NC Division of Water Resources
Planning Section
Modeling and Assessment Branch

Memorandum

October 28, 2020

To: Fred Tarver and Forest Shepherd, Basin Planning Branch

From: Adugna Kebede, Modeling and Assessment Branch

Subject: Streamflow Trends for selected Chowan River Basin Stations

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The Modeling and Assessment Branch (MAB) carried out streamflow trend analysis for selected Chowan River Basin stations.

Trends in 7Q10 flows for selected Chowan River Basin flow gages were explored using the Mann-Kendall trend test. The 7Q10 is the lowest 7-day average flow that occurs (on average) once every 10 years. It is the low-flow estimate which is mostly used to define critical conditions to set permit limits for NPDES dischargers. The trend analysis was performed using the USGS Computer Program for the Kendall Family of Trend Tests (Helsel, et al., 2006). In addition, temporal changes in daily streamflow statistics across an annual time period for the period of record were explored using the EGRET software (Hirsch and De Cicco, 2015). These included, water year daily minimum flow, 7-day minimum flow, daily median flow, daily mean flow, and daily maximum flow. The USGS defines the water year as beginning on October 1 and ending on September 30 the following year. A recently developed exploratory tool, the Quantile-Kendall plot (Hirsch, 2018, Choquette, et al., 2019) was also used to evaluate flow trends across the range of streamflow values at a given site for an annual time-frame.

The Mann-Kendall Test

The Mann-Kendall test is used to perform trend analysis on 7Q10 flow data for selected Chowan USGS stations (Table 1). The Mann-Kendall test is a statistical test widely used for the analysis of trend in hydrologic time series. It is a non-parametric test where the null hypothesis H_0 is that there is no trend and the alternative hypothesis H_1, is that there is a trend. The trend test was performed using the USGS Computer Program for the Kendall Family of Trend Tests. The 7Q10 data used for the analysis were estimated using the Water Resources Information, Storage, Analysis, and Retrieval System (WRISARS), hosted by NC Division of Water Resources. The 7Q10 values were computed for a 10-year and 30-year window. These values represent the first year of the forward looking window where N= 10 and N =30. More than a 10-year or 30-year window was required to capture the respective number of years with complete records for some stations.

Table 1: Selected USGS gaging stations in the Chowan Basin		
Station	**USGS Gage**	**Period of Record**
Ahoskie Creek at Ahoskie, NC	02053500	1950-2019
Potecasi Creek near Union, NC	02053200	1958-2019
Nottoway River near Sebrell, VA	02047000	1941-2019
Meherrin River at Emporia, VA	02052000	1951-2019
Blackwater River near Franklin, VA	02049500	1944-2019

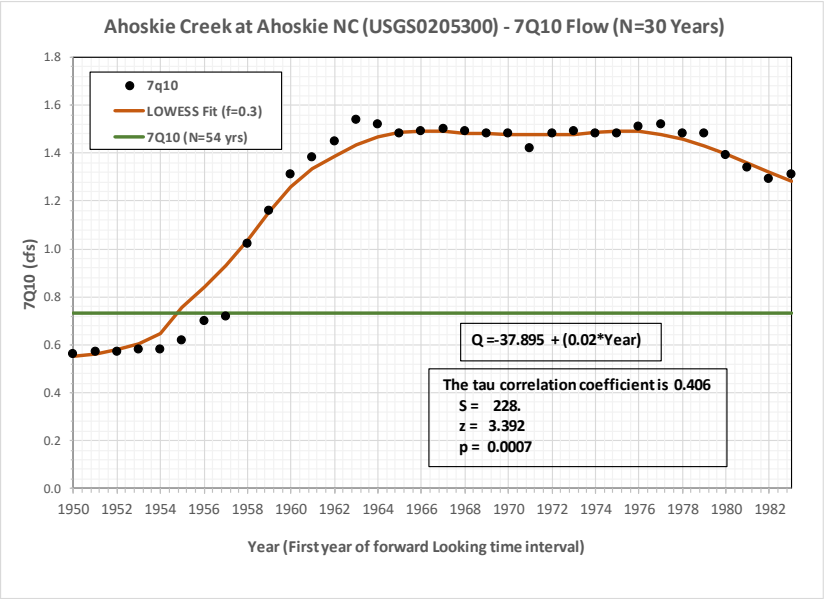
The results of the trend test on the data from the selected USGS gages are given in Table 2 and Table 3 and Figure 1. The results show that significantly increasing trend in the 30-yr window 7Q10 flows are observed for Ahoskie Creek at Ahoskie, NC and Nottoway River near Sebrell, VA and significantly decreasing trend for Potecasi Creek near Union, NC and Blackwater River near Franklin, VA. The trend for Meherrin River at Emporia, VA was not significant. For the 10-yr window 7Q10 flows, increasing trend was observed for Ahoskie Creek at Ahoskie, NC and decreasing trends were observed for Potecasi Creek near Union, NC and Blackwater River near Franklin, VA. The 10-yr window 7Q10 flows trend for Nottoway River near Sebrell, VA and for Meherrin River at Emporia, VA were not significant.

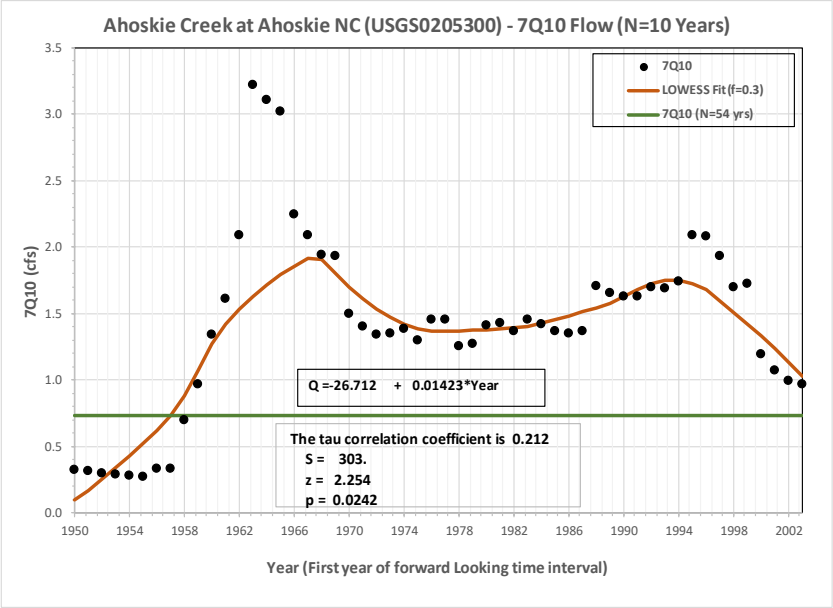
	Table 2: Trends[1] in annual 7Q10 streamflow for selected waterbodies in the Chowan Basin (30-Year 7Q10)					
Station	**USGS Gage**	**Period of Record**	**Kendall's Tau**	**Mann-Kendall Statistic (S)**	**Slope (cfs/year)**	**Trend***
Ahoskie Creek at Ahoskie, NC	02053500	1950-2019	0.406	228	0.02	Increasing
Potecasi Creek near Union, NC	02053200	1958-2019	-0.699	-193	-0.0714	Decreasing
Nottoway River near Sebrell, VA	02047000	1941-2019	0.264	238	0.04864	Increasing
Meherrin River at Emporia, VA	02052000	1951-2019	-0.239	-104	-0.1775	No significant Trend
Blackwater River near Franklin, VA	02049500	1944-2019	-0.934	-692	-0.04091	Decreasing

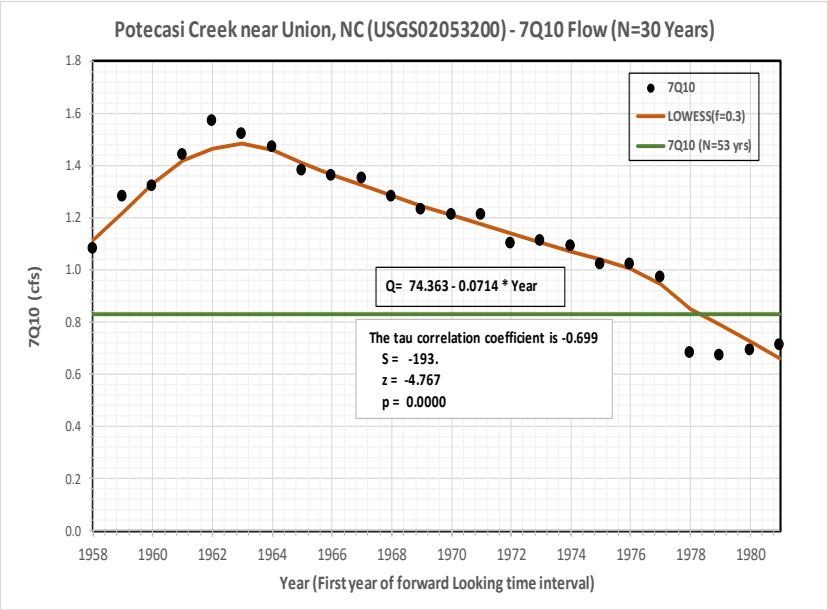
	Table 3: Trends[1] in annual 7Q10 streamflow for selected waterbodies in the Chowan Basin (10-Year 7Q10)					
Station	**USGS Gage**	**Period of Record**	**Kendall's Tau**	**Mann-Kendall Statistic (S)**	**Slope (cfs/year)**	**Trend***
Ahoskie Creek at Ahoskie, NC	02053500	1950-2019	0.212	303	0.01423	Increasing
Potecasi Creek near Union, NC	02053200	1958-2019	-0.603	-570	-0.0333	Decreasing
Nottoway River near Sebrell, VA	02047000	1941-2019	-0.055	-108	-0.0308	No significant Trend
Meherrin River at Emporia, VA	02052000	1951-2019	-0.106	-130	-0.11	No Significant trend
Blackwater River near Franklin, VA	02049500	1944-2019	-0.592	-1013	-0.03115	Decreasing

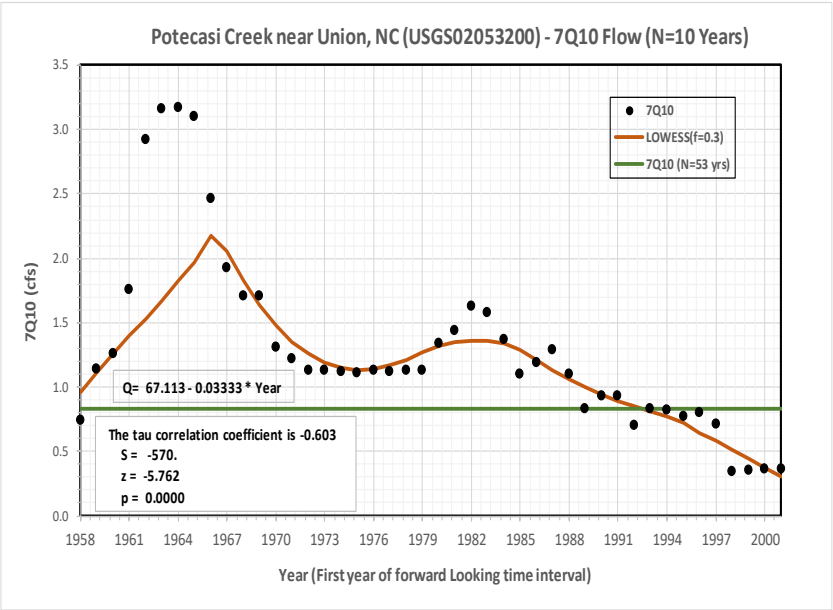
[1]*Mann-Kendall trend test (USGS Computer Program for the Kendall Family of Trend Tests)*

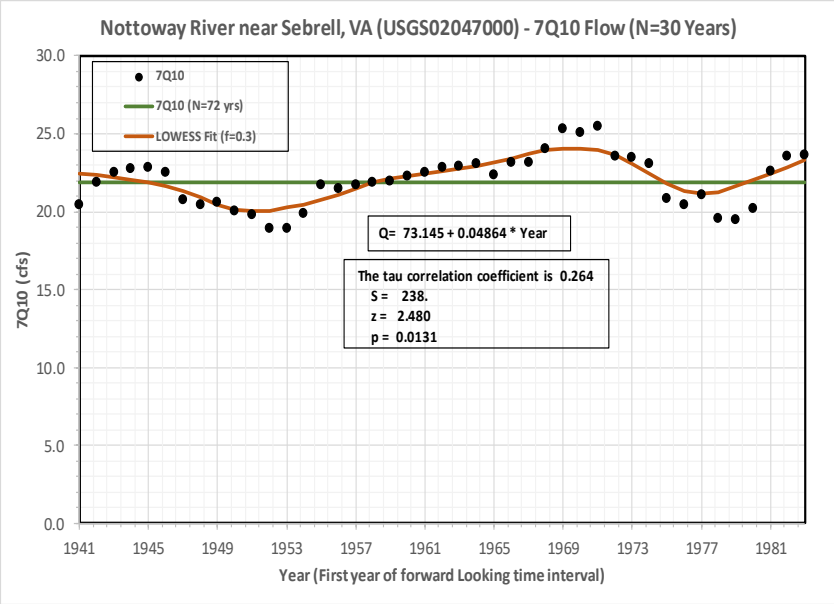
**A threshold significance level of 0.05 (α=0.05) was used; a p-value of less than 0.05 means that the trend is considered significant*

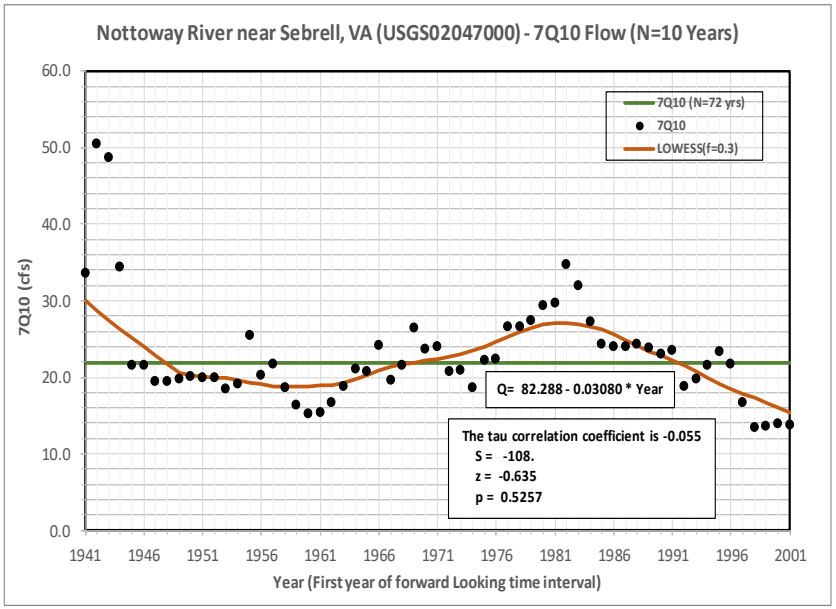

Ahoskie Creek at Ahoskie NC (USGS0205300) - 7Q10 Flow (N=30 Years)
7q10
LOWESS Fit (f=0.3)
7Q10 (N=54 yrs)
Q =-37.895 + (0.02*Year)
The tau correlation coefficient is 0.406
S = 228.
z = 3.392
p = 0.0007
7Q10 (cfs)
Year (First year of forward Looking time interval)

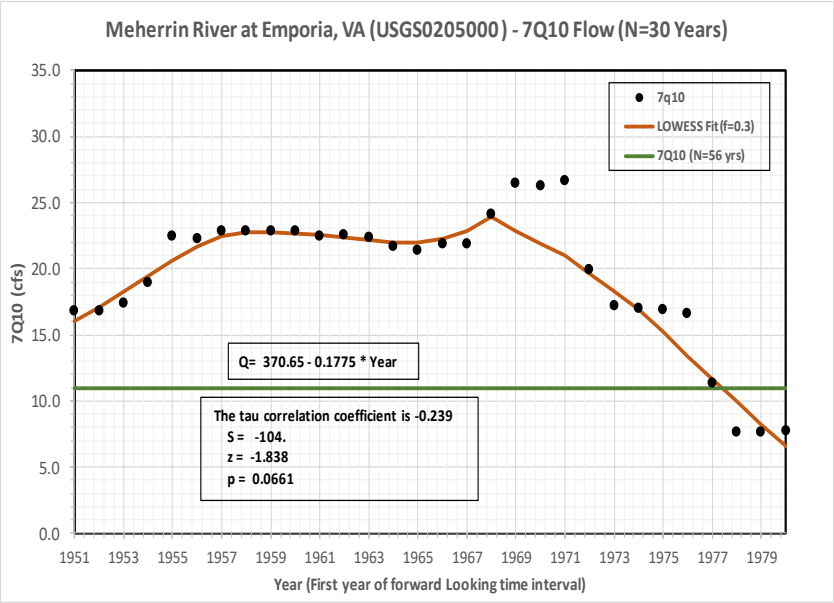

Ahoskie Creek at Ahoskie NC (USGS0205300) - 7Q10 Flow (N=10 Years)
7Q10
LOWESS Fit (f=0.3)
7Q10 (N=54 yrs)
Q =-26.712 + 0.01423*Year
The tau correlation coefficient is 0.212
S = 303.
z = 2.254
p = 0.0242
7Q10 (cfs)
Year (First year of forward Looking time interval)

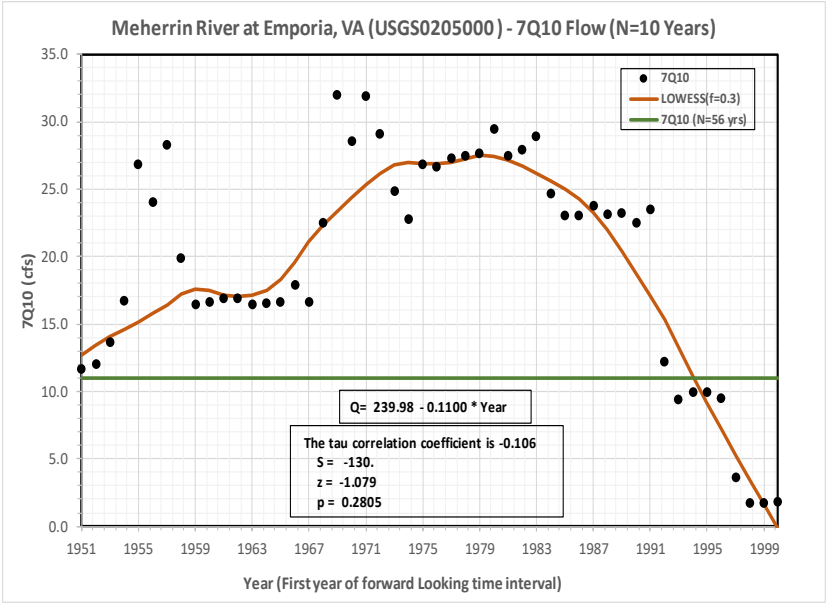

Potecasi Creek near Union, NC (USGS02053200) - 7Q10 Flow (N=30 Years)
7Q10
LOWESS(f=0.3)
7Q10 (N=53 yrs)
Q= 74.363 - 0.0714 * Year
The tau correlation coefficient is -0.699
S = -193.
z = -4.767
p = 0.0000
7Q10 (cfs)
Year (First year of forward Looking time interval)

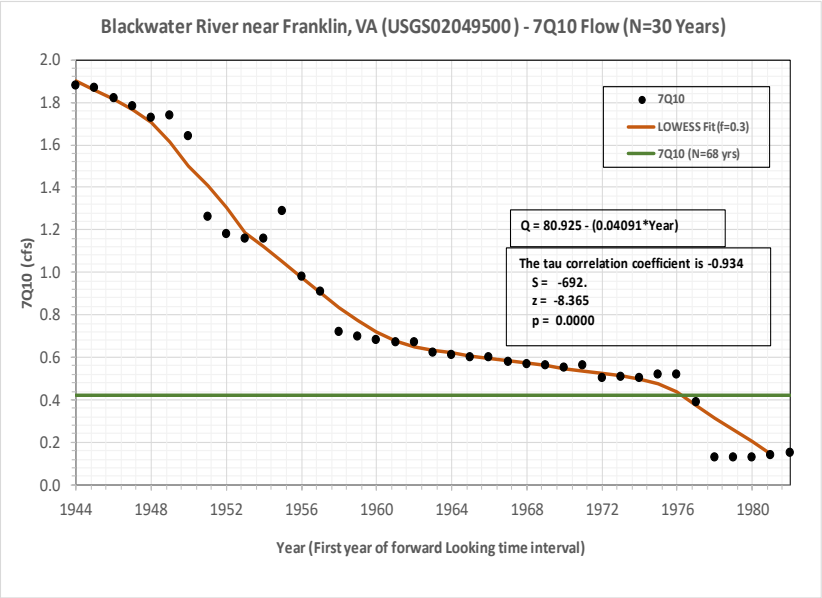

Potecasi Creek near Union, NC (USGS02053200) - 7Q10 Flow (N=10 Years)
7Q10
LOWESS(f=0.3)
7Q10 (N=53 yrs)
Q= 67.113 - 0.03333 * Year
The tau correlation coefficient is -0.603
S = -570.
z = -5.762
p = 0.0000
7Q10 (cfs)
Year (First year of forward Looking time interval)


Nottoway River near Sebrell, VA (USGS02047000) - 7Q10 Flow (N=30 Years)
7Q10
7Q10 (N=72 yrs)
LOWESS Fit (f=0.3)
Q= 73.145 + 0.04864 * Year
The tau correlation coefficient is 0.264
S = 238.
z = 2.480
p = 0.0131
7Q10 (cfs)
Year (First year of forward Looking time interval)


Nottoway River near Sebrell, VA (USGS02047000) - 7Q10 Flow (N=10 Years)
7Q10 (N=72 yrs)
7Q10
LOWESS(f=0.3)
Q= 82.288 - 0.03080 * Year
The tau correlation coefficient is -0.055
S = -108.
z = -0.635
p = 0.5257
7Q10 (cfs)
Year (First year of forward Looking time interval)


Meherrin River at Emporia, VA (USGS0205000) - 7Q10 Flow (N=30 Years)
7q10
LOWESS Fit (f=0.3)
7Q10 (N=56 yrs)
Q= 370.65 - 0.1775 * Year
The tau correlation coefficient is -0.239
S = -104.
z = -1.838
p = 0.0661
7Q10 (cfs)
Year (First year of forward Looking time interval)


Meherrin River at Emporia, VA (USGS0205000) - 7Q10 Flow (N=10 Years)
7Q10
LOWESS(f=0.3)
7Q10 (N=56 yrs)
Q= 239.98 - 0.1100 * Year
The tau correlation coefficient is -0.106
S = -130.
z = -1.079
p = 0.2805
7Q10 (cfs)
Year (First year of forward Looking time interval)



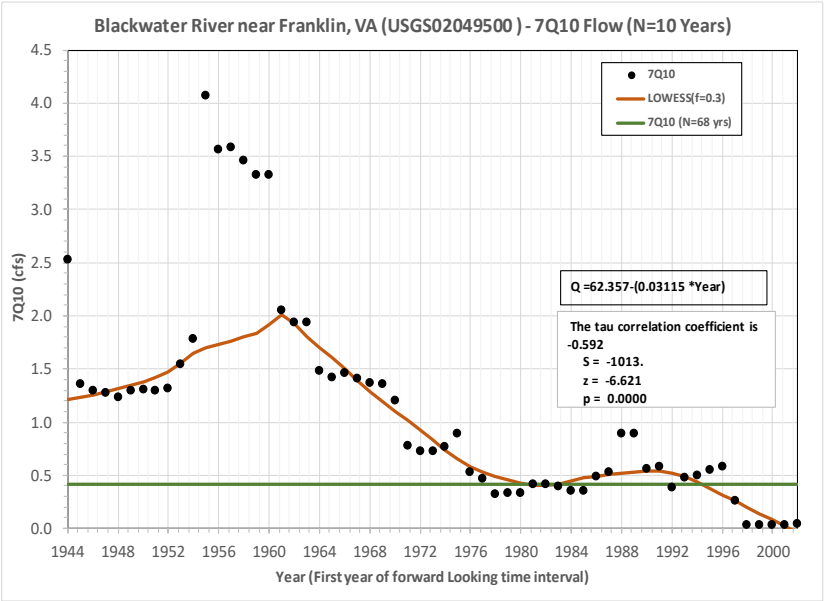


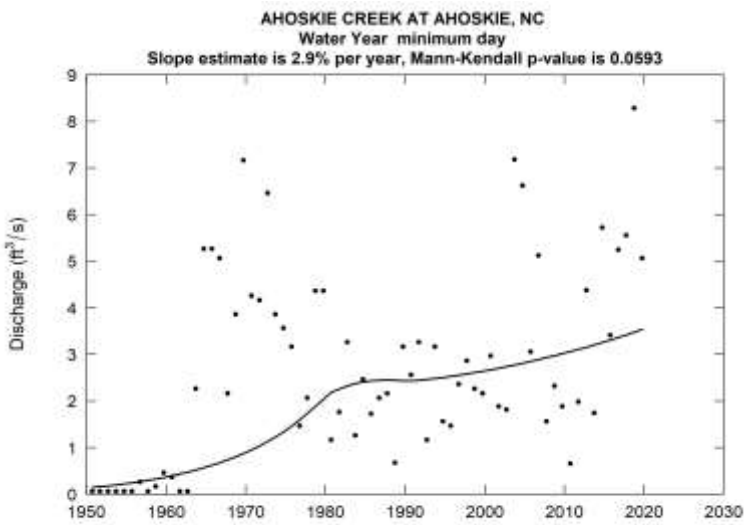
Figure 1. Trend in 7Q10 flow at selected Chowan River Basin Stations

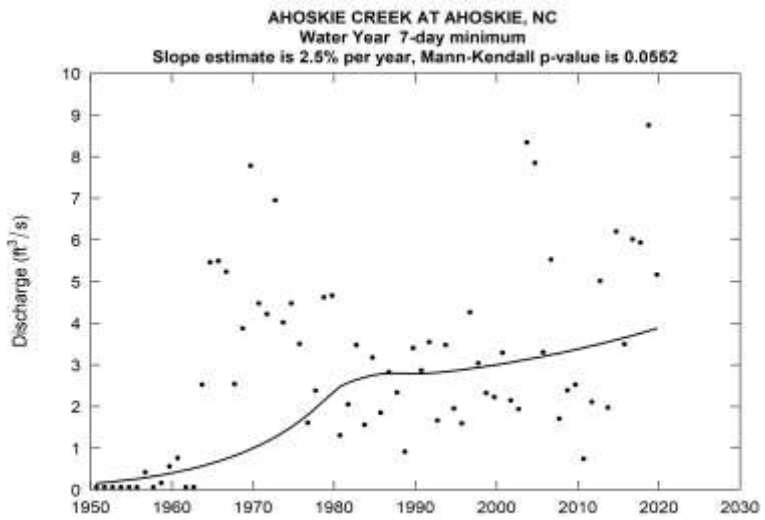
Trends in Daily flow for annual time-frame

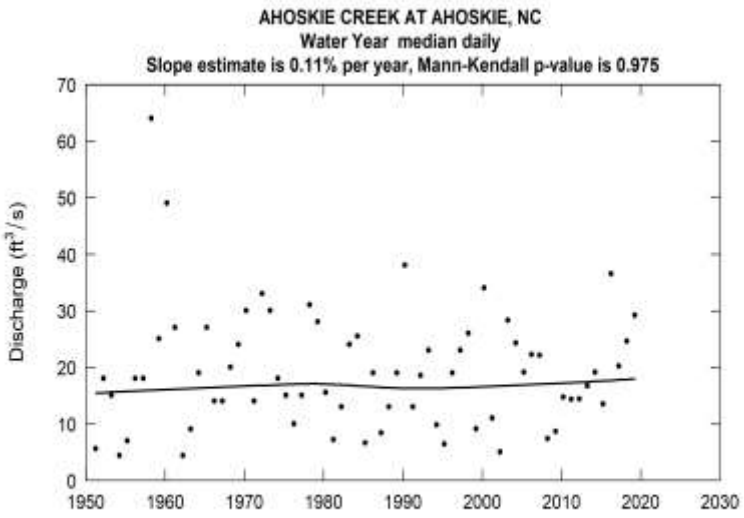
In addition to the trend test for the 7Q10 flows, trends in the water year daily minimum flow, 7-day minimum flow, daily median flow, daily mean flow, and daily maximum flow were performed for the period of record at the selected stations to explore the nature and extent of the streamflow changes in the Chowan Basin using the EGRET software (Hirsch and De Cicco, 2015). The plots for Ahoskie Creek station are provided (Figure 2) to show examples of these plots. The plots for the other stations are included in Appendix A.

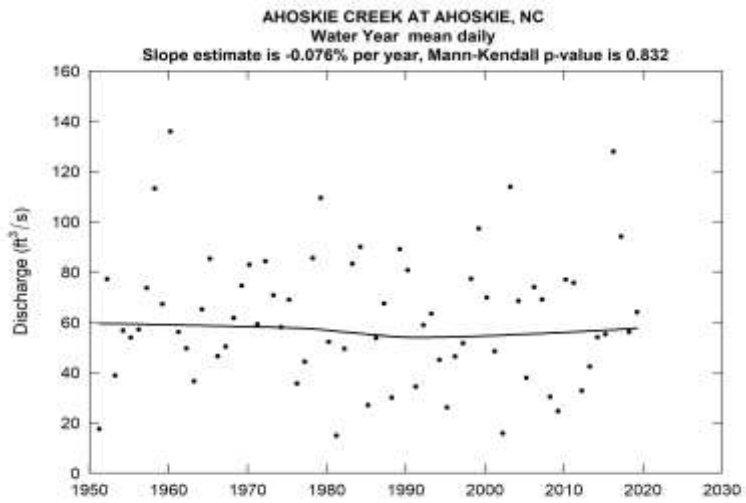
Using the site Ahoskie Creek at Ahoskie, NC for the period from February 1, 1950, through September 30, 2019, as an example, trends in daily flow statistics for an annual time-frame are shown in Fig. 2. Positive trends are observed in all five annual statistics except the water year mean daily flow, which has shown a negative trend. The slopes, indicating trend magnitude, are quite different for the different statistics. The largest slope is associated with the annual minimum day flows (2.9% per year). The smallest positive slope is for the median daily flow (0.11% per year). A trend of 2.9% per year in the slope of the annual minimum day indicates a total increase in the annual minimum day's flow over this 70-year period of 640%. The trend in the median daily flow of 0.11% per year translates to a total increase of 8% over this period. Negative trends are observed in the mean daily flow with a reduction of -0.076% per year. This indicates that the annual mean daily flow decreased by a total of 5% over the 70-year period. For Ahoskie Creek, the trend in flow across the full range of the flow distribution is positive and of substantial magnitude, particularly for the lower extremes of the flow distribution for all five annual statistics except the water year mean daily flow.

Summary of the trend results in selected flow statistics for the selected Chowan River Basin stations is given in Table 4. The results show that there were significant upward trends in minimum day and 7-day minimum flow for Ahoskie Creek and significant downward trend for Nottoway River and Blackwater River. The trends for median and mean flows were not significant for the selected sites. While the maximum day flow increased significantly for the Blackwater River the trends in maximum day flow for the other stations were not significant.


AHOSKIE CREEK AT AHOSKIE, NC
Water Year minimum day
Slope estimate is 2.9% per year, Mann-Kendall p-value is 0.0593
Discharge (ft³/s)


AHOSKIE CREEK AT AHOSKIE, NC
Water Year 7-day minimum
Slope estimate is 2.5% per year, Mann-Kendall p-value is 0.0552
Discharge (ft³/s)


AHOSKIE CREEK AT AHOSKIE, NC
Water Year median daily
Slope estimate is 0.11% per year, Mann-Kendall p-value is 0.975
Discharge (ft³/s)


AHOSKIE CREEK AT AHOSKIE, NC
Water Year mean daily
Slope estimate is -0.076% per year, Mann-Kendall p-value is 0.832
Discharge (ft³/s)

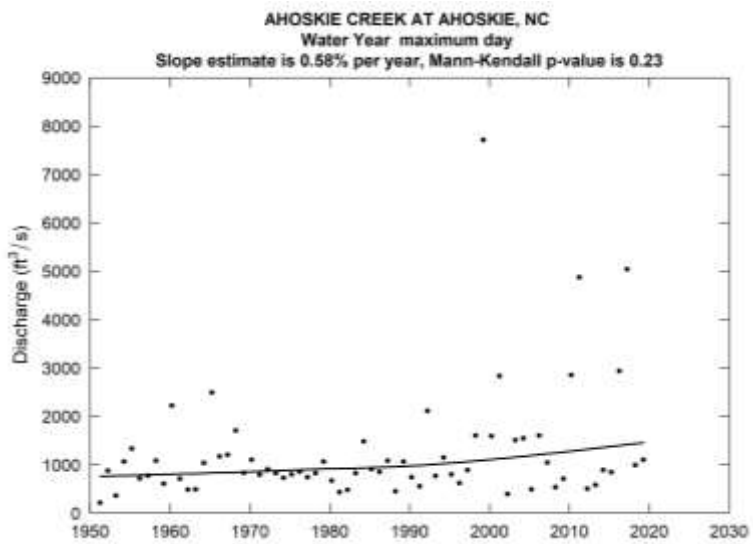


Figure 2. Trend in selected flow statistics for Ahoskie Creek, Ahoskie. NC

Table 4. Trends in selected flow statistics for selected waterbodies in the Chowan Basin						
Station	**USGS Gage**	**Minimum**	**7-day Minimum**	**Median**	**Mean**	**Maximum**
Ahoskie Creek at Ahoskie, NC	02053500	Increasing (2.9% per year)*	Increasing (2.5% per year)	No trend (0.11 per year)	No trend (-0.076 per year)	No trend (0.58% per year)
Potecasi Creek near Union, NC	02053200	No trend (-0.25% per year)	No trend (0.021% per year)	No trend (-0.32% per year)	No trend (-0.021% per year)	No trend (0.68% per year)
Nottoway River near Sebrell, VA	02047000	Decreasing (-0.8% per year)	Decreasing (-0.87% per year)	No Trend (-0.2% per year)	No Trend (-0.012% per year)	No Trend (0.071% per year)
Meherrin River at Emporia, VA	02052000	No trend (0.39% per year)	No trend (-0.32% per year)	No trend (-0.38% per year)	No trend (-0.21% per year)	No trend (0.26% per year)
Blackwater River near Franklin, VA	02049500	Decreasing (-2% per year)	Decreasing (-2.2% per year)	No Trend (0.09% per year)	No Trend (0.18% per year)	Increasing (0.81% per year)

* ***Slope in % per year is shown in parenthesis***

Quantile-Kendall plot

A recently developed type of plot, the Quantile-Kendall plot (Hirsch, 2018), was used to explore flow trends at the selected sites in the Chowan River Basin. The Quantile-Kendall plot (Hirsch, 2018) is an exploratory plot constructed using a trend slope computed for a given order statistic. The Quantile-Kendall plots, derived using daily flow records, are used to evaluate flow trends across the range of flow values at a given site for a specified time-frame (Annual time frame for the Chowan analysis). Flows from every year are ranked from 1 to 365 (one being the lowest flow of the year). A trend slope is then calculated for the first ordered flow for each year over the specified period of years and this slope is plotted as the left most point on the graphs. The trend test and the associated Thiel-Sen slope estimates are computed and plotted in a similar manner for each consecutive rank. The 365th rank is the slope representing the highest flows for each year. The Quantile-Kendall plots for an annual timeframe show results of 365 Mann-Kendall trend tests, and the associated Thiel-Sen slope estimates, for each of the 365 ranks (order statistics) over a specified period of years.

In these plots, the trend slopes are computed using the Thiel-Sen slope estimator (Sen, 1968; Thiel, 1950) of the logarithms of the values shown and then transformed to percentage changes per year (Hirsch and De Cicco, 2015). The strength of the statistical evidence for these trends is evaluated using the Mann-Kendall trend test, adjusted for serial correlation using the adjustment method proposed by Yue et al. (2002). The strength of the evidence is characterized by the likelihood that the direction of the estimated trend is correct, computed from the Mann-Kendall test p-values as [1 − (p / 2)]. The color in these plots represents the p value for the Mann-Kendall test for trend as described above. Red indicates a trend that is significant at alpha = 0.05. Black indicates an attained significance between 0.05 and 0.1. The grey dots are trends that are not significant at the alpha level of 0.1. The likelihood designations follow the pattern used by Hirsch et al. (2015) and are shown in this table.

Likelihood designation	Range of likelihood values
Highly likely	0.95 *to* 1.00
Very likely	0.90 *to* <0.95
Likely	0.67 *to* <0.90
Uncertain	0.50 *to* <0.67

Using the stream gage at Ahoskie Creek at Ahoskie, NC as an example, trends in flow across the entire frequency distribution of flows are shown in the Quantile-Kendall plot in Fig. 3. There are substantial positive trends at the lower extreme of the flow distribution (less than 0.01 non-exceedance probability) and highly likely negative trends in the upper middle part of the flow duration curve (0.6 to 0.9 non-exceedance probability). These trends can be considered very likely or highly likely upwards for almost all order statistics in the lower extreme of the distribution. The percentage increases in low flows were much more substantial than those at high flows and were the least substantial near the median and higher flow part of the

distribution. The trends in middle range flow (0.025 - 0.6 non-exceedance probability) and in the higher flow range (>0.9 non-exceedance probability) are classified as unlikely.

Quantile-Kendall plots comparing flow trend results among the five selected sites for the period of record are shown in Fig. 4 to Fig 7. The flow trends indicated that positive or negative trends were unlikely across the entire frequency distribution of flows for Potecasi Creek near Union, NC and Meherrin River at Emporia, VA stations. For Nottoway River near Sebrell, VA, only the flows in the range of 0.10 to 0.20 non-exceedance probability were observed to exhibit very likely downward trend. For the Blackwater River near Franklin, VA site there are substantial negative trends at the lower extreme of the flow distribution (less than 0.05 non-exceedance probability) and considerable positive trends at the higher extreme of the flow duration curve (> 0.95 non-exceedance probability), and these trends can be considered very likely or highly likely downwards for almost all order statistics in the lower extreme of the distribution, and very likely upwards for all flows in the higher extreme part of the distribution.

Overall the Ahoskie and the Black River period of record show the greatest evidence for flow trends among these sites.

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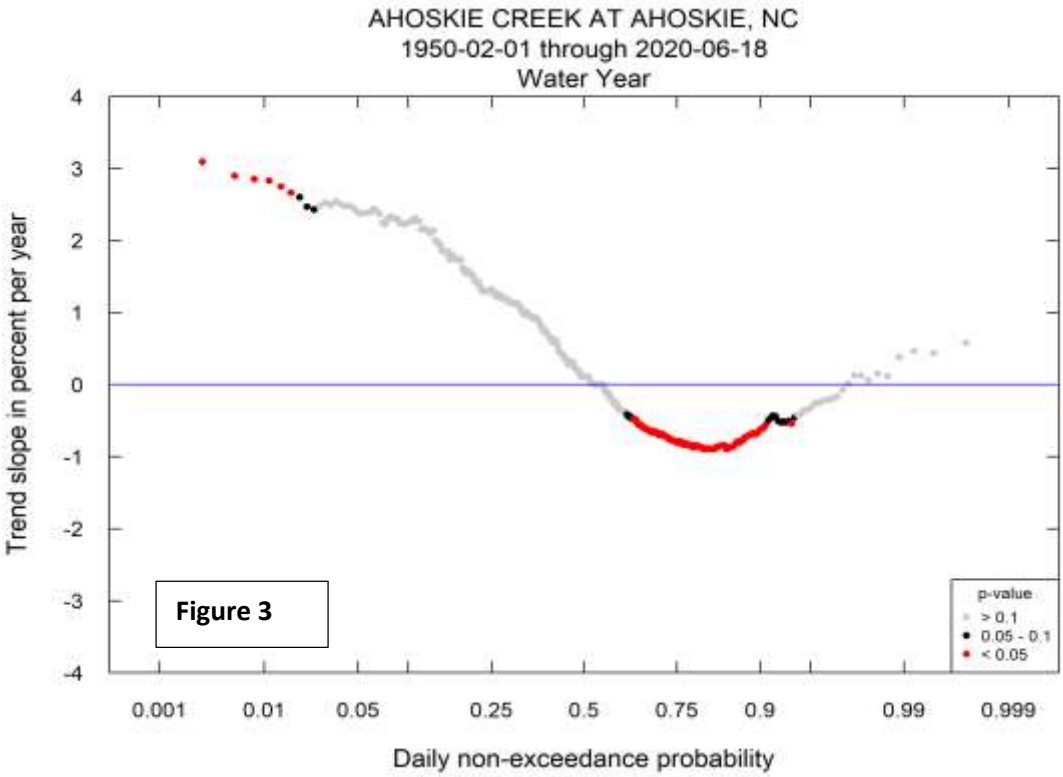
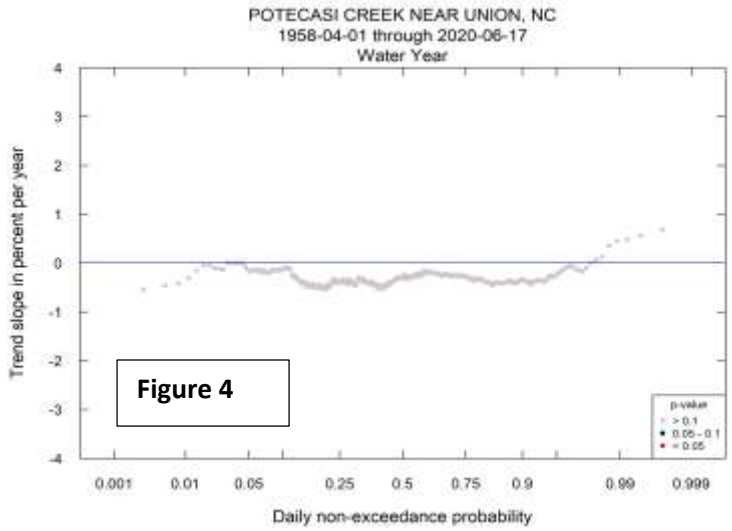
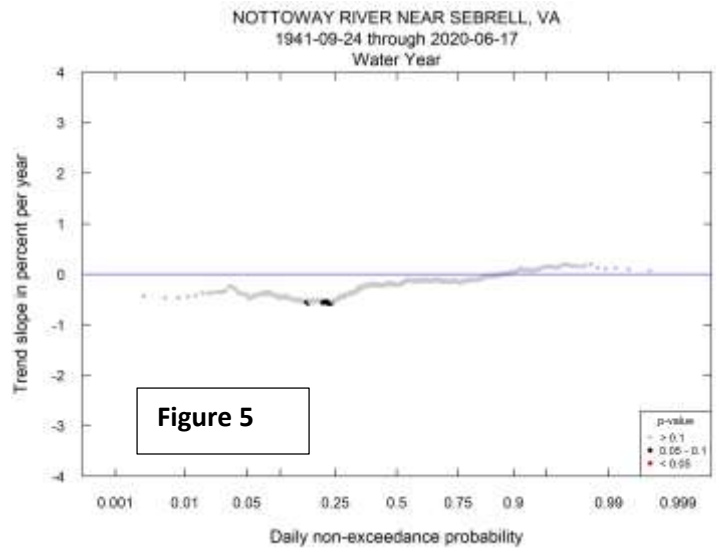
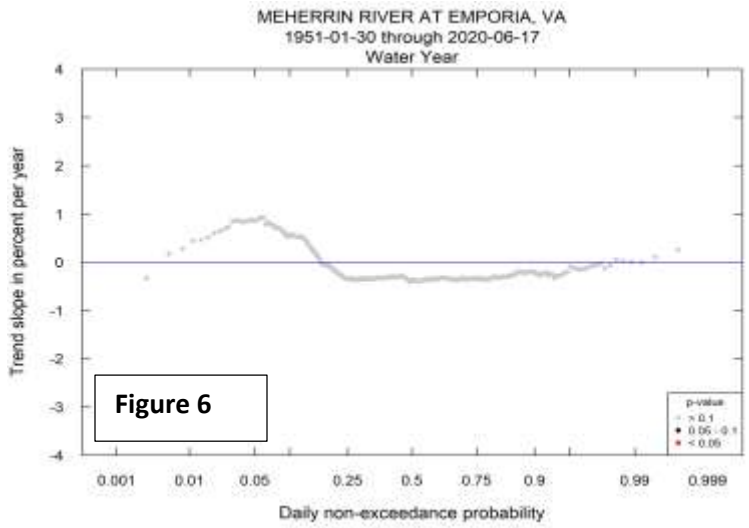
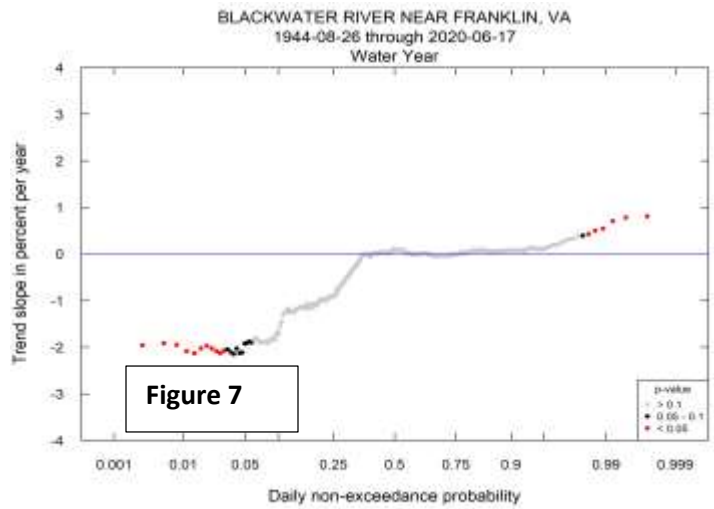


Figure 3. **Quantile-Kendall plots for Ahoskie Creek**









Figures 4 to 7. Quantile-Kendall plots for selected Chowan River Basin Stations

Summary

Trends in streamflow for selected Chowan River Basin flow gages were explored using the Mann-Kendall trend test. In addition, temporal changes in daily streamflow statistics across an annual time period for the period of record were explored using the EGRET. The Quantile-Kendall plot was also used to evaluate flow trends across the range of streamflow values at a given site for an annual time-frame. While the 30-Year 7Q10 flow increased significantly for Ahoskie Creek and Nottoway River it decreased for Blackwater River and Potecasi Creek. Significantly upward trends were observed in minimum day and 7-day minimum flow for Ahoskie Creek and significant downward trend were observed for Nottoway River and Blackwater River. The maximum day flow increased significantly for the Blackwater River. The Quantile-Kendall plot show that trends for Ahoskie Creek can be considered very likely or highly likely upwards for almost all order statistics in the lower extreme of the distribution, and very likely or highly likely downwards for all flows in the upper middle part of the distribution. For Blackwater River, these trends can be considered very likely or highly likely downwards for almost all order statistics in the lower extreme of the distribution, and very likely upwards for all flows in the higher extreme part of the distribution. The Ahoskie and the Blackwater River period of record show the overall greatest evidence for flow trends among these sites.

References

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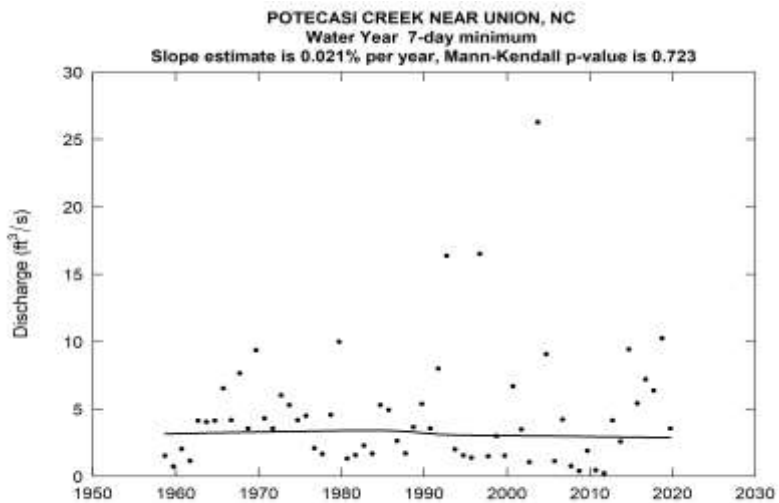
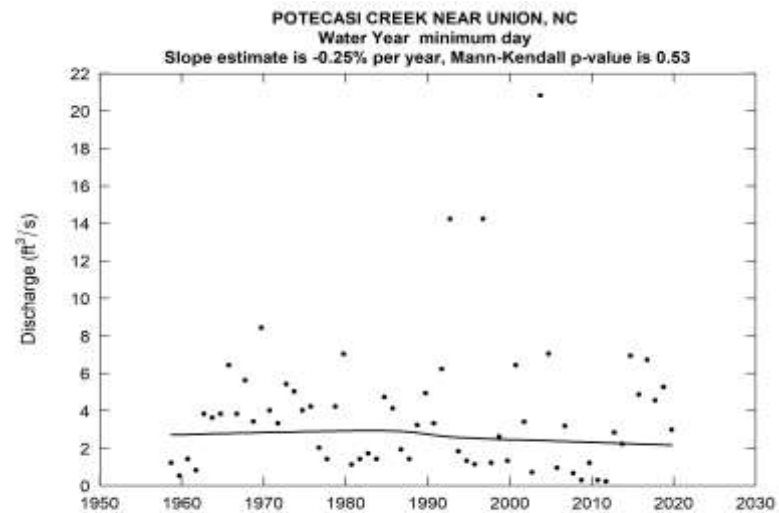
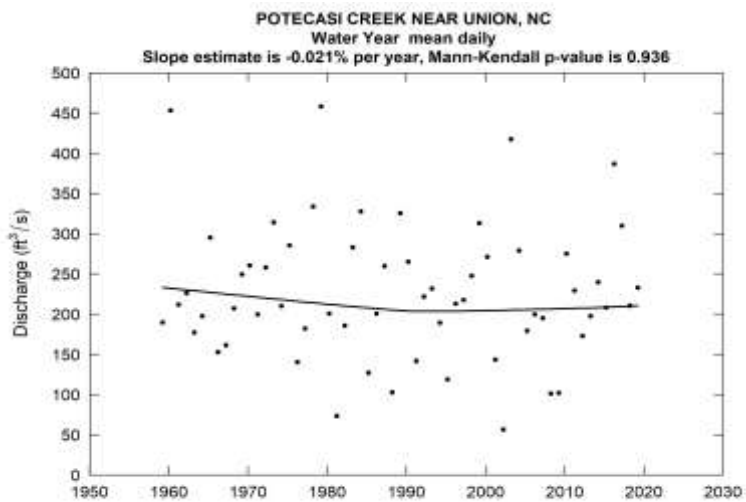
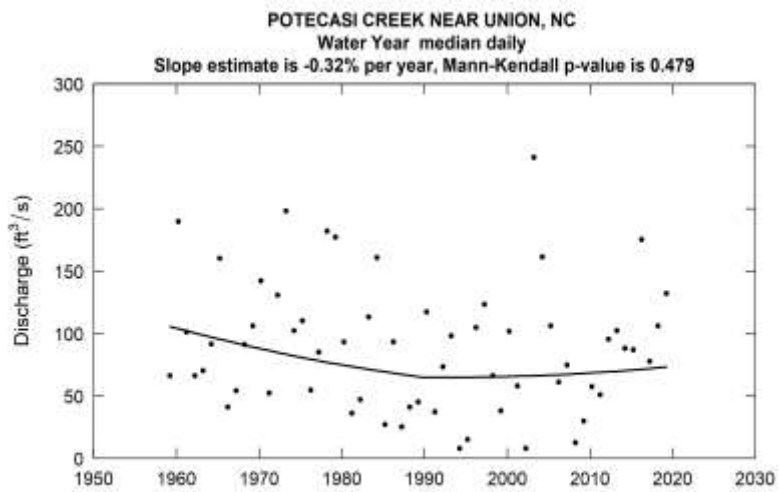
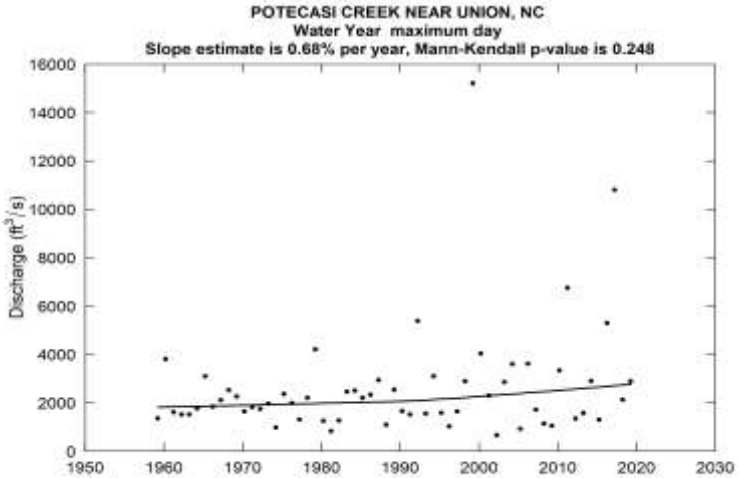
Appendix A
Plots of Selected Flow Statistics

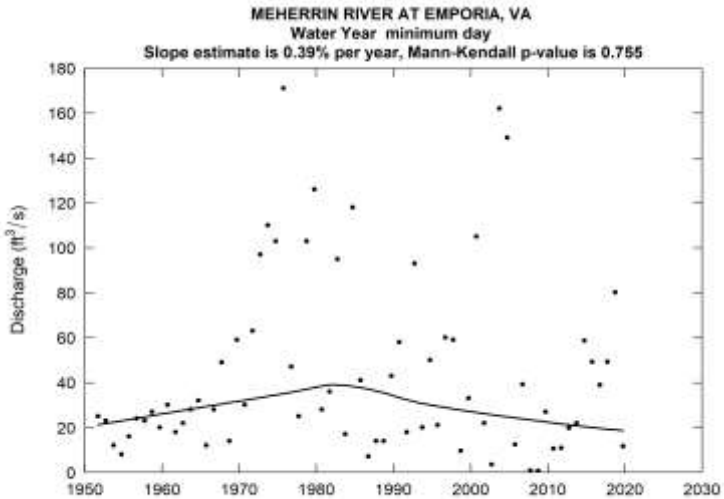

POTECASI CREEK NEAR UNION, NC
Water Year 7-day minimum
Slope estimate is 0.021% per year, Mann-Kendall p-value is 0.723
Discharge (ft3/s)
0
5
10
15
20
25
30
1950
1960
1970
1980
1990
2000
2010
2020
2030

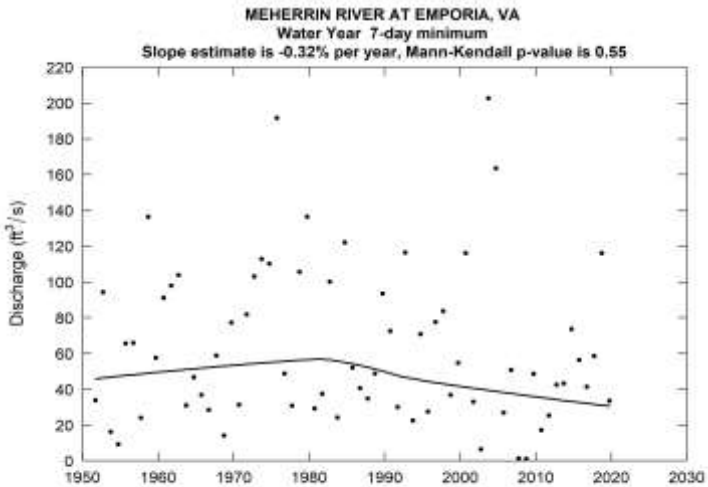

POTECASI CREEK NEAR UNION, NC
Water Year minimum day
Slope estimate is -0.25% per year, Mann-Kendall p-value is 0.53
Discharge (ft3/s)
0
2
4
6
8
10
12
14
16
18
20
22
1950
1960
1970
1980
1990
2000
2010
2020
2030

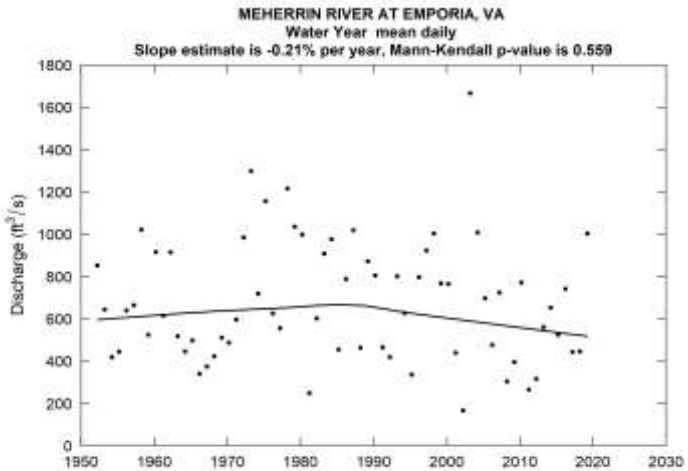

POTECASI CREEK NEAR UNION, NC
Water Year mean daily
Slope estimate is -0.021% per year, Mann-Kendall p-value is 0.936
Discharge (ft3/s)
0
50
100
150
200
250
300
350
400
450
500
1950
1960
1970
1980
1990
2000
2010
2020
2030

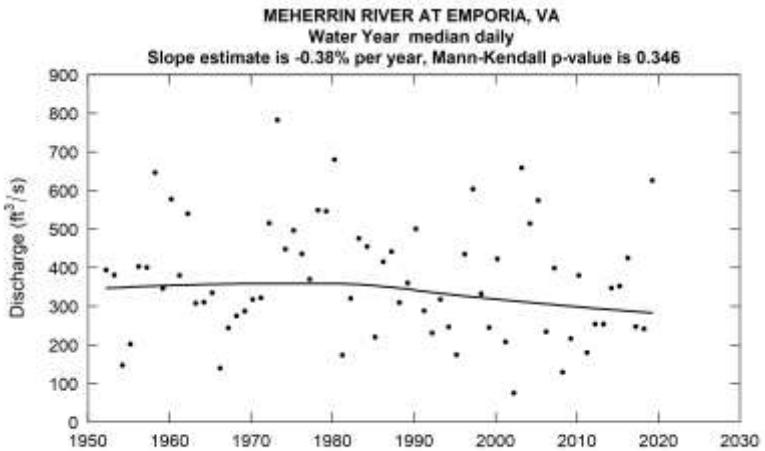

POTECASI CREEK NEAR UNION, NC
Water Year median daily
Slope estimate is -0.32% per year, Mann-Kendall p-value is 0.479
Discharge (ft3/s)
0
50
100
150
200
250
300
1950
1960
1970
1980
1990
2000
2010
2020
2030

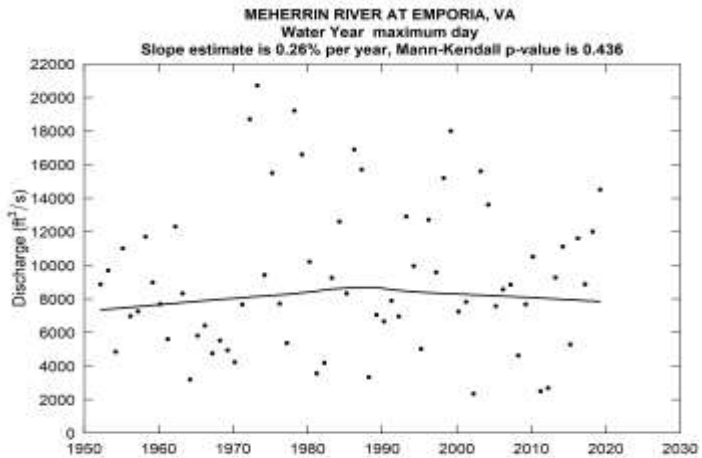

POTECASI CREEK NEAR UNION, NC
Water Year maximum day
Slope estimate is 0.68% per year, Mann-Kendall p-value is 0.248
Discharge (ft³/s)
0
2000
4000
6000
8000
10000
12000
14000
16000
1950
1960
1970
1980
1990
2000
2010
2020
2030

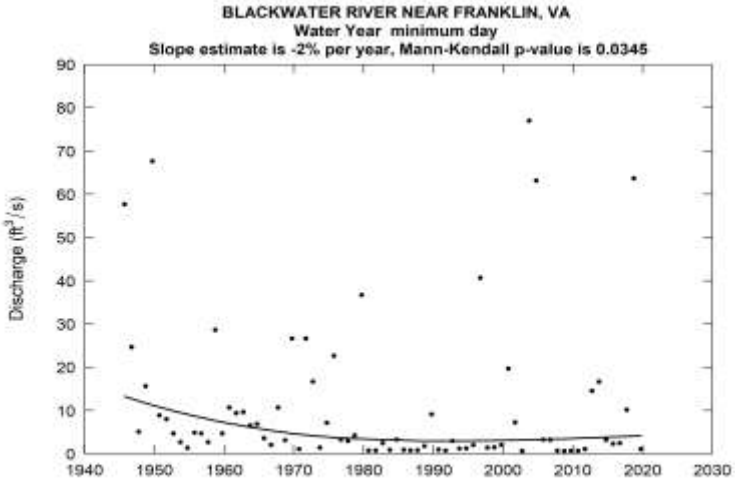

MEHERRIN RIVER AT EMPORIA, VA
Water Year minimum day
Slope estimate is 0.39% per year, Mann-Kendall p-value is 0.755
Discharge (ft³/s)
0
20
40
60
80
100
120
140
160
180
1950
1960
1970
1980
1990
2000
2010
2020
2030

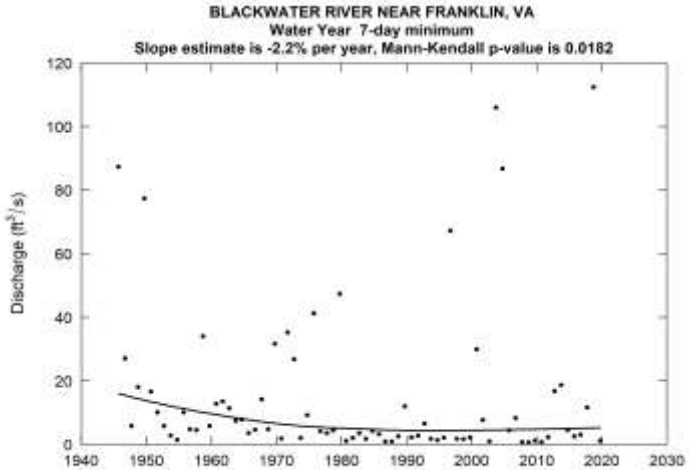

MEHERRIN RIVER AT EMPORIA, VA
Water Year 7-day minimum
Slope estimate is -0.32% per year, Mann-Kendall p-value is 0.55
Discharge (ft³/s)
0
20
40
60
80
100
120
140
160
180
200
220
1950
1960
1970
1980
1990
2000
2010
2020
2030

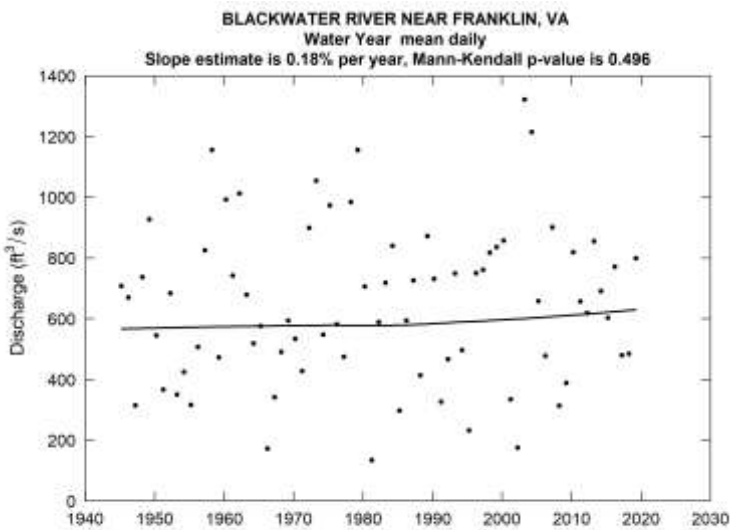

MEHERRIN RIVER AT EMPORIA, VA
Water Year mean daily
Slope estimate is -0.21% per year, Mann-Kendall p-value is 0.559
Discharge (ft³/s)
0
200
400
600
800
1000
1200
1400
1600
1800
1950
1960
1970
1980
1990
2000
2010
2020
2030

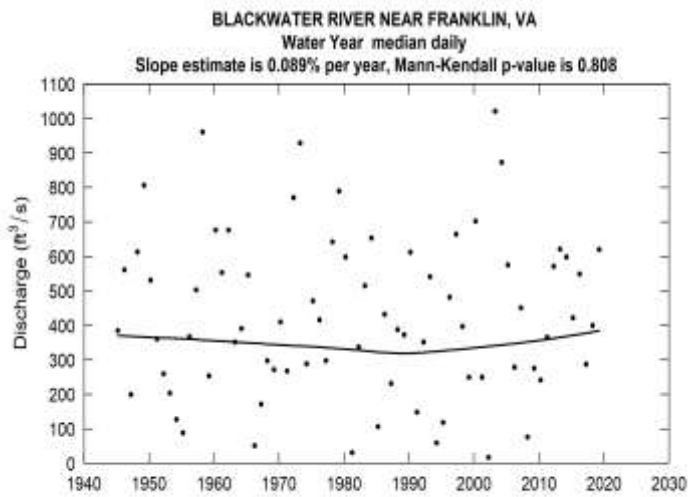

MEHERRIN RIVER AT EMPORIA, VA
Water Year median daily
Slope estimate is -0.38% per year, Mann-Kendall p-value is 0.346
Discharge (ft³/s)
0
100
200
300
400
500
600
700
800
900
1950
1960
1970
1980
1990
2000
2010
2020
2030

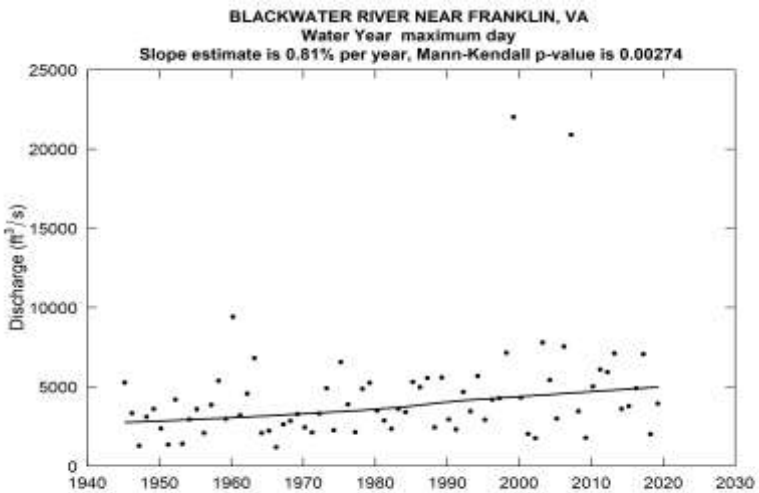

MEHERRIN RIVER AT EMPORIA, VA
Water Year maximum day
Slope estimate is 0.26% per year, Mann-Kendall p-value is 0.436
Discharge (ft³/s)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
1950
1960
1970
1980
1990
2000
2010
2020
2030

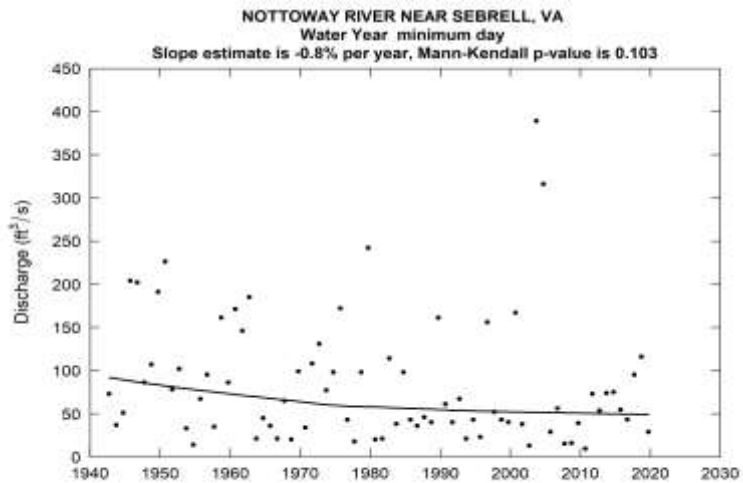

BLACKWATER RIVER NEAR FRANKLIN, VA
Water Year minimum day
Slope estimate is -2% per year, Mann-Kendall p-value is 0.0345
Discharge (ft³/s)
0
10
20
30
40
50
60
70
80
90
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030

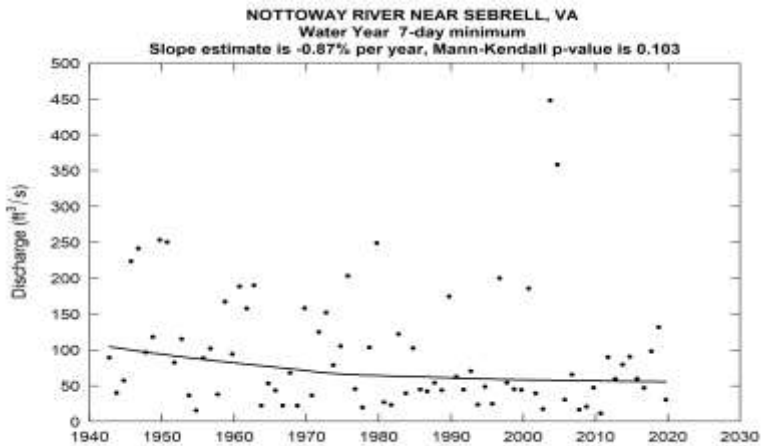

BLACKWATER RIVER NEAR FRANKLIN, VA
Water Year 7-day minimum
Slope estimate is -2.2% per year, Mann-Kendall p-value is 0.0182
Discharge (ft³/s)
0
20
40
60
80
100
120
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030

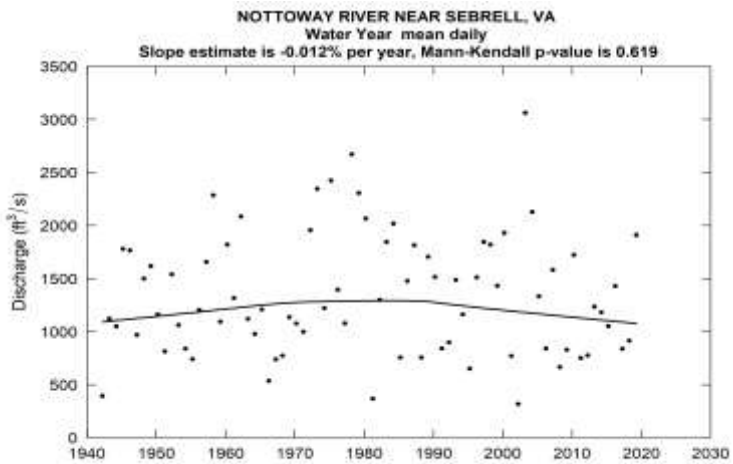

BLACKWATER RIVER NEAR FRANKLIN, VA
Water Year mean daily
Slope estimate is 0.18% per year, Mann-Kendall p-value is 0.496
Discharge (ft³/s)
0
200
400
600
800
1000
1200
1400
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030

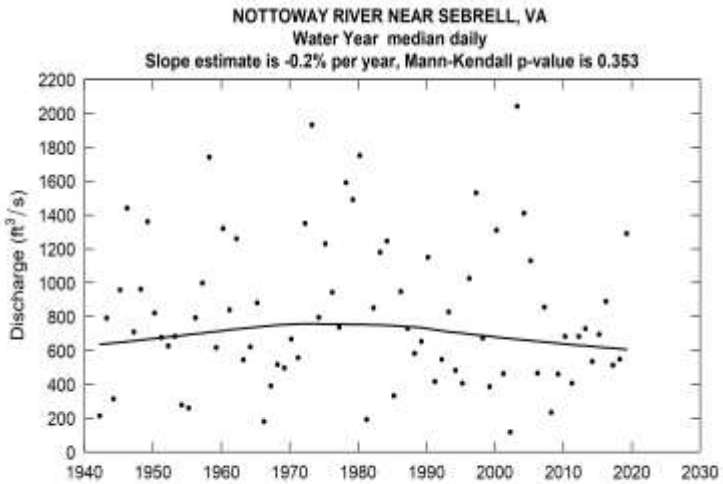

BLACKWATER RIVER NEAR FRANKLIN, VA
Water Year median daily
Slope estimate is 0.089% per year, Mann-Kendall p-value is 0.808
Discharge (ft³/s)
0
100
200
300
400
500
600
700
800
900
1000
1100
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030

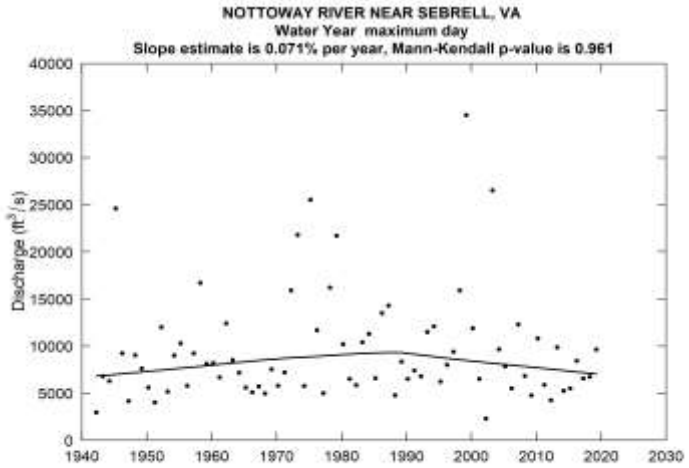

BLACKWATER RIVER NEAR FRANKLIN, VA
Water Year maximum day
Slope estimate is 0.81% per year, Mann-Kendall p-value is 0.00274
Discharge (ft³/s)
0
5000
10000
15000
20000
25000
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030


NOTTOWAY RIVER NEAR SEBRELL, VA
Water Year minimum day
Slope estimate is -0.8% per year, Mann-Kendall p-value is 0.103
Discharge (ft³/s)
0
50
100
150
200
250
300
350
400
450
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030


NOTTOWAY RIVER NEAR SEBRELL, VA
Water Year 7-day minimum
Slope estimate is -0.87% per year, Mann-Kendall p-value is 0.103
Discharge (ft³/s)
0
50
100
150
200
250
300
350
400
450
500
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030


NOTTOWAY RIVER NEAR SEBRELL, VA
Water Year mean daily
Slope estimate is -0.012% per year, Mann-Kendall p-value is 0.619
Discharge (ft³/s)
0
500
1000
1500
2000
2500
3000
3500
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030


NOTTOWAY RIVER NEAR SEBRELL, VA
Water Year median daily
Slope estimate is -0.2% per year, Mann-Kendall p-value is 0.353
Discharge (ft³/s)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030


NOTTOWAY RIVER NEAR SEBRELL, VA
Water Year maximum day
Slope estimate is 0.071% per year, Mann-Kendall p-value is 0.961
Discharge (ft³/s)
0
5000
10000
15000
20000
25000
30000
35000
40000
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030