Appendix II
Baseflow Separation Review and Analysis

BASEFLOW SEPARATION REVIEW AND ANALYSIS

FINAL REPORT

Prepared for

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1.0 INTRODUCTION

Estimating the groundwater contribution to surface water systems is challenging, especially in karst terrains like those in the Suwannee River Water Management District (District). One method that can be applied to estimate this baseflow (groundwater) contribution to the gaged streamflow is the chemical mass balance approach for baseflow separation. In this method the conductivity of water (referred to as specific conductance when measured at standard temperature of 25°C) is used to estimate the relative proportions of groundwater and surface water in gaged streamflow. By definition, specific conductance of water is a measure of the capacity of water to conduct electrical current, measured at 25°C. The longer the water is in contact with karstic limestone, the higher its specific conductance value. This characteristic can thus be used to estimate the relative contribution of groundwater and surface water based on measured specific conductance value at a gage location. Accurate estimates of groundwater inputs to the surface water systems are critical for understanding surface water and groundwater dynamics and for analyzing potential changes in the relative groundwater contribution over time due to climatic or anthropogenic impacts.

A couple of years ago, the District conducted a chemical baseflow separation analysis with the objective of developing long-term estimates of baseflow at 23 locations of interest across the District. As part of this effort, the District produced a preliminary draft technical report and estimated baseflow timeseries at the 23 gages. In an effort to review and finalize the methodology that the District was in the process of implementing, the District contacted Wood Environment and Infrastructure Solutions (Wood) and authorized a study with the following objectives:

- Review the District's methodology, the partially completed draft report, and the estimates of baseflow to verify that the method is appropriate and accurately applied.
- Propose revisions as needed to appropriately and accurately estimate baseflow using specific conductance.
- Provide recommendations on the use of the specific conductance-based baseflow estimation methods for selected District gages.
- Provide final scripts in R format to perform chemical baseflow specifications per the documented methodology.

The following section provide details about specific task elements of the study.

2.0 CHEMICAL BASEFLOW SEPARATION WITH LOGISTIC REGRESSION

The chemical mass balance (CMB) baseflow separation method uses concurrent streamflow discharge and specific conductance data to estimate the baseflow contribution to the observed discharge (Stewart et al. 2007). In the current study (consistent with the District's methodology), the relationship between streamflow and specific conductance was assumed to follow a logistic form (unique for each location of interest) whose parameters were derived using regression analysis. The logistic relationship (once derived using regression) can be used to hindcast historical specific conductance values from observed streamflow. The hindcasted specific conductance data in conjunction with the observed streamflow data can be used to estimate historical baseflow time series using the CMB method (**Section 2.3**). As part of this study six sites (see **Section 2.1**) were selected to perform a detailed review of District's preliminary methodology including draft results and associated programming scripts.

As described in subsequent sections, the combined use of logistic regression (for hindcasting of specific conductance data) and the CMB method (utilizing hindcasted specific conductance data and observed streamflow data) to estimate historical baseflow is referred to as the *logistic/CMB method*.

2.1. Data Sources

Streamflow discharge data for the six sites of interest (through 12/31/2019) were imported directly from the USGS Water Services repository (http://waterservices.usgs.gov/; parameter code 00060). Specific conductance observations including continuous (daily) data from USGS and grab sample data from the District (Hydstra) were provided by the District. See **Table 1** for streamflow discharge and conductance periods of record. The conductance periods of record in **Table 1** reflect continuous data from USGS and/or grab sample data from the District (Hydstra).

In some instances, multiple conductance values were available for a given date. When replicate observations were available from both sources (USGS and Hydstra), the grab sample data (Hydstra) were retained and the USGS data were discarded. When replicate grab sample observations (Hydstra) were reported, the arithmetic mean of the reported values was used.

Table 1 - Streamflow and Conductance Data Included for Analysis

Gage Location	Site ID	Streamflow Parameter	Data Source	Period of Record
Ellaville	02319500	Discharge	USGS	02/01/1927 – 12/31/2019
		Conductance	Hydstra	02/10/1989 – 08/24/2017
Branford	02320500	Discharge	USGS	07/01/1931 – 12/31/2019
		Conductance	USGS & Hydstra	07/18/1977 – 12/31/2019
Worthington	02321500	Discharge	USGS	10/01/1931 – 12/31/2019
		Conductance	USGS & Hydstra	02/15/1989 – 12/04/2019
Ft. White	02322500	Discharge	USGS	10/01/1927 – 12/31/2019
		Conductance	USGS & Hydstra	07/18/1977 – 12/31/2019
Hildreth	02322800	Discharge	USGS	11/01/2000 – 12/31/2019
		Conductance	USGS & Hydstra	01/26/1982 – 12/31/2019
Ichetucknee	02322700	Discharge	USGS	02/05/2002 – 12/31/2019
		Conductance	USGS & Hydstra	01/19/2017 – 12/31/2019

2.2. Visual Diagnostics

Whether a particular gage location is a good candidate for baseflow separation using the logistic/CMB method depends both on the location (hydrogeology) and on the availability of data: The consistency and stability of the observed specific conductance values associated with groundwater vary by location, and the availability and quality of data are important to ensure that the logistic relationship (regression analysis) is robust and provides a reasonable estimate of historical conductance values. Visual diagnostic test were thus conducted to (1) compare the streamflow discharge frequency distribution during the period of record used for regression (~ 20 -30 years) was generally similar to the discharge frequency of the entire discharge record (~ greater than 80 years); and (2) assess whether observed streamflow discharge and conductance exhibited an approximately logistic relationship.

2.3. Chemical Mass Balance (CMB) Method

Per the CMB method (Stewart et al. 2007), the baseflow component Q_{BF} of gaged streamflow discharge Q_{SF} can be estimated using the mass-balance equation

$$Q_{BF} = Q_{SF}\left(\frac{C_{SF} - C_{RO}}{C_{BF} - C_{RO}}\right) \tag{1}$$

where Q is discharge (cfs), C is conductance (μS/cm), and the subscripts BF is baseflow, SF is streamflow, and RO is surface runoff.

<u>The CMB method assumes that for a given location</u>:

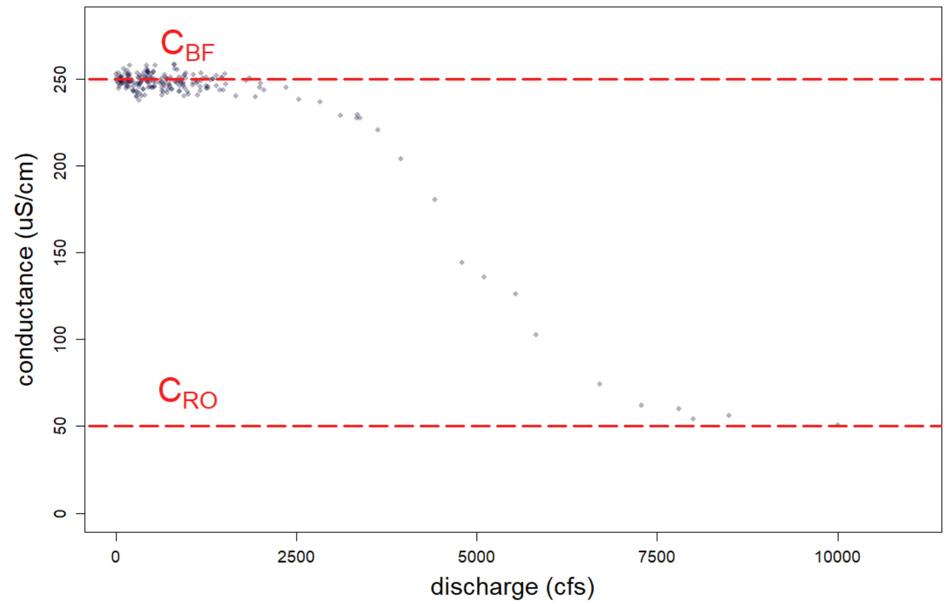
(1) Baseflow and runoff are the primary fluxes to streamflow, and other fluxes are negligible.

(2) Site-specific C_{BF} and C_{RO} values characterize streamflow conductance values during extreme low (baseflow) and high (runoff) flow, respectively.

(3) Site-specific C_{BF} and C_{RO} values remain constant throughout the period of record.

The characteristic site-specific baseflow and runoff specific conductance values C_{BF} and C_{RO} can be estimated from a set of concurrent streamflow discharge and conductance observations, using a scatterplot to identify conductance-value plateaus under high and low discharge conditions, respectively (**Figure 1**). Once C_{BF} and C_{RO} are established for a site (for instance, 250 μS/cm and 50 μS/cm from example **Figure 1**), observed stream discharge (Q_{SF}) and specific conductance data (C_{SF}) can be used to estimate the baseflow contribution (Q_{BF}) using **Equation 1**.

Figure 1 - Scatterplot of an example dataset for streamflow discharge and conductance (gray points)



2.4. Logistic Regression

The CMB method requires concurrent streamflow discharge and conductance observations (Q_{SF} and C_{SF}), but the discharge record typically extends further back in time than the conductance record (**Table 1**). Thus, a logistic regression analysis (also referred to as calibration) was conducted to develop a logistic function (also referred to as a logistic model) that can be used to hindcast historical specific conductance data based on historical discharge observations at a given gage location.

The logistic regression fits a sigmoidal (S-shaped) curve to the specific conductance and discharge data from a given gage location:

$$y = \text{bottom} + \frac{\text{top} - \text{bottom}}{\left[1 + 10^{\text{slope}\,(\text{xmid} - x)}\right]^{\text{sym}}} \qquad (2)$$

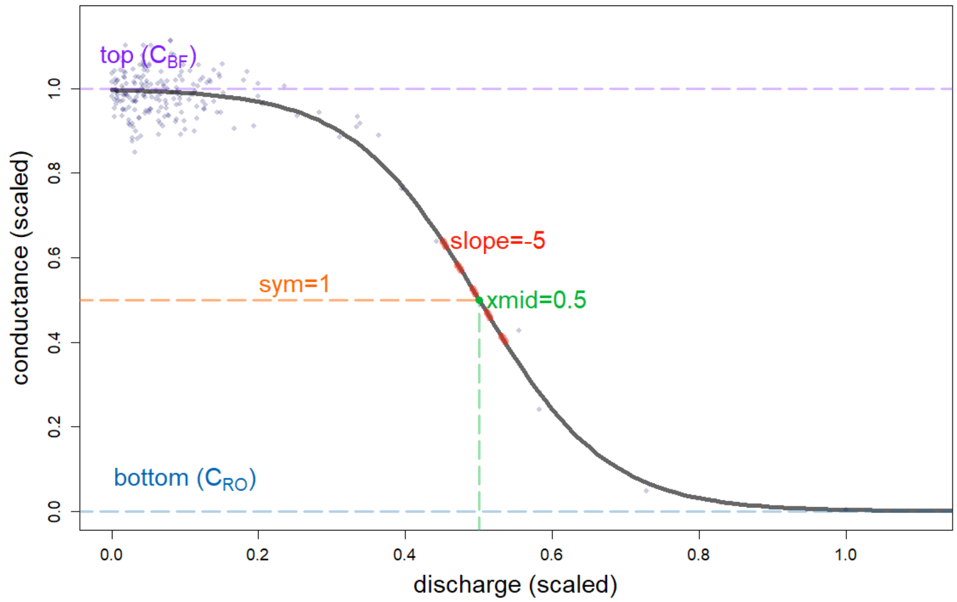
where *y* is conductance (uS/cm); *x* is discharge (cfs); and *top*, *bottom*, *xmid*, *slope*, and *sym* are fitting parameters (Commo & Bot 2016). While each logistic model includes all five parameters (**Equation 2**), the regression can be more or less *constrained*: A fully unconstrained model (referred to as a 5-parameter model) results from allowing the regression procedure to estimate values for all five parameters. In contrast, the regression may be constrained by explicitly specifying values for one or more of the five parameters, rather than allowing the regression to estimate the values. Thus, the logistic model can be fit with as few as two (*xmid* and *slope*) or as many as five unconstrained parameters, and the number of unconstrained parameters is referred to as *npars* (**Table 2**). The 3- and 4-parameter models un-constrain the *top* (in addition to *xmid* and *slope*) and *bottom* (in addition to *xmid, slope,* and *top*) parameters, respectively, to adjust the curve's upper and lower asymptotes. In the fully unconstrained 5-parameter model, the *sym* parameter introduces vertical asymmetry to the logistic curve by adjusting the vertical position of the curve's inflection point upward ($0 \leq sym < 1$) or downward ($sym > 1$) from $sym = 1$. **Figure 2** shows an example of a logistic model for the sample data shown in **Figure 1**.

The regression analysis estimates the values of unconstrained parameters by minimizing the sum of squared errors between the logistic curve (black) and the data (gray points). Because the logistic model assigns one and only one conductance value to each discharge value in the domain, in important assumption of the logistic model is that there is an approximately 1:1 relationship between streamflow discharge Q_{SF} and conductance C_{SF}.

Table 2 - Logistic Regression Parameters and Description

Number of Unconstrained Parameters (*npars*)	Unconstrained Parameters	Parameter Value if Constrained	Description
2	*xmid*	N/A	*x*-value at inflection point
	slope	N/A	slope near inflection point
3	*top*	maximum conductance	upper asymptote (baseflow conductance C_{BF})
4	*bottom*	minimum conductance	lower asymptote (runoff conductance C_{RO})
5	*sym*	1	asymmetry coefficient (vertically symmetric when s=1)

Figure 2 - Logistic fit to simulated data



2.5. Goodness of Fit

The Nash-Sutcliffe coefficient of efficiency (NSE) is used to assess each logistic model's fit to the data (Nash & Sutcliffe 1970):

$$NSE = 1 - \frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} = 1 - \left(\frac{RMSE}{\sigma}\right)^2 \quad (3)$$

where y_i and $\hat{y}_i$ are the i^{th} observed and predicted conductance values, respectively; and $\bar{y}$ is the mean observed conductance. Equivalently, the NSE can be expressed in terms of the ratio between the root-mean-squared error (RMSE) of the model and the standard deviation (σ) of the data. NSE values may range from –∞ to 1. A value of NSE = 1 represents a perfect fit. A value of NSE = 0 indicates that the model predictions are as accurate as the mean of the observed data, and NSE values > 0 indicate that the model is a better predictor than the observed mean. For each model, the reported "Training NSE" value represents the model's fit to the data used to calibrate or *train* the model (in-sample data).

The primary objective of developing the logistic relationship between specific conductance and stream discharge data is to hindcast historical specific conductance values based on observed stream discharge values—a predictive endeavor. Therefore, it is important to estimate each logistic model's *out-of-sample error*, as an indication of the model's capability to predict data that were not used to calibrate the model. A *5-fold cross-validation* (CV) procedure was applied to estimate the out-of-sample NSE (**Equation 3**). The CV procedure involves splitting the observed dataset into five *folds* (or parts) of approximately equal length. The logistic model is then calibrated (logistic regression) using four of the five folds (80% of the data) and is used subsequently to predict the remaining 20% of the data (the *test set*). The procedure is performed five times so that each fold takes a turn as the test set. The reported out-of-sample NSE value ("Test NSE") for a location is the arithmetic mean of the five NSE values computed from prediction of the five folds. For acceptance of a logistic model for a given location, a minimum threshold of out-of-sample NSE ≥ 0.50 was adopted (Moriasi et al. 2007).

2.6. Baseflow Hindcasts

In addition to hindcasting historical conductance values C_{SF} based on observed streamflow discharge, the logistic model provides *top* and *bottom* parameters that may be considered as estimates of the baseflow conductance (C_{BF}) and runoff conductance (C_{RO}), respectively (**Figure 1**). Baseflow over the entire discharge period of record was hindcasted using the regressed logistic model's estimates for C_{SF}, C_{BF}, and C_{RO} and the associated discharge observations Q_{SF} (plugging values into **Equation 1**).

The reliability of each logistic/CMB baseflow hindcast was evaluated against benchmark baseflow estimates computed directly from the observed specific conductance (not estimated from logistic regression) and concurrent discharge values, using the CMB method (**Equation 1**). Each CMB benchmark baseflow estimate relied on C_{BF} and C_{RO} values derived from a visual assessment of the discharge-conductance scatterplot for each site (**Table 3**). Baseflow hindcasts were evaluated on the basis of the goodness of fit (NSE), exceedance curve plots, and estimated baseflow index (BFI). The BFI, calculated as total baseflow divided by total streamflow, is an estimate of the percentage of total streamflow attributable to baseflow over a given period. This evaluation enables a final verification as to whether estimated baseflow characteristics (patterns and relative contribution to streamflow) were consistent between the period of observed data (calibration period) and the period of the hindcasted data.

Table 3 - Runoff and Baseflow Conductance Values Adopted for Estimating CMB Benchmarks

Gage Location	C_{RO} (uS/cm)	C_{BF} (uS/cm)
Ellaville	50	350
Branford	50	350
Worthington	65	250
Fort White	80	400
Hildreth	50	400

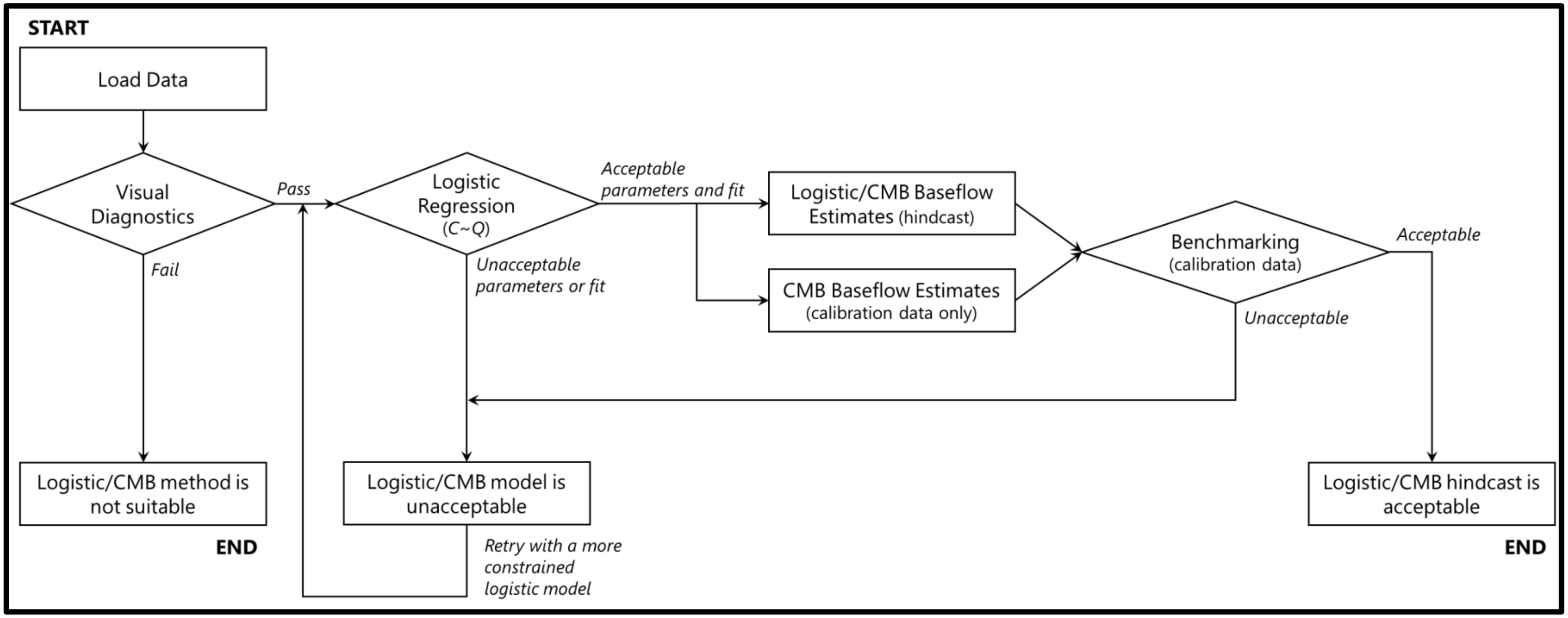
2.7. Logistic Regression / CMB Workflow

Figure 3 summarizes the framework for developing a logistic/CMB model and evaluating the reliability of the model and the associated baseflow hindcast.

The logistic/CMB method begins with visual diagnostics to screen gage locations whose available conductance and discharge data (calibration data) are not representative of the full discharge record or for which the calibration data do not show a logistic relationship. Calibration data that pass the diagnostic tests can be used to develop the logistic relationship between observed conductance and discharge. For each gage location, the first step is to attempt development of a fully unconstrained 5-parameter logistic model (*npars*=5). However, if the fully unconstrained model does not generate acceptable estimates for C_{BF} or C_{RO} (e.g. C_{RO}<0), or if the model does not achieve acceptable out-of-sample prediction skill (Test NSE > 0.50), more constrained models (i.e. *npars*=4, *npars*=3, and so on) are attempted until these screening criteria are met (see **Section 2.5**). Next, the least constrained logistic model that meets the screening criteria is selected to hindcast specific conductance values from the observed discharge data at the gage of interest. The hindcasted conductance values and observed discharge values are then applied to the CMB equation (**Equation 1**) to hindcast baseflow over the full discharge period of record. Finally, the hindcasted baseflow values are evaluated against the benchmark baseflow values computed directly from the CMB method (as described in **Section 2.6**).

Ultimately, a logistic/CMB baseflow hindcast may be considered acceptable if (1) diagnostic results are acceptable; (2) the CMB assumptions are met; (3) the logistic regression generates reasonable parameters and a good fit to out-of-sample data; and (4) the logistic/CMB baseflow hindcast acceptably corresponds to the CMB baseflow benchmark. An acceptable logistic/CMB baseflow hindcast should be reviewed for consistency with the relevant theory and knowledge of the site and associated basin and should also compared against baseflow estimates yielded by other methods (e.g. HYSEP).

Figure 3 - Workflow diagram for the development and evaluation of a logistic/CMB model and baseflow hindcast



3.0 BASEFLOW HINDCASTING RESULTS

Visual diagnostics indicated that application of the logistic/CMB method might be suitable for five of the six gage locations (all but Ichetucknee). For each of these five locations, the selected logistic model (highlighted in yellow) estimated reasonable C_{BF} and C_{RO} values and predicted out-of-sample data with acceptable skill (**Table 4**). Further, each selected model generated a baseflow hindcast that resembled the associated CMB baseflow benchmark, with some important discrepancies detailed in the following subsections; the model for Worthington performed particularly well. Full results from the selected logistic/CMB models and their associated hindcasts are provided below, and results from the rejected models are provided in **Attachment A**.

Table 4 - Summary of Logistic/CMB Results at Five Gage Locations
[Selected Logistic Models are Highlighted in Yellow]

Gage Location	*npars*	C_{RO} (uS/cm)	C_{BF} (uS/cm)	Test NSE	BFI (%)
Ellaville	5	-21	313	0.765	42.4
	4	43	361	0.761	24.7
Branford	5	-83	352	0.622	59.3
	4	80	382	0.619	32.7
	3	29	409	0.619	37.9
Worthington	5	-15	211	0.706	40.8
	4	50	229	0.704	16.5
Fort White	5	37	395	0.656	73.2
Hildreth	5	-66	390	0.646	89.2
	4	129	407	0.612	77.3
	3	43	416	0.610	80.3

3.1. Ellaville

Diagnostics indicated that the Ellaville gage location is a good candidate for the logistic/CMB method. The calibration data represent the 0^{th} through the 99.7^{th} percentile of discharge magnitudes, and their distribution is similar to the distribution of the full record (**Figure 4**). The discharge-conductance scatterplot exhibits a logistic form, but the vertical scatter apparent in the scatterplot strains the assumption of a 1:1 discharge-conductance relationship (**Figure 4**, *bottom right*).

Regression with the 5-parameter logistic model achieved good fits to both in-sample (NSE=0.797) and out-of-sample conductance data (NSE=0.765). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=313 uS/cm and C_{RO}=–21 uS/cm. The negative C_{RO} value rendered this model unreliable for hindcasting baseflow.

Regression with the 4-parameter logistic model achieved good fits to both in-sample (NSE=0.793) and out-of-sample conductance data (NSE=0.761). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=361 uS/cm and C_{RO}=43 uS/cm (**Figure 5**). The baseflow hindcast generated by the 4-parameter logistic/CMB model is shown in **Figure 6**.

The CMB method estimated a baseflow contribution of 24.9% based on the calibration data. Relative to the CMB benchmark, the logistic/CMB method resulted in a similar baseflow contribution (26.0%) during the calibration period but overestimated baseflow for the lowest 72% of discharge magnitudes and underestimated baseflow for the highest 28% of discharge magnitudes relative to the benchmark (**Figure 7**). The logistic/CMB hindcast estimated a long-term BFI of 24.7%.

The baseflow hindcast exhibits an upper limit such that baseflow does not exceed a maximum value (1822 cfs) for streamflow discharge magnitudes beyond 6390 cfs (**Figure 8**). This ceiling in the baseflow hydrograph (**Figure 6**) manifests as a plateau in the baseflow exceedance curve (**Figure 7**, *lower right*).

Figure 4 - Diagnostics for Ellaville. **Discharge time series (top left), percentile plot (top right), and density histograms (bottom left) for the full discharge record (gray) and calibration data (red). Bottom right: Discharge-conductance scatterplot on a single-log scale**

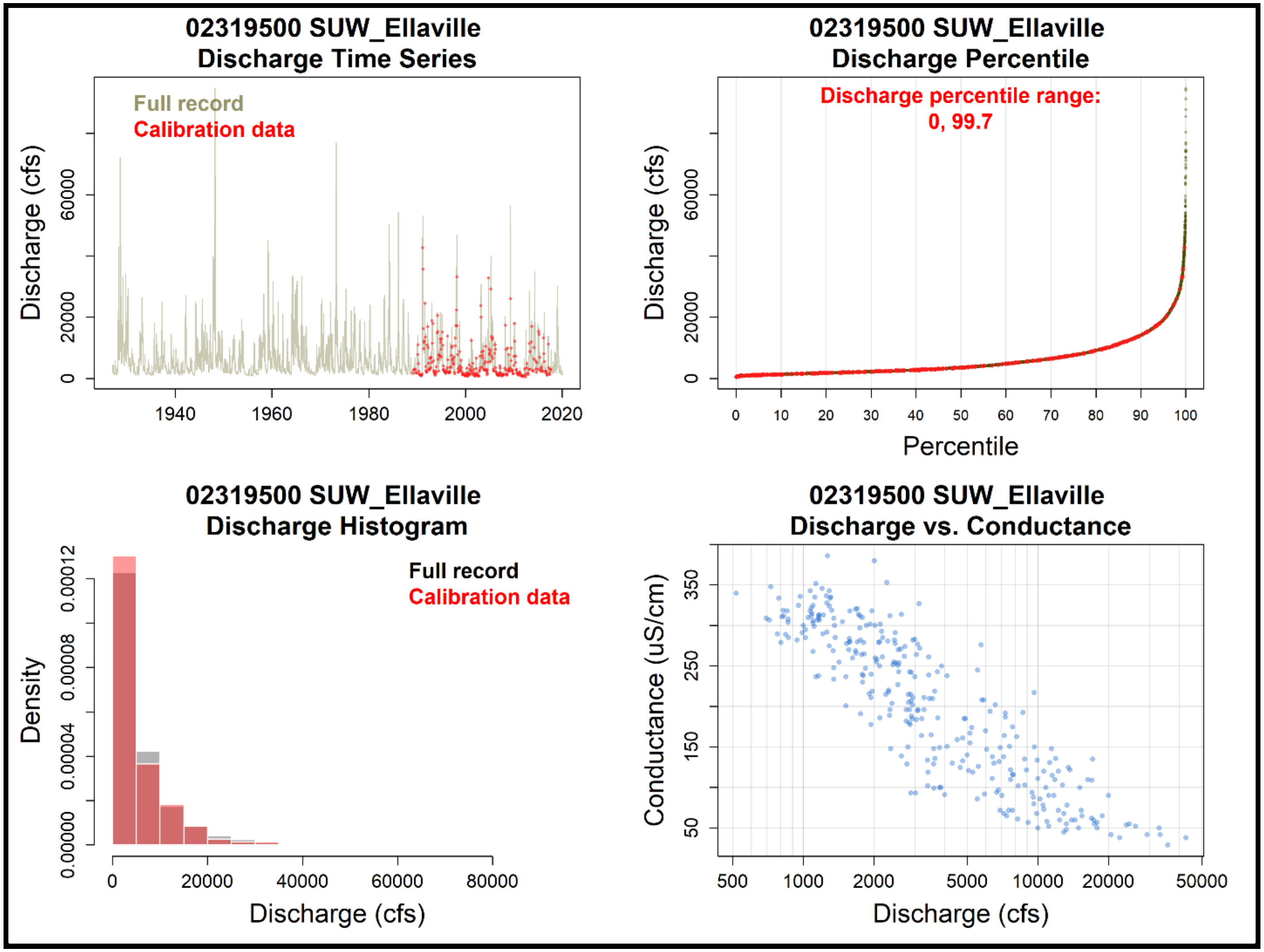


Figure 5 - Results of the 4-parameter logistic model for Ellaville. ***Top*****: The Logistic curve (red) provided a good fit to the data (blue) and Estimated reasonable top and bottom parameter values.** ***Bottom left*****: The model performed well on out-of-sample data.** ***Bottom right*****: Scatterplot of discharge and observed (black) and predicted (red) conductance values (linear scale)**

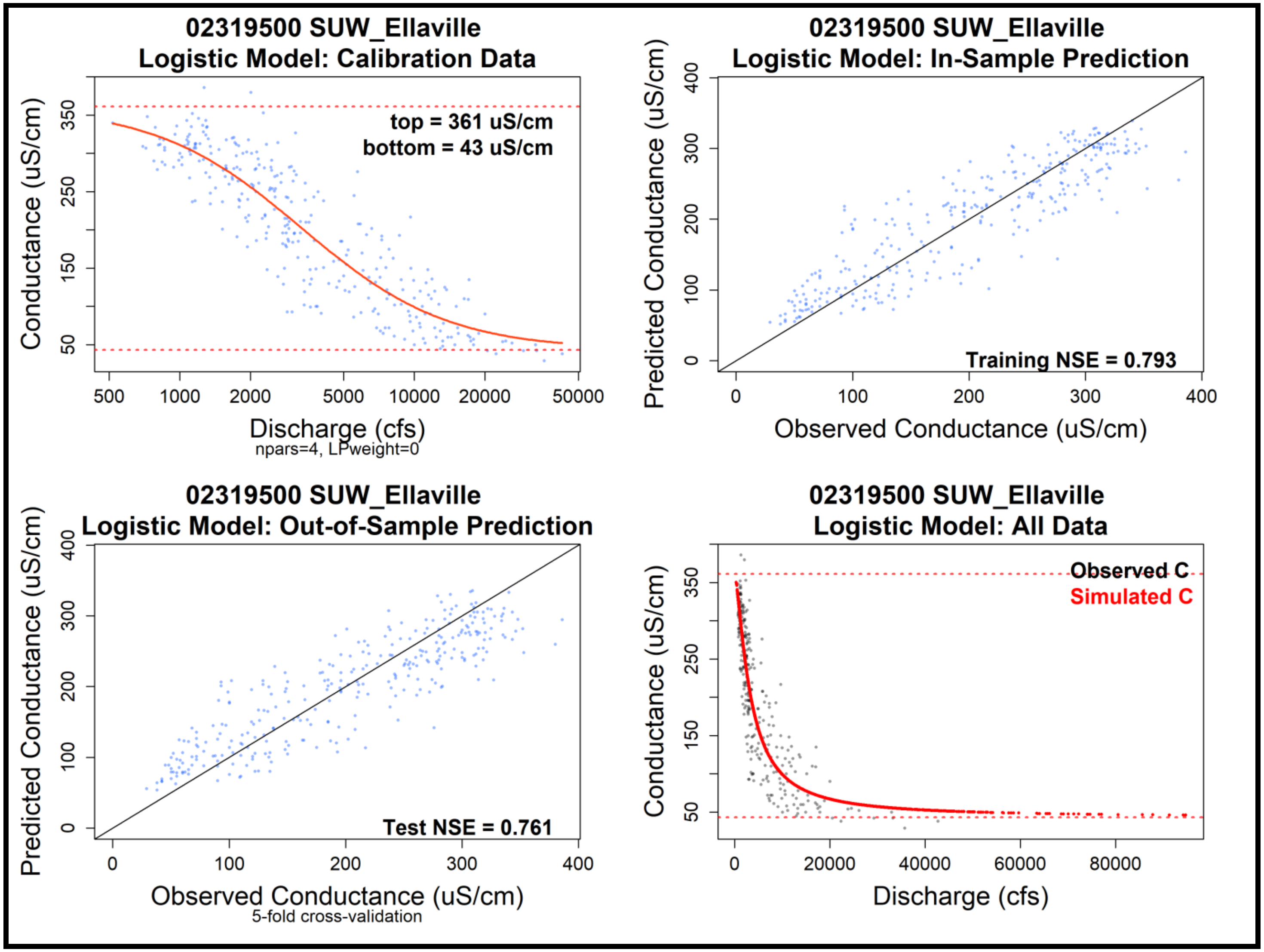


Figure 6 - Baseflow hindcast for Ellaville, based on the 4-parameter logistic model

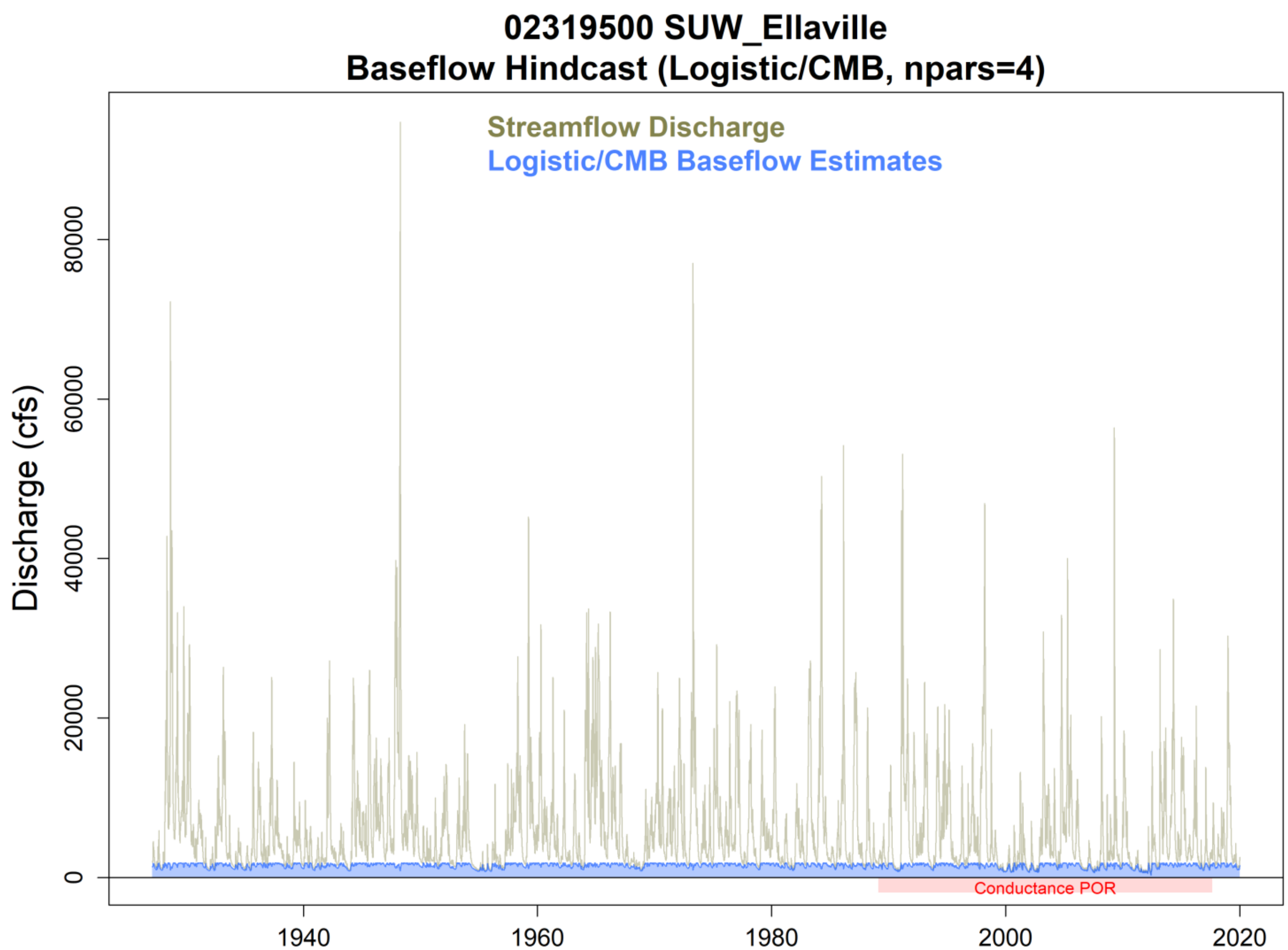


Figure 7 - Logistic/CMB baseflow hindcast (4-parameter model) against the CMB benchmark estimates for Ellaville. *Top left*: Baseflow estimates generated by the logistic/CMB (blue) and CMB benchmark (red) methods during the calibration period. *Top right*: Scatterplot of baseflow estimates generated by the two methods. *Bottom left*: Exceedance curves for baseflow estimates generated by the logistic/CMB (blue) and CMB (red) methods during the calibration period. *Bottom right*: Exceedance curve for the full baseflow hindcast generated by the logistic/CMB method

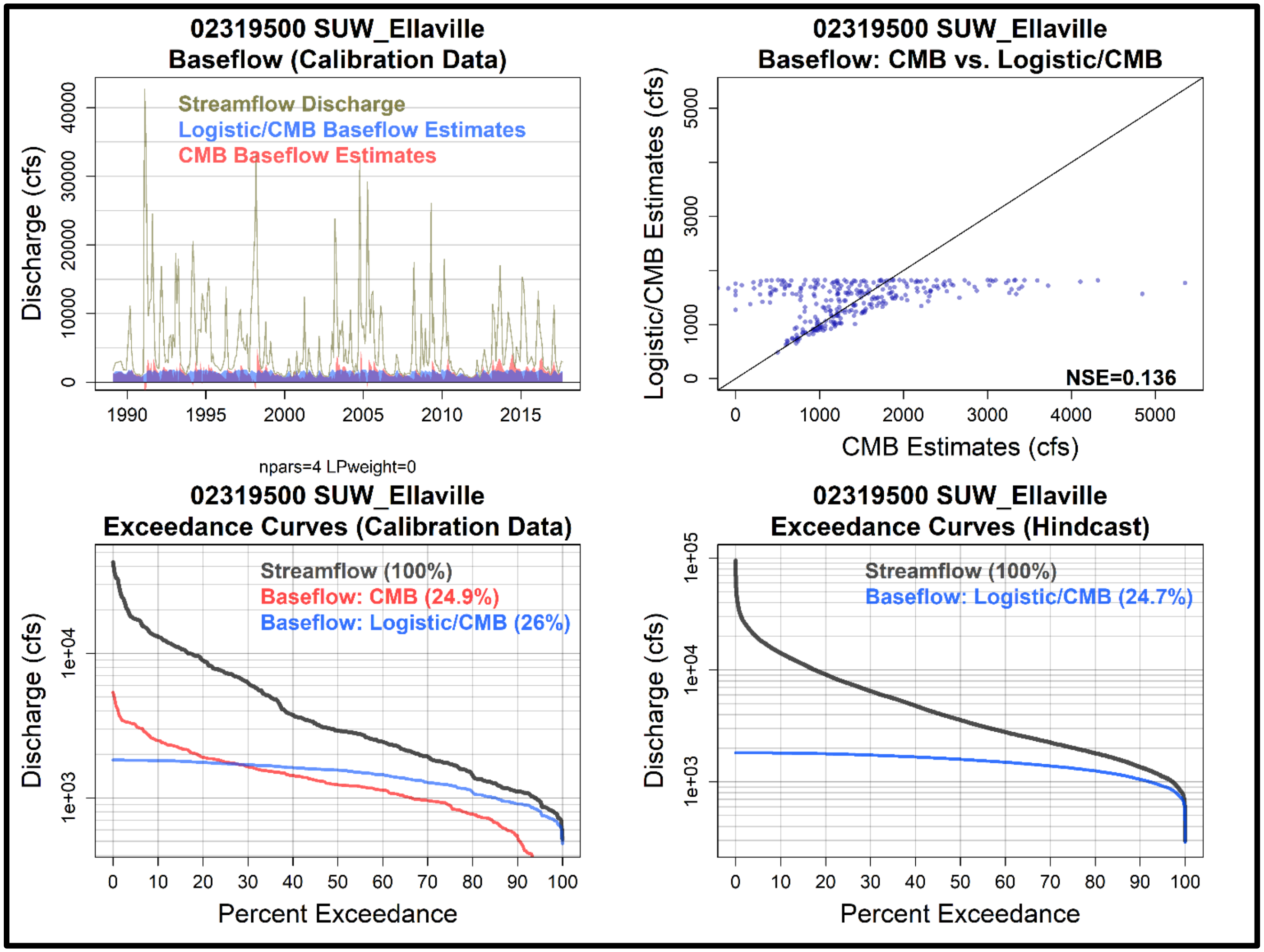
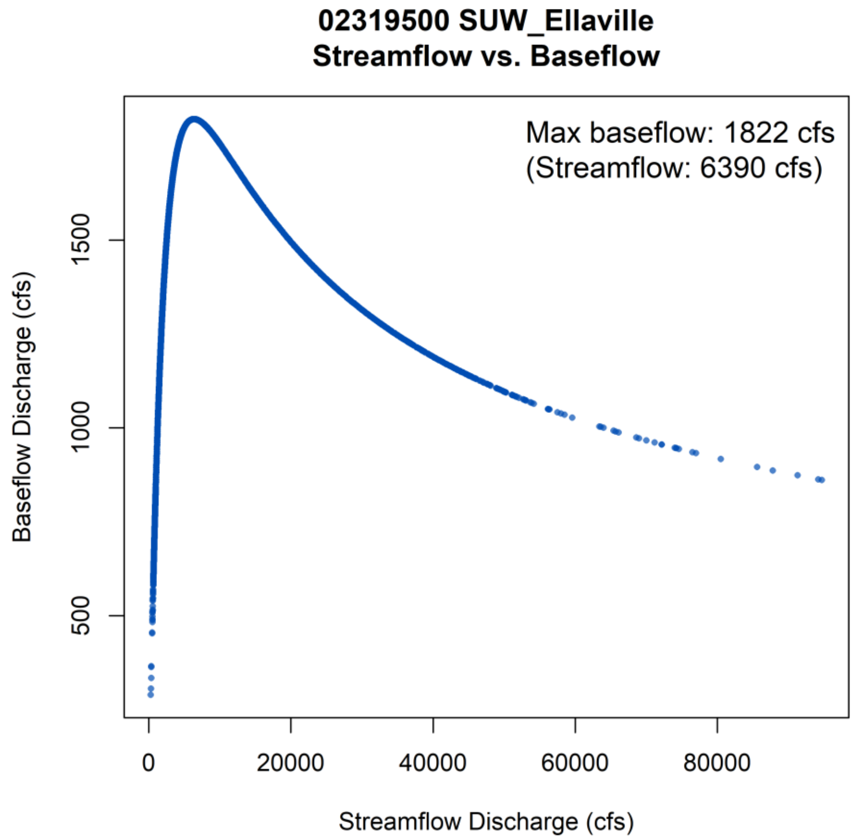


Figure 8 - Observed streamflow and hindcasted baseflow for Ellaville



3.2. Branford

Diagnostics indicated that the Branford gage location is a good candidate for the logistic/CMB method. The calibration data represent the 0.1th through the 99.6th percentile of discharge magnitudes, and their distribution is similar to the distribution of the full record (**Figure 9**). The discharge-conductance scatterplot exhibits a logistic form, but the vertical scatter apparent in the scatterplot strains the assumption of a 1:1 discharge-conductance relationship (**Figure 9**, *bottom right*).

Regression with the 5-parameter logistic model achieved good fits to both in-sample (NSE=0.702) and out-of-sample conductance data (NSE=0.622). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=352 uS/cm and C_{RO}=–83 uS/cm. The negative C_{RO} value rendered this model unreliable for hindcasting baseflow.

Regression with the 4-parameter logistic model achieved good fits to both in-sample (NSE=0.697) and out-of-sample conductance data (NSE=0.619). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=382 uS/cm and C_{RO}=80 uS/cm. The overestimated C_{RO} value rendered this model unreliable for hindcasting baseflow (see **Table 3**).

Regression with the 3-parameter logistic model achieved good fits to both in-sample (NSE=0.695) and out-of-sample conductance data (NSE=0.619). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=409 uS/cm and C_{RO}=29 uS/cm (**Figure 10**). The baseflow hindcast generated by the 3-parameter logistic/CMB model is shown in **Figure 11**.

The CMB method estimated a baseflow contribution of 54.6% based on the calibration data. Relative to the CMB benchmark, the 3-parameter logistic/CMB method resulted in a similar baseflow contribution (48.3%) during the calibration period. The logistic/CMB exceedance curve tracked the benchmark curve for most baseflow magnitudes but underestimated for the highest magnitudes and overestimated baseflow for the lowest magnitudes during the calibration period (**Figure 12**). The logistic/CMB hindcast estimated a long-term BFI of 37.9%.

The baseflow hindcast exhibits an upper limit such that baseflow does not exceed a maximum value (3105 cfs) for streamflow discharge magnitudes beyond 8030 cfs (**Figure 13**). This ceiling in the baseflow hydrograph (**Figure 11**) manifests as a plateau in the baseflow exceedance curve (**Figure 12**, *lower right*).

Figure 9 - Diagnostics for Branford. Discharge time series (*top left*), percentile plot (*top right*), and density histograms (*bottom left*) for the full discharge record (gray) and calibration data (red). *Bottom right*: Discharge-conductance scatterplot on a single-log scale

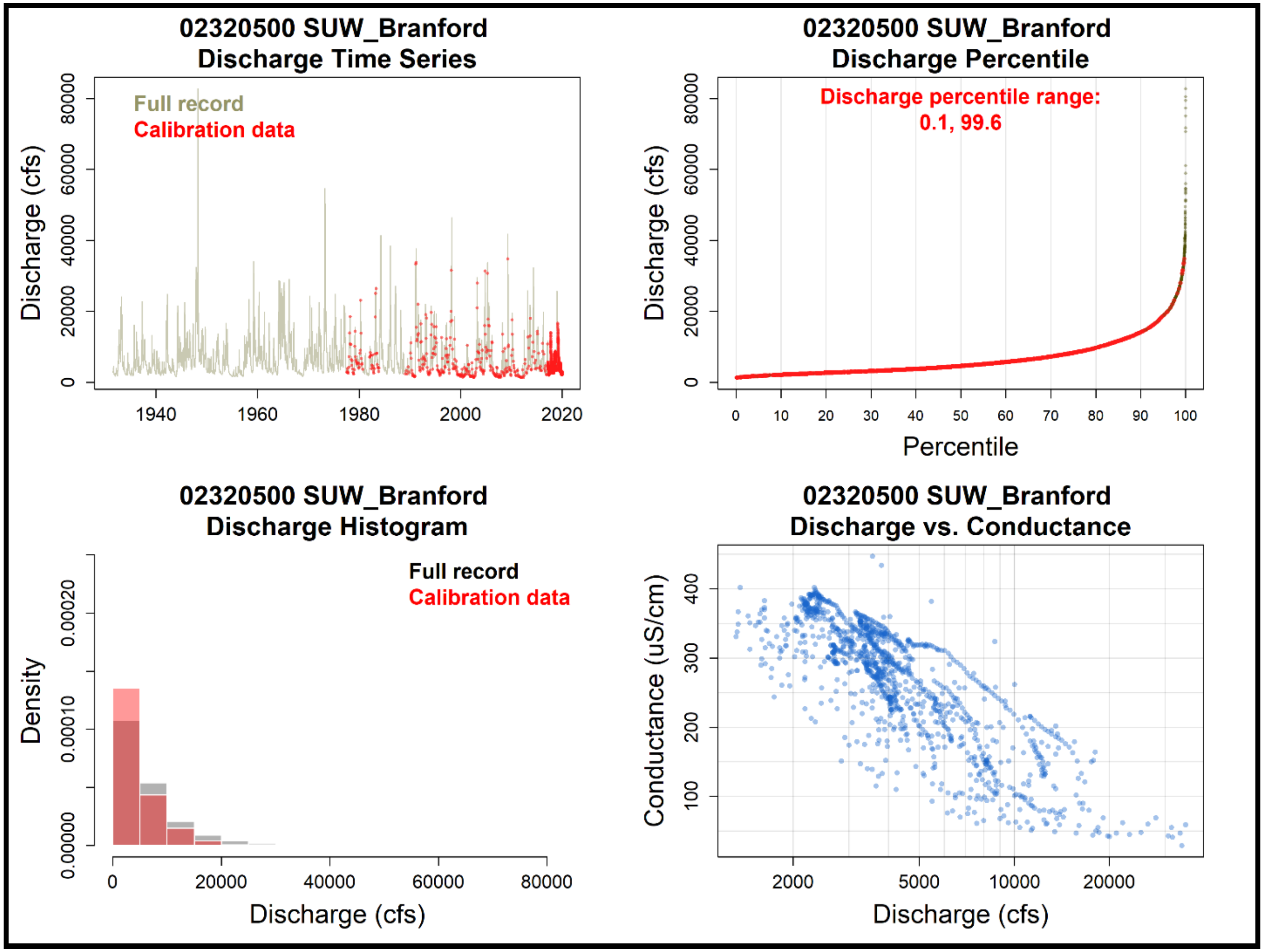


Figure 10 - Results of the 3-parameter logistic model for Branford. *Top*: The logistic curve (red) provided a good fit to the data (blue) and estimated reasonable top and bottom parameter values. *Bottom left*: The model performed well on out-of-sample data. *Bottom right*: Scatterplot of discharge and observed (black) and predicted (red) conductance values (linear scale).

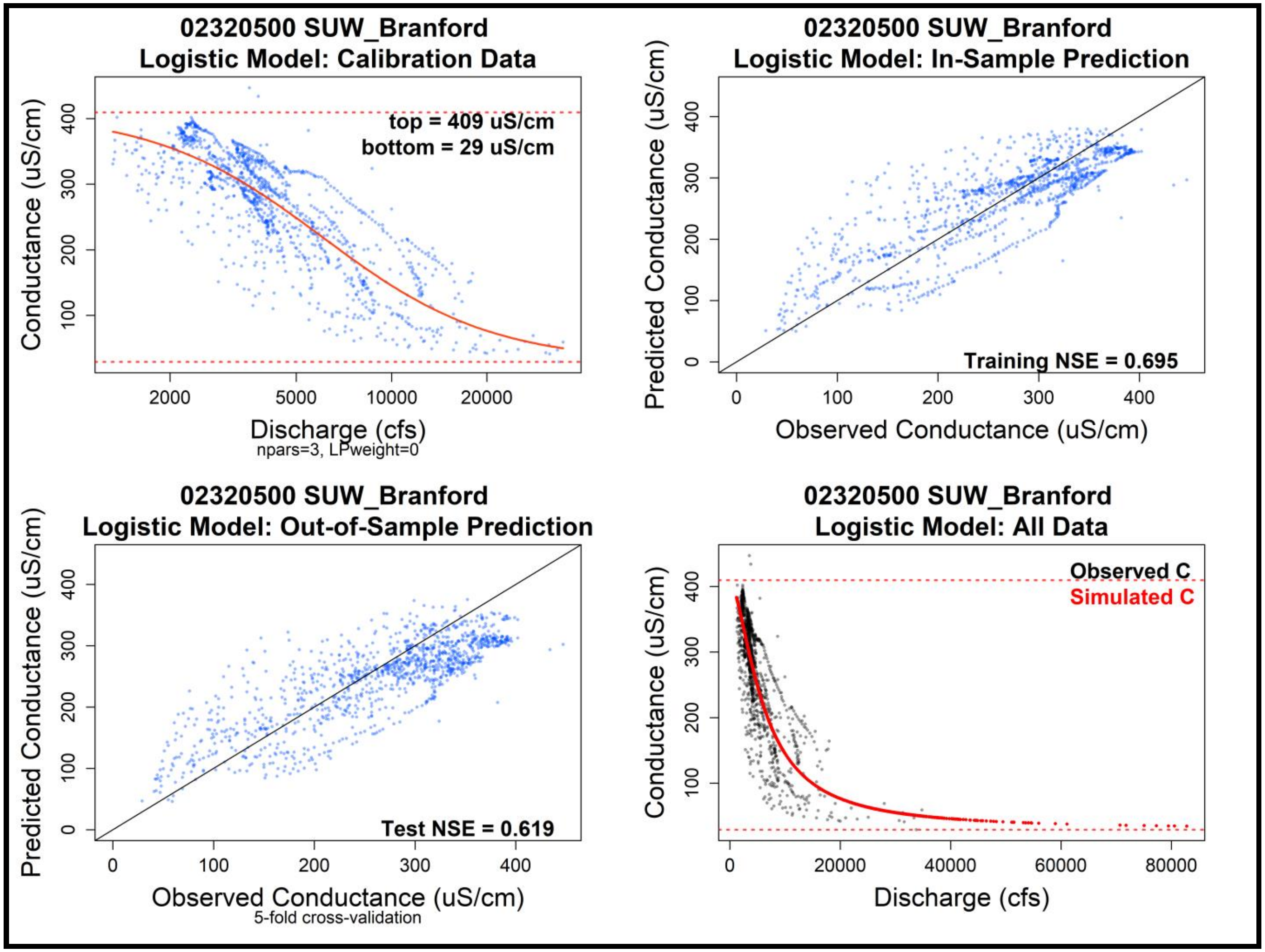


Figure 11 - Baseflow hindcast for Branford, based on the 3-parameter logistic model

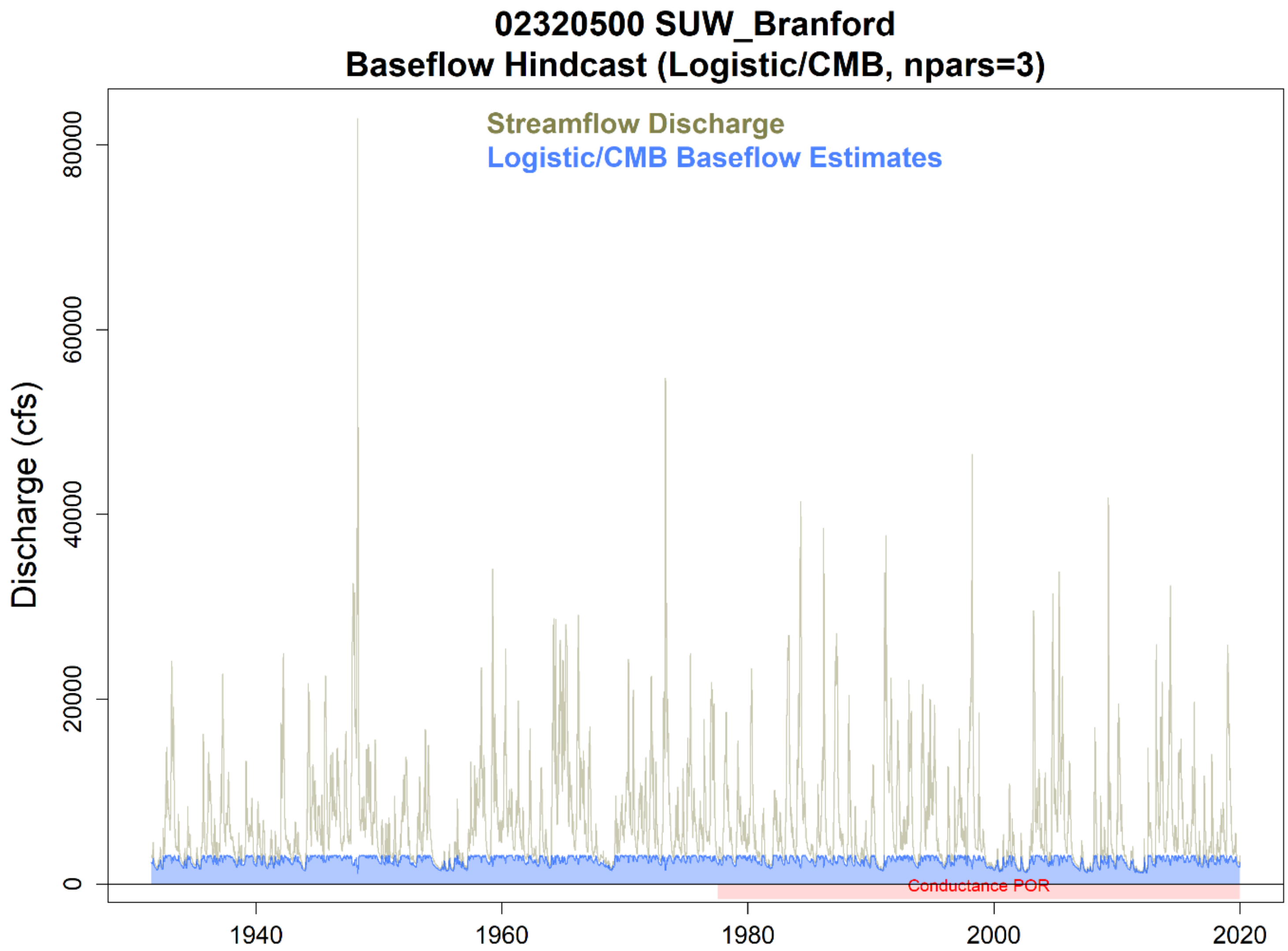


Figure 12 - Logistic/CMB baseflow hindcast (3-parameter model) against the CMB benchmark estimates for Branford. *Top left*: Baseflow estimates generated by the logistic/CMB (blue) and CMB benchmark (red) methods during the calibration period. *Top right*: Scatterplot of baseflow estimates generated by the two methods. *Bottom left*: Exceedance curves for baseflow estimates generated by the logistic/CMB (blue) and CMB (red) methods during the calibration period. *Bottom right*: Exceedance curve for the full baseflow hindcast generated by the logistic/CMB method.

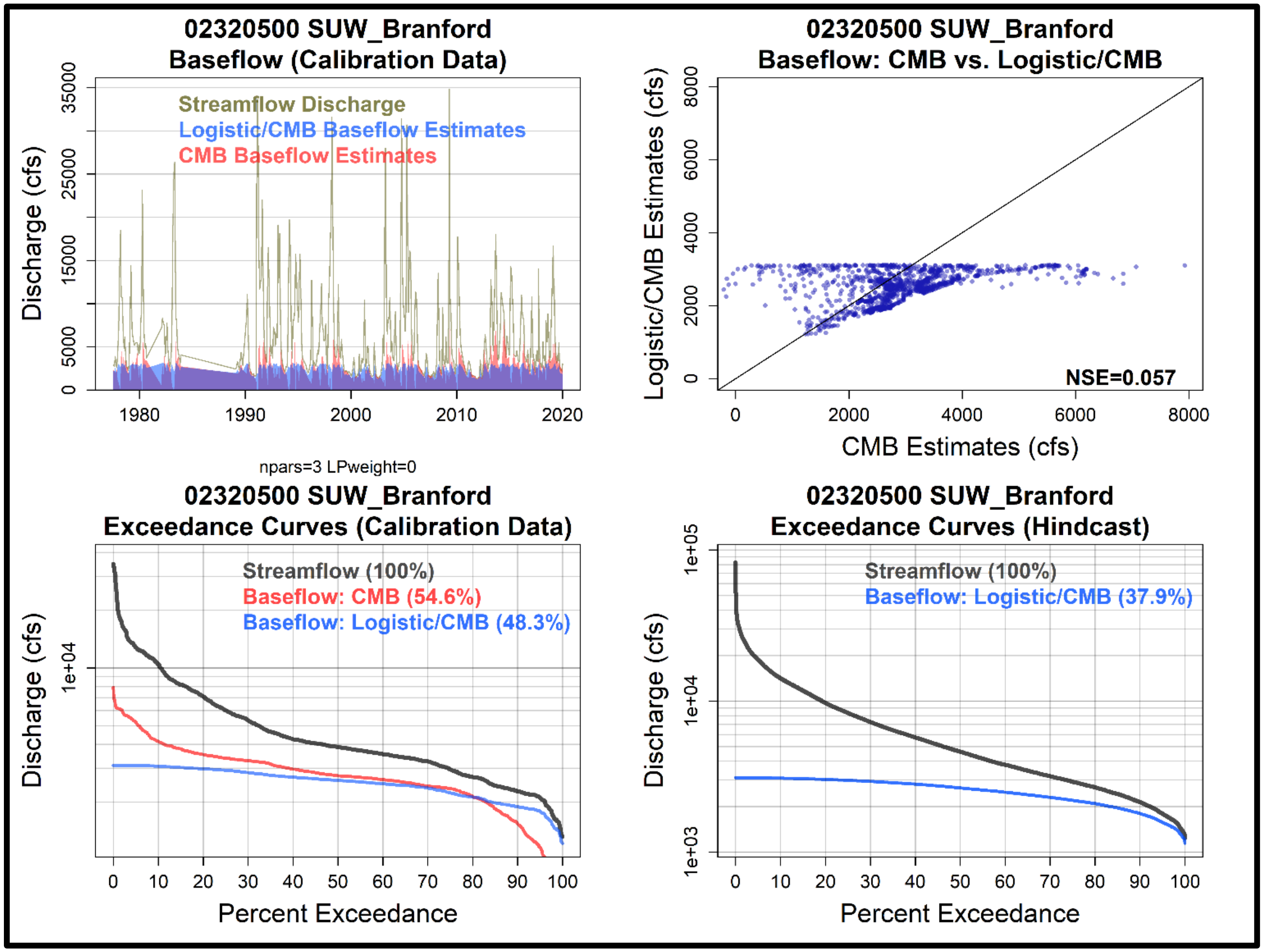
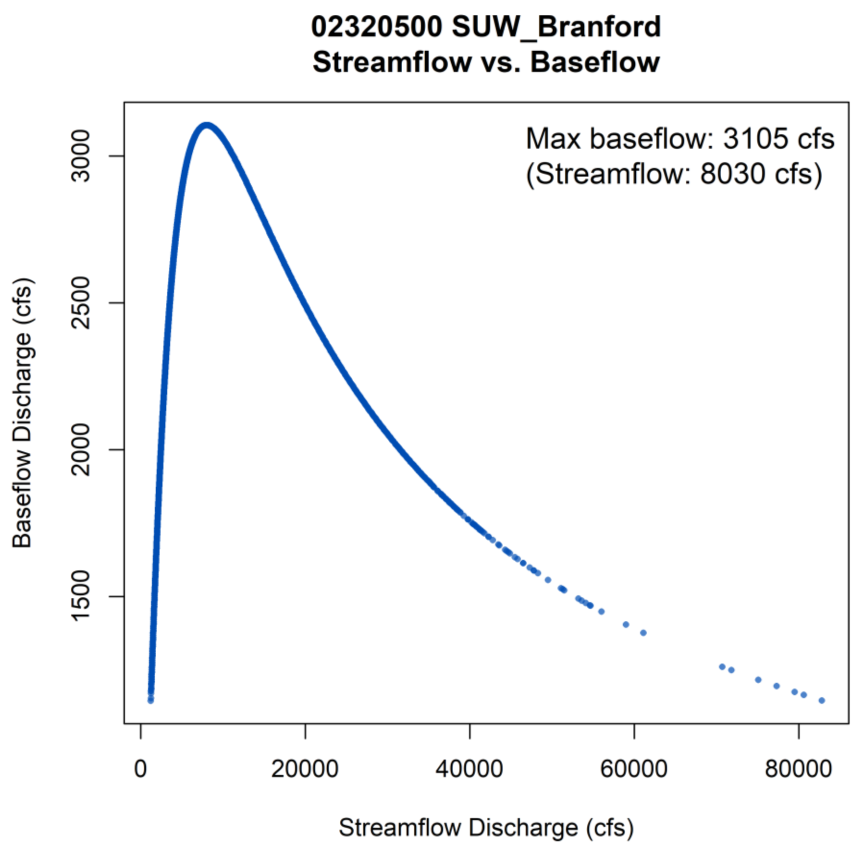


Figure 13 - Observed streamflow and hindcasted baseflow for Branford



3.3. Worthington

Diagnostics indicated that the Worthington gage location is a good candidate for the logistic/CMB method. The calibration data represent the 0^{th} through the 100^{th} percentile of discharge magnitudes, and their distribution is similar to the distribution of the full record (**Figure 14**). The discharge-conductance scatterplot exhibits a logistic form and approximates a 1:1 relationship with relatively minor vertical scatter (**Figure 14**, *bottom right*).

Regression with the 5-parameter logistic model achieved good fits to both in-sample (NSE=0.793) and out-of-sample conductance data (NSE=0.706). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=211 uS/cm and C_{RO}=–15 uS/cm. The negative C_{RO} value rendered this model unreliable for hindcasting baseflow.

Regression with the 4-parameter logistic model achieved good fits to both in-sample (NSE=0.790) and out-of-sample conductance data (NSE=0.704). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=229 uS/cm and C_{RO}=50 uS/cm (**Figure 15**). The baseflow hindcast generated by the 4-parameter logistic/CMB model is shown in **Figure 16**.

The CMB method estimated a baseflow contribution of 6.8% based on the calibration data. Relative to the CMB benchmark, the 4-parameter logistic/CMB method resulted in a greater baseflow contribution (17.0%) and a similarly shaped exceedance curve that overestimated all baseflows during the calibration period relative to the benchmark (**Figure 17**). The logistic/CMB hindcast estimated a long-term BFI of 16.5%.

In contrast to baseflow hindcasts for other sites, the Worthington hindcast did not exhibit an upper limit. The baseflow estimates increased monotonically with streamflow (**Figure 18**).

Figure 14 - Diagnostics for Worthington. Discharge time series (*top left*), percentile plot (*top right*), and density histograms (*bottom left*) for the full discharge record (gray) and calibration data (red). *Bottom right*: Discharge-conductance scatterplot on a single-log scale.

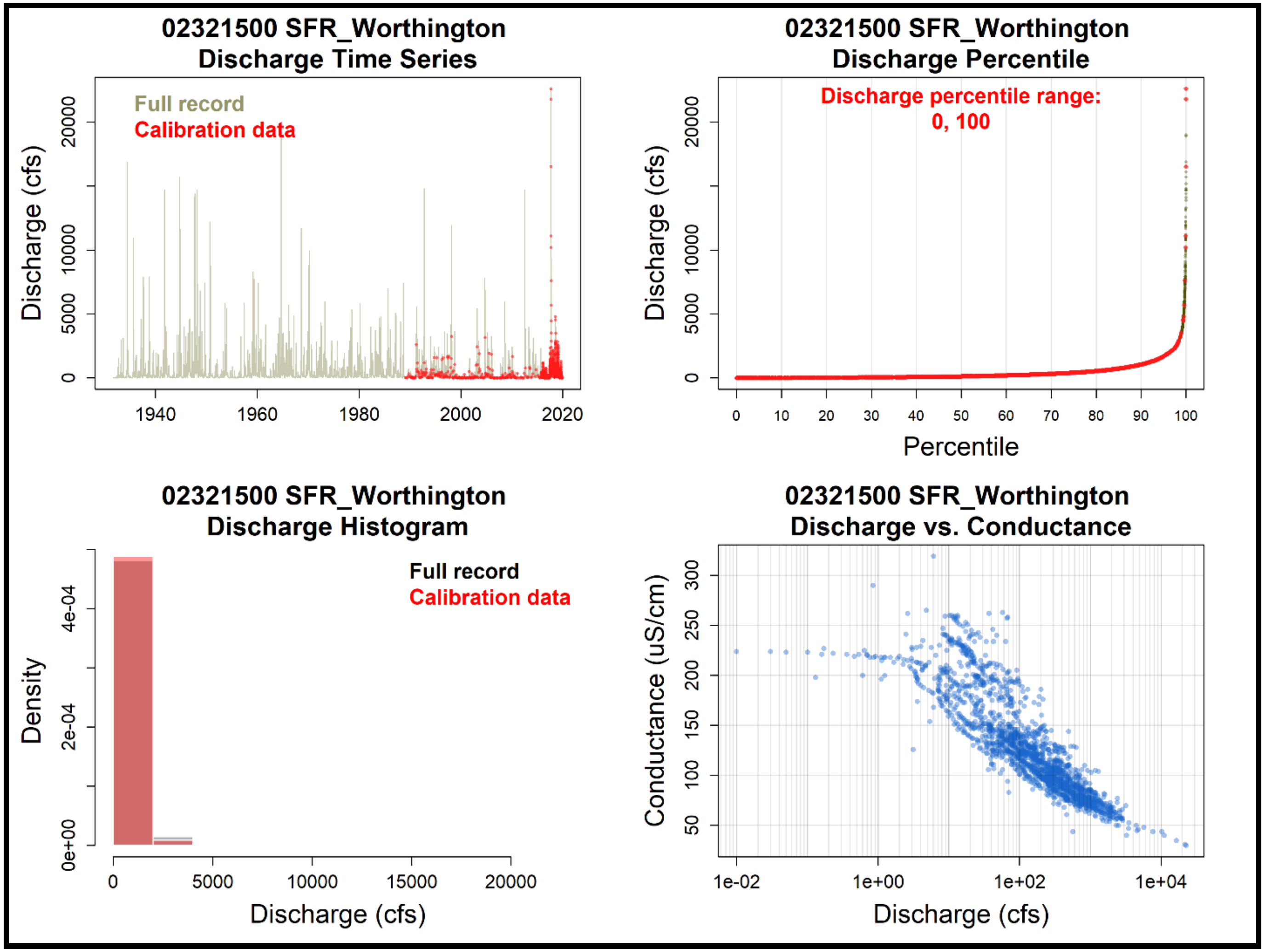


Figure 15 - Results of the 4-parameter logistic model for Worthington. Top: The logistic curve (red) provided a good fit to the data (blue) and estimated reasonable top and bottom parameter values. Bottom left: The model performed well on out-of-sample data. Bottom right: Scatterplot of discharge and observed (black) and predicted (red) conductance values (linear scale).

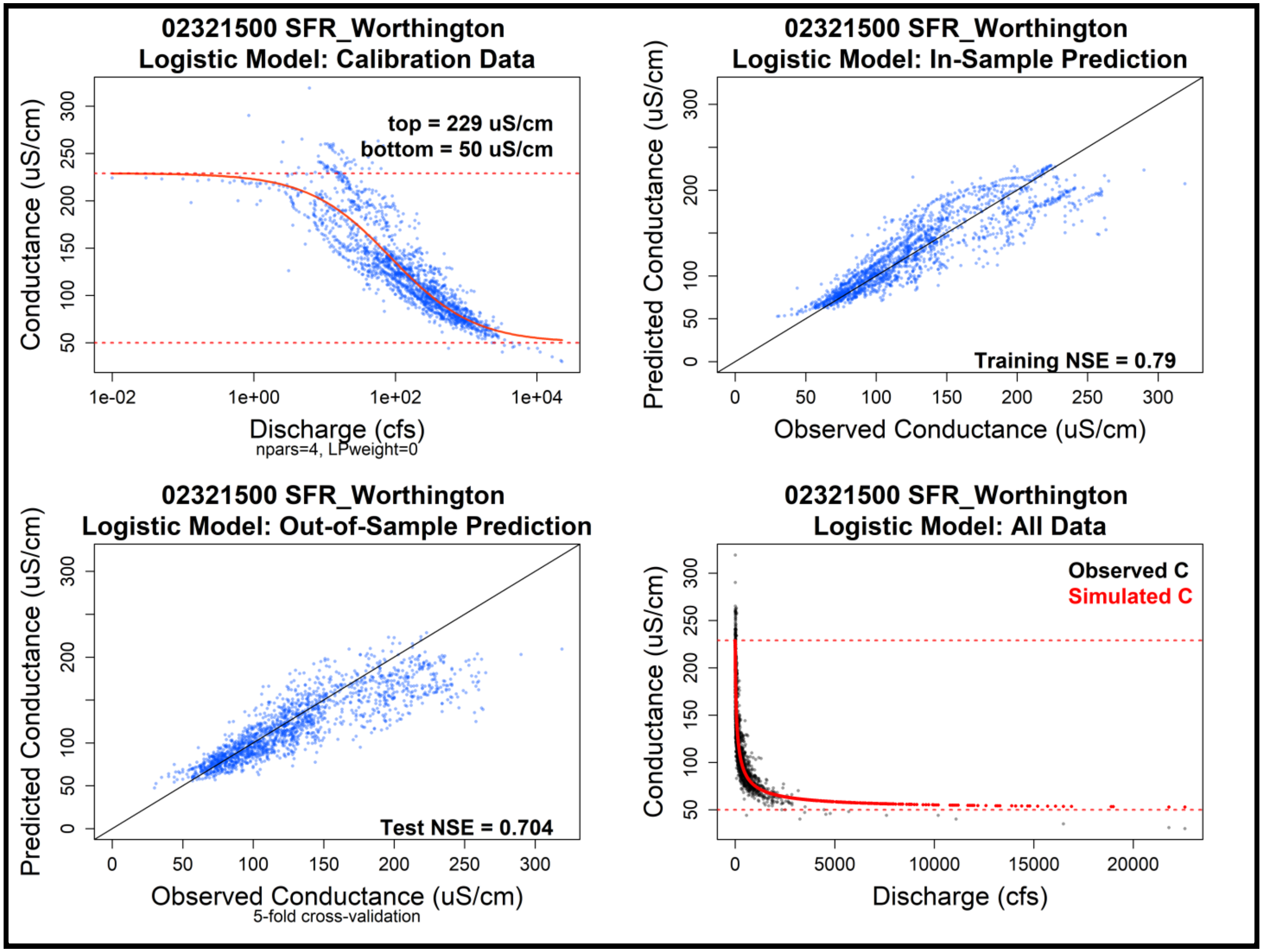


Figure 16 - Baseflow hindcast for Worthington, based on the 4-parameter logistic model

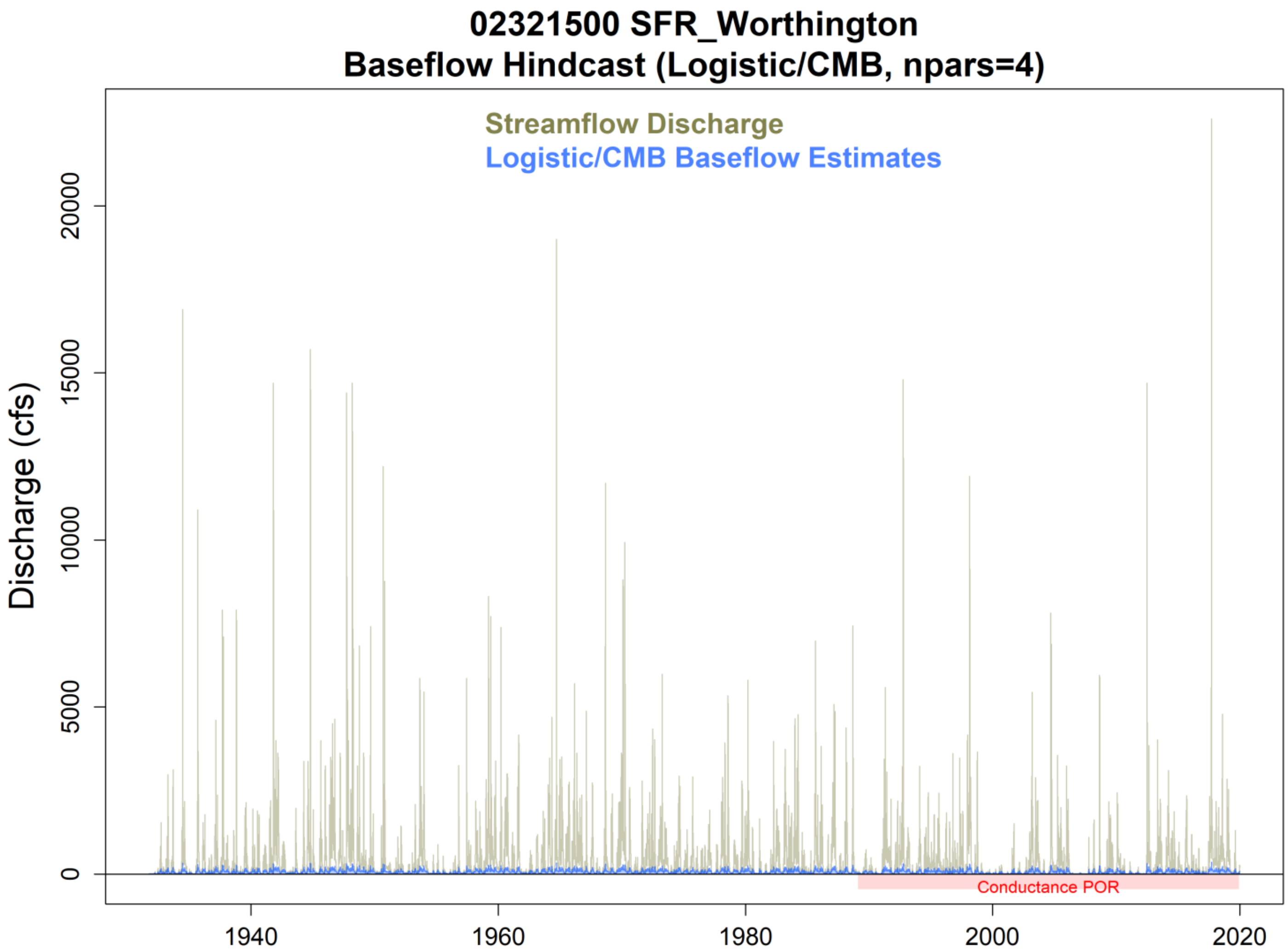


Figure 17 - Logistic/CMB baseflow hindcast (4-parameter model) against the CMB benchmark estimates for Worthington. *Top left*: Baseflow estimates generated by the logistic/CMB (blue) and CMB benchmark (red) methods during the calibration period. *Top right*: Scatterplot of baseflow estimates generated by the two methods. *Bottom left*: Exceedance curves for baseflow estimates generated by the logistic/CMB (blue) and CMB (red) methods during the calibration period. *Bottom right*: Exceedance curve for the full baseflow hindcast generated by the logistic/CMB method.

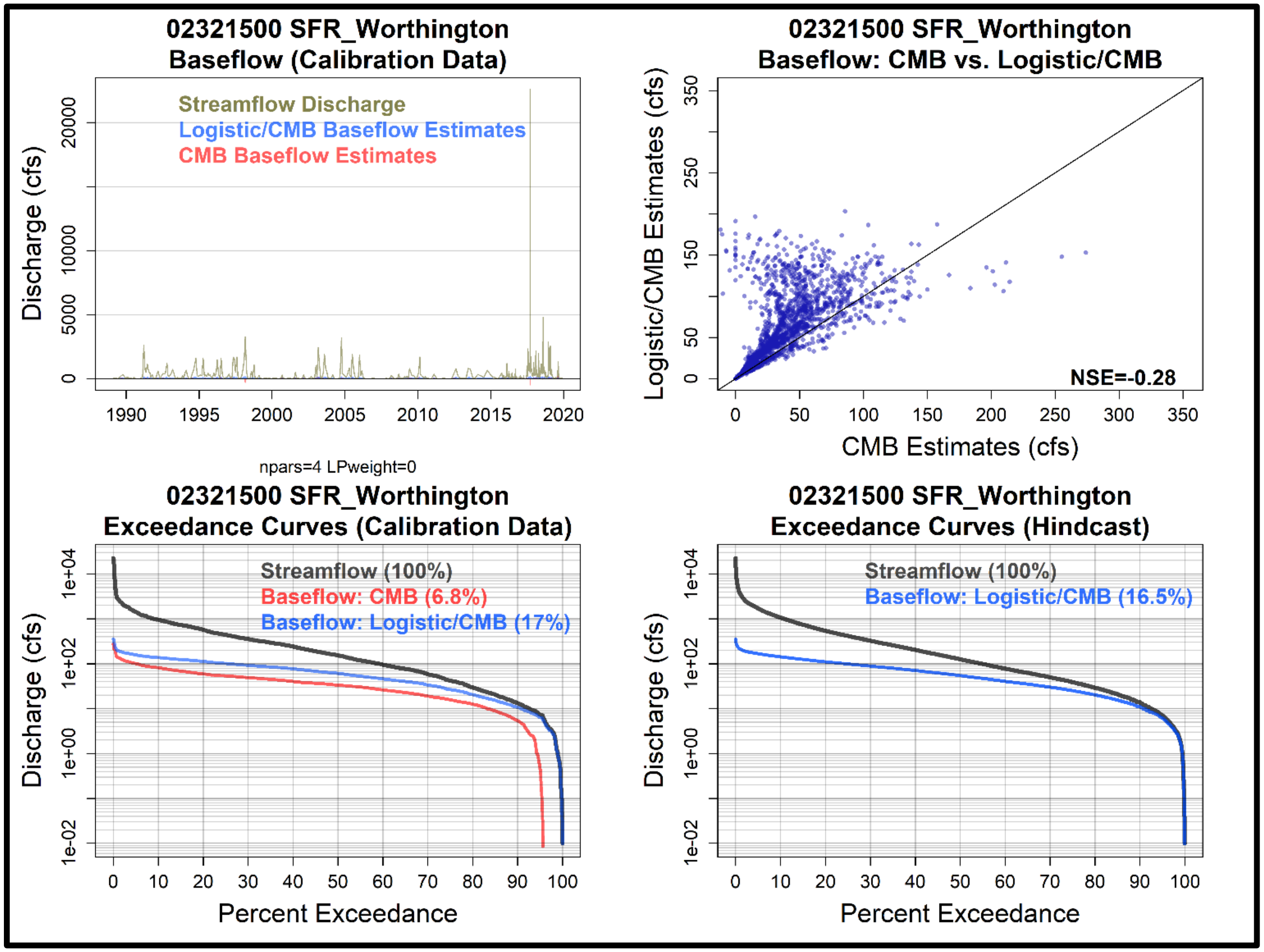
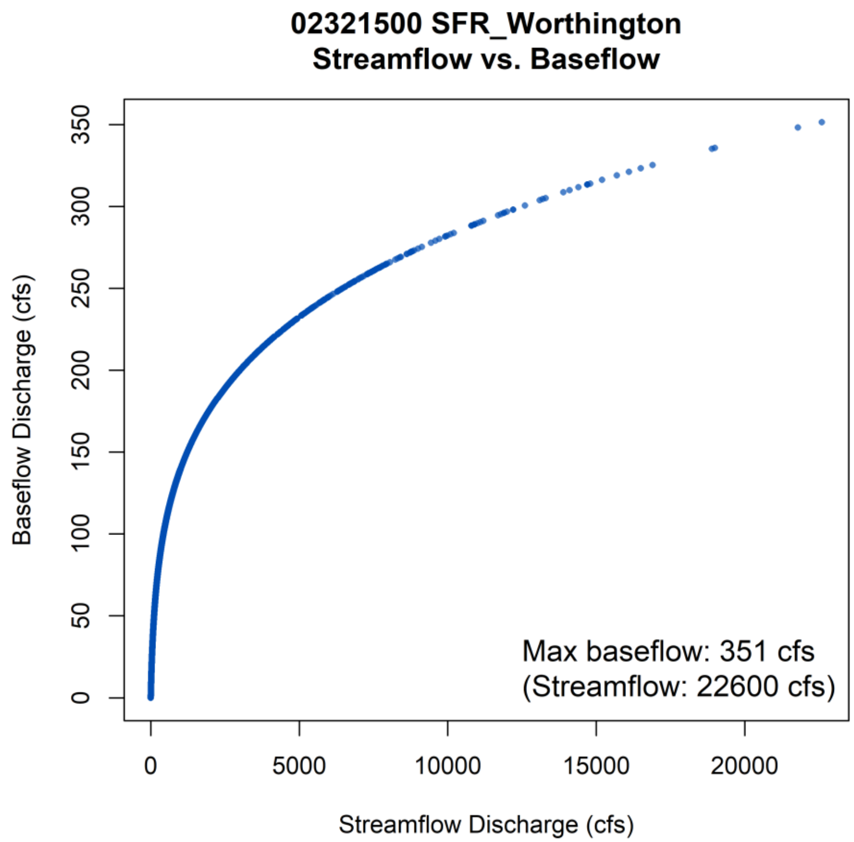


Figure 18 - Observed streamflow and hindcasted baseflow for Worthington



3.4. Fort White

Diagnostics indicated that the Fort White gage location is a good candidate for the logistic/CMB method. The calibration data represent the 0^{th} through the 100^{th} percentile of discharge magnitudes, and their distribution is similar to the distribution of the full record (**Figure 19**). The discharge-conductance scatterplot exhibits a logistic form, but the vertical scatter apparent in the scatterplot strains the assumption of a 1:1 discharge-conductance relationship (**Figure 19**, *bottom right*).

Regression with the 5-parameter logistic model achieved good fits to both in-sample (NSE=0.696) and out-of-sample conductance data (NSE=0.656). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=395 uS/cm and C_{RO}=37 uS/cm (**Figure 20**). The baseflow hindcast generated by the 4-parameter logistic/CMB model is shown in **Figure 21**.

The CMB method estimated a baseflow contribution of 73.0% based on the calibration data. Relative to the CMB benchmark, the 5-parameter logistic/CMB method resulted in a similar baseflow contribution (77.3%) during the calibration period but overestimated baseflow for the lowest 74% of discharge magnitudes and underestimated baseflow for the highest 26% of streamflow discharge magnitudes relative to the benchmark (**Figure 22**). The logistic/CMB hindcast estimated a long-term BFI of 73.2%.

The baseflow hindcast exhibits an upper limit such that baseflow does not exceed a maximum value (1259 cfs) for streamflow discharge magnitudes beyond 1410 cfs (**Figure 23**). This ceiling in the baseflow hydrograph (**Figure 21**) manifests as a plateau in the baseflow exceedance curve (**Figure 22**, *lower right*).

Figure 19 - Diagnostics for Fort White. Discharge time series (*top left*), percentile plot (*top right*), and density histograms (*bottom left*) for the full discharge record (gray) and calibration data (red). *Bottom right*: Discharge-conductance scatterplot on a single-log scale.

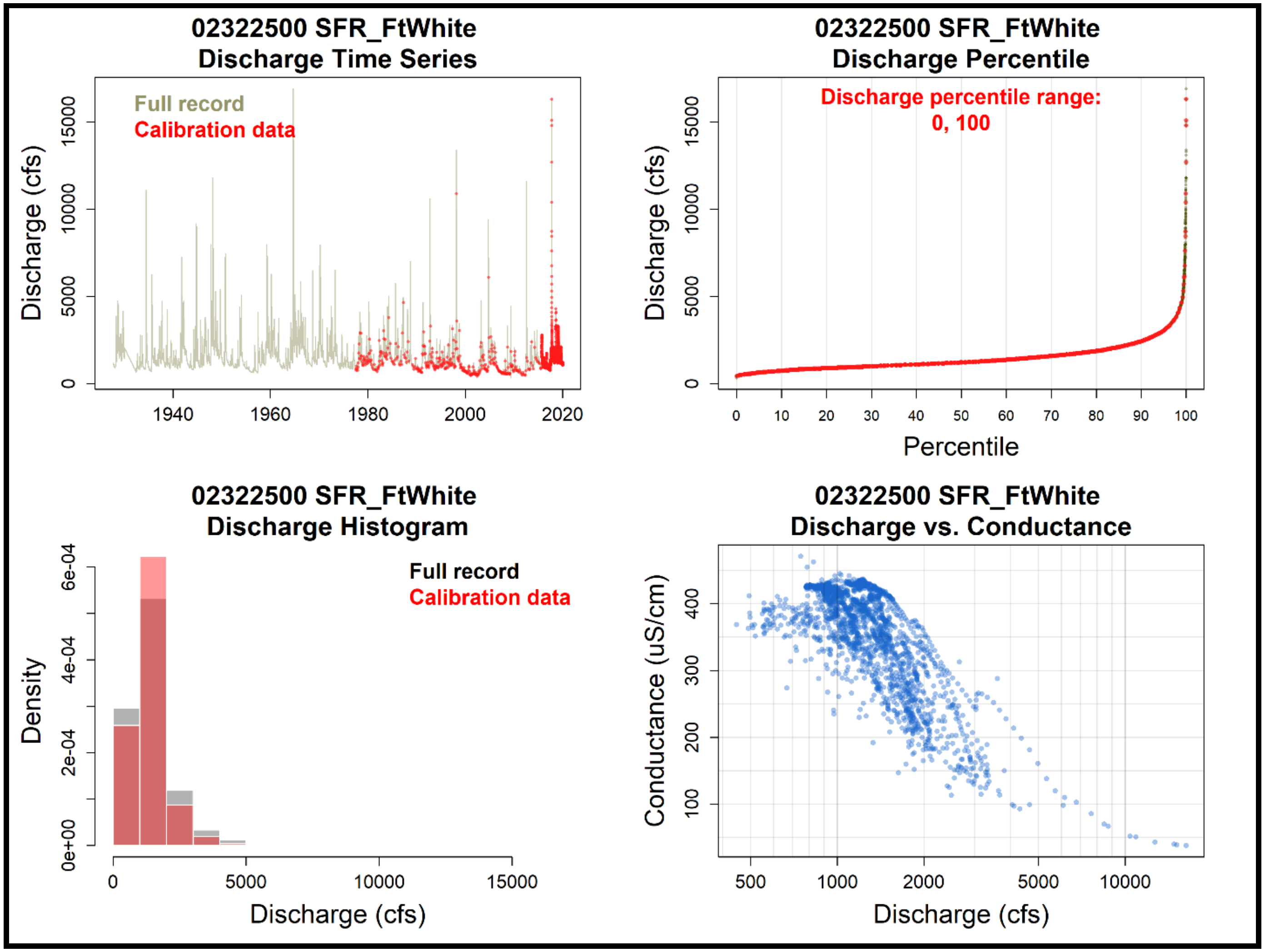


Figure 20 - Results of the 5-parameter logistic model for Fort White. *Top*: The logistic curve (red) provided a good fit to the data (blue), estimated a reasonable bottom parameter, and somewhat overestimated the top parameter. *Bottom left*: The model performed well on out-of-sample data. *Bottom right*: Scatterplot of discharge and observed (black) and predicted (red) conductance values (linear scale).

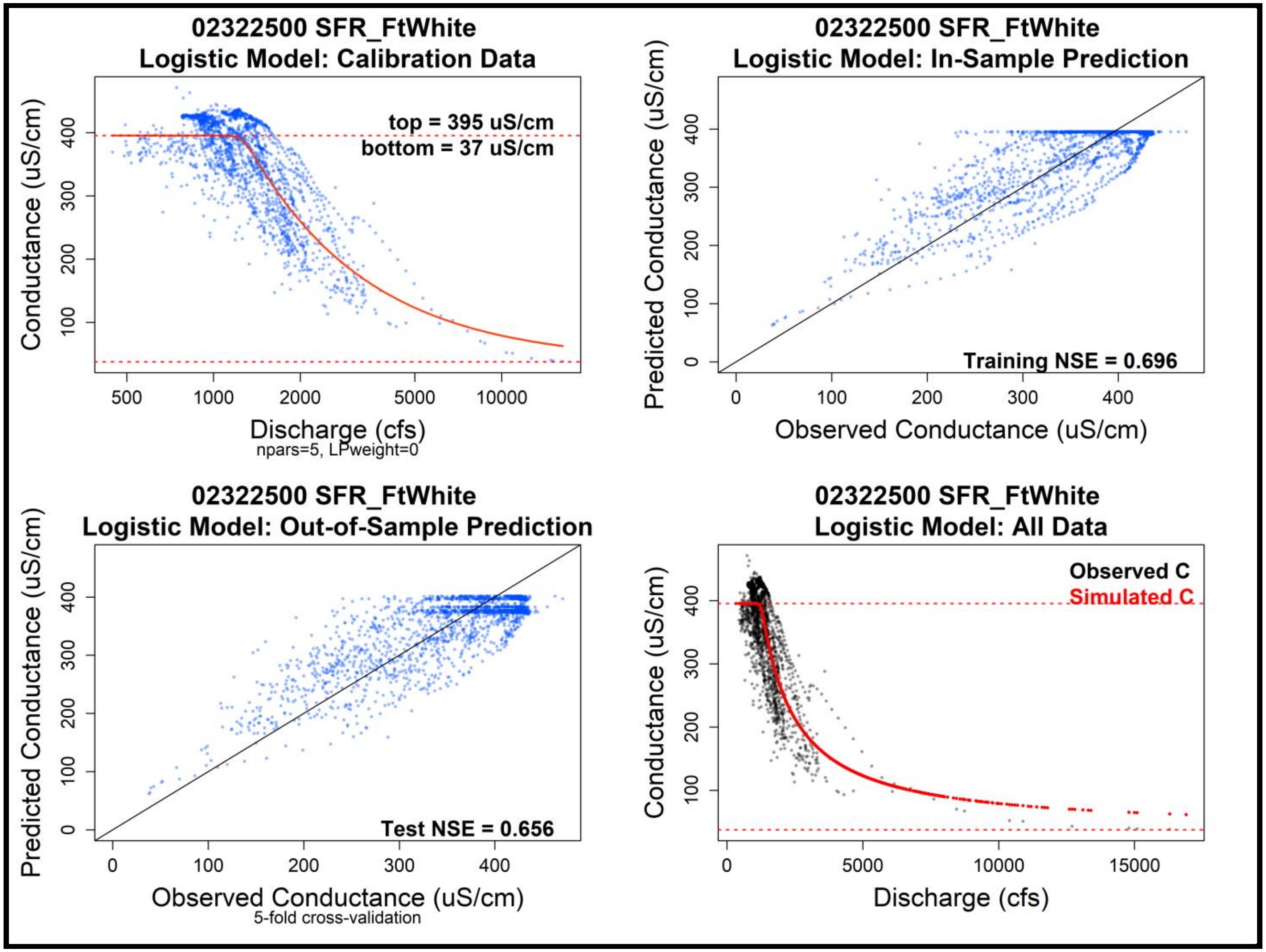


Figure 21 - Baseflow hindcast for Fort White, based on the 5-parameter logistic model

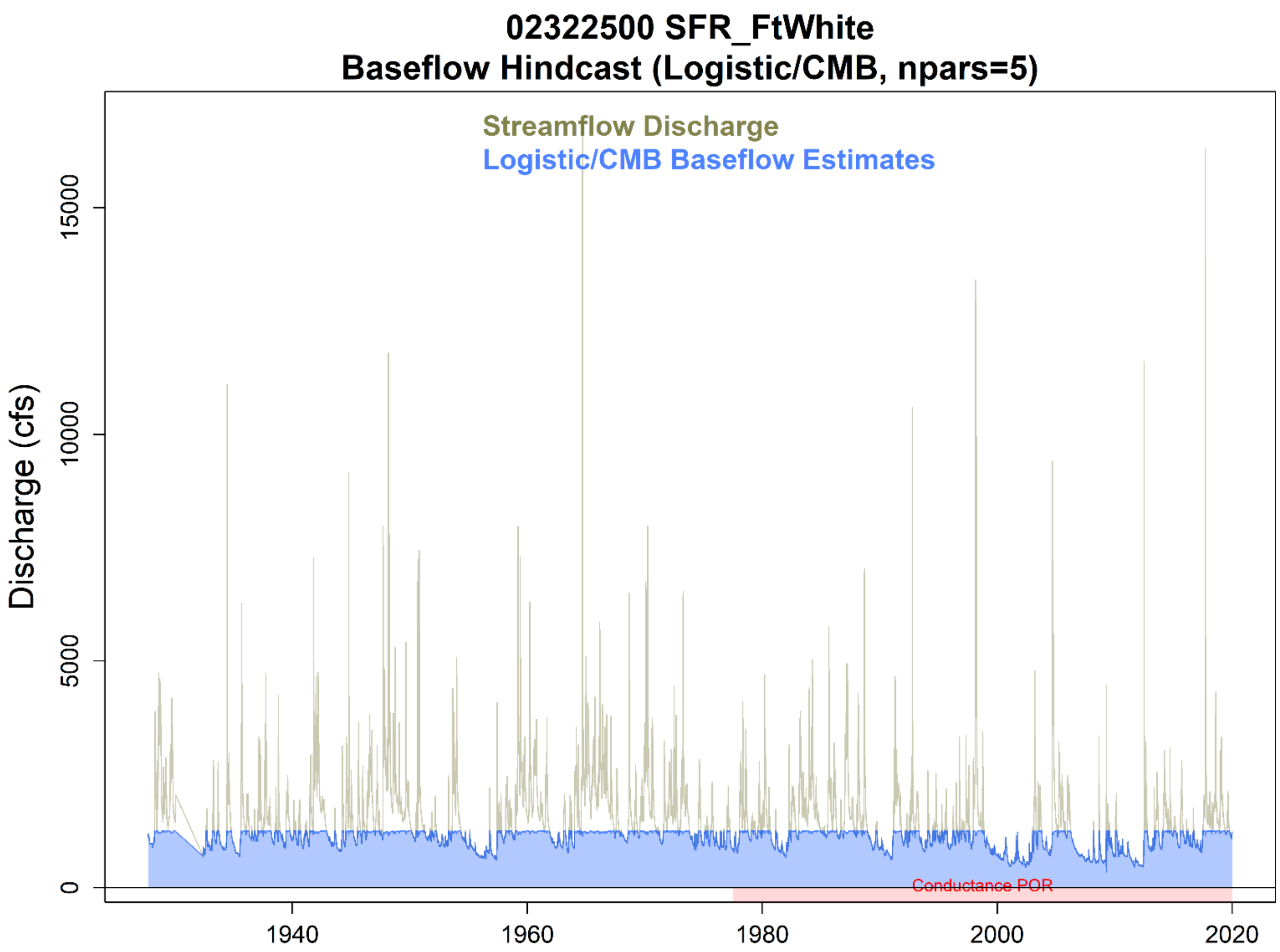


Figure 22 - Logistic/CMB baseflow hindcast (5-parameter model) against the CMB benchmark estimates for Fort White. *Top left*: Baseflow estimates generated by the logistic/CMB (blue) and CMB benchmark (red) methods during the calibration period. *Top right*: Scatterplot of baseflow estimates generated by the two methods. *Bottom left*: Exceedance curves for baseflow estimates generated by the logistic/CMB (blue) and CMB (red) methods during the calibration period. *Bottom right*: Exceedance curve for the full baseflow hindcast generated by the logistic/CMB method.

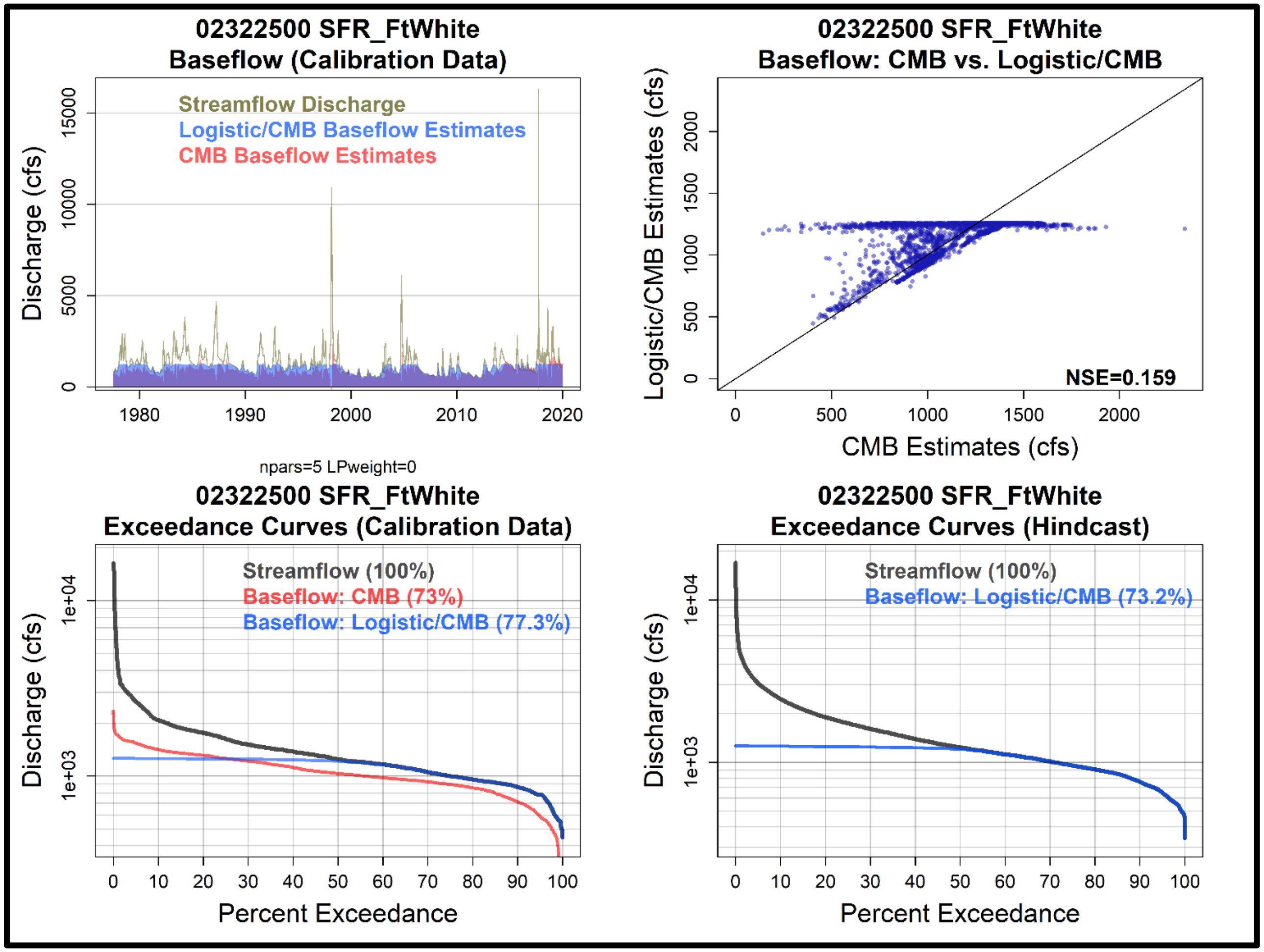
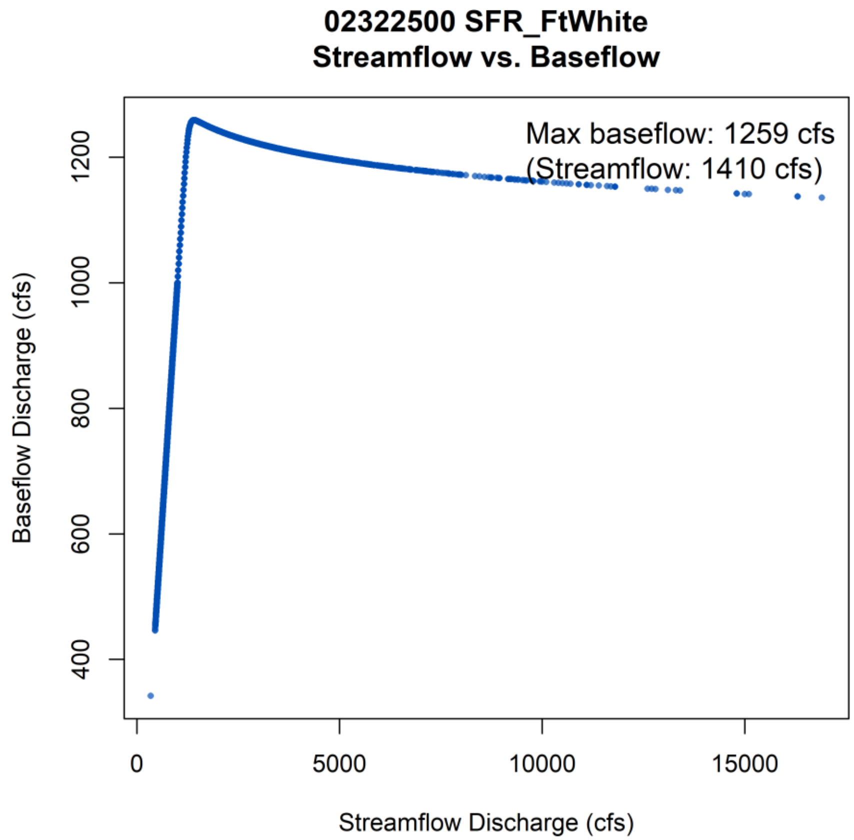


Figure 23 - Observed streamflow and hindcasted baseflow for Fort White



3.5. Hildreth

Diagnostics indicated that the Hildreth gage location is a good candidate for the logistic/CMB method. The calibration data represent the 0.4th through the 100th percentile of discharge magnitudes, and their distribution is similar to the distribution of the full record (**Figure 24**). The discharge-conductance scatterplot exhibits a logistic form, but the vertical scatter apparent in the scatterplot strains the assumption of a 1:1 discharge-conductance relationship (**Figure 24**, *bottom right*).

Regression with the 5-parameter logistic model achieved good fits to both in-sample (NSE=0.666) and out-of-sample conductance data (NSE=0.646). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=390 uS/cm and C_{RO}=–66 uS/cm. The negative C_{RO} value rendered this model unreliable for hindcasting baseflow.

Regression with the 4-parameter logistic model achieved good fits to both in-sample (NSE=0.632) and out-of-sample conductance data (NSE=0.612). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=407 uS/cm and C_{RO}=129 uS/cm. The overestimated C_{RO} value rendered this model unreliable for hindcasting baseflow.

Regression with the 3-parameter logistic model achieved good fits to both in-sample (NSE=0.626) and out-of-sample conductance data (NSE=0.610). Based on the regression's *top* and *bottom* parameters, streamflow conductance bounds were estimated at C_{BF}=416 uS/cm and C_{RO}=43 uS/cm (**Figure 25**). The baseflow hindcast generated by the 3-parameter logistic/CMB model is shown in **Figure 26**.

The CMB method estimated a baseflow contribution of 79.8% based on the calibration data. Relative to the CMB benchmark, the 3-parameter logistic/CMB method resulted in a similar baseflow contribution (76.4%). The logistic/CMB exceedance curve closely tracked the benchmark exceedance curve for most discharge magnitudes but underestimated baseflow for the highest 10% of discharge magnitudes during the calibration period relative to the benchmark (**Figure 27**). The logistic/CMB hindcast estimated a long-term BFI of 80.3%.

The baseflow hindcast exhibits an upper limit such that baseflow does not exceed a maximum value (1842 cfs) for streamflow discharge magnitudes beyond 2770 cfs (**Figure 28**). This ceiling in the baseflow hydrograph (**Figure 26**) manifests as a plateau in the baseflow exceedance curve (**Figure 27**, *lower right*).

Figure 24 - Diagnostics for Hildreth. Discharge time series (*top left*), percentile plot (*top right*), and density histograms (*bottom left*) for the full discharge record (gray) and calibration data (red). *Bottom right*: Discharge-conductance scatterplot on a single-log scale.

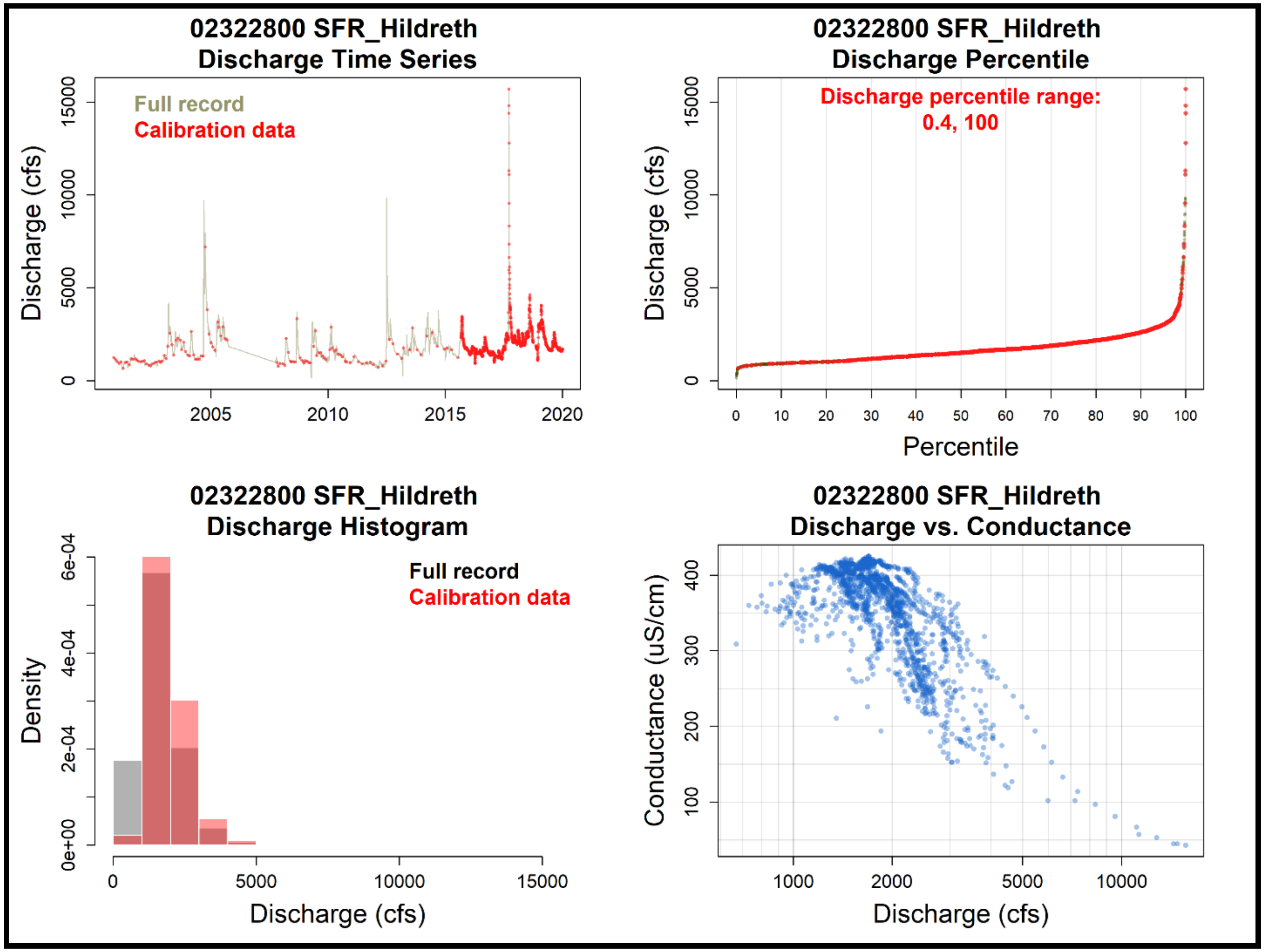


Figure 25 - Results of the 3-parameter logistic model for Hildreth. Top: The logistic curve (red) provided a good fit to the data (blue), estimated reasonable top and bottom parameter values. Bottom left: The model performed well on out-of-sample data. Bottom right: Scatterplot of discharge and observed (black) and predicted (red) conductance values (linear scale).

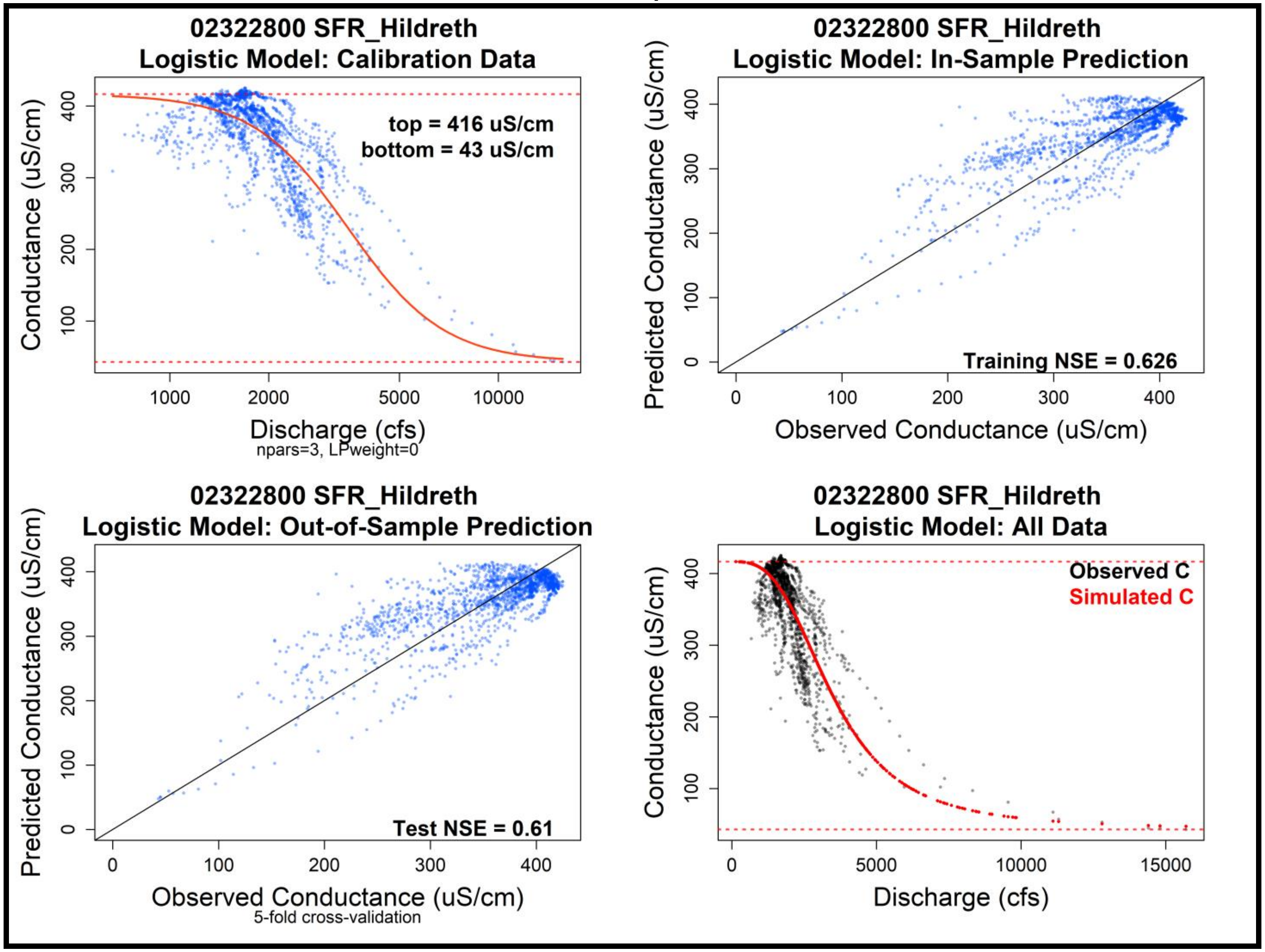


Figure 26 - Baseflow hindcast for Hildreth, based on the 3-parameter logistic model

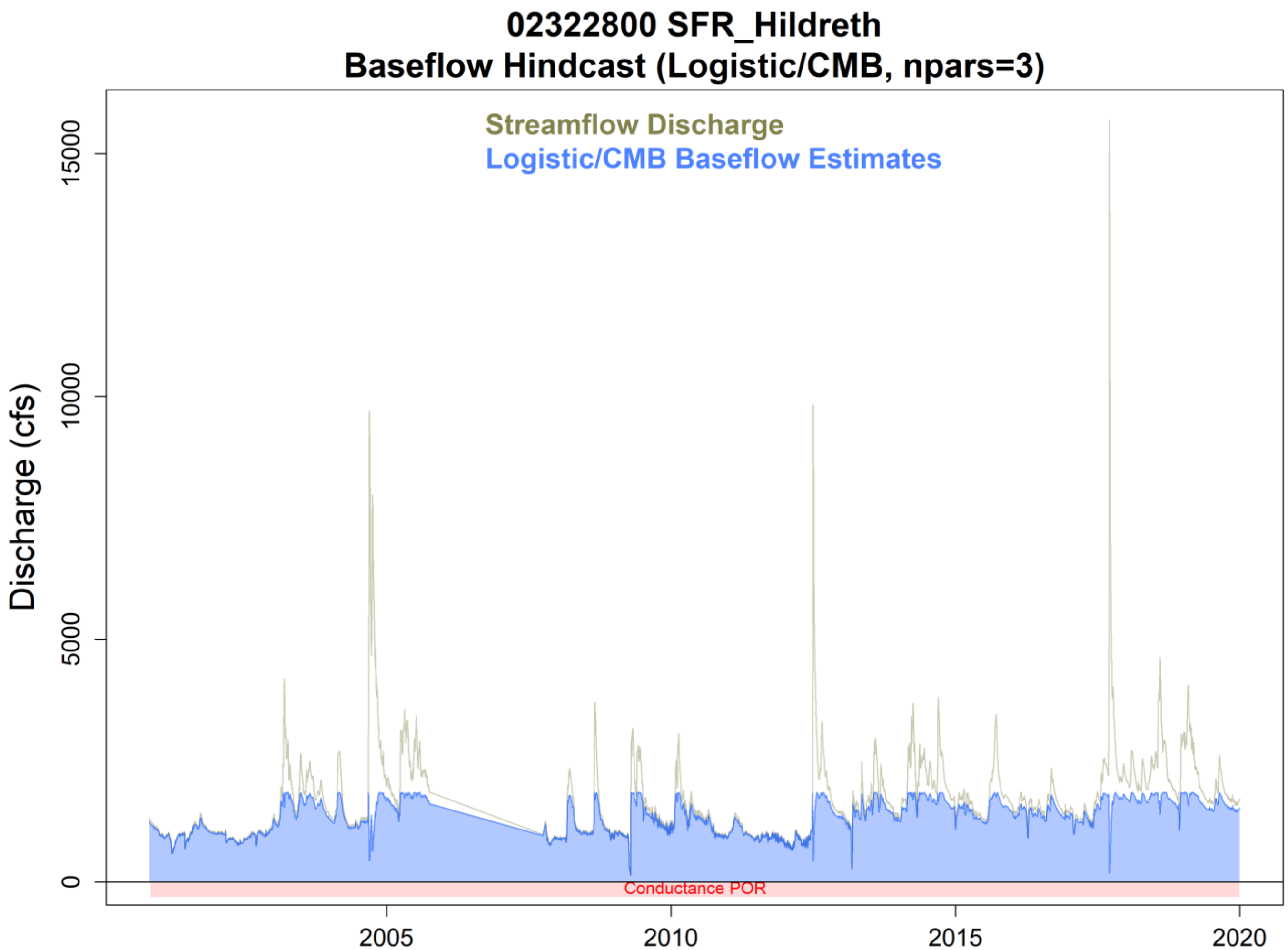


Figure 27 - Logistic/CMB baseflow hindcast (3-parameter model) against the CMB benchmark estimates for Hildreth. *Top left*: Baseflow estimates generated by the logistic/CMB (blue) and CMB benchmark (red) methods during the calibration period. *Top right*: Scatterplot of baseflow estimates generated by the two methods. *Bottom left*: Exceedance curves for baseflow estimates generated by the logistic/CMB (blue) and CMB (red) methods during the calibration period. *Bottom right*: Exceedance curve for the full baseflow hindcast generated by the logistic/CMB method.

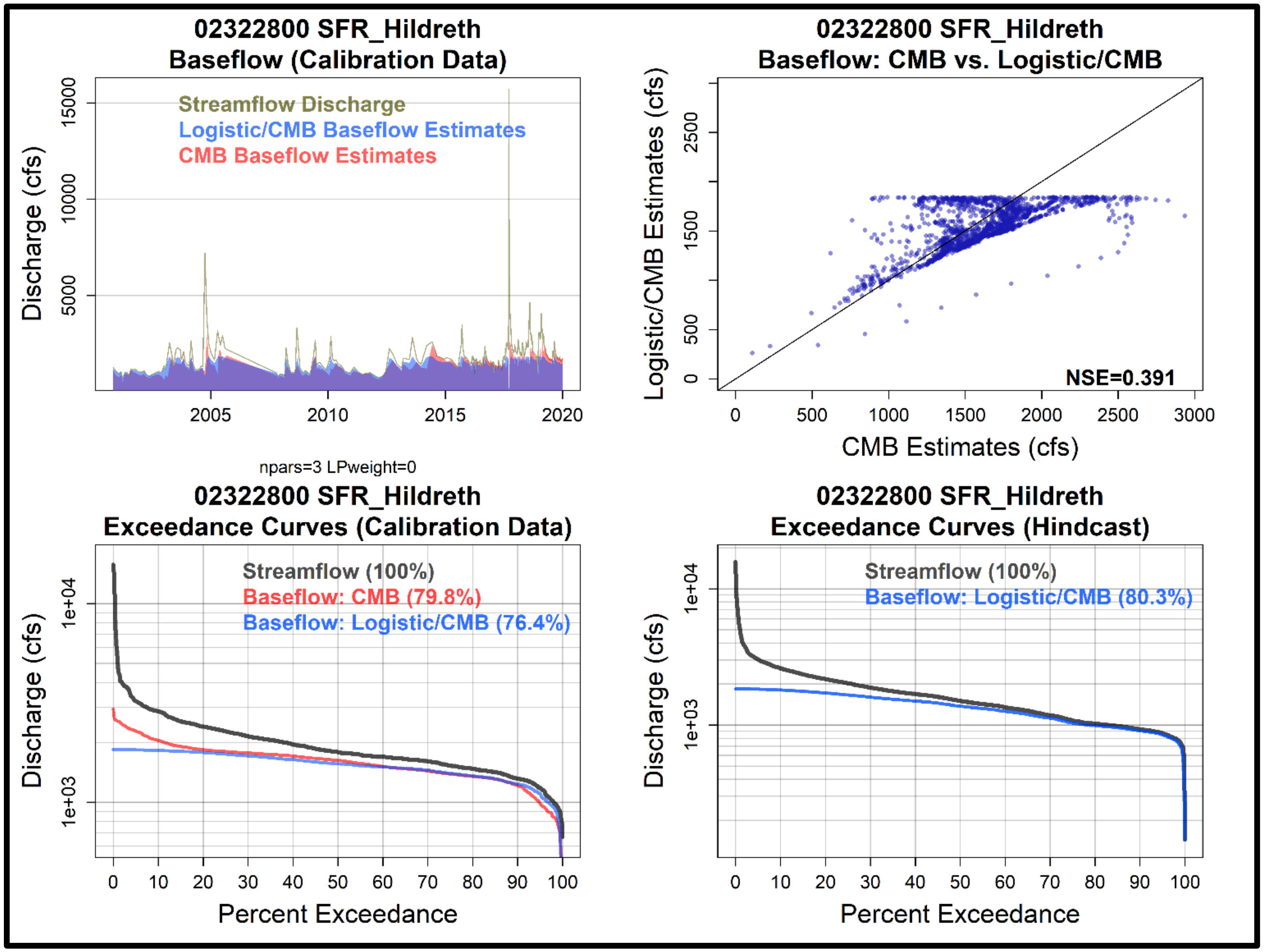
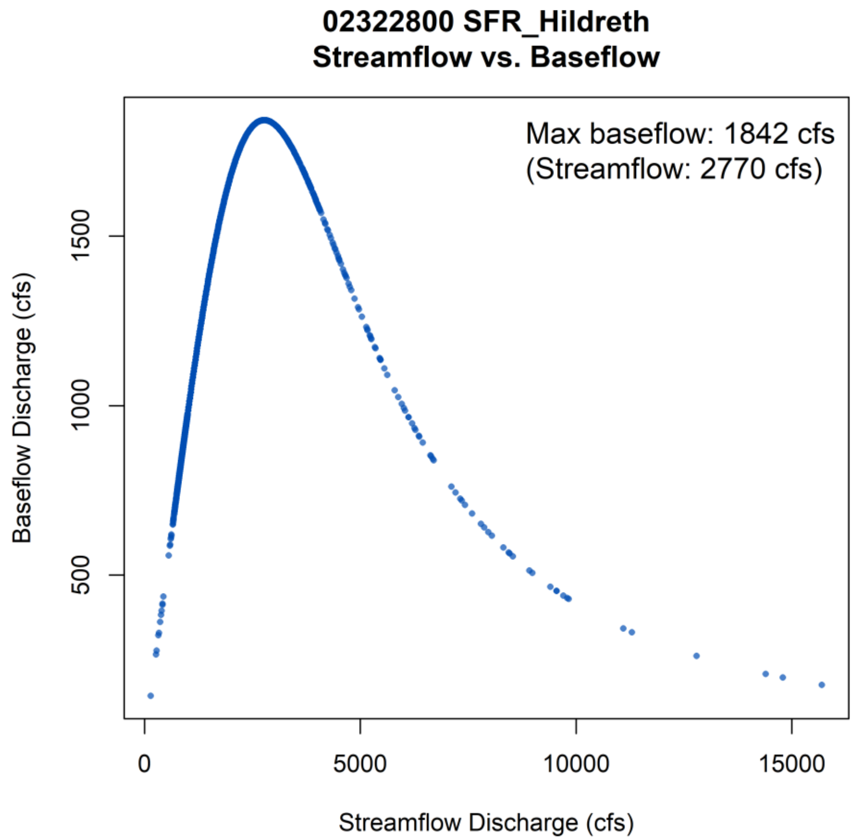


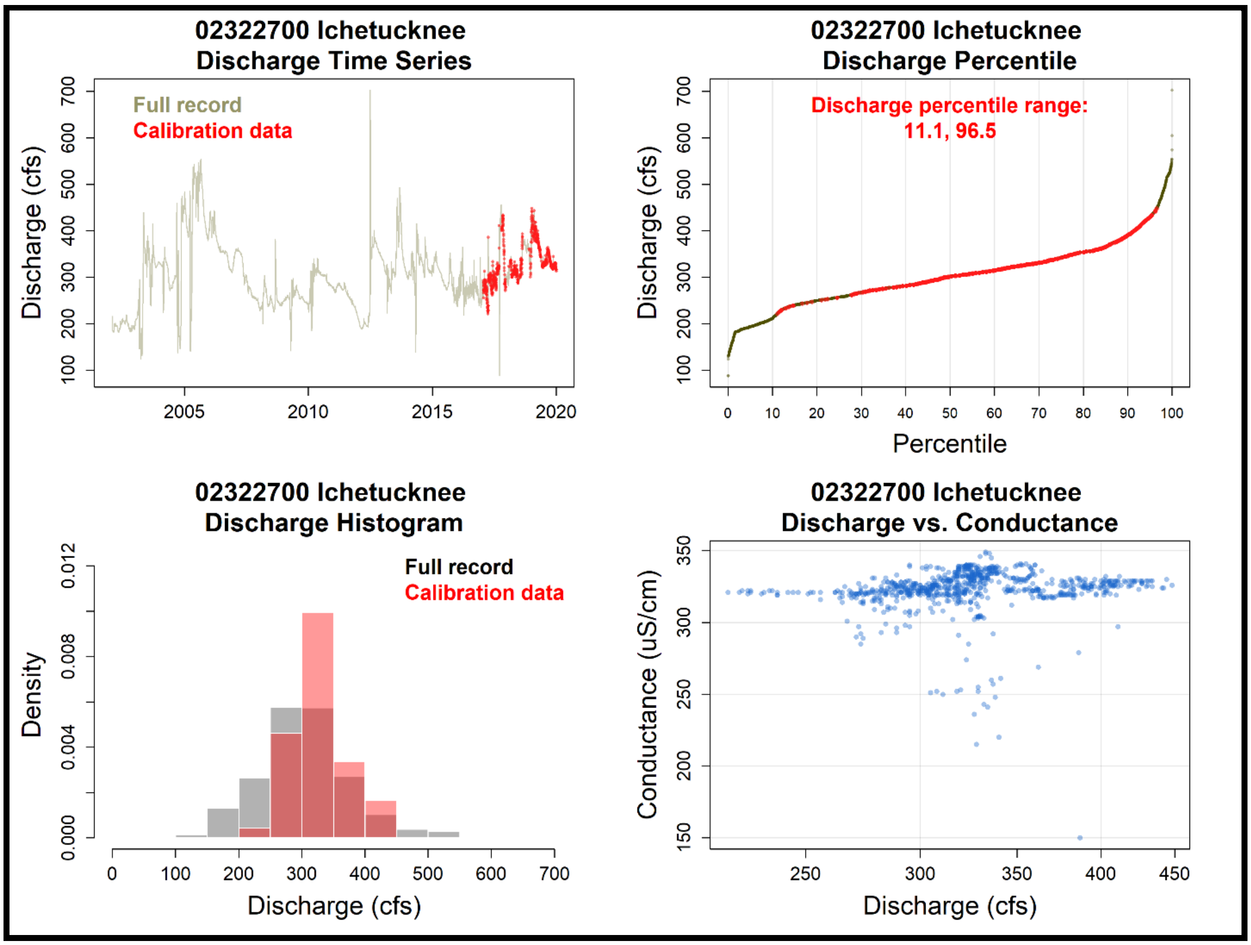
Figure 28 - Observed streamflow and hindcasted baseflow for Hildreth



3.6. Ichetucknee

Diagnostics indicated that the Ichetucknee gage location is a not good candidate for the logistic/CMB method. The calibration data are for this site are less than highly representative of the full discharge record, capturing only the 11.1 through the 96.5 percentile of discharge magnitudes. Further, the calibration data overrepresent moderate discharge magnitudes and underrepresent low and high discharge magnitudes (**Figure *29***). However, the discharge-conductance scatterplot does not exhibit a logistic form; conductance remained relatively constant without regard to discharge (**Figure *29***, *bottom right*).

Figure 29 - Diagnostics for Ichetucknee. Discharge time series (*top left*), percentile plot (*top right*), and density histograms (*bottom left*) for the full discharge record (gray) and calibration data (red). *Bottom right*: Discharge-conductance scatterplot on a single-log scale.



4.0 <u>COMPARISON OF BASEFLOW SEPARATION METHODS</u>

4.1. Logistic/CMB and Calibrated HYSEP (Sliding Interval Method)

As part of an earlier project by Wood in 2018, the Calibrated HYSEP sliding-interval method (Sloto & Crouse 1996) was applied to estimate baseflow for several of the sites considered in **Section 3**: Ellaville, Branford, Worthington, and Fort White. The HYSEP method was calibrated (by adjusting the *2N** parameter) to provide the closest possible match to cumulative baseflow estimates yielded by the CMB method (using concurrent observed specific conductance and discharge data) over the available conductance period of record. Below, the baseflow estimates developed for the current analysis (logistic/CMB method) are compared to those from the earlier HYSEP work.

Based on the logistic/CMB method, baseflow hindcasts for Ellaville, Branford, and Fort White exhibited an apparent upper limit, such that baseflow estimates did not exceed a certain magnitude regardless of the level of streamflow discharge. This effect is visible in the baseflow hydrographs (**Figure 31, 33 & 37**), wherein the logistic/CMB estimates appear capped at a low level relative to the HYSEP estimates; and on the left-hand side of the associated exceedance curves (**Figure 30, 32 & 36**), wherein the top 40% or more of baseflow magnitudes are nearly equal. Whereas the HYSEP exceedance curve for each site resembles its logistic/CMB counterpart for low to moderate baseflow magnitudes, the HYSEP curve slopes sharply upward on the far left-hand side of the plot to mirror the shape of the associated streamflow discharge curve. That is, the primary difference between the HYSEP and logistic/CMB estimates at these two sites is that for moderate to high streamflow discharge magnitudes, the logistic/CMB method predicted a relatively constant level of baseflow, while HYSEP attributed more of the streamflow to baseflow. As a result, the HYSEP method estimated a higher percentage of streamflow as baseflow (BFI) at Ellaville and Branford relative to the logistic/CMB method; at Fort White, the logistic/CMB model estimated a higher BFI than did HYSEP (**Table 5**).

For Worthington, the logistic/CMB baseflow hindcast did not exhibit the upper limit seen at other sites, and the logistic/CMB and HYSEP methods yielded similar baseflow estimates (**Figure 34 & 35**). Baseflow estimated by each method accounted for a relatively small percentage of streamflow (**Table 5**).

Table 5 - Baseflow Index Estimated by Logistic/CMB and HYSEP Methods

Gage Location	Logistic/CMB Baseflow Index (%)	Calibrated HYSEP Baseflow Index (%)
Ellaville	24.7 %	31.3 %
Branford	37.9 %	43.1 %
Worthington	16.5 %	14.0 %
Fort White	73.2 %	72.4 %

Figure 30 - Exceedance curves for Ellaville

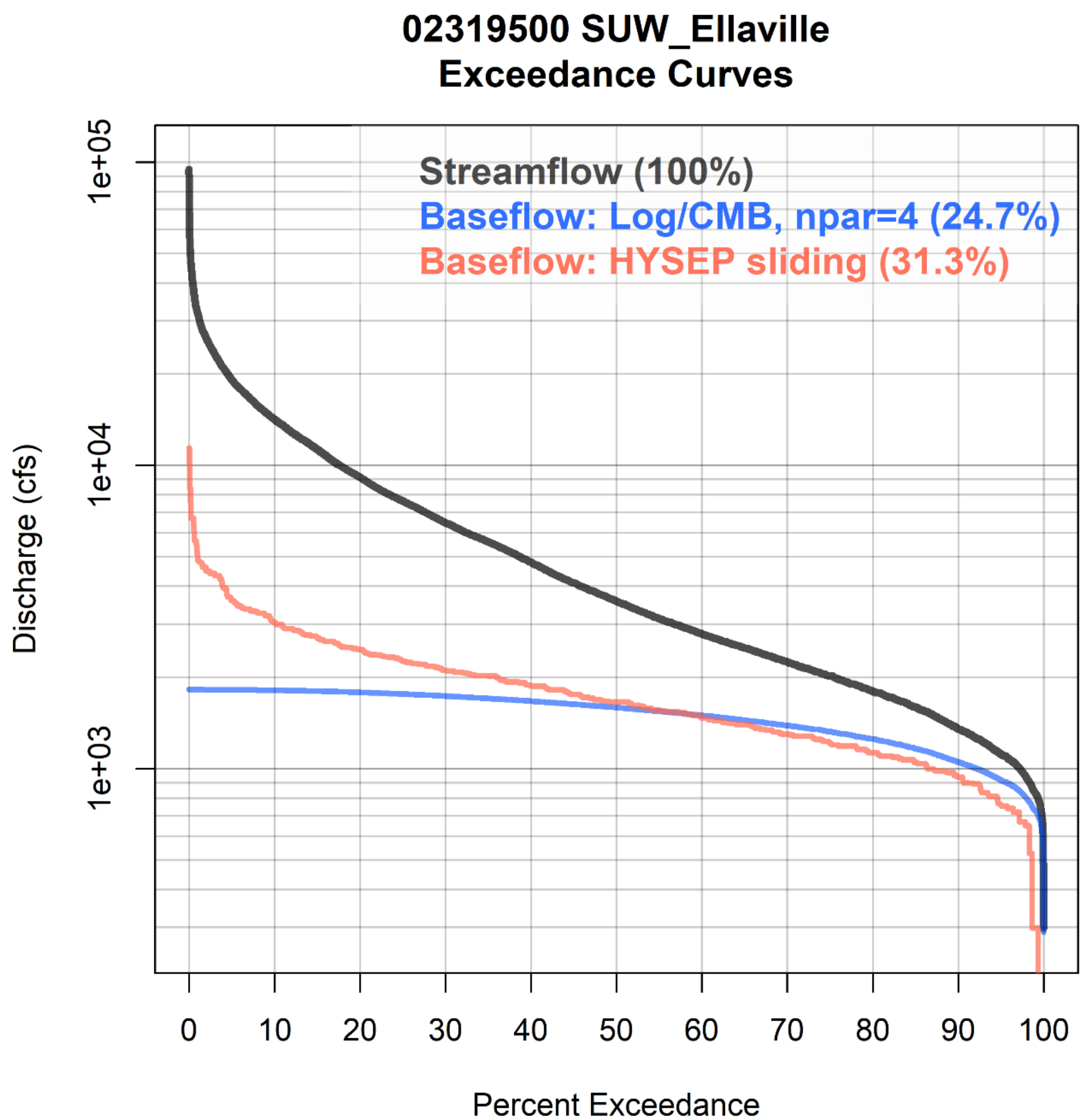


Figure 31 - Streamflow and baseflow hydrographs for Ellaville

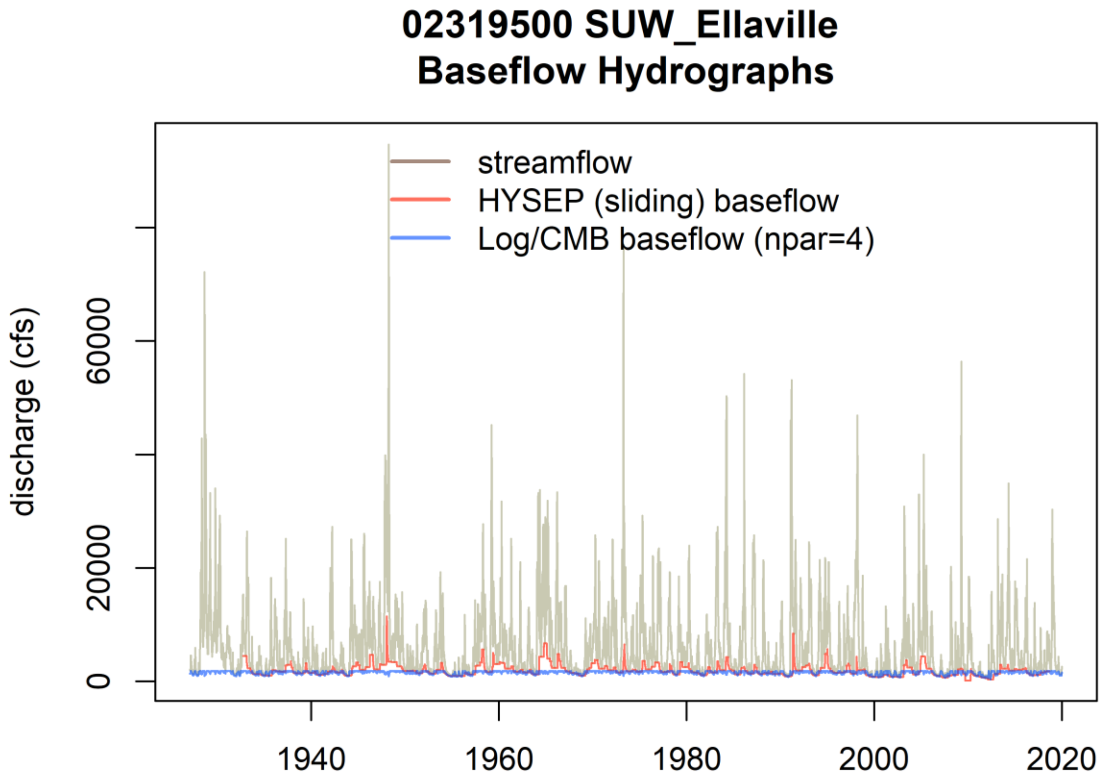


Figure 32 - Exceedance curves for Branford

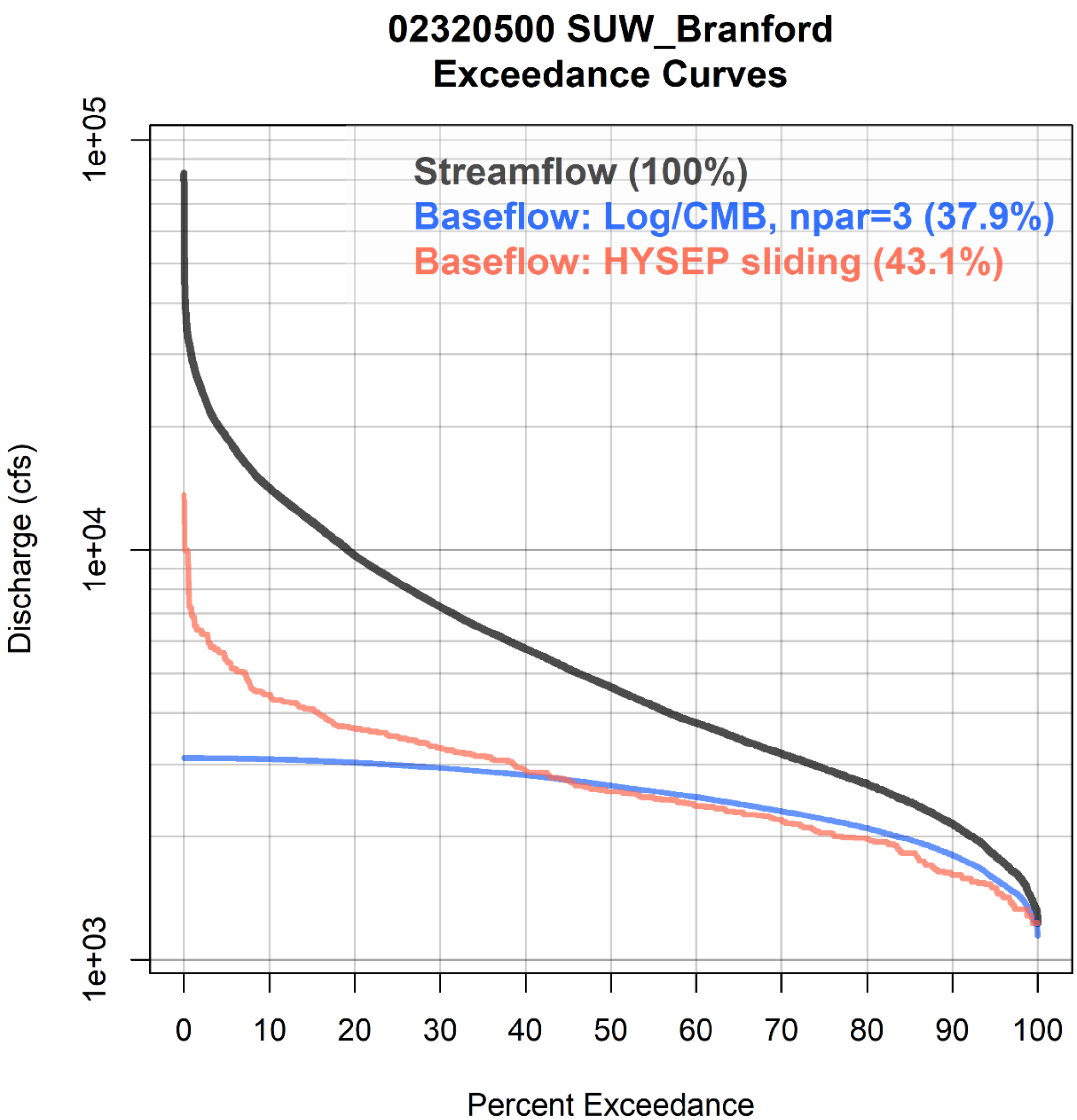


Figure 33 - Streamflow and baseflow hydrographs for Branford

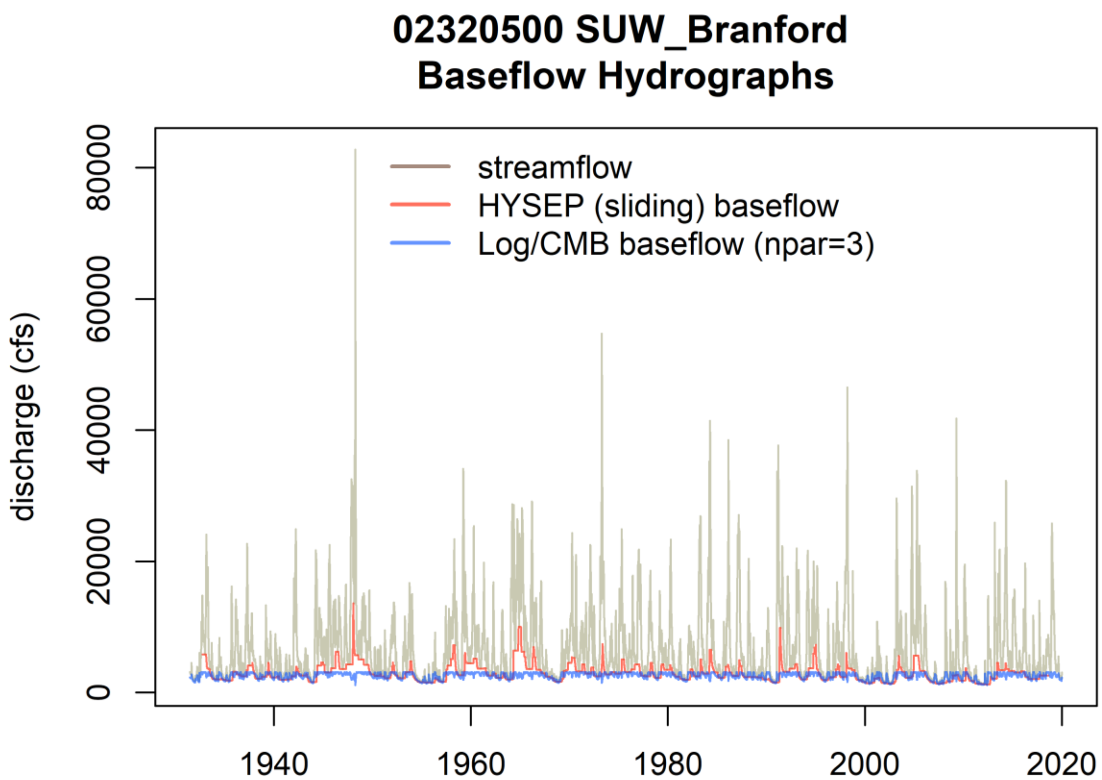


Figure 34 - Exceedance curves for Worthington

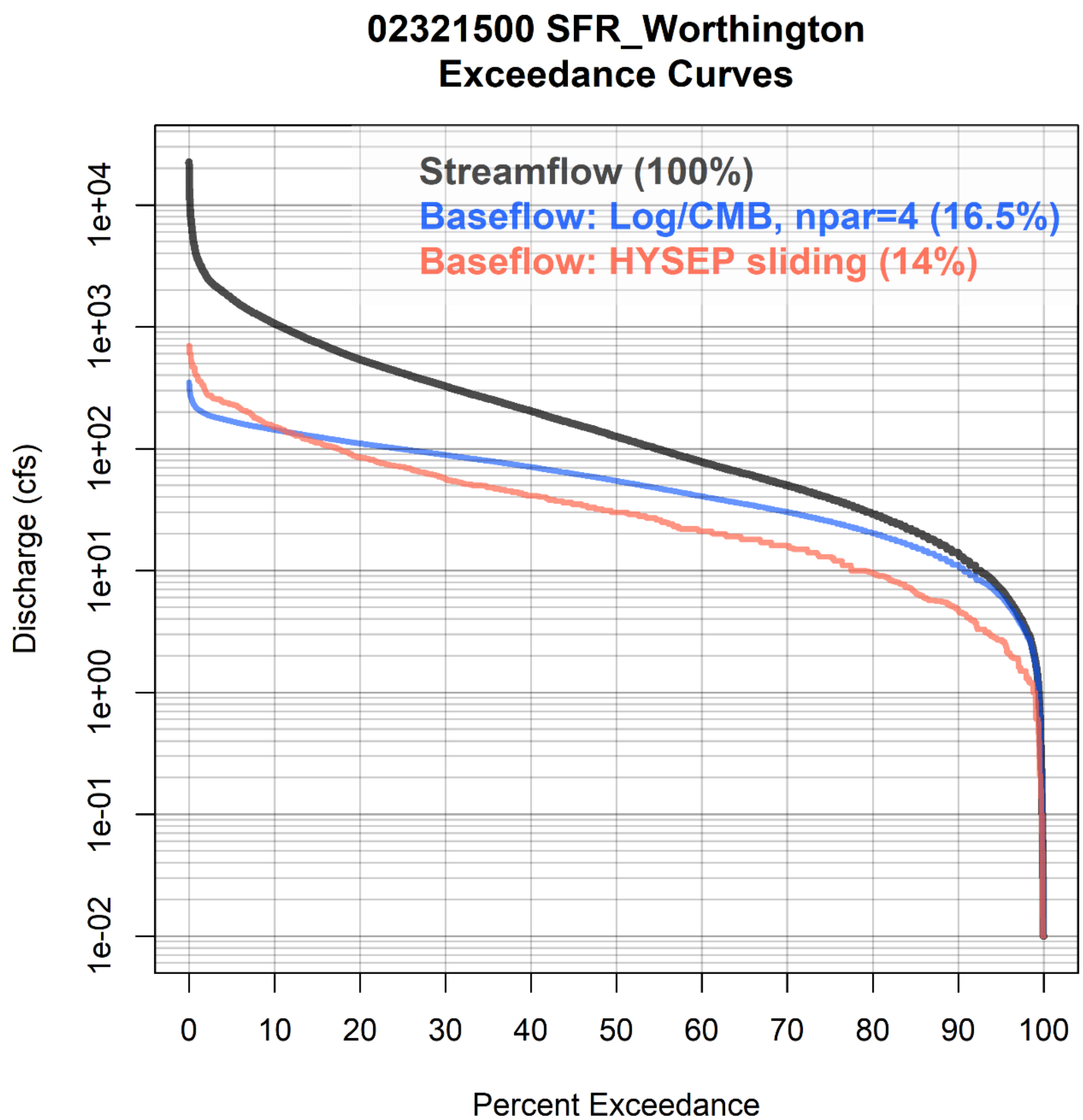


Figure 35 - Streamflow and baseflow hydrographs for Worthington

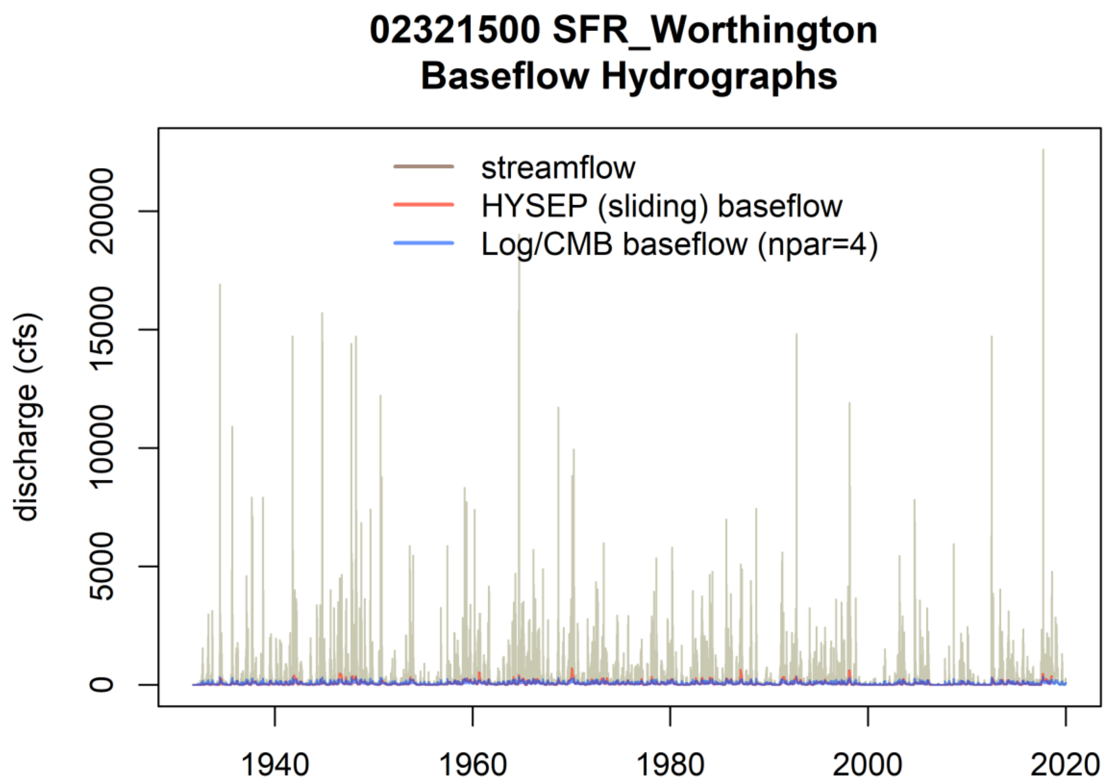


Figure 36 - Exceedance curves for Fort White

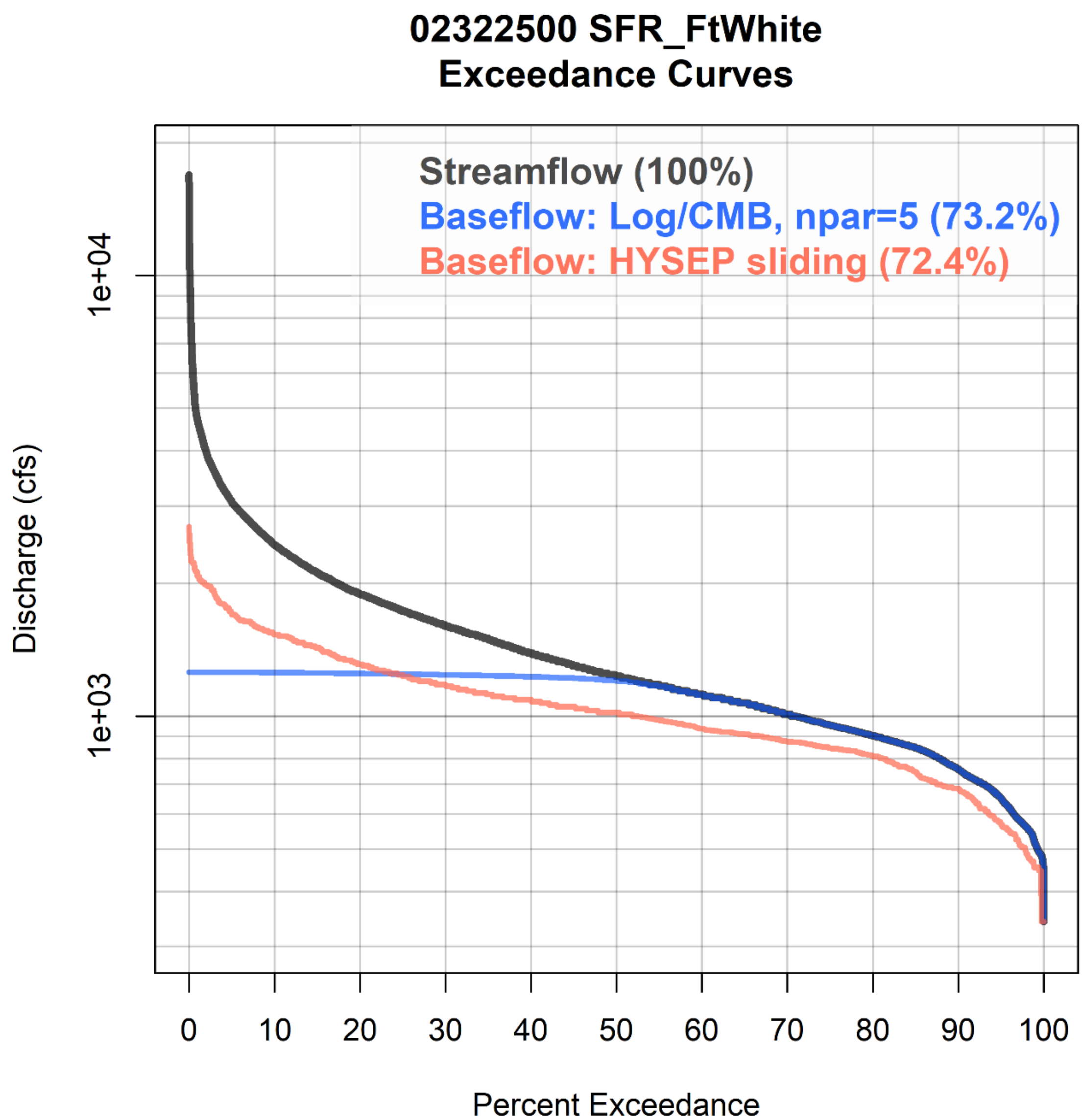
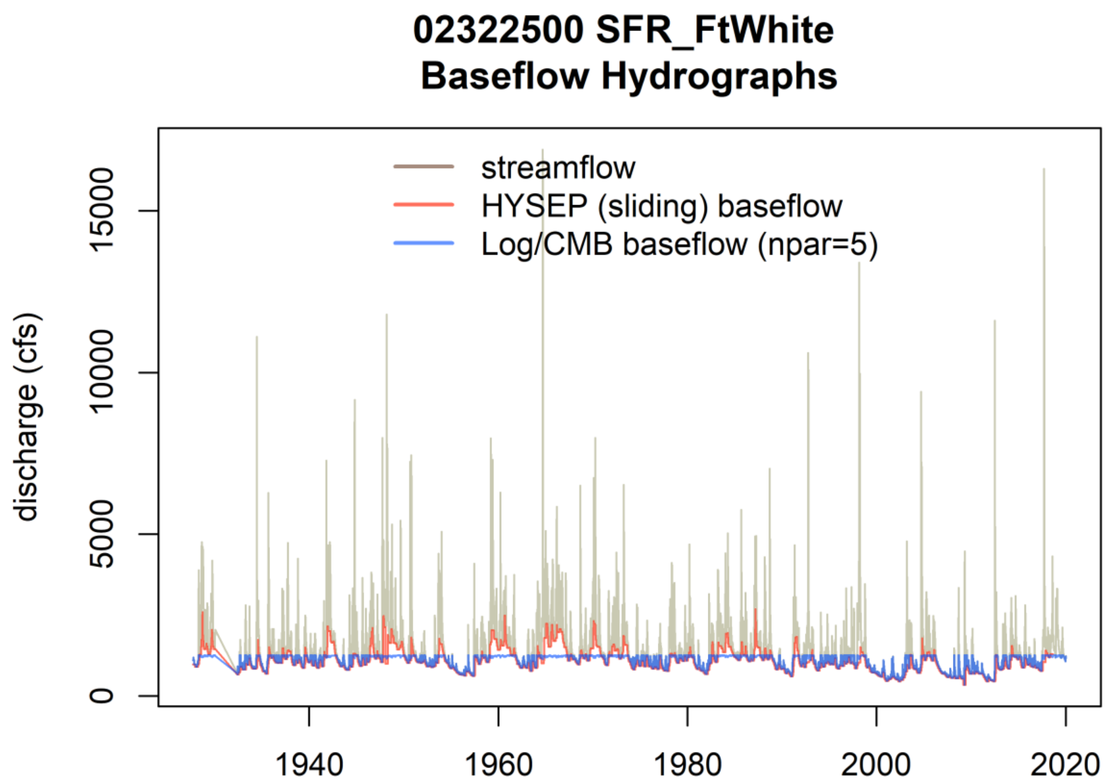


Figure 37 - Streamflow and baseflow hydrographs for Fort White

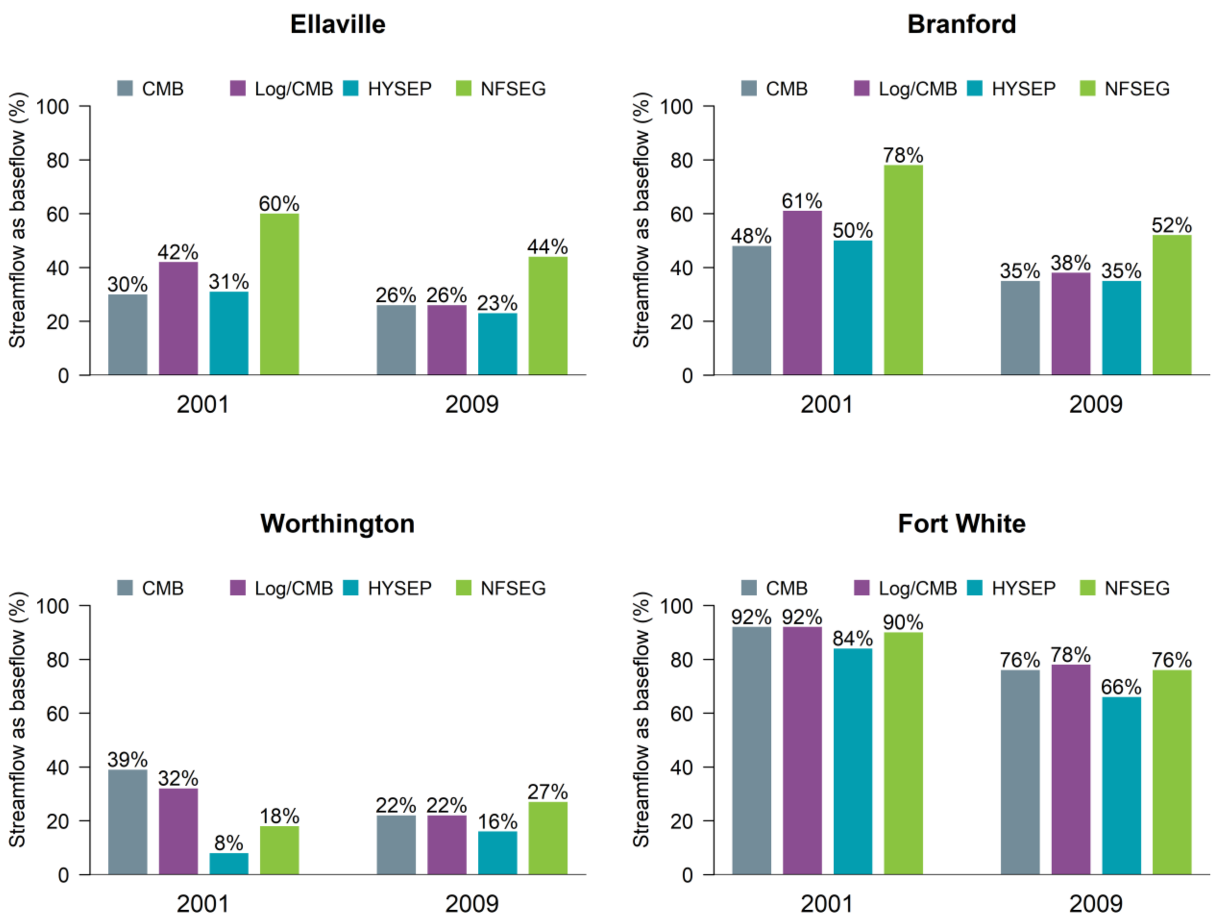


4.2. North Florida-Southeast Georgia (NFSEG) Model Baseflow Estimates

The NFSEG regional groundwater flow model provided estimates of the mean annual percentage of streamflow discharge attributable to baseflow at various sites in 2001 and 2009. In **Figure 38**, these results are compared against the mean baseflow estimates yielded by the CMB (benchmark), logistic/CMB, and calibrated sliding-interval HYSEP methods.

For Ellaville and Branford, the NFSEG models overestimated baseflow relative to the CMB benchmarks, and the HYSEP estimates most closely matched the benchmarks. For Worthington, the logistic/CMB estimates most closely matched the CMB benchmarks. For Fort White, both the NFSEG and the logistic/CMB estimates closely matched the CMB benchmarks.

Figure 38 - Average percentage of streamflow discharge as baseflow in 2001 and 2009: Comparison of CMB, logistic/CMB, HYSEP, and NFSEG estimates



4.3. Gage Pickup

The streamflow pickup between the Fort White and Worthington gages was computed as a proxy for observed baseflow at the Fort White station, by subtracting daily discharge values between each site (**Figure 39**). The gage pickup series, which accounted for 74.3% of streamflow at Fort White, serves as a basis for comparing baseflow estimates yielded by the logistic/CMB and calibrated HYSEP methods. Gage pickup was better approximated by the HYSEP model, which attributed 72.4% of Fort White streamflow to baseflow and generated a similarly shaped exceedance curve (**Figure 40**). The 5-parameter logistic/CMB model overestimated baseflow during low to moderate discharges and underestimated baseflow during high discharges, relative to gage pickup. For visual clarity, the baseflow hindcast generated by the logistic/CMB model is omitted from **Figure 39**; see **Figure 37** to compare the Fort White baseflow hydrographs yielded by the logistic/CMB and HYSEP methods.

Figure 39 - Hydrographs for gage pickup and HYSEP baseflow at Fort White

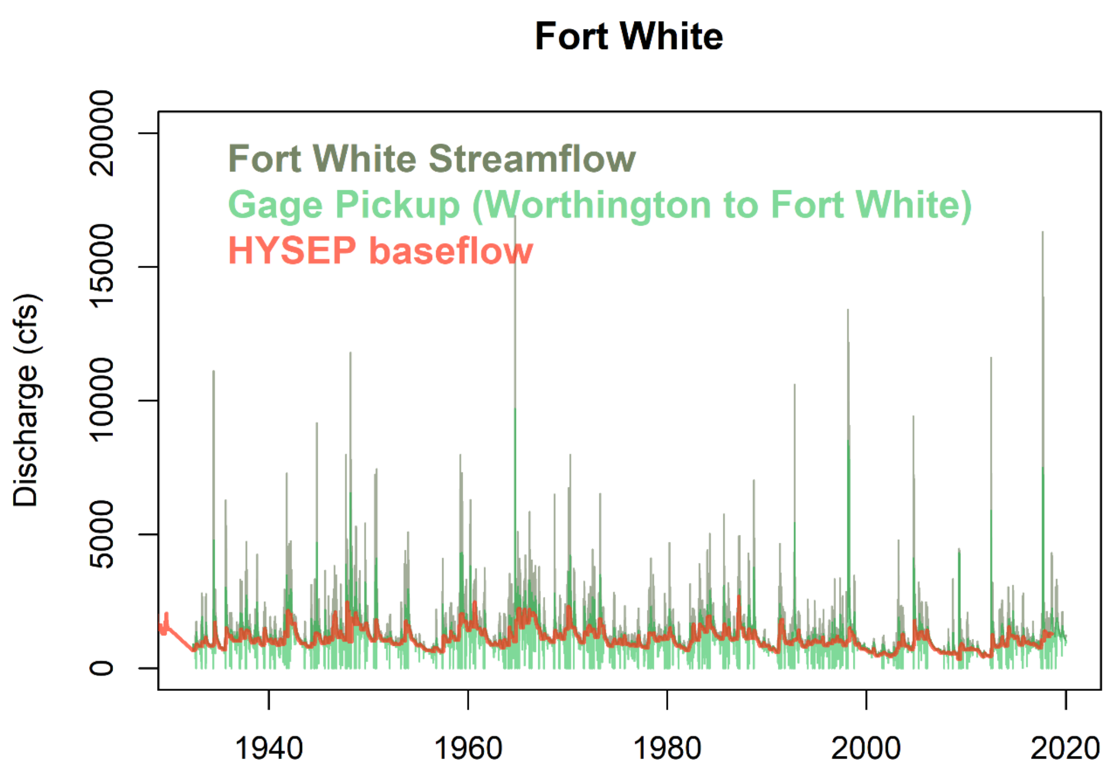
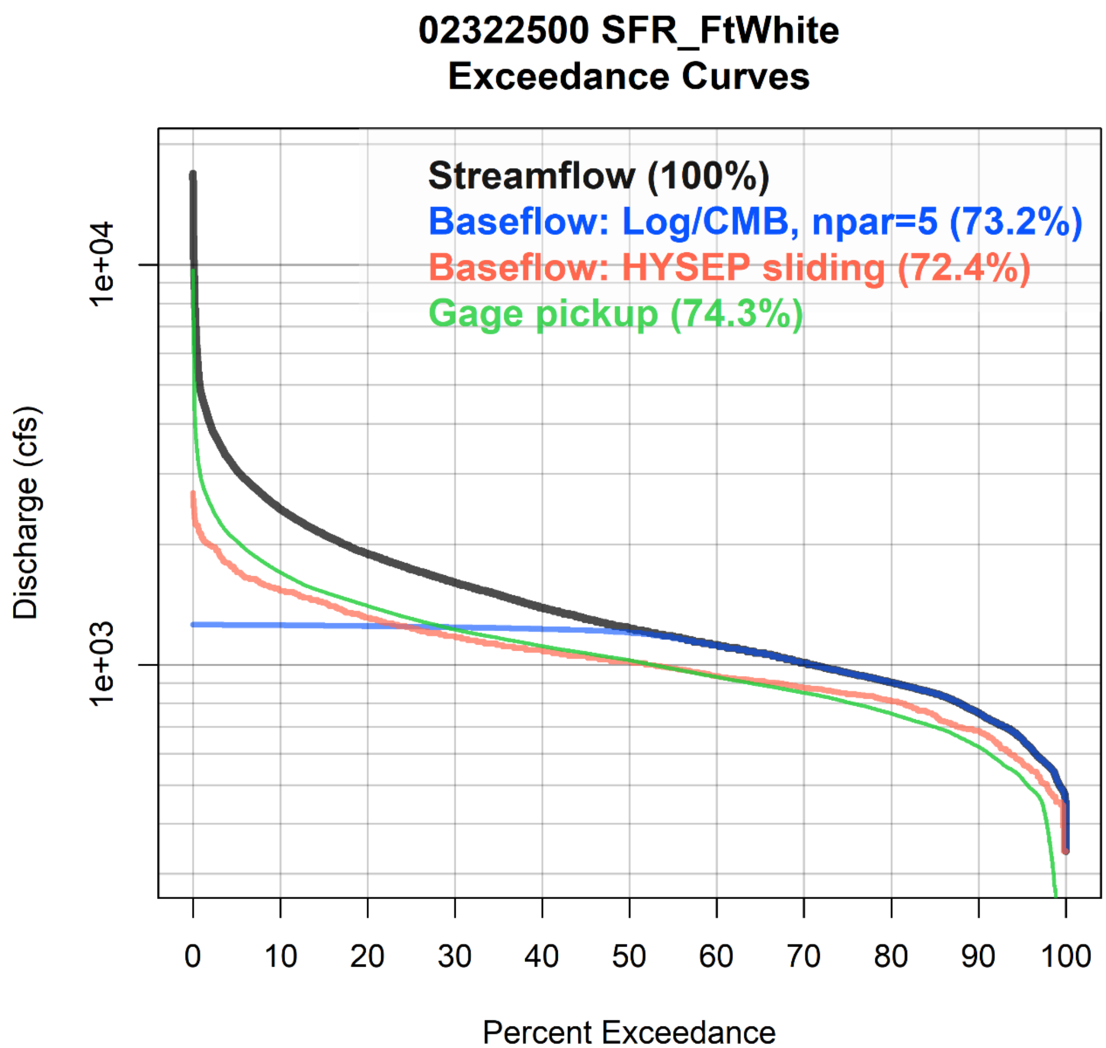


Figure 40 - Exceedance curves for baseflow estimated by logistic/CMB, calibrated HYSEP, and gage pickup at Fort White



5.0 LOGISTIC REGRESSION ON RISING AND FALLING LIMBS

For each of the gage sites analyzed in **Section 3**, an important assumption of the logistic/CMB method—that discharge and conductance exhibit an approximately 1:1 relationship—was strained. To explore a potential remedy to this problem, the data associated with the rising and falling limbs of the Branford streamflow hydrograph were separated; the logistic/CMB method was applied independently to each subset, by developing two logistic models; and the two resulting sets of baseflow estimates were compiled to generate a single baseflow hindcast. The Branford data were divided into 'rising limb' and 'falling limb' subsets by differencing the streamflow discharge record: Streamflow observations associated with non-negative differences were assigned to the 'rising limb' subset, and observations associated with negative differences were assigned to the 'falling limb' subset.

Figure 41 depicts the distributions of the 'rising limb' and 'falling limb' subsets for Branford. Although the two distributions of conductance values overlap, the median conductance of the 'falling limb' data (297 uS/cm) is greater than that of the 'rising limb' data (244 uS/cm). Further, the discharge-conductance scatterplot shows that conductance values in the 'falling limb' subset rest somewhat above those in the 'rising limb' subset, and, for any given level of discharge, each subset generally occupies a narrower vertical range than the full dataset. These differences in the distributions suggest that fitting a separate logistic model to each subset might reduce the problem of vertical scatter.

A 3-parameter logistic model for the 'falling limb' subset and a 5-parameter model for the 'rising limb' subset generated conductance estimates that were inputted to the CMB equation to estimate baseflow. **Figure 42** depicts the streamflow and baseflow hydrographs; red and blue points embedded in the streamflow hydrograph indicate observations assigned to the 'rising limb' and 'falling limb' subsets.

Importantly, the exceedance curve for estimated baseflow exhibits an abrupt kink separating moderate and high flows—an undesirable mathematical artifact that presumably resulted from joining results from two independently derived logistic models (**Figure 43**). A similar (and often more pronounced) kink was also generated by other logistic model specifications attempted for Branford.

Figure 41 - Distributions of the rising and falling limb data for Branford

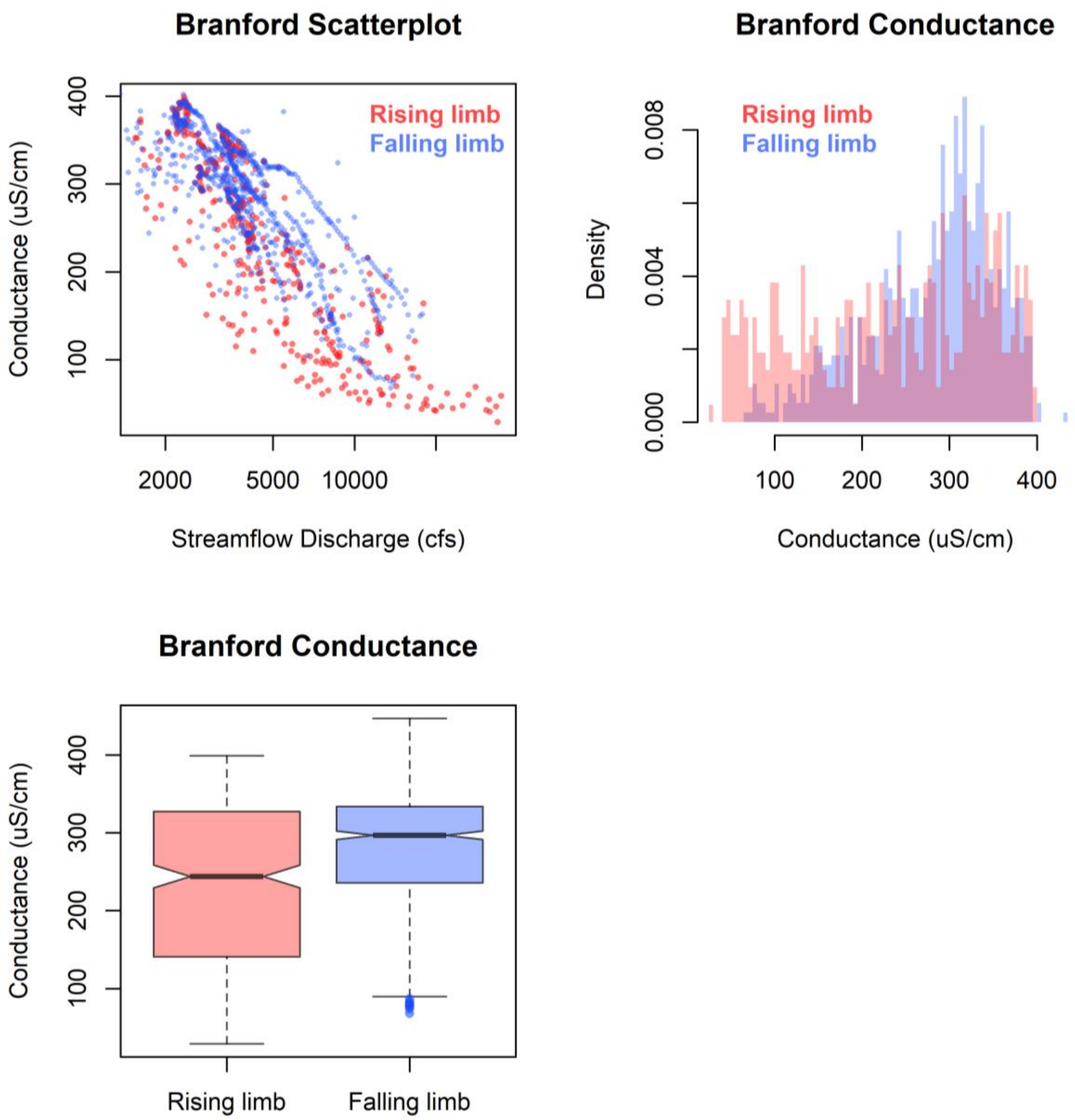


Figure 42 - Streamflow and baseflow hydrographs for Branford, based on independent logistic fits to rising and falling limbs

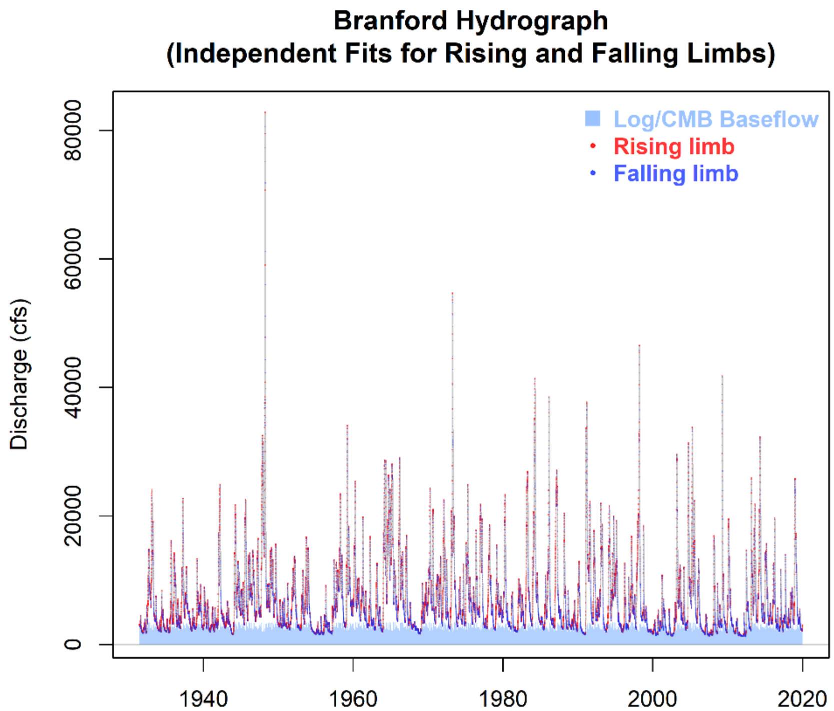
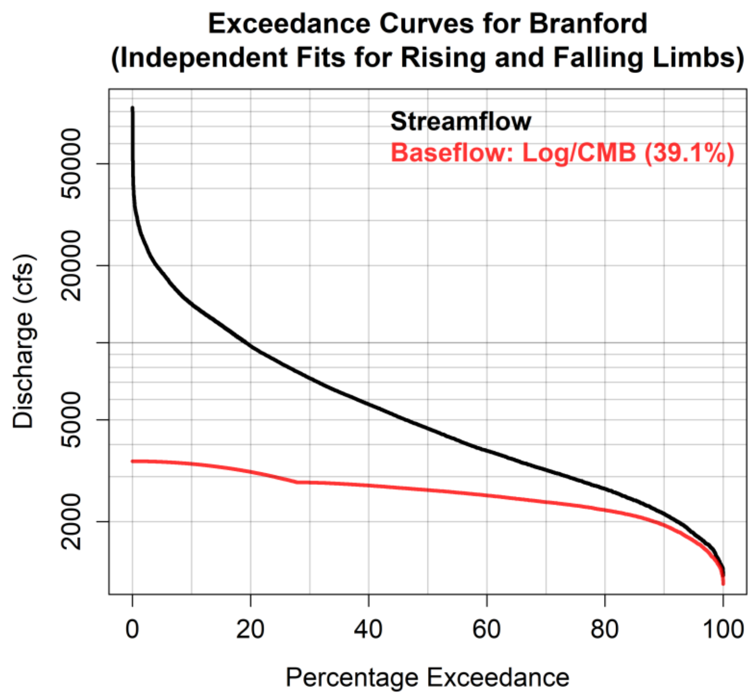


Figure 43 - Exceedance curves for Branford, based on independent logistic fits to rising and falling limbs



6.0 <u>SUMMARY AND RECOMMENDATIONS</u>

Visual diagnostics indicated that the logistic/CMB method might be appropriate for hindcasting baseflow at the Ellaville, Branford, Worthington, Fort White, and Hildreth gage locations. However, with the exception of Worthington, the discharge-conductance scatterplots for these locations exhibited substantial vertical scatter that strained or violated the assumption that the discharge-conductance relationship could be reasonably approximated by 1:1 logistic relationship. The vertical scatter might reflect variable conductance in baseflow and runoff (in contrast to the assumption of constant conductance for each flux), complex interactions between baseflow and runoff that might be expected in a karstic landscape (e.g. runoff-sourced streamflow recharging bank storage, followed by ion-enriched bank discharge to the stream), or non-negligible influence from other hydrological fluxes or chemical transformations (e.g. in-stream biogeochemistry).

Attempts to address the strained 1:1 discharge-conductance assumption at the Branford gage location, by modeling the rising- and falling-limb data independently, failed to improve reliability of the logistic/CMB method (**Section 5.0**). The conductance data associated with the rising and falling limbs of the Branford streamflow hydrograph were distributed differently, to suggest that the distinction between rising and falling limbs may be useful. However, application of independent models for each subset of data yielded 'kinked' exceedance curves that contradicted theoretical knowledge.

The Ichetucknee gage location was identified as a poor candidate for the logistic/CMB method (**Figure 29**). In particular, the discharge-conductance scatterplot made clear that conductance remained relatively constant under variable discharge conditions. This observation is consistent with the understanding that Ichetucknee is dominated by spring discharge (high conductance) with relatively little influence from runoff.

The Worthington location stood apart as a near-ideal example of the logistic/CMB method in application. Visual diagnostics showed full representation of the range of the discharge record in the calibration data, and the discharge-conductance scatterplot showed relatively little vertical scatter, particularly at the high-discharge end (**Figure 14**). Further, the 4-parameter logistic model estimated reasonable top and bottom parameters (relative to values in **Table 3**) and performed well during cross-validation (**Figure 15**). The logistic/CMB baseflow exceedance curve was similar in shape to that of the CMB benchmark, although the logistic/CMB model largely overestimated baseflow during the calibration period relative to the benchmark (**Figure 17**). On the other hand, the CMB baseflow for 2001 and 2009 was most closely matched by the logistic/CMB estimates (**Figure 38**), outperforming both the calibrated HYSEP method and NFSEG estimates (**Section 4.2**).

With the exception of Worthington, the logistic/CMB baseflow hindcasts exhibited upper limits to suggest that baseflow did not substantially increase beyond a certain level of streamflow discharge. This effect manifested as ceilings in the baseflow hydrographs and plateaus in the corresponding exceedance curves. The plateauing effect contradicted the CMB benchmarks, whose exceedance curves showed increasing baseflow under the highest-discharge conditions. The effect emerged as an artifact of the logistic/CMB models when the discharge-conductance scatterplot exhibited vertical scatter and was most apparent when there was substantial scatter on the high-discharge end of the scatterplot where the tail of the logistic function was relatively flat (e.g. Ellaville): The logistic function modeled relatively variable conductance observations (variable with respect to streamflow discharge) as relatively constant by overestimating baseflow when conductance was below the logistic curve and underestimating baseflow when conductance was above the curve. The combined effect was an apparent maximum in the estimated baseflow, as variable conductance observations were effectively collapsed onto the flatter end of the logistic function corresponding to high streamflow discharges. While a maximum baseflow magnitude may be theoretically appealing—for instance, a large runoff event may fill the stream, ceasing baseflow discharge once the stream head exceeds the bank head—the upper limits generated by the logistic/CMB models are highly sensitive to the model specification (*npars*) and should be treated as statistical artifacts rather than reliable representations of the hydrology. That is, while a baseflow maximum may be realistic, one should not rely on the logistic/CMB models to estimate that maximum. The sensitivity of apparent upper limits, baseflow hindcasts, and estimated BFIs to model specifications is evident in the streamflow-baseflow discharge scatterplots and hydrographs included in **Attachment A**. For instance, maximum baseflow was estimated at 10864 cfs and 1822 cfs by the 5- and 4-parameter models for Ellaville, respectively; BFI estimates were 42.4% and 24.7%, respectively. At Branford, maximum baseflow was estimated at 15967 cfs, 2759 cfs, and 3105 cfs by the 5-, 4-, and 3-parameter models, respectively; BFI estimates were 59.3%, 32.7%, and 37.9%, respectively.

Because hindcasting with the logistic/CMB method is a predictive endeavor, *nonstationarity* is an important concern: A fundamental assumption of this method is that the recent past (the calibration period) serves as a reliable basis for hindcasting baseflow into the more distant past (the discharge period of record). While cross-validation and CMB benchmarking provided important tests to evaluate logistic/CMB models and hindcasts, respectively, these checks were limited to using the calibration period as the basis for comparison, and nonstationarity in the discharge-conductance relationship was not accounted for by the model selection/evaluation procedures summarized in **Figure 3**. The effect of nonstationarity should therefore be considered carefully, as land use changes, shifts in groundwater withdrawal regimes, and climate change may have altered the discharge-conductance relationship over time.

In summary, the logistic/CMB method appears to have performed well for Worthington, the site with the least influence from baseflow, and the calibrated sliding-interval HYSEP method yielded similar estimates. However, the primary benefit of the logistic/CMB method—its basis in first principles (conservation of mass)—was more often overshadowed by important limitations that cast doubt on its reliability as a general method for baseflow separation: (1) The 1:1 discharge-conductance relationship was strained at most sites; and (2) non-stationarity is likely ubiquitous, and the uncertainty it implies for hindcasting is important and inevitable. The calibrated sliding-interval HYSEP method, which is not prone to the limitations above, provided an interesting contrast (**Section 4.1**). On the one hand, both the logistic/CMB and HYSEP methods yielded similar baseflow estimates for low to moderate discharges at Ellaville, Branford, and Fort White. On the other hand, the HYSEP-estimated baseflows increased under high-discharge conditions, to contrast with the logistic/CMB estimates that exhibited the plateauing effect. Whether an upper limit to baseflow is realistic should be investigated further on a site- or basin-specific basis. At best, the logistic/CMB method may be reliable at sites where interactions among runoff, baseflow, and conductance are relatively straightforward and where non-stationarity is not a serious concern; otherwise, the calibrated HYSEP method was found to be more appropriate.

7.0 REFERENCES

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