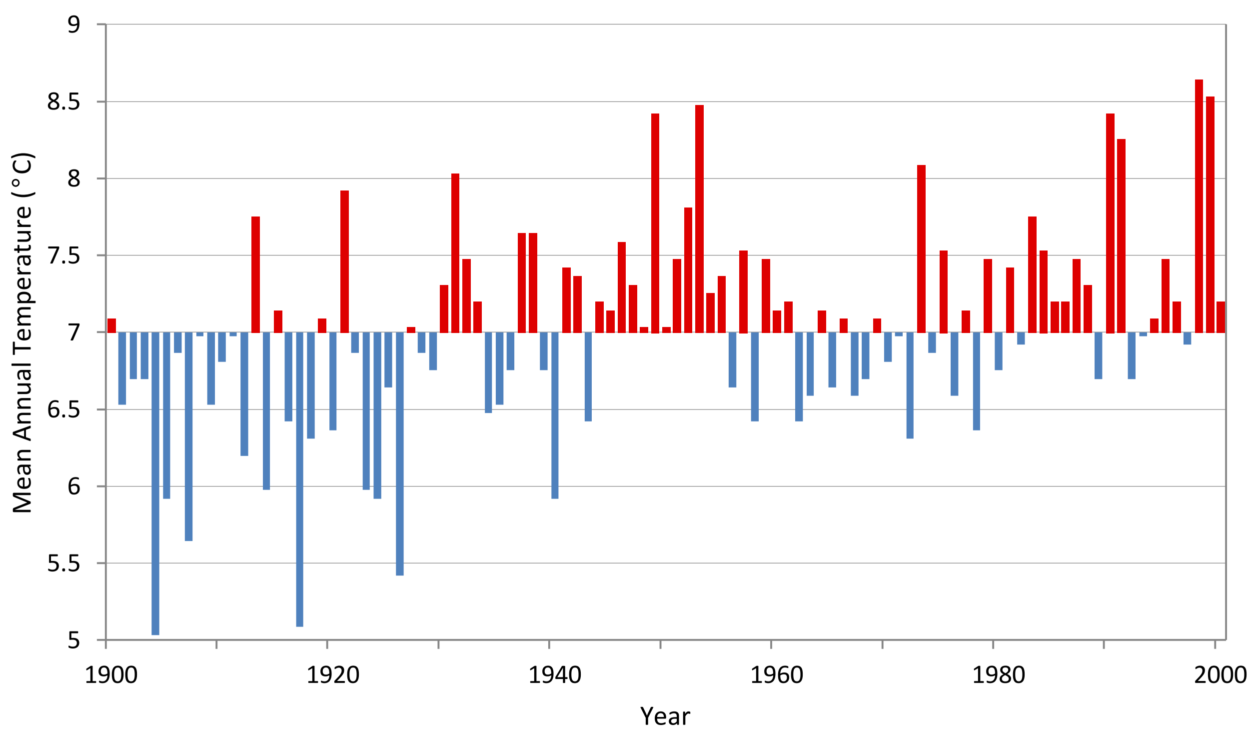

Figure 13. Mean annual temperatures for the northeastern US from 1900 through 2000. The time series is an areally weighted average of temperature records from 56 stations in the region (after Clean-Air Cool Planet and Wake, 2005).

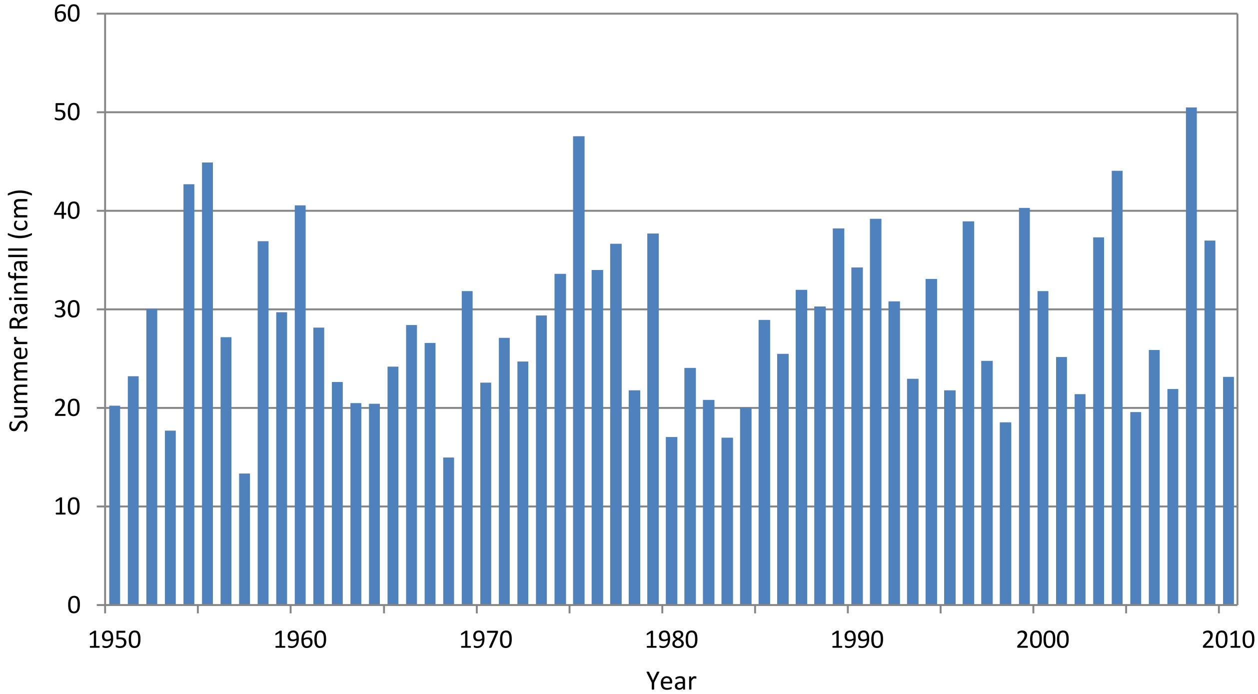

Figure 14. Total summer (July through September) rainfall for Massachusetts from 1950 through 2010. The time series is an average of precipitation records from six stations in the state (Massachusetts DCR, 2014).

Low-flow quantiles decreased by an especially large factor between the pre- and post-1996 periods at three gaging stations: the gages on the Nashoba Brook near Acton, MA, the Parker River at Byfield, MA, and the Nipmuc River near Harrisville, RI (Figures A2, A3, and A5, respectively). The pronounced drops in low flows were particularly severe at the Parker River at Byfield, MA streamgage, where the post-1996 FDC above the 75-percent exceedance probability displayed a marked downward slope. These anomalous changes in FDCs could in part be the result of human alterations of the natural streamflow regime, for which there is evidence in the Parker River watershed, where considerable increases in water withdrawals for public water supply and industrial uses since 1990 have been documented (Gomez and Sullivan, 2003). The three rivers with observed decreases in very low flows so severe as to appear as outliers were all situated in the eastern hydrologic region. Human influences on low streamflows are more likely to arise in the eastern hydrologic region of Massachusetts, where more than two-thirds of the state's population resides (U.S. Census Bureau, 2011). Increased water withdrawals and urban development (area of impervious surfaces) reduce baseflows, and could have significant impacts on low streamflows in southern New England during this century, above and beyond reductions already caused by increased evapotranspiration and more frequent droughts.

When the RF regression equations were applied to 15 of the gaging stations used in their analyses (Part I) and 21 additional stations in southern New England (Part II) for the period of climatic years 1996-2011, the models performed well overall, accurately estimating 90-percent prediction intervals for more than 90-percent of gaging stations at most of the ten estimated flow-durations (Appendices A through F). Flow-durations were accurately predicted at 94.4% of sites for the Q50 and Q60 flows, 97.2% of sites for the Q70, Q75, Q85, and Q90 flows, and 100% of sites for the Q80 flows. For the three models (Q95, Q98, and Q99) that failed at more than 10% of sites overall, the failure rates and sample set size were such that the models could not be rejected as inaccurate with greater than 95% certainty ($p > 0.05$). However, the prediction intervals for the estimated streamflows were relatively wide, in many cases spanning more than an order of magnitude, with the widest prediction intervals being for the lowest flows. By comparison, the entire FDC for streams in southern New England generally span only about three orders of magnitude. The sizes of the models' prediction intervals are directly related to their precisions, and thus their value to end users. Although the RF models may be statistically accurate, their imprecision could detract from their utility as predictive tools for practical hydrologic applications. The usefulness of the RF models, as with any model, is ultimately determined by user design thresholds and tolerances for imprecision.

While the RF equations were generally accurate in estimating flow-durations for the post-1996 period, they displayed clear biases towards underestimating the Q50, Q60, Q70, and Q75 flows (e.g., Figures B1, C1, E1, and F1). The biases were present for streams in both hydrologic regions and for sites both within and outside of Massachusetts. These model tendencies towards underestimation were likely caused by increases in annual precipitation in southern New England between 1950 and 2011, resulting in higher streamflows at the more median quantiles. The RF regression equations, which were based on pre-1996 discharge data, cannot account for changes in climate variables since 1996 that have altered natural streamflow regimes. Increasing precipitation over the 21st century is likely to amplify the existing RF model biases towards underestimation of the more median low-flow quantiles and increase the rate of model failures due to underestimation of these flows. While there did not yet appear to be statistical biases towards overestimation of the lowest flows for the post-1996 period, projected decreases in summer baseflows in New England over the 21st century due to increasing temperatures and other regional climate changes, such as more severe and frequent droughts, have the potential to cause biases in the models towards overestimation of very low streamflows. In watersheds increasingly influenced by water withdrawals and urban land use, as many basins in the eastern hydrologic region are, additional decreases in low flows over the coming decades are likely to occur, which would further decrease the ability of the RF regression equations to accurately estimate low flows.

The increases observed in most streamflow quantiles between the pre- and post-1970 (water year) periods, and consecutively between the pre-1970, 1971-1995, and 1996-2012 periods (Appendix G), are not surprising given the observed increases in average precipitation in southern New England during these periods. For 13 of the 17 gaging sites examined in the Part

III analysis, the increases in most streamflow quantiles between the pre-1970 and 1971-1995 periods were greater than the increases between the 1971-1995 and 1996-2012 periods. This is consistent with the findings of Hayhoe et al. (2007), who found greater increases in annual and seasonal precipitation in the northeastern US prior to 1970 than for the period since 1970. The increases in most streamflow quantiles (excluding very low flows) across the time periods analyzed, although varying in degree and the parts of the FDC affected, were in evidence at all 17 gaging stations in the sample set, and likely driven by the observed trend towards increasing precipitation in southern New England during these periods.

As in the analyses of the streamgages in Parts I and II, which used the end of climatic year 1995 to divide the gages' periods of record, the trend towards increasing streamflow quantiles at the gaging sites in Part III was slowed or reversed for the lowest flows. These decreases—or smaller increases—in very low flows were more pronounced, more common, and affected a greater portion of the FDC for the 1996-2012 period than for either of the earlier periods, suggesting an accelerating downward forcing on these flows. This distinct drop in the lowest streamflow quantiles for the most recent period could be the result of increasing temperatures and relatively unchanged summer precipitation in southern New England since 1970, which in combination would depress summer baseflows. Additionally, although one criterion for selection of a gaging station to be used in the analyses was that it monitored an unregulated or nearly unregulated stream, there are few watersheds in southern New England that are completely free of human influences, either by direct manipulation of streamflows or the presence of areas of impervious surfaces. Therefore, the effects of anthropogenic factors on low flows should not be discounted as a possible source of the observed downward trends, especially in the more populated eastern hydrologic region of southern New England.

The plotting of 20-year streamflow quantiles for each of the ten flow-durations of interest for each of the 16 gaging stations in Part IV (Appendix H), revealed information about trends in low-flow quantiles at the gaging sites that would otherwise have remained hidden. In addition to supporting the general findings of the first three parts of this study—that most flow-durations increased through the latter half of the last century, while very low flows increased to a lesser extent or decreased—the moving quantiles displayed an apparent inflection point around the beginning of water year 1992 (last year of the 20-year period for which the quantile was calculated). Very low streamflows—particularly the Q98 and Q99 flows—showed increases or only very slight decreases prior to 1992, and decreases after 1992. This flattening or reversal of trend direction for the lowest flows was evident to some extent at every station, always around the early 1990s.

The existence of an inflection point in 20-year low-flow quantiles around 1992 is likely the result of a combination of climatic and anthropogenic factors, as well as the particular way the data were divided for analysis. Annual and summer temperatures in the New England region have shown steady increases since the mid-20th century, offsetting the effects of increasing annual precipitation by increasing evapotranspiration rates (Hayhoe et al., 2007). Moreover, summer precipitation at many locations in Massachusetts has been steady or shown decreasing trends since 1970 (Massachusetts DCR, 2014). Increasing human influences in southern New England over the last half-century, including greater water withdrawals and urban land use, also contribute to reduced baseflows (Armstrong et al., 2008). Finally, the peak in 20-year low-flow quantiles (typically observed at or around the 1973-1992 period) include both of the unusually wet years of 1973 and 1991. As a result, the spike in low-flow quantiles is in part a consequence of the statistical method used to analyze the data. Figure 15 shows 1-year Q99 flows for the

Wading River near Norton, MA streamgage from 1952 to 2012, with the local peak values at the beginning of the 1970s and 1990s being evident. Additional wet or dry years would be expected to similarly affect 20-year quantiles, suggesting that this period may be too short to produce very robust trends.

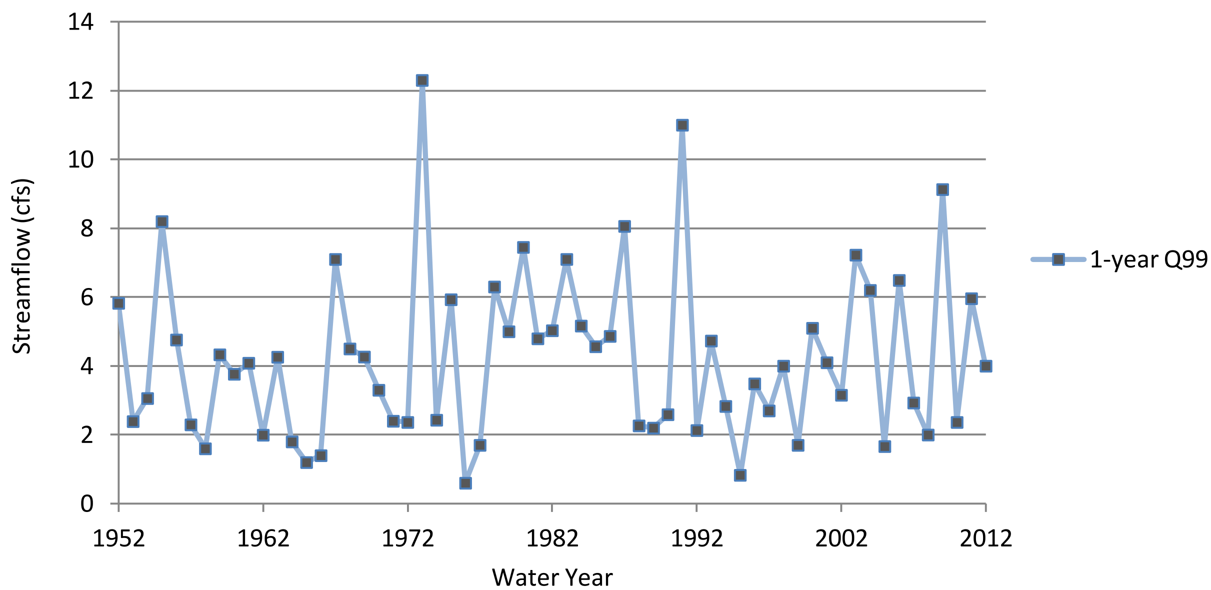

Figure 15. One-year Q99 flows for the gaging station on the Wading River near Norton, MA for water years 1952-2012. The two highest 1-year Q99 flows occurred in 1973 and 1991.

Trends in 20-year streamflow quantiles over the gaging stations' entire periods of record (POR) were strongest for the more median flows (Q50 to Q75); the inflection point for very low flows around 1992 reduced the strength of POR trends for these quantiles (Appendix I, Tables I1-I4). To better capture the more recent trends, especially in very low flows, lines of best fit were also applied to 20-year quantiles for just the period of water years 1992 to 2012 (Figure 12b). Trends for the post-1992 period were stronger than those for the entire POR for the Q85, Q90, Q95, Q98, and Q99 flows (Table 6). To estimate when the RF equations will no longer by valid (when actual flows will be outside the 90-percent prediction intervals for the estimates), POR and post-1992 trend lines for all ten flow-durations were projected into the future to the point (failure year) where the flows met the upper or lower bound of the prediction interval. A critical assumption of the POR and post-1992 best-fit line extensions is that these trends are linear and will continue to be over the foreseeable future. The trend line projections cannot account for future non-linear changes in climate variables, but the estimates of failure dates provided by the trend analyses are generally consistent with the historic changes in streamflow quantiles observed in Parts I, II, and III of the investigation.

Because two trend analyses were performed—for the station PORs and for the post-1992 periods—two failure years were estimated for each flow-duration model, in addition to whether the failure would be due to overestimation or underestimation. Which of the two estimated failure years should be considered a better approximation is dependent on the goodness-of-fit metrics (*p* values) for the trend lines. The analyses that had a greater number of trend lines with significant *p* values ($p < 0.05$) were considered to provide a better approximation (Table 6). Figure 16 presents an example of a POR trend-line extension for the Q50 flow at the Green River at Williamstown, MA streamgage, and Figure 17 presents an example of a post-1992 trend-line extension for the Q99 flow at the Squannacook River near West Groton, MA streamgage. The quantile trends at these gages were typical of the general trends observed in the analysis. For the Q50 through Q75 flows, stronger trends were seen in the POR analysis, while for the Q85 trends, there were a greater number of significant trends in the post-1992 analysis (Table 6). This is not surprising given that the lower flows were more greatly affected by the apparent 1992 inflection point. The Q80 analysis displayed an equal number of significant trends for both the POR and post-1992 analyses, so the more conservative (sooner) estimated failure year (2066) was chosen as the best first approximation (Table I5).

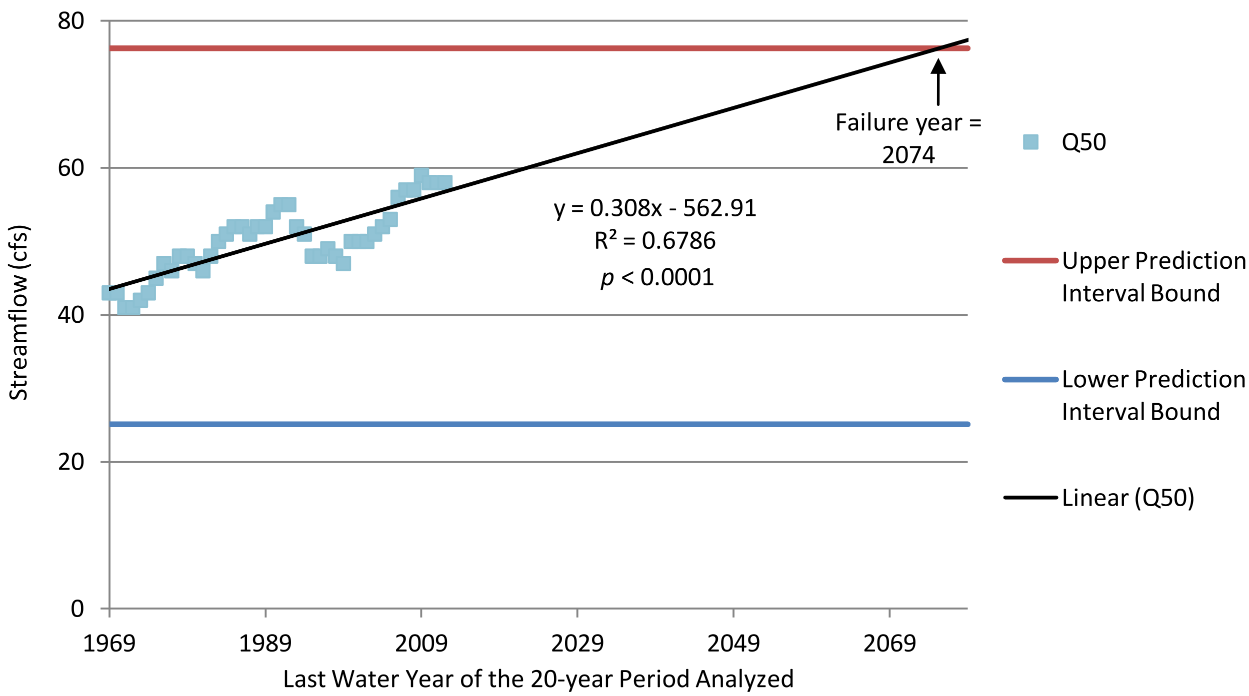

Figure 16. Period-of-record trend line extension for 20-year Q50 flows at the Green River at Williamstown, MA streamgage. If the observed trend continues, the Q50 RF model will fail due to underestimation at this site in 2074.

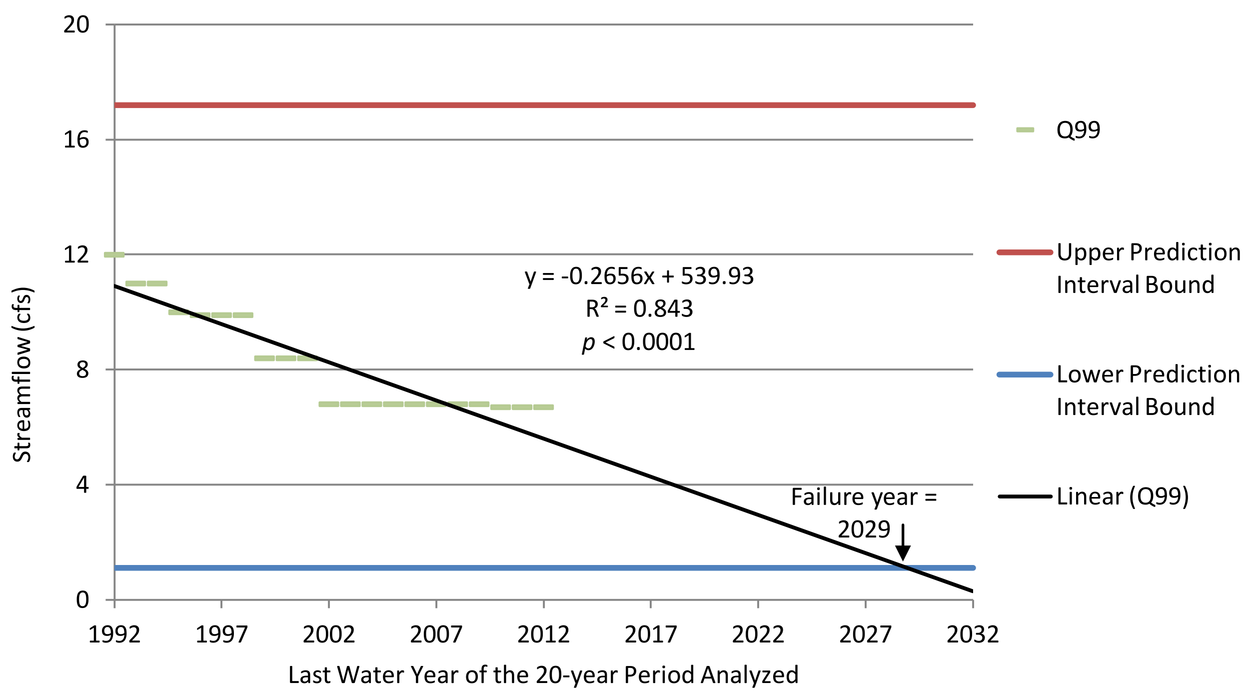

Figure 17. Post-1992 trend line extension for 20-year Q99 flows at the Squannacook River near West Groton, MA streamgage. If the observed trend continues, the Q99 RF model will fail due to overestimation at this site in 2029.

Collectively, the four parts of this study present a picture of a hydro-climatologic system in southern New England in which increasing precipitation and temperature indices are driving multiple and sometimes opposing trends in streamflow statistics. The results show that median low-flow quantiles (Q50 through Q80 flows) are generally increasing, moderately low flows (Q85 and Q90) are relatively steady, and very low flows (Q95, Q98, and Q99) are decreasing in the region. While it is difficult to predict when the RF models will no longer be valid, changes in streamflow characteristics in southern New England since 1996 appear to have already generated a certain degree of bias in the models towards underestimation of more median low-flows and overestimation of very low flows. Despite these biases, many of the equations may continue to produce acceptable estimates for several decades to come because of the relatively wide prediction intervals associated with the estimates. The results of this investigation indicate that the first models to lose validity will likely be those for the lowest flows (Q98 and Q99). If the trends in these streamflow quantiles over the last two decades continue, the models for these flows could be rendered invalid by as soon as 2018, with other models losing validity within the following decades. It is therefore recommended that the RF streamflow estimation equations be reformulated within the next decade using more recent streamflow data. Given the significant changes in climate variables projected for the New England region over the 21st century, it is likely that the equations will need to be validated and recalibrated approximately every 20 years to account for the effects of nonstationarity on unregulated streamflows.

Conclusion

Increasing attention has been drawn to the need for accurate streamflow estimates in ungaged basins, which are required for effective water resources management, infrastructure design, and environmental protection. Streamflow models, typically derived by regional regression techniques, transfer historic data from a group of gaging stations in a region to an ungaged basin of interest using physical basin characteristics as explanatory variables. However, such streamflow models assume relatively unchanging climatic variables, such as air temperature and precipitation, which can have significant effects on a watershed's streamflow characteristics. Climate projections for the New England region over the 21st century indicate higher annual precipitation but relatively unchanged summer rainfall, higher temperatures, and longer periods of drought between rainfall events. These climatic changes—and the corresponding changes in streamflows they bring about—threaten to decrease the accuracies of existing streamflow estimation methods for the southern New England region.

The analyses of historic daily streamflow data carried out in this investigation revealed several changes in streamflows in southern New England watersheds since the mid-20th century. Periods of record of streamflow data were divided using both 1970 and 1996 as cut dates, and flow-duration curves for the gaging stations were computed using data from each of the shorter periods. Additionally, 20-year moving quantiles were calculated for a set of 16 stations using their entire periods of record through water year 2012. The results indicate that, on average, more median streamflows (Q50 through Q80 flows) have increased since the mid-20th century, moderately low flows (Q85 through Q90 flows) have been relatively unchanged, and very low flows (Q95 through Q99 flows) have decreased. The beginning of water year 1992 appeared to mark an inflection point for very low flow characteristics in southern New England, before which these flows were increasing or relatively unchanged, and after which these flows showed marked decreases. The increases observed in the majority of streamflow quantiles are almost certainly the result of increasing average precipitation, while the decreases in very low flows are likely linked to increasing temperatures (causing greater evapotranspiration), steady or decreasing summer precipitation, and anthropogenic factors such as increasing urban development and areas of impervious surface. The local peak in 20-year quantiles observed around the 1973-1992 period was also likely augmented by the wet years of 1973 and 1991.

The Ries and Friesz (2000) (RF) regression equations continue to estimate daily streamflow quantiles within a 90% confidence range, both within Massachusetts and in neighboring states, despite changes in streamflows in the region since the equations were developed. Although observed flow-durations were generally within the prediction intervals for the estimated flows, watershed responses to regional climate change appear to have rendered the RF models biased towards underestimating more median streamflows and overestimating very low flows. These biases are expected to increase with projected increases in mean precipitation and temperature in the New England region over the 21st century. The confidence intervals for the RF equations are relatively wide—in many cases spanning an order of magnitude or more—and their usefulness is ultimately dependent upon user design parameters and tolerances.

For the RF models to remain valid, actual streamflows must be within the estimated 90-percent prediction intervals for more than 90% of stream sites. If streamflows in southern New England continue their observed trends, the RF equations in their present form will begin to lose validity over the coming decades. Exactly when the models will no longer be valid depends on the rate of change of regional climate variables, drainage basin responses to those changes, and the particular streamflow quantile being modeled. It is likely that decreases in very low flows due to increasing summer temperatures will cause the models for these flows to lose validity (due to overestimation) before increases in annual precipitation cause the models for the more median flows to no longer be valid (due to underestimation). The trend analyses performed on period-of-record and post-1992 streamflow suggest that the regression equation for the Q99 flow could lose its stated accuracy by as early as 2018. The trend analyses, in combination with the observed recent changes in streamflows in southern New England and climate projections for the region, suggest that the RF models, especially those for the lowest flows, should be reformulated within the next decade to account for changes in streamflows due to nonstationarity, and validated approximately every 20 years thereafter to ensure the model estimates continue to be reliable to end users.

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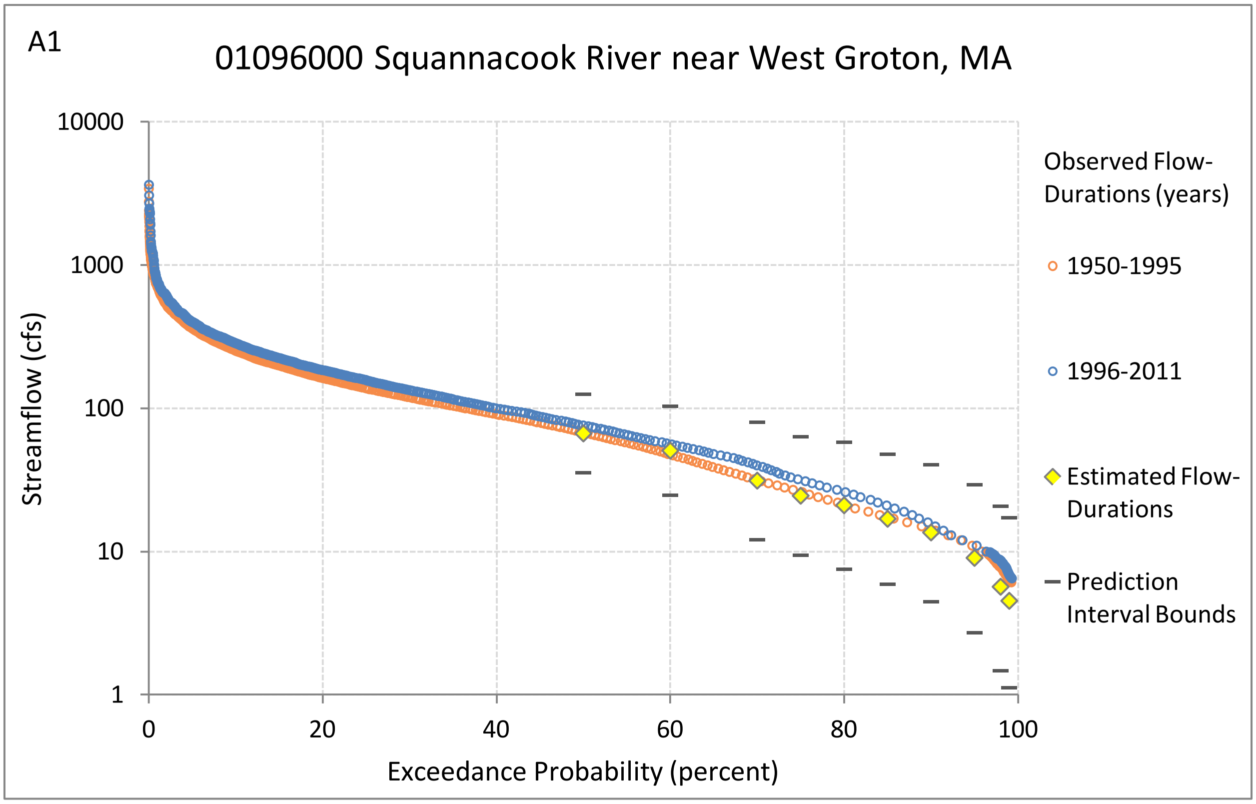
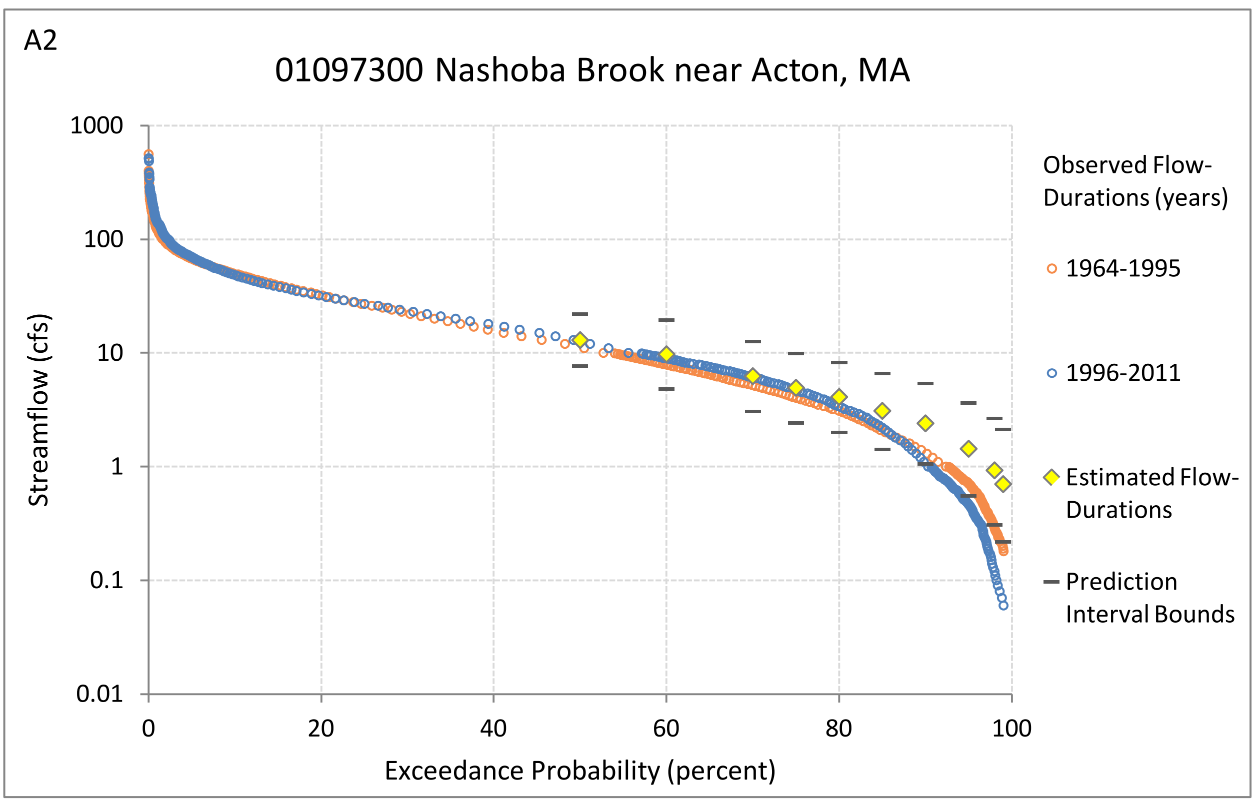
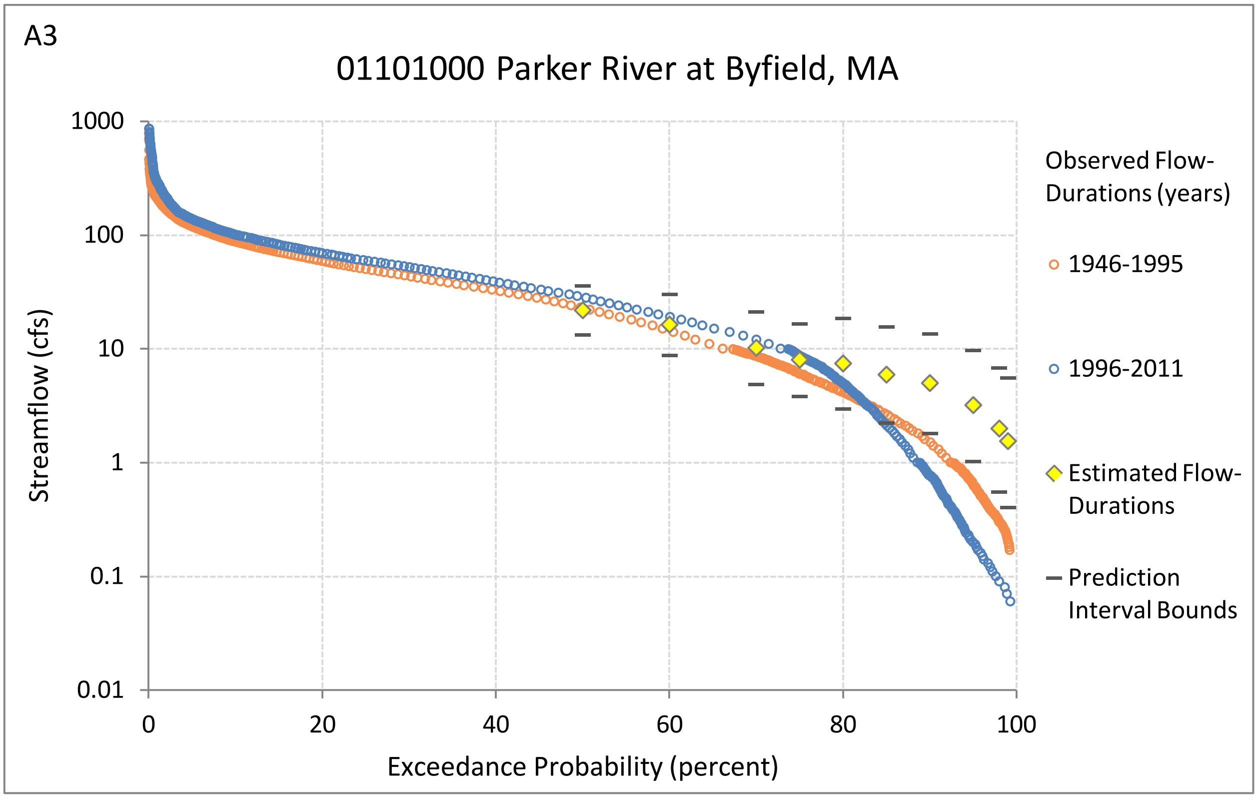
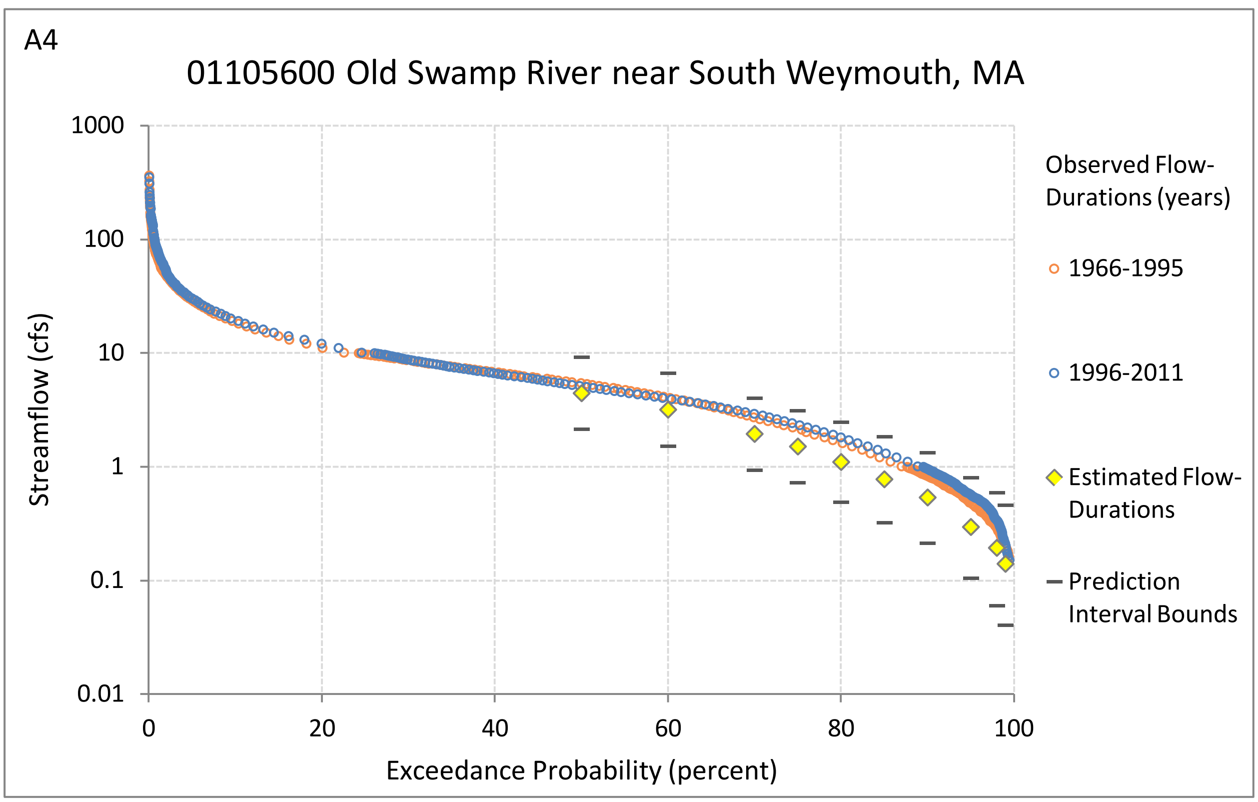
Appendix A

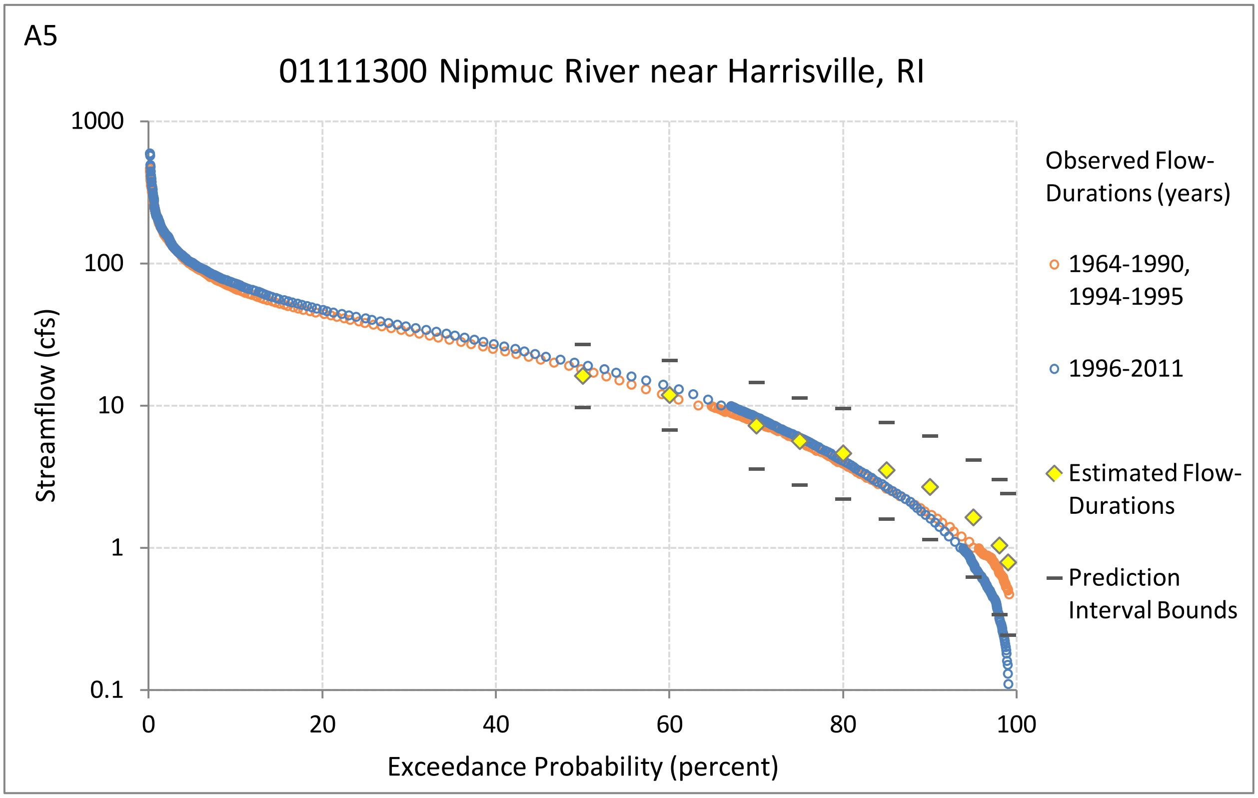
Part I Flow-Duration Curves


A1
01096000 Squannacook River near West Groton, MA
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1950-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

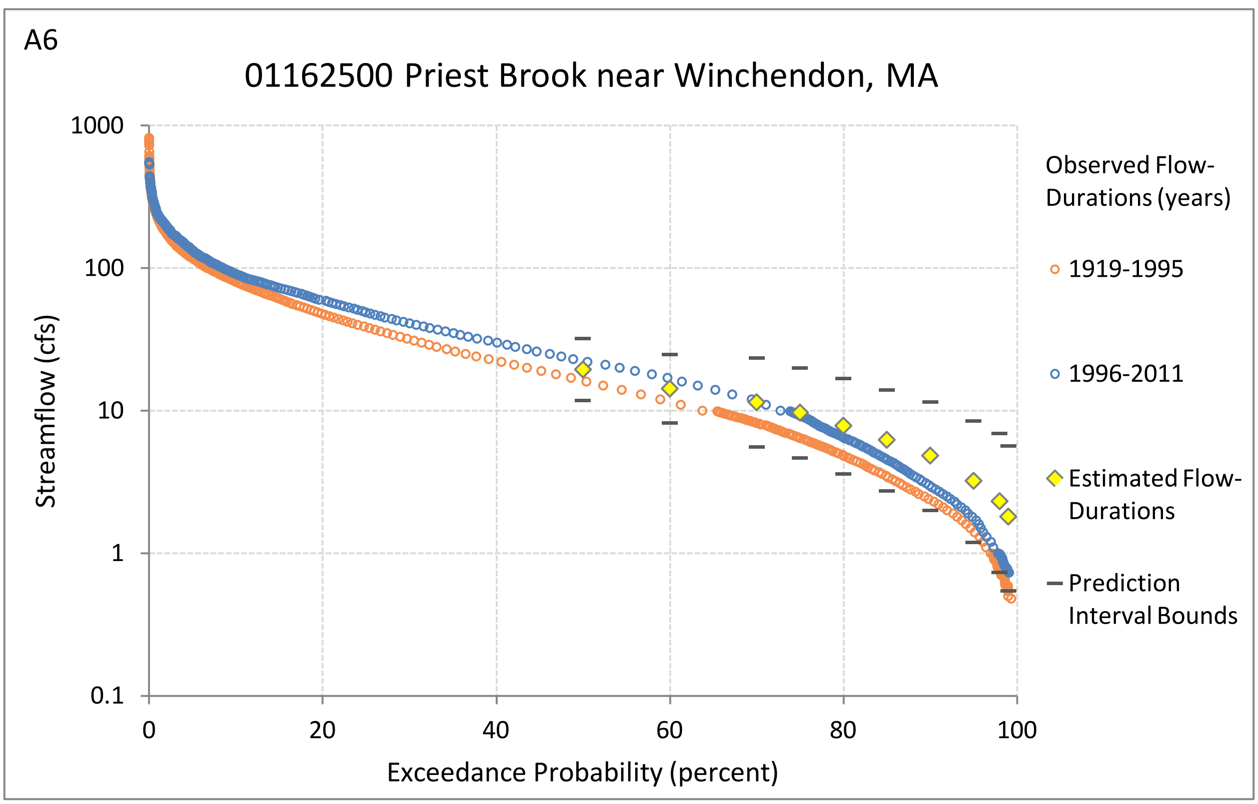

A2
01097300 Nashoba Brook near Acton, MA
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1964-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


A3
01101000 Parker River at Byfield, MA
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1946-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

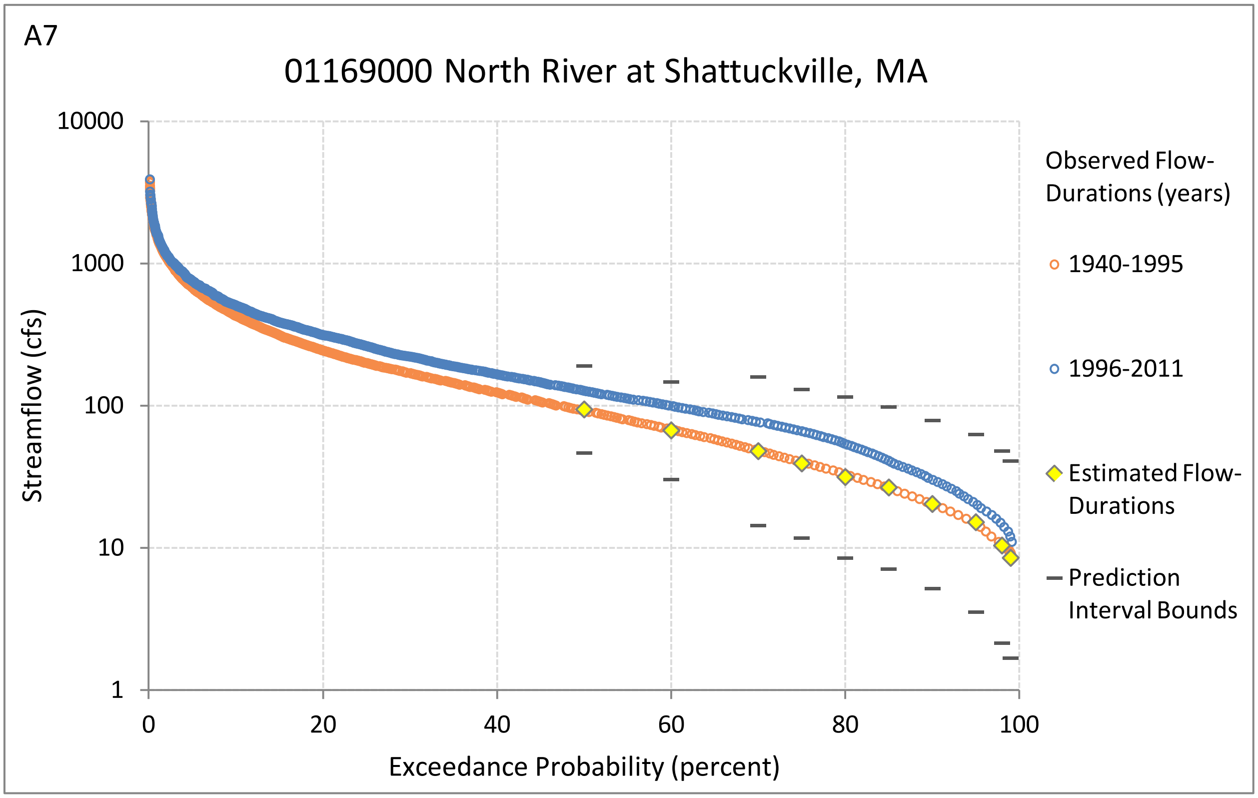

A4
01105600 Old Swamp River near South Weymouth, MA
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1966-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

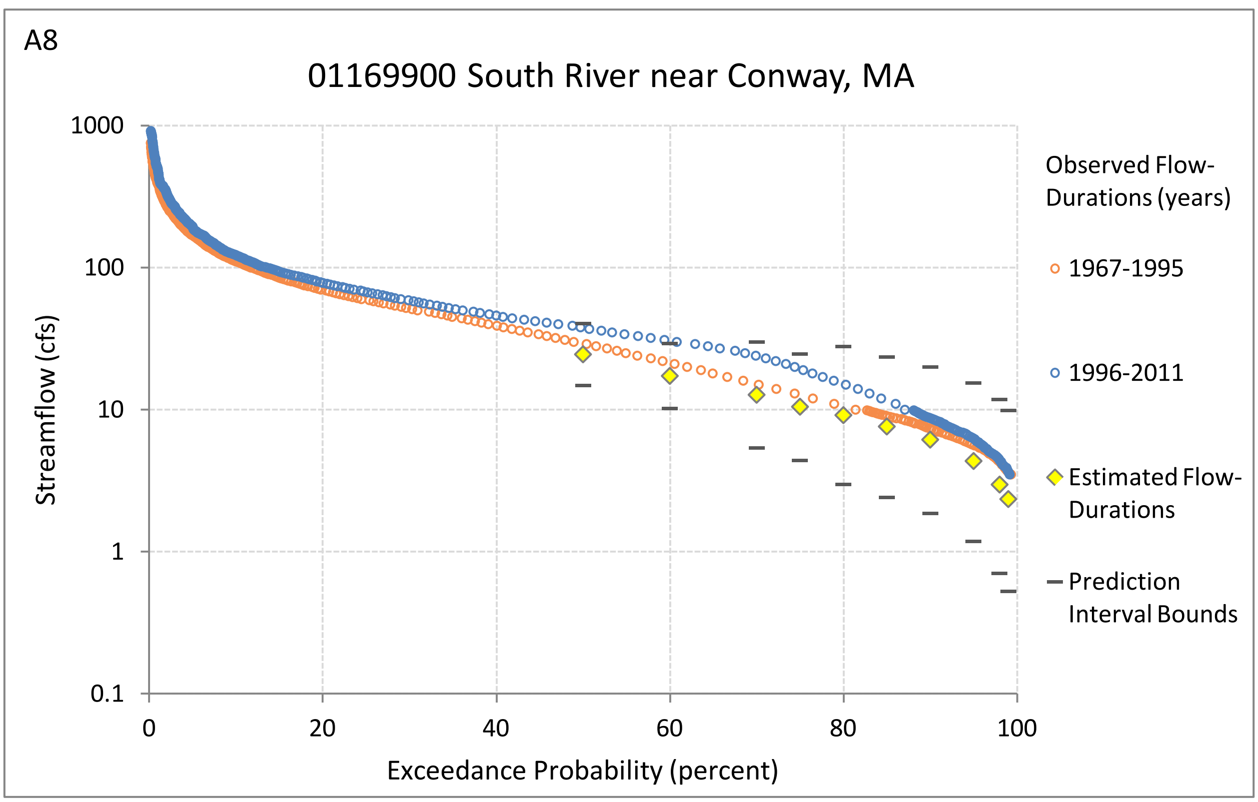


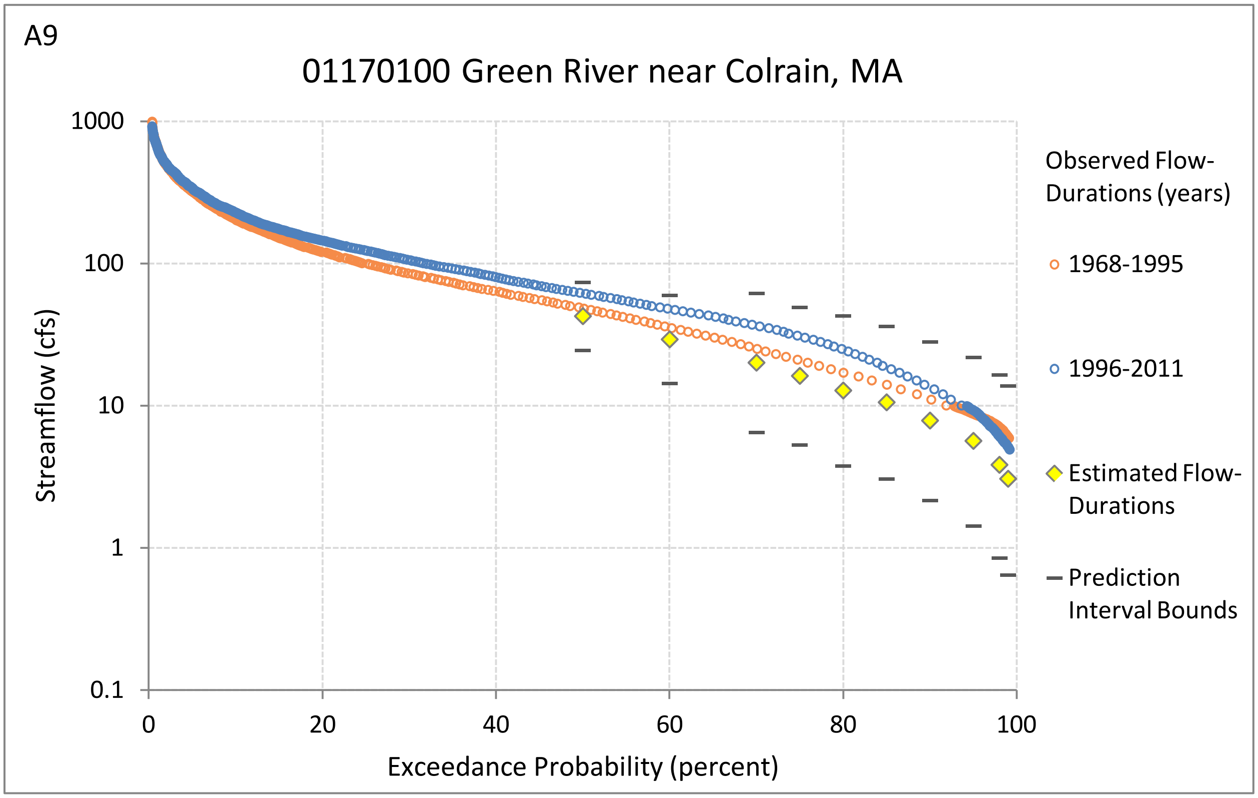
A5
01111300 Nipmuc River near Harrisville, RI
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1964-1990, 1994-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

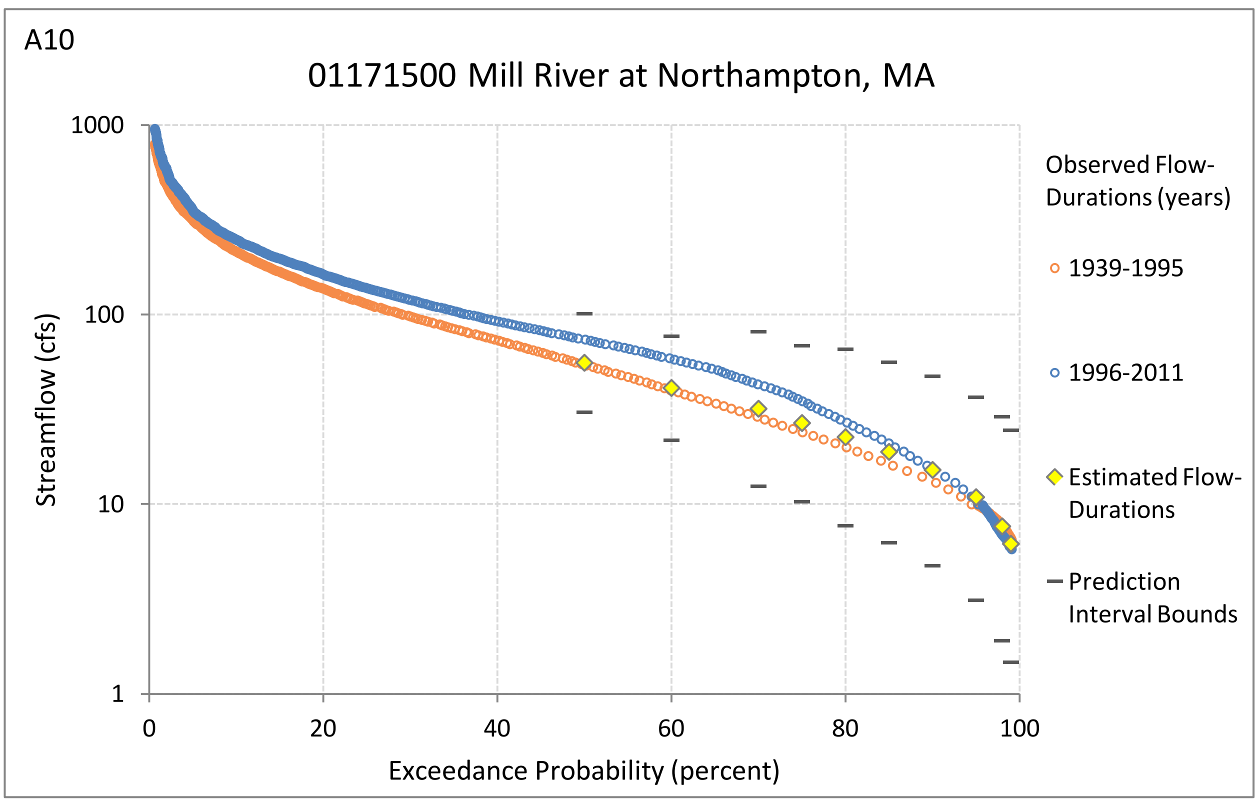


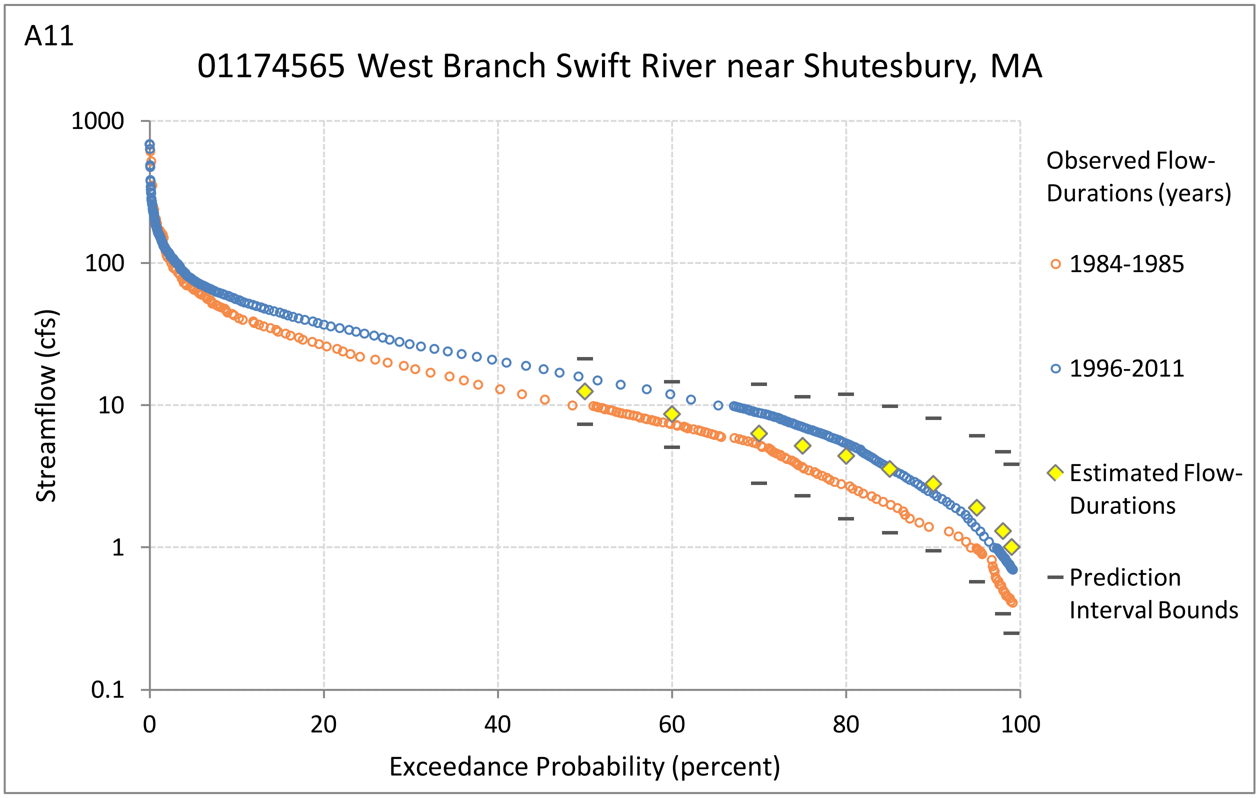
A6
01162500 Priest Brook near Winchendon, MA
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1919-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

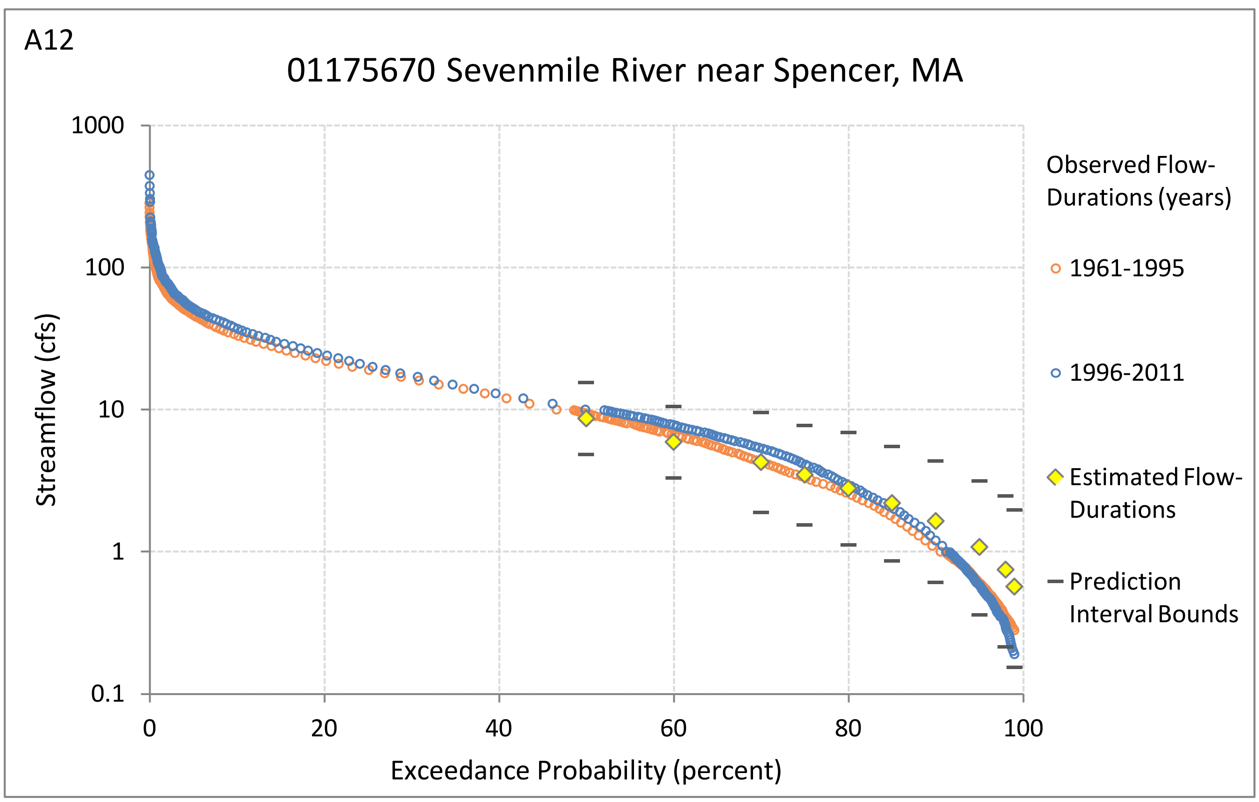

A7
01169000 North River at Shattuckville, MA
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1940-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

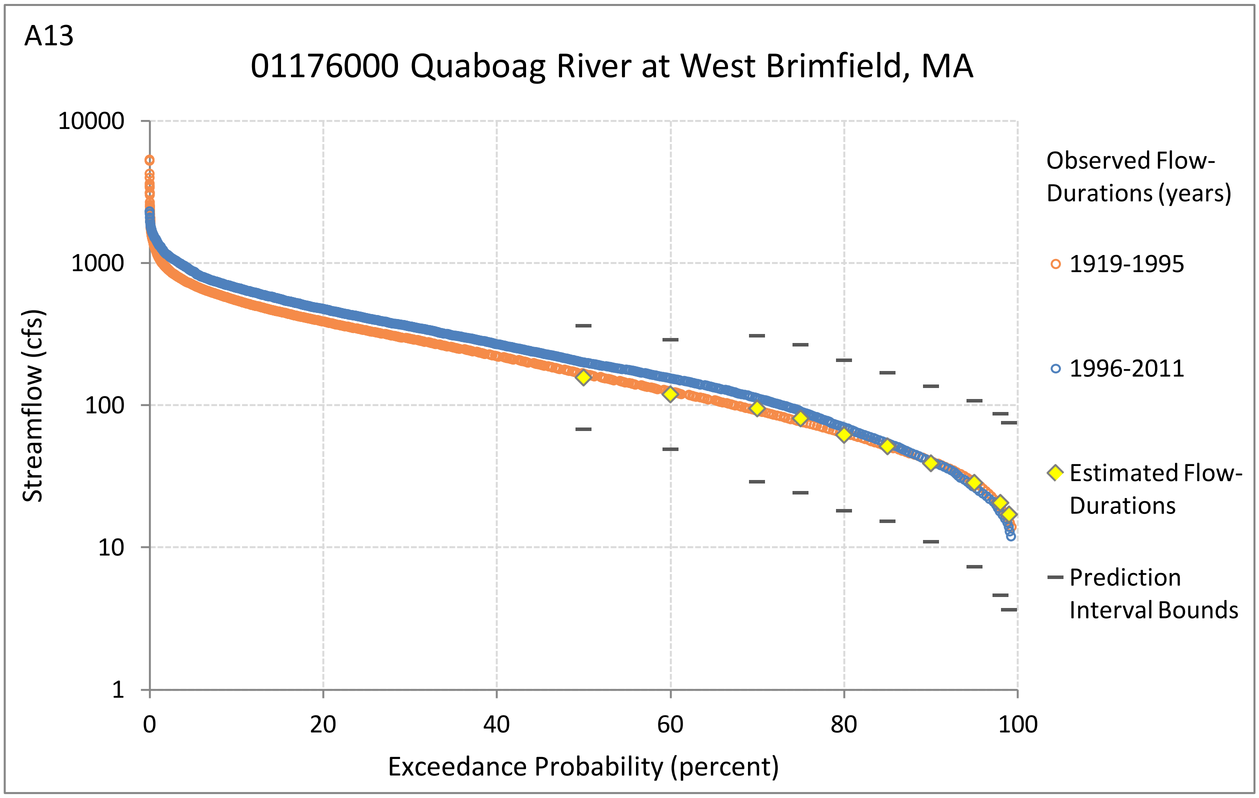

A8
01169900 South River near Conway, MA
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1967-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

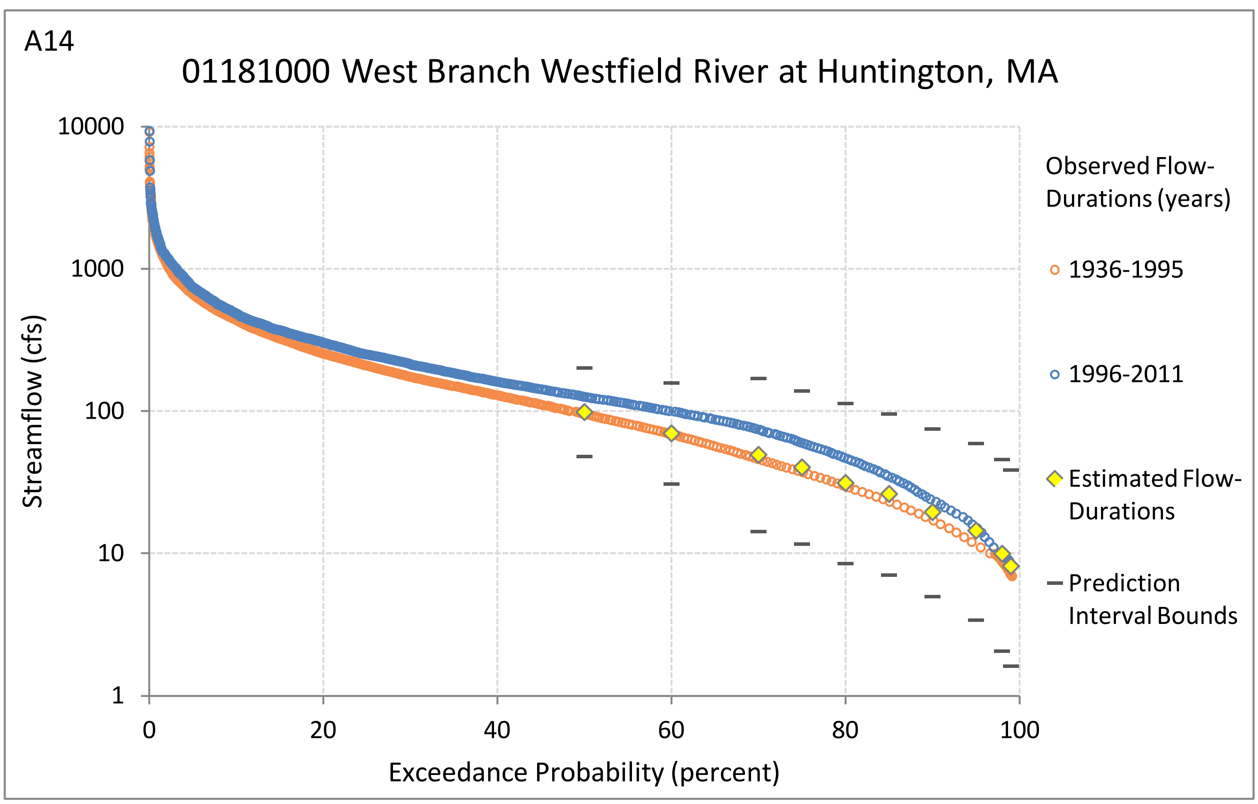

A9
01170100 Green River near Colrain, MA
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1968-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

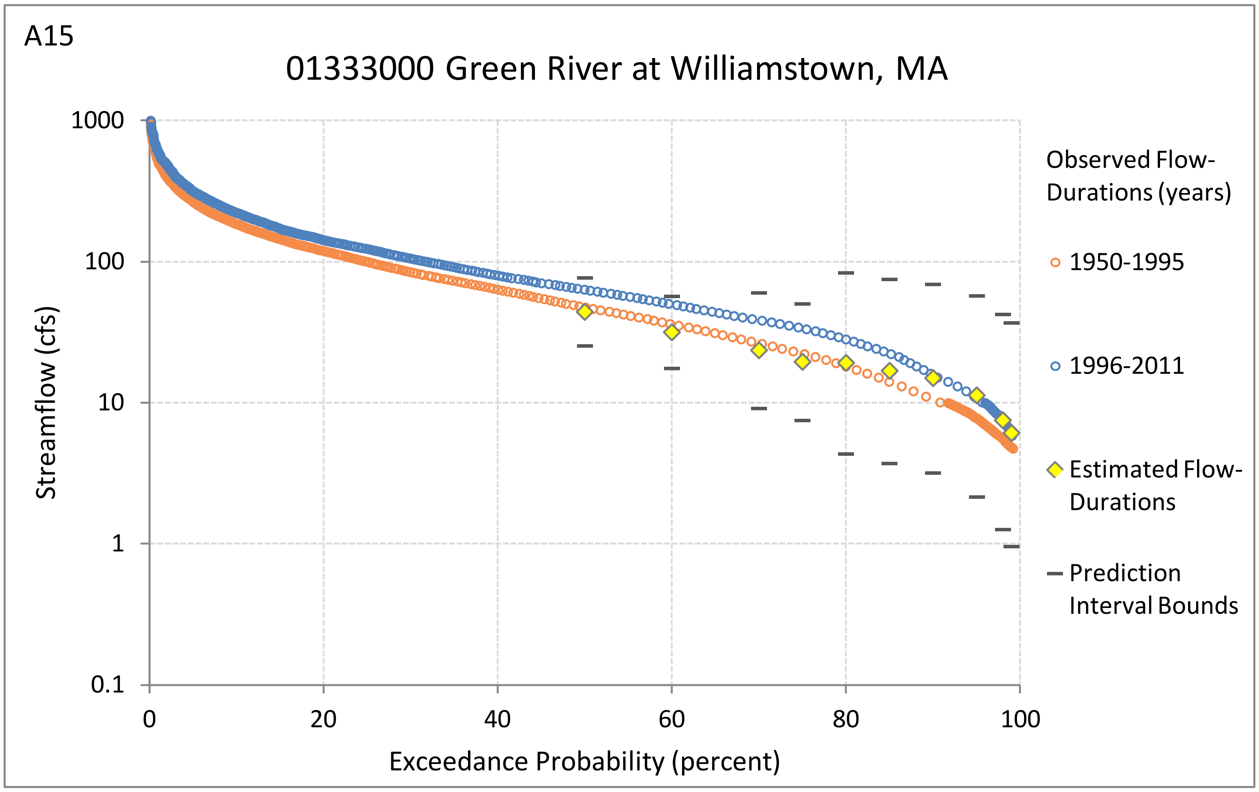

A10
01171500 Mill River at Northampton, MA
Streamflow (cfs)
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1939-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


A11
01174565 West Branch Swift River near Shutesbury, MA
1000
100
10
1
0.1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1984-1985
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


A12
01175670 Sevenmile River near Spencer, MA
1000
100
10
1
0.1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1961-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


A13
01176000 Quaboag River at West Brimfield, MA
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1919-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

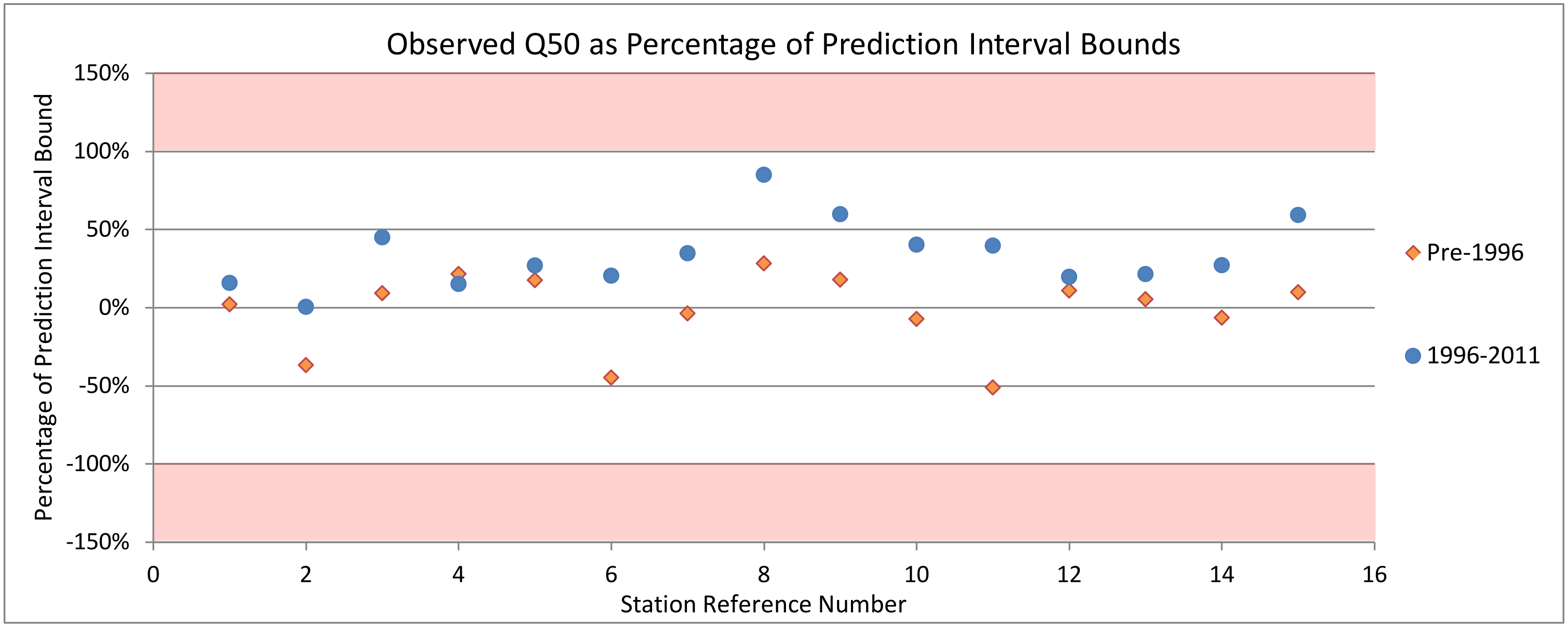

A14
01181000 West Branch Westfield River at Huntington, MA
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1936-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


A15
01333000 Green River at Williamstown, MA
1000
100
10
1
0.1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1950-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

Appendix B

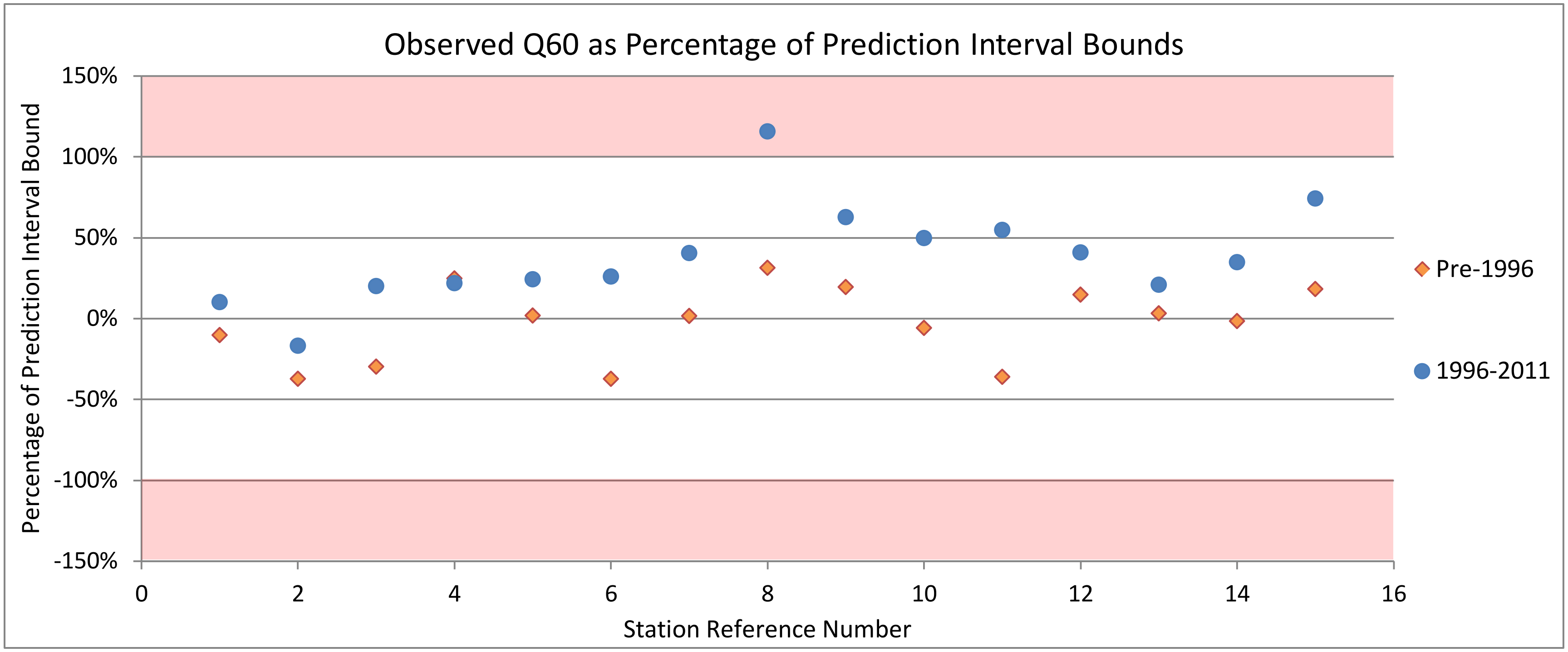
Part I Observed Flow-Durations as Percentage of Prediction Interval Bounds

B1



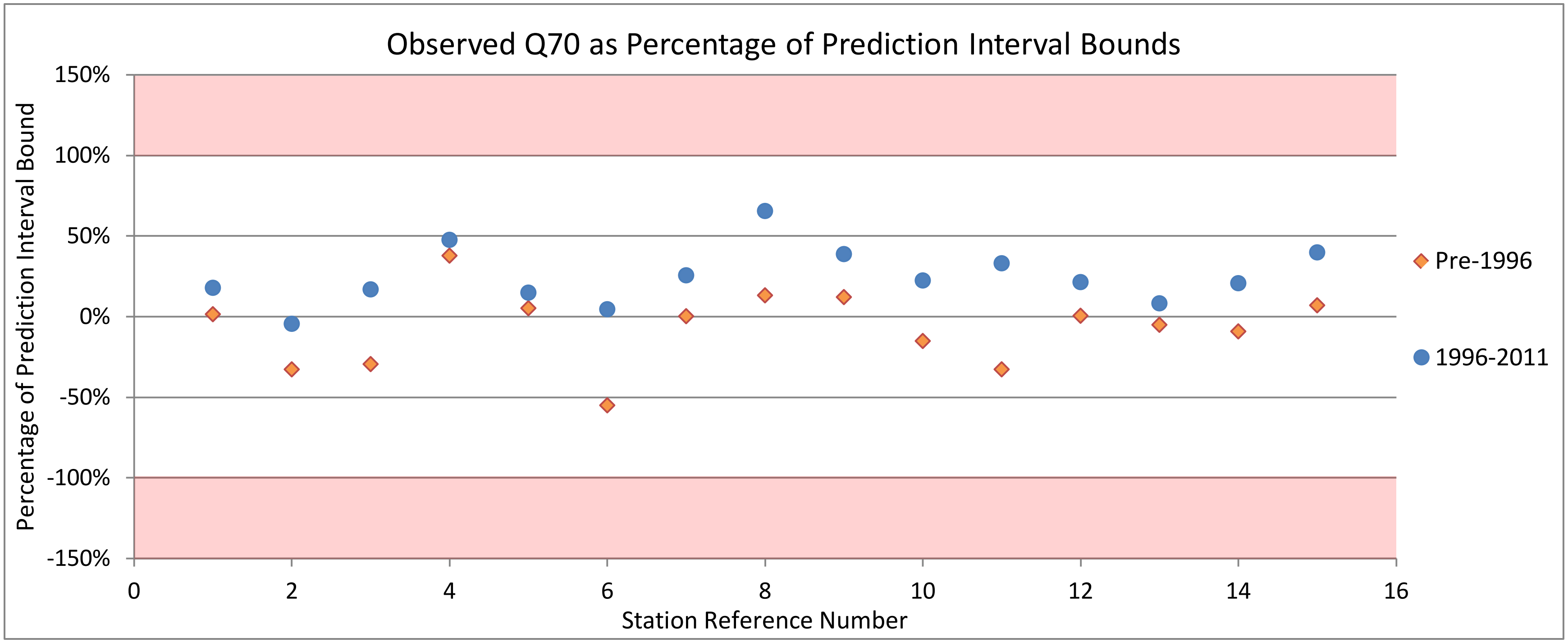
Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

B2



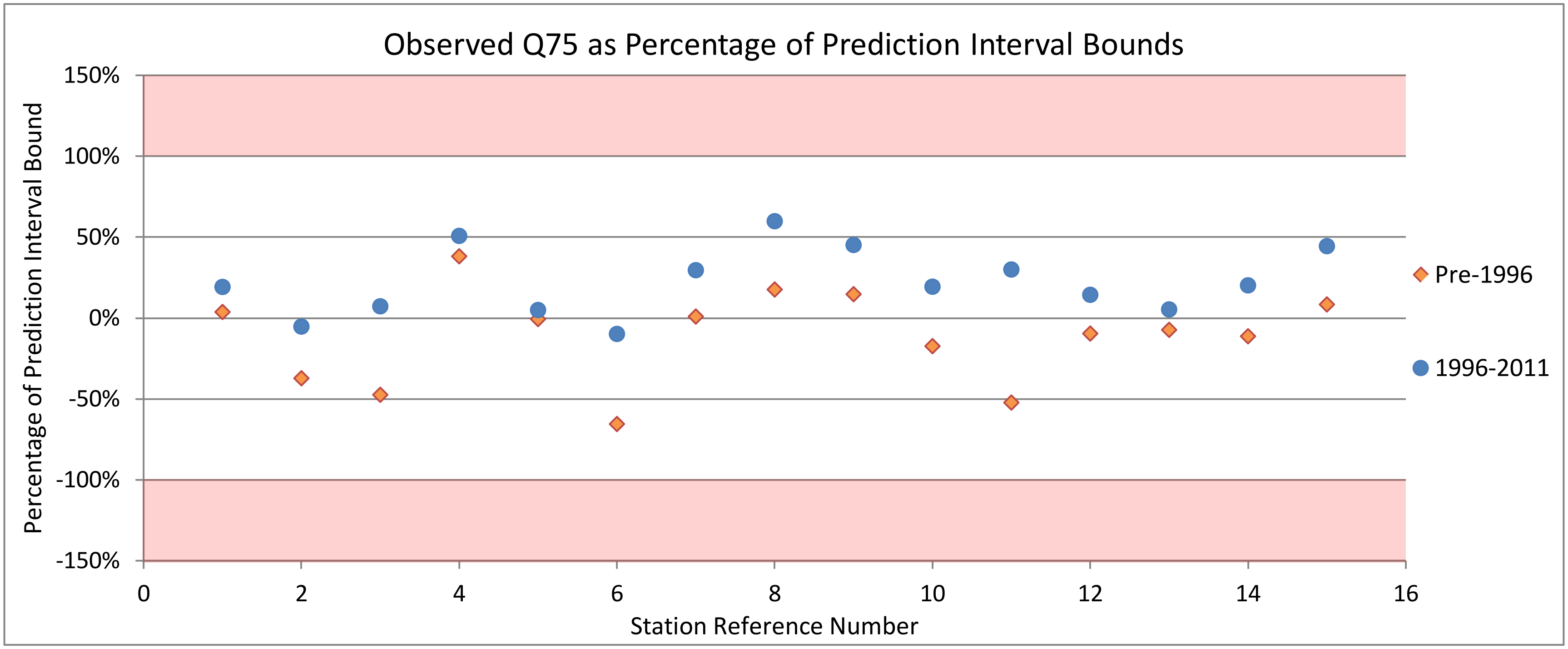
Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

B3



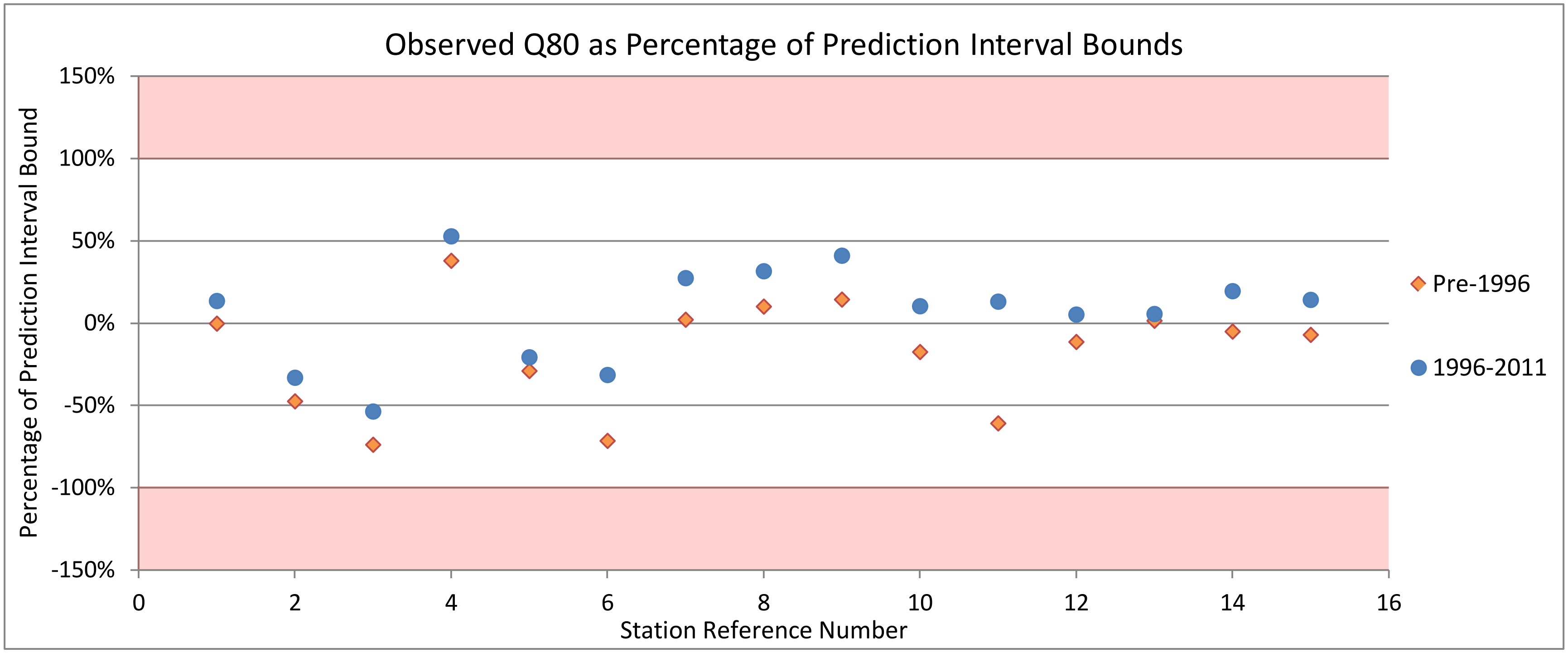
Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

B4



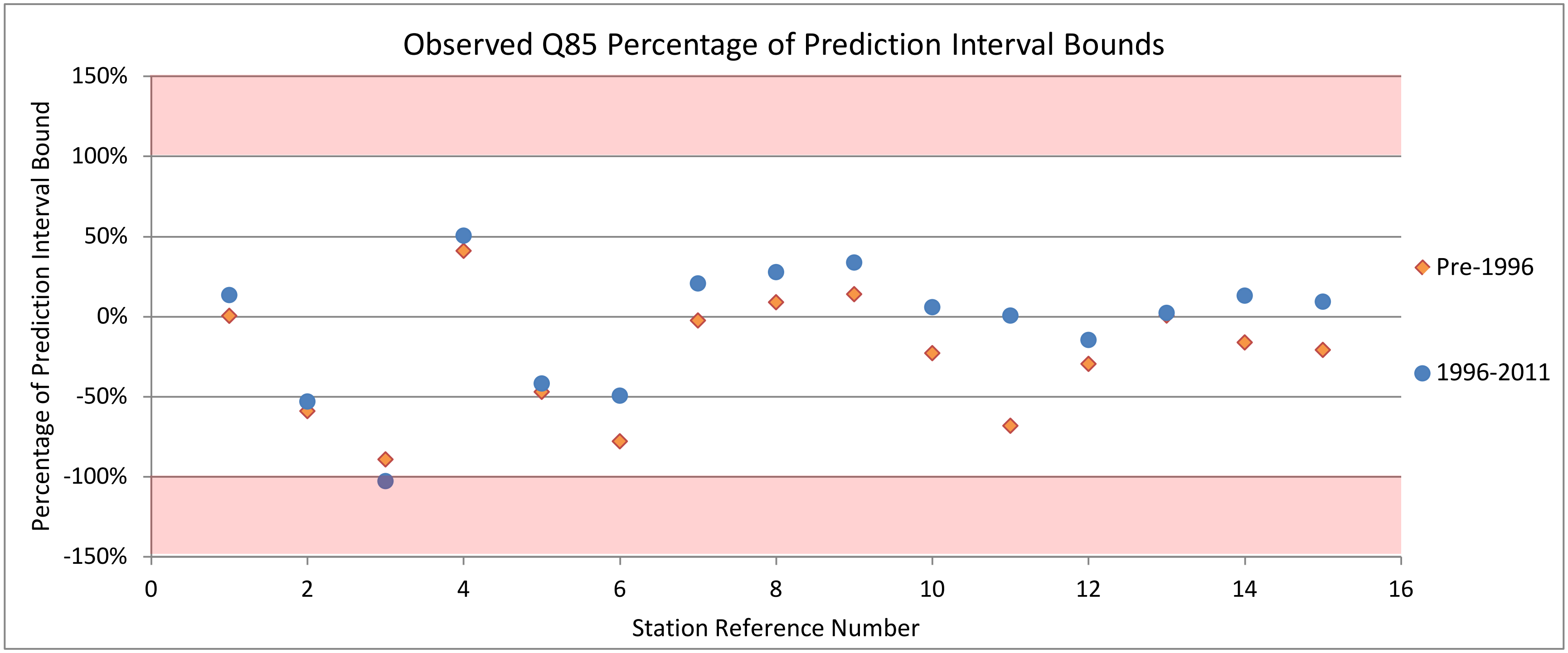
Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

B5



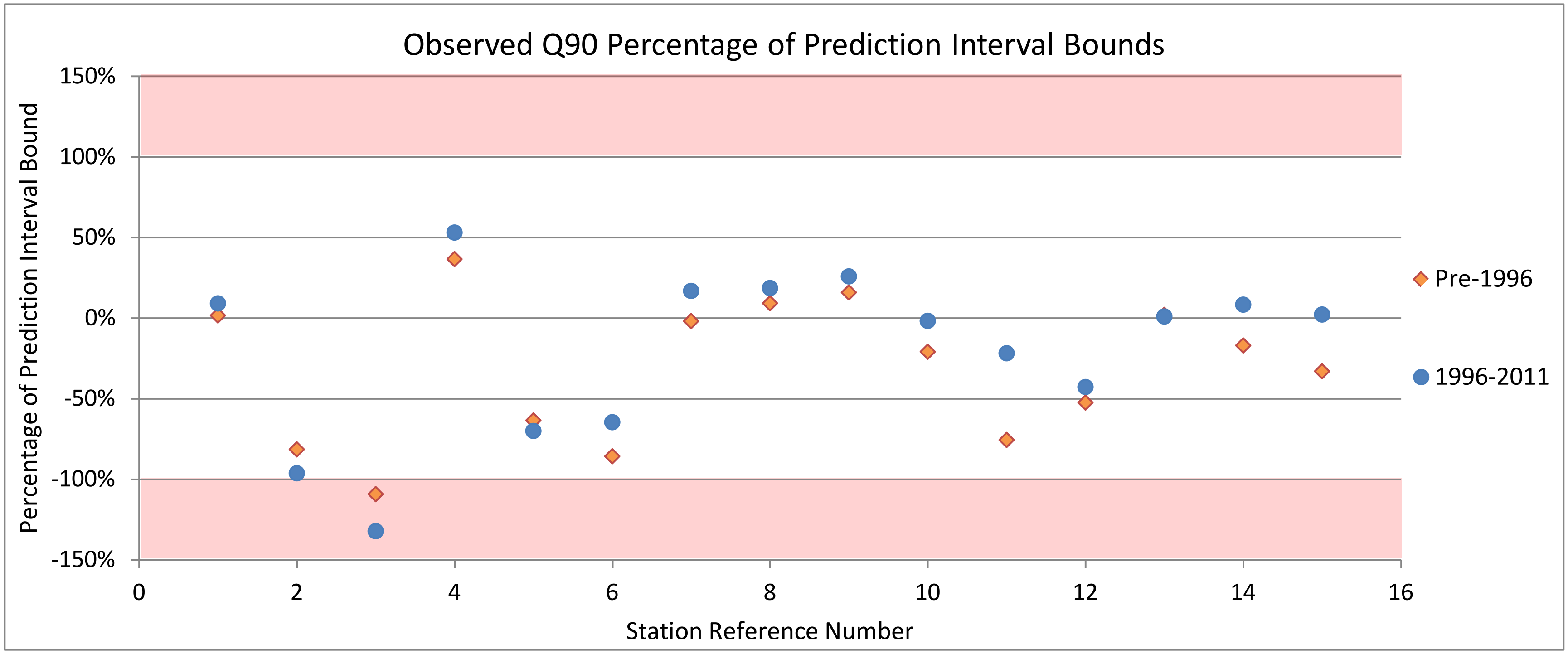
Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

B6



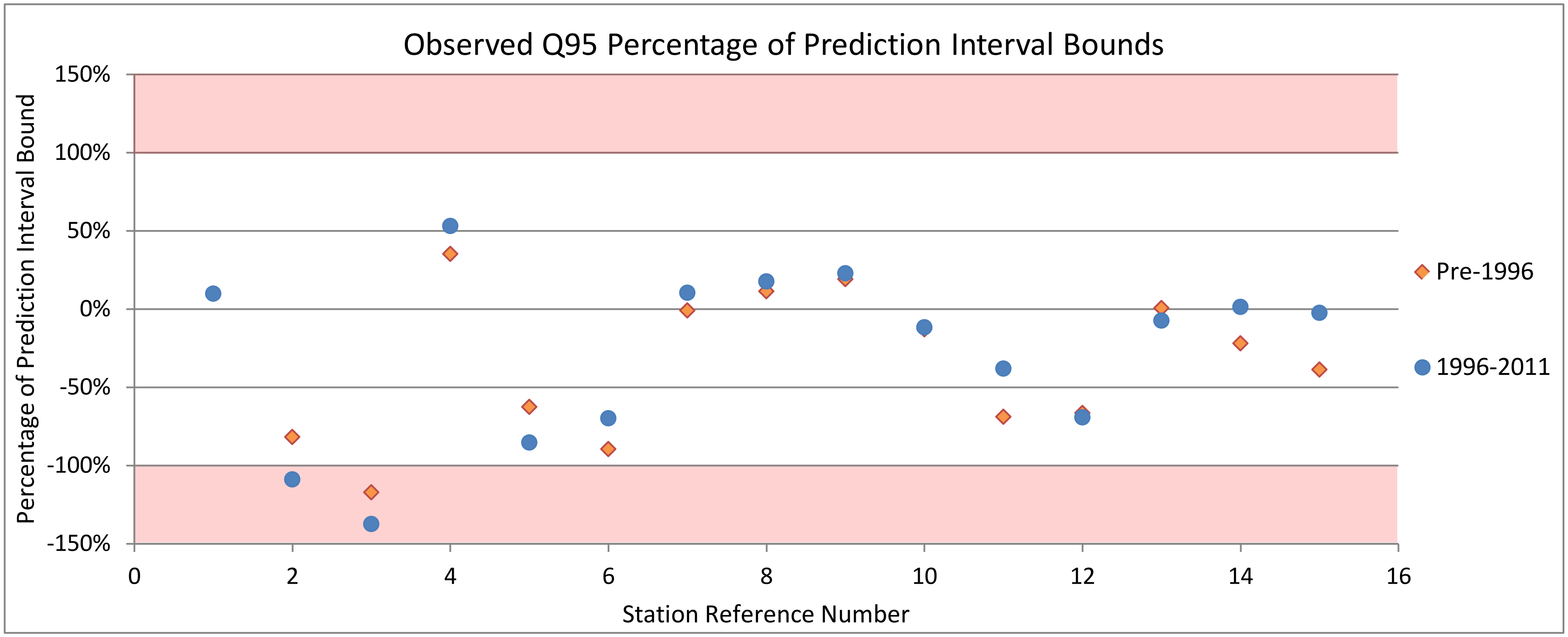
Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

B7



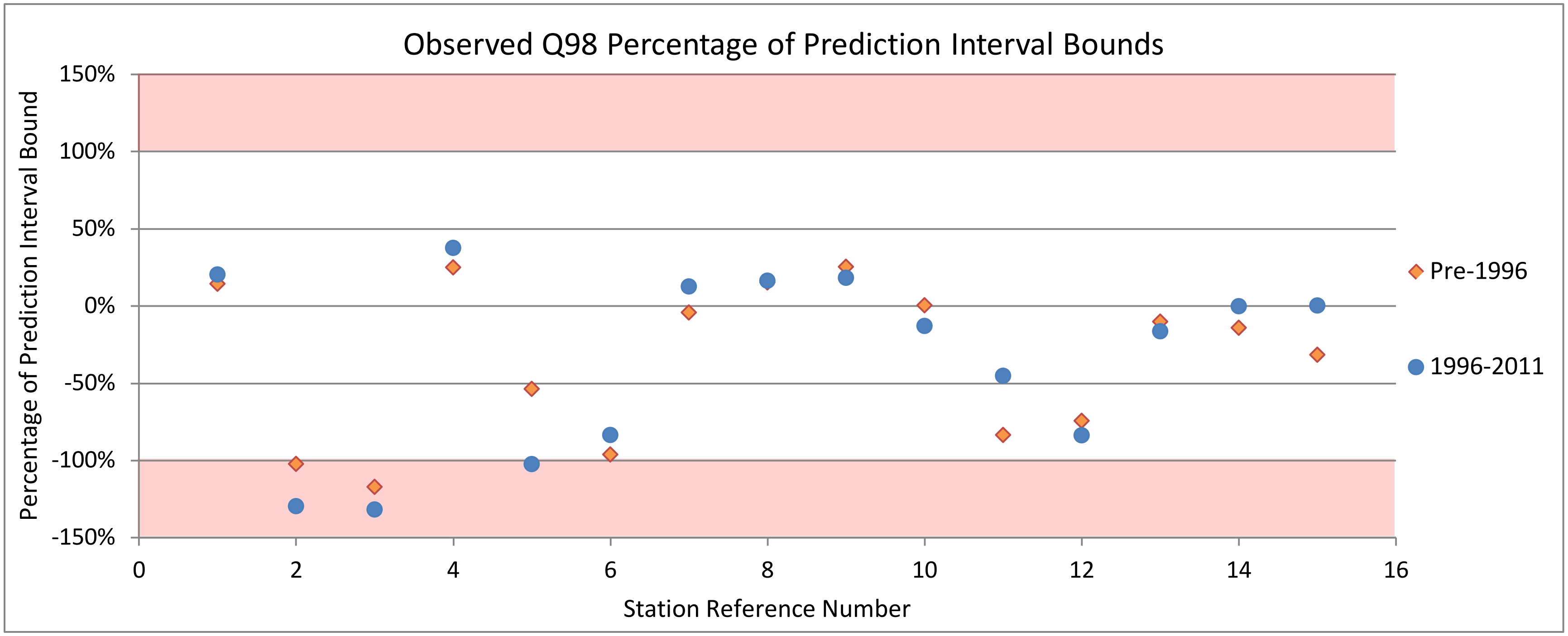
Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

B8



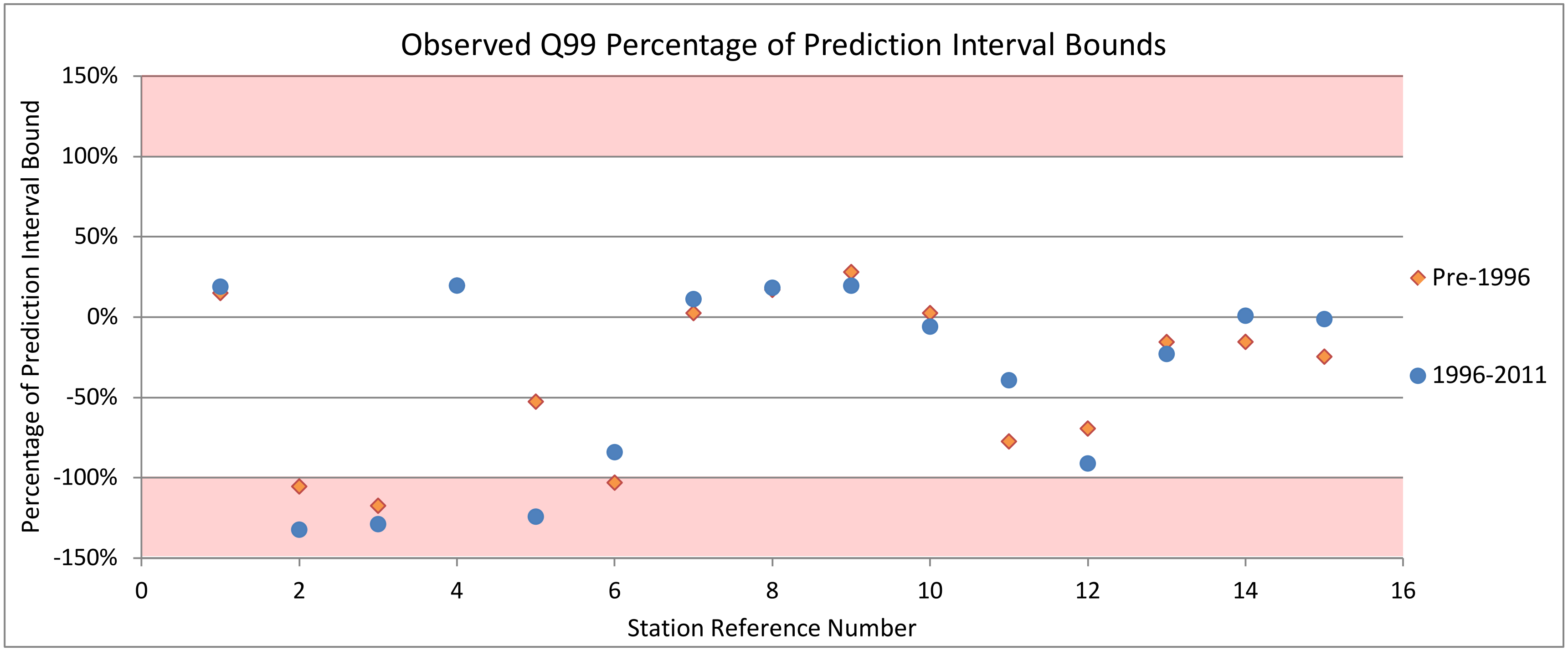
Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

B9



Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

B10



Station Reference Number	USGS Station Number	USGS Station Name	Station Reference Number	USGS Station Number	USGS Station Name
1	01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	9	01170100	GREEN RIVER NEAR COLRAIN, MA
2	01097300	NASHOBA BROOK NEAR ACTON, MA	10	01171500	MILL RIVER AT NORTHAMPTON, MA
3	01101000	PARKER RIVER AT BYFIELD, MA	11	01174565	WEST BRANCH SWIFT RIVER NEAR SHUTESBURY, MA
4	01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	12	01175670	SEVENMILE RIVER NEAR SPENCER, MA
5	01111300	NIPMUC RIVER NEAR HARRISVILLE, RI	13	01176000	QUABOG RIVER AT WEST BRIMFIELD, MA
6	01162500	PRIEST BROOK NEAR WINCHENDON, MA	14	01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
7	01169000	NORTH RIVER AT SHATTUCKVILLE, MA	15	01333000	GREEN RIVER AT WILLIAMSTOWN, MA
8	01169900	SOUTH RIVER NEAR CONWAY, MA	-	-	-

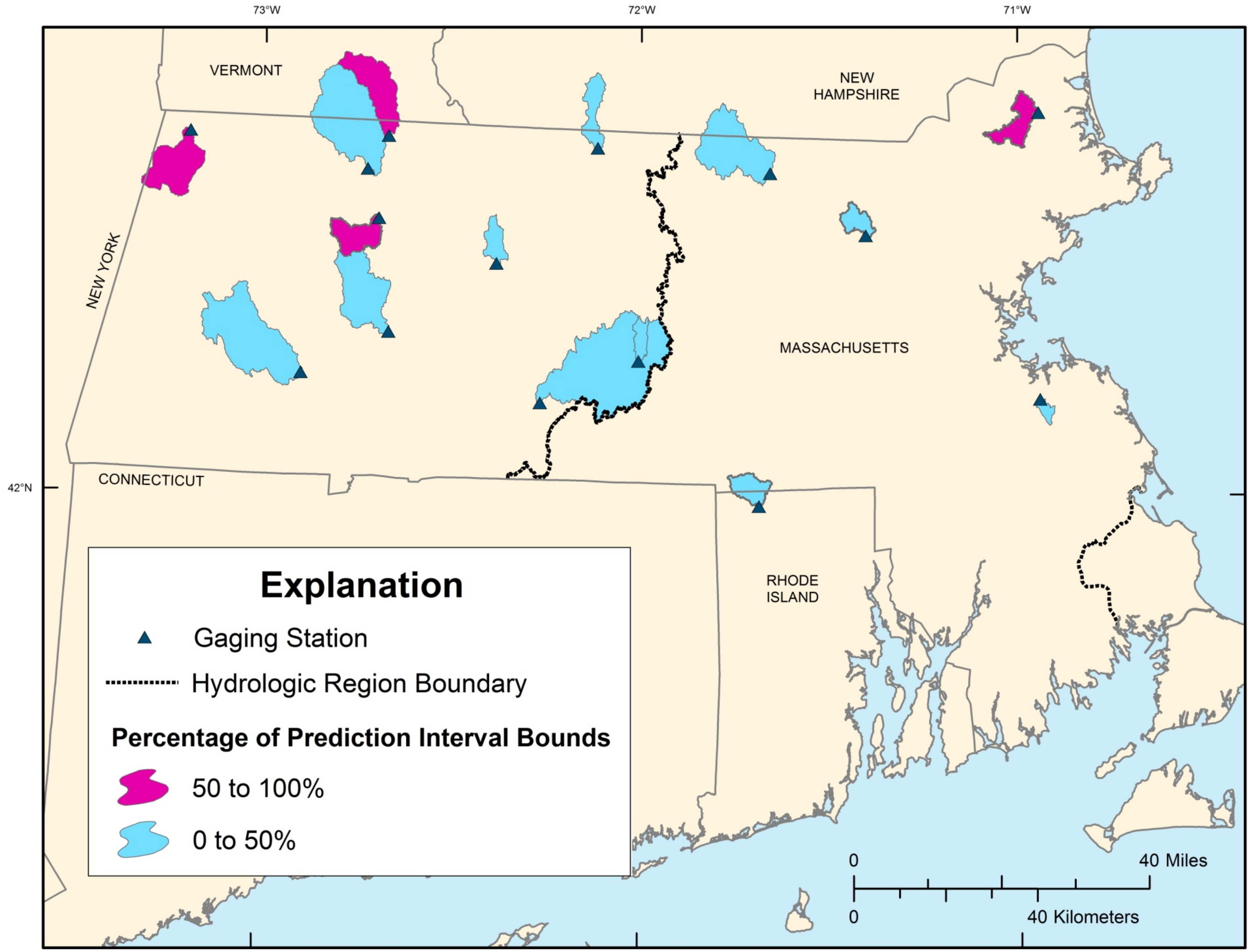
Appendix C

Part I RF Model Performance Maps

(Compared to 1996-2011 Data)

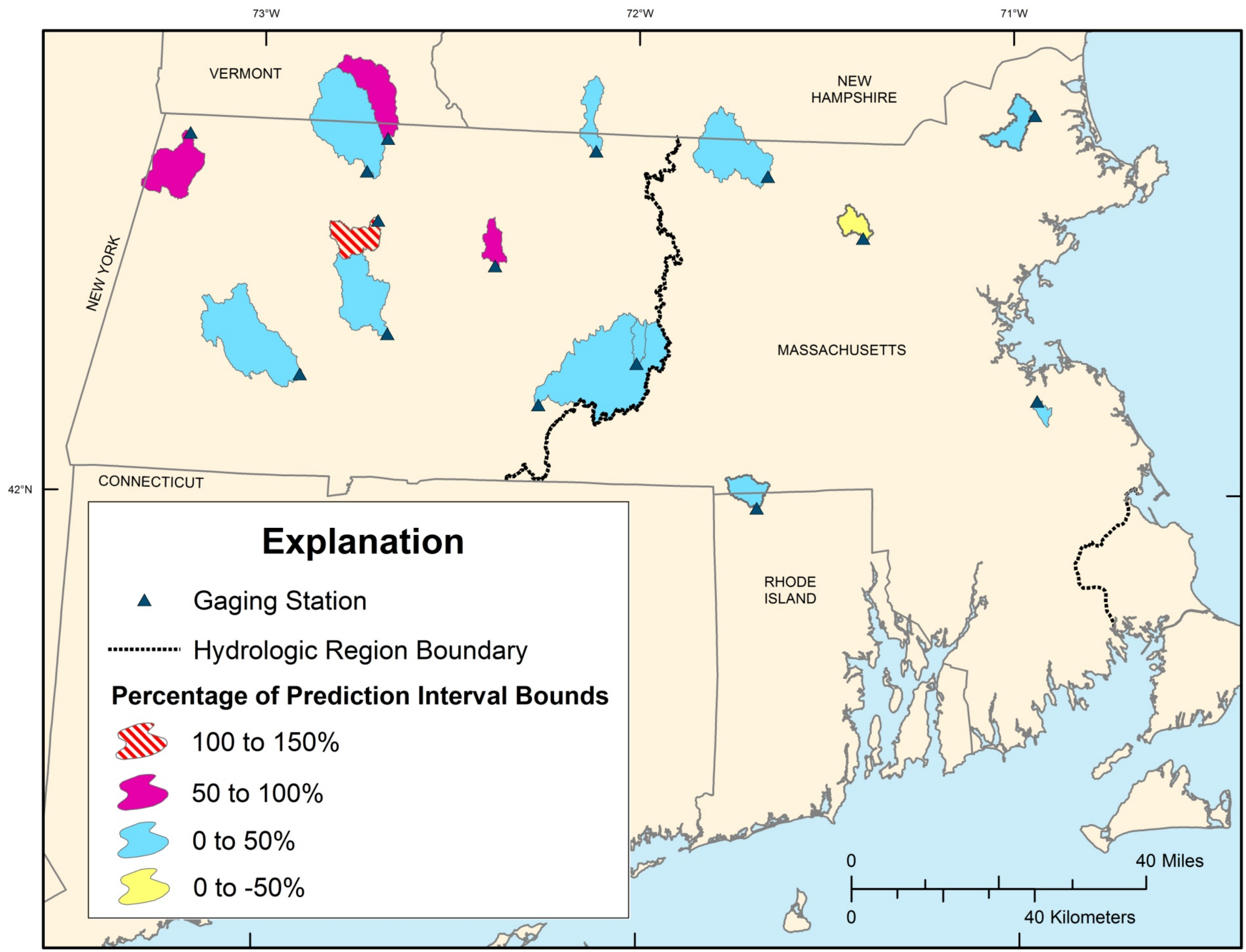
C1

50-Percent Duration Flow



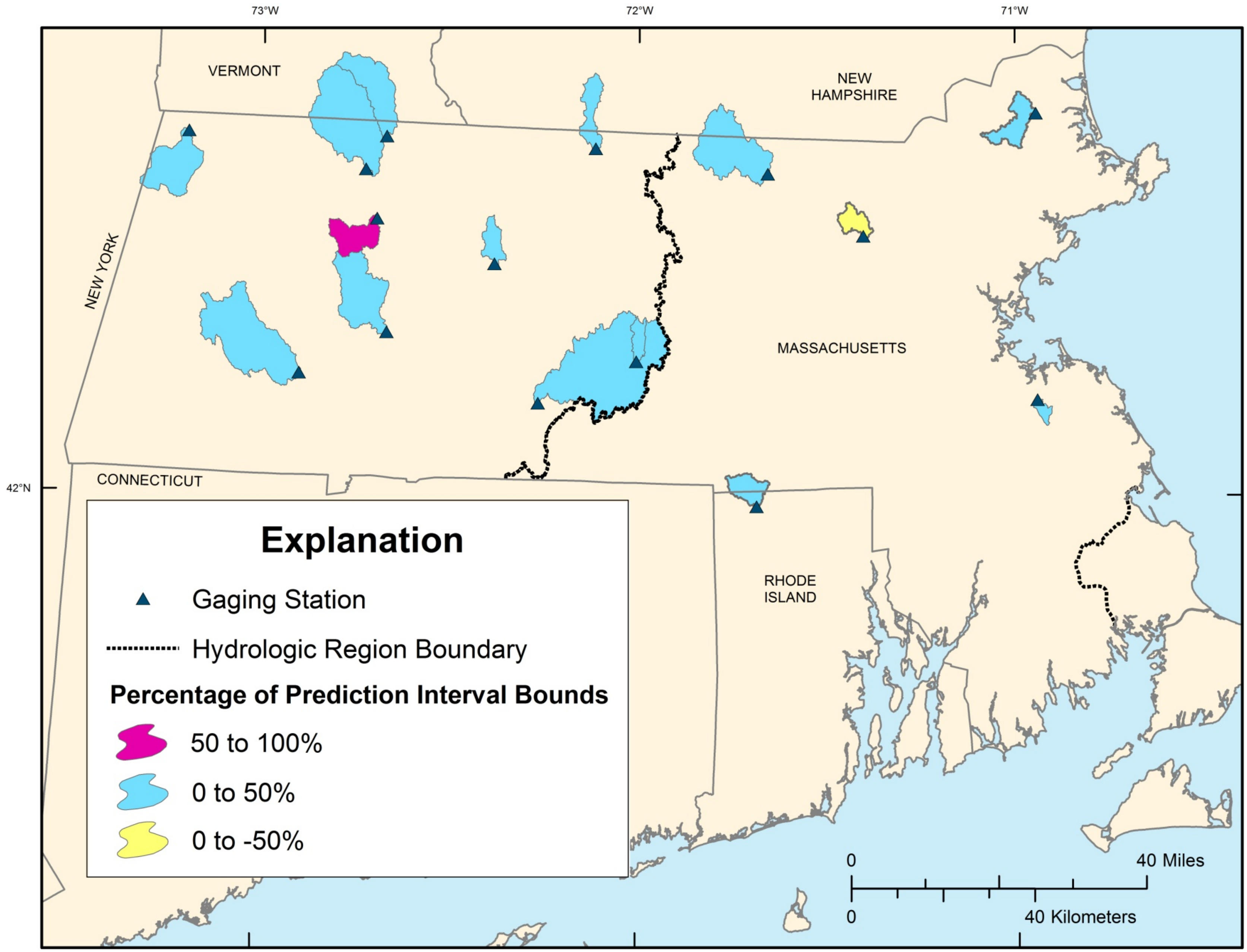
C2

60-Percent Duration Flow



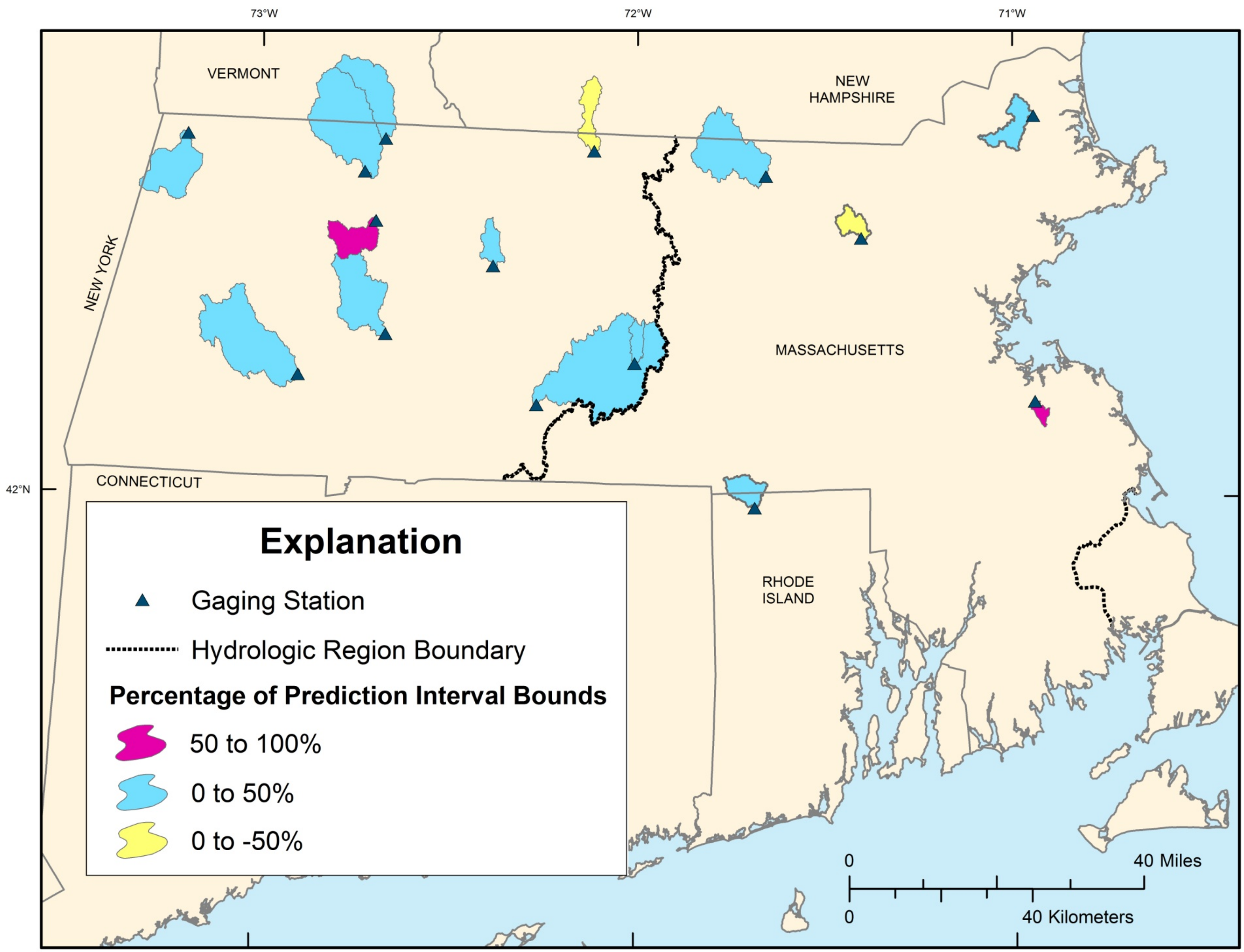
C3

70-Percent Duration Flow



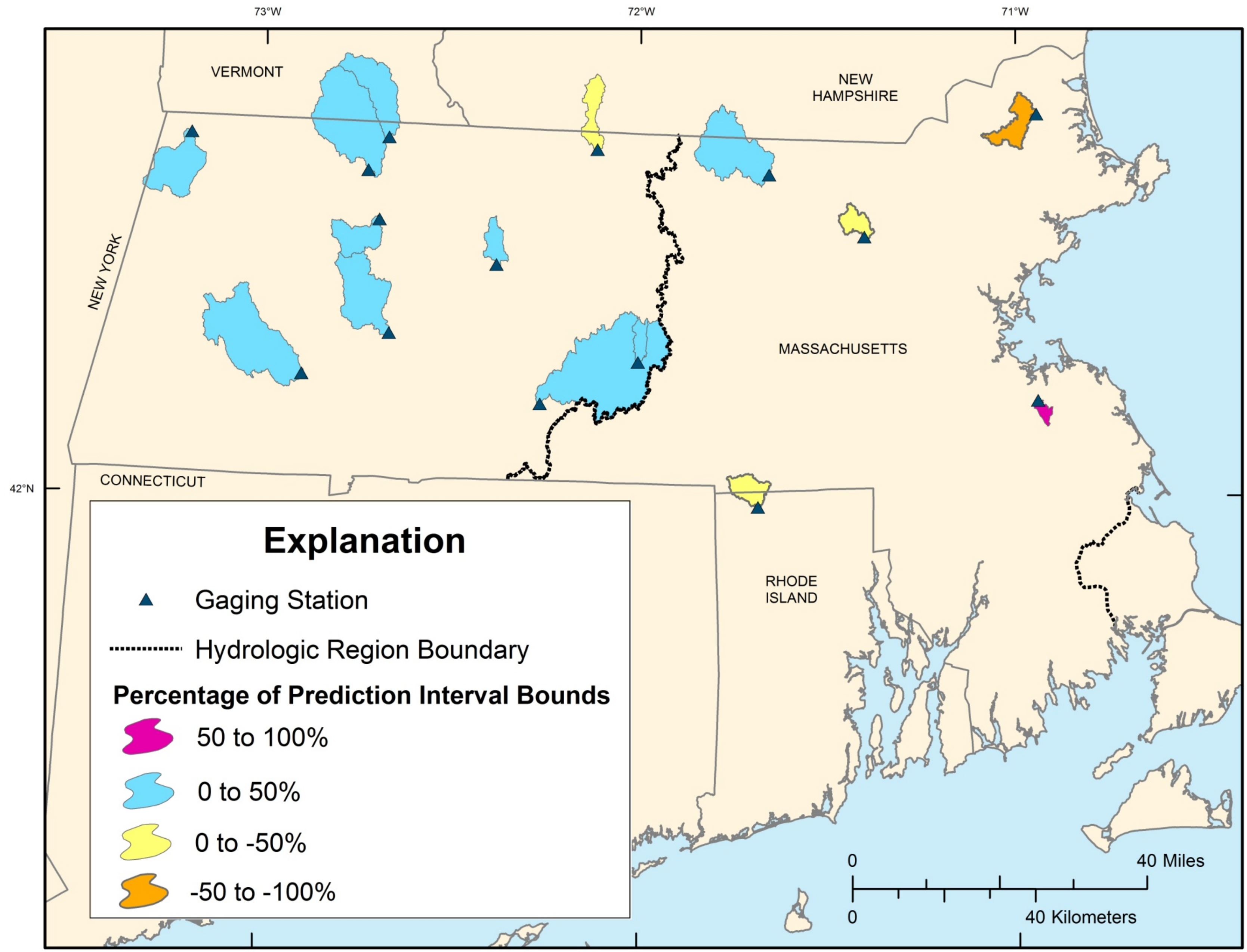
C4

75-Percent Duration Flow



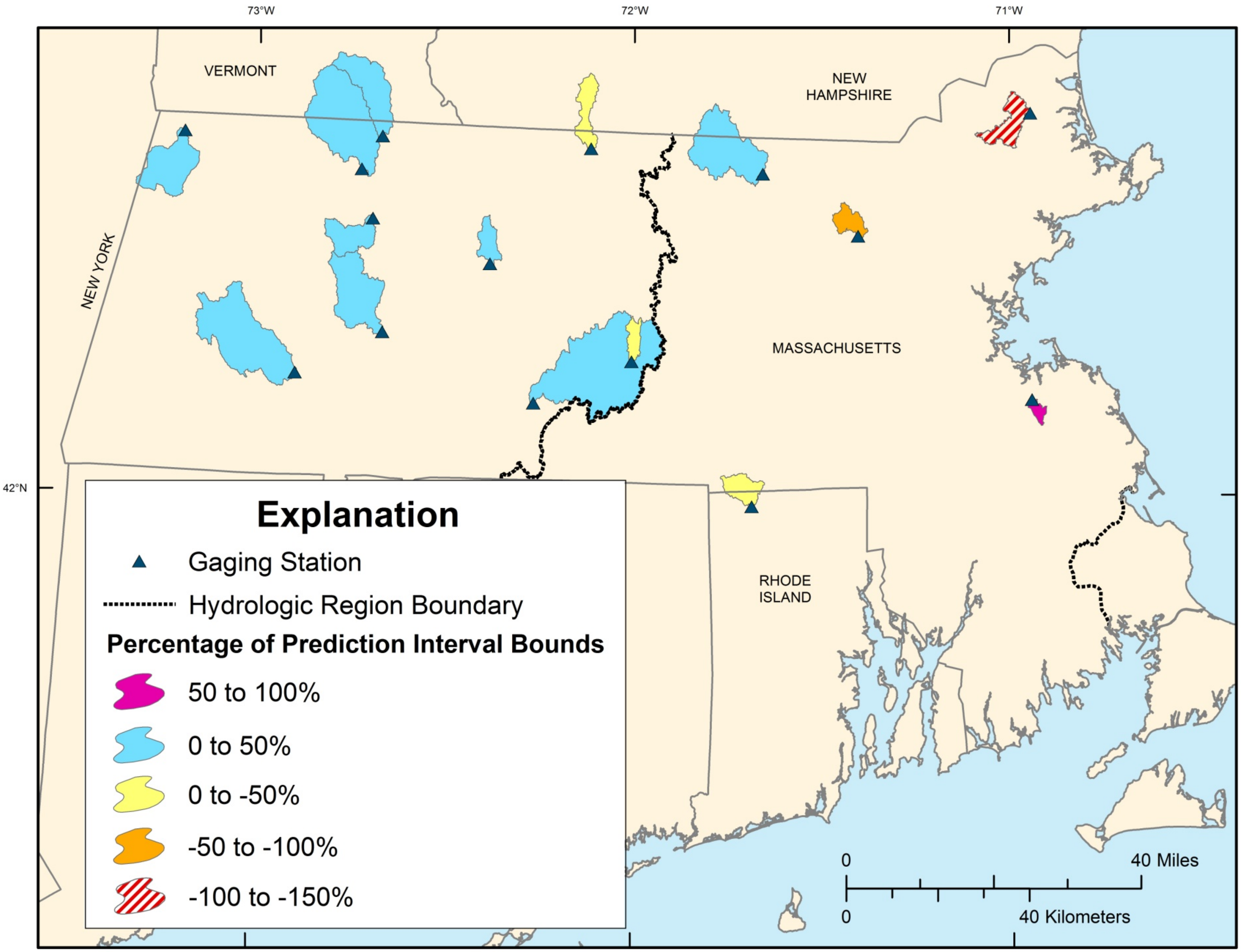
C5

80-Percent Duration Flow



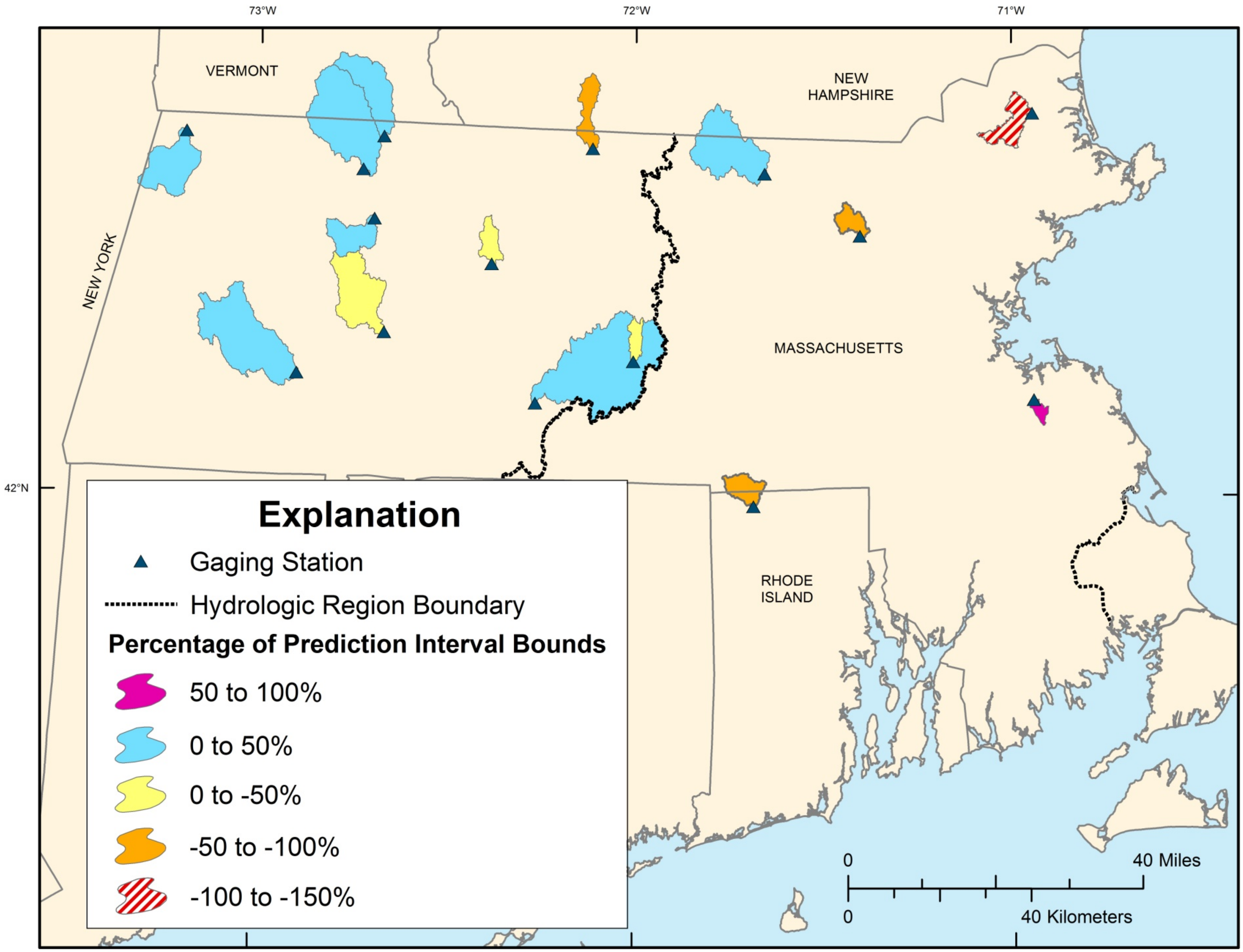
C6

85-Percent Duration Flow



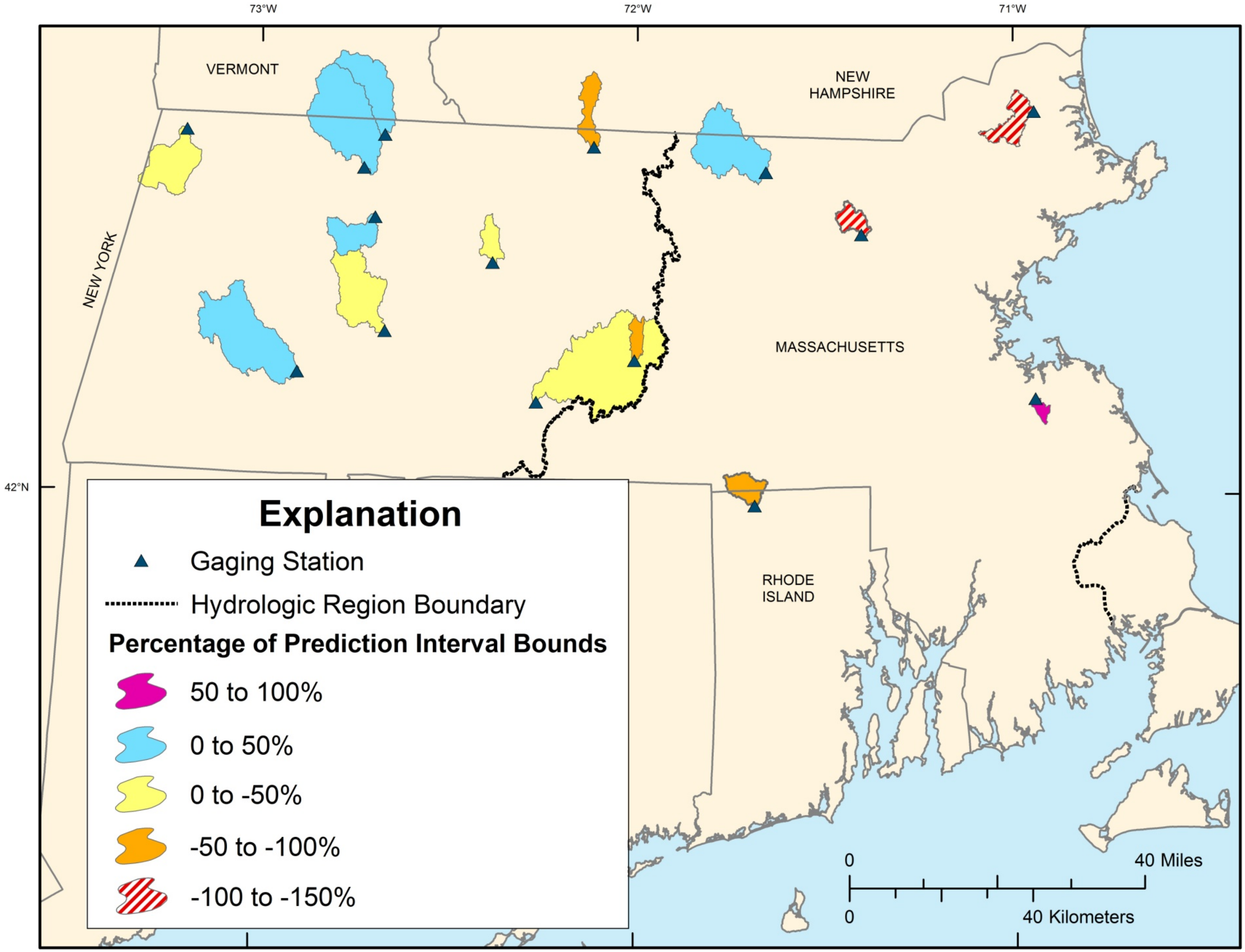
C7

90-Percent Duration Flow

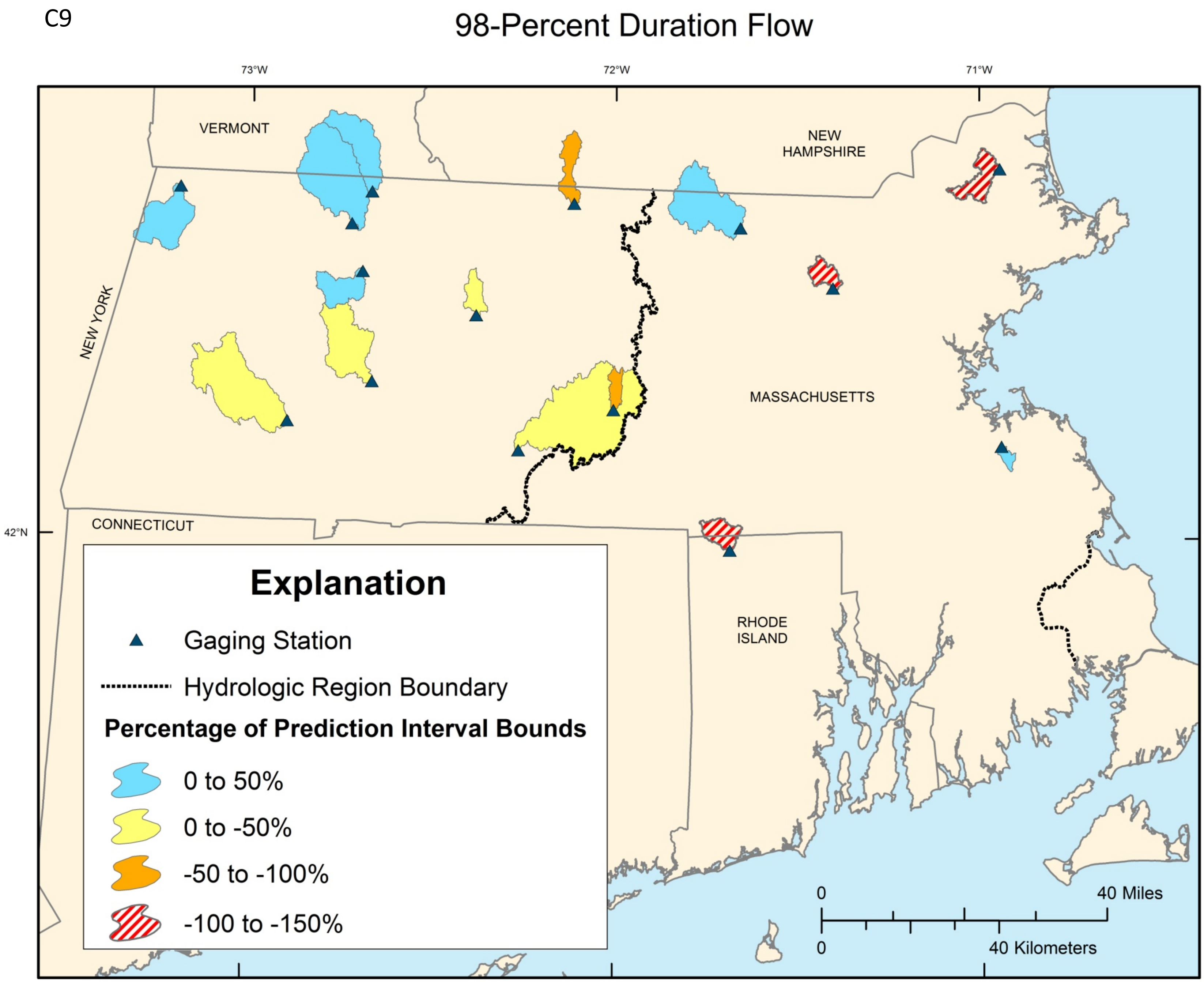


C8

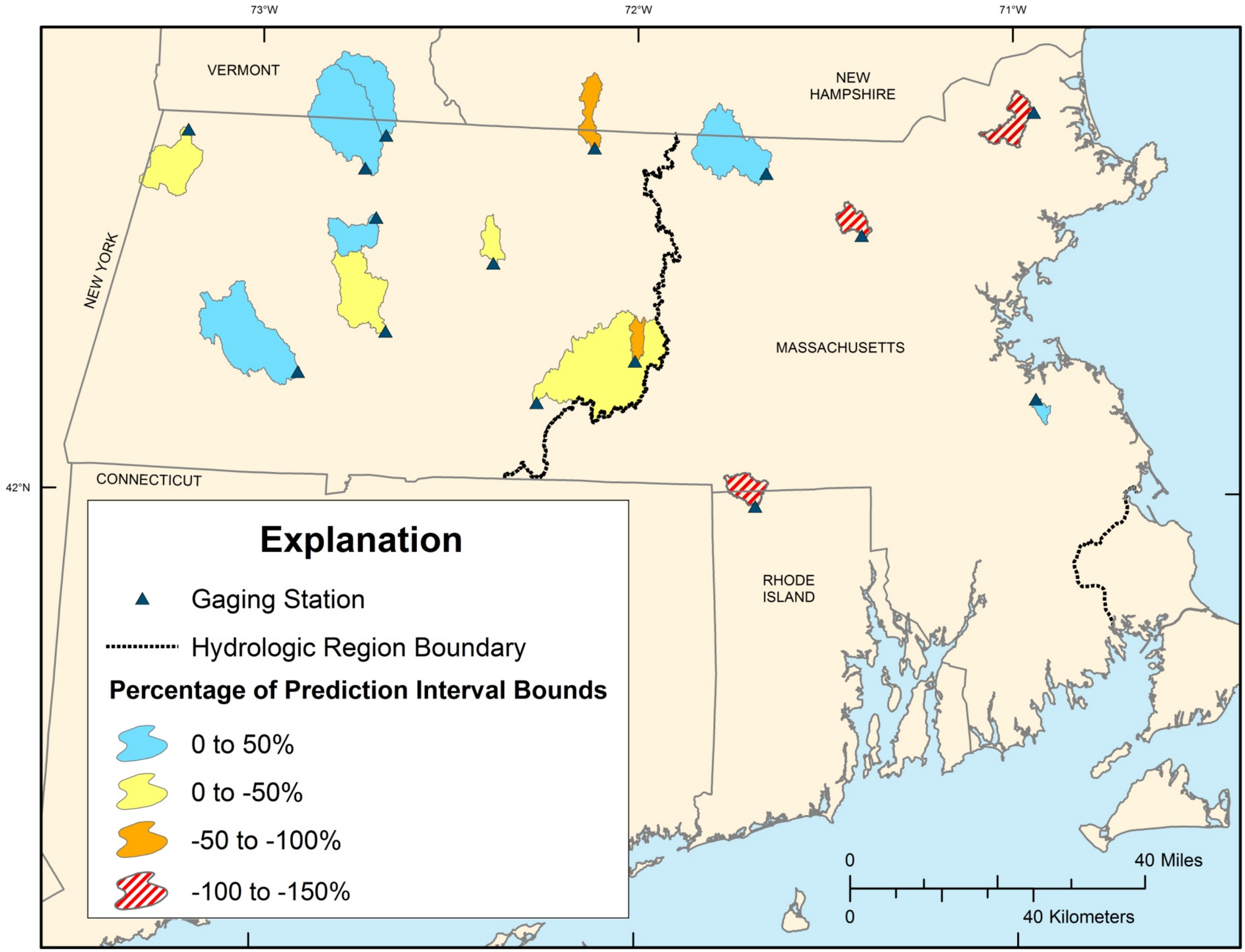
95-Percent Duration Flow



C9

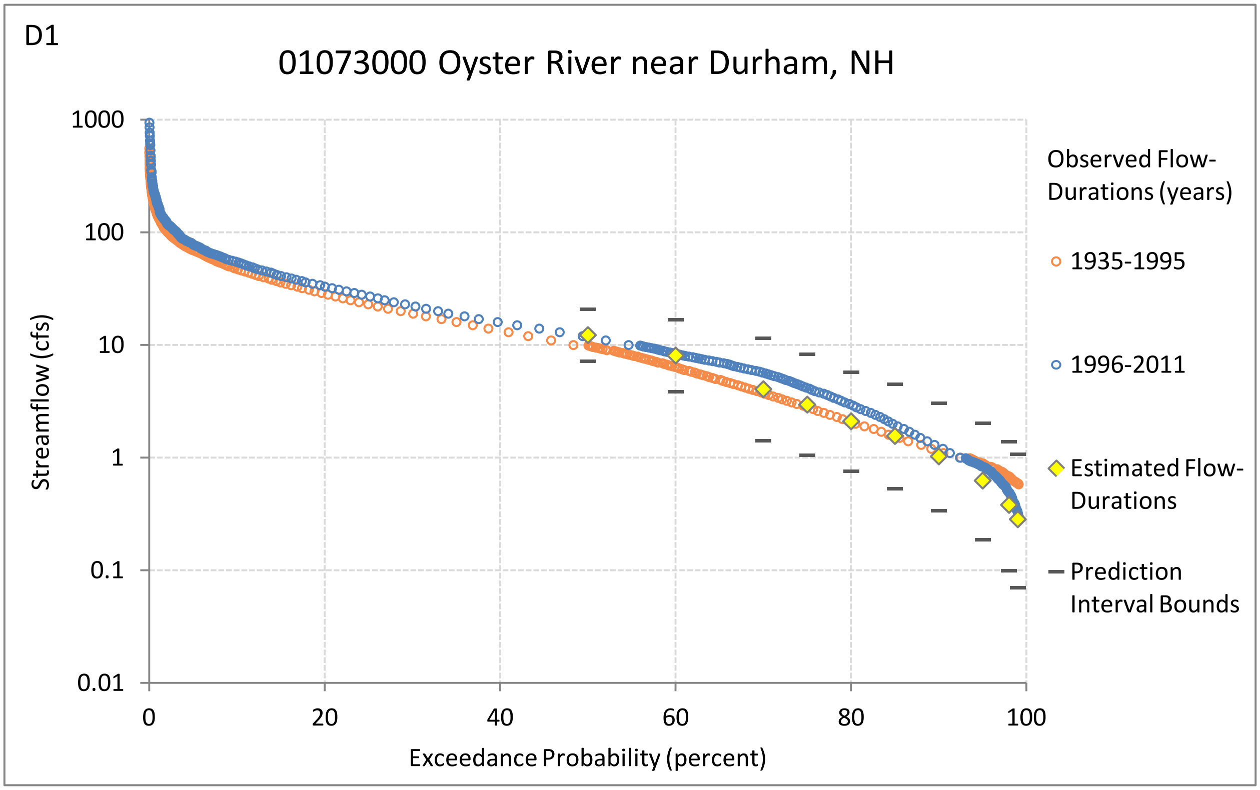

98-Percent Duration Flow
73°W
72°W
71°W
42°N
VERMONT
NEW HAMPSHIRE
NEW YORK
MASSACHUSETTS
CONNECTICUT
RHODE ISLAND
Explanation
Gaging Station
Hydrologic Region Boundary
Percentage of Prediction Interval Bounds
0 to 50%
0 to -50%
-50 to -100%
-100 to -150%
0
40 Miles
0
40 Kilometers

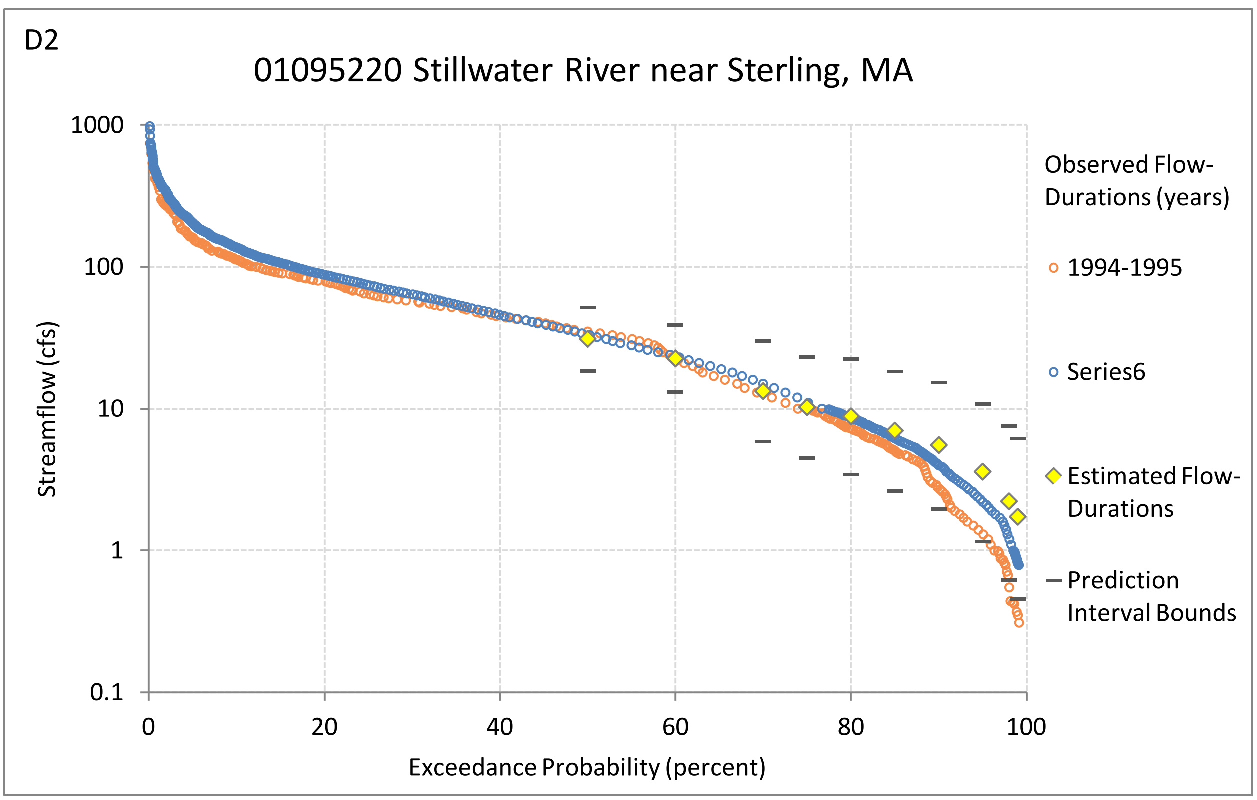
99-Percent Duration Flow

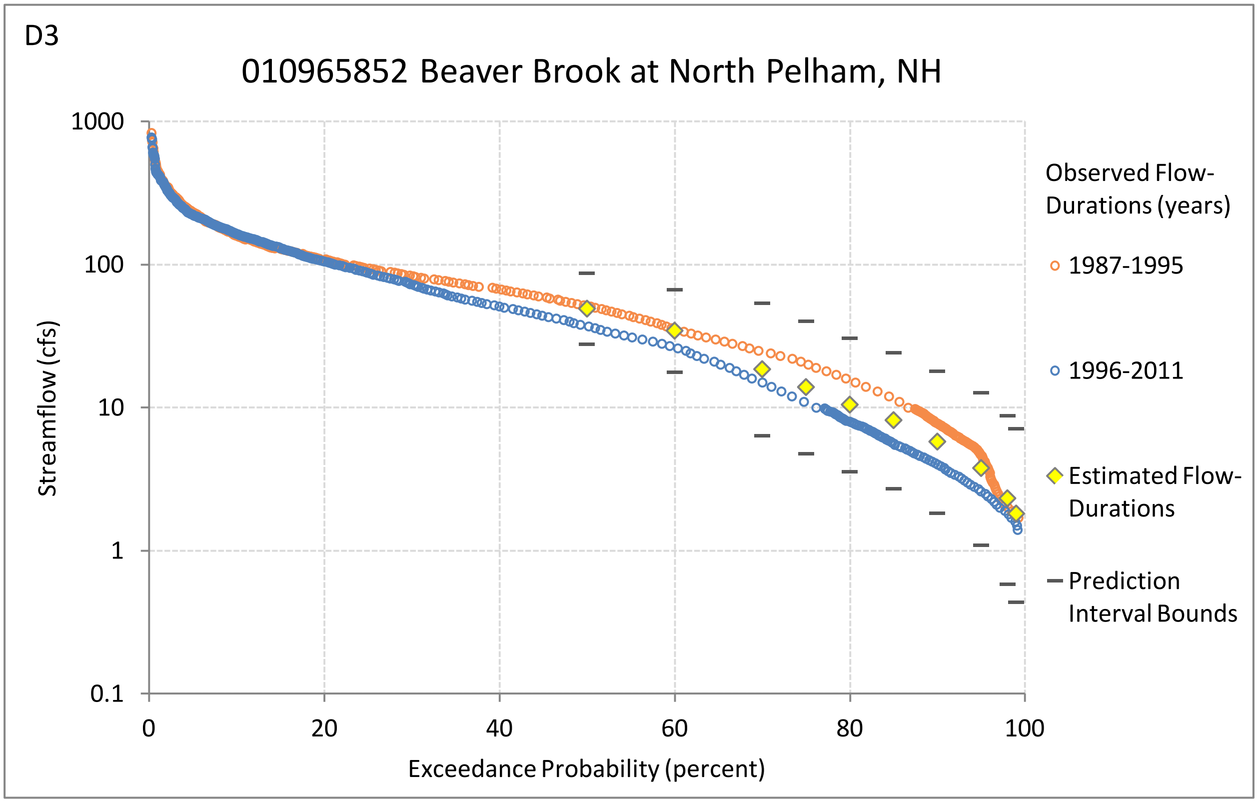


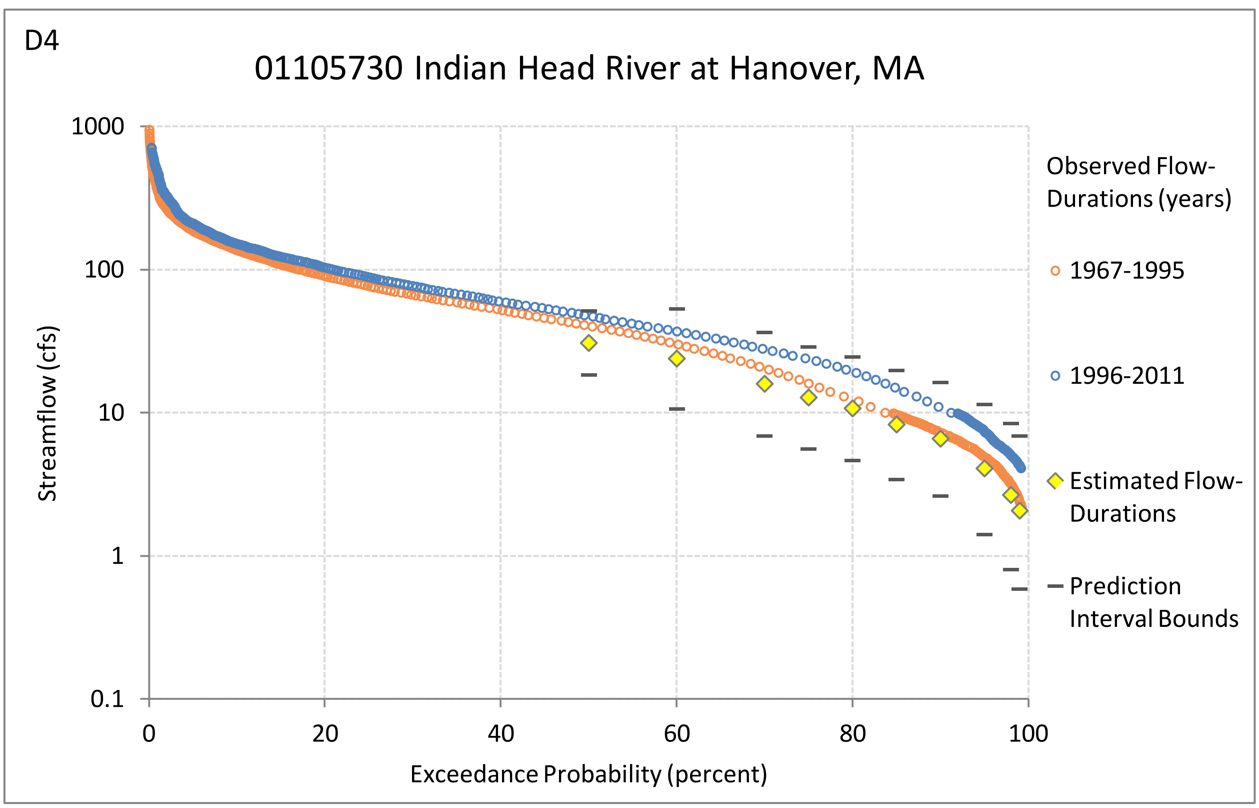
Appendix D

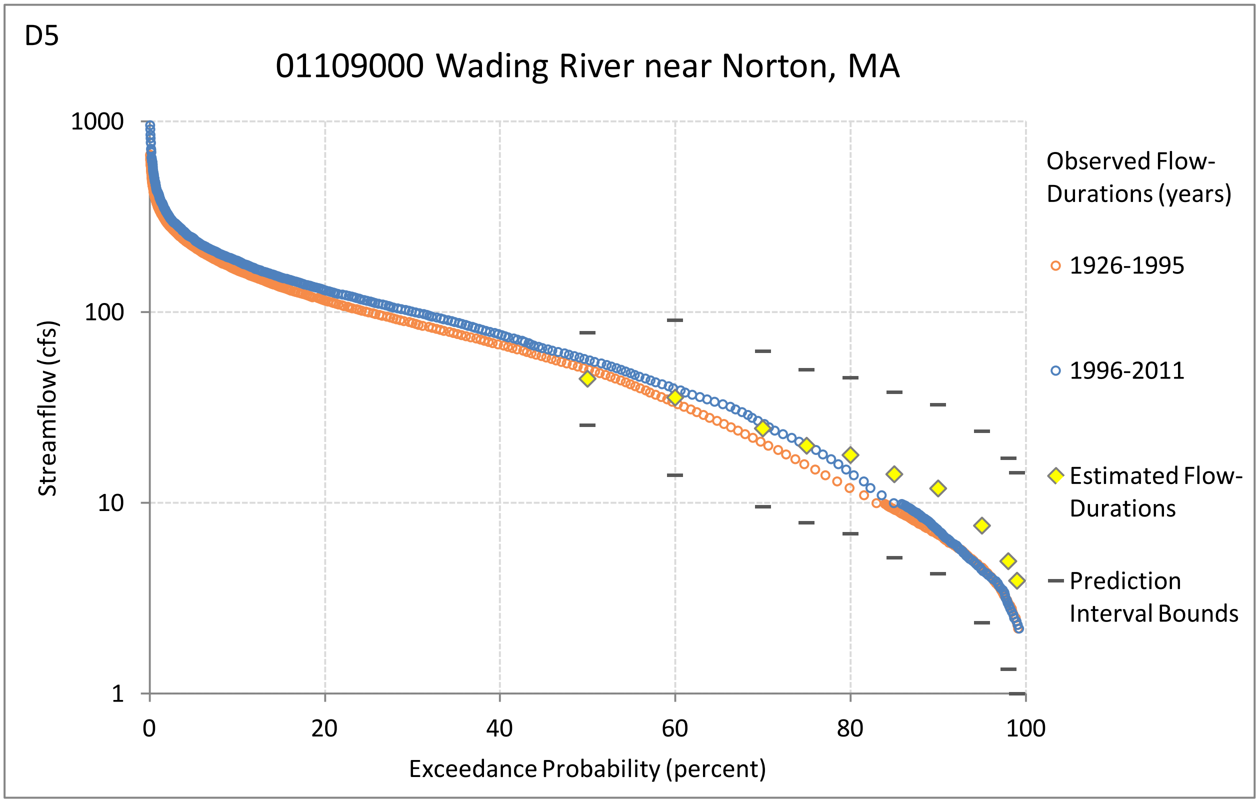
Part II Flow-Duration Curves

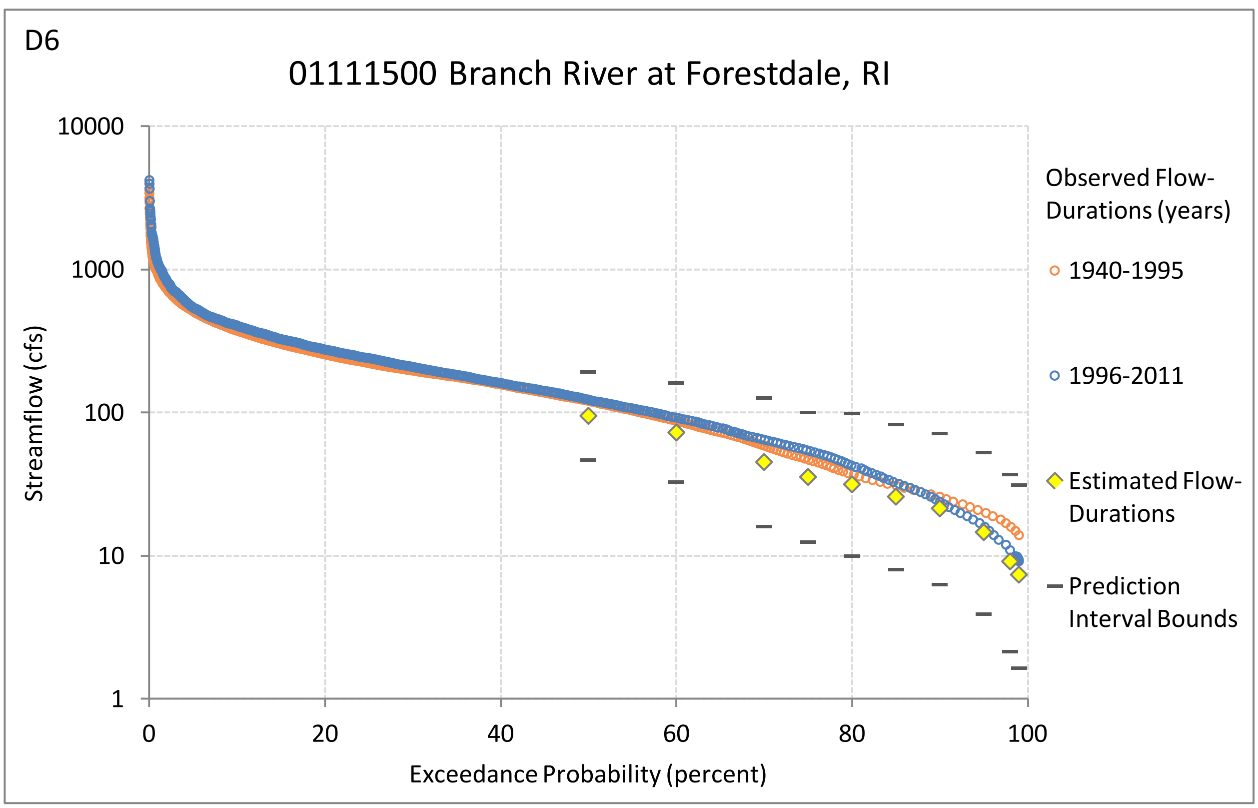

D1
01073000 Oyster River near Durham, NH
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1935-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

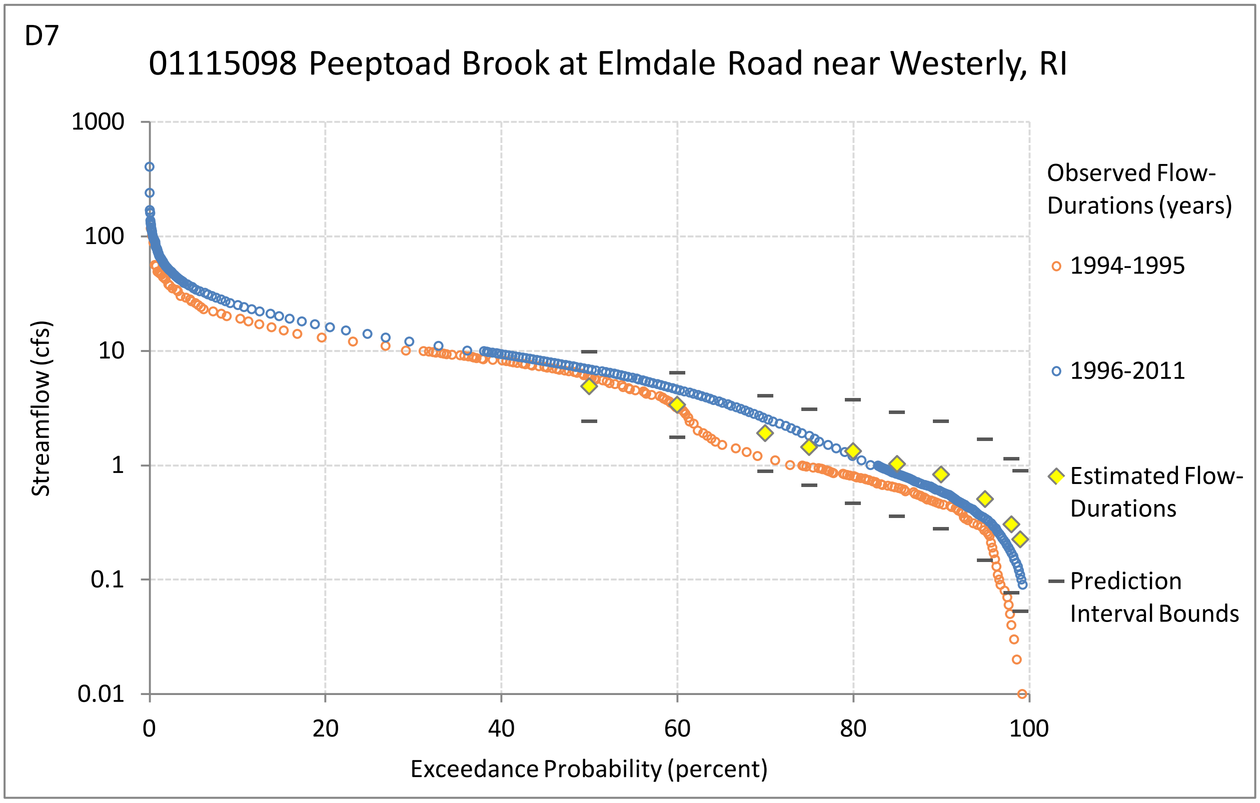

D2
01095220 Stillwater River near Sterling, MA
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1994-1995
Series6
Estimated Flow-Durations
Prediction Interval Bounds

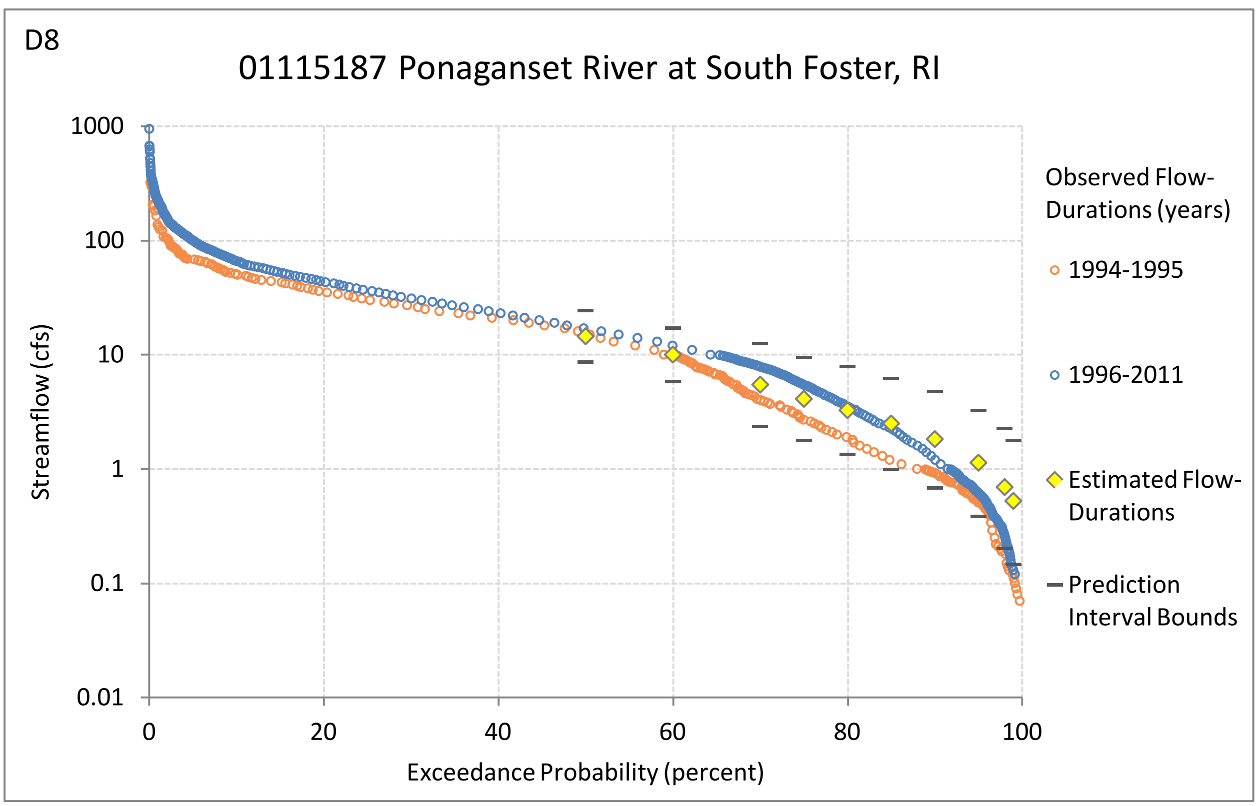

D3
010965852 Beaver Brook at North Pelham, NH
1000
100
10
1
0.1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1987-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

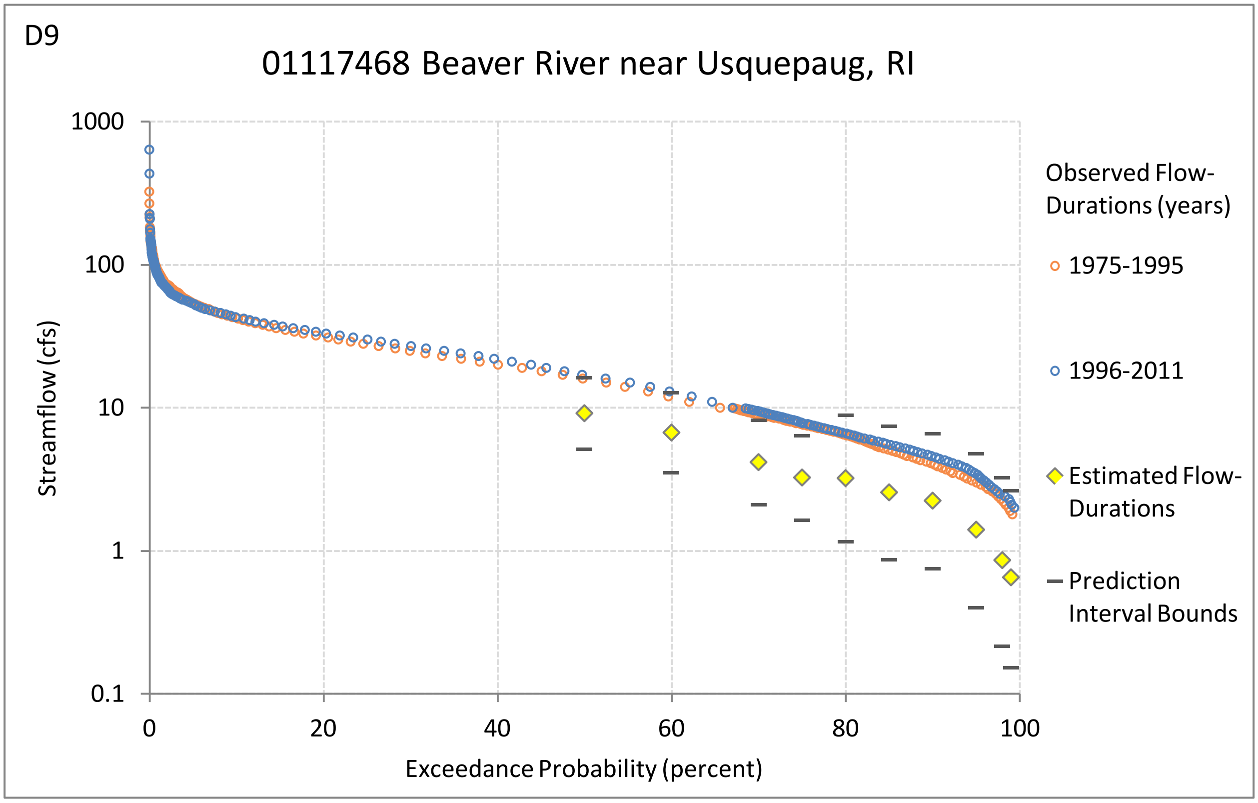

D4
01105730 Indian Head River at Hanover, MA
1000
100
10
1
0.1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1967-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

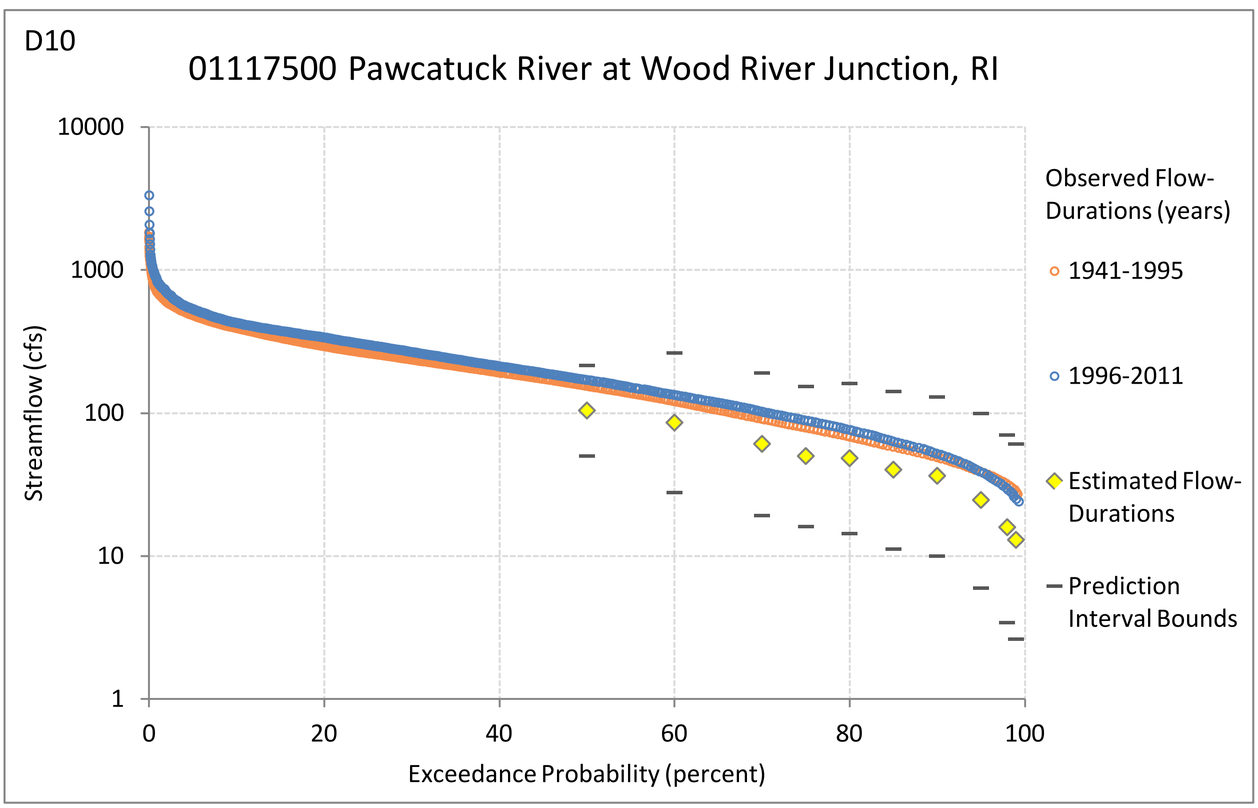

D5
01109000 Wading River near Norton, MA
1000
100
10
1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1926-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

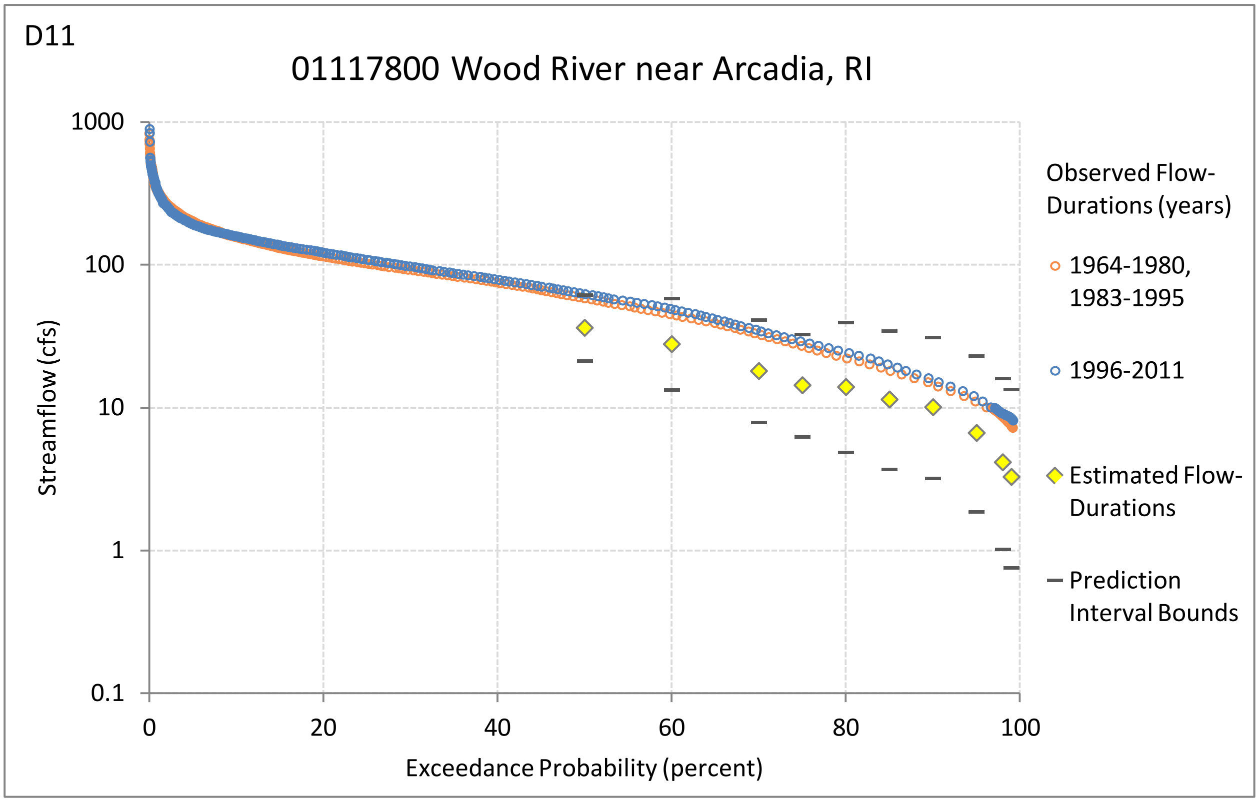

D6
01111500 Branch River at Forestdale, RI
10000
1000
100
10
1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1940-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


D7
01115098 Peeptoad Brook at Elmdale Road near Westerly, RI
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1994-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

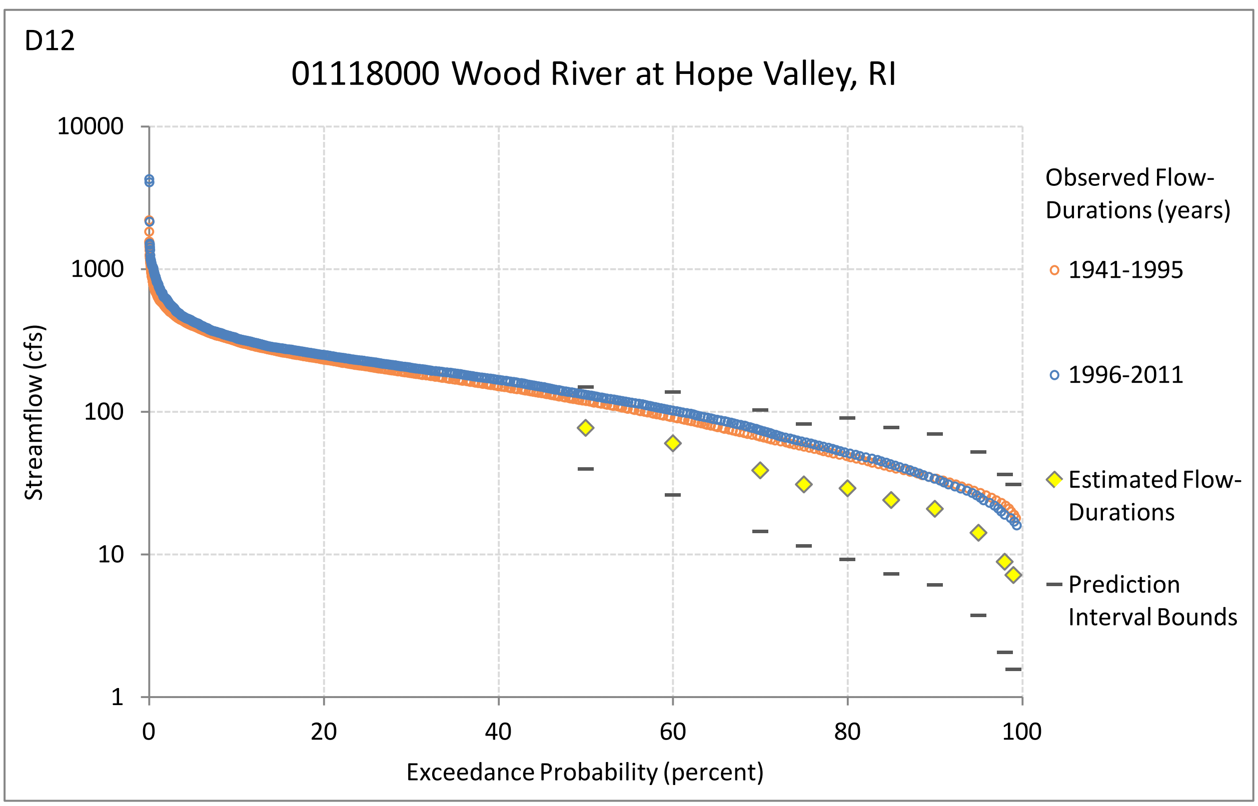

D8
01115187 Ponaganset River at South Foster, RI
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1994-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


D9
01117468 Beaver River near Usquepaug, RI
1000
100
10
1
0.1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1975-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

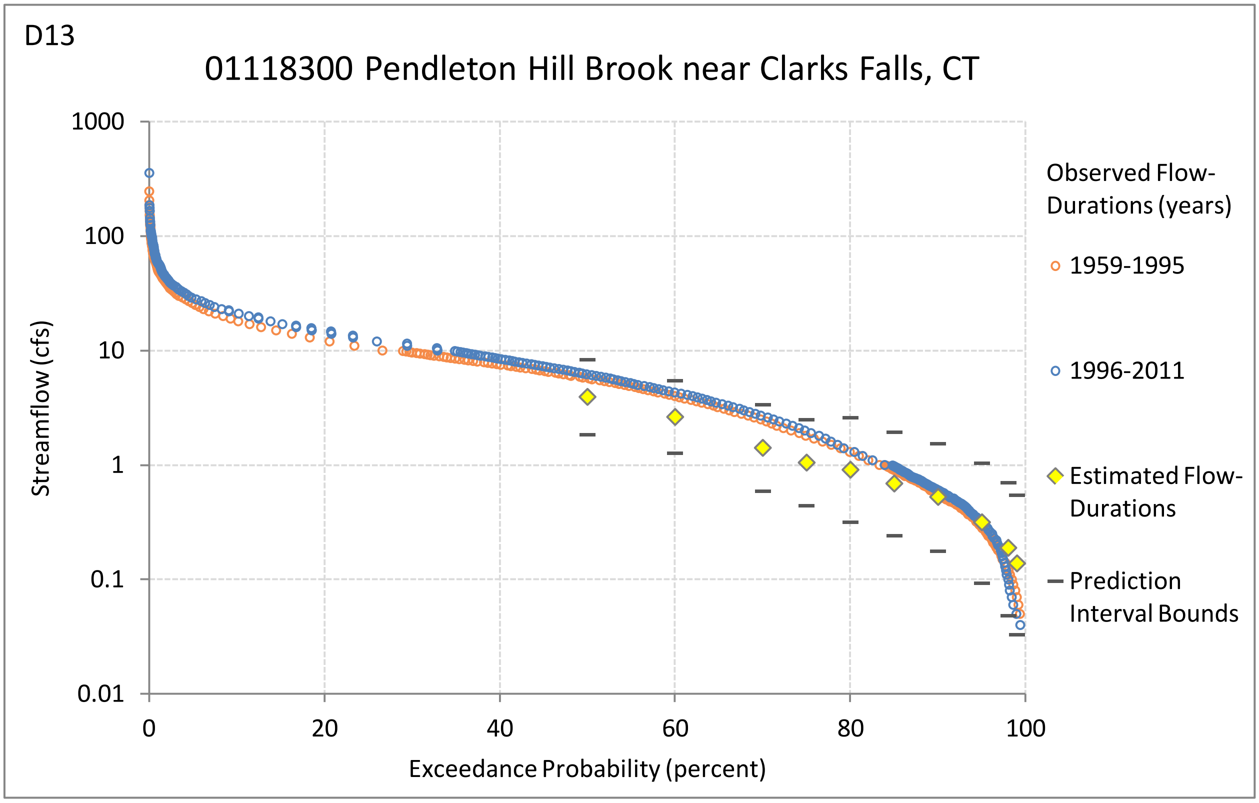

D10
01117500 Pawcatuck River at Wood River Junction, RI
10000
1000
100
10
1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1941-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

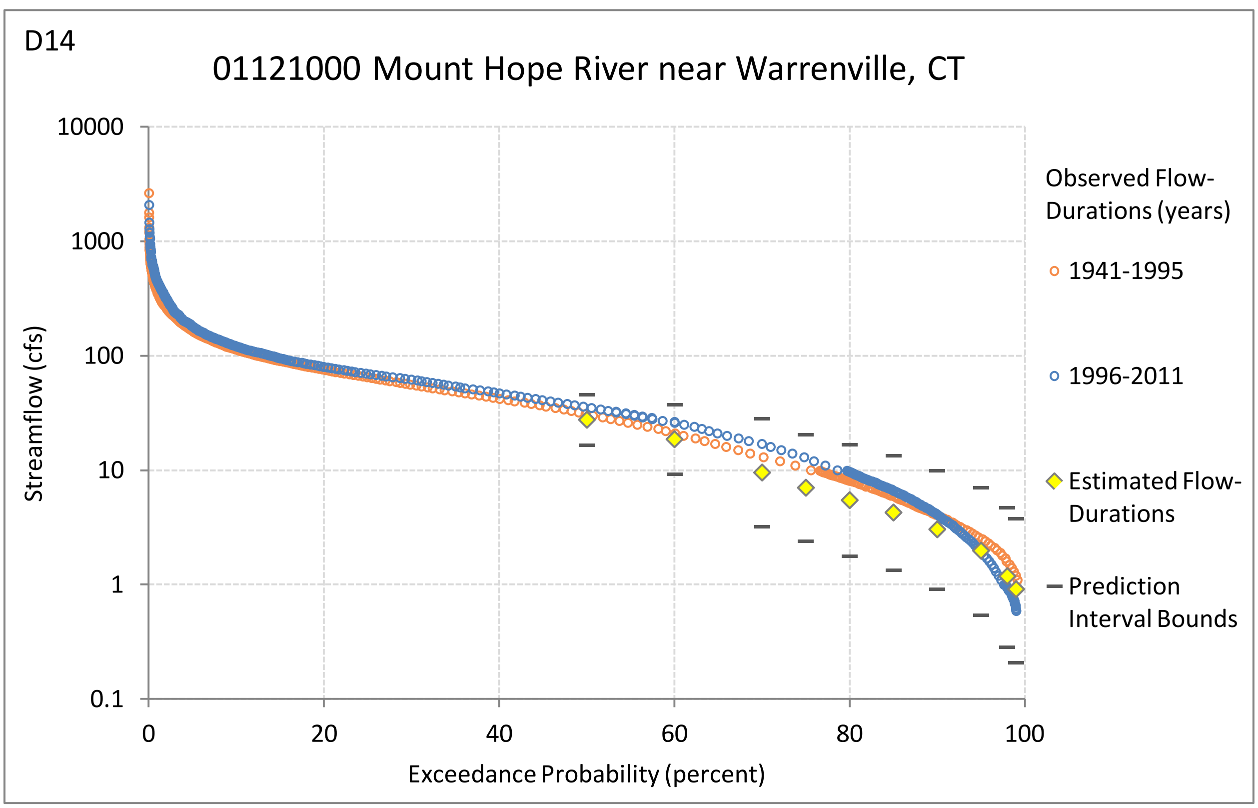


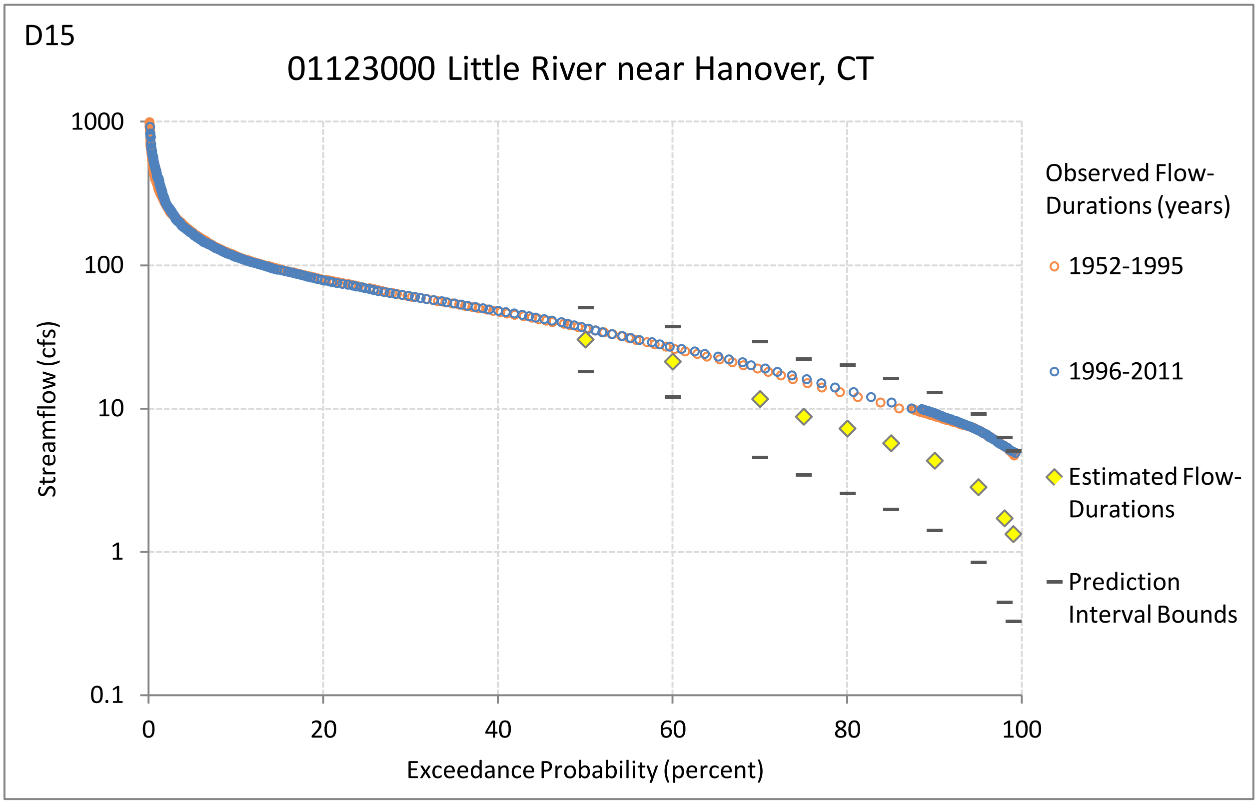
D11
01117800 Wood River near Arcadia, RI
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1964-1980, 1983-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds



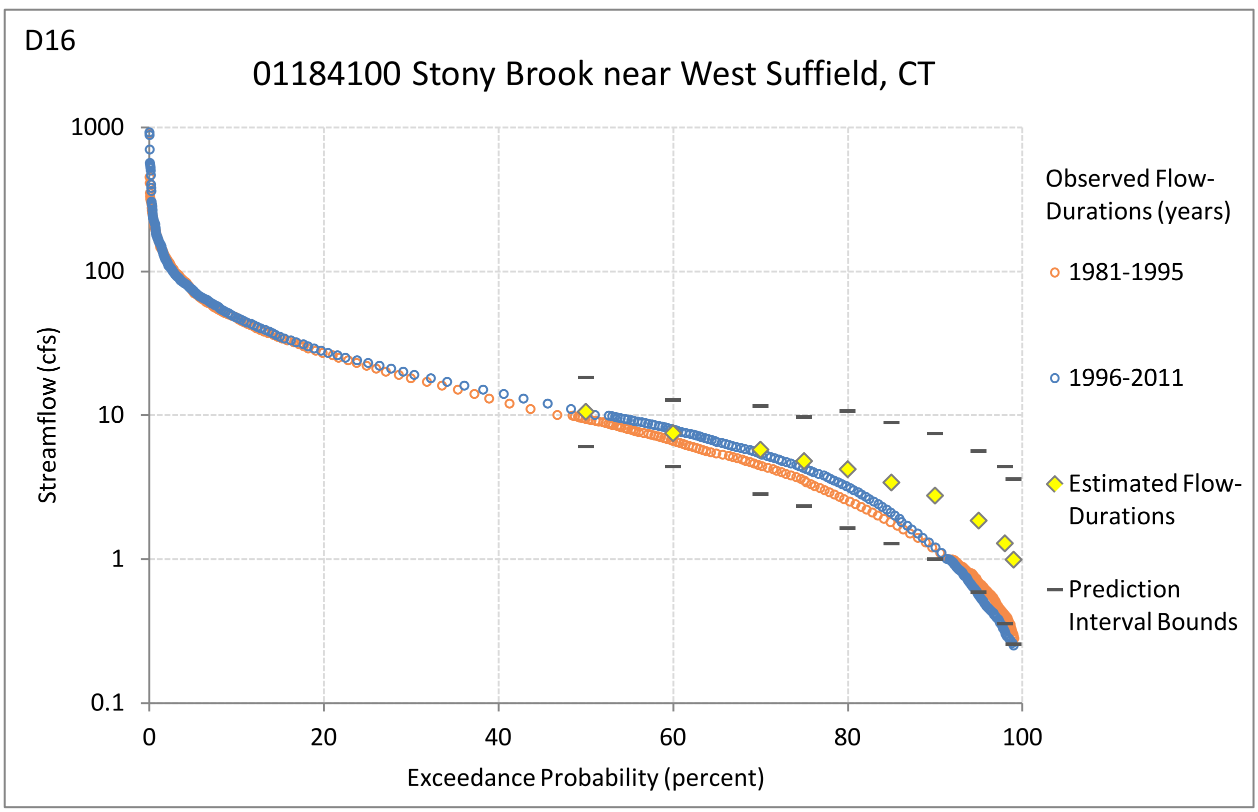
D12
01118000 Wood River at Hope Valley, RI
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1941-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


D13
01118300 Pendleton Hill Brook near Clarks Falls, CT
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1959-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

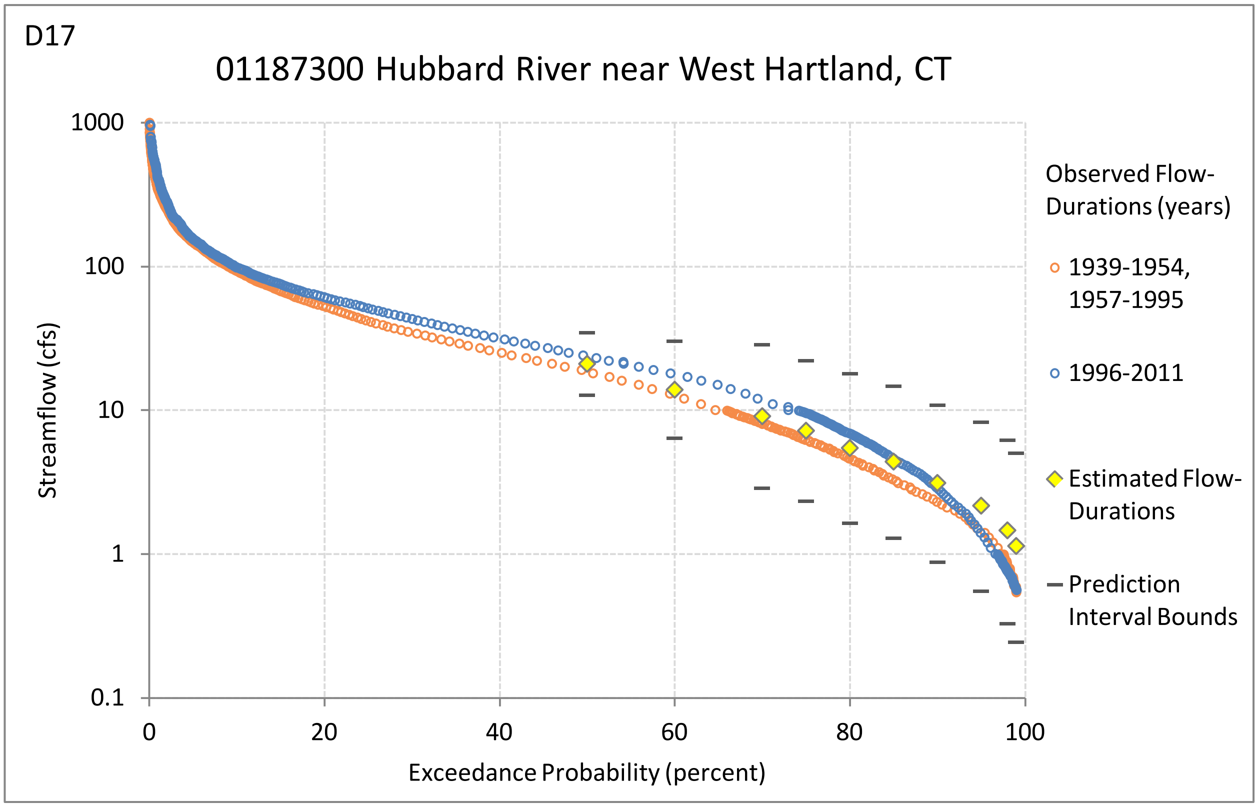

D14
01121000 Mount Hope River near Warrenville, CT
Streamflow (cfs)
10000
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1941-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

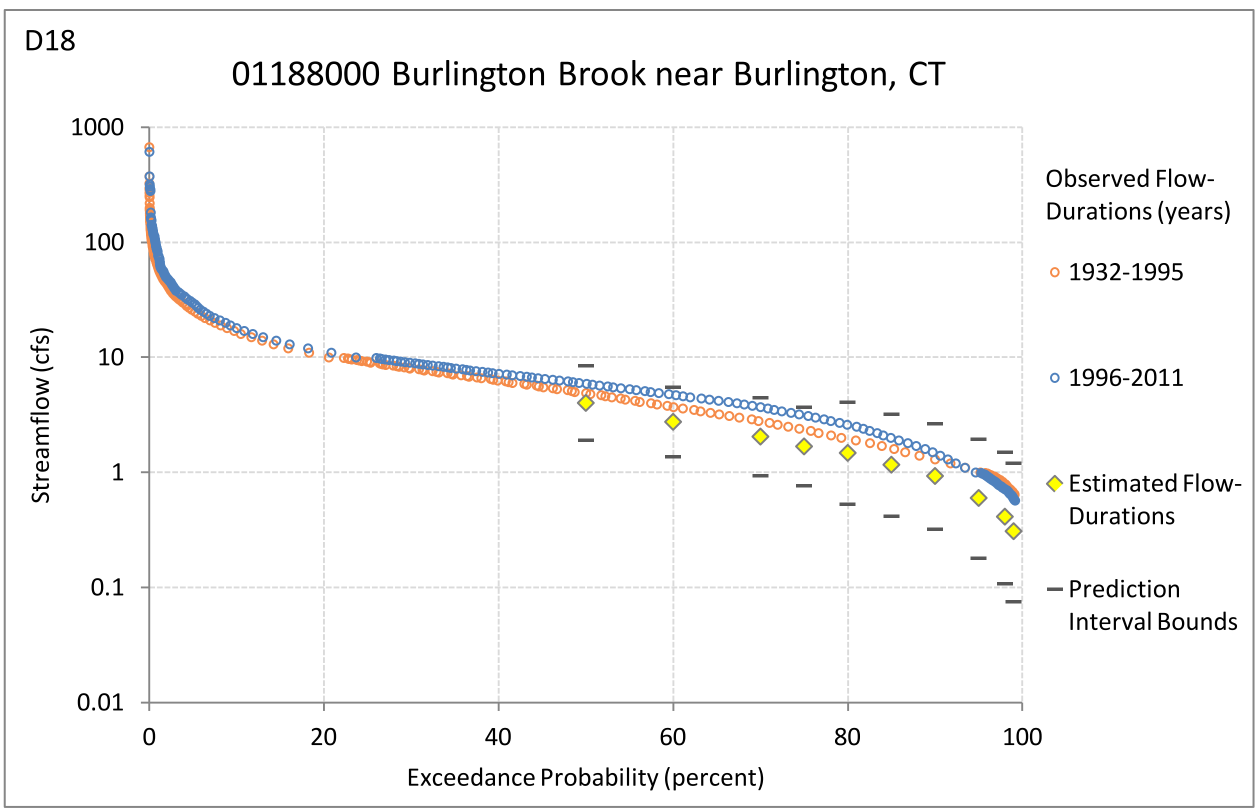


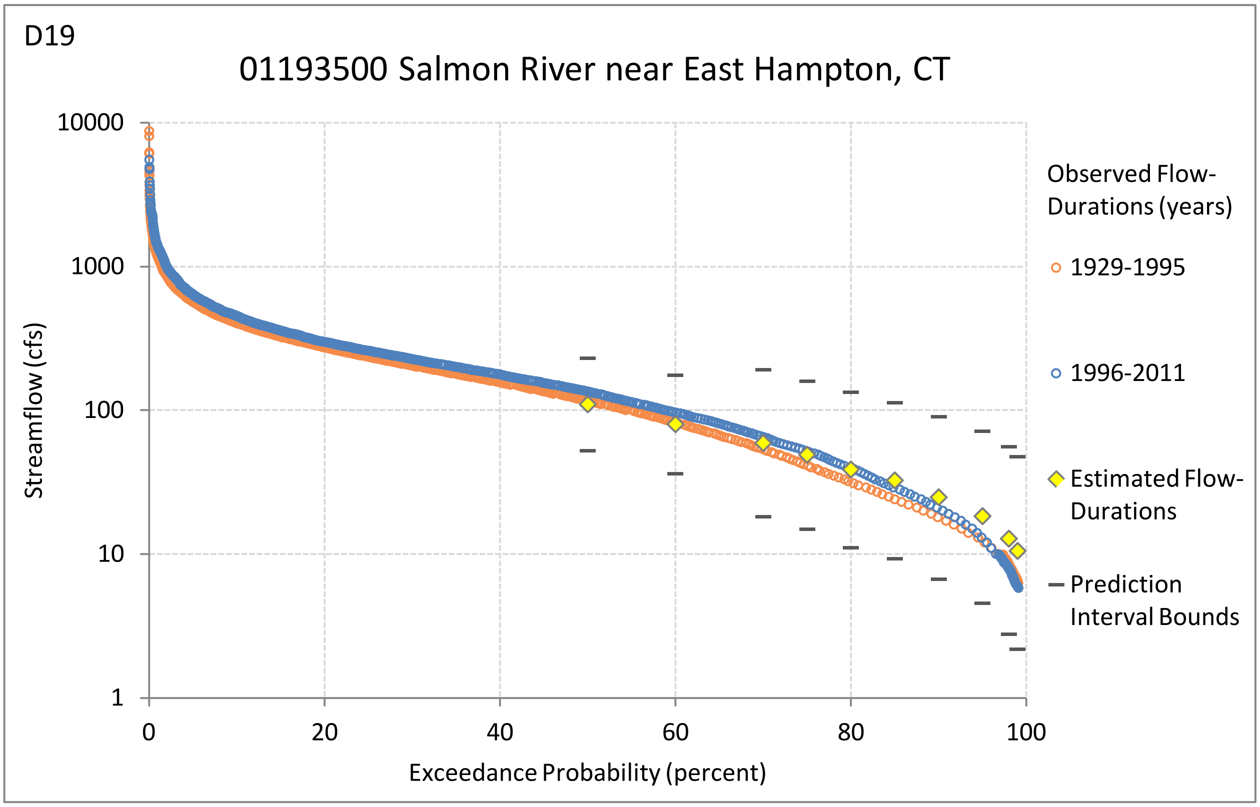
D15
01123000 Little River near Hanover, CT
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1952-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

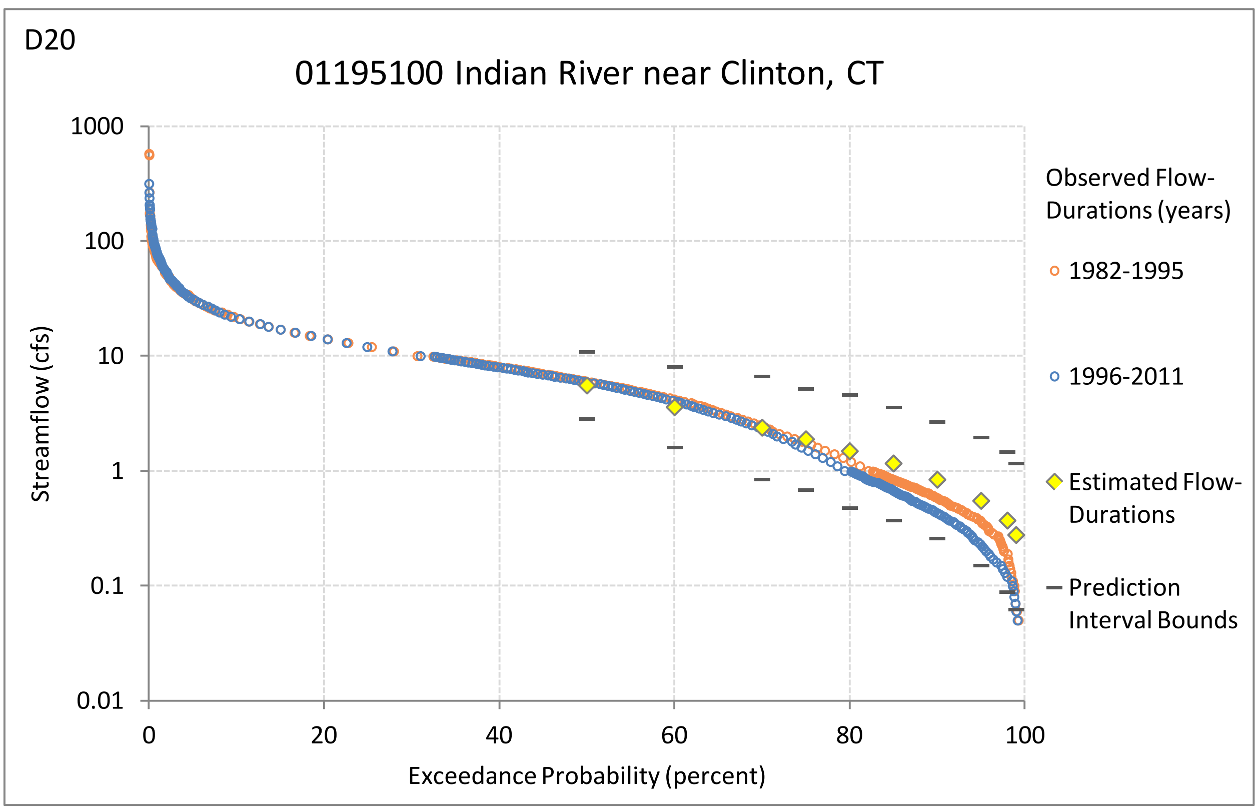


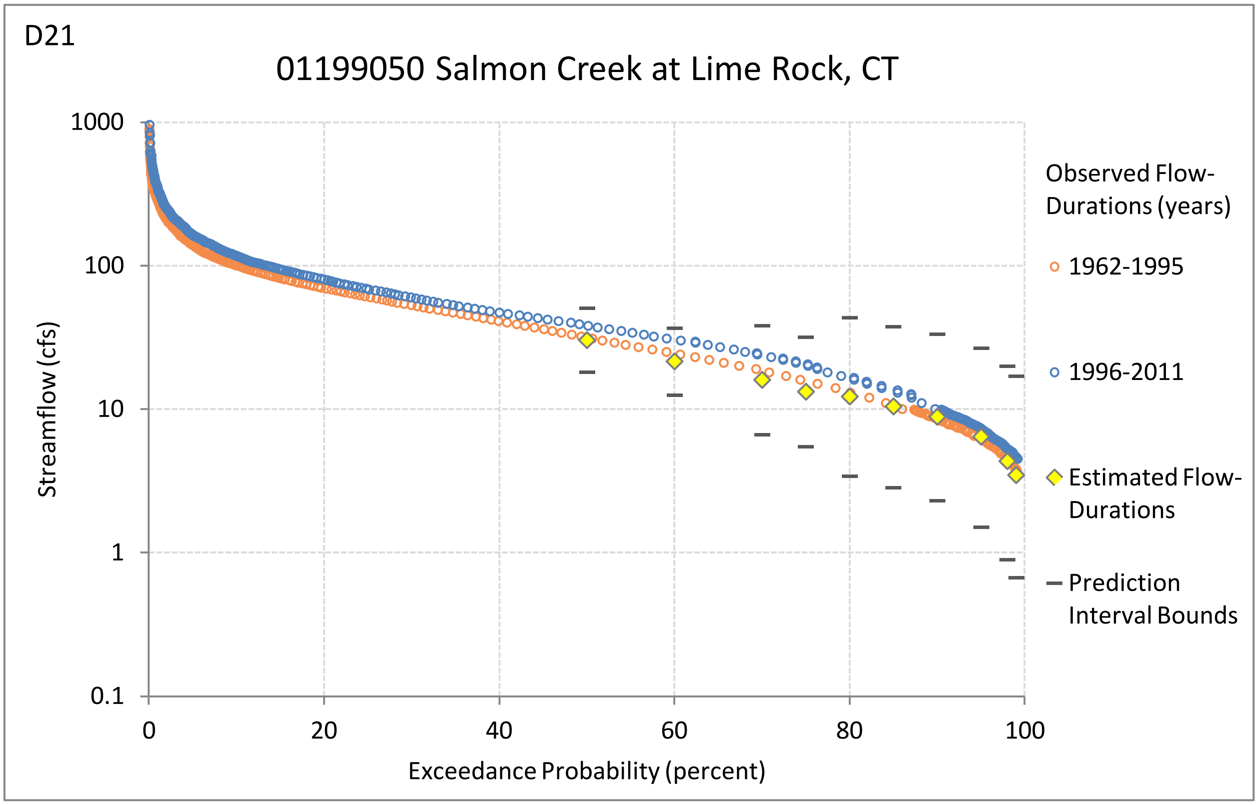
D16
01184100 Stony Brook near West Suffield, CT
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1981-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


D17
01187300 Hubbard River near West Hartland, CT
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1939-1954, 1957-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


D18
01188000 Burlington Brook near Burlington, CT
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1932-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


D19
01193500 Salmon River near East Hampton, CT
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1929-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds


D20
01195100 Indian River near Clinton, CT
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1982-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

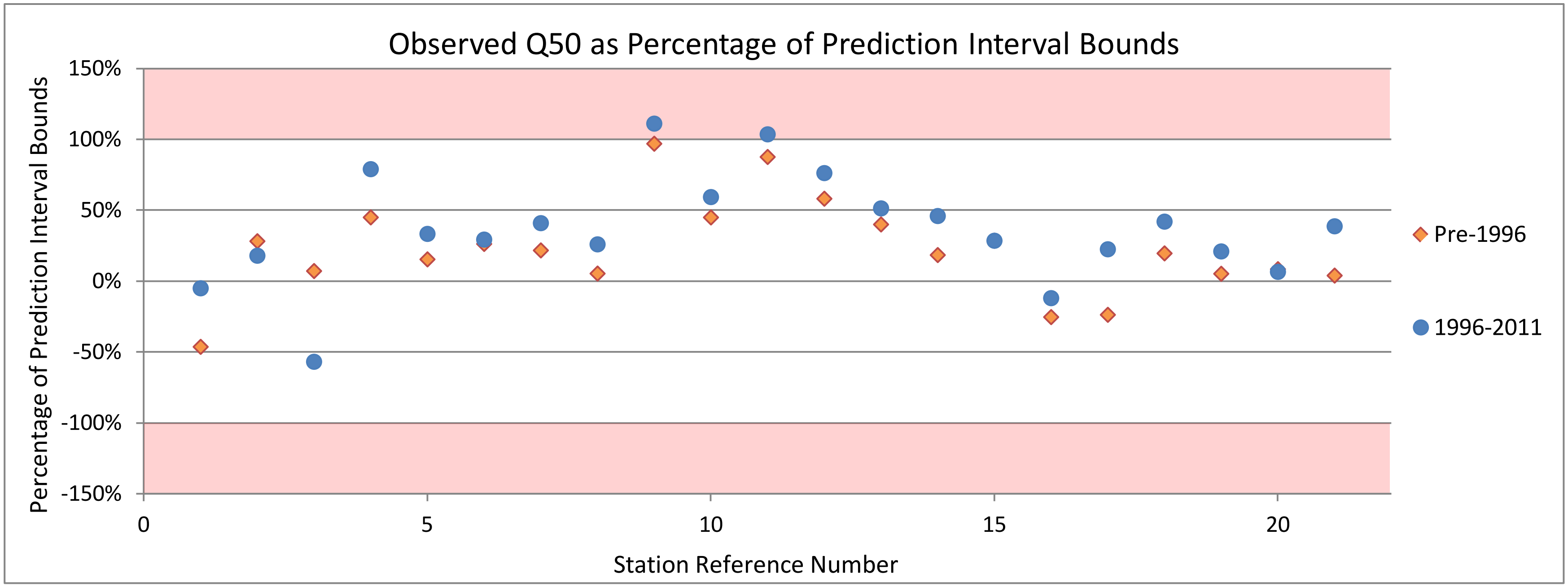

D21
01199050 Salmon Creek at Lime Rock, CT
1000
100
10
1
0.1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1962-1995
1996-2011
Estimated Flow-Durations
Prediction Interval Bounds

Appendix E

Part II Observed Flow-Durations as Percentage of

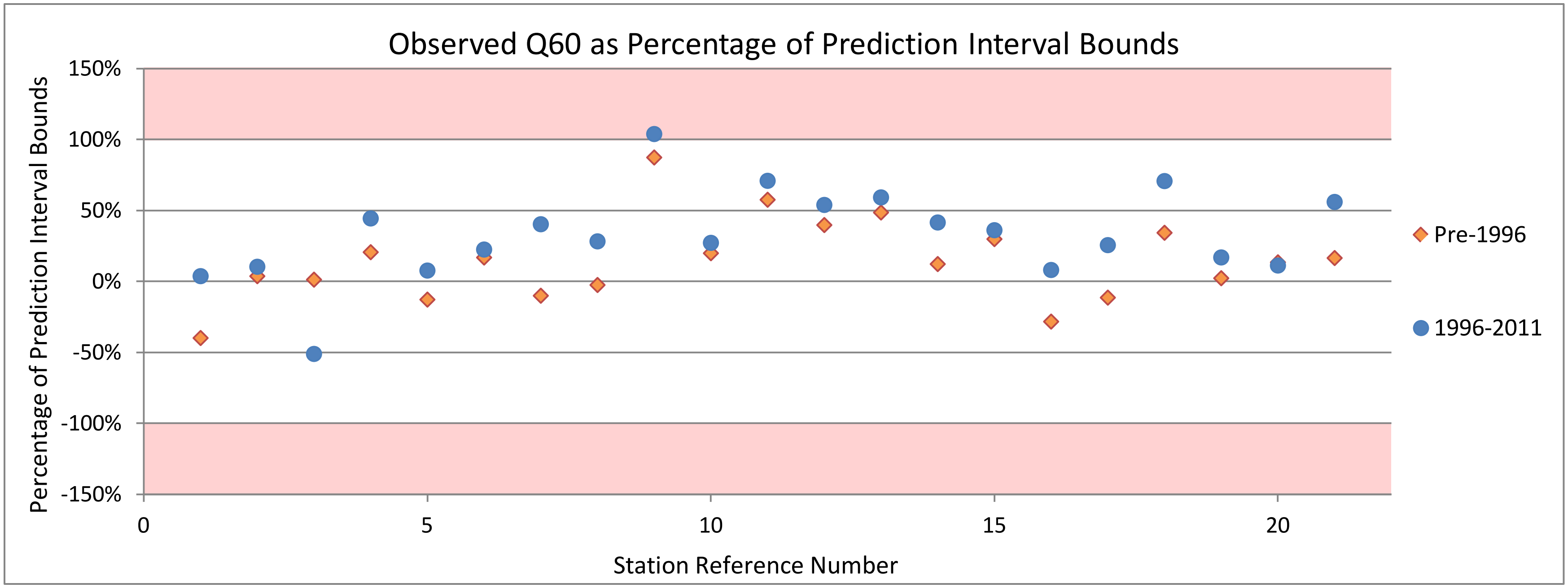
Prediction Interval Bounds

E1



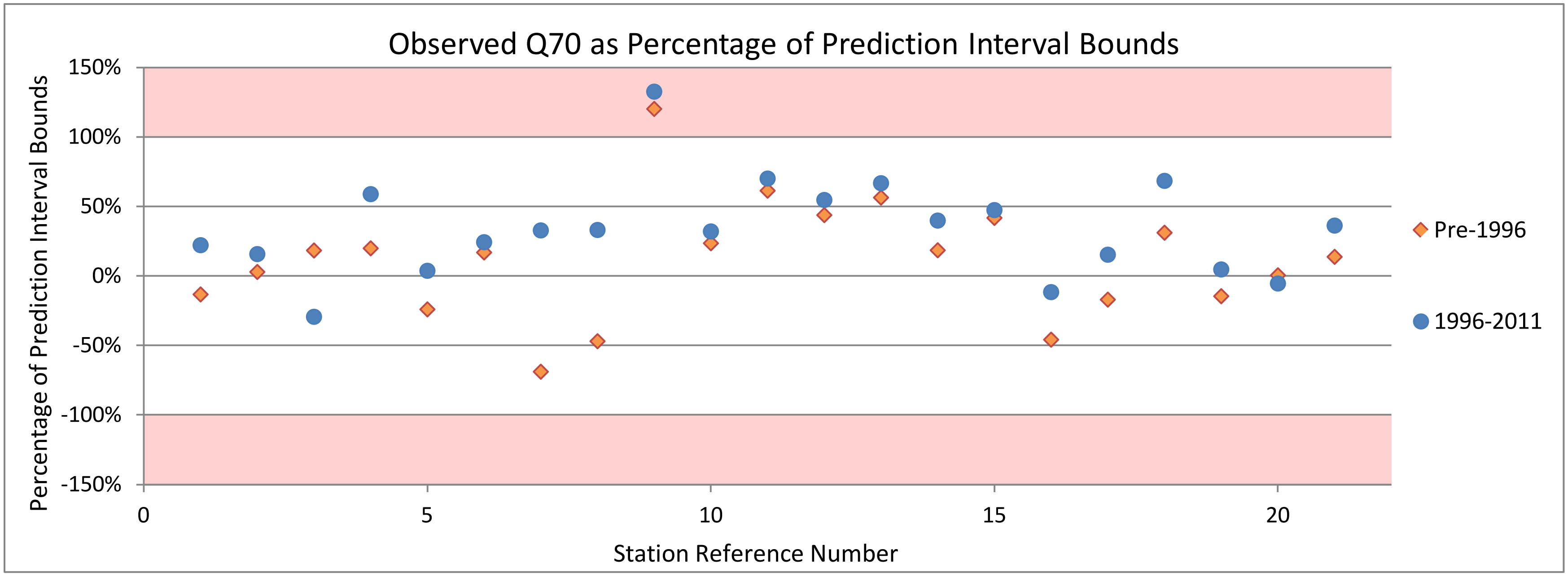
Station Reference Number	Station Number	Station Name	Station Reference Number	Station Number	Station Name
1	01073000	Oyster River near Durham, NH	12	01118000	Wood River at Hope Valley, RI
2	01095220	Stillwater River near Sterling, MA	13	01118300	Pendleton Hill Brook near Clarks Falls, CT
3	010965852	Beaver Brook at North Pelham, MA	14	01121000	Mount Hope River near Warrenville, CT
4	01105730	Indian Head River at Hanover, MA	15	01123000	Little River near Hanover, CT
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

E2



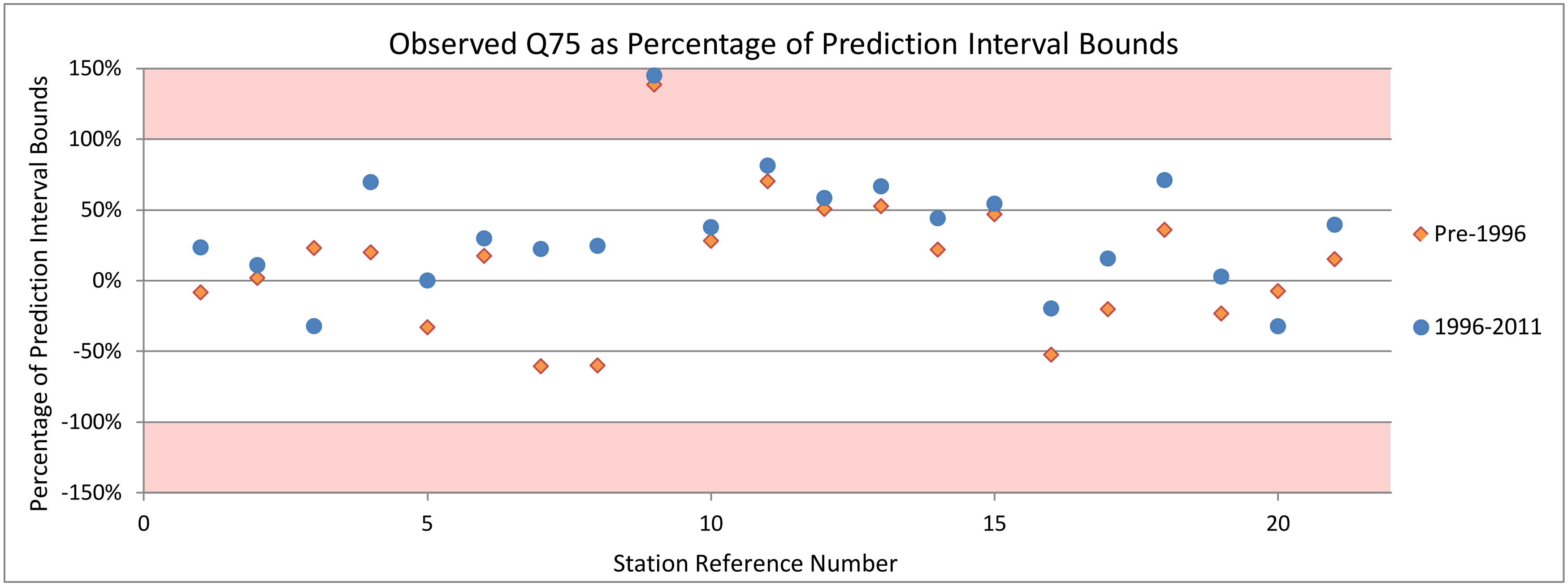
Station Reference Number	Station Number	Station Name	Station Reference Number	Station Number	Station Name
1	01073000	Oyster River near Durham, NH	12	01118000	Wood River at Hope Valley, RI
2	01095220	Stillwater River near Sterling, MA	13	01118300	Pendleton Hill Brook near Clarks Falls, CT
3	010965852	Beaver Brook at North Pelham, MA	14	01121000	Mount Hope River near Warrenville, CT
4	01105730	Indian Head River at Hanover, MA	15	01123000	Little River near Hanover, CT
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

E3



Station Reference Number	Station Number	Station Name	Station Reference Number	Station Number	Station Name
1	01073000	Oyster River near Durham, NH	12	01118000	Wood River at Hope Valley, RI
2	01095220	Stillwater River near Sterling, MA	13	01118300	Pendleton Hill Brook near Clarks Falls, CT
3	010965852	Beaver Brook at North Pelham, MA	14	01121000	Mount Hope River near Warrenville, CT
4	01105730	Indian Head River at Hanover, MA	15	01123000	Little River near Hanover, CT
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

E4



Station Reference Number	Station Number	Station Name	Station Reference Number	Station Number	Station Name
1	01073000	Oyster River near Durham, NH	12	01118000	Wood River at Hope Valley, RI
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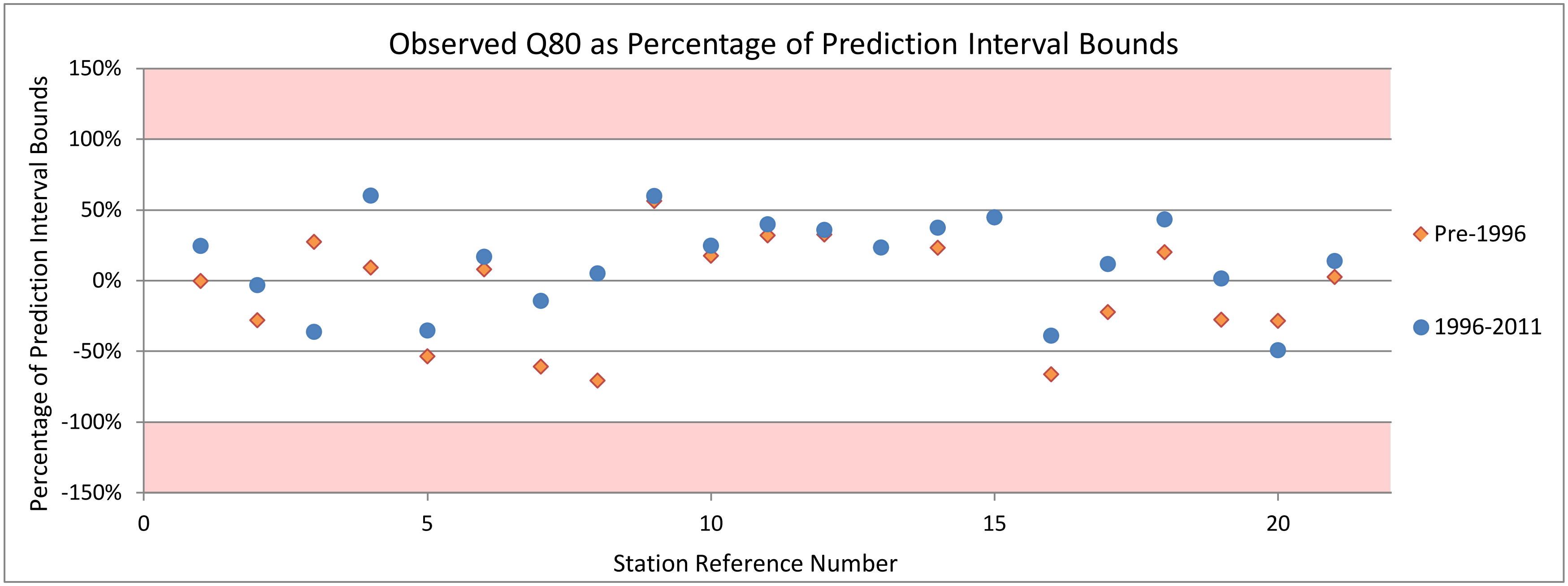
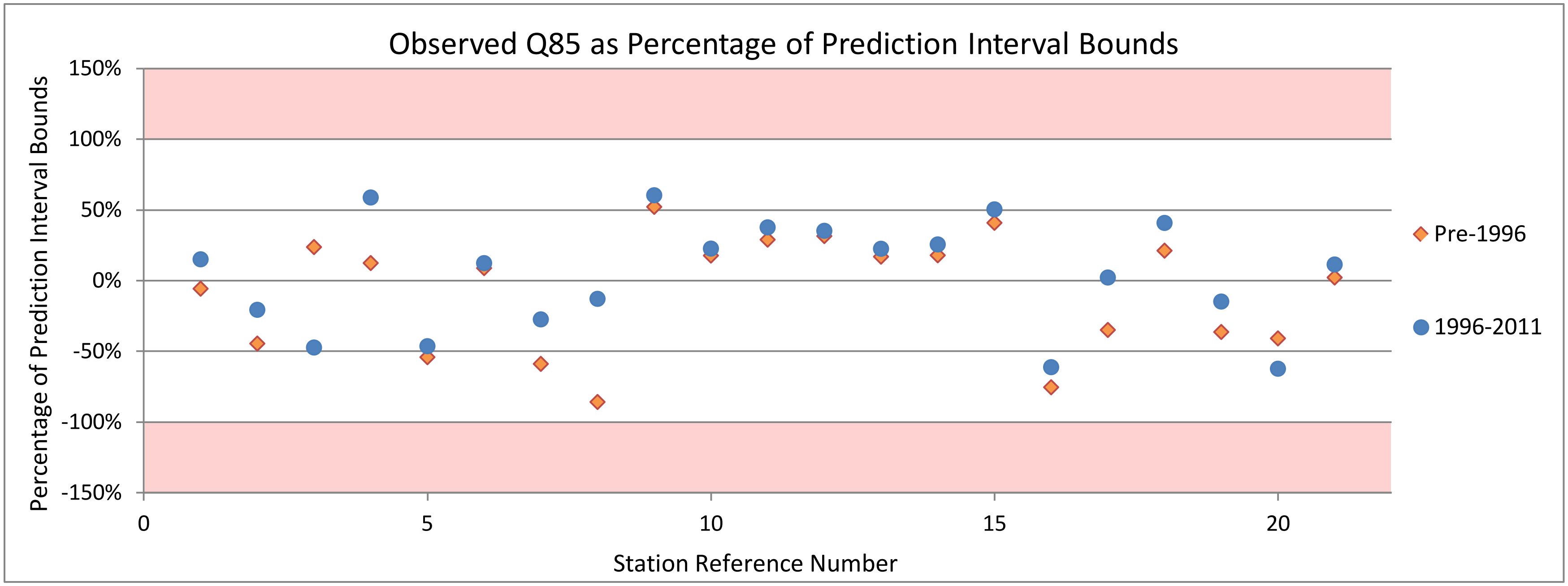
3	010965852	Beaver Brook at North Pelham, MA	14	01121000	Mount Hope River near Warrenville, CT
4	01105730	Indian Head River at Hanover, MA	15	01123000	Little River near Hanover, CT
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

E5



Station Reference Number	Station Number	Station Name	Station Reference Number	Station Number	Station Name
1	01073000	Oyster River near Durham, NH	12	01118000	Wood River at Hope Valley, RI
2	01095220	Stillwater River near Sterling, MA	13	01118300	Pendleton Hill Brook near Clarks Falls, CT
3	010965852	Beaver Brook at North Pelham, MA	14	01121000	Mount Hope River near Warrenville, CT
4	01105730	Indian Head River at Hanover, MA	15	01123000	Little River near Hanover, CT
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

E6



Station Reference Number	Station Number	Station Name	Station Reference Number	Station Number	Station Name
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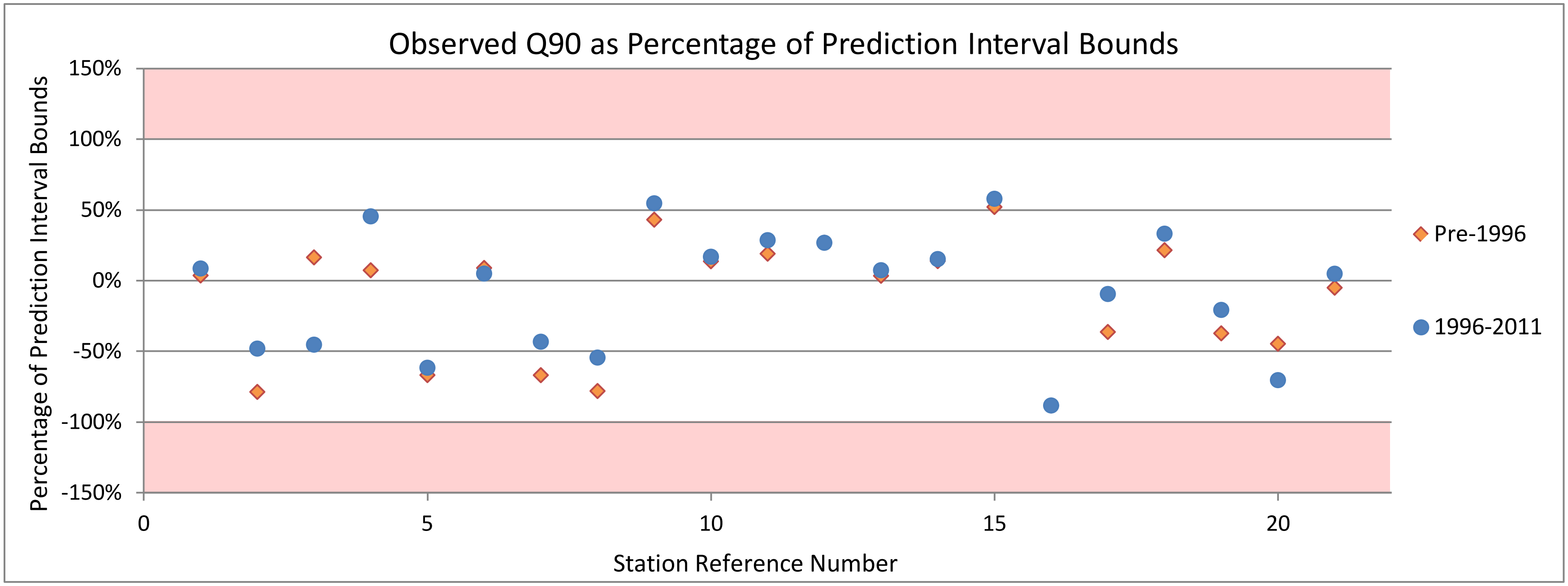
3	010965852	Beaver Brook at North Pelham, MA	14	01121000	Mount Hope River near Warrenville, CT
4	01105730	Indian Head River at Hanover, MA	15	01123000	Little River near Hanover, CT
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

E7



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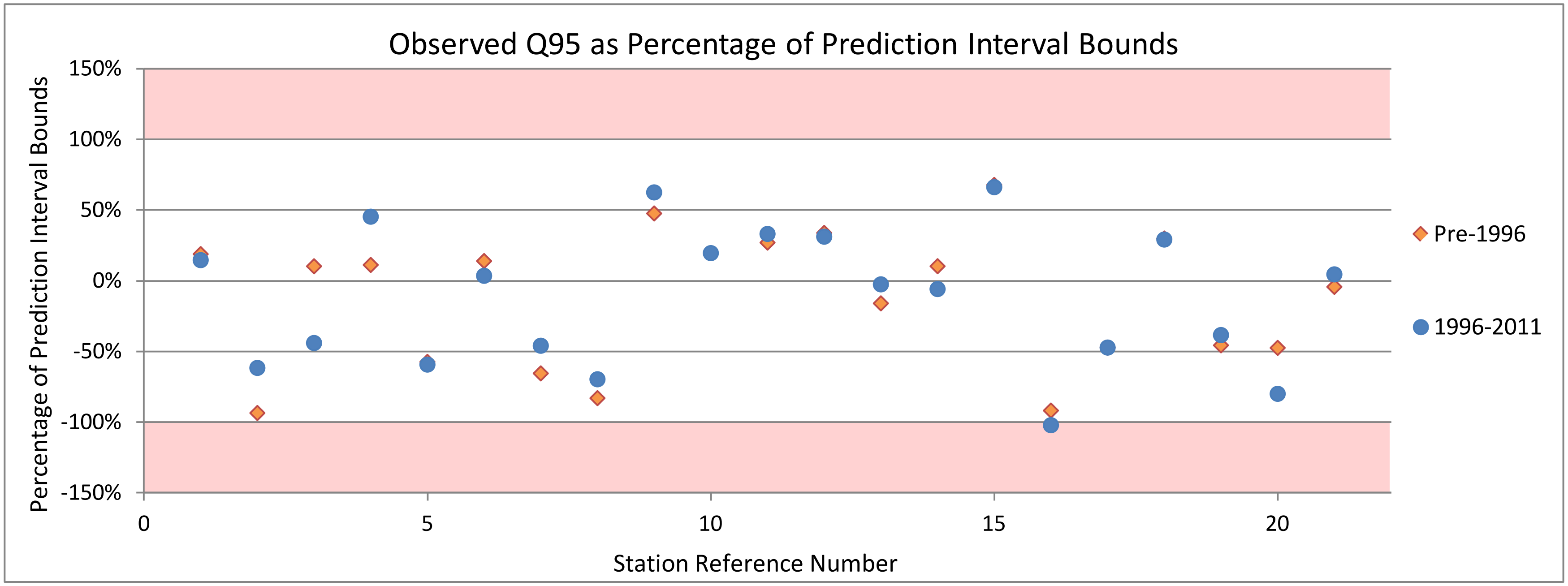
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

E8



Station Reference Number	Station Number	Station Name	Station Reference Number	Station Number	Station Name
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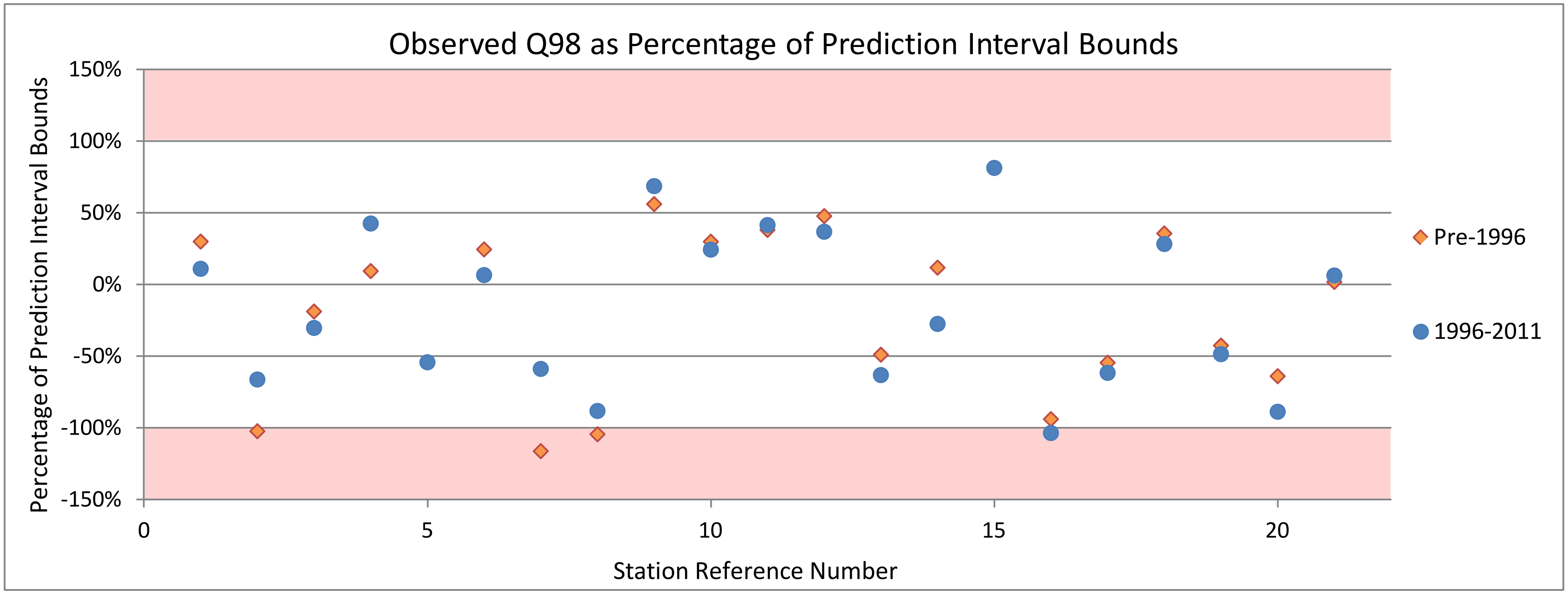
4	01105730	Indian Head River at Hanover, MA	15	01123000	Little River near Hanover, CT
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

E9



Station Reference Number	Station Number	Station Name	Station Reference Number	Station Number	Station Name
1	01073000	Oyster River near Durham, NH	12	01118000	Wood River at Hope Valley, RI
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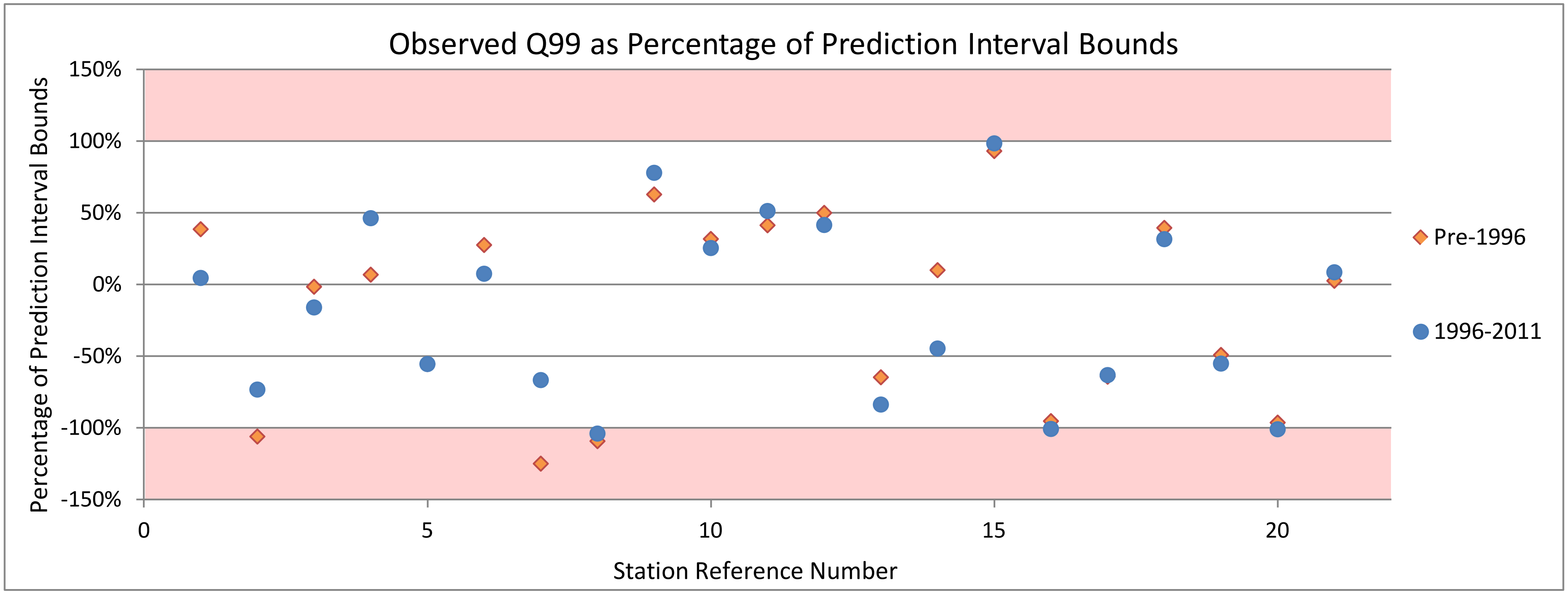
3	010965852	Beaver Brook at North Pelham, MA	14	01121000	Mount Hope River near Warrenville, CT
4	01105730	Indian Head River at Hanover, MA	15	01123000	Little River near Hanover, CT
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

E10



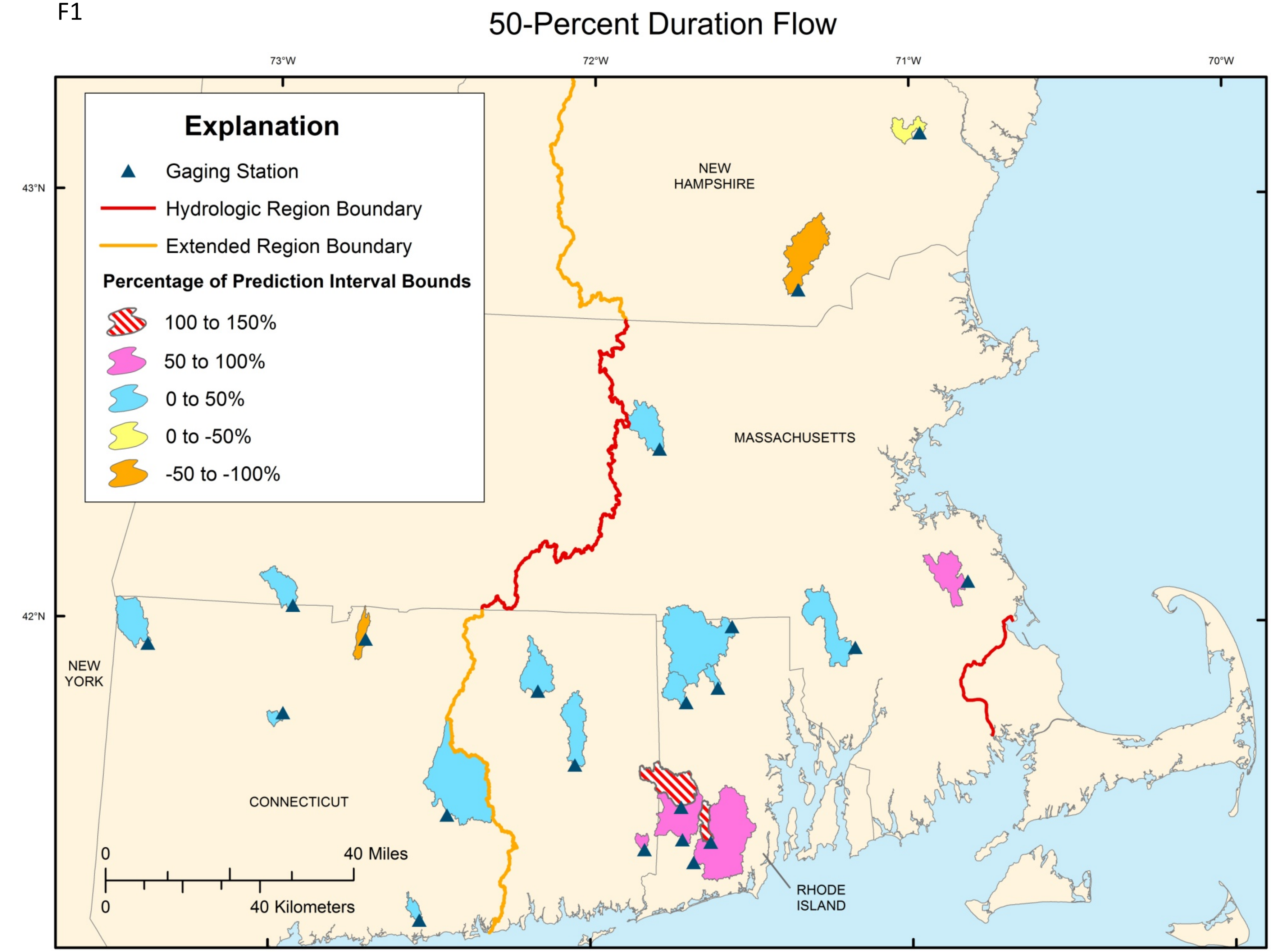
Station Reference Number	Station Number	Station Name	Station Reference Number	Station Number	Station Name
1	01073000	Oyster River near Durham, NH	12	01118000	Wood River at Hope Valley, RI
2	01095220	Stillwater River near Sterling, MA	13	01118300	Pendleton Hill Brook near Clarks Falls, CT
3	010965852	Beaver Brook at North Pelham, MA	14	01121000	Mount Hope River near Warrenville, CT
4	01105730	Indian Head River at Hanover, MA	15	01123000	Little River near Hanover, CT
5	01109000	Wading River near Norton, MA	16	01184100	Stony Brook near West Suffield, CT
6	01111500	Branch River at Forestdale, RI	17	01187300	Hubbard River near West Hartland, CT
7	01115098	Peeptoad Brook at Elmdale Road near North Scituate, RI	18	01188000	Burlington Brook near Burlington, CT
8	01115187	Ponaganset River at South Foster, RI	19	01193500	Salmon River near East Hampton, CT
9	01117468	Beaver River near Usquepaug, RI	20	01195100	Indian River near Clinton, CT
10	01117500	Pawcatuck River at Wood River Junction, RI	21	01199050	Salmon Creek at Lime Rock, CT
11	01117800	Wood River near Arcadia, RI	-	-	-

Appendix F

Part II RF Model Performance Maps

(Compared to 1996-2011 Data)

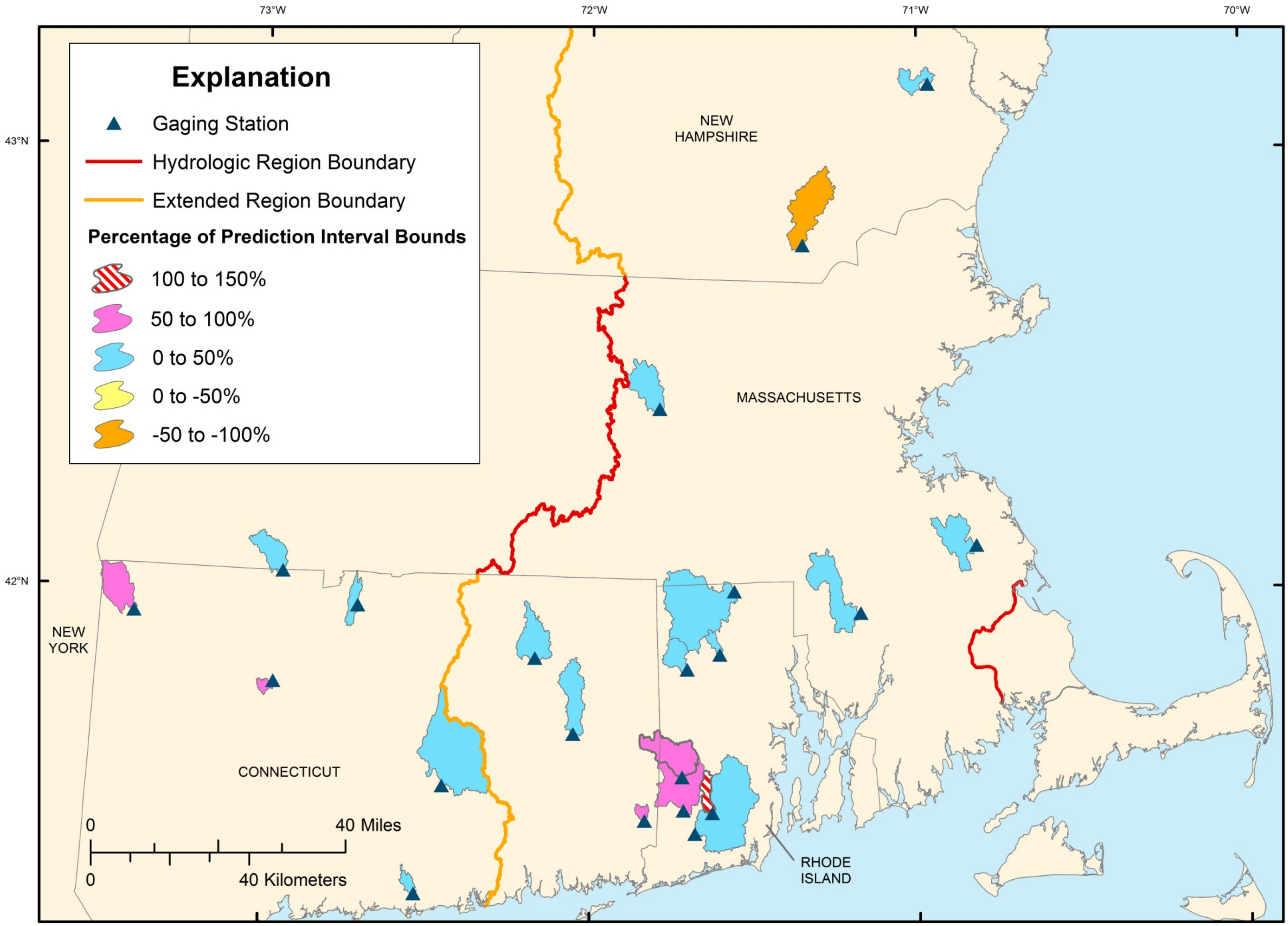
F1



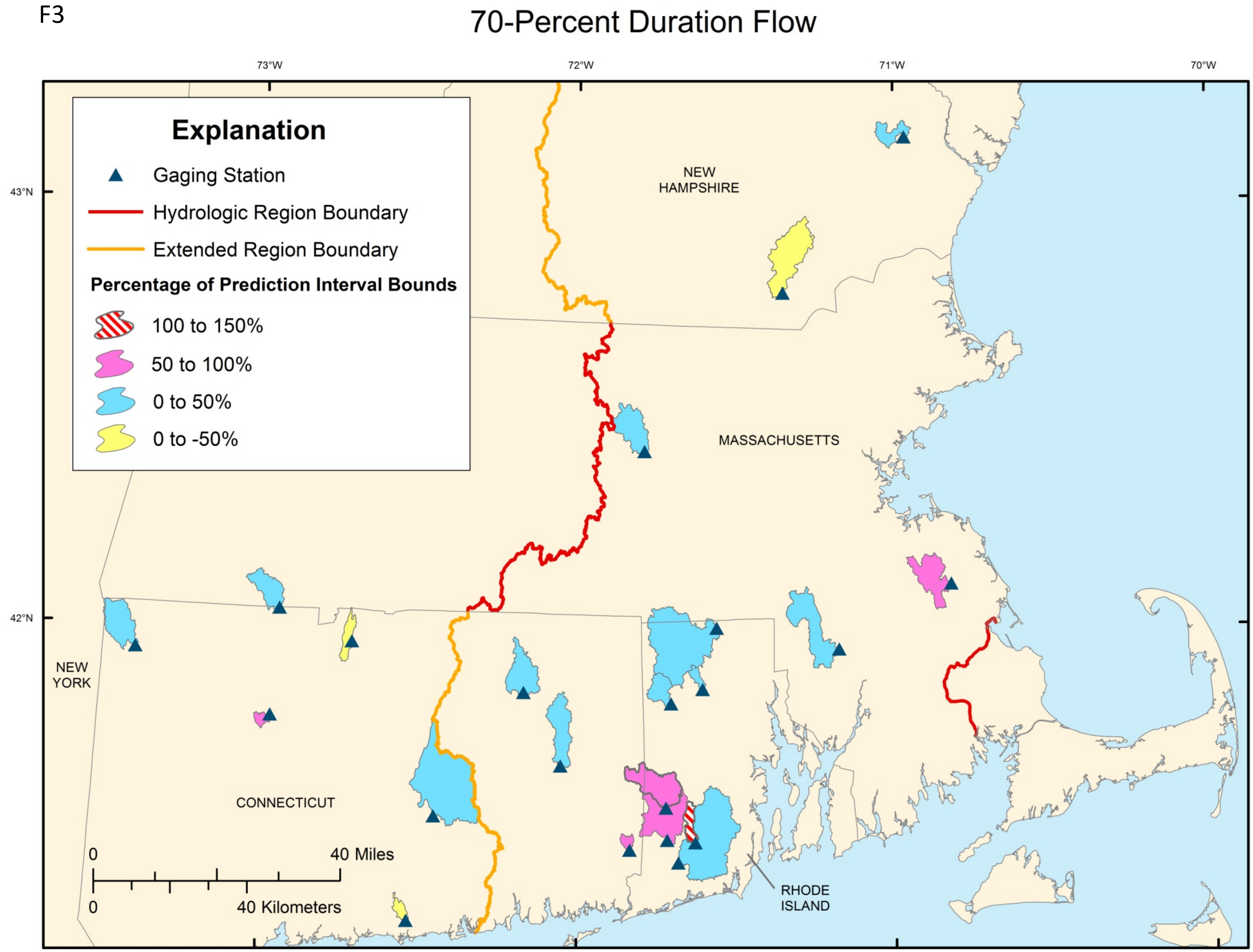
50-Percent Duration Flow
73°W
72°W
71°W
70°W
43°N
42°N
Explanation
Gaging Station
Hydrologic Region Boundary
Extended Region Boundary
Percentage of Prediction Interval Bounds
100 to 150%
50 to 100%
0 to 50%
0 to -50%
-50 to -100%
NEW HAMPSHIRE
MASSACHUSETTS
NEW YORK
CONNECTICUT
RHODE ISLAND
0
40 Miles
0
40 Kilometers

F2

60-Percent Duration Flow



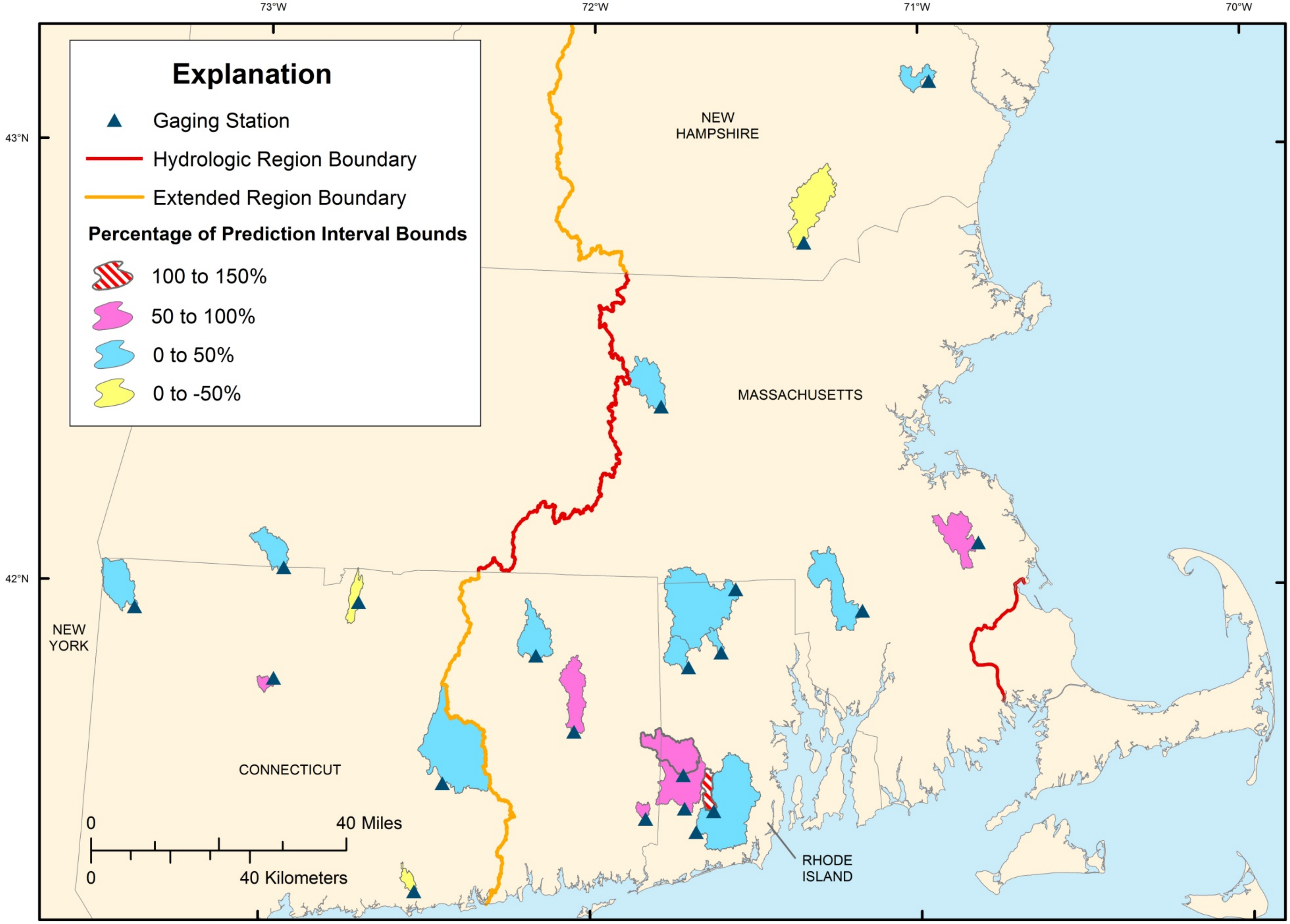
F3



70-Percent Duration Flow
73°W
72°W
71°W
70°W
43°N
42°N
Explanation
Gaging Station
Hydrologic Region Boundary
Extended Region Boundary
Percentage of Prediction Interval Bounds
100 to 150%
50 to 100%
0 to 50%
0 to -50%
NEW HAMPSHIRE
MASSACHUSETTS
NEW YORK
CONNECTICUT
RHODE ISLAND
0
40 Miles
0
40 Kilometers

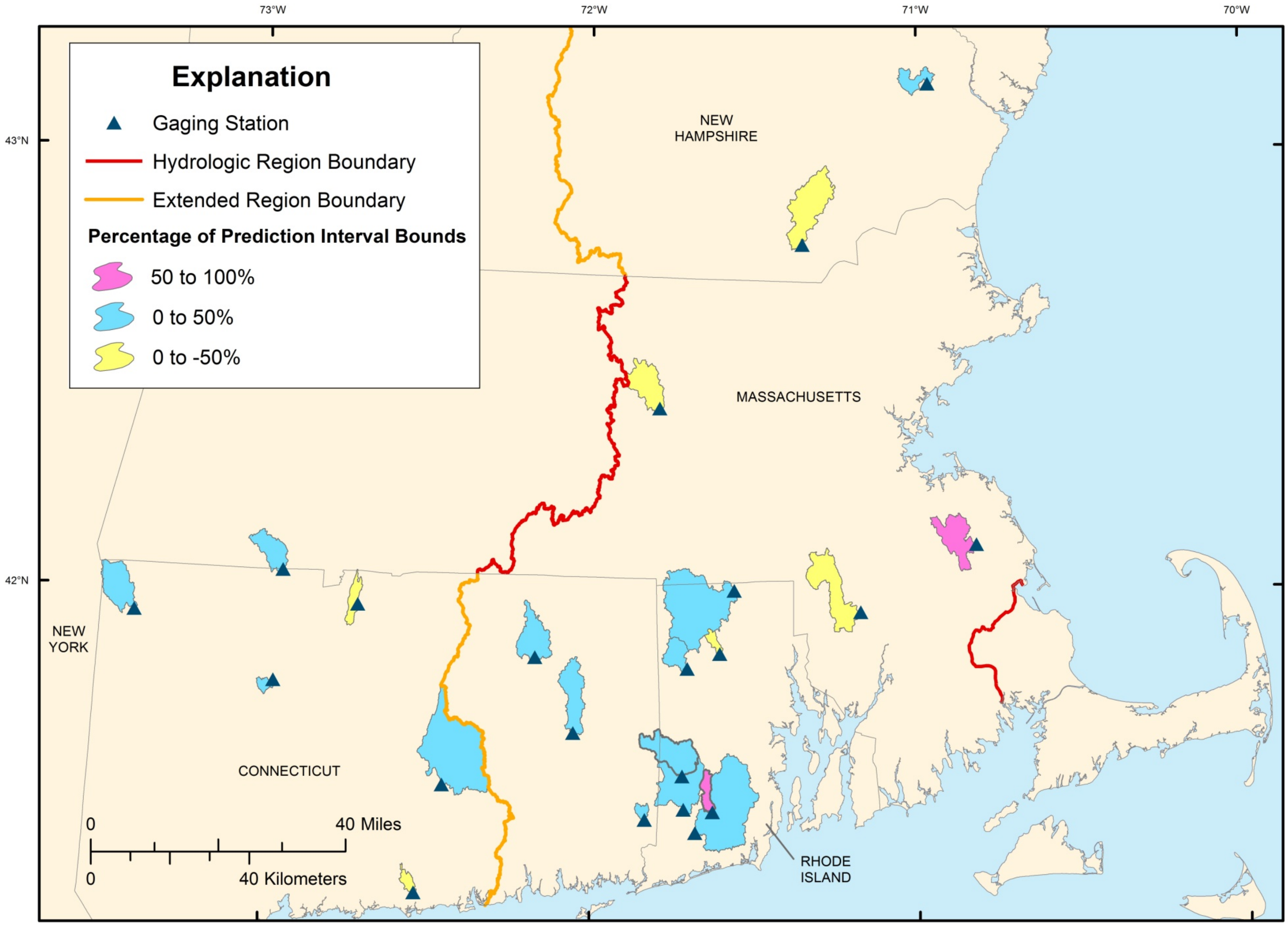
F4

75-Percent Duration Flow



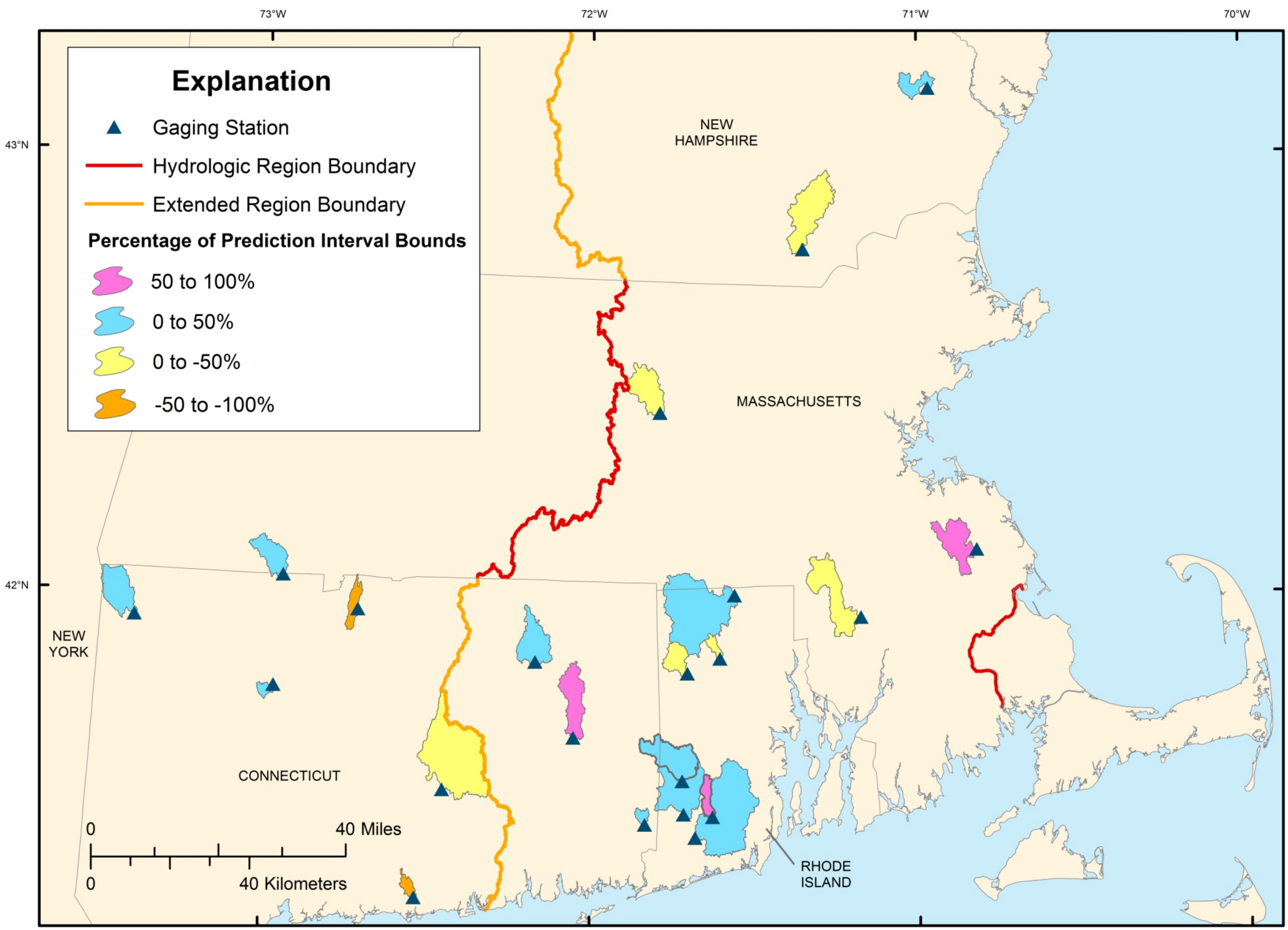
F5

80-Percent Duration Flow



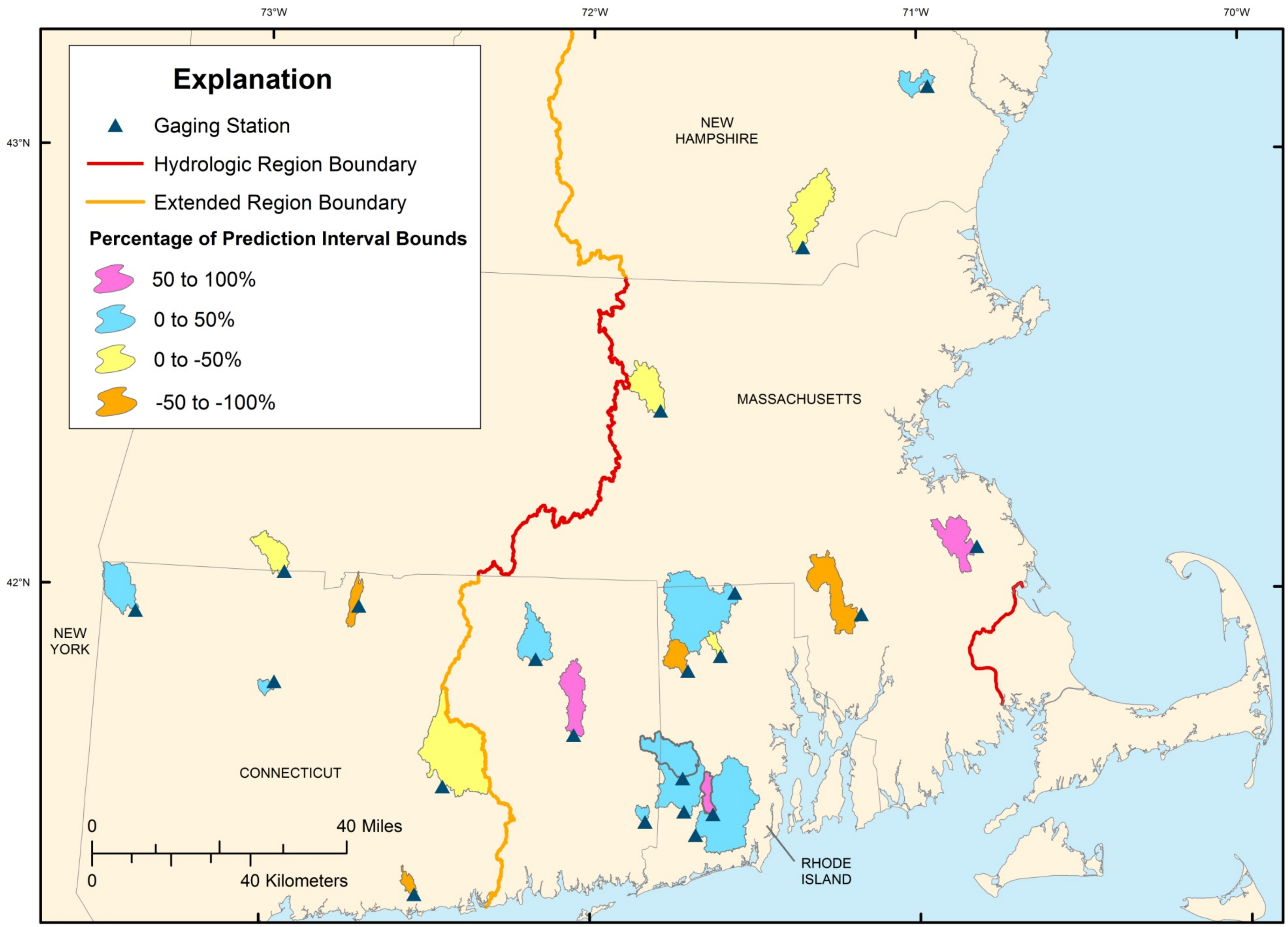
F6

85-Percent Duration Flow



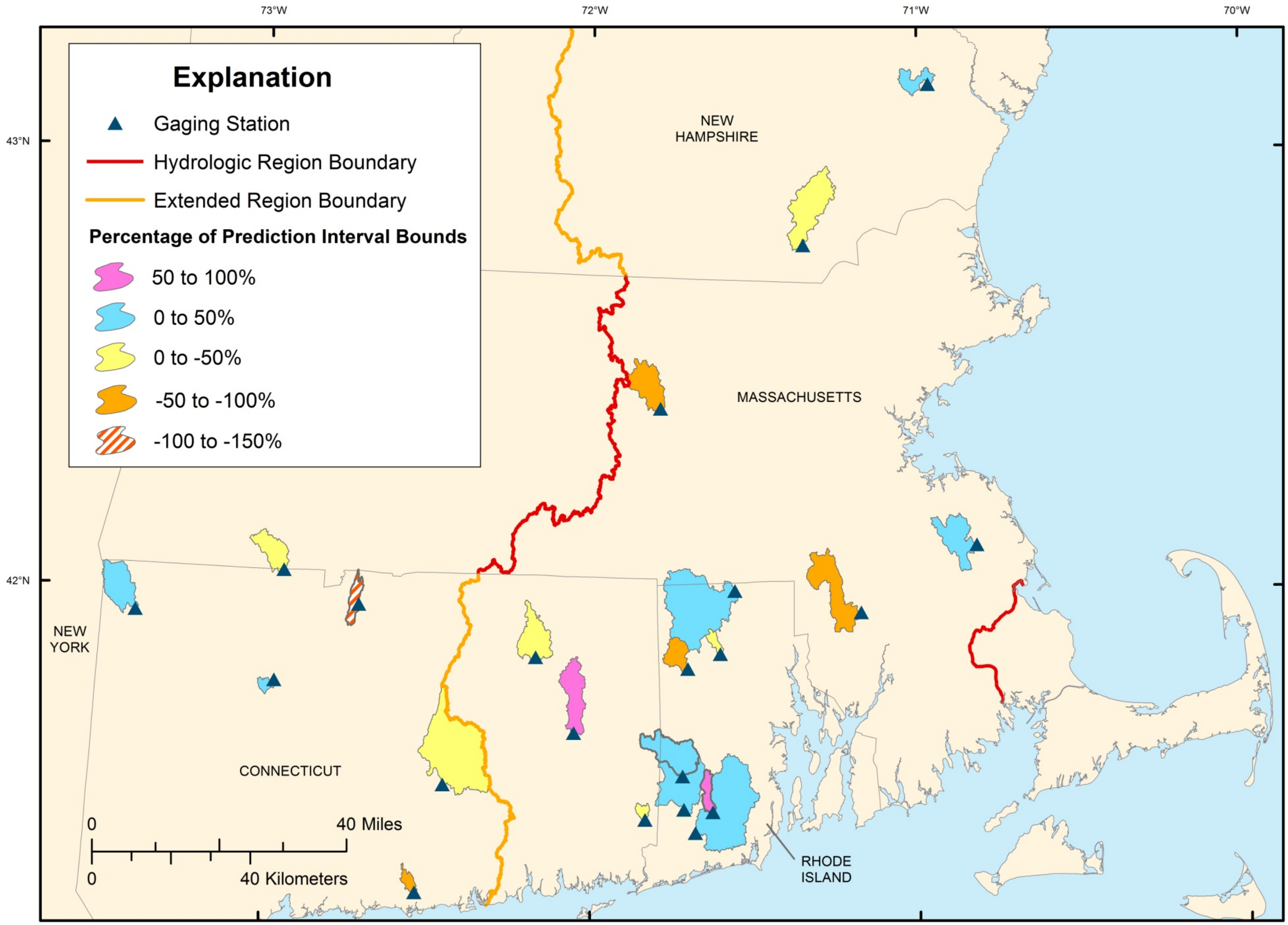
F7

90-Percent Duration Flow



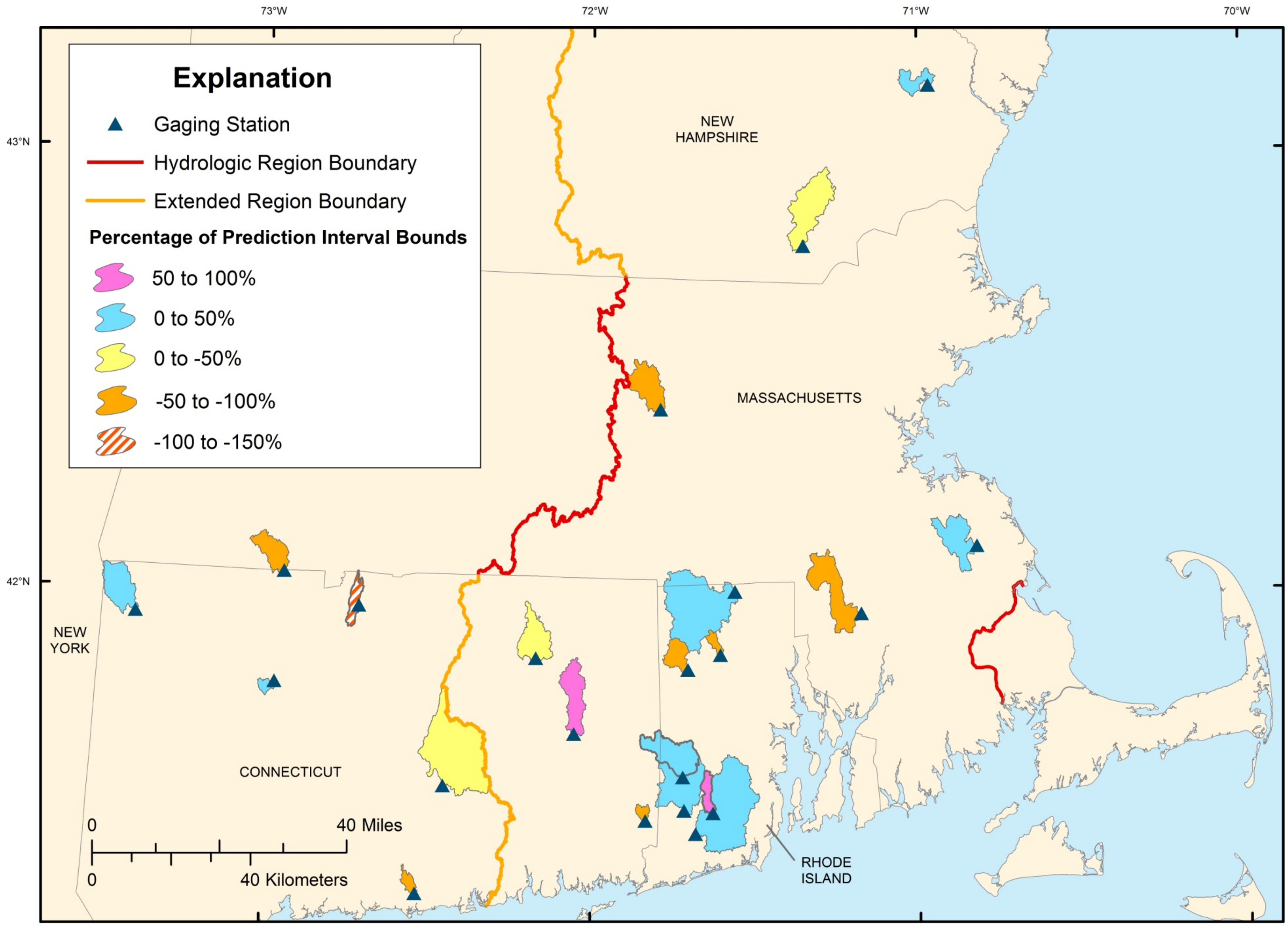
F8

95-Percent Duration Flow



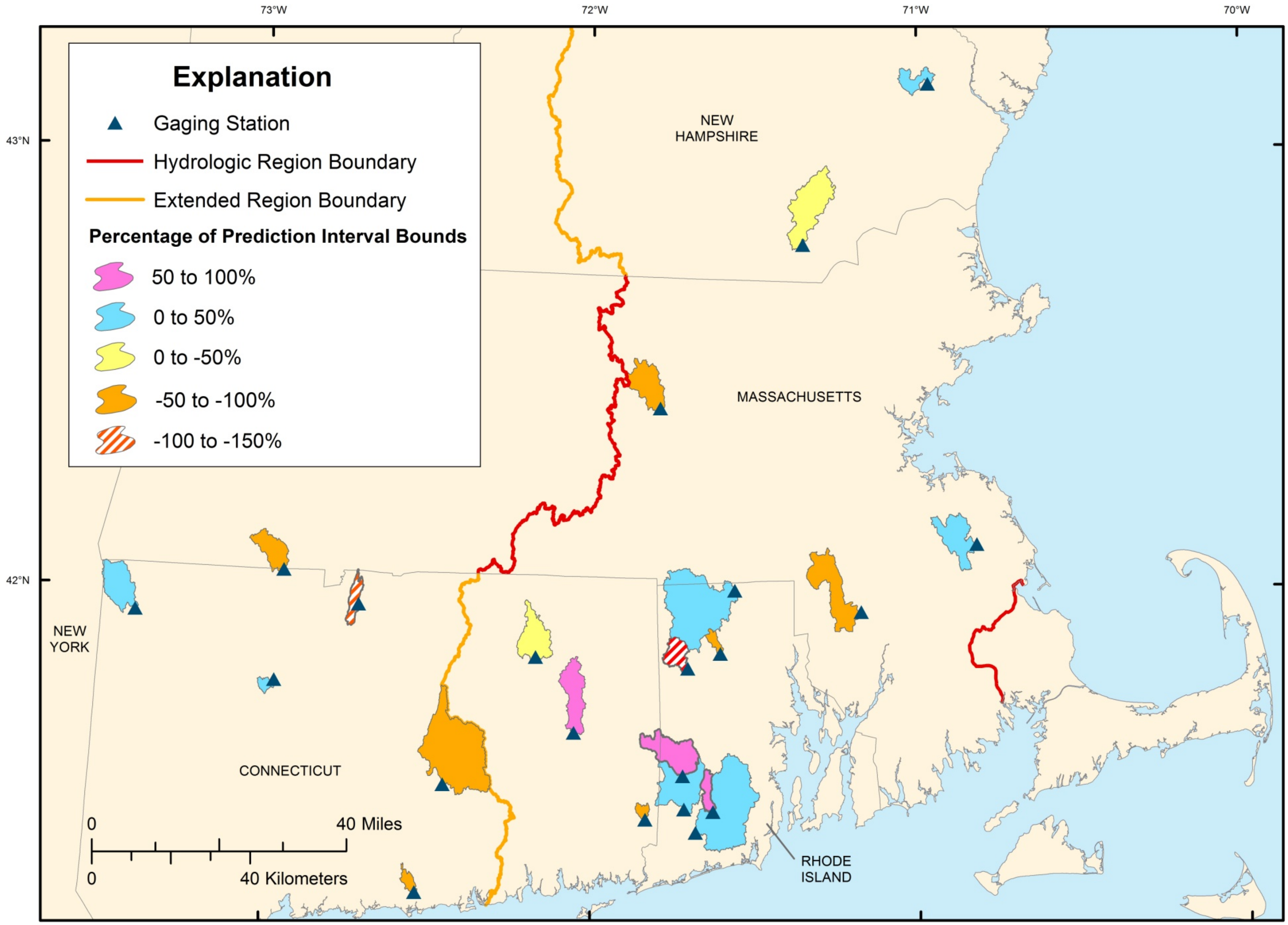
F9

98-Percent Duration Flow



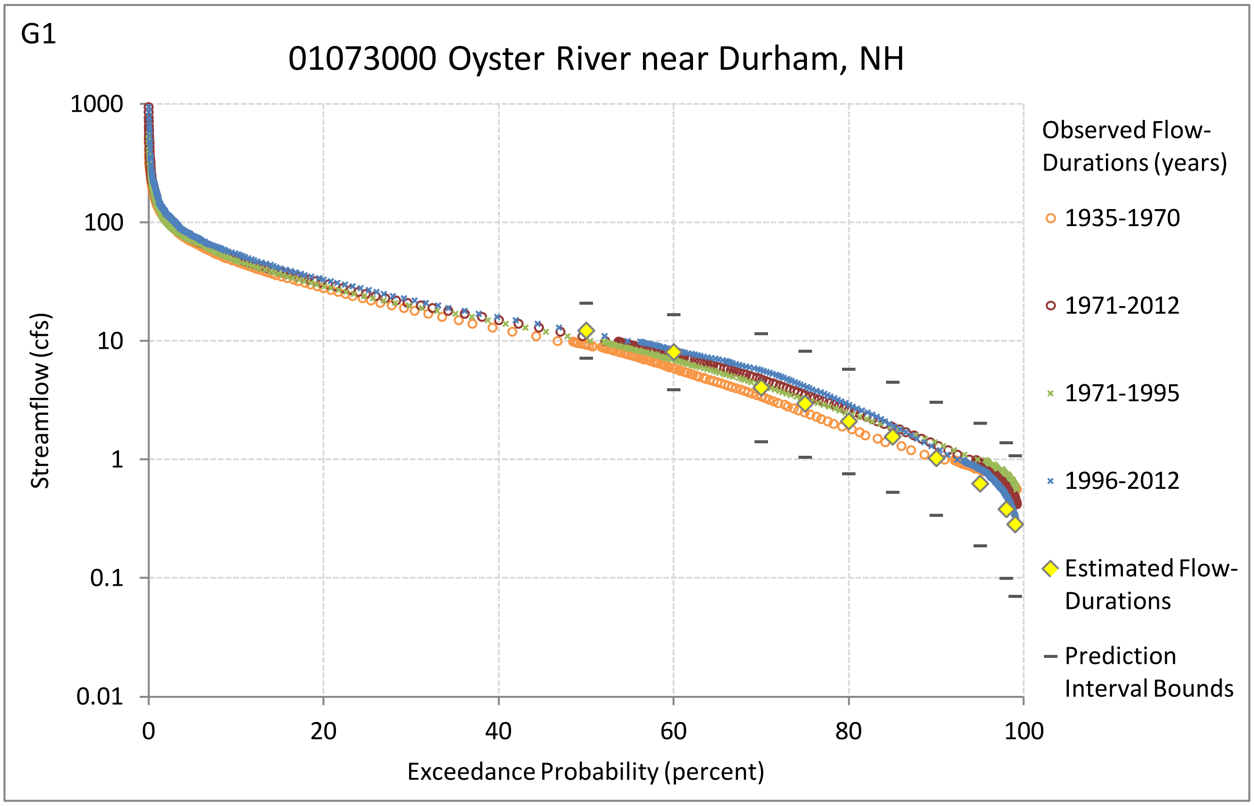
F10

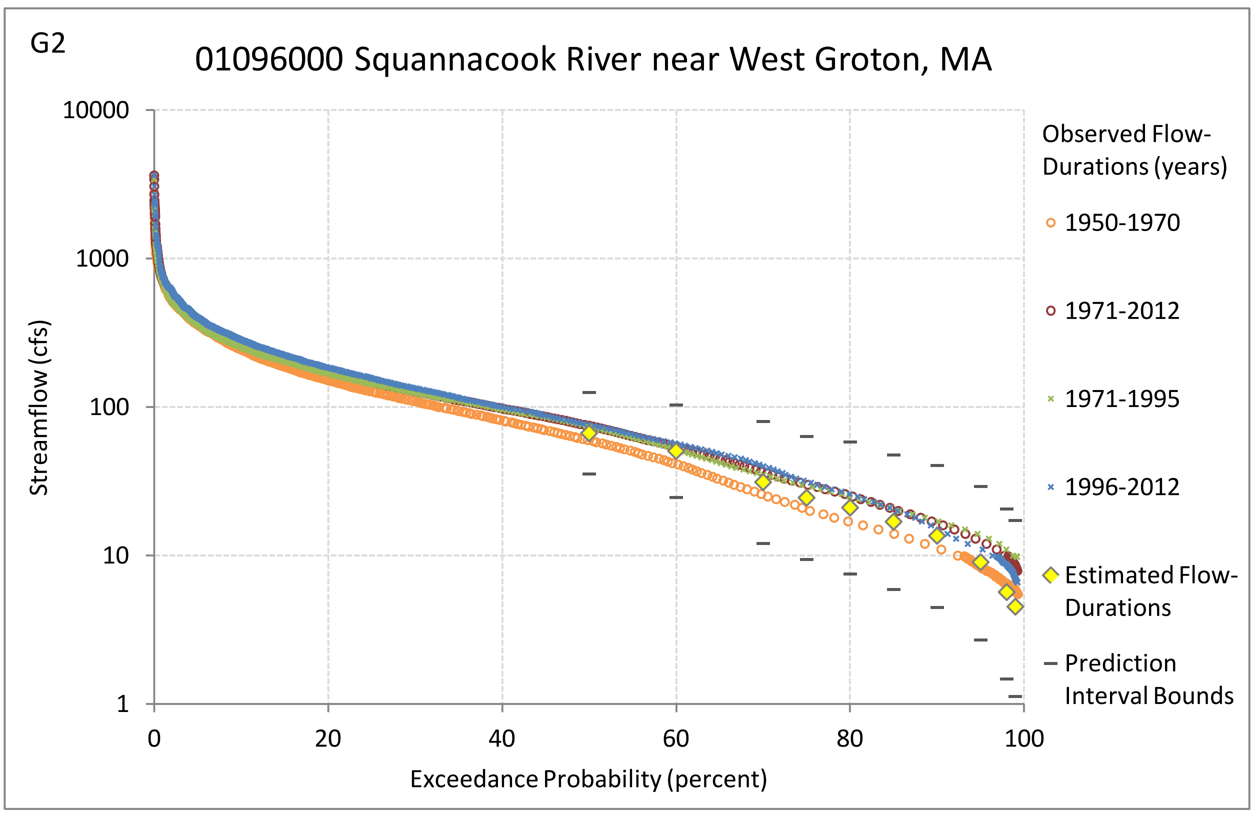
99-Percent Duration Flow

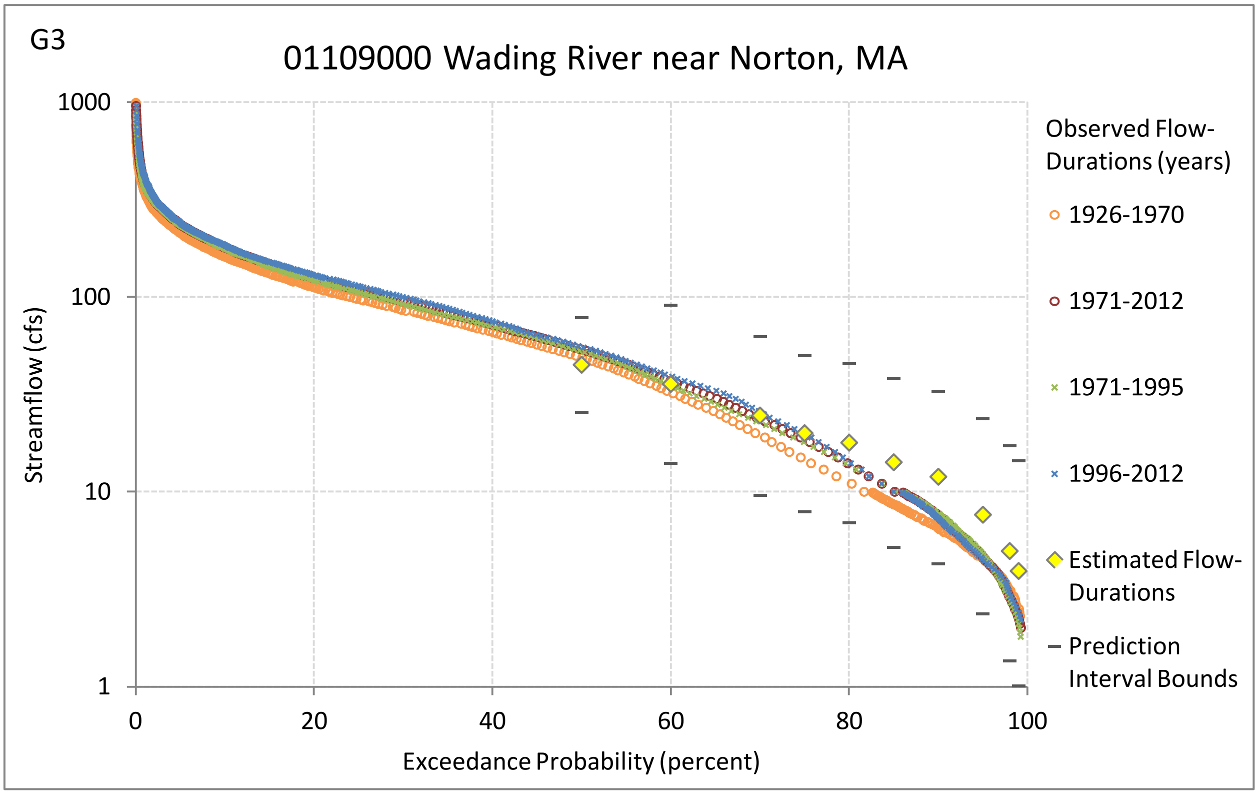


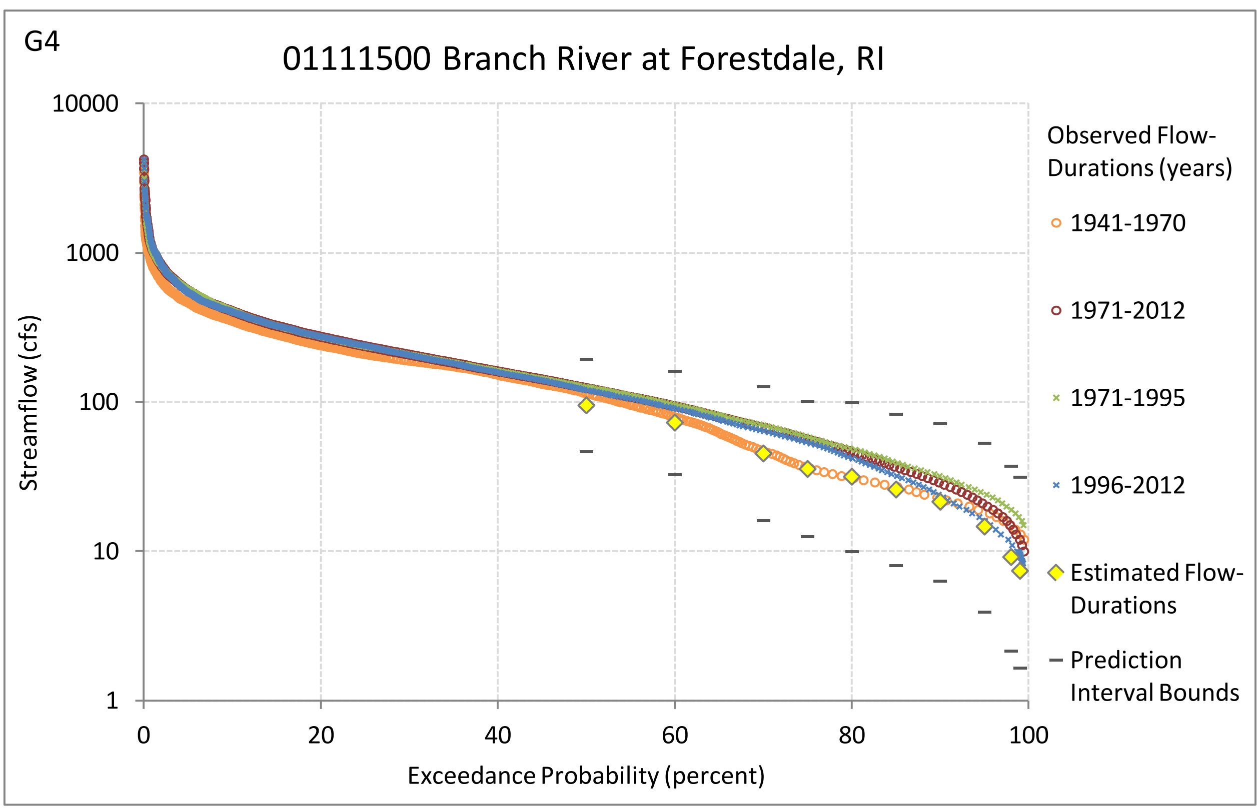
Appendix G

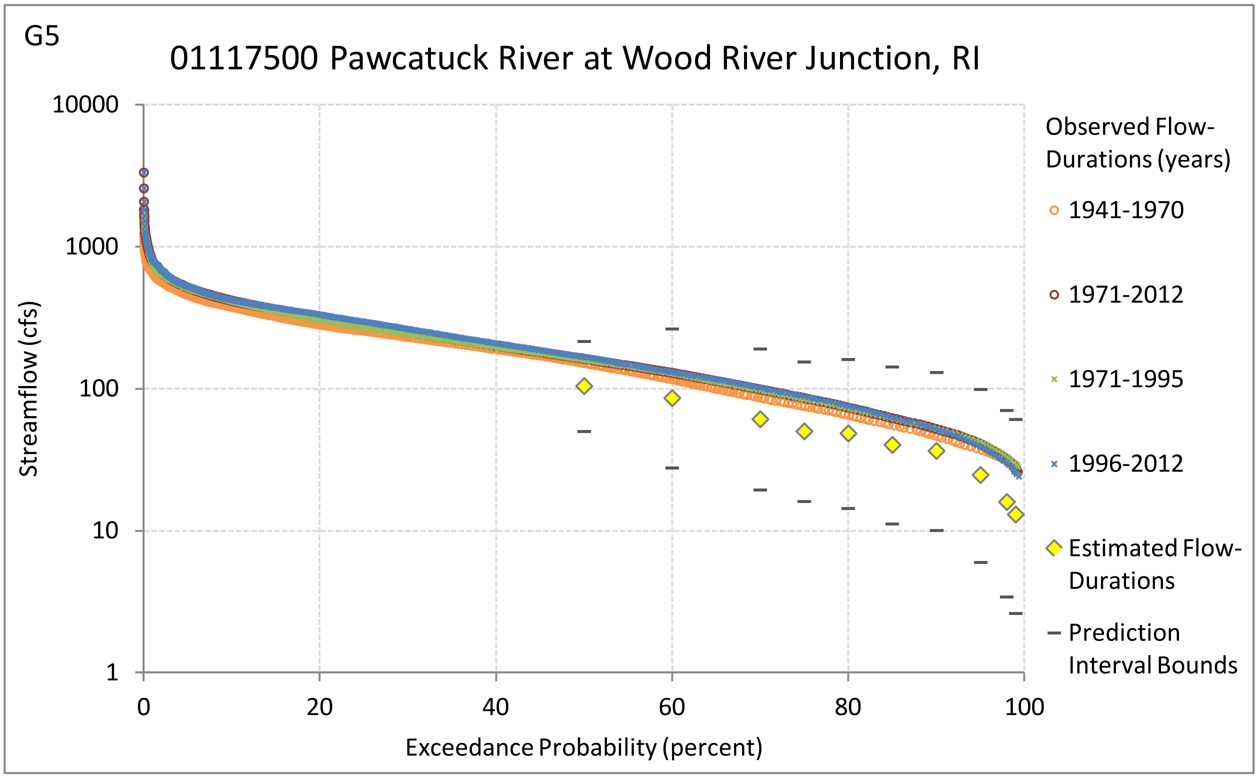
Part III Flow-Duration Curves


G1
01073000 Oyster River near Durham, NH
Streamflow (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1935-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

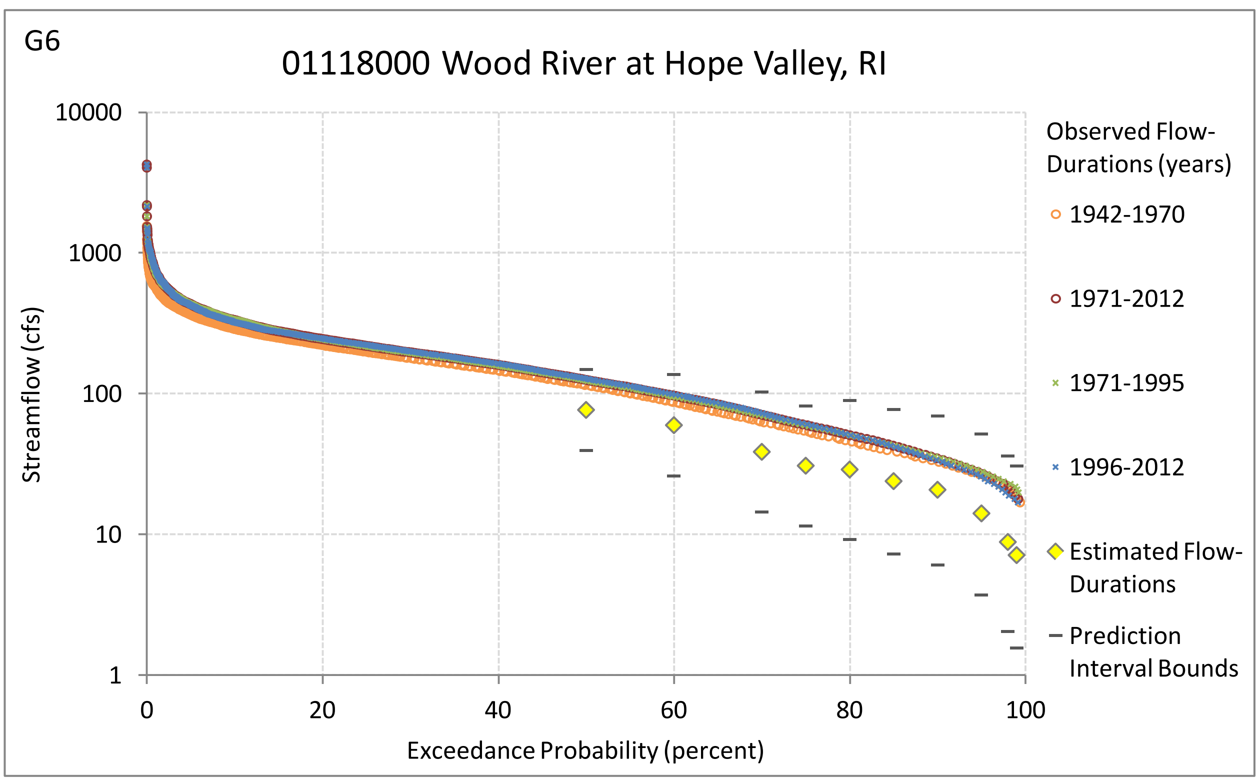

G2
01096000 Squannacook River near West Groton, MA
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1950-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds


G3
01109000 Wading River near Norton, MA
Streamflow (cfs)
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1926-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

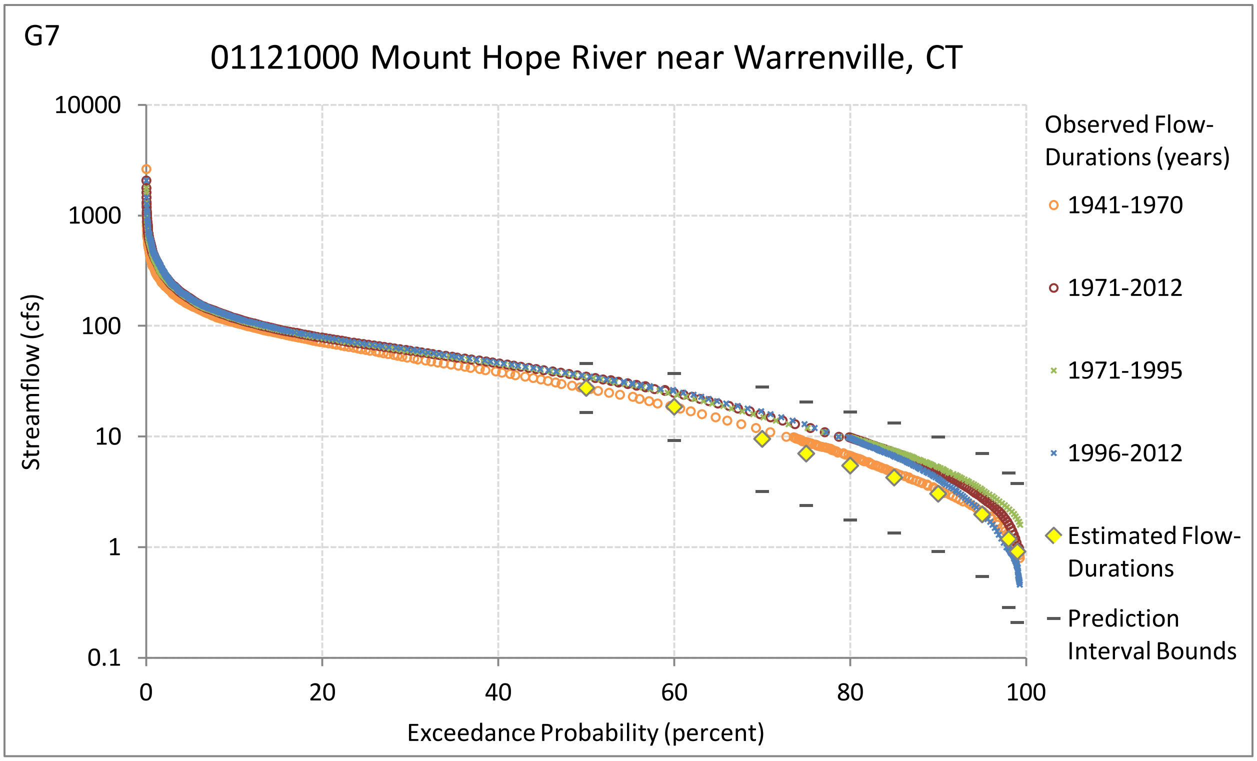

G4
01111500 Branch River at Forestdale, RI
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1941-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

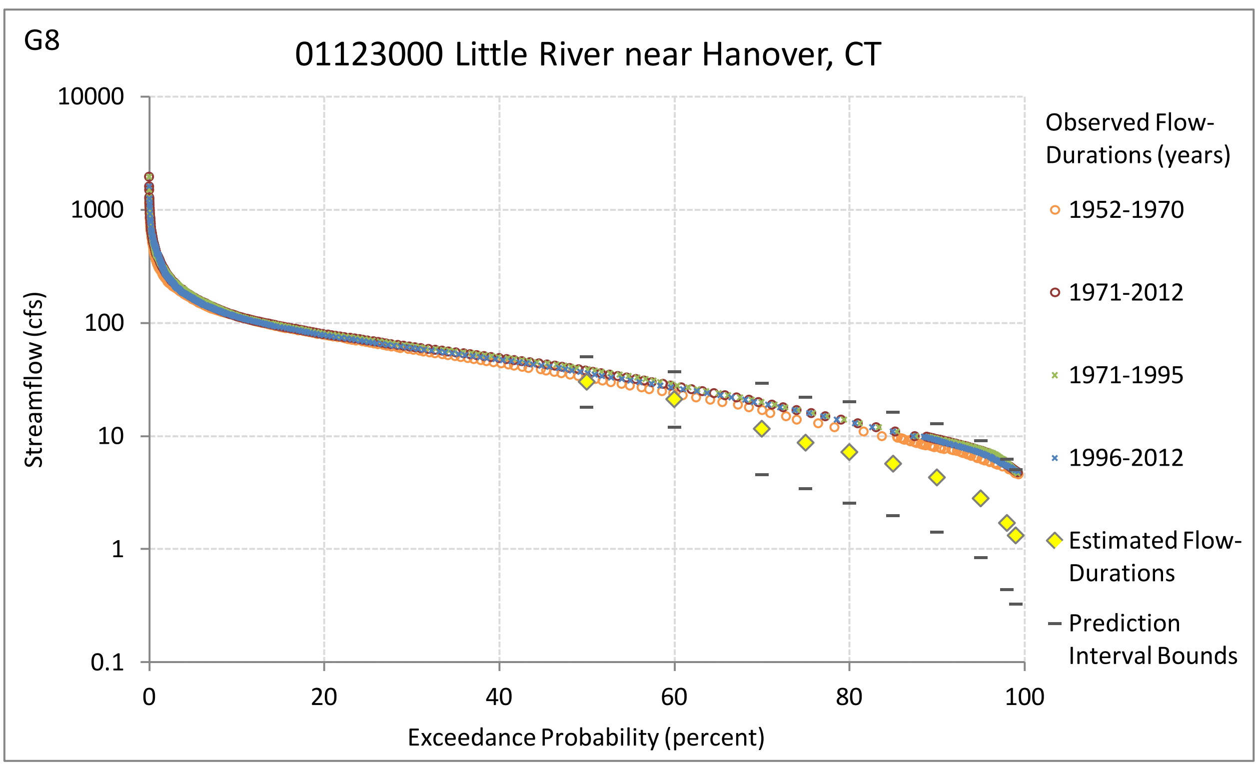


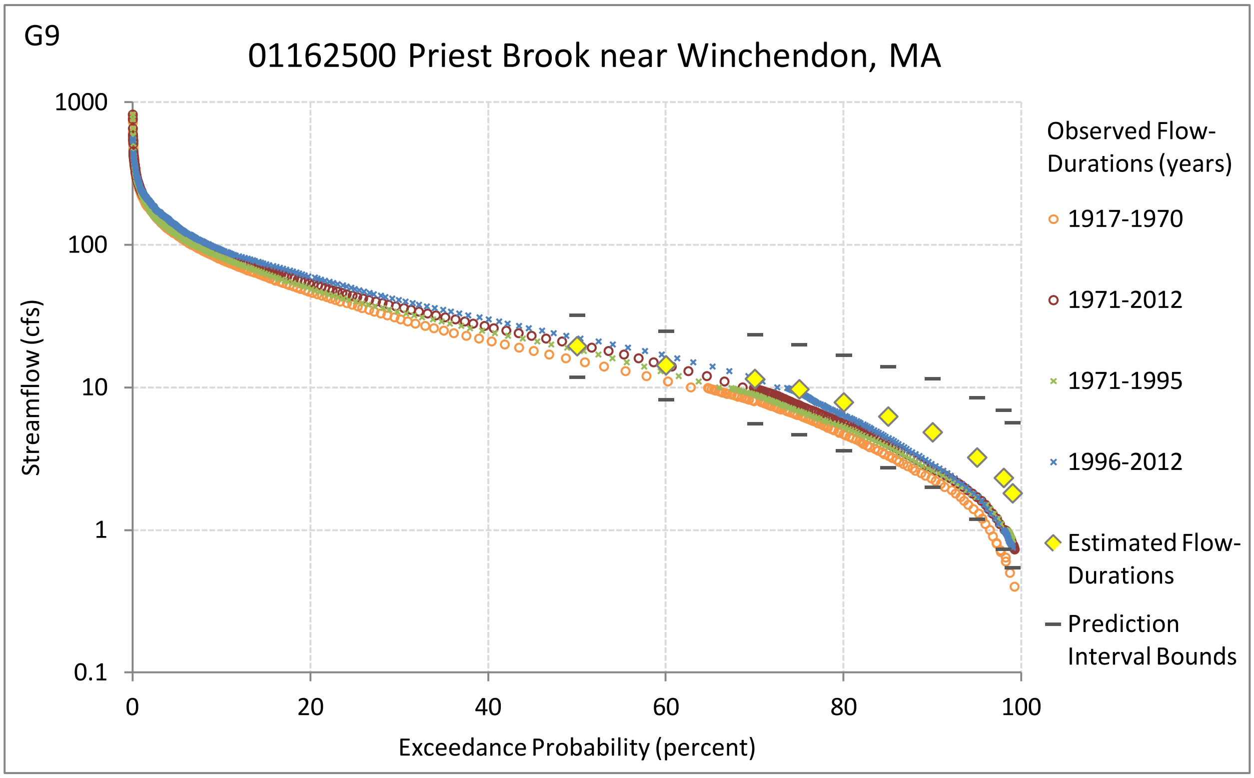
G5
01117500 Pawcatuck River at Wood River Junction, RI
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1941-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

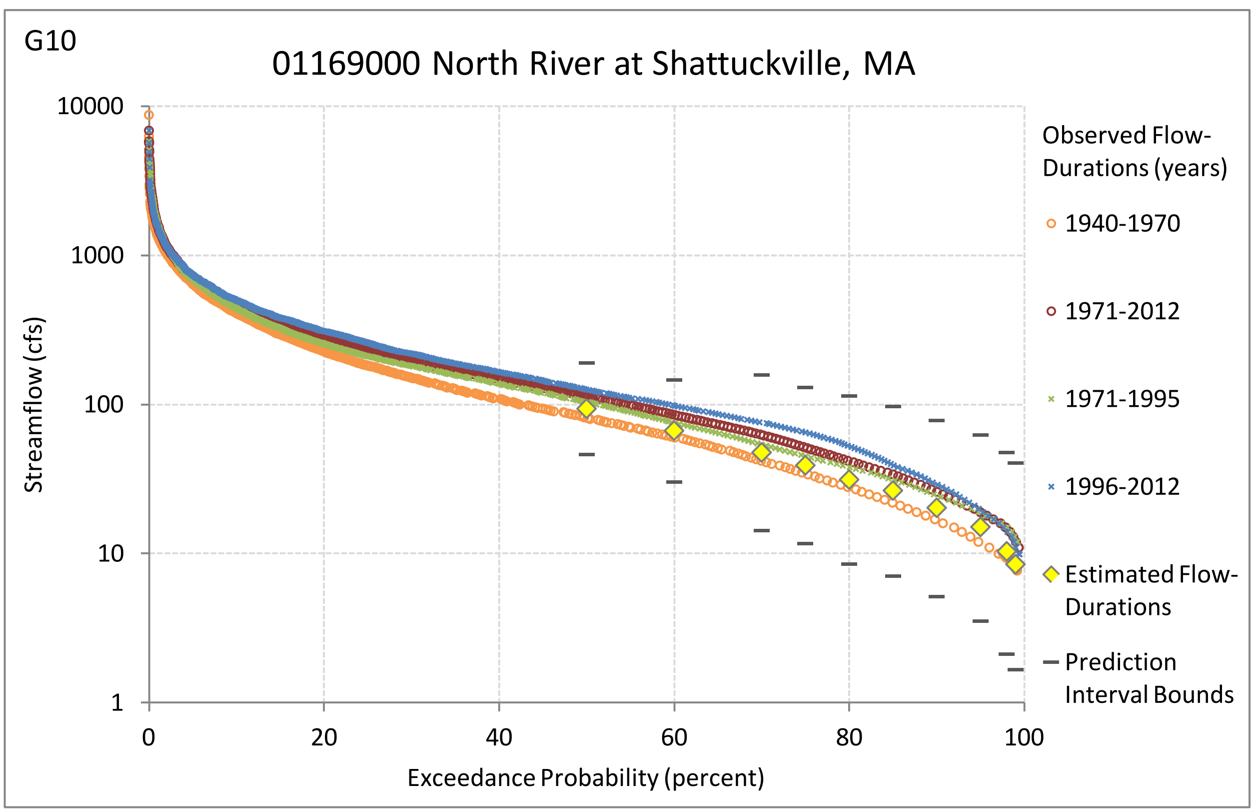


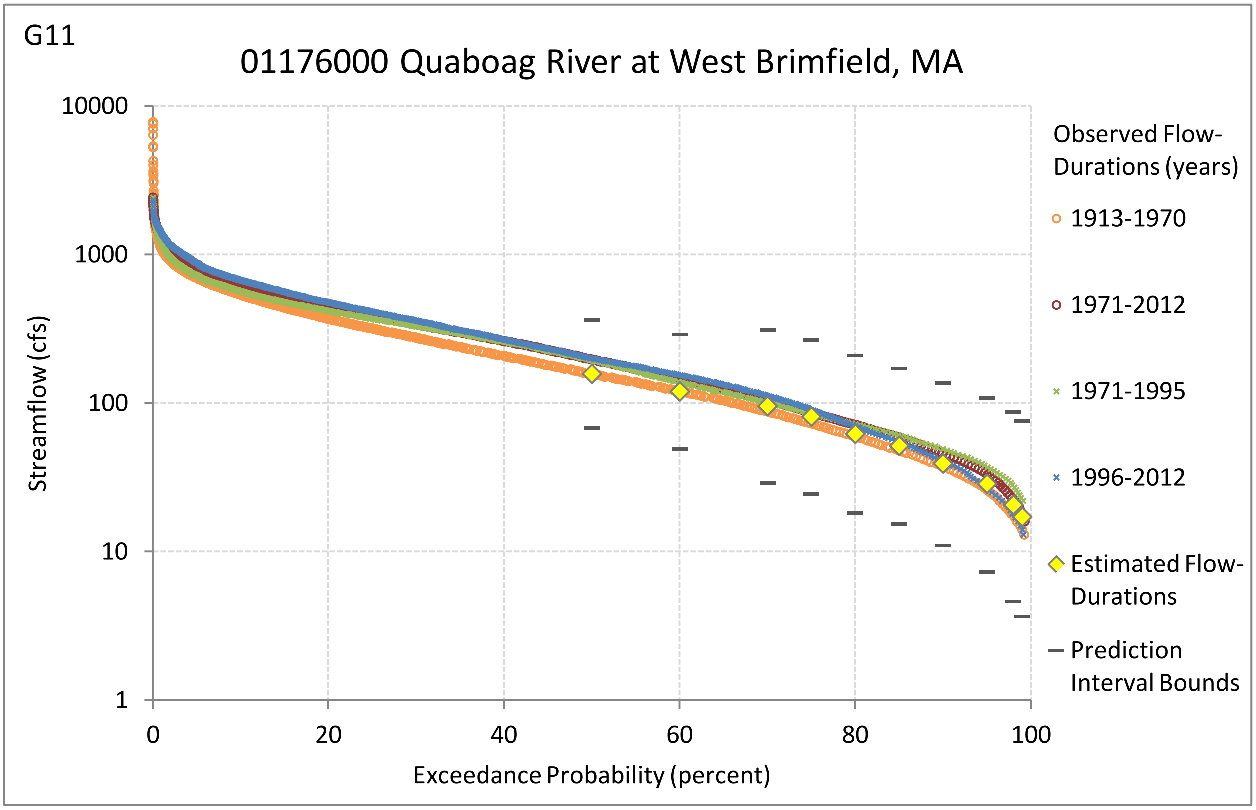
G6
01118000 Wood River at Hope Valley, RI
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1942-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

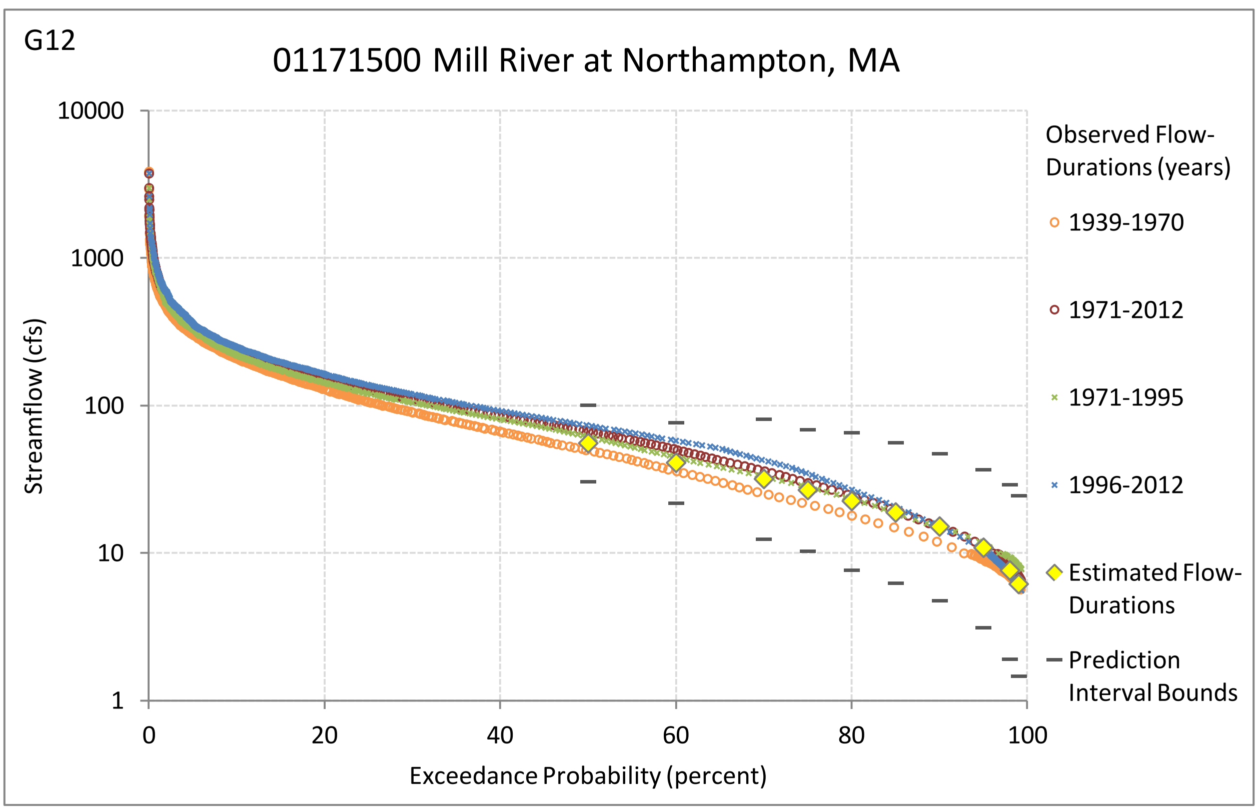

G7
01121000 Mount Hope River near Warrenville, CT
Streamflow (cfs)
10000
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1941-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

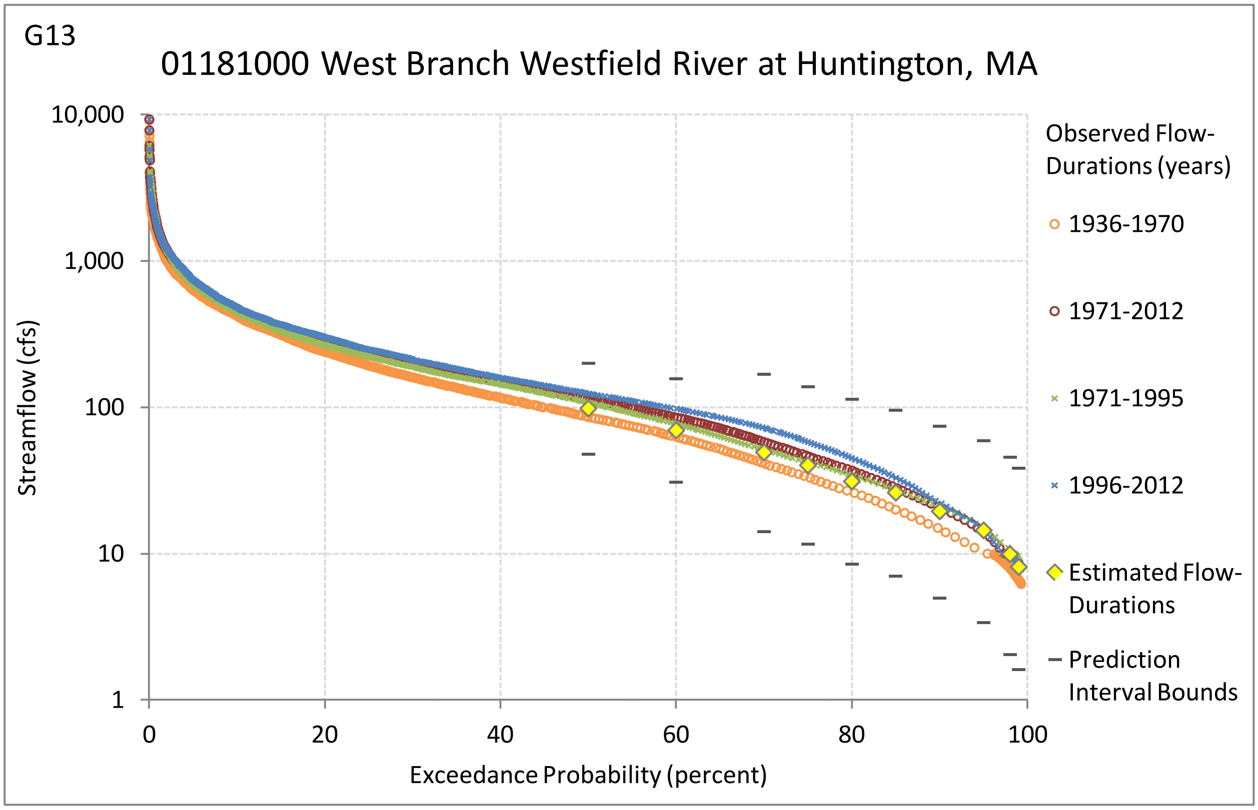

G8
01123000 Little River near Hanover, CT
Streamflow (cfs)
10000
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1952-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

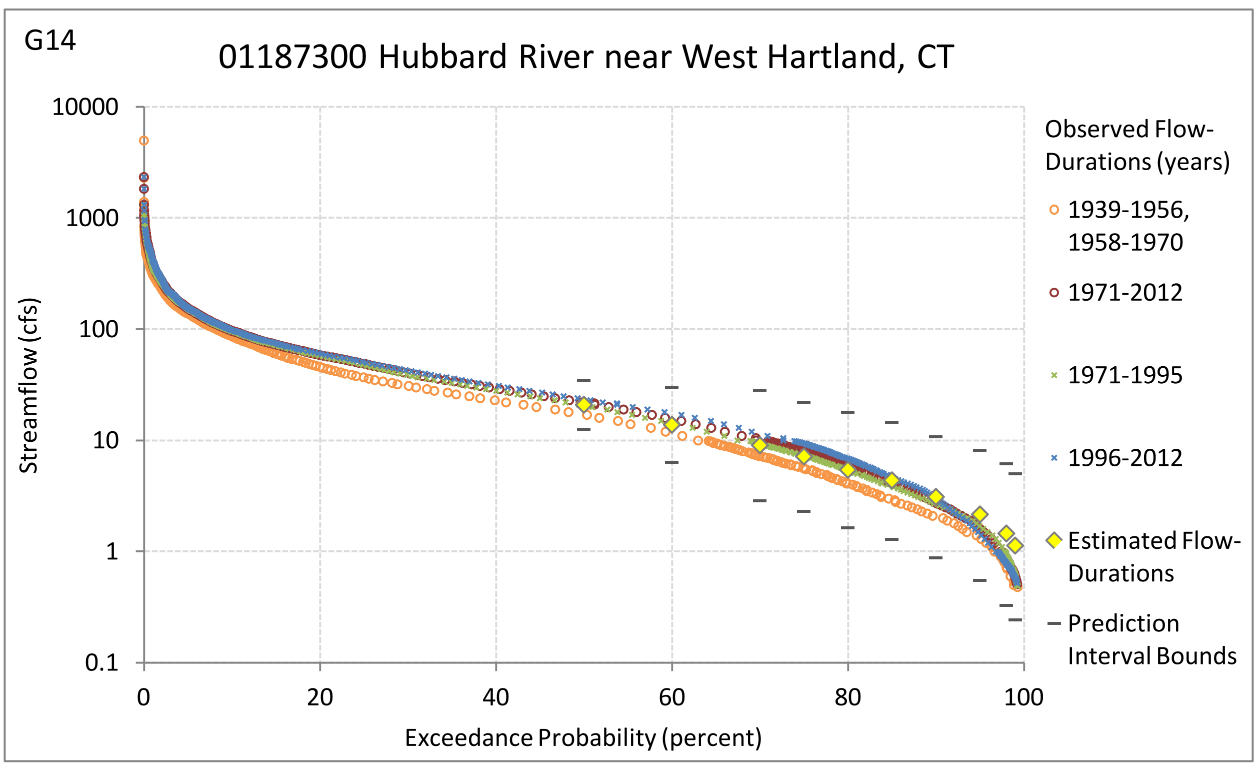

G9
01162500 Priest Brook near Winchendon, MA
Streamflow (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1917-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

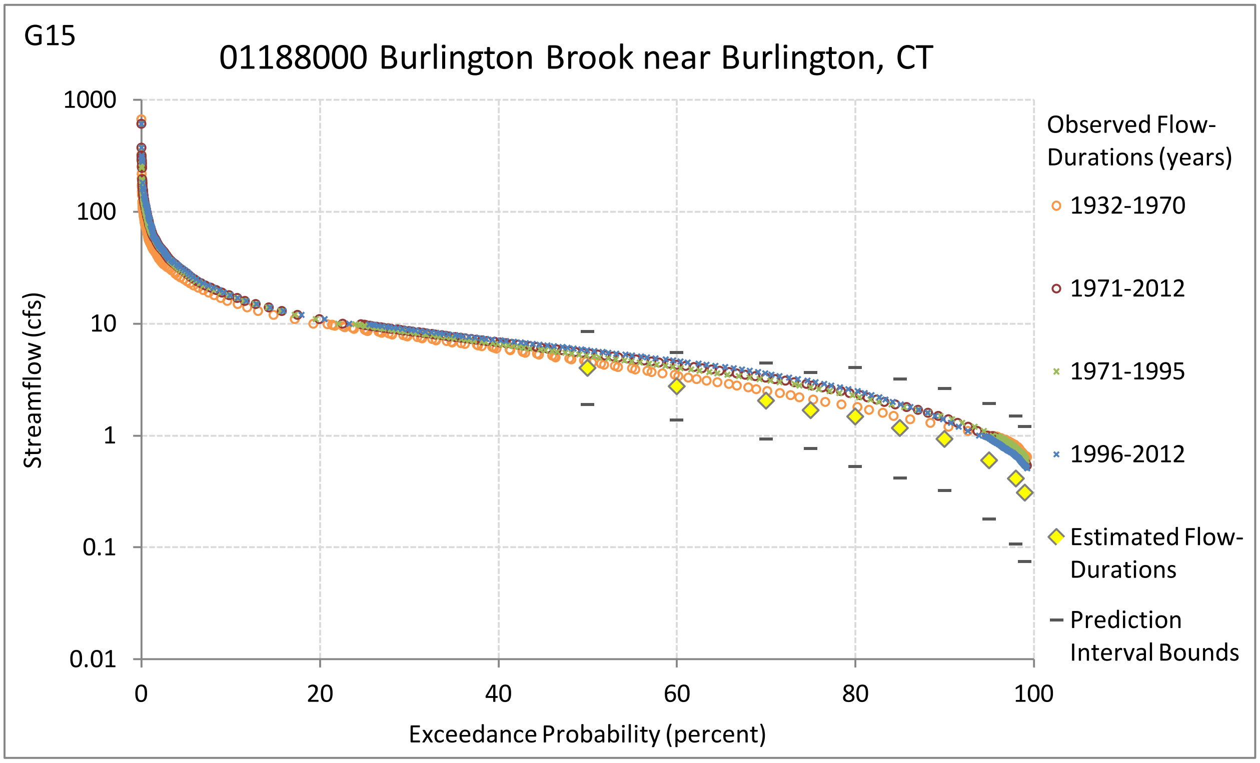

G10
01169000 North River at Shattuckville, MA
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1940-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

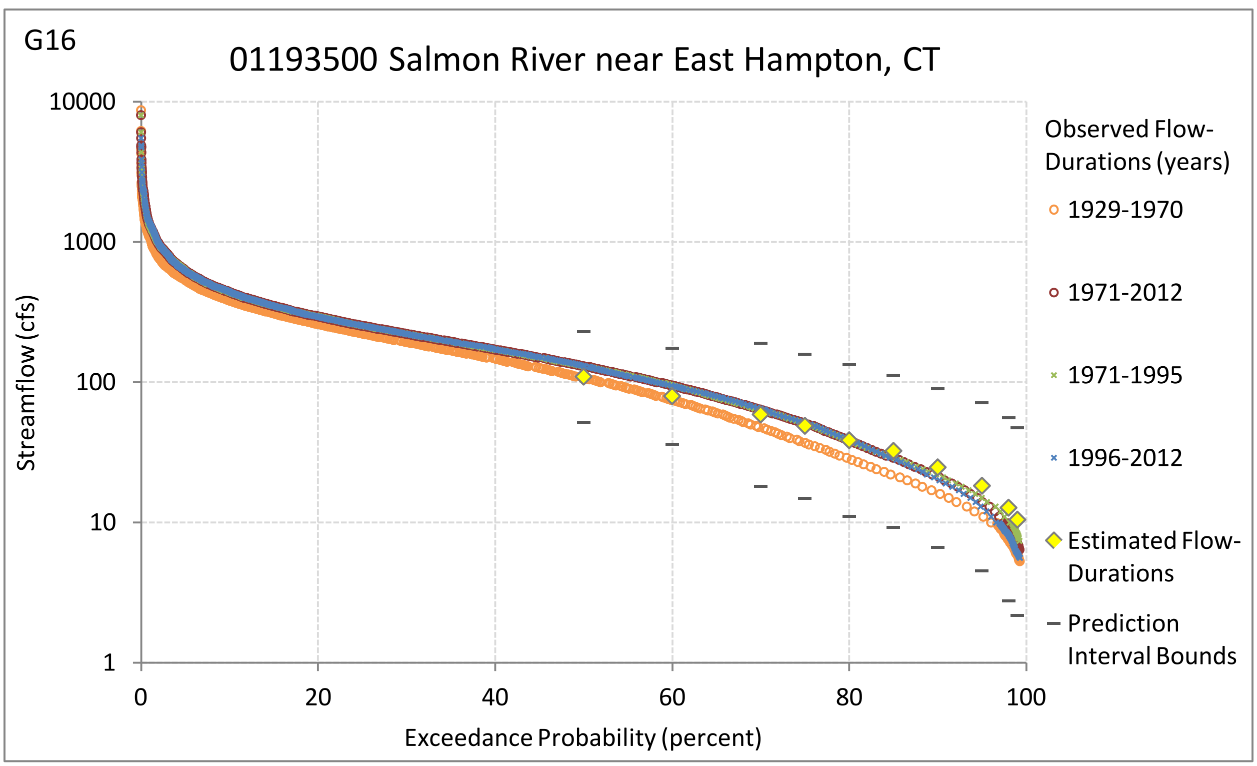

G11
01176000 Quaboag River at West Brimfield, MA
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1913-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

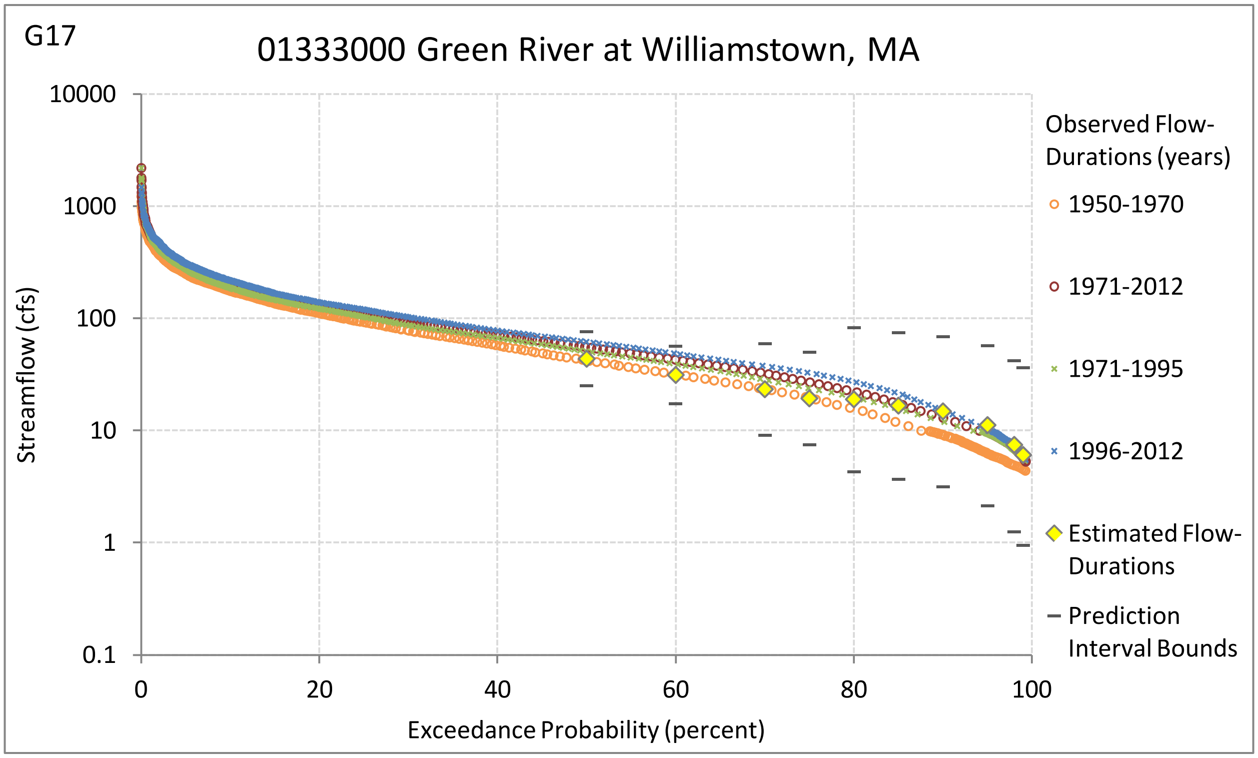

G12
01171500 Mill River at Northampton, MA
Streamflow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1939-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds


G13
01181000 West Branch Westfield River at Huntington, MA
10,000
1,000
100
10
1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1936-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds


G14
01187300 Hubbard River near West Hartland, CT
10000
1000
100
10
1
0.1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1939-1956, 1958-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds


G15
01188000 Burlington Brook near Burlington, CT
1000
100
10
1
0.1
0.01
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1932-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

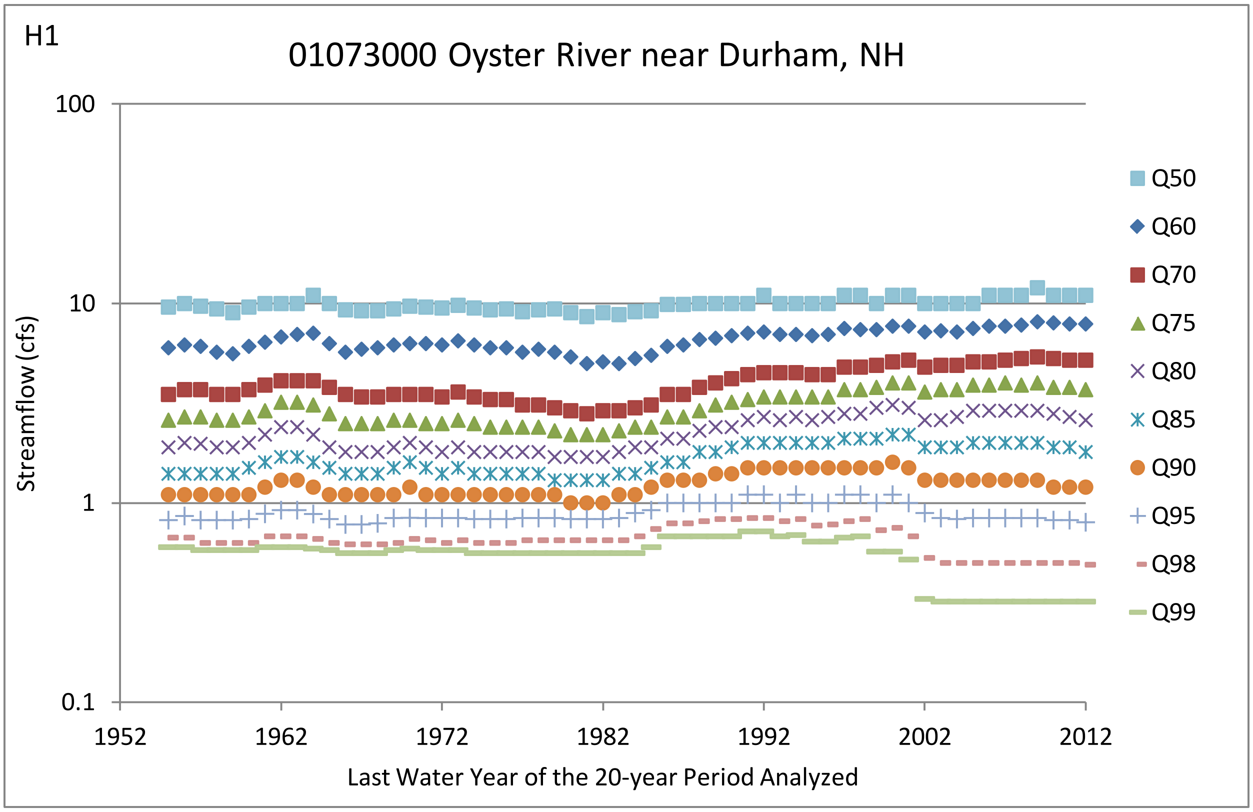

G16
01193500 Salmon River near East Hampton, CT
10000
1000
100
10
1
Streamflow (cfs)
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1929-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

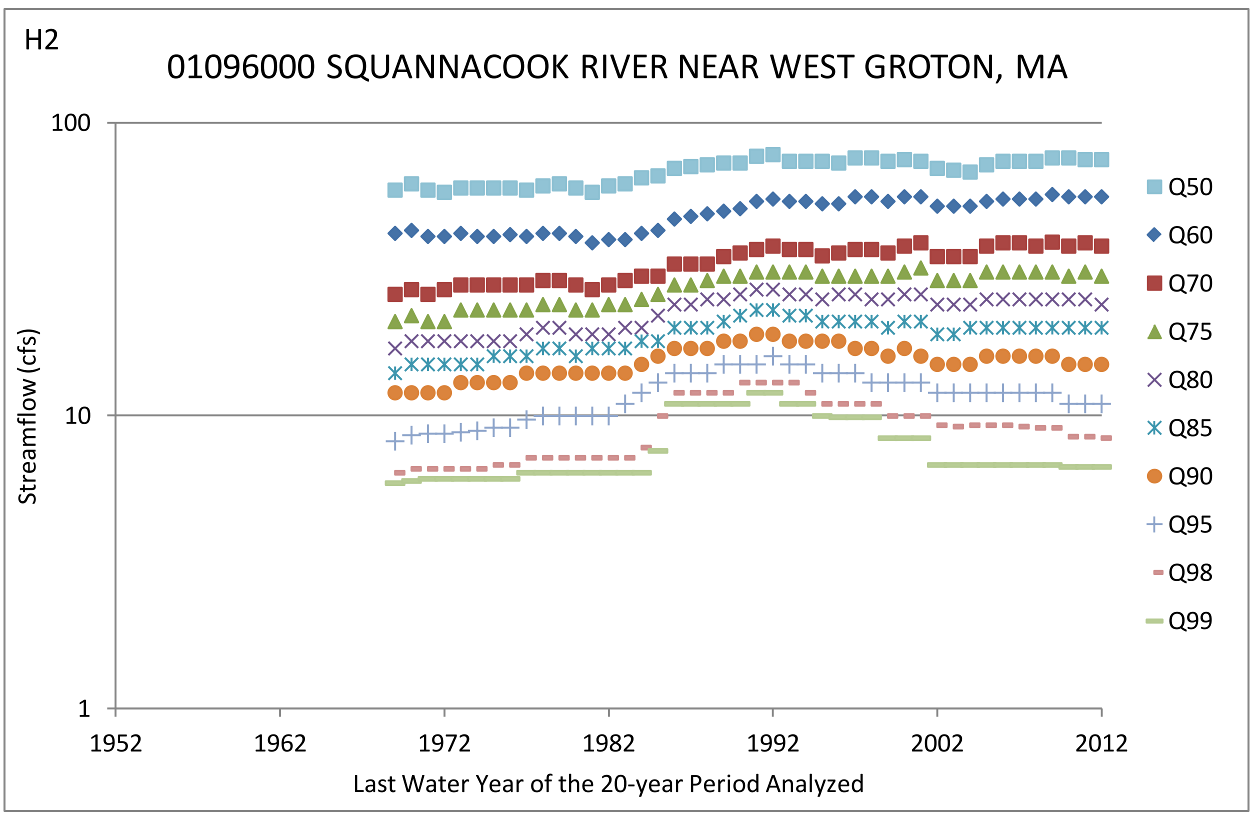


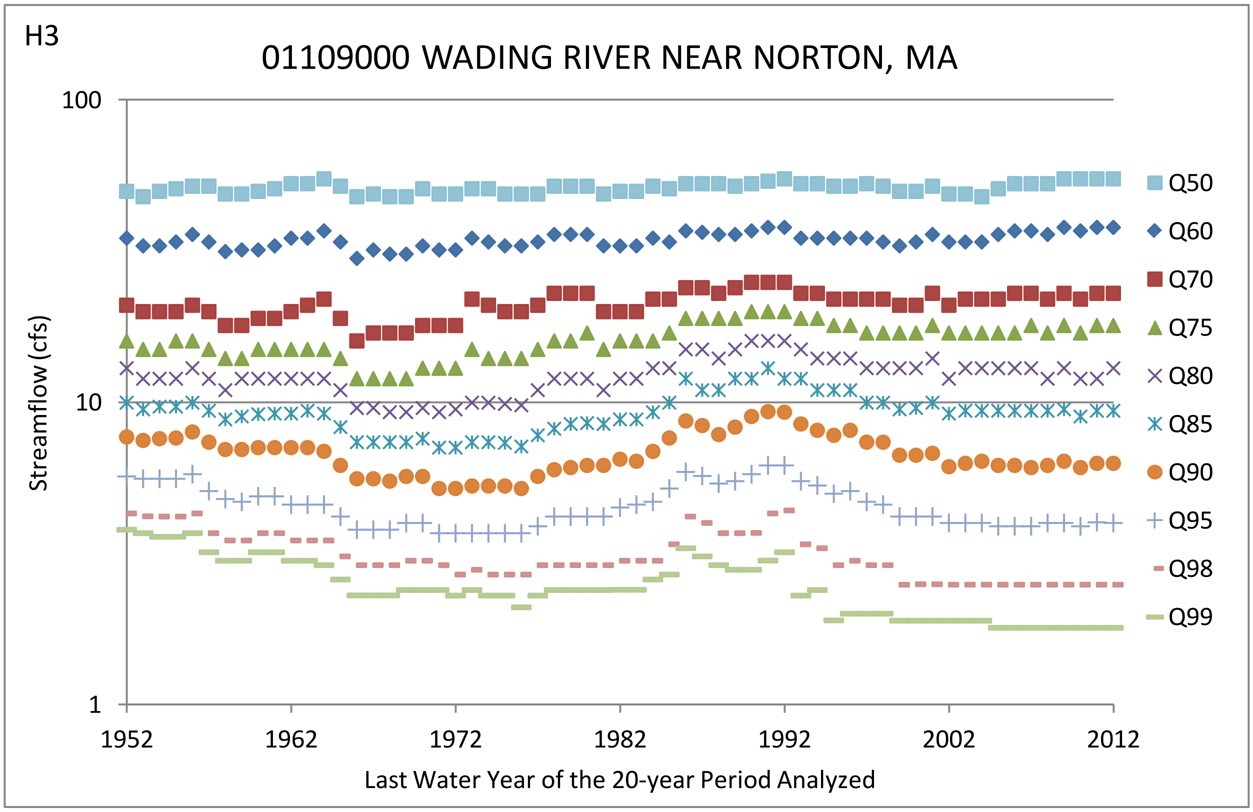
G17
01333000 Green River at Williamstown, MA
Streamflow (cfs)
10000
1000
100
10
1
0.1
0
20
40
60
80
100
Exceedance Probability (percent)
Observed Flow-Durations (years)
1950-1970
1971-2012
1971-1995
1996-2012
Estimated Flow-Durations
Prediction Interval Bounds

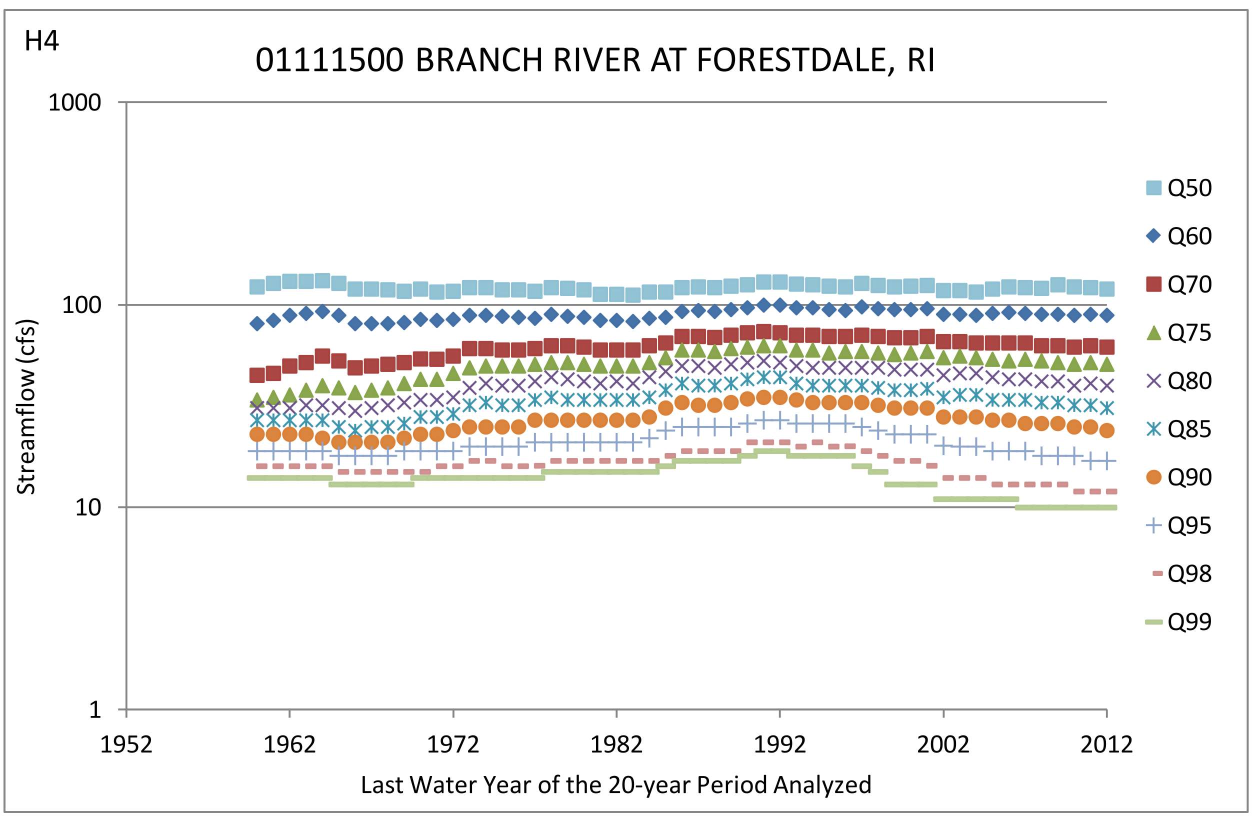
Appendix H

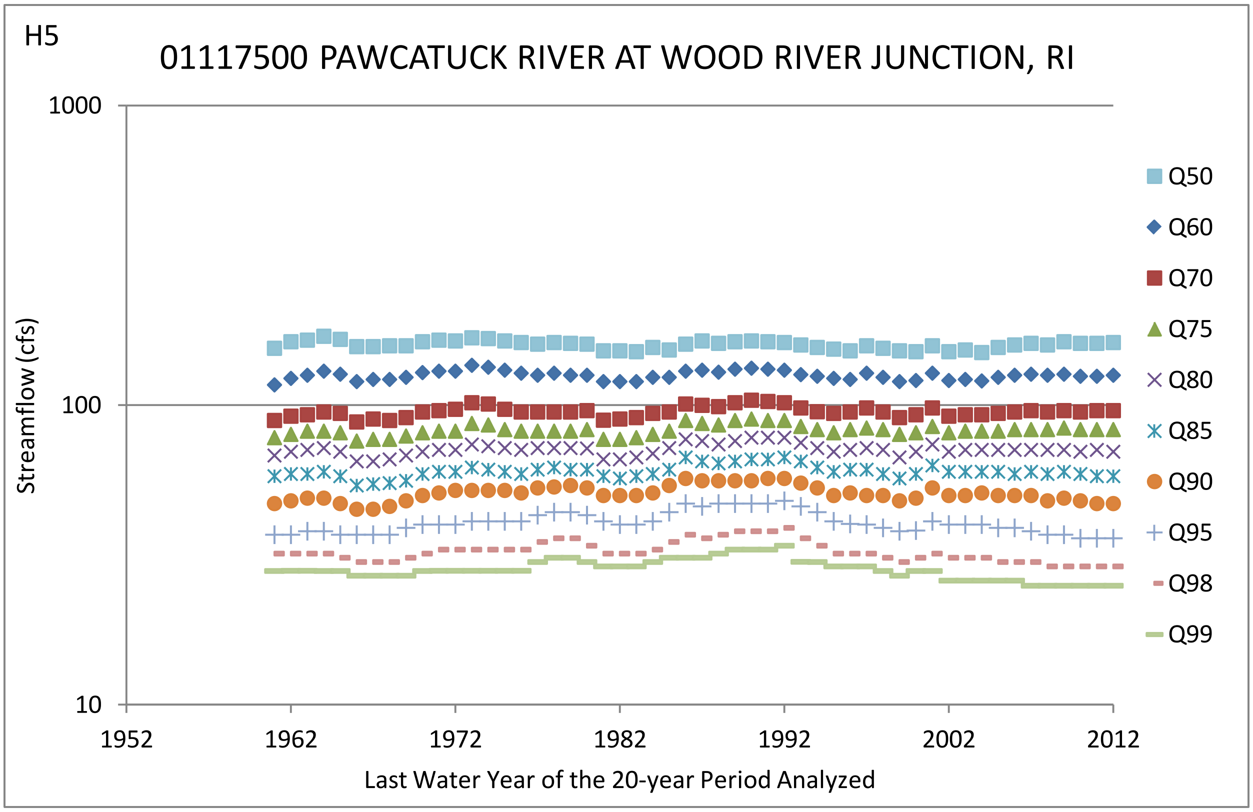
Part IV 20-Year Moving Quantiles

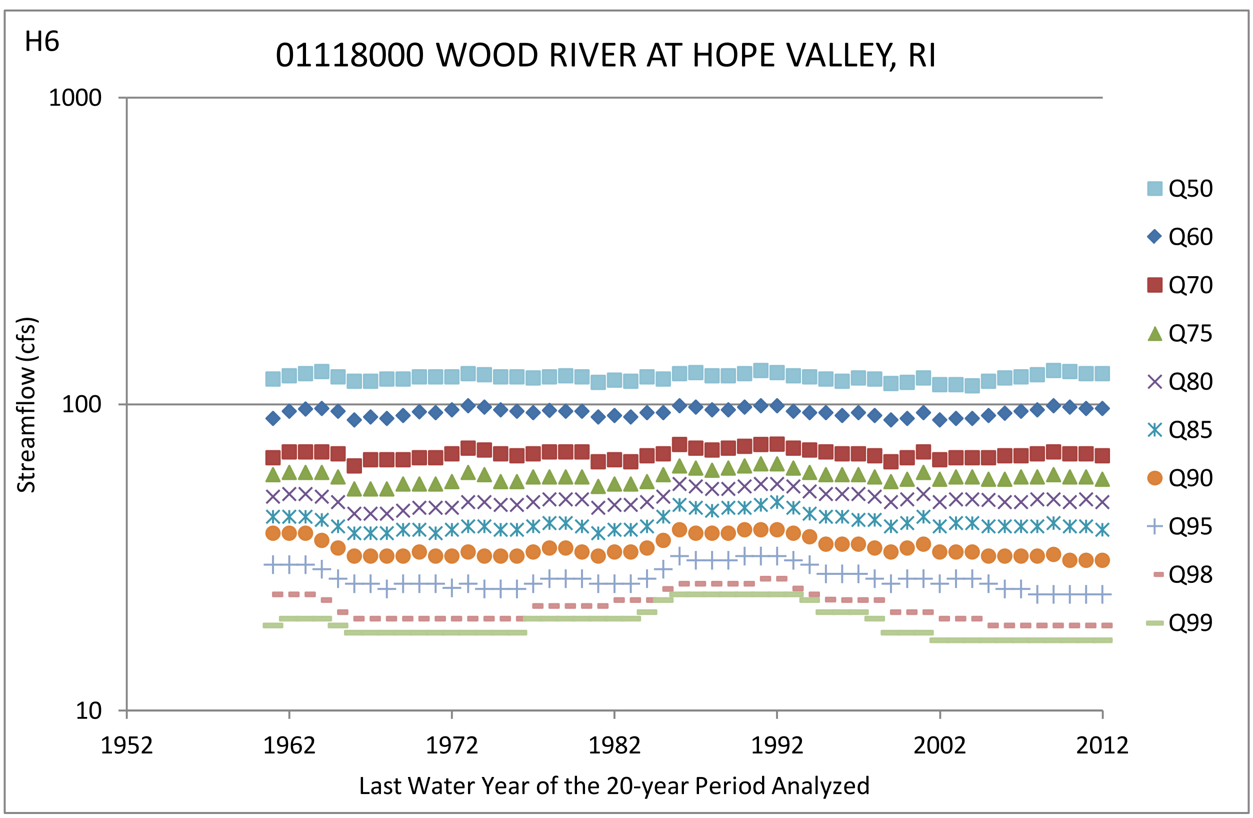

H1
01073000 Oyster River near Durham, NH
100
10
1
0.1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

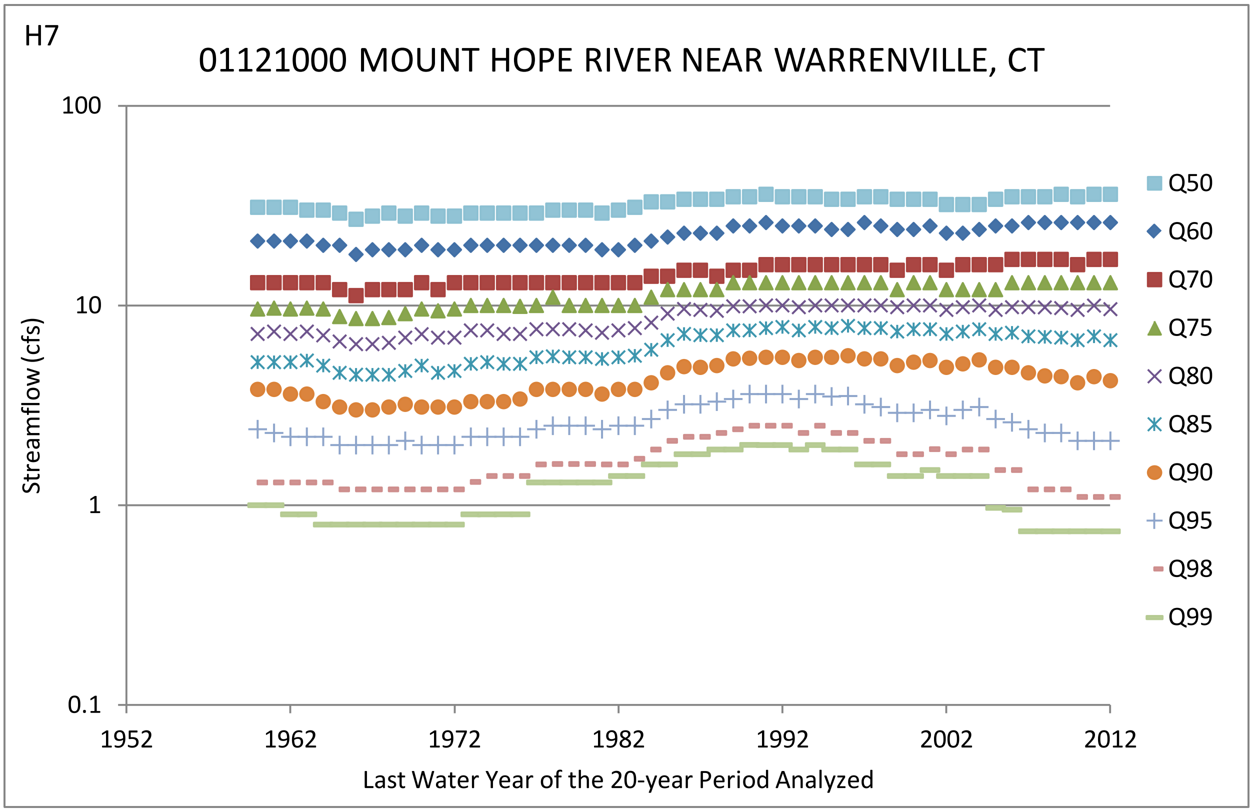

H2
01096000 SQUANNACOOK RIVER NEAR WEST GROTON, MA
100
10
1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

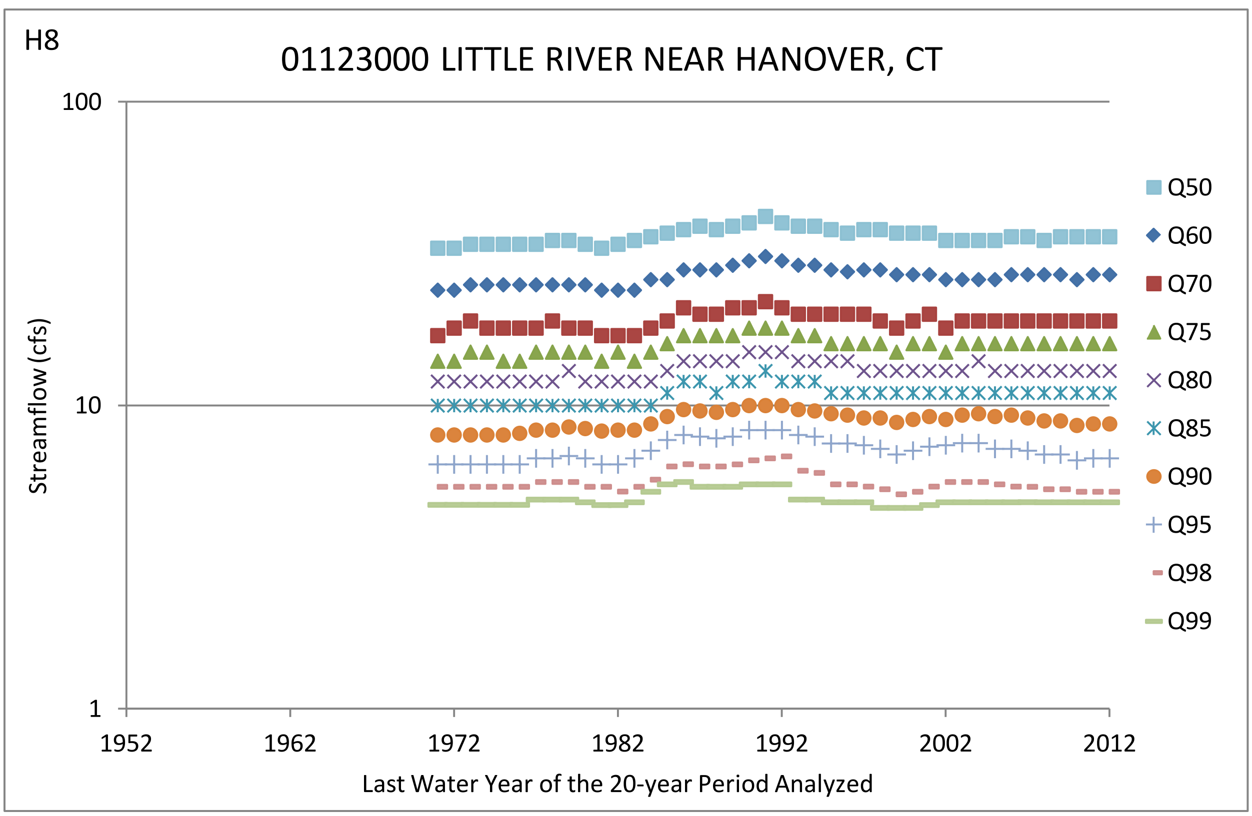

H3
01109000 WADING RIVER NEAR NORTON, MA
100
10
1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

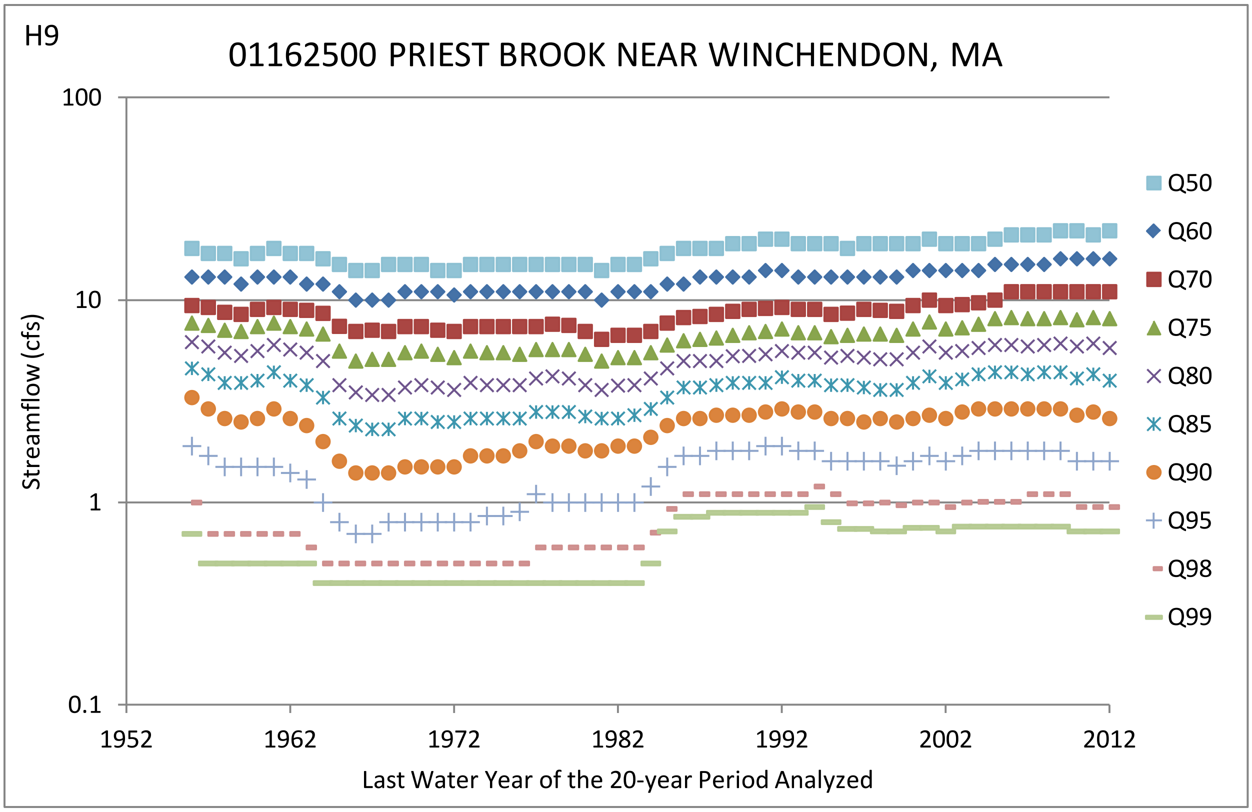

H4
01111500 BRANCH RIVER AT FORESTDALE, RI
1000
100
10
1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

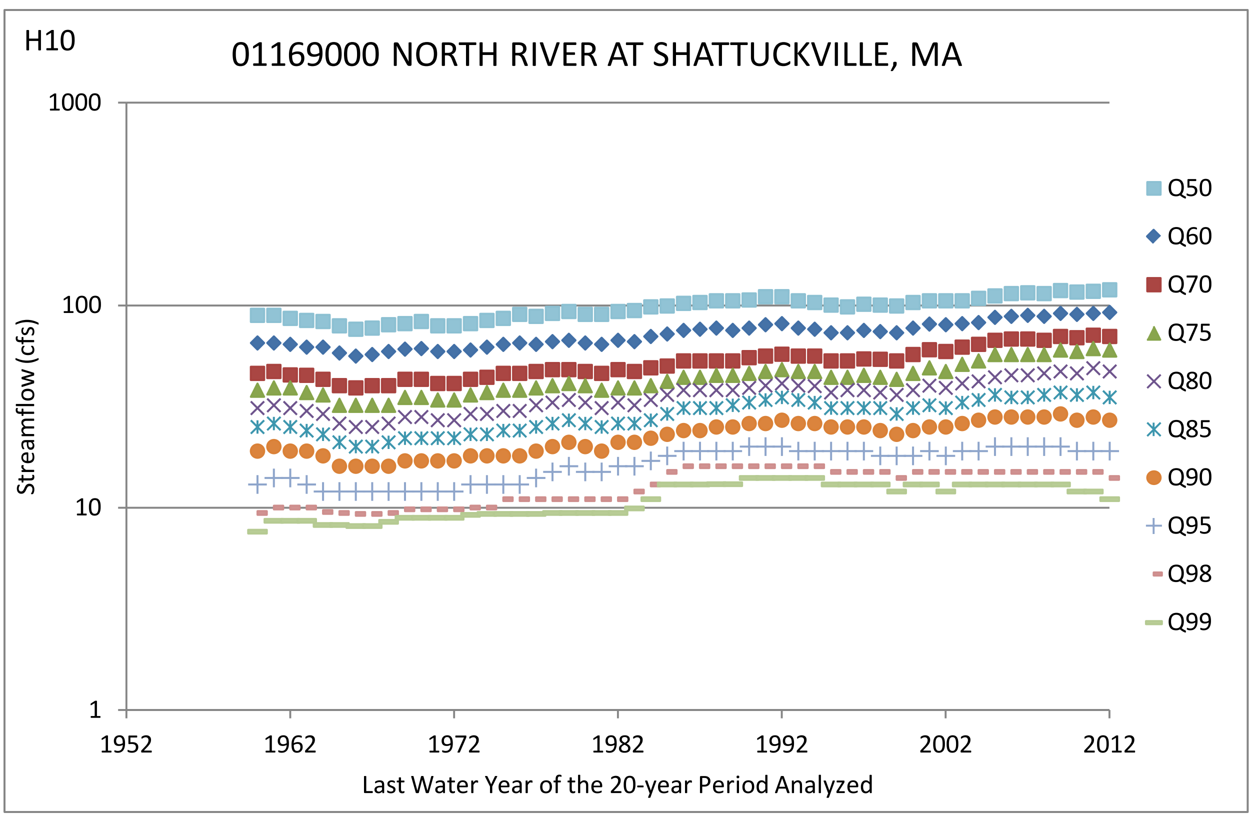

H5
01117500 PAWCATUCK RIVER AT WOOD RIVER JUNCTION, RI
Streamflow (cfs)
1000
100
10
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

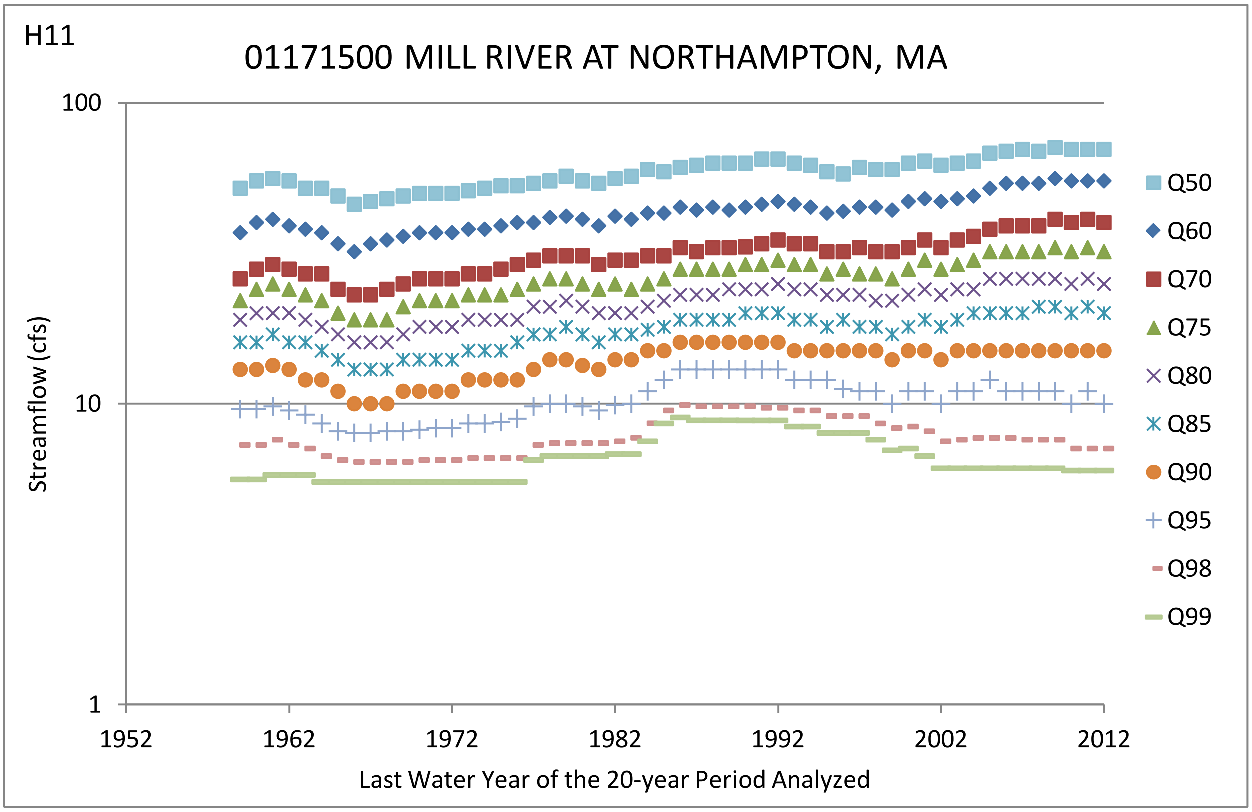

H6
01118000 WOOD RIVER AT HOPE VALLEY, RI
Streamflow (cfs)
1000
100
10
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

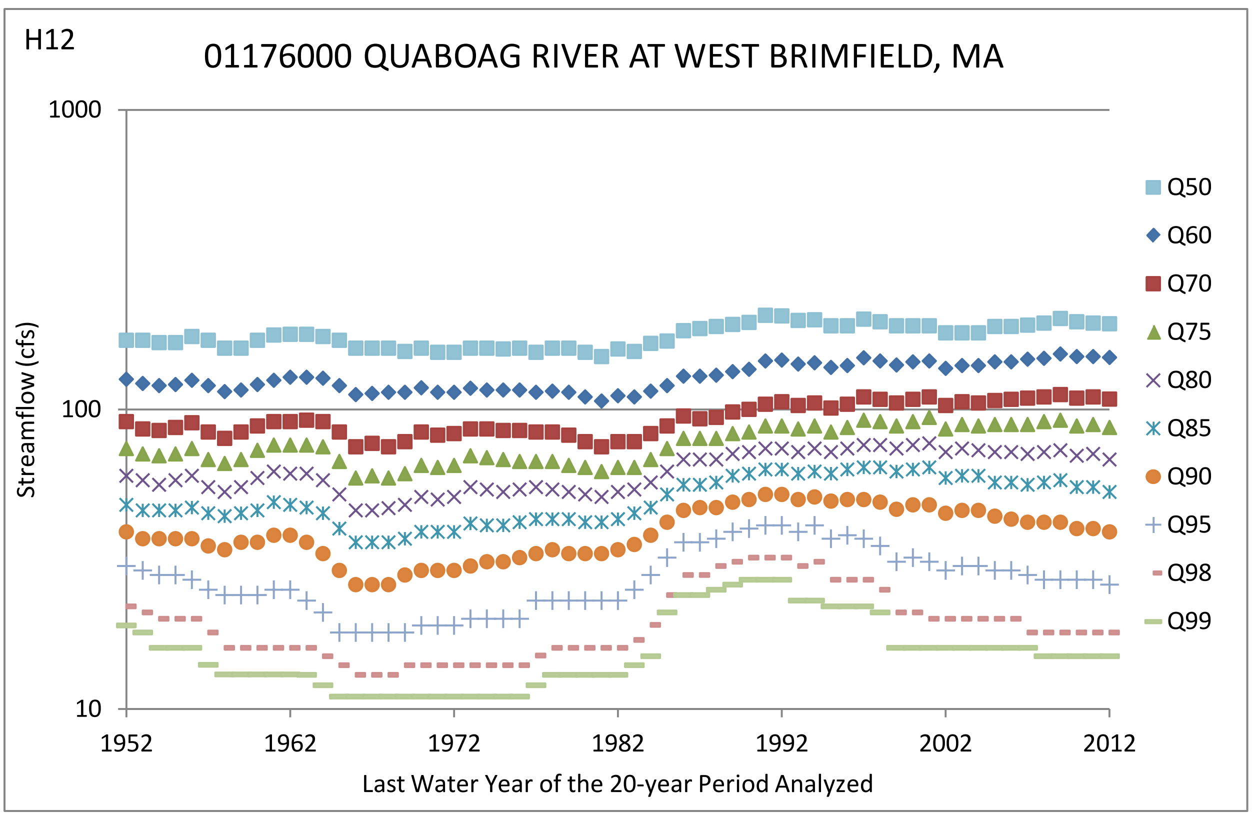

H7
01121000 MOUNT HOPE RIVER NEAR WARRENVILLE, CT
Streamflow (cfs)
100
10
1
0.1
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

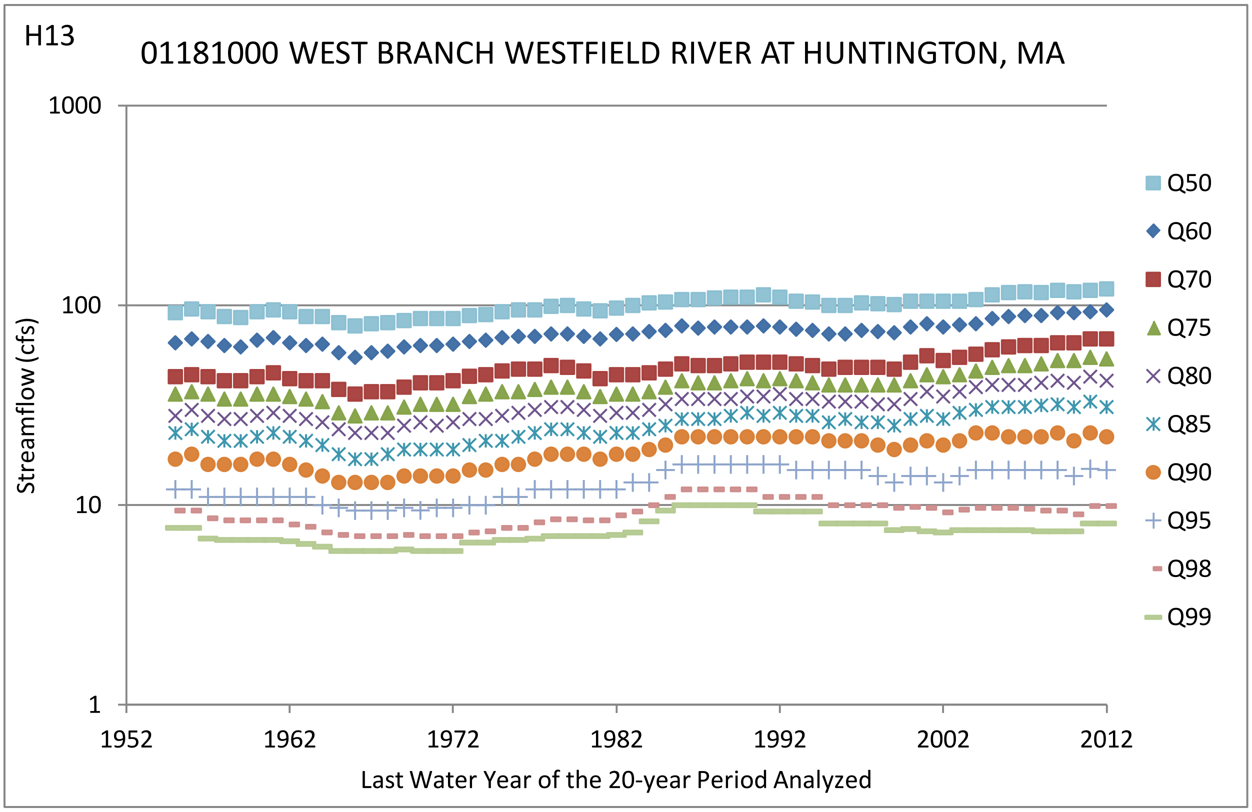

H8
01123000 LITTLE RIVER NEAR HANOVER, CT
Streamflow (cfs)
100
10
1
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

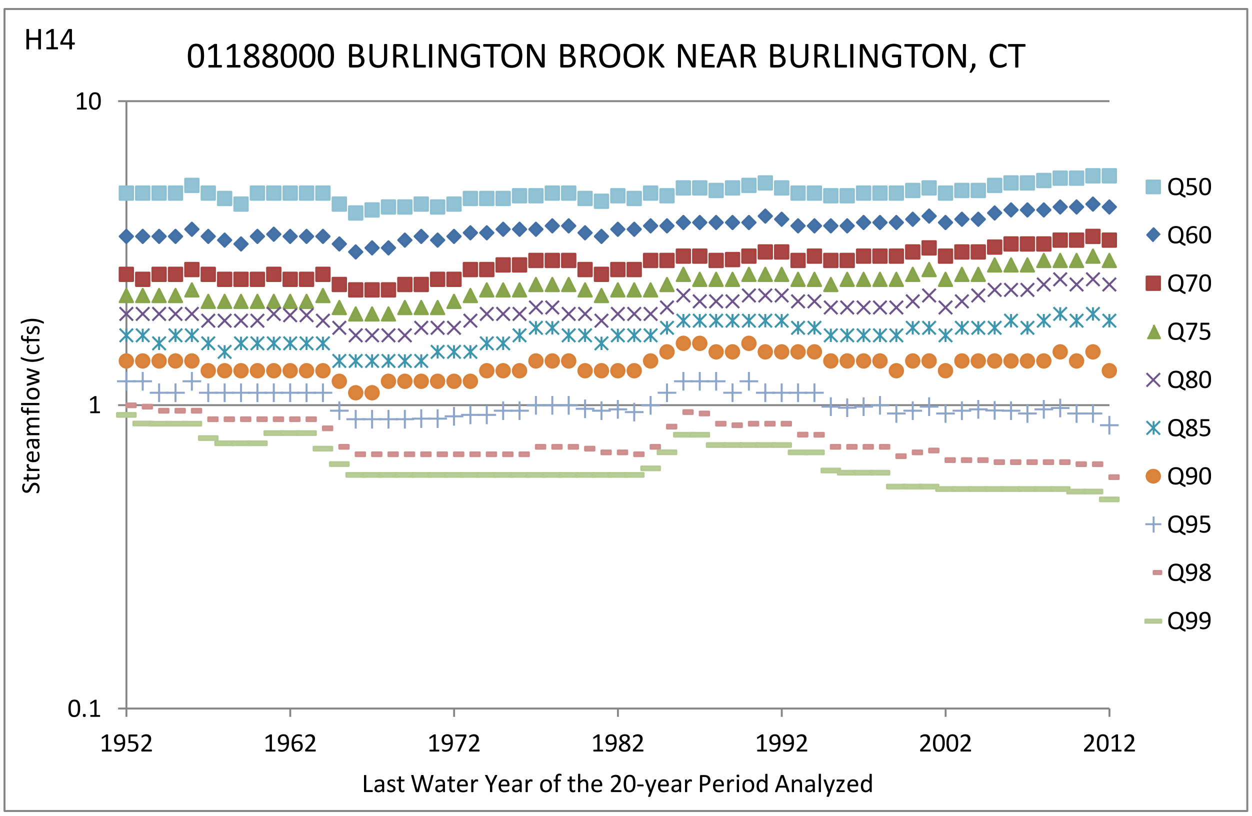

H9
01162500 PRIEST BROOK NEAR WINCHENDON, MA
100
10
1
0.1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

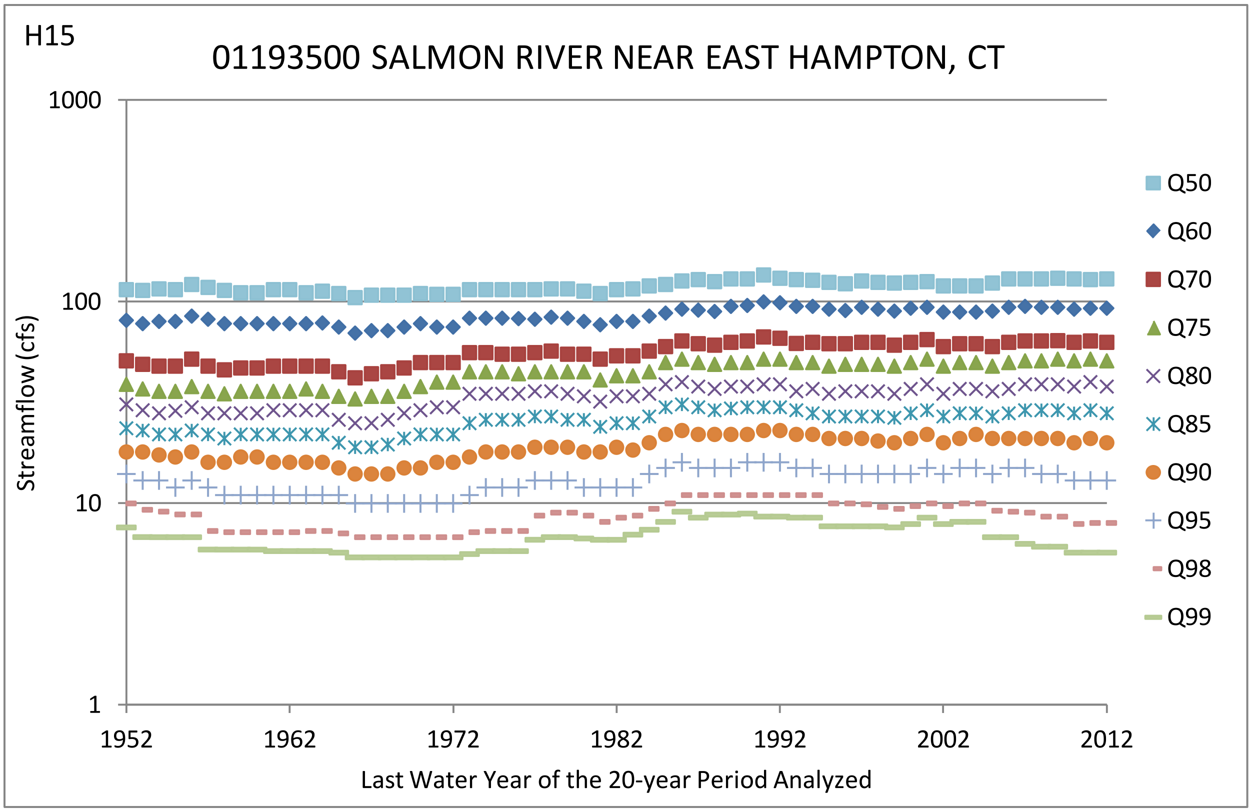

H10
01169000 NORTH RIVER AT SHATTUCKVILLE, MA
1000
100
10
1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

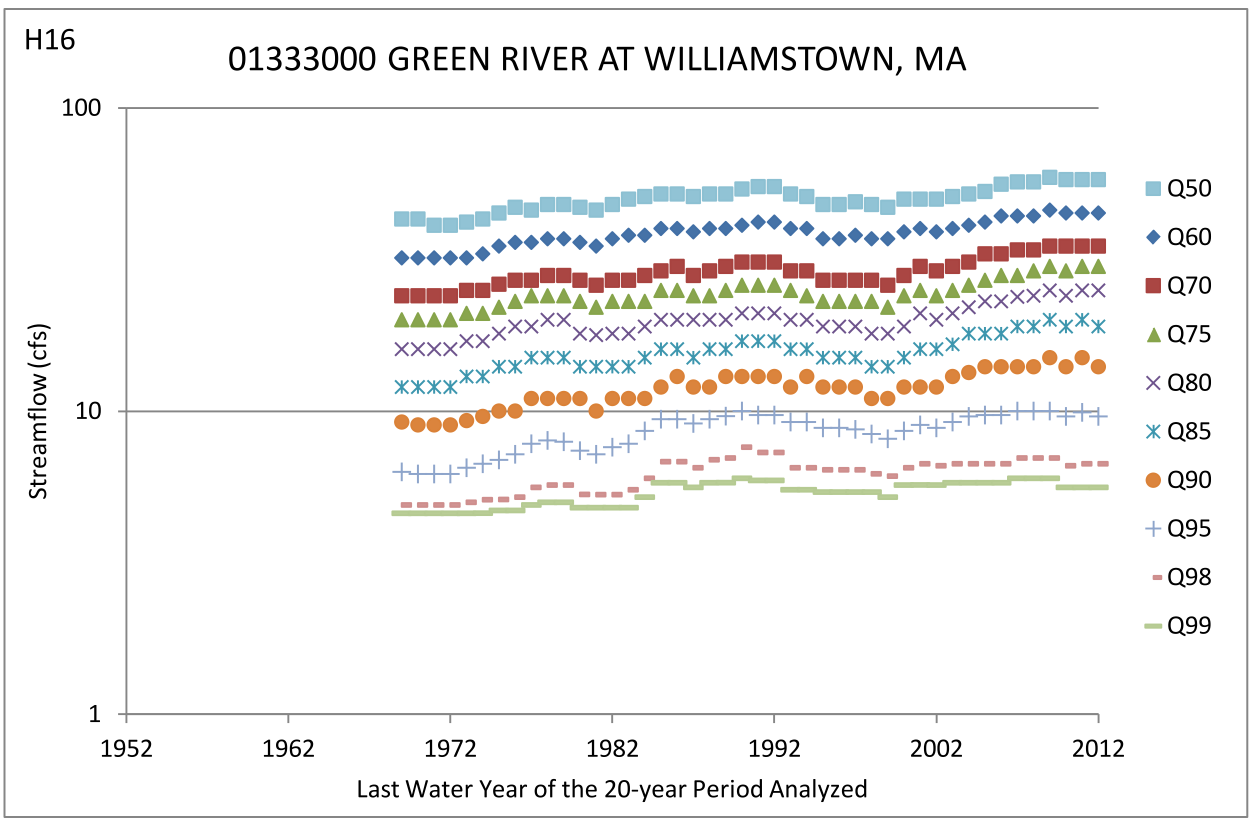

H11
01171500 MILL RIVER AT NORTHAMPTON, MA
Streamflow (cfs)
100
10
1
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99


H12
01176000 QUABOAG RIVER AT WEST BRIMFIELD, MA
Streamflow (cfs)
1000
100
10
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99


H13
01181000 WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA
1000
100
10
1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99


H14
01188000 BURLINGTON BROOK NEAR BURLINGTON, CT
10
1
0.1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99


H15
01193500 SALMON RIVER NEAR EAST HAMPTON, CT
1000
100
10
1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99


H16
01333000 GREEN RIVER AT WILLIAMSTOWN, MA
100
10
1
Streamflow (cfs)
1952
1962
1972
1982
1992
2002
2012
Last Water Year of the 20-year Period Analyzed
Q50
Q60
Q70
Q75
Q80
Q85
Q90
Q95
Q98
Q99

Appendix I

Part IV Quantile Trend Analysis Data

I1

	Station Number	Station Name	Q50 R^2	p	Failure year	Overestimate (O) or Under-estimate (U)
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.366	**<0.0001**	2413	U
	01096000	Squannacook River near West Groton, MA	0.7048	**<0.0001**	2118	U
	01109000	Wading River near Norton, MA	0.3001	**<0.0001**	2430	U
	01111500	Branch River at Forestdale, RI	0.0006	0.8604	11732	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.1264	**0.009**	2921	O
	01118000	Wood River at Hope Valley, RI	0.002	0.7505	10246	O
	01121000	Mount Hope River near Warrenville, CT	0.6672	**<0.0001**	2081	U
	01123000	Little River near Hanover, CT	0.1041	**0.0348**	2233	U
	01162500	Priest Brook near Winchendon, MA	0.5905	**<0.0001**	2115	U
	01169000	North River at Shattuckville, MA	0.8444	**<0.0001**	2113	U
	01171500	Mill River at Northampton, MA	0.8108	**<0.0001**	2093	U
	01176000	Quabog River at West Brimfield, MA	0.514	**<0.0001**	2363	U
	01181000	West Branch Westfield River at Huntington, MA	0.7374	**<0.0001**	2166	U
	01188000	Burlington Brook near Burlington, CT	0.3812	**<0.0001**	2314	U
	01193500	Salmon River near East Hampton, CT	0.6192	**<0.0001**	2311	U
	01333000	Green River at Williamstown, MA	0.6786	**<0.0001**	2074	U
	Year at which Q50 model will fail at >10% of stations				2081	
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.2159	**0.0294**	2235	U
	01096000	Squannacook River near West Groton, MA	0.0087	0.6797	3068	O
	01109000	Wading River near Norton, MA	0.0524	0.3055	2327	U
	01111500	Branch River at Forestdale, RI	0.3027	**0.008**	2249	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.1473	0.0778	2228	U
	01118000	Wood River at Hope Valley, RI	0.0784	0.2069	2148	U
	01121000	Mount Hope River near Warrenville, CT	0.0485	0.3247	2270	U
	01123000	Little River near Hanover, CT	0.6337	**<0.0001**	2100	O
	01162500	Priest Brook near Winchendon, MA	0.6379	**<0.0001**	2080	U
	01169000	North River at Shattuckville, MA	0.8444	**<0.0001**	2093	U
	01171500	Mill River at Northampton, MA	0.6778	**<0.0001**	2067	U
	01176000	Quabog River at West Brimfield, MA	0.0488	0.3232	2518	O
	01181000	West Branch Westfield River at Huntington, MA	0.6967	**<0.0001**	2098	U
	01188000	Burlington Brook near Burlington, CT	0.7595	**<0.0001**	2086	U
	01193500	Salmon River near East Hampton, CT	0.0561	0.2886	2732	U
	01333000	Green River at Williamstown, MA	0.5466	**<0.0001**	2051	U
	Year at which Q50 model will fail at >10% of stations				2067	

I2

	Station Number	Station Name	Q60 R^2	*p*	Failure year	Overestimate (O) or Under-estimate (U)
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.4892	**<0.0001**	2282	U
	01096000	Squannacook River near West Groton, MA	0.8057	**<0.0001**	2111	U
	01109000	Wading River near Norton, MA	0.3381	**<0.0001**	2976	U
	01111500	Branch River at Forestdale, RI	0.2913	**<0.0001**	2391	U
	01117500	Pawcatuck River at Wood River Junction, RI	0.0067	0.5601	6277	O
	01118000	Wood River at Hope Valley, RI	0.0018	0.7629	7245	U
	01121000	Mount Hope River near Warrenville, CT	0.7337	**<0.0001**	2087	U
	01123000	Little River near Hanover, CT	0.1941	**0.0031**	2154	U
	01162500	Priest Brook near Winchendon, MA	0.5041	**<0.0001**	2157	U
	01169000	North River at Shattuckville, MA	0.8651	**<0.0001**	2105	U
	01171500	Mill River at Northampton, MA	0.8422	**<0.0001**	2081	U
	01176000	Quabog River at West Brimfield, MA	0.3168	**<0.0001**	2515	U
	01181000	West Branch Westfield River at Huntington, MA	0.7888	**<0.0001**	2152	U
	01188000	Burlington Brook near Burlington, CT	0.7785	**<0.0001**	2084	U
	01193500	Salmon River near East Hampton, CT	0.6641	**<0.0001**	2248	U
	01333000	Green River at Williamstown, MA	0.7552	**<0.0001**	2057	U
	Year at which Q60 model will fail at >10% of stations				2081	
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.6954	**<0.0001**	2197	U
	01096000	Squannacook River near West Groton, MA	0.1098	0.1319	2594	U
	01109000	Wading River near Norton, MA	0.2512	**0.0175**	2432	U
	01111500	Branch River at Forestdale, RI	0.7725	**<0.0001**	2125	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.0001	0.9648	19563	O
	01118000	Wood River at Hope Valley, RI	0.0724	0.2259	2324	U
	01121000	Mount Hope River near Warrenville, CT	0.1912	**0.0418**	2175	U
	01123000	Little River near Hanover, CT	0.5183	**0.0002**	2122	O
	01162500	Priest Brook near Winchendon, MA	0.8244	**<0.0001**	2067	U
	01169000	North River at Shattuckville, MA	0.7768	**<0.0001**	2069	U
	01171500	Mill River at Northampton, MA	0.8196	**<0.0001**	2045	U
	01176000	Quabog River at West Brimfield, MA	0.3097	**0.0071**	2373	U
	01181000	West Branch Westfield River at Huntington, MA	0.8408	**<0.0001**	2068	U
	01188000	Burlington Brook near Burlington, CT	0.8323	**<0.0001**	2039	U
	01193500	Salmon River near East Hampton, CT	0.0472	0.3313	2648	O
	01333000	Green River at Williamstown, MA	0.6128	**<0.0001**	2041	U
	Year at which Q60 model will fail at >10% of stations				2041	

I3

			Q70			
	Station Number	**Station Name**	**R^2**	***p***	**Failure year**	**Overestimate (O) or Under-estimate (U)**
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.5453	**<0.0001**	2216	U
	01096000	Squannacook River near West Groton, MA	0.8548	**<0.0001**	2132	U
	01109000	Wading River near Norton, MA	0.283	**<0.0001**	2739	U
	01111500	Branch River at Forestdale, RI	0.5282	**<0.0001**	2168	U
	01117500	Pawcatuck River at Wood River Junction, RI	0.0483	0.1138	3708	U
	01118000	Wood River at Hope Valley, RI	0.0068	0.5572	4508	U
	01121000	Mount Hope River near Warrenville, CT	0.8507	**<0.0001**	2118	U
	01123000	Little River near Hanover, CT	0.104	**0.0349**	2310	U
	01162500	Priest Brook near Winchendon, MA	0.3845	**<0.0001**	2282	U
	01169000	North River at Shattuckville, MA	0.8669	**<0.0001**	2177	U
	01171500	Mill River at Northampton, MA	0.8427	**<0.0001**	2164	U
	01176000	Quabog River at West Brimfield, MA	0.2904	**<0.0001**	2854	U
	01181000	West Branch Westfield River at Huntington, MA	0.739	**<0.0001**	2287	U
	01188000	Burlington Brook near Burlington, CT	0.7987	**<0.0001**	2080	U
	01193500	Salmon River near East Hampton, CT	0.7747	**<0.0001**	2391	U
	01333000	Green River at Williamstown, MA	0.6998	**<0.0001**	2139	U
	Year at which Q70 model will fail at >10% of stations		2118			
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.7877	**<0.0001**	2157	U
	01096000	Squannacook River near West Groton, MA	0.1973	**0.0384**	2413	U
	01109000	Wading River near Norton, MA	0.0049	0.7569	3229	O
	01111500	Branch River at Forestdale, RI	0.9352	**<0.0001**	2096	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.0603	0.2707	2822	O
	01118000	Wood River at Hope Valley, RI	0.172	0.055	2388	O
	01121000	Mount Hope River near Warrenville, CT	0.3474	**0.0039**	2210	U
	01123000	Little River near Hanover, CT	0.3547	**0.0035**	2217	O
	01162500	Priest Brook near Winchendon, MA	0.8202	**<0.0001**	2098	U
	01169000	North River at Shattuckville, MA	0.8406	**<0.0001**	2101	U
	01171500	Mill River at Northampton, MA	0.733	**<0.0001**	2102	U
	01176000	Quabog River at West Brimfield, MA	0.3857	**0.002**	2709	U
	01181000	West Branch Westfield River at Huntington, MA	0.8574	**<0.0001**	2110	U
	01188000	Burlington Brook near Burlington, CT	0.8055	**<0.0001**	2045	U
	01193500	Salmon River near East Hampton, CT	0.0034	0.7966	11284	U
	01333000	Green River at Williamstown, MA	0.6891	**<0.0001**	2071	U
	Year at which model Q70 will fail at >10% of stations		2071			

I4

	Station Number	Station Name	Q75 R^2	*p*	Failure year	Overestimate (O) or Under-estimate (U)
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.5743	**<0.0001**	2181	U
	01096000	Squannacook River near West Groton, MA	0.7907	**<0.0001**	2130	U
	01109000	Wading River near Norton, MA	0.2697	**<0.0001**	2615	U
	01111500	Branch River at Forestdale, RI	0.5376	**<0.0001**	2114	U
	01117500	Pawcatuck River at Wood River Junction, RI	0.1074	**0.0166**	2971	U
	01118000	Wood River at Hope Valley, RI	0.0472	0.1181	2606	U
	01121000	Mount Hope River near Warrenville, CT	0.7906	**<0.0001**	2092	U
	01123000	Little River near Hanover, CT	0.2107	**0.002**	2141	U
	01162500	Priest Brook near Winchendon, MA	0.2415	**<0.0001**	2426	U
	01169000	North River at Shattuckville, MA	0.8338	**<0.0001**	2167	U
	01171500	Mill River at Northampton, MA	0.8097	**<0.0001**	2180	U
	01176000	Quabog River at West Brimfield, MA	0.2328	**<0.0001**	2913	U
	01181000	West Branch Westfield River at Huntington, MA	0.7511	**<0.0001**	2275	U
	01188000	Burlington Brook near Burlington, CT	0.774	**<0.0001**	2075	U
	01193500	Salmon River near East Hampton, CT	0.7895	**<0.0001**	2367	U
	01333000	Green River at Williamstown, MA	0.6833	**<0.0001**	2136	U
	Year at which Q75 model will fail at >10% of stations		2092			
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.474	**0.0004**	2189	U
	01096000	Squannacook River near West Groton, MA	0	1.000	None	U
	01109000	Wading River near Norton, MA	0.1956	**0.0393**	2163	O
	01111500	Branch River at Forestdale, RI	0.9224	**<0.0001**	2084	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.1943	**0.04**	2908	O
	01118000	Wood River at Hope Valley, RI	0.3468	**0.0039**	2270	O
	01121000	Mount Hope River near Warrenville, CT	0.3109	**0.007**	4657	O
	01123000	Little River near Hanover, CT	0.1922	**0.0413**	2287	O
	01162500	Priest Brook near Winchendon, MA	0.7648	**<0.0001**	2149	U
	01169000	North River at Shattuckville, MA	0.7942	**<0.0001**	2089	U
	01171500	Mill River at Northampton, MA	0.5882	**<0.0001**	2145	U
	01176000	Quabog River at West Brimfield, MA	0.0512	0.3113	4069	U
	01181000	West Branch Westfield River at Huntington, MA	0.8517	**<0.0001**	2119	U
	01188000	Burlington Brook near Burlington, CT	0.787	**<0.0001**	2038	U
	01193500	Salmon River near East Hampton, CT	0.1542	0.0706	3236	U
	01333000	Green River at Williamstown, MA	0.6876	**<0.0001**	2070	U
	Year at which Q75 model will fail at >10% of stations		2070			

I5

	Station Number	Station Name	Q80 R^2	Q80 *p*	Q80 Failure year	Q80 Overestimate (O) or Under-estimate (U)
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.5976	**<0.0001**	2158	U
	01096000	Squannacook River near West Groton, MA	0.6723	**<0.0001**	2160	U
	01109000	Wading River near Norton, MA	0.073	**0.0247**	3436	U
	01111500	Branch River at Forestdale, RI	0.4593	**<0.0001**	2176	U
	01117500	Pawcatuck River at Wood River Junction, RI	0.0472	0.1181	3972	U
	01118000	Wood River at Hope Valley, RI	0.0805	**0.0395**	2761	U
	01121000	Mount Hope River near Warrenville, CT	0.7816	**<0.0001**	2082	U
	01123000	Little River near Hanover, CT	0.1707	**0.0059**	2221	U
	01162500	Priest Brook near Winchendon, MA	0.2074	**0.0003**	2465	U
	01169000	North River at Shattuckville, MA	0.8566	**<0.0001**	2192	U
	01171500	Mill River at Northampton, MA	0.7907	**<0.0001**	2252	U
	01176000	Quabog River at West Brimfield, MA	0.1513	**0.0003**	2970	U
	01181000	West Branch Westfield River at Huntington, MA	0.7862	**<0.0001**	2271	U
	01188000	Burlington Brook near Burlington, CT	0.6445	**<0.0001**	2189	U
	01193500	Salmon River near East Hampton, CT	0.6868	**<0.0001**	2502	U
	01333000	Green River at Williamstown, MA	0.7106	**<0.0001**	2377	U
	Year at which Q80 model will fail at >10% of stations		2158			
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.0322	0.4243	2694	U
	01096000	Squannacook River near West Groton, MA	0.4018	**0.0015**	2215	O
	01109000	Wading River near Norton, MA	0.567	**<0.0001**	2054	O
	01111500	Branch River at Forestdale, RI	0.9474	**<0.0001**	2066	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.4135	**0.0012**	2374	O
	01118000	Wood River at Hope Valley, RI	0.6242	**<0.0001**	2162	O
	01121000	Mount Hope River near Warrenville, CT	0.803	**<0.0001**	2475	O
	01123000	Little River near Hanover, CT	0.4488	**0.0006**	2175	O
	01162500	Priest Brook near Winchendon, MA	0.5663	**<0.0001**	2283	U
	01169000	North River at Shattuckville, MA	0.702	**<0.0001**	2141	U
	01171500	Mill River at Northampton, MA	0.4104	**0.0013**	2293	U
	01176000	Quabog River at West Brimfield, MA	0.355	**0.0034**	2263	O
	01181000	West Branch Westfield River at Huntington, MA	0.7776	**<0.0001**	2142	U
	01188000	Burlington Brook near Burlington, CT	0.66	**<0.0001**	2077	U
	01193500	Salmon River near East Hampton, CT	0.2749	**0.0122**	2739	U
	01333000	Green River at Williamstown, MA	0.7214	**<0.0001**	2188	U
	Year at which Q80 model will fail at >10% of stations		2066			

I6

			Q85			
	Station Number	**Station Name**	**R^2**	***p***	**Failure year**	**Overestimate (O) or Under-estimate (U)**
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.5909	**<0.0001**	2205	U
	01096000	Squannacook River near West Groton, MA	0.5538	**<0.0001**	2194	U
	01109000	Wading River near Norton, MA	0.0373	0.1118	4145	U
	01111500	Branch River at Forestdale, RI	0.3519	**<0.0001**	2221	U
	01117500	Pawcatuck River at Wood River Junction, RI	0.0481	0.1146	3902	U
	01118000	Wood River at Hope Valley, RI	0.0249	0.2591	3313	U
	01121000	Mount Hope River near Warrenville, CT	0.6956	**<0.0001**	2091	U
	01123000	Little River near Hanover, CT	0.2285	**0.0012**	2159	U
	01162500	Priest Brook near Winchendon, MA	0.2087	**0.0003**	2512	U
	01169000	North River at Shattuckville, MA	0.8276	**<0.0001**	2212	U
	01171500	Mill River at Northampton, MA	0.7111	**<0.0001**	2299	U
	01176000	Quabog River at West Brimfield, MA	0.1053	**0.0029**	3017	U
	01181000	West Branch Westfield River at Huntington, MA	0.7494	**<0.0001**	2303	U
	01188000	Burlington Brook near Burlington, CT	0.4833	**<0.0001**	2241	U
	01193500	Salmon River near East Hampton, CT	0.6190	**<0.0001**	2619	U
	01333000	Green River at Williamstown, MA	0.7358	**<0.0001**	2404	U
	Year at which Q85 model will fail at >10% of stations				2159	
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.2184	**0.0283**	2207	O
	01096000	Squannacook River near West Groton, MA	0.5468	**<0.0001**	2127	O
	01109000	Wading River near Norton, MA	0.6843	**<0.0001**	2042	O
	01111500	Branch River at Forestdale, RI	0.9537	**<0.0001**	2052	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.7017	**<0.0001**	2206	O
	01118000	Wood River at Hope Valley, RI	0.6687	**<0.0001**	2118	O
	01121000	Mount Hope River near Warrenville, CT	0.825	**<0.0001**	2116	O
	01123000	Little River near Hanover, CT	0.3682	**0.0028**	2260	O
	01162500	Priest Brook near Winchendon, MA	0.3296	**0.0052**	2408	U
	01169000	North River at Shattuckville, MA	0.4011	**0.0016**	2263	U
	01171500	Mill River at Northampton, MA	0.4002	**0.0016**	2316	U
	01176000	Quabog River at West Brimfield, MA	0.7309	**<0.0001**	2098	O
	01181000	West Branch Westfield River at Huntington, MA	0.6133	**<0.0001**	2224	U
	01188000	Burlington Brook near Burlington, CT	0.3934	**0.0018**	2153	U
	01193500	Salmon River near East Hampton, CT	0.0295	0.4447	5209	U
	01333000	Green River at Williamstown, MA	0.6484	**<0.0001**	2233	U
	Year at which Q85 model will fail at >10% of stations				2052	

I7

	Station Number	Station Name	Q90 R^2	*p*	Failure year	Overestimate (O) or Under-estimate (U)
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.3485	**<0.0001**	2312	U
	01096000	Squannacook River near West Groton, MA	0.3143	**<0.0001**	2274	U
	01109000	Wading River near Norton, MA	0.0052	0.556	2656	O
	01111500	Branch River at Forestdale, RI	0.2762	**<0.0001**	2299	U
	01117500	Pawcatuck River at Wood River Junction, RI	0.0097	0.4829	5861	U
	01118000	Wood River at Hope Valley, RI	0.0235	0.2731	3085	O
	01121000	Mount Hope River near Warrenville, CT	0.5336	**<0.0001**	2126	U
	01123000	Little River near Hanover, CT	0.2373	**0.0009**	2155	U
	01162500	Priest Brook near Winchendon, MA	0.2351	**<0.0001**	2556	U
	01169000	North River at Shattuckville, MA	0.8398	**<0.0001**	2216	U
	01171500	Mill River at Northampton, MA	0.5508	**<0.0001**	2380	U
	01176000	Quabog River at West Brimfield, MA	0.0286	0.1288	3832	U
	01181000	West Branch Westfield River at Huntington, MA	0.6897	**<0.0001**	2339	U
	01188000	Burlington Brook near Burlington, CT	0.1847	**0.0004**	2415	U
	01193500	Salmon River near East Hampton, CT	0.5225	**<0.0001**	2720	U
	01333000	Green River at Williamstown, MA	0.7827	**<0.0001**	2488	U
	Year at which Q90 model will fail at >10% of stations				2155	
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.7704	**<0.0001**	2054	O
	01096000	Squannacook River near West Groton, MA	0.72	**<0.0001**	2072	O
	01109000	Wading River near Norton, MA	0.7558	**<0.0001**	2022	O
	01111500	Branch River at Forestdale, RI	0.969	**<0.0001**	2044	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.6902	**<0.0001**	2137	O
	01118000	Wood River at Hope Valley, RI	0.8465	**<0.0001**	2085	O
	01121000	Mount Hope River near Warrenville, CT	0.9227	**<0.0001**	2060	O
	01123000	Little River near Hanover, CT	0.5817	**<0.0001**	2181	O
	01162500	Priest Brook near Winchendon, MA	0.0818	0.1969	3203	U
	01169000	North River at Shattuckville, MA	0.3771	**0.0024**	2321	U
	01171500	Mill River at Northampton, MA	0.0216	0.514	3115	O
	01176000	Quabog River at West Brimfield, MA	0.954	**<0.0001**	2057	O
	01181000	West Branch Westfield River at Huntington, MA	0.1391	**0.0874**	2795	U
	01188000	Burlington Brook near Burlington, CT	0.0539	0.2985	2508	O
	01193500	Salmon River near East Hampton, CT	0.2501	**0.0178**	2230	O
	01333000	Green River at Williamstown, MA	0.567	**<0.0001**	2384	U
	Year at which Q90 model will fail at >10% of stations		2044			

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	Station Number	Station Name	Q95 R^2	*p*	Failure year	Overestimate (O) or Under-estimate (U)
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.1142	**0.0089**	2595	U
	01096000	Squannacook River near West Groton, MA	0.2624	**0.0003**	2187	U
	01109000	Wading River near Norton, MA	0.1182	**0.0038**	2159	O
	01111500	Branch River at Forestdale, RI	0.045	0.1236	2765	U
	01117500	Pawcatuck River at Wood River Junction, RI	0.00005	0.9599	23741	O
	01118000	Wood River at Hope Valley, RI	0.0316	0.2029	2826	O
	01121000	Mount Hope River near Warrenville, CT	0.1943	**0.0009**	2275	U
	01123000	Little River near Hanover, CT	0.0828	0.0613	2130	U
	01162500	Priest Brook near Winchendon, MA	0.318	**<0.0001**	2499	U
	01169000	North River at Shattuckville, MA	0.7912	**<0.0001**	2251	U
	01171500	Mill River at Northampton, MA	0.364	**<0.0001**	2434	U
	01176000	Quabog River at West Brimfield, MA	0.0003	0.8773	6393	O
	01181000	West Branch Westfield River at Huntington, MA	0.6102	**<0.0001**	2426	U
	01188000	Burlington Brook near Burlington, CT	0.1349	**0.0031**	2467	O
	01193500	Salmon River near East Hampton, CT	0.2912	**<0.0001**	3123	U
	01333000	Green River at Williamstown, MA	0.6941	**<0.0001**	2604	U
	Year at which Q95 model will fail at >10% of stations		2159			
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.7497	**<0.0001**	2046	O
	01096000	Squannacook River near West Groton, MA	0.8902	**<0.0001**	2049	O
	01109000	Wading River near Norton, MA	0.7188	**<0.0001**	2023	O
	01111500	Branch River at Forestdale, RI	0.9612	**<0.0001**	2034	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.6902	**<0.0001**	2081	O
	01118000	Wood River at Hope Valley, RI	0.8615	**<0.0001**	2068	O
	01121000	Mount Hope River near Warrenville, CT	0.9368	**<0.0001**	2032	O
	01123000	Little River near Hanover, CT	0.6993	**<0.0001**	2113	O
	01162500	Priest Brook near Winchendon, MA	0.0031	0.8056	2472	O
	01169000	North River at Shattuckville, MA	0.0763	0.2134	3407	U
	01171500	Mill River at Northampton, MA	0.3598	**0.0032**	2109	O
	01176000	Quabog River at West Brimfield, MA	0.9010	**<0.0001**	2035	O
	01181000	West Branch Westfield River at Huntington, MA	0.0021	0.8395	4027	O
	01188000	Burlington Brook near Burlington, CT	0.6021	**<0.0001**	2110	O
	01193500	Salmon River near East Hampton, CT	0.2969	**0.0087**	2145	O
	01333000	Green River at Williamstown, MA	0.3645	**0.0029**	2860	U
	Year at which Q95 model will fail at >10% of stations		2032			

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	Station Number	Station Name	Q98 R^2	Q98 *p*	Q98 Failure year	Q98 Overestimate (O) or Under-estimate (U)
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.0238	0.2434	2452	O
	01096000	Squannacook River near West Groton, MA	0.2075	**0.0017**	2142	U
	01109000	Wading River near Norton, MA	0.3934	**<0.0001**	2076	O
	01111500	Branch River at Forestdale, RI	0.0307	0.2051	3894	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.0483	0.1138	2737	O
	01118000	Wood River at Hope Valley, RI	0.0313	0.205	2682	O
	01121000	Mount Hope River near Warrenville, CT	0.093	**0.0249**	2322	U
	01123000	Little River near Hanover, CT	0.029	0.2749	2791	O
	01162500	Priest Brook near Winchendon, MA	0.5254	**<0.0001**	2567	U
	01169000	North River at Shattuckville, MA	0.721	**<0.0001**	2232	U
	01171500	Mill River at Northampton, MA	0.1737	**0.0015**	2687	U
	01176000	Quabog River at West Brimfield, MA	0.0065	0.4715	2852	O
	01181000	West Branch Westfield River at Huntington, MA	0.3213	**<0.0001**	2707	U
	01188000	Burlington Brook near Burlington, CT	0.4117	**<0.0001**	2126	O
	01193500	Salmon River near East Hampton, CT	0.157	**0.001**	3595	U
	01333000	Green River at Williamstown, MA	0.6013	**<0.0001**	2750	U
	Year at which Q98 model will fail at >10% of stations		2126			
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.8292	**<0.0001**	2030	O
	01096000	Squannacook River near West Groton, MA	0.87	**<0.0001**	2044	O
	01109000	Wading River near Norton, MA	0.5384	**0.0001**	2028	O
	01111500	Branch River at Forestdale, RI	0.9323	**<0.0001**	2029	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.0565	0.2868	2085	O
	01118000	Wood River at Hope Valley, RI	0.8539	**<0.0001**	2056	O
	01121000	Mount Hope River near Warrenville, CT	0.9349	**<0.0001**	2022	O
	01123000	Little River near Hanover, CT	0.4025	**0.0015**	2132	O
	01162500	Priest Brook near Winchendon, MA	0.1645	0.0611	2073	O
	01169000	North River at Shattuckville, MA	0.3031	**0.0079**	2293	O
	01171500	Mill River at Northampton, MA	0.9106	**<0.0001**	2050	O
	01176000	Quabog River at West Brimfield, MA	0.8409	**<0.0001**	2027	O
	01181000	West Branch Westfield River at Huntington, MA	0.5117	**0.0002**	2126	O
	01188000	Burlington Brook near Burlington, CT	0.8235	**<0.0001**	2057	O
	01193500	Salmon River near East Hampton, CT	0.8454	**<0.0001**	2050	O
	01333000	Green River at Williamstown, MA	0.1112	0.1294	4362	U
	Year at which Q98 model will fail at >10% of stations		2027			

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			Q99			
	Station Number	**Station Name**	**R^2**	***p***	**Failure year**	**Overestimate (O) or Under-estimate (U)**
Period of Record Trend Analysis	01073000	Oyster River near Durham, NH	0.2521	**<0.0001**	2114	O
	01096000	Squannacook River near West Groton, MA	0.0431	0.1712	2267	U
	01109000	Wading River near Norton, MA	0.5199	**<0.0001**	2057	O
	01111500	Branch River at Forestdale, RI	0.0763	**0.0432**	2261	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.0754	**0.0466**	2612	O
	01118000	Wood River at Hope Valley, RI	0.0151	0.3807	2904	O
	01121000	Mount Hope River near Warrenville, CT	0.0685	0.0559	2318	U
	01123000	Little River near Hanover, CT	0.0123	0.4789	3659	O
	01162500	Priest Brook near Winchendon, MA	0.4798	**<0.0001**	2612	U
	01169000	North River at Shattuckville, MA	0.6882	**<0.0001**	2248	U
	01171500	Mill River at Northampton, MA	0.1247	**0.0082**	2664	U
	01176000	Quabog River at West Brimfield, MA	0.0019	0.6974	3549	O
	01181000	West Branch Westfield River at Huntington, MA	0.238	**<0.0001**	2889	U
	01188000	Burlington Brook near Burlington, CT	0.488	**<0.0001**	2132	O
	01193500	Salmon River near East Hampton, CT	0.1299	**0.003**	3856	U
	01333000	Green River at Williamstown, MA	0.6515	**<0.0001**	3006	U
	Year at which Q99 model will fail at >10% of stations		2114			
Post-1992 Trend Analysis	01073000	Oyster River near Durham, NH	0.8314	**<0.0001**	2016	O
	01096000	Squannacook River near West Groton, MA	0.843	**<0.0001**	2029	O
	01109000	Wading River near Norton, MA	0.4701	**0.0004**	2028	O
	01111500	Branch River at Forestdale, RI	0.8784	**<0.0001**	2025	O
	01117500	Pawcatuck River at Wood River Junction, RI	0.8249	**<0.0001**	2074	O
	01118000	Wood River at Hope Valley, RI	0.7616	**<0.0001**	2051	O
	01121000	Mount Hope River near Warrenville, CT	0.0031	0.8056	2018	O
	01123000	Little River near Hanover, CT	0.0936	0.1661	2512	O
	01162500	Priest Brook near Winchendon, MA	0.3759	**0.0024**	2026	O
	01169000	North River at Shattuckville, MA	0.4571	**0.0006**	2143	O
	01171500	Mill River at Northampton, MA	0.8539	**<0.0001**	2039	O
	01176000	Quabog River at West Brimfield, MA	0.7611	**<0.0001**	2029	O
	01181000	West Branch Westfield River at Huntington, MA	0.4222	**0.0011**	2093	O
	01188000	Burlington Brook near Burlington, CT	0.7233	**<0.0001**	2053	O
	01193500	Salmon River near East Hampton, CT	0.7612	**<0.0001**	2038	O
	01333000	Green River at Williamstown, MA	0.2163	**0.0292**	3842	U
	Year at which Q99 model will fail at >10% of stations		2018			