# Appendix G. Critical Period Analysis

This appendix is a deliberative document related to determination of an appropriate critical period for developing the Chesapeake Bay total maximum daily load (TMDL).

# Appendix G - Determination of Critical Conditions for the Chesapeake Bay TMDL

## Introduction

The Chesapeake Bay TMDL must be developed to attain applicable water quality standards. Critical conditions for stream flow pollutant loading and water quality parameters must be taken into account. The objective is to select a three-year period as the critical period. The Water Quality Goal Team decided that the critical period would be selected from the previously selected hydrologic period 1991-2000 because that timeframe is representative of long-term hydrology, is within the model calibration period and would facilitate modeling operations (see Section 6.1.1 and Appendix F). A three-year period was selected in order to coincide with the Chesapeake Bay water quality criteria assessment period (USEPA 2003). The critical period should be representative of an approximate 10-year return period to maintain consistency with other TMDLs develop and published by the Chesapeake Bay watershed jurisdictions.

The following sections discuss the process for determining the critical period based on determining the return period for each of the three-year time frames within the 1991-2000 hydrologic period using various methods.

## Approaches Used in Previous TMDLs to Select the Critical Period

To determine if there is consistent approach to establishing a critical period among the Chesapeake Bay watershed jurisdictions, Tetra Tech staff explored each jurisdiction’s water quality standards, polled the seven watershed jurisdictions, and referenced previously completed TMDLs.

Generally, the jurisdictions’ water quality standards do not address a method for establishing the critical hydrologic period. Further, EPA does not have specific guidance or regulations on how to determine critical period. EPA only requires that critical conditions and seasonal variations are considered (40 CFR §130.7 (c)(1)). EPA Region 3’s approach has been that jurisdictions may use any method for determining critical conditions and seasonal variations as long as the approach is supported by sound science.

In polling the jurisdictions regarding their approaches to determining the hydrology critical period, all jurisdictions reported that the determination is dependent on the pollutant, the water quality standards, the TMDL endpoint and the amount of flow data available. All jurisdictions reported that the critical period was determined using a representative data set capturing a range of high, low and average flows. Maryland, the District of Columbia and Virginia reported selecting the critical period based on using a dry year, an average year and a wet year. Maryland also indicated that in some TMDLs time-variable models use the worst condition in the calibration period. Although, nutrient TMDLs with steady state models use 7Q10 flows as the critical period. Delaware reported using the 7Q10 for free flowing streams and using the monthly or seasonally average as the critical condition for the calibration period for tidal streams. Pennsylvania reported recently beginning to use the growing season average as the critical period for nutrient TMDLs. West Virginia watershed TMDLs use representative precipitation induced flow data over a 6-year period with high, low and average conditions.

A review of TMDLs completed for tidal influenced streams and estuaries along the Atlantic and Gulf Coasts revealed that there is no consistent method for determining the critical period. This review was not intended to be exhaustive, but to reveal general patterns of methodology across the country. Most TMDLs used a critical period that was protective during low flows, rather than high flows, which is the condition of interest for the Chesapeake Bay TMDL.

The most commonly identified method for establishing the critical period was the use of 7Q10 flows. The Louisiana Standard Operating Procedures for Louisiana TMDL Technical Procedures (LDEQ 2009) specifically outlines the summer critical conditions as 7Q10 or 0.1 cfs, whichever is greater, or for tidal streams 1/3 of the average or typical flow averaged over one tidal cycle. Similarly winter critical conditions are 7Q10 of 1 cfs, whichever is greater, or for tidal streams 1/3 of the average or typical flow averaged over one tidal cycle.

Other examples of using 7Q10 flows include:

- **Total Maximum Daily Load Analysis for Nanticoke River and Broad Creek, Delaware (DNREC 1998)** The model for this dissolved oxygen (DO), total nitrogen, and total phosphorus TMDL was developed and calibrated using hydrologic and hydrodynamic from 1992, a dry year. Hydrodynamic Model was run using 7Q10 flows, water quality model was run using 1992 pollutant loads.

- **Organic Enrichment/Dissolved Oxygen TMDL Rabbit Creek and Dog River, Alabama (ADEM 2005).** The hydrology of the LSPC model was calibrated for the period of record, October 1, 1996 through September 30, 2000. For the purposes of this TMDL the 2000-year was utilized as the critical low flow period. 2000 was a relatively dry year and was one of the time periods over which the models were calibrated, lending confidence to the simulations. The time period of the model simulation was from 2000 to 2001. This time period was selected based on the availability and relevance of the observed data to the current conditions in the watershed. The model was calibrated for the year 2000, which represented both high and low flow periods. In 2000, flows were very low and near critical 7Q10 conditions, while in 2001 flows were higher.

- **TMDL Bayou Sara/Norton Creek – Mobile River Basin Organic Enrichment/DO (ADEM 1996).** Summer (May –November) TMDL critical conditions and MOS were established as 7Q10 flows and 30°C. The winter (December –April) TMDL critical conditions and MOS were established as 7Q2 and 20 °C.

- **Total Maximum Daily Load Cooper River, Wando River, Charleston Harbor System, South Carolina (SCDHEC 2002).** Critical conditions for this dissolved oxygen TMDL were determined in the model by setting water quality parameters to represent 75/25 percentiles. The average spring and neap tidal conditions were evaluated with fresh water inflow set to approximate a 7Q10 recurrence, and algal processes were turned off. The model was calibrated to a three-day period and validated on a two-day period in 1993. The seasonal critical period was considered to be the low flow, high temperature conditions associated with summer and early fall.

- **Total Maximum Daily Load Ashley River, South Carolina. (SCDEHC 2003).** The recommended critical flow period includes setting uncontrolled freshwater inflows to 7Q10 flows and selecting the seaward tidal boundary to represent a full lunar month including both spring and neap tides. These conditions approach worst-case conditions for the impact of point sources on river DO levels. The wasteloads determined for these critical conditions are considered to be protective of the river DO standard when river flow is equal to or greater than 7Q10 since higher flows would provide greater dilution. Higher river flows are expected during wet weather, so the wasteloads should be protective under these conditions.

Another common method for determining the critical period was the selection of a three-year time span based on precipitation, selected to include a wet year, a dry year and a normal year. Some examples of this approach include:

- **Total Maximum Daily Load Analysis for Indian River, Indian River Bay and Rehoboth Bay, Delaware (DNREC 1998).** This is a nitrogen and phosphorus TMDL. The baseline period was established as 1988 through 1990. The hydrologic condition of the year 1988 was considered to represent a dry year, 1989 a wet year, and 1990 a normal year. No indication of the full data set from which the baseline period was established was given.

- **Total Maximum Daily Loads of Nitrogen and Phosphorus for Baltimore Harbor in Anne Arundel, Baltimore, Carroll, and Howard Counties and Baltimore City, Maryland (MDE 2006).** The baseline conditions scenario represents the observed conditions of the Harbor and its tributaries from 1995-1997. Simulating the system for three years accounts for various loading and hydrologic conditions, which represent possible critical conditions and seasonal variations of the system. For example, the 1995-1997 period includes an average year (1995), a wet year (1996) and a dry year (1997).

- **Total Maximum Daily Load Organic Enrichment/Dissolved Oxygen Threemile Creek, Alabama (ADEM 2006).** The hydrology of the LSPC model was calibrated for the period of record, October 1, 1996 through September 30, 2000. The time period of the model simulation was from 2000 to 2001. This time period was selected based on the availability and relevance of the observed data to the current conditions in the watershed. The model was calibrated for the year 2000, which represented both high and low flow periods. The model was simulated from May 2000 through April 2001 to account for both summer (May through November) and winter (December through April) conditions. In the natural conditions model, two critical periods were selected to establish seasonal TMDLs. A period during June 2000 was simulated under natural conditions which resulted in a minimum DO concentration of 1.91 mg/L at a 5 ft depth. This June event defines critical conditions in Threemile Creek during the summer season. A period during April of 2001, the model simulated natural condition is 2.26 mg/L at a 5 ft depth and defines the winter critical period. A low flow period with high temperatures for both summer and winter seasons was utilized to represent the worst-case conditions.

- **Total Maximum Daily Loads of Nutrients/Biochemical Oxygen Demand for the Anacostia River Basin, Montgomery and Prince George's Counties, Maryland and The District of Columbia. (MDE and District of Columbia Department of the Environment 2008).** The critical condition and seasonality was accounted for in the TMDL analysis by the choice of simulation period, 1995-1997. This three-year time period represents a relatively dry year (1995), a wet year (1996), and an average year (1997), based on precipitation data, and accounts for various hydrological conditions including the critical condition.

Two TMDLs used the period of the worst hypoxia as the critical period. Dissolved oxygen exceedances for Long Island Sound s were dominated by point sources. Further details regarding the TMDLs include:

- **A Total Maximum Daily Load Analysis to Achieve Water Quality Standards for Dissolved Oxygen in Long Island Sound (NYSDEC and CTDEP 2000)**. Annual surveys from 1986-1998 and a review of historical data indicated that the 1988-1989 modeling time frame was the most severe period of hypoxia on record. As a result, model simulations of reduced nitrogen inputs were used to predict water quality conditions that would result during the same physical conditions that exist during the 1988-89 period. The use of 1988-89 worst case scenario was considered an implicit margin of safety.

- **Total Maximum Daily Load for Nitrogen in the Peconic Estuary Program Study Area Including Waterbodies Currently Impaired Due to Low Dissolved Oxygen: the Lower Peconic River and Tidal Tributaries; Western Flanders Bay and Lower Sawmill Creek; and Meetinghouse Creek, Terrys Creek and Tributaries (Peconic Estuary Program 2007)**. The Environmental Fluid Dynamics Code (EFDC) model was calibrated using an eight-year period from October 1, 1988 to September 30, 1996 and validated using the six-year period from October 1, 196 through September 30, 2002. Model calibration and verification included all seasons of the year, as well as extreme wet and dry years. Monitoring data indicated that the October 2000 to September 2002 time frame was the most severe period of hypoxia on record from 1988-2002. October 1, 2000 to September 30, 2002 was selected as the critical period for the TMDL model runs.

In some cases, the data set either does not contain a critical year or several years are included to capture a range of temperature and flow concentrations. The *TMDLs for The Little Assawoman Bay and Tributaries and Ponds of the Indian River, Indian River Bay, and Rehoboth Bay* (DNREC 2004) is an example of the former. There was no “worst” year for dissolved oxygen, nitrogen and phosphorus during the three-year period in question, so the average over the three summers was used as the critical (design) condition. The *TMDL for Nutrients in the Lower Charles River Basin, Massachusetts* (MassDEP and USEPA 2007) is an example of the latter. A continuous five-year simulation was run. The 1998-2002 period was selected because it represented some of the lowest summer flows throughout the 23 period of record. Low flows at or near the 7Q10 flow value were observed during three of the summers during the selected critical period.

Two of the TMDLs reviewed had limited data sets, so the critical period was chosen based on the period with the most data available. Examples of this approach include:

- **Total Maximum Daily Loads of Nitrogen and Phosphorus for the Upper and Middle Chester River, Kent and Queen Anne’s Counties, Maryland (MDE 2006).** The models were calibrated to the period of 1997-1999, which was the most recent period for which all of the needed data were available and consistent with the Chesapeake Bay Program modeling efforts of the Tributary Strategies. Only the output from 1997 was used to investigate different nutrient loading scenarios and calculate the annual average and growing season TMDLs for the Upper and Middle Chester Rivers because in 1999, the region experienced extreme weather conditions (prolonged drought followed by Hurricane Floyd) resulting in atypically high flows and loads. Based on the flow gauge, it was determined that the flow in 1997 was representative of the average annual flow and loads. The timeframe selected includes representative wet and dry periods, accounting for seasonality and critical conditions.

- **Total Maximum Daily Load for Dissolved Oxygen in Mill Creek, Northampton County, Virginia (VADEQ 2009).** The observations show that the instantaneous DO levels fell below the water quality criterion of 4 mg/L minimum repeatedly throughout the period of 1997-2003. Because the nutrients data in the watershed were not available, an interactive approach of calibration of watershed and in-stream water quality model was conducted using all available in-stream monitoring data. The water quality model was calibrated in Mill Creek using the observation data. A six-year model simulation (1998-2003) was conducted. Seasonal variations involved changes in surface runoff, stream flow, and water quality condition as a result of hydrologic and climatologic patterns. These were accounted for by the use of this long-term simulation to estimate the current load and reduction targets.

### *Initial Analysis by Malcolm Pirnie*

The consulting firm Malcolm Pirnie, representing the stakeholders from the Maryland Association of Municipal Wastewater Agencies, Inc (MAMWA) and the Virginia Association of Municipal Wastewater Agencies, Inc. (VAMWA) conducted an independent analysis of the inflows to the Chesapeake Bay to determine whether the initially selected critical period of 1996-1998 may represent a hydrologic condition with a longer return period than 10 years (Malcolm Pirnie 2009).

Malcolm Pirnie analyzed the flows from the Potomac River and the Susquehanna River, which together contribute most of the flow to the Chesapeake Bay, for the period 1967 through 2009. The average daily inflow from January through May was calculated for each year and for each three-year period within the 42-year period of record. January through May was selected as the period of interest because studies have indicated that the magnitude and extent of hypoxia in the Chesapeake Bay is largely controlled by freshwater and nutrient inputs during the preceding winter and spring months (freshet).

Results indicated that 1996-1998 had the highest average January through May inflow over the entire period of record and would result in a return period of 40 years. The year 1996 had January through May inflows in the 93rd percentile and 1998 had flows in the 98th percentile. High flows in 1996 were attributed to rainfall on winter snowpack in January 1996, resulting in an event know as the “Big Melt.”

Based on these results, Malcolm Pirnie indicated that the critical condition would be too extreme if 1996-1998 is selected as the critical period. Malcolm Pirnie recommended using 1993-1995 or 1994-1996 as the critical period because they represent return flows much closer to a 10-year return period.

## Replication of Malcolm Pirnie Results

To confirm the results of the Malcolm Pirnie analysis, Tetra Tech staff replicated the approach used in the Malcolm Pirnie flow analysis. The analysis was repeated using both the flow data presented in the Malcolm Pirnie technical memo (Malcolm Pirnie 2009) and the raw flow data from the USGS. Although the replicated three-year averages based on the flows in the technical memo did not match exactly what was presented in the technical memo, the minor discrepancies did not affect the percentile calculations. Similarly, the three-year running averages using the raw USGS data resulted in minor discrepancies from the Malcolm Pirnie results. Despite the small differences, Tetra Tech's replication yielded the same results as the Malcolm Pirnie technical memo (Malcolm Pirnie 2009).

## Analysis to Support Critical Period Selection

Additional analyses were performed to further explore the options for the selection of the critical period.

**Preliminary analysis included an exploration of the results of including the nine major rivers in the flow analysis and expanding the combinations of different monthly flow durations beyond January to May to include other monthly duration combinations from September through July. Data was analyzed for 1978 through 2009 because the Patuxent flow gage did not begin until 1977. Refer to Table G-1 for the gages used in the analysis and the time period for which data was available. Running three-year average flows were calculated for 25 different month combinations for the entire period of evaluation. The probability of each three-year flow average was determined using the Weibull Plotting Position. The return period is the inverse of the probability. This method differed from the approach in the Malcolm Pirnie analysis (Malcolm Pirnie 2009), which used percentile ranks. A regression was also performed on the three-year flow averages to determine if there was a correlation with the dissolved oxygen percent exceedances. The percent dissolved oxygen exceedances were provided by the EPA Chesapeake Bay Program Office (CBPO) and represent volume exceedances. The analysis was run with and without the use of tributary multipliers, which were developed by the CBPO because flows from different tributaries do not impact conditions in the Bay equally. These factors are the estuarine delivery factors presented in the section 6.9.2.1. The CBPO multipliers were translated to a 0.0 to 1.0 scale and are included in**

**Table G-2. Without the multipliers the Susquehanna and Potomac Rivers contribute approximately 80 percent of the flow to the Bay. With the multipliers, the two rivers contribute approximately 95 percent of the effective load. (**

Figure G-1 and Figure G-2).

**Table G-1. Flow Gages and Time Period of Available Data.**

| Gage ID | Description | Start | End |
|---|---|---|---|
| 1668000 | Rappahannock River near Fredericksburg, VA | 9/19/1907 | 8/25/2009 |
| 1646502 | Potomac River (Adjusted) near Washington, DC | 3/1/1930 | 7/31/2009 |

| | | | |
|---|---|---|---|
| 2037500 | James River near Richmond, VA | 10/1/1934 | 8/25/2009 |
| 1674500 | Mattaponi River near Beulahville, VA | 9/19/1941 | 8/25/2009 |
| 1673000 | Pamunkey River near Hanover, VA | 10/1/1941 | 8/25/2009 |
| 1491000 | Choptank River near Greensboro, MD | 1/1/1948 | 8/25/2009 |
| 1578310 | Susquehanna River at Conowingo, MD | 10/1/1967 | 8/25/2009 |
| 2041650 | Appomattox River at Matoaca, VA | 10/1/1969 | 8/25/2009 |
| 1594440 | Patuxtent River near Bowie, MD | 6/27/1977 | 8/25/2009 |

**Table G-2. Chesapeake Bay tributaries flow multiplier ratios.**

| Major River Basin | Multiplier | Adjusted Ratio |
|---|---|---|
| Appomattox | 0.533111028 | 0.017 |
| Choptank | 6.929861533 | 0.217 |
| James | 0.533111028 | 0.017 |
| Mattaponi | 0.798423188 | 0.025 |
| Pamunkey | 0.798423188 | 0.025 |
| Patuxent | 3.093385849 | 0.097 |
| Potomac | 6.188243619 | 0.193 |
| Rappahannock | 2.809613056 | 0.088 |
| Susquehanna | 10.3187158 | 0.322 |
| | | 1.000 |

Source: EPA Chesapeake Bay Program Office.

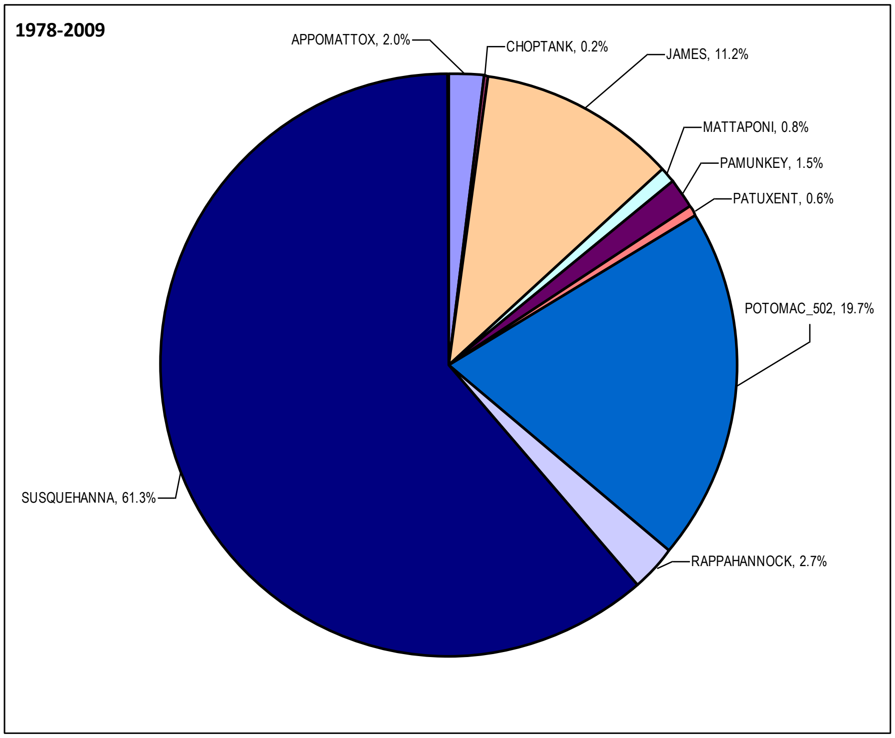

**Figure G-1. Tributary flow contributions without multiplier ratios.**

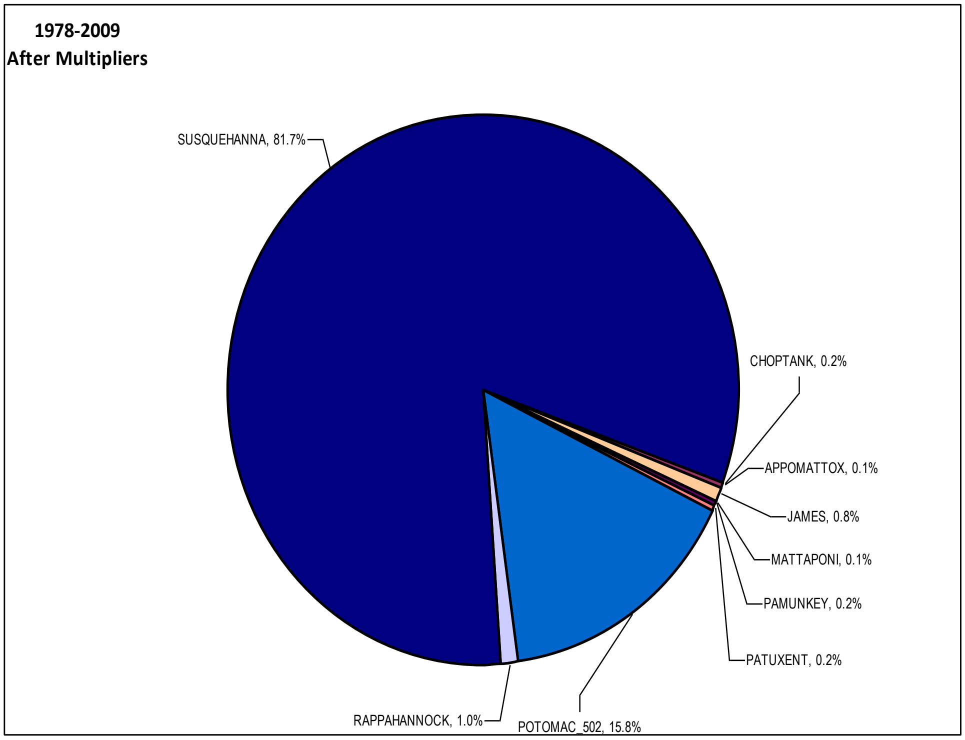

**Figure G-2. Tributary flow contributions with the multiplier ratios.**

Results of the analysis, as shown in Table G-3 and Table G-4, indicated that the monthly span should be extended beyond the January through May period suggested in the Malcolm Pirnie analysis (Malcolm Pirnie 2009) because the three-year flow averages with the highest correlation to dissolved oxygen exceedances generally included longer monthly spans. The three-year average flow with the highest correlation to DO exceedances was September through June. Findings also suggested that 1996-1998 had closer to a 15-year return period for months when flow was more closely correlated with dissolve oxygen exccedances. The other possible critical periods 1992-1994 and 1993-1995 had generally lower than 10-year return periods and return periods greater than 10 years when flow was not strongly correlated with DO exceedances. Return periods greater than six years are highlighted in Tables G-3 and G-4 and only three-year average flows with at least one monthly interval with a six-year or greater return period are shown. There were no three-year average flows with return periods greater than six years for any of the years between 1978 and 1991.

**Table G-3. Return periods and $R^2$ correlation between various monthly durations and dissolved oxygen percent exceedances without the Tributary Multiplier Ratio.**

| % DO Exceedences ---> | | 25.87% | 25.92% | 24.26% | 27.84% | 26.05% | 31.11% | 27.24% |
|---|---|---|---|---|---|---|---|---|
| Interval | R2 | 1992-1994 | 1993-1995 | 1994-1996 | 1996-1998 | 1997-1999 | 2003-2005 | 2004-2006 |
| | | Return Period | | | | | | |
| SEP-JUNE | 0.54 | 4.43 | 6.20 | 3.44 | 15.50 | 2.58 | 31.00 | 7.75 |
| NOV-JUNE | 0.53 | 6.20 | 7.75 | 5.17 | 31.00 | 2.07 | 15.50 | 4.43 |
| SEP-JULY | 0.53 | 4.43 | 5.17 | 3.44 | 15.50 | 2.58 | 31.00 | 10.33 |
| NOV-JULY | 0.52 | 6.20 | 7.75 | 4.43 | 15.50 | 2.07 | 31.00 | 5.17 |
| DEC-JUNE | 0.52 | 7.75 | 6.20 | 4.43 | 31.00 | 2.38 | 15.50 | 3.88 |
| SEP-MAY | 0.51 | 4.43 | 6.20 | 3.88 | 15.50 | 3.10 | 31.00 | 7.75 |
| DEC-JULY | 0.51 | 6.20 | 7.75 | 4.43 | 31.00 | 2.21 | 15.50 | 3.88 |
| OCT-JUNE | 0.50 | 5.17 | 6.20 | 4.43 | 15.50 | 2.38 | 31.00 | 7.75 |
| OCT-JULY | 0.49 | 5.17 | 6.20 | 4.43 | 15.50 | 2.21 | 31.00 | 7.75 |
| NOV-MAY | 0.48 | 6.20 | 7.75 | 5.17 | 31.00 | 3.10 | 15.50 | 4.43 |
| SEP-APR | 0.48 | 4.43 | 5.17 | 3.44 | 15.50 | 3.10 | 31.00 | 10.33 |
| OCT-MAY | 0.46 | 5.17 | 7.75 | 4.43 | 31.00 | 2.82 | 10.33 | 6.20 |
| DEC-MAY | 0.46 | 10.33 | 7.75 | 5.17 | 31.00 | 2.82 | 6.20 | 3.88 |
| JAN-JUNE | 0.44 | 10.33 | 6.20 | 4.43 | 31.00 | 2.58 | 5.17 | 2.21 |
| JAN-JULY | 0.44 | 6.20 | 5.17 | 4.43 | 31.00 | 2.21 | 7.75 | 2.82 |
| NOV-APR | 0.44 | 7.75 | 10.33 | 4.43 | 31.00 | 3.10 | 15.50 | 5.17 |
| OCT-APR | 0.42 | 5.17 | 7.75 | 3.44 | 31.00 | 3.10 | 15.50 | 6.20 |
| SEP-MAR | 0.42 | 2.82 | 3.44 | 3.88 | 15.50 | 4.43 | 31.00 | 10.33 |
| DEC-APR | 0.40 | 10.33 | 15.50 | 5.17 | 31.00 | 3.10 | 6.20 | 4.43 |
| NOV-MAR | 0.39 | 3.10 | 3.44 | 6.20 | 31.00 | 4.43 | 15.50 | 7.75 |
| JAN-MAY | 0.37 | 10.33 | 7.75 | 6.20 | 31.00 | 3.10 | 4.43 | 2.21 |
| OCT-MAR | 0.36 | 2.82 | 3.44 | 4.43 | 31.00 | 3.88 | 10.33 | 7.75 |
| DEC-MAR | 0.36 | 3.44 | 5.17 | 7.75 | 31.00 | 4.43 | 10.33 | 6.20 |
| JAN-APR | 0.32 | 31.00 | 15.50 | 6.20 | 10.33 | 3.44 | 3.88 | 2.38 |
| JAN-MAR | 0.26 | 5.17 | 6.20 | 10.33 | 31.00 | 7.75 | 3.88 | 2.58 |

**Table G-4. Return periods and $R^2$ correlation between various monthly durations and dissolved oxygen percent exceedances with the Tributary Multiplier Ratio.**

| % DO Exceedences ---> | | 25.87% | 25.92% | 24.26% | 27.84% | 26.05% | 31.11% | 27.24% |
|---|---|---|---|---|---|---|---|---|
| Interval | R2 | 1992-1994 | 1993-1995 | 1994-1996 | 1996-1998 | 1997-1999 | 2003-2005 | 2004-2006 |
| | | Return Period | | | | | | |
| SEP-JUNE | 0.53 | 4.43 | 5.17 | 3.44 | 7.75 | 2.21 | 31.00 | 15.50 |
| NOV-JUNE | 0.53 | 5.17 | 6.20 | 4.43 | 15.50 | 1.94 | 31.00 | 7.75 |
| DEC-JUNE | 0.52 | 6.20 | 7.75 | 3.88 | 15.50 | 1.94 | 31.00 | 4.43 |
| SEP-JULY | 0.52 | 3.88 | 5.17 | 3.44 | 10.33 | 2.07 | 31.00 | 15.50 |
| NOV-JULY | 0.52 | 5.17 | 6.20 | 4.43 | 15.50 | 1.94 | 31.00 | 10.33 |
| DEC-JULY | 0.51 | 5.17 | 6.20 | 3.88 | 15.50 | 1.94 | 31.00 | 7.75 |
| OCT-JUNE | 0.49 | 5.17 | 6.20 | 3.88 | 15.50 | 2.07 | 31.00 | 7.75 |
| SEP-MAY | 0.49 | 4.43 | 5.17 | 3.88 | 7.75 | 2.58 | 31.00 | 15.50 |
| OCT-JULY | 0.48 | 5.17 | 6.20 | 3.88 | 15.50 | 1.94 | 31.00 | 10.33 |
| NOV-MAY | 0.46 | 6.20 | 7.75 | 4.43 | 31.00 | 2.38 | 15.50 | 5.17 |
| SEP-APR | 0.46 | 4.43 | 5.17 | 3.44 | 6.20 | 2.82 | 31.00 | 15.50 |
| JAN-JULY | 0.46 | 10.33 | 5.17 | 4.43 | 31.00 | 1.55 | 15.50 | 3.88 |
| JAN-JUNE | 0.46 | 10.33 | 6.20 | 4.43 | 31.00 | 1.82 | 5.17 | 2.82 |
| DEC-MAY | 0.45 | 7.75 | 10.33 | 5.17 | 31.00 | 2.21 | 6.20 | 4.43 |
| OCT-MAY | 0.44 | 5.17 | 6.20 | 3.88 | 15.50 | 2.21 | 10.33 | 7.75 |
| NOV-APR | 0.42 | 7.75 | 10.33 | 3.88 | 15.50 | 2.58 | 31.00 | 6.20 |
| SEP-MAR | 0.41 | 2.07 | 3.10 | 3.88 | 10.33 | 4.43 | 15.50 | 31.00 |
| OCT-APR | 0.41 | 5.17 | 6.20 | 3.44 | 10.33 | 2.58 | 31.00 | 7.75 |
| DEC-APR | 0.40 | 15.50 | 31.00 | 4.43 | 10.33 | 2.58 | 7.75 | 5.17 |
| NOV-MAR | 0.38 | 2.58 | 3.10 | 5.17 | 31.00 | 3.44 | 15.50 | 10.33 |
| JAN-MAY | 0.37 | 15.50 | 7.75 | 6.20 | 31.00 | 2.38 | 5.17 | 2.82 |
| DEC-MAR | 0.37 | 2.58 | 3.44 | 6.20 | 31.00 | 3.88 | 15.50 | 10.33 |
| OCT-MAR | 0.35 | 2.38 | 3.10 | 4.43 | 31.00 | 3.44 | 10.33 | 15.50 |
| JAN-APR | 0.32 | 31.00 | 15.50 | 6.20 | 10.33 | 2.58 | 5.17 | 3.44 |
| JAN-MAR | 0.28 | 2.58 | 3.88 | 10.33 | 31.00 | 7.75 | 6.20 | 2.82 |

## *Analysis of Critical Period Using the Log Pearson III Method*

After determining the return period using the Weibull Plotting Position method, a second method, the Log Pearson III Method (U. S. Interagency Advisory Committee on Water Data 1982; Ponce 1989), was used to determine whether the return period changed significantly depending on the method of calculation. The Log Pearson III method provides a smooth fit through the plotting position data and in essence smoothens out the predicted values. This analysis was conducted over the same 1978 through 2009 time period and focused on monthly spans with the highest correlation between flow and DO exceedances. Results in Table G-5 and Table G-6 show that there are some changes in the return periods, but the conclusion in terms of candidate years remains the same. This method of determining the return period was used in subsequent analyses.

**Table G-5. Log Pearson III method for determining return period, without Tributary Multiplier Ratio.**

**Without Multiplier**

| % DO Exceedences | 25.87% | 25.92% | 24.26% | 27.84% | 31.11% | 27.24% |
|---|---|---|---|---|---|---|
| Year | 1992-1994 | 1993-1995 | 1994-1996 | 1996-1998 | 2003-2005 | 2004-2006 |
| Sep-June | 4.38 | 4.90 | 3.77 | 17.99 | 34.80 | 12.37 |
| Nov-June | 7.45 | 7.90 | 5.46 | 20.71 | 19.09 | 5.36 |
| Sep-July | 4.16 | 4.79 | 4.05 | 16.77 | 36.03 | 14.15 |
| Nov-July | 6.79 | 7.53 | 6.02 | 18.95 | 20.33 | 6.59 |
| Dec-June | 9.19 | 9.11 | 6.68 | 19.70 | 15.89 | 4.24 |
| Sep-May | 4.90 | 5.74 | 3.80 | 17.77 | 23.83 | 11.69 |
| Dec-July | 8.39 | 8.66 | 7.26 | 18.14 | 17.24 | 4.97 |
| Oct-June | 5.44 | 6.15 | 4.60 | 19.99 | 21.57 | 7.16 |
| Flow (Sep-June) (cfs) | 81,791 | 83,254 | 80,099 | 95,684 | 101,516 | 92,106 |
| Flow (Nov-June) (cfs) | 97,725 | 98,368 | 94,810 | 108,161 | 107,300 | 94,664 |
| Flow (Sep-July) (cfs) | 76,755 | 78,432 | 76,487 | 89,677 | 96,200 | 88,110 |
| Flow (Nov-July) (cfs) | 89,756 | 90,753 | 88,724 | 99,399 | 100,142 | 89,485 |
| Flow (Dec-June) (cfs) | 104,233 | 104,117 | 100,461 | 111,988 | 109,418 | 95,653 |
| Flow (Sep-May) (cfs) | 86,706 | 88,203 | 83,278 | 100,501 | 103,783 | 96,146 |
| Flow (Dec-July) (cfs) | 94,451 | 94,829 | 92,906 | 101,658 | 101,107 | 89,709 |
| Flow (Oct-June) (cfs) | 88,780 | 89,746 | 87,057 | 101,106 | 101,688 | 91,140 |

**Table G-6. Log Pearson III method for determining return period, with Tributary Multiplier Ratio.**

**With Multiplier**

| % DO Exceedences | 25.87% | 25.92% | 24.26% | 27.84% | 31.11% | 27.24% |
|---|---|---|---|---|---|---|
| Year | 1992-1994 | 1993-1995 | 1994-1996 | 1996-1998 | 2003-2005 | 2004-2006 |
| Sep-June | 4.39 | 5.17 | 3.87 | 13.21 | 35.52 | 18.76 |
| Nov-June | 7.47 | 8.19 | 5.70 | 16.84 | 19.21 | 8.52 |
| Sep-July | 4.19 | 4.83 | 4.04 | 12.21 | 36.18 | 21.53 |
| Nov-July | 6.85 | 7.48 | 5.98 | 16.06 | 21.37 | 10.34 |
| Dec-June | 9.17 | 9.27 | 6.76 | 16.02 | 17.64 | 6.88 |
| Sep-May | 4.92 | 6.32 | 4.08 | 13.12 | 24.42 | 17.15 |
| Dec-July | 8.38 | 8.39 | 7.08 | 14.58 | 18.76 | 8.73 |
| Oct-June | 5.40 | 6.41 | 4.67 | 16.09 | 22.11 | 10.74 |
| Flow (Sep-June) (cfs) | 19,682 | 20,141 | 19,338 | 22,251 | 24,445 | 23,100 |
| Flow (Nov-June) (cfs) | 23,429 | 23,668 | 22,837 | 25,294 | 25,648 | 23,779 |
| Flow (Sep-July) (cfs) | 18,494 | 18,892 | 18,400 | 20,891 | 23,136 | 22,147 |
| Flow (Nov-July) (cfs) | 21,550 | 21,739 | 21,292 | 23,285 | 23,910 | 22,535 |
| Flow (Dec-June) (cfs) | 24,860 | 24,893 | 24,069 | 26,006 | 26,242 | 24,110 |
| Flow (Sep-May) (cfs) | 20,897 | 21,462 | 20,265 | 23,415 | 25,103 | 24,122 |
| Flow (Dec-July) (cfs) | 22,568 | 22,569 | 22,178 | 23,659 | 24,214 | 22,671 |
| Flow (Oct-June) (cfs) | 21,337 | 21,662 | 20,998 | 23,689 | 24,436 | 22,921 |

## *Analysis of Critical Period Using Expanded Flow Data*

Given some concern that the 30-year period from 1978 through 2009 was of insufficient length to fully capture the return period over the full time period of flow data and was artificially lowering the most extreme return period to 30 years, an extended analysis was performed for the years 1930 through 2009 but only included the Potomac and Susquehanna rivers. The Potomac and Susquehanna rivers account for almost 80 percent of the total flow to the Chesapeake Bay, and if the CBPO allocation multipliers are used these two rivers account for almost 95 percent of the total inflow to the Chesapeake Bay. Hence, these two flow gages were considered sufficient for analysis purposes. These two USGS flow gages were previously described in Table G-1.

The Susquehanna River at Conowingo gage flow data runs from October 1, 1967 to the present. The period prior to October 1, 1967 was patched using data from the Susquehanna River at Harrisburg gage (01570500 – October 1, 1890 to August 25, 2009) using a simple drainage area ratio method. The daily fresh water inflow from the Potomac River and the Susquehanna River were weighed using the adjusted tributary multipliers provided by the CBPO (Table G-7).

**Table G-7. Adjusted tributary flow multiplier ratios.**

| Gage | Multiplier | Adjusted Ratio |
|---|---|---|
| Potomac | 6.188 | 0.375 |
| Susquehanna | 10.317 | 0.625 |

Source: EPA Chesapeake Bay Program Office.

The analysis using the extended time period followed the same procedure as previous analyses except that the data was extended back to 1930, only the weighted flow data based on multipliers was used, and the Log Pearson III method was used to determine the return period. Table G-8 lists the return periods for each of the monthly intervals for the extended time period, with return periods greater than six years highlighted.

**Table G-8. Extended time period (1930-2009) return periods.**

| % DO Exceedences | 24.97% | 25.87% | 25.92% | 24.26% | 22.58% | 27.84% | 31.11% | 27.24% |
|---|---|---|---|---|---|---|---|---|
| Year | 1991-1993 | 1992-1994 | 1993-1995 | 1994-1996 | 1995-1997 | 1996-1998 | 2003-2005 | 2004-2006 |
| jan-july | 2.69 | 11.80 | 8.95 | 8.72 | 1.77 | 16.28 | 11.76 | 4.37 |
| jan-june | 3.05 | 13.72 | 9.84 | 8.14 | 1.69 | 17.59 | 9.71 | 3.03 |
| jan-may | 4.61 | 24.98 | 19.13 | 10.56 | 1.69 | 25.43 | 7.20 | 2.73 |
| jan-apr | 7.48 | 39.45 | 34.34 | 10.82 | 1.81 | 16.67 | 7.48 | 3.59 |
| jan-mar | 2.18 | 3.24 | 4.32 | 13.91 | 4.28 | 46.60 | 5.51 | 4.33 |
| dec-july | 3.03 | 9.20 | 9.15 | 7.92 | 2.69 | 15.66 | 20.18 | 9.88 |
| dec-june | 3.35 | 9.90 | 9.98 | 7.52 | 2.62 | 17.02 | 19.14 | 7.95 |
| dec-may | 4.76 | 16.77 | 17.73 | 9.20 | 2.76 | 23.09 | 16.70 | 8.14 |
| dec-apr | 6.96 | 20.14 | 23.89 | 9.10 | 3.01 | 16.01 | 16.48 | 9.99 |
| dec-mar | 2.68 | 3.49 | 5.42 | 9.87 | 7.27 | 31.16 | 13.94 | 13.66 |
| nov-july | 1.66 | 2.08 | 3.29 | 2.63 | 3.11 | 2.75 | 1.35 | 1.31 |
| nov-june | 3.39 | 8.92 | 9.67 | 7.10 | 3.18 | 20.60 | 25.44 | 10.69 |
| nov-may | 4.68 | 13.11 | 15.60 | 8.48 | 3.43 | 28.01 | 21.32 | 11.48 |
| nov-apr | 6.51 | 16.24 | 19.83 | 8.46 | 3.78 | 19.26 | 21.02 | 15.07 |
| nov-mar | 2.84 | 3.43 | 5.51 | 8.90 | 8.28 | 34.04 | 17.98 | 17.83 |
| oct-july | 3.64 | 6.50 | 7.38 | 6.27 | 3.71 | 18.35 | 32.07 | 18.23 |
| oct-june | 4.12 | 6.98 | 8.03 | 5.91 | 3.72 | 19.90 | 31.72 | 15.37 |
| oct-may | 5.69 | 9.02 | 10.95 | 7.06 | 4.09 | 25.80 | 26.88 | 16.45 |
| oct-apr | 7.66 | 10.82 | 14.96 | 7.08 | 4.40 | 18.91 | 26.38 | 19.62 |
| oct-mar | 3.42 | 2.92 | 4.50 | 7.25 | 8.82 | 29.23 | 20.77 | 22.25 |
| sep-july | 3.39 | 5.40 | 6.73 | 5.06 | 4.18 | 17.56 | 69.44 | 38.08 |
| sep-june | 3.86 | 5.81 | 7.27 | 4.87 | 4.26 | 18.29 | 62.21 | 30.68 |
| sep-may | 4.93 | 7.51 | 9.31 | 5.64 | 4.62 | 21.90 | 56.34 | 34.77 |
| sep-apr | 6.60 | 8.70 | 11.93 | 5.68 | 4.90 | 17.28 | 52.38 | 40.22 |
| sep-mar | 3.25 | 2.74 | 4.31 | 5.78 | 9.16 | 23.34 | 40.15 | 43.20 |

The monthly intervals with high correlations with DO exceedances are September – June, November – June, December – June, September – July and December – July. Table G-9 highlights the return periods for the monthly intervals with high correlations with DO exceedances.

**Table G-9. Return periods for monthly intervals highly correlated to Chesapeake Bay dissolved oxygen criteria exceedances.**

| Interval | 1992-1994 | 1993-1995 | 1994-1996 | 1996-1998 |
|---|---|---|---|---|
| September – June | 5.81 | 7.27 | 4.87 | 18.29 |
| November – June | 8.92 | 9.67 | 7.10 | 20.60 |
| December – June | 9.90 | 9.98 | 7.52 | 17.02 |
| September - July | 5.40 | 6.73 | 5.06 | 17.56 |
| December - July | 9.20 | 9.15 | 7.92 | 15.66 |

## Analysis of Critical Period using De-Trended Flow Data

As was previously noted, initial analysis of the three-year average flows from 1978 through 2009 did not reveal any three year periods prior to 1992 with return periods greater than six years for the monthly intervals included in the analysis. This indicates a potential increasing trend in flow volume over the last several decades. De-trending removes any flow trends over time and allows for an equal comparison of current and historic flows. It can remove the effects of urbanization and other impacts, which are apparent in the flow data.

The first step in de-trending was to determine if there is a significant trend in the flow data. The slope of the trend line is 0.1878. The Kendall Tau ranking correlation coefficient was used to determine if this is a statistically significant trend. The Tau value can range between -1 and 1 with a positive number indicating an increasing trend and a negative number indicating a decreasing trend. The flow data from 1930 through 2009 had a positive Tau value. A p-value $<0.05$ indicates a statistically significant trend. The time-series flow data had a p-value of 0.0042, which is statistically significant. Figure G-3 shows the trend line in the raw data.

After establishing there is a statistically significant increasing trend in the flow data, a de-trended time-series was developed. Two different methods were used to fit a trend line through the time-series data – Linear Least Squares Regression, and the Locally Weighted Scatter Plot Smoothner (LOWESS) (Helsel and Hirsch 2002 and NIST/SEMATECH).

The linear regression trend line was estimated by fitting the time-series data using a trend line of the form $y=mx+c$ (where m is the slope, c is the intercept, y being the dependent variable i.e. flow and x the independent variable time). The LOWESS fit is determined by specifying a smoothening parameter which defines the subset of data which will be used for the local fit. The LOESS technique performs a weighted least square regression fit (on a subset of points) in a moving range around the X value (time), where the values in the moving range are weighted according to their distance from this X value. For this analysis a smoothning parameter of 0.33 was found to fit the data trend reasonably well. Details of the LOWESS computation can be found at: http://www.itl.nist.gov/div898/handbook/pmd/section1/dep/dep144.htm.

The residuals were then calculated for each method (i.e. the difference between the observed and predicted values along the trend line). Finally the residuals were added to the last point in the time series (the maximum value) to generate a de-trended time series. To confirm that no trend exists in the resulting de-trended time series using the linear regression approach, the linear slope was calculated. The slope was zero, indicating that there was no remain trend. For the de-trended time-series using the LOWESS regression the presence of no trend in the time-series was confirmed using a p-value. The p-value of the de-trended data was 1.2376, indicating a statistically insignificant trend ($p\text{-value} < 0.05$ is significant). Figure G-4 plots the de-trended data.

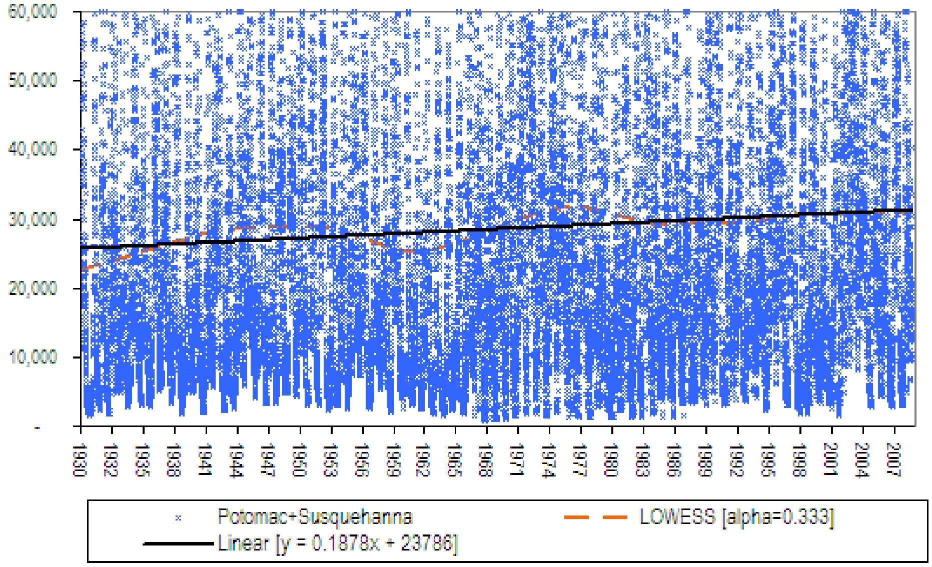

**Figure G-3. Raw flow data with trend line.**

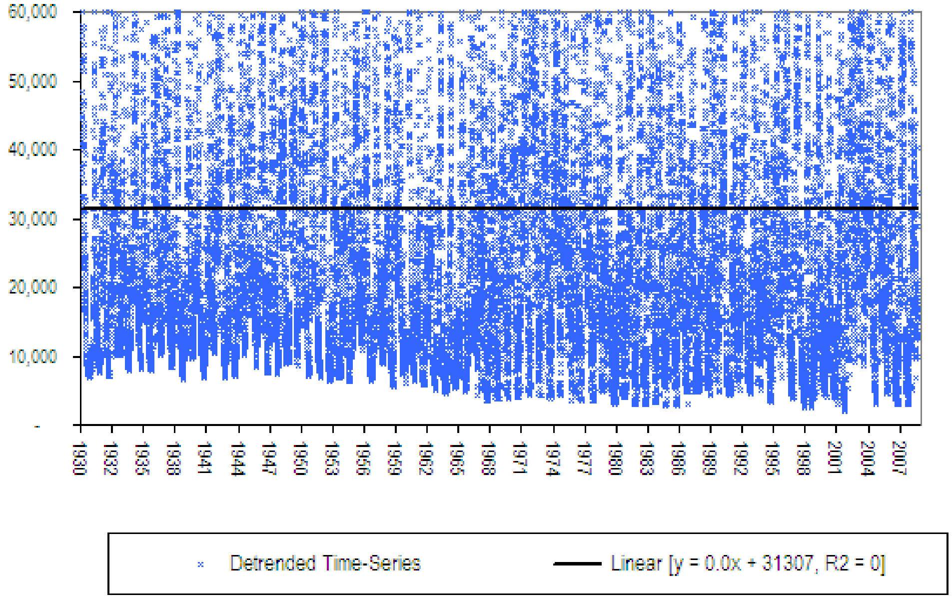

**Figure G-4. De-trended data with slope of zero**

### *Linear Regression to Determine Return Period*

Using the linear regression de-trended data yielded revised return periods, which can be found in Table G-10. Table G-11 highlights return periods for the monthly spans with the highest correlation to dissolved oxygen exceedances.

**Table G-10. De-trending analysis results using linear regression.**

| % DO Exceedences | 25.87% | 25.92% | 24.26% | 22.58% | 27.84% | 31.11% | 27.24% |
|---|---|---|---|---|---|---|---|
| Year | 1992-1994 | 1993-1995 | 1994-1996 | 1995-1997 | 1996-1998 | 2003-2005 | 2004-2006 |
| jan-july | 7.53 | 5.51 | 5.14 | 1.41 | 9.02 | 6.05 | 2.49 |
| jan-june | 8.57 | 6.62 | 4.89 | 1.39 | 9.82 | 5.28 | 1.97 |
| jan-may | 16.31 | 11.91 | 6.84 | 1.41 | 15.37 | 3.88 | 1.85 |
| jan-apr | 26.99 | 22.35 | 7.73 | 1.54 | 10.27 | 4.50 | 2.46 |
| jan-mar | 2.67 | 3.36 | 9.85 | 3.28 | 34.34 | 3.92 | 3.10 |
| dec-july | 6.52 | 6.34 | 4.95 | 1.95 | 9.54 | 11.75 | 5.74 |
| dec-june | 7.38 | 7.36 | 4.83 | 1.95 | 10.73 | 11.13 | 4.48 |
| dec-may | 11.05 | 11.80 | 6.33 | 2.06 | 15.37 | 9.18 | 4.57 |
| dec-apr | 16.93 | 19.29 | 6.92 | 2.28 | 11.43 | 10.39 | 6.93 |
| dec-mar | 2.83 | 4.30 | 8.35 | 5.44 | 26.43 | 9.67 | 9.45 |
| nov-july | 2.80 | 4.80 | 3.61 | 4.36 | 3.69 | 1.46 | 1.41 |
| nov-june | 6.35 | 7.03 | 4.60 | 2.29 | 14.35 | 15.47 | 6.38 |
| nov-may | 9.00 | 10.18 | 5.63 | 2.44 | 19.11 | 13.24 | 6.80 |
| nov-apr | 12.56 | 16.41 | 6.16 | 2.77 | 15.06 | 14.98 | 9.32 |
| nov-mar | 2.75 | 4.30 | 7.17 | 6.40 | 29.15 | 13.42 | 13.06 |
| oct-july | 4.31 | 4.71 | 4.05 | 2.48 | 12.57 | 19.18 | 9.92 |
| oct-june | 4.64 | 5.26 | 3.96 | 2.58 | 13.94 | 18.36 | 8.54 |
| oct-may | 6.42 | 7.83 | 4.53 | 2.79 | 18.18 | 16.63 | 9.13 |
| oct-apr | 8.37 | 10.70 | 4.77 | 3.12 | 14.50 | 18.16 | 13.31 |
| oct-mar | 2.29 | 3.42 | 5.25 | 6.88 | 23.92 | 15.97 | 16.78 |
| sep-july | 3.75 | 4.39 | 3.45 | 2.81 | 11.30 | 40.03 | 21.57 |
| sep-june | 4.00 | 4.73 | 3.31 | 2.87 | 13.01 | 42.41 | 18.94 |
| sep-may | 4.91 | 6.67 | 3.79 | 3.13 | 16.03 | 37.44 | 20.99 |
| sep-apr | 6.53 | 8.84 | 4.01 | 3.48 | 12.77 | 39.63 | 29.60 |
| sep-mar | 2.14 | 3.23 | 4.29 | 7.21 | 19.30 | 32.86 | 34.85 |

**Table G-11: Return periods for monthly intervals highly correlated to Chesapeake Bay dissolved oxygen criteria exceedances using linear regression de-trended flow data.**

| Interval | 1992-1994 | 1993-1995 | 1994-1996 | 1996-1998 |
|---|---|---|---|---|
| September – June | 4.00 | 4.73 | 3.31 | 13.01 |
| November – June | 6.35 | 7.03 | 4.60 | 14.35 |
| December – June | 7.38 | 7.36 | 4.83 | 10.73 |
| September - July | 3.75 | 4.39 | 3.45 | 11.30 |
| December - July | 6.52 | 6.34 | 4.95 | 9.54 |

### *LOWESS Polynomial Regression*

Using LOWESS regression to de-trend the data, the three-year return periods were recalculated (Tables G-12 and G-13).

**Table G-12. De-trending analysis results using LOWESS polynomial regression.**

| % DO Exceedences | 24.97% | 25.87% | 25.92% | 24.26% | 22.58% | 27.84% | 31.11% | 27.24% |
|---|---|---|---|---|---|---|---|---|
| Year | 1991-1993 | 1992-1994 | 1993-1995 | 1994-1996 | 1995-1997 | 1996-1998 | 2003-2005 | 2004-2006 |
| jan-july | 2.25 | 11.24 | 8.10 | 7.33 | 1.42 | 11.81 | 7.30 | 2.60 |
| jan-june | 2.57 | 13.21 | 9.07 | 6.67 | 1.40 | 13.47 | 6.26 | 1.98 |
| jan-may | 3.88 | 23.61 | 17.29 | 8.59 | 1.44 | 18.30 | 4.16 | 1.88 |
| jan-apr | 6.54 | 38.98 | 32.42 | 9.11 | 1.58 | 12.20 | 4.73 | 2.53 |
| jan-mar | 1.98 | 3.00 | 3.95 | 13.24 | 3.61 | 44.48 | 4.14 | 3.21 |
| dec-july | 2.61 | 9.21 | 8.92 | 7.01 | 2.06 | 12.92 | 15.91 | 7.02 |
| dec-june | 2.99 | 9.92 | 9.82 | 6.55 | 2.05 | 14.52 | 14.78 | 4.95 |
| dec-may | 4.23 | 17.41 | 18.11 | 8.19 | 2.15 | 19.58 | 11.04 | 4.92 |
| dec-apr | 6.39 | 21.35 | 25.19 | 8.30 | 2.44 | 13.25 | 12.00 | 7.63 |
| dec-mar | 2.39 | 3.18 | 4.99 | 9.93 | 6.51 | 35.53 | 11.54 | 11.12 |
| nov-july | 1.73 | 2.15 | 3.58 | 2.65 | 3.13 | 2.67 | 1.30 | 1.31 |
| nov-june | 3.02 | 8.93 | 9.61 | 6.16 | 2.47 | 18.92 | 19.92 | 7.68 |
| nov-may | 4.13 | 14.14 | 16.91 | 7.59 | 2.62 | 28.85 | 17.34 | 7.96 |
| nov-apr | 5.91 | 17.53 | 22.63 | 7.72 | 3.00 | 17.97 | 17.60 | 10.73 |
| nov-mar | 2.47 | 3.08 | 4.99 | 8.85 | 7.67 | 44.25 | 16.87 | 16.58 |
| oct-july | 3.16 | 6.30 | 7.20 | 5.28 | 2.81 | 18.23 | 31.63 | 14.98 |
| oct-june | 3.63 | 6.83 | 7.95 | 4.91 | 2.85 | 20.09 | 30.32 | 11.10 |
| oct-may | 4.95 | 9.06 | 11.49 | 5.97 | 3.06 | 28.12 | 23.30 | 11.96 |
| oct-apr | 7.36 | 11.36 | 16.16 | 6.17 | 3.45 | 17.97 | 22.69 | 16.49 |
| oct-mar | 3.10 | 2.57 | 4.14 | 6.83 | 8.28 | 33.96 | 19.30 | 20.54 |
| sep-july | 3.00 | 4.97 | 6.38 | 4.44 | 3.18 | 16.66 | 81.73 | 36.71 |
| sep-june | 3.32 | 5.35 | 7.02 | 4.21 | 3.24 | 18.26 | 82.60 | 29.70 |
| sep-may | 4.46 | 7.18 | 9.27 | 4.63 | 3.51 | 22.56 | 73.13 | 34.38 |
| sep-apr | 6.09 | 8.59 | 12.46 | 4.76 | 4.01 | 16.11 | 59.30 | 40.07 |
| sep-mar | 2.92 | 2.37 | 3.87 | 5.01 | 8.65 | 25.51 | 44.82 | 48.49 |

**Table G-13: Return periods for monthly intervals highly correlated to Chesapeake Bay dissolved oxygen criteria exceedances using LOWESS polynomial regression de-trended flow data.**

| Interval | 1992-1994 | 1993-1995 | 1994-1996 | 1996-1998 |
|---|---|---|---|---|
| September – June | 5.35 | 7.02 | 4.21 | 18.26 |
| November – June | 8.93 | 9.61 | 6.16 | 18.92 |
| December – June | 9.92 | 9.82 | 6.55 | 14.52 |
| September - July | 4.97 | 6.38 | 4.44 | 16.66 |
| December - July | 9.21 | 8.92 | 7.01 | 12.92 |

## *Summary of analyses*

There is no strict guidance on determining the critical period and others have determined the critical period for TMDLs based on data availability, capturing the worst conditions in the period of record, capturing a range of flows, or 7Q10 flow. The availability of many decades of flow and water quality monitoring data in the Chesapeake Bay watershed allowed the opportunity to select a critical period from a group of candidate periods so there is some freedom to follow a very rational approach to the selection of the period. Of the above criteria that others have used to set critical periods, the idea of a 10-year return period is common and amenable to analysis.

The analyses presented here take into account two methods of calculating probability, two methods of giving weight to more effective basins, two time periods to calculate long term probability, and two de-trending methods. All methods are more or less relevant and are considered as a group to determine the critical period most indicative of a 10-year return period. Of the candidate periods, 1996-1998 and 1993-1995 are closest to the 10-year return period. Table G-14 below summarizes the results from these two candidate periods.

**Table G-14. Summary of results for 1993-1995 and 1996-1998 periods.**

| | **All Tributaries (1978 - 2009)** | | **Potomac + Susquehanna (1930 - 2009)** | | |
|---|---|---|---|---|---|
| | **Without Multiplier** | **With Multiplier** | **With Multiplier** | **With Multiplier** | **With Multiplier** |
| | **No De-trending** | **No De-trending** | **No De-trending** | **De-trended (Linear regression)** | **De-trended (LOWESS)** |
| Year | 1993-1995 | | | | |
| Median (High $r^2$) | 7.53 | 7.48 | 7.27 | 6.34 | 8.92 |
| Mean (High $r^2$) | 6.84 | 6.99 | 7.39 | 5.97 | 8.35 |
| Median (All monthly spans) | | | 9.31 | 6.62 | 9.07 |
| Mean (All monthly spans) | | | 11.28 | 8.05 | 11.26 |
| **Overall Range 1993 - 1995** | **5.97-11.28** | | | | |
| Year | 1996-1998 | | | | |
| Median (High $r^2$) | 18.95 | 16.02 | 17.56 | 11.3 | 16.66 |
| Mean (High $r^2$) | 18.82 | 14.87 | 15.24 | 11.78 | 16.26 |
| Median (All monthly spans) | | | 19.26 | 14.35 | 18.26 |
| Mean (All monthly spans) | | | 21.63 | 15.57 | 21.05 |
| **Overall Range 1996 - 1998** | **11.30-21.63** | | | | |

Using the above table to compare 1993-1995 and 1996-1998, it is clear that in all methods of determining the return period, the 1996-1998 period has a return period of greater than 10 years. The period 1993-1995 is generally evaluated to be slightly below a 10-year return period, but the overall range incorporates the 10-year period. 1993-1995 was selected the Water Quality Goal Implementation Team as the most appropriate critical period because it was the most consistent with existing Chesapeake Bay watershed jurisdictions' practices.

## References

Alabama Department of Environmental Management (ADEM). 1996. TMDL Bayou Sara/Norton Creek – Mobile River Basin Organic Enrichment/DO.

ADEM. 2005. Organic Enrichment/Dissolved Oxygen TMDL Rabbit Creek and Dog River.

ADEM. 2006. Total Maximum Daily Load Organic Enrichment/Dissolved Oxygen Threemile Creek, Alabama.

Delaware Department of Natural Resources and Environmental Control (DNREC). 1998. Total Maximum Daily Load Analysis for Indian River, Indian River Bay and Rehoboth Bay, Delaware. Dover, DE.

DNREC. 1998. Total Maximum Daily Load Analysis for Nanticoke River and Broad Creek, Delaware. Dover, DE.

DNREC. 2004. TMDLs for The Little Assawoman Bay and Tributaries and Ponds of the Indian River, Indian River Bay, and Rehoboth Bay. Prepared by ENTRIX, Inc. and J.E. Edinger Associates, Inc. New Castle, DE and Wayne, PA.

Helsel, D.R., and Hirsch, R.M.. 2002. Techniques of Water-Resources Investigations of the United States Geological Survey. Chapter A3: Statistical methods in water resources. Book 4, Hydrologic Analysis and Interpretation.

Malcolm Pirnie, Inc.. 2009. Technical Memorandum: Analysis of January-May Inflows to the Chesapeake Bay During the 1996-98 Period.

MDE (Maryland Department of the Environment). 2006. Total Maximum Daily Loads of Nitrogen and Phosphorus for Baltimore Harbor in Anne Arundel, Baltimore, Carroll, and Howard Counties and Baltimore City, Maryland. Baltimore, MD.

MDE (Maryland Department of the Environment). 2006. Total Maximum Daily Loads of Nitrogen and Phosphorus for the Upper and Middle Chester River, Kent and Queen Anne's Counties, Maryland. Baltimore, MD.

Massachusetts Department of Environmental Protection and US Environmental Protection Agency, New England Region (MassDEP and USEPA) 2007. TMDL for Nutrients in the Lower Charles River Basin, Massachusetts. Worcester and Boston, MA.

MDE and District of Columbia Department of the Environment. 2008. Total Maximum Daily Loads of Nutrients/Biochemical Oxygen Demand for the Anacostia River Basin, Montgomery and Prince George's Counties, Maryland and The District of Columbia. Baltimore, MD.

National Institute of Standards and Technology (NIST) and SEMATECH. e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/, U.S. Commerce Department's Technology Administration. Last updated: 7/18/2006.

New York State Department of Environmental Conservation and Connecticut Department of Environmental Protection. 2000. A Total Maximum Daily Load Analysis to Achieve Water Quality Standards for Dissolved Oxygen in Long Island Sound. Albany, NY and Hartford, CT.

Peconic Estuary Program. 2007. Total Maximum Daily Load for Nitrogen in the Peconic Estuary Program Study Area Including Waterbodies Currently Impaired Due to Low Dissolved Oxygen: the Lower Peconic River and Tidal Tributaries; Western Flanders Bay and Lower Sawmill Creek; and Meetinghouse Creek, Terrys Creek and Tributaries. Yaphank, NY.

Ponce, V. M., 1989. Engineering Hydrology: Principles and Practices. ISBN 0-13-277831. Prentice-Hall, Inc.

SCDHEC (South Carolina Department of Health and Environmental Control). 2002. Total Maximum Daily Load Cooper River, Wando River, Charleston Harbor System, South Carolina.

SCDHEC (South Carolina Department of Health and Environmental Control). 2003. Total Maximum Daily Load Ashley River, South Carolina.

VADEQ (Virginia Department of Environmental Quality). 2009. Total Maximum Daily Load for Dissolved Oxygen in Mill Creek, Northampton County, Virginia. Prepared by Virginia Institute of Marine Science. Gloucester Point, VA.

USEPA (U.S. Environmental Protection Agency). 2003a. *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll* a *for the Chesapeake Bay and Its Tidal Tributaries*. EPA 903-R-03-002. U.S. Environmental Protection Agency, Region 3, Chesapeake Bay Program Office, Annapolis, MD.

U. S. Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood-flow frequency: Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston, Va., 183 p., http://water.usgs.gov/osw/bulletin17b/bulletin_17B.html