United States Environmental Protection Agency

An Approach for Using Load Duration Curves in the Development of TMDLs

An Approach for Using Load Duration Curves in the Development of TMDLs

EPA 841-B-07-006
August 2007

Watershed Branch (4503T)
Office of Wetlands, Oceans and Watersheds
U.S. Environmental Protection Agency
1200 Pennsylvania Ave. NW
Washington, DC 20460

Document posted at:
http://www.epa.gov/owow/tmdl/techsupp.html

U.S. Environmental Protection Agency

August 2007
Office of Wetlands, Oceans, & Watersheds
U.S. Environmental Protection Agency

This guide provides an overview on the use of duration curves for developing Total Maximum Daily Loads (TMDLs). It is written for TMDL practitioners who are familiar with relevant technical approaches and legal requirements. The guide describes basic steps needed to develop duration curves, which identify loading capacities, load and wasteload allocations, margins of safety, and seasonal variations. The guide also discusses some considerations and limitations in using the approach, and includes several case examples.

The duration curve approach allows for characterizing water quality concentrations (or water quality data) at different flow regimes. The method provides a visual display of the relationship between stream flow and loading capacity. Using the duration curve framework, the frequency and magnitude of water quality standard exceedances, allowable loadings, and size of load reductions are easily presented and can be better understood.

The duration curve approach is particularly applicable because stream flow is an important factor in the determination of loading capacities. This method accounts for how stream flow patterns affect changes in water quality over the course of a year (i.e., seasonal variation that must be considered in TMDL development). Duration curves also provide a means to link water quality concerns with key watershed processes that may be important considerations in TMDL development. Basic principles of hydrology can help identify the relative importance of factors such as water storage or storm events, which subsequently affect water quality.

Water quality analysts should assess the appropriateness of using this framework to develop a particular TMDL. An underlying premise of the duration curve approach is correlation of water quality impairments to flow conditions. The duration curve alone does not consider specific fate and transport mechanisms, which may vary depending on watershed or pollutant characteristics. Such processes may include sediment attenuation, plant uptake of nutrients, chemical transformations, or bioaccumulation. Practitioners should consider using a separate analytical tool to develop a TMDL when factors other than flow significantly affect a water body's loading capacity.

Disclaimer

This document provides technical information to TMDL practitioners who are familiar with the relevant technical approaches and legal requirements pertaining to developing TMDLs and refers to statutory and regulatory provisions that contain legally binding requirements. This document does not substitute for those provisions or regulations, nor is it a regulation itself. Thus, it does not impose legally binding requirements on EPA or States, who retain the discretion to adopt approaches on a case-by-case basis that differ from this information. Interested parties are free to raise questions about the appropriateness of the application of this information to a particular situation, and EPA will consider whether or not the technical approaches are appropriate in that situation.

Table of Contents

1. DEVELOPMENT OF FLOW DURATION CURVES 1
   a. What is a Flow Duration Curve? 1
   b. Where to Get Flow Information 2
   c. Duration Curve Intervals and Zones 2

2. DEVELOPMENT OF LOAD DURATION CURVES AND TMDLS 3
   a. Numeric Water Quality Targets 3
   b. Interpreting Load Duration Curves to Assess Water Quality 5
   c. Margin of Safety 6
   d. Development of Allocations 7
   e. Seasonal Variation 9
   f. Summary 11

3. APPROPRIATE USE OF LOAD DURATION CURVES 12
   a. Appropriate When Flow is Primary Driver 12
   b. Water Quality Standards Designed for All Flow Regimes 12

4. CONSIDERATIONS 13
   a. Source Characterization 13
   b. Large Scale Watershed Situations 13
   c. Range of Flows Versus Single Condition 14
   d. Storm Events and Hydrograph Separation 15
   e. Utility in Identifying Potential Source Areas 16

5. CONNECTING TO IMPLEMENTATION AND RESULTS 17

APPENDICES

A. LOAD DURATION CURVE TMDLS – CASE EXAMPLE 19
B. ADDITIONAL EXAMPLES OF USING LOAD DURATION CURVE APPROACH 37
C. TARGETING POTENTIAL SOLUTIONS AND CONNECTING TO IMPLEMENTATION 55
D. ACRONYMS AND REFERENCES 65

List of Figures

Figure 1-1 General Form of the Flow Duration Curve 1
Figure 1-2 General Form of the Flow Duration Curve 3
Figure 2-1 Nitrate Loading Capacity Using Duration Curve Framework 4
Figure 2-2 Ambient Water Quality Data Using a Duration Curve Framework 5
Figure 2-3 Example TMDL Using Duration Curve Framework 9
Figure 2-4 Mississippi River Seasonal Flow Patterns 10
Figure 2-5 Mississippi River Monthly Variation 10

List of Figures *(cont.)*

Figure 4-1 Fraction Analysis of Storm Flow Relative to Total Streamflow............... 15
Figure 5-1 Duration Curve with Contributing Area Focus... 17
Figure 5-2 Documenting Erosion Control Program Results...................................... 18
Figure B-1 Chloride Loading Capacity Using Duration Curve Framework................ 38
Figure B-2 Nitrate Loading Capacity Using Duration Curve Framework 39
Figure B-3 Phosphorus Loading Capacity Using Duration Curve Framework........... 40
Figure B-4 Example Sediment Rating Curve 41
Figure B-5 Sediment Loading Capacity Using Duration Curve Framework 42
Figure B-6 Bacteria Loading Capacity Using Duration Curve Framework 43
Figure B-7 Concentration-Based TMDL.. 44
Figure B-8 TSS Loading Capacity Using Duration Curve Framework....................... 45
Figure B-9 Middle Fork LeBuche River TMDL Using Duration Curve Framework . 47
Figure B-10 Bacteria Loading Capacity Using Duration Curve Framework 48
Figure B-11 Development of E. Coli Upper Target 49
Figure B-12 Development of Daily Value Based on Monthly Target........................... 50
Figure B-13 Relationship Between 30-day Geometric Mean and Daily Target............ 51
Figure B-14 Monthly Bacteria Loading Capacity Using Duration Curve Framework . 53
Figure C-1 Duration Curve as General Indicator of Hydrologic Condition 57
Figure C-2 Duration Curve with Contributing Area Focus 58
Figure C-3 Duration Curve with Targeted Activity Focus 59
Figure C-4 Duration Curve with Delivery Mechanism Focus..................................... 60
Figure C-5 Documenting Program Results Using Duration Curve Framework.......... 63
Figure C-6 Documenting Program Results Using Duration Curve Framework.......... 63

List of Tables

Table 2-1 Approaches for Developing TMDL “Margin of Safety” 6
Table 2-2 Example TMDL Using Duration Curve Framework..................................... 8
Table 4-1 Example Source Area / Hydrologic Condition Considerations................... 16
Table 5-1 Example TMDL Summary Using Duration Curve Framework.................. 18
Table B-1 Calculation of Chloride Loads.. 38
Table B-2 Calculation of Phosphorus Loads 39
Table B-3 Calculation of Bacteria Loads.. 43
Table B-4 Middle Fork LeBuche River TMDL Summary 46
Table B-5 Werbaldo Creek TMDL Summary 51
Table B-6 Swamp Creek Monthly Mean Flows 52
Table C-1 Example Management Practice / Hydrologic Condition Considerations ... 62

1. DEVELOPMENT OF FLOW DURATION CURVES

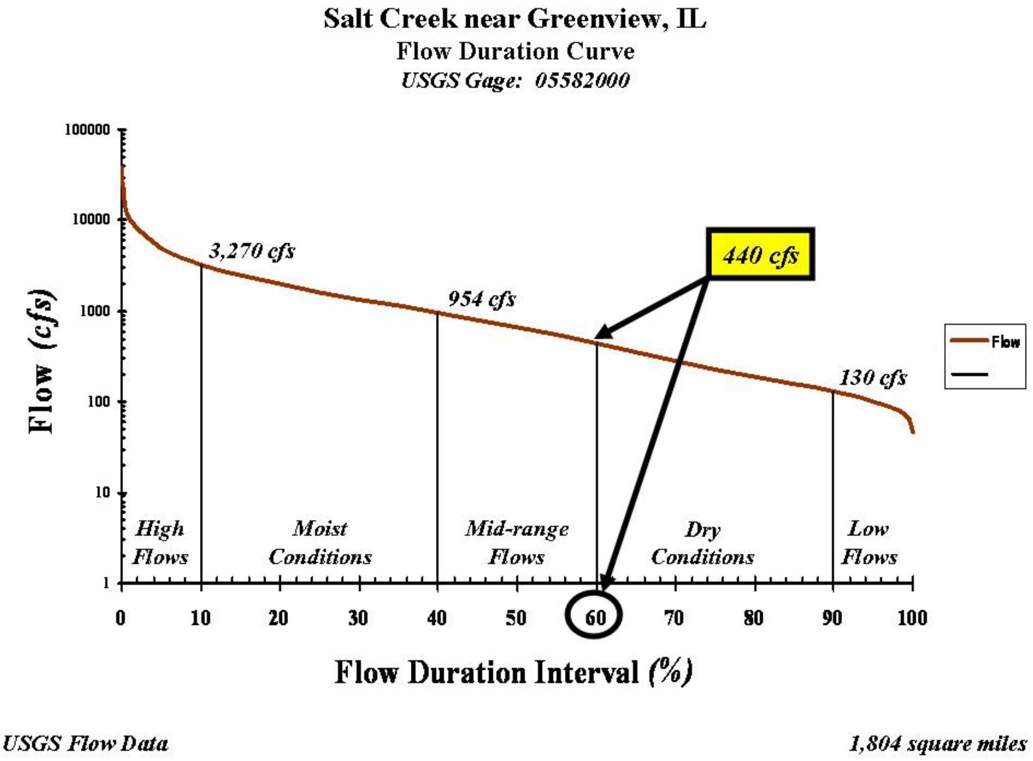
1a. What is a Flow Duration Curve?

Flow duration curve analysis looks at the cumulative frequency of historic flow data over a specified period. A flow duration curve relates flow values to the *percent of time* those *values* have been *met or exceeded*. The use of *"percent of time"* provides a uniform scale ranging between 0 and 100. Thus, the full range of stream flows is considered. Low flows are exceeded a majority of the time, while floods are exceeded infrequently.

A basic flow duration curve runs from high to low along the x-axis, as illustrated in Figure 1-1. The x-axis represents the duration amount, or *"percent of time"*, as in a cumulative frequency distribution. The y-axis represents the flow value (e.g., cubic feet per second) associated with that *"percent of time"* (or duration).

Flow duration curve development typically uses daily average discharge rates, which are sorted from the highest value to the lowest *(Figure 1-1)*. Using this convention, flow duration intervals are expressed as a percentage, with zero corresponding to the highest stream discharge in the record (i.e., flood conditions) and 100 to the lowest (i.e., drought conditions). Thus, a flow duration interval of sixty associated with a stream discharge of 440 cubic feet per second (cfs) implies that sixty percent of all observed daily average stream discharge values equal or exceed 440 cfs.

Figure 1-1. General Form of the Flow Duration Curve



1b. Where to Get Flow Information

Information on river flows across the United States is readily available from the U.S. Geological Survey (USGS). Stream flow conditions on any given day can be highly variable, depending on watershed characteristics and weather patterns. Due to the wide range of variability that can occur in stream flows, hydrologists have long been interested in knowing the percentage of days in a year when given flows occur. The mechanics of constructing the flow duration curve in Figure 1-1 involved three steps. Daily average flow data was first downloaded from the USGS National Web site (http://waterdata.usgs.gov/nwis/sw). Data was then read into a spreadsheet to determine duration curve intervals covering the full range of flows. Lastly, flow duration curve information was copied from the spreadsheet into a graphics package to create the labeled display.

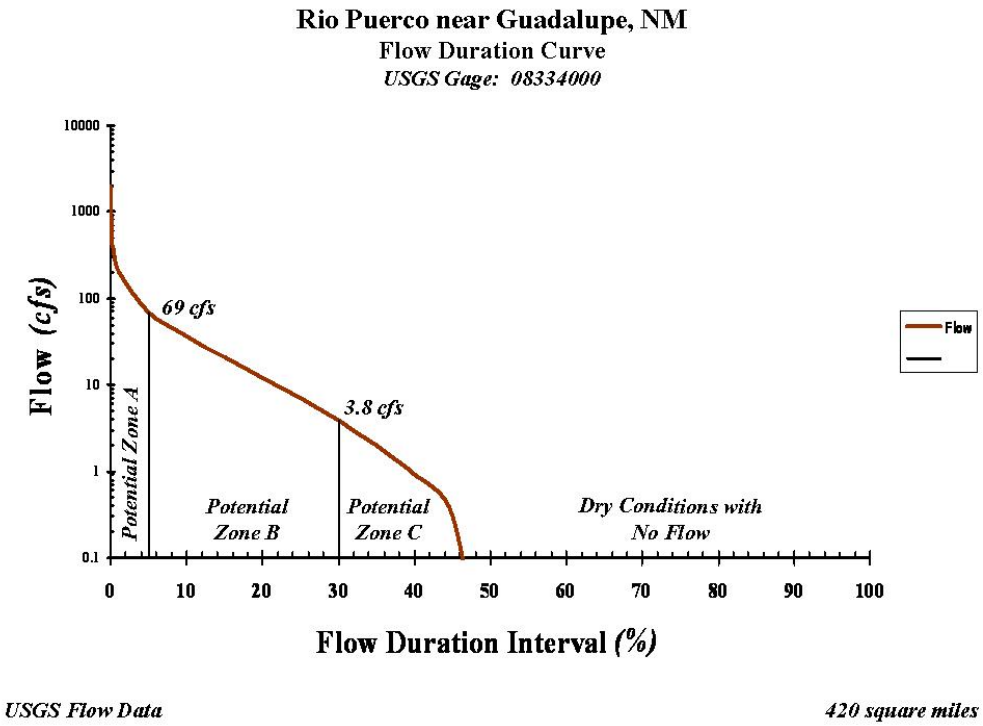
Not all waters or watersheds have gaging stations or flow data available. In such cases estimation techniques are needed *(USEPA, 2007)*. For instance, it may be appropriate to use flow data of a similar, representative water body to develop the duration curve, based on regression methods or drainage area ratios. The use of rainfall / runoff models can also be used to develop stream flow estimates for use in a duration curve analysis.

1c. Duration Curve Intervals and Zones

Duration curve analysis identifies intervals, which can be used as a general indicator of hydrologic condition (i.e., wet versus dry and to what degree). Flow duration curve intervals can be grouped into several broad categories or zones. These zones provide additional insight about conditions and patterns associated with the impairment. A common way to look at the duration curve is by dividing it into five zones, as illustrated in Figure 1-1: one representing *high flows (0-10%)*, another for *moist conditions (10-40%)*, one covering *mid-range flows (40-60%)*, another for *dry conditions (60-90%)*, and one representing *low flows (90-100%)*.

This particular approach places the midpoints of the moist, mid-range, and dry zones at the 25th, 50th, and 75th percentiles respectively (i.e., the quartiles). The high zone is centered at the 5th percentile, while the low zone is centered at the 95th percentile. Other schemes can be used, depending on local hydrology and the water quality issues being addressed by assessment efforts. For example, Figure 1-2 shows a flow duration curve for a stream in the arid Southwest, where there is no flow more that half the time. In this case, an alternative approach might consider use of two, three, or four zones, depending on the water quality concerns being addressed by the TMDL. Again, the benefit of using zones is to provide insight regarding patterns associated with concerns.

Figure 1-2. General Form of the Flow Duration Curve



2. DEVELOPMENT OF LOAD DURATION CURVES AND TMDLS

Flow duration curves serve as the foundation for development of load duration curves, on which TMDLs can be based. A load duration curve is developed by multiplying stream flow with the numeric water quality target (usually a water quality criterion) and a conversion factor for the pollutant of concern. The following section provides a general discussion of the elements to be addressed in developing a TMDL using the load duration curve framework. A specific case study is presented in Appendix A, which illustrates how this framework was applied to develop a fecal coliform TMDL.

2a. Numeric Water Quality Targets

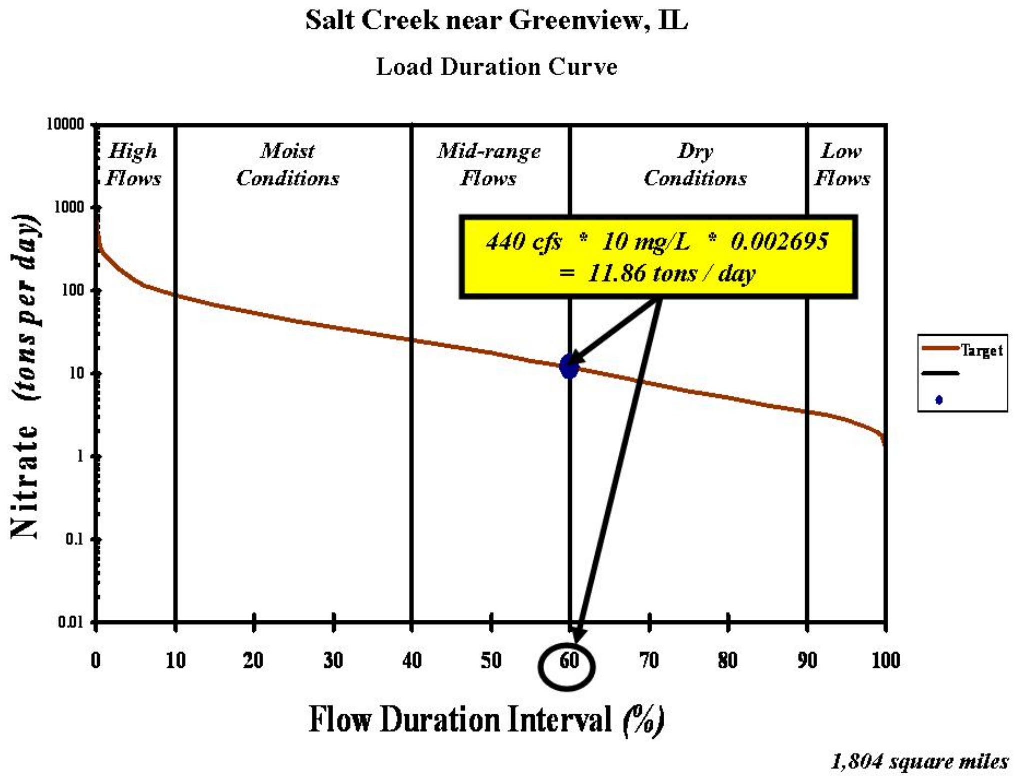
The numeric water quality target represents the quantitative value used to measure whether or not the applicable water quality standard (WQS) is attained. Generally, the target is the water quality criterion contained in the WQS for the pollutant of concern. The target may be constant across all flow conditions (e.g., chloride, nitrate, phosphorus, or bacteria). The target could also vary with flow (e.g., sediment). Because the water quality criterion is crucial in the development of the loading capacity, the absence of numeric criteria poses challenges (e.g., sediment, nutrients). As efforts continue to develop and adopt numeric sediment and/or nutrient criteria, practitioners should evaluate whether an appropriate interim or site-specific, numeric endpoint can be identified prior using the duration framework for TMDLs. Otherwise, alternative analytical methods should be explored.

Numeric water quality targets are translated into TMDLs through the loading capacity. EPA's current regulation defines loading capacity as *"the greatest amount of loading that a water can receive without violating water quality standards"*. The loading capacity provides a reference, which helps guide pollutant reduction efforts needed to bring a water into compliance with standards.

Basic hydrology represents a logical starting point to identify a loading capacity. First, loads are directly proportional to flows (i.e., load equals flow times concentration times a conversion factor). Second, water quality parameters are often related to stream flow rates. For instance, sediment concentrations typically increase with rising flows as a result of factors such as channel scour from higher velocities. Other parameters, such as chloride, may be more concentrated at low flows and more diluted by increased water volumes at higher flows.

Flow patterns play a major role when considering loading capacities in TMDL development, regardless of the technical approach used. Duration curves, however, provide the added benefit of looking at the full range of flow conditions. Figure 2-1 illustrates an example loading capacity curve developed using a duration curve framework based on the flow duration curve shown in Figure 1-1. A sample calculation is shown at one point along the curve corresponding to a flow duration interval of 60 using a nitrate target of 10 mg/L. Appendix B provides specific details on how loading capacity duration curves are developed for use in TMDLs.

<u>Figure 2-1</u>. Nitrate Loading Capacity Using Duration Curve Framework



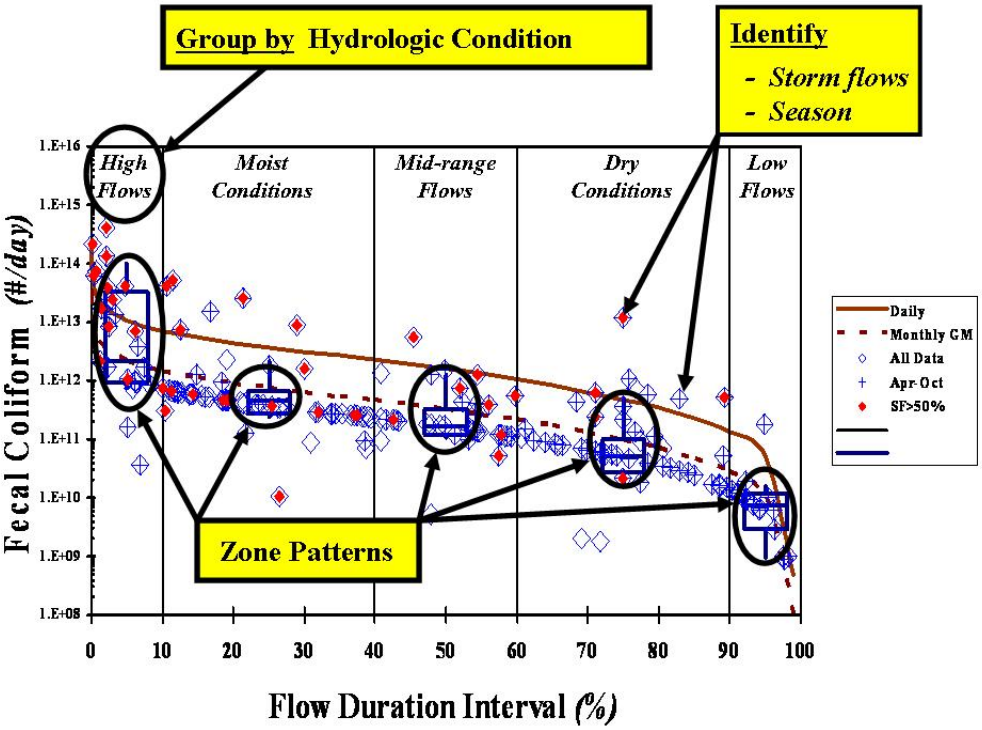
2b. Interpreting Load Duration Curves to Assess Water Quality

When using the duration curve framework in the context of developing a TMDL, it is important to keep in mind that the entire duration curve should be applied to account for the various flow regimes. Ambient water quality data, taken with some measure or estimate of flow at the time of sampling, can be used to compute an instantaneous load. Using the relative percent exceedance from the flow duration curve that corresponds to the stream discharge at the time the water quality sample was taken, the computed load can be plotted in a duration curve format (Figure 2-2).

By displaying instantaneous loads calculated from ambient water quality data and the daily average flow on the date of the sample (expressed as a flow duration curve interval), a pattern develops, which describes the characteristics of the water quality impairment. Loads that plot above the curve indicate an exceedance of the water quality criterion, while those below the load duration curve show compliance.

The pattern of impairment can be examined to see if it occurs across all flow conditions, corresponds strictly to high flow events, or conversely, only to low flows. Impairments observed in the low flow zone typically indicate the influence of point sources, while those further left generally reflect potential nonpoint source contributions. This concept is illustrated in Figure 2-2. Data may also be separated by season (e.g., spring runoff versus summer base flow). For example, Figure 2-2 uses a "+" to identify those ambient samples collected during primary contact recreation season (April – October).

Figure 2-2. Ambient Water Quality Data Using a Duration Curve Framework



The utility of duration curve zones for pattern analysis can be further enhanced to characterize wet-weather concerns. Some measure or estimate of flow is available to develop the duration curves. As a result, stream discharge measurements on days preceding collection of the ambient water quality sample may also be examined. This concept is illustrated in Figure 2-2 by comparing the flow on the day the sample was collected with the flow on the preceding day. Any one-day increase in flow (above some designated minimum threshold) is assumed to be the result of a surface runoff event (unless the stream is regulated by an upstream reservoir). In Figure 2-2, these samples are identified with a shaded diamond.

2c. Margin of Safety

A *"margin of safety"* (MOS) is typically expressed either as unallocated assimilative capacity or as conservative analytical assumptions used in establishing the TMDL (e.g., derivation of numeric targets, modeling assumptions or effectiveness of proposed controls). The *"margin of safety"* may be explicitly stated as an added, separate quantity in the TMDL calculation. The *"margin of safety"* may also be implicit, as in conservative assumptions. Table 2-1 presents six common approaches for incorporating a *"margin of safety"* into TMDLs. Some States may have established approaches for determining the MOS either explicitly or implicitly as a step in their TMDL development process (as indicated in Table 2-1). These approaches should be taken into consideration when identifying the MOS using a duration curve framework.

Table 2-1. Approaches for Developing TMDL *"Margin of Safety"*

Type of Margin of Safety	Approaches
Explicit	• Set numeric targets at more conservative levels than analytical results indicate • Add a safety factor to pollutant loading estimates • Do not allocate part of available loading capacity; reserve for MOS
Implicit	• Conservative assumptions in derivation of numeric targets • Conservative assumptions when developing numeric model applications • Conservative assumptions when analyzing prospective feasibility of practices and restoration activities.

Using a duration curve framework, one option could be to identify an explicit *"margin of safety"* for each listed reach and corresponding set of flow zones. For example, one way to define the MOS could be based on the difference between the loading capacity as calculated at the mid-point of each of the five flow zones, and the loading capacity calculated at the minimum flow in each zone. Given that the loading capacity is typically much less at the minimum flow of a zone as compared to the mid-point, a substantial *"margin of safety"* is provided. The *"margin of safety"* ensures that allocations will not exceed the load associated with the minimum flow in each zone. This approach also allows for recognition that the uncertainty associated with effluent limits and water quality may vary across different flow conditions. For instance, because of changes in variability at different flow regimes, the uncertainty may be greater under high flow conditions than at low flow (or vice versa).

Because the allocations are a direct function of flow, accounting for potential flow variability is an appropriate way to address the *"margin of safety"*. Although minimum flows over long periods of record at the USGS gage sites are typically used when defining the MOS for the low flow zone, the effect of point source discharges on effluent dominated streams should also be considered. Adjustments to the MOS may be needed to account for situations where the only flow under low flow conditions is treatment plant discharges.

An explicit *"margin of safety"* identified using a duration curve framework is basically unallocated assimilative capacity intended to account for uncertainty (e.g., loads from tributary streams, effectiveness of controls, etc.). As new information becomes available, this unallocated capacity may be attributed to nonpoint sources including tributary streams (which could then be added to the load allocation); or it may be attributed to point sources (and become part of the waste load allocations).

2d. Development of Allocations

Allocations represent those portions of a receiving water's loading capacity attributed to point sources (waste load allocations) or to nonpoint sources and natural background (load allocations). Allocations are a key part of the TMDL; they represent the basic road map to water quality standards attainment. The duration curve framework provides a reasonable way to define allocations because it allows adjustments, which reflect differences in the types of sources that may be dominant under various flow conditions.

For instance, in effluent dominated streams wastewater treatment facilities (WWTFs) exert a significant influence on water quality at low flows. Under a duration curve framework, the allocation or portion of the loading capacity attributed to WWTFs can be greater in the low flow zone. Similarly, runoff from nonpoint sources tends to dominate water quality under high flow conditions. Thus, the allocation or portion of the loading capacity for nonpoint sources can be greater under moist and high flow conditions using a duration curve framework.

Waste load allocation development for continuous point source discharges is relatively straightforward using a duration curve framework. Consideration of pollution control measures is typically done in conjunction with NPDES permit development. Waste load allocations (WLAs) can be expressed at one level across the entire duration curve, or WLAs may be tiered to specific flow levels and the corresponding flow duration interval. Common methods used for allocating waste loads described in TMDL guidance (EPA, 1991) include equal percent removal, equal effluent concentrations, and hybrid methods. These allocation schemes can easily be applied to a duration curve framework.

Storm water and nonpoint sources of pollutants, on the other hand, present a greater challenge because pollutants are transported to surface waters by a variety of mechanisms (e.g., runoff, snowmelt, groundwater infiltration). Best management practices (BMPs) generally focus on source control and / or delivery reduction. Common methods in use to develop either WLAs for storm water or load allocations for nonpoint sources are also applicable under a duration curve framework. Examples include consideration of jurisdictional area, land use, or impervious cover.

An advantage of the duration curve framework is that allocations can be adjusted by zone. This may be needed to account for different source areas and delivery mechanisms that may dominate under different flow conditions. Table 2-2 summarizes the TMDL framework using the duration curve approach, showing the TMDL (equivalent to the loading capacity), the *"margin of safety"*, and the amount available for allocations (both load and waste load).

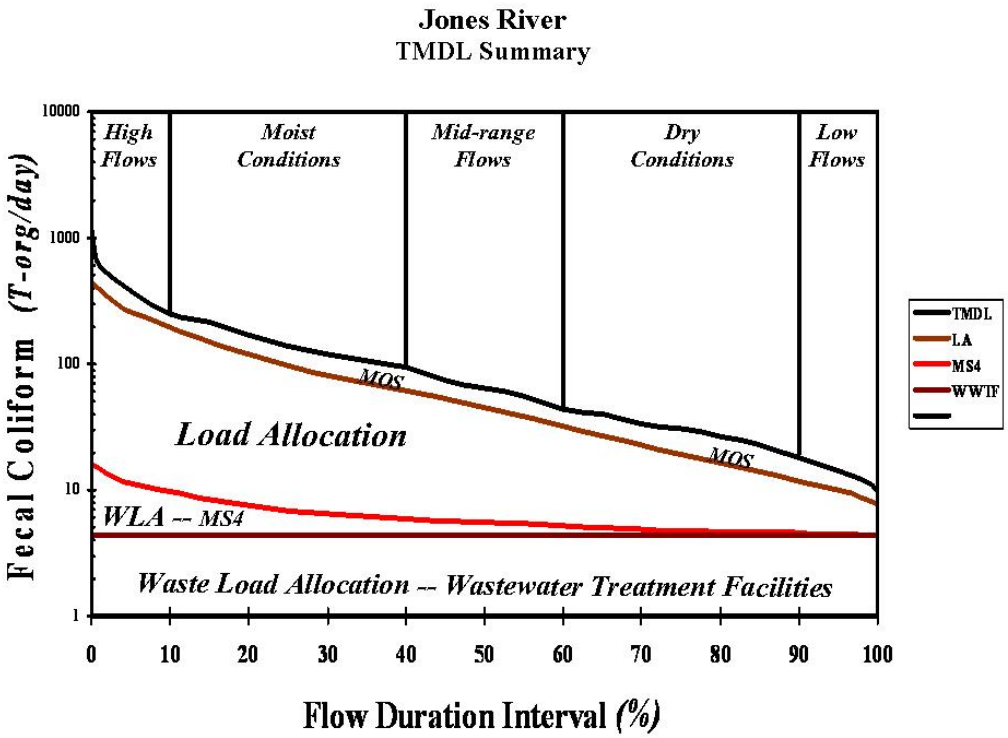
***Table 2-2*.** Example TMDL Using Duration Curve Framework

Segment ID	**Name**	**TMDL Component**	**Duration Curve Zone** *(Expressed as T-org/day)*				
			High	**Moist**	**Mid**	**Dry**	**Low**
Q21-01	**Quepote Brook**						
		TMDL	19.87	9.37	4.09	2.20	1.29
		MOS	4.31	3.92	0.76	0.66	0.77
		LA	9.18	3.10	1.88	0.79	0.35
	Korston DPW *(WWTP)*	WLA	0.12	0.12	0.12	0.12	0.12
	Loburn *(WWTP)*	WLA	0.05	0.05	0.05	0.05	0.05
	Korston DPW *(MS4/P1)*	WLA	3.81	1.33	0.80	0.36	0.00
	Loburn *(MS4/P2)*	WLA	2.40	0.85	0.48	0.22	0.00

Figure 2-3 illustrates a TMDL using a duration curve framework. Waste load allocations are specified for municipal treatment plants that reflect NPDES permit limits. In the case of both Table 2-2 and Figure 2-3, these waste load allocations are based on technology-based effluent limits at facility design flows. The waste load allocations are constant across all flow conditions and ensure that water quality standards will be attained.

Waste load allocations are also identified for municipal separate storm sewer systems (MS4), which reflect increased loads under higher flow conditions. In the Figure 2-3 example, storm water waste load allocations for MS4 communities are based on the percent jurisdictional area approach. In this case, three percent of the watershed falls within the jurisdiction of MS4 communities. Thus, the MS4 wasteload allocation is three percent of the available allocation for each zone. The remaining ninety-seven percent is designated for nonpoint sources and natural background as load allocation for each zone. Load allocations and MS4 waste load allocations have been determined at the mid-point of each zone based on appropriate portions. The allocation curves are determined by interpolating between these points.

Figure 2-3. Example TMDL Using Duration Curve Framework



2e. Seasonal Variation

The Clean Water Act (CWA) §303(d) states that in identifying TMDLs: *"such load shall be established at a level necessary to implement the applicable water quality standards with seasonal variations"*. Seasonal variation in flow is a key part of TMDL development. Figure 2-4 shows an example of seasonal flow patterns using monthly statistics for the Mississippi River at Winona. Flow is expressed as a unit area rate (i.e., cubic feet per second (cfs) per square mile). Unit area rates, determined by dividing the drainage area at the gage into the flow, enable a consistent way to compare flows from watersheds of different sizes.

Another way to view seasonal variation is through the use of flow duration curves. Figure 2-5 illustrates monthly flow data expressed as duration curve intervals for the Mississippi River at Winona. The *"box and whisker"* format allows analysis of general patterns by conveying information on the distribution of the data. For example, April flows for the Mississippi River at Winona and its tributaries are typically in the high and moist zones (median flow around 9%). Accordingly, consideration of seasonal variation in TMDL development and implementation planning to address water quality concerns in April would focus on source areas typical of these conditions. For this region, moist conditions in April generally reflect more saturated soil conditions, when upland sources such as cultivated fields exert a greater influence on stream flow and water quality.

Figure 2-4. Mississippi River Seasonal Flow Patterns

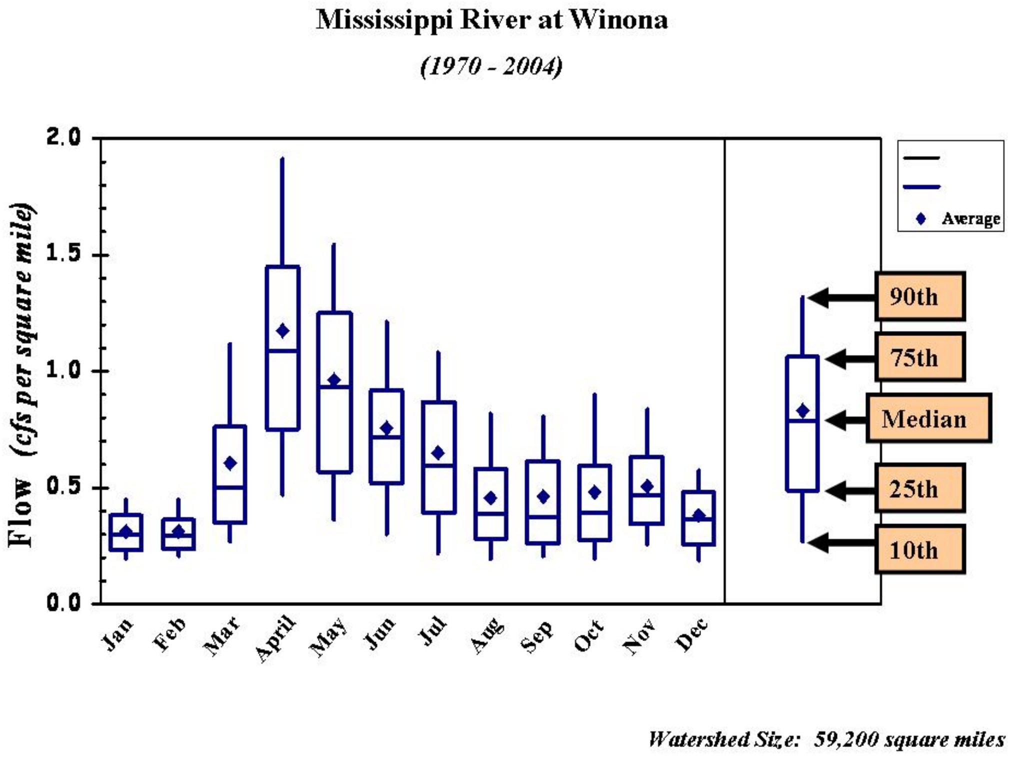
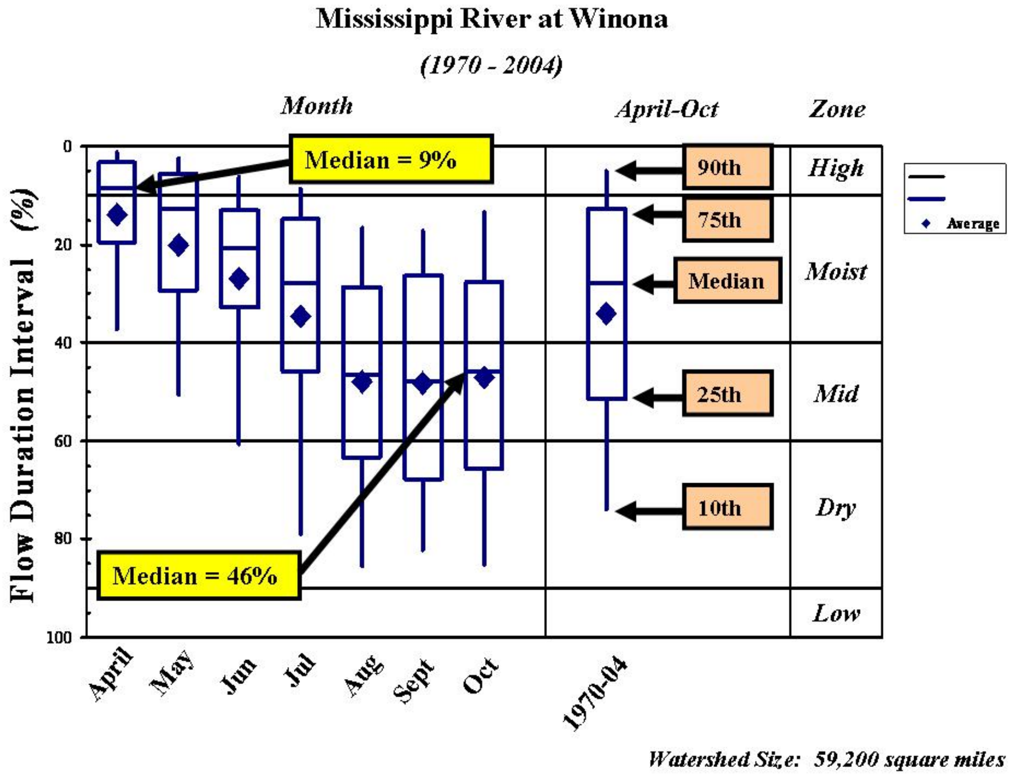


Figure 2-5. Mississippi River Monthly Variation



Conversely, August and September flows generally fall in the mid-range zone (median flow around 46%). Flows from tributary rivers to the upper Mississippi are even lower, typically falling into the dry zone during these months. This shifts TMDL development and implementation planning to source areas representative of these conditions. For these tributaries to the Mississippi River, source assessment and implementation planning might focus on wastewater treatment plant discharges or activities that have a direct influence on streamside riparian areas (e.g., straight pipes and livestock access).

2f. Summary

The use of duration curves provides a technical framework for identifying *"daily loads"* in TMDL development, which accounts for the variable nature of water quality associated with different stream flow rates. Specifically, a maximum daily concentration limit can be used with basic hydrology and a duration curve to identify a TMDL that covers the full range of flow conditions. With this approach, the maximum *"daily load"* can be identified for any given day based on the stream flow. Identification of a loading capacity using the duration curve framework is driven by the flow duration curve and a water quality criterion or target value. The target may be constant across all flow conditions (e.g., chloride) or the target may vary with flow (e.g., sediment rating curves).

Under the duration curve framework, the loading capacity is essentially the curve itself. The loading capacity, which sets the *"total maximum daily load"* on any given day, is determined by the flow on the particular day of interest. The use of duration curve zones can help provide a simplified summary through the identification of discrete loading capacity points by zone. Using a duration curve framework, an explicit *"margin of safety"* can be identified for each listed reach and corresponding set of flow zones. Allocations within the TMDL are set in a way that reflects dominant concerns associated with appropriate hydrologic conditions.

Appendix B includes example calculations for chloride, nitrate, phosphorus, total suspended solids, and bacteria. Appendix B also provides a discussion on ways the duration curve framework can be used to address different averaging periods (other than daily) in identifying loading capacities, particularly where a concentration-based target exists (expressed as monthly, seasonal, or annual average values).

3. APPROPRIATE USE OF LOAD DURATION CURVES

A few words about the appropriate use of the duration curve approach follow. First and perhaps most importantly, water quality analysts should assess the appropriateness of using this framework to develop a particular TMDL. Practitioners should also consider the suitability of using it as the sole basis for assessment versus supplementing its use with other analytical tools, such as water quality models.

3a. Appropriate When Flow is Primary Driver

An underlying premise of the duration curve approach is correlation of water quality impairments to flow conditions. The duration curve alone does not consider specific fate and transport mechanisms, which may vary depending on watershed or pollutant characteristics. Such processes may include sediment attenuation, plant uptake of nutrients, or chemical transformations.

The duration curve is more appropriate in cases where flow is a primary driver in pollutant delivery mechanisms, and other processes are a relatively insignificant part of the total loading. Flow, in many cases, is the principal force behind habitat modification, stream bank erosion, and other concerns preventing attainment of designated uses. Use of a duration curve in flow-induced nonpoint source situations more generally reflects actual loadings than in cases where flow is only one of many components influencing the overall loading. Practitioners should consider using a separate analytical tool to develop a TMDL when factors other than flow significantly affect a water body’s loading capacity. For example, use of the duration curve approach may not work in situations involving lakes or large coastal embayments, where factors other than stream flow exert a major effect on observed water quality conditions.

3b. Water Quality Standards Designed for All Flow Regimes

Another assumption behind the duration curve framework is that applicable water quality standards are protective of the designated use(s) over the entire flow regime. For a majority of pollutants, water quality criteria do not identify specific restrictions. When these special conditions exist, practitioners should evaluate the appropriateness of the duration curve method, or determine if there is a means to work within those provisions.

A possible scenario of a flow provision is where criteria explicitly state applicability at the 7Q10 flow. This reduces the importance of the criteria during the remaining flows (e.g., moderate to wet weather). In this example, the utility of the duration curve method is better suited as a diagnostic tool identifying magnitude and frequency of concerns across all flows. Similarly, the State adopted water quality standards may include a flow exemption (e.g., high flows), which should be considered when using the duration curve framework for TMDL development. Another situation may be where the bacteria criterion applies only during the swimming season. In order to work within this type of provision, the duration curve could be analyzed for just the relevant months or time period.

4. CONSIDERATIONS

This section discusses some potential concerns and considerations with utilizing the duration curve approach to develop TMDLs.

4a. Source Characterization

The duration curve method, by itself, is limited in the ability to track individual source loadings or relative source contributions within a watershed. Additional analysis is needed to identify pollutant contributions from different types of potential sources and activities (e.g., construction zone versus agricultural area) or individual sources of a similar source category (e.g., WWTF #1 versus WWTF #2). Without such analysis, it could be difficult to distinguish WLAs and LAs for individual sources.

Practitioners interested in more precise source characterization should consider supplementing the duration curve framework with a separate analysis. An added analytical tool might aid in evaluating allocation scenarios and tracking individual sources or source categories. This could allow for improved targeting of monitoring and restoration activities.

Information about individual sources could also be made available, where existing load contributions and reductions are central to evaluating potential water quality trading options. For example, a duration curve analysis might highlight the importance of low flow, point source issues. Depending on the manner in which the analysis is applied, the resulting TMDL could be based on the assumption that all point sources should be treated the same (i.e., the same loading from each source despite their relative location in the watershed and existing effluent loads).

Use of a separate or supplemental analysis is also beneficial in cases where bacteria pose a water quality problem. In this context, applying a duration curve in concert with microbial or bacterial source tracking data might allow for distinction of various bacteria sources (i.e., domestic pet, human, geese, deer, etc.). This information can provide direction on how the TMDL loadings could be allocated. For instance, practitioners may choose to impose load reductions to sources that are anthropogenic or controllable, and carry over wildlife sources at existing loading rates.

4b. Large Scale Watershed SituationsError! Bookmark not defined.

Depending on the pollutant of concern as well as the number and types of sources, it can be beneficial to divide a watershed into subwatersheds as a first step in the TMDL development process. Basically, a duration curve analysis is performed for each subwatershed, resulting in multiple, more refined loading capacity curves and subsequent allocations. Working on a subwatershed level is important in addressing issues with relative source contributions or spatial variations in the loading capacity, and can be useful in calculating more site-specific allocations. The following examples illustrate when it might be necessary to discern relative source contributions, isolate impaired waters, or address spatial variation.

- *Discerning relative source contributions*. In cases involving multiple point sources within a watershed, where each point source has a different effect on the receiving water, it might be useful to evaluate each point source individually (i.e., divide the watershed so that some or all of the point sources are isolated). The resulting duration curves could show that the loading of one point source comprises a larger portion its relative loading capacity than another, potentially highlighting the relative impact of each point source. When there are multiple nonpoint source loadings, applying the duration curve framework on a subwatershed scale may also help to reveal more localized impacts.

- *Isolating impaired waters*. Sometimes only a few tributaries within a watershed are impaired, warranting a TMDL analysis on a smaller scale. Rather than evaluating the entire watershed, isolating the impaired tributaries into individual subwatersheds can allow for a more meaningful, site-specific duration curve analysis.

- *Addressing spatial variation in loading capacity*. Larger watersheds comprised of multiple second and third order streams often exhibit a range of assimilative capacities in different parts of the watershed. An illustration of an extreme case is the differing loading capacities of a headwater stream versus a first-order stream near the mouth of a watershed. As such, it might be advantageous to divide a larger watershed into smaller units.

It is important to note that subwatersheds are interconnected, which may need to be accounted for on a case-by-case basis. Also, dealing with ungaged, headwater streams could present some obstacles in constructing a duration curve, as there is usually less data available on such waters.

4c. Range of Flows Versus Single Condition

Summarizing a duration or loading capacity curve into a single point may be practicable from an implementation standpoint, but could negate the strength of the duration curve framework. One aspect of concern regarding this practice is the selection of a single condition (i.e., one point as opposed to using the entire curve). Some TMDLs focus on capturing the magnitude of the highest observed exceedance. However, such TMDLs may be overly protective of the water quality standard, potentially inviting issues regarding reasonable assurance. Alternatively, some TMDLs focus on the average or median flow exceedance value, potentially resulting in allocations that are not protective enough during higher flow events. For this reason it is appropriate to apply the entire duration curve in the context of a TMDL. Another option is to categorize the duration curve into several zones, allowing the resultant TMDL to adequately capture different types of flow events.

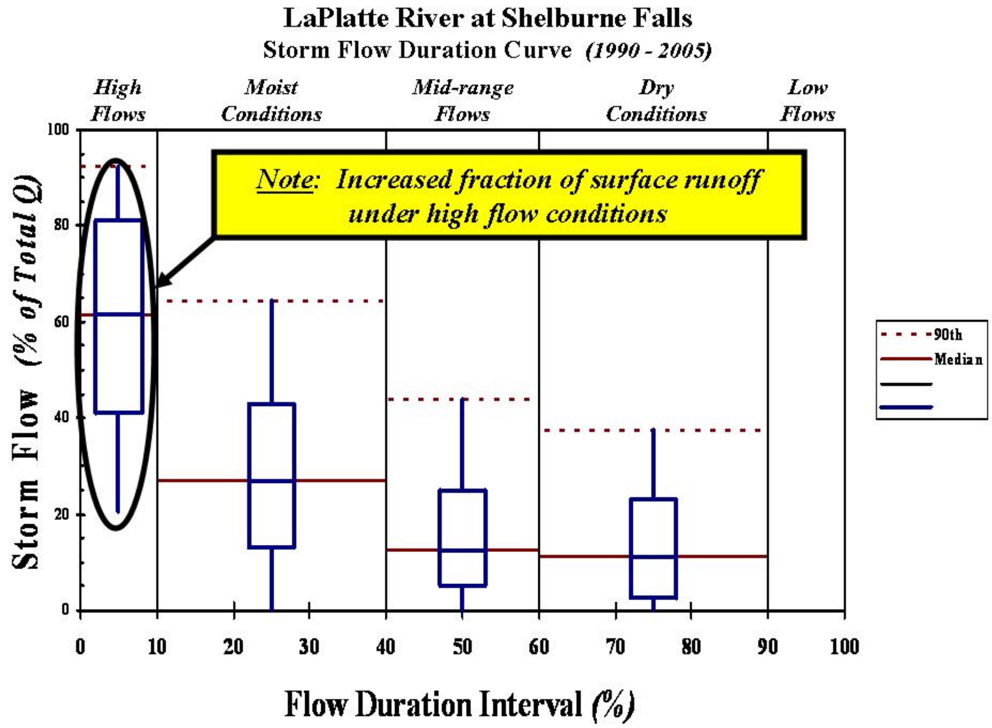
4d. Storm Events and Hydrograph Separation

Surface runoff following rain events can be one of the most significant transport mechanisms of sediment and other nonpoint source pollutants. Precipitation is obviously the driving mechanism responsible for storm flows and associated surface runoff. Rainfall / runoff models, such as HSPF, SWAT, or SWMM, are generally used to provide detailed estimates of the timing and magnitude of storm flows. However, these can also be very rigorous and time-consuming approaches.

Use of duration curves can help provide another method to examine general watershed response patterns. Streamflow hydrographs can be separated into base-flow and surface-runoff components *(Sloto and Crouse, 1996).* The base-flow component is traditionally associated with groundwater discharge and the surface-runoff component with precipitation that enters the stream as overland flow. Information from hydrograph separation can be displayed using duration curve intervals to examine the percentage (or fraction) of total flow that consists of base flow and storm flow.

Figure 4-1 illustrates the potential effect that storm flows may exert across the range of flow conditions, grouped by duration curve zone using data for the LaPlatte River. In Figure 4-1, surface runoff has its greatest effect during high flow conditions (median value of 61 percent). In such cases, sediment and other pollutants delivered to stream systems associated with surface erosion will also be greatest during high flows.

***Figure 4-1*.** Fraction Analysis of Storm Flow Relative to Total Streamflow



USGS Gage Duration Interval & Hydrograph Separation *44.6 square miles*

4e. Utility in Identifying Potential Source AreasError! Bookmark not defined.

Duration curves are based on the entire range of flow conditions observed for any given drainage. A major advantage of their use is the ability to consider the general hydrologic condition of the watershed, and subsequently, to enhance development of source assessments. Pollutant delivery mechanisms likely to exert the greatest influence on receiving waters (e.g., point source discharges, surface runoff) can be matched with potential source areas appropriate for those conditions (e.g., riparian zones, impervious areas, uplands). Table 4-1 illustrates an approach, as a simple example, which could be used to assess source areas based on the potential relative importance of delivery mechanisms under the range of hydrologic conditions.

Table 4-1**.** Example Source Area / Hydrologic Condition Considerations

Contributing Source Area	**Duration Curve Zone**				
	High Flow	**Moist**	**Mid-Range**	**Dry**	**Low Flow**
Point Source				*M*	*H*
On-site wastewater systems			*H*	*M*	
Riparian Areas		*H*	*H*	*H*	
Storm water: Impervious Areas		*H*	*H*	*H*	
Combined sewer overflows	*H*	*H*	*H*		
Storm water: Upland	*H*	*H*	*M*		
Bank erosion	*H*	*M*			

Note: Potential relative importance of source area to contribute loads under given hydrologic condition *(H: High; M: Medium)*

Table 4-1 describes an array of potential contributing source areas common to many watersheds where TMDLs are being developed. This table provides an organizational framework, which can be used to guide source assessment efforts. For instance, point sources tend to have the most dominant effect on water quality under low flow conditions. Thus, Table 4-1 identifies the low flow zone as a relative high priority for assessment of point sources.

Similarly, surface runoff from upland sources tends to exert a greater effect on water quality during higher flow conditions (e.g., high, moist, mid-range zones). Accordingly, Table 4-1 identifies these zones as a relative high priority for assessment of storm water sources from upland areas.

Ambient water quality monitoring data displayed in a duration curve framework (as shown earlier in Figure 2-2) coupled with the Table 4-1 format can also help identify potential source areas more likely to dominate under the different zones. Patterns associated with certain source categories are often apparent when visually assessing data by flow conditions.

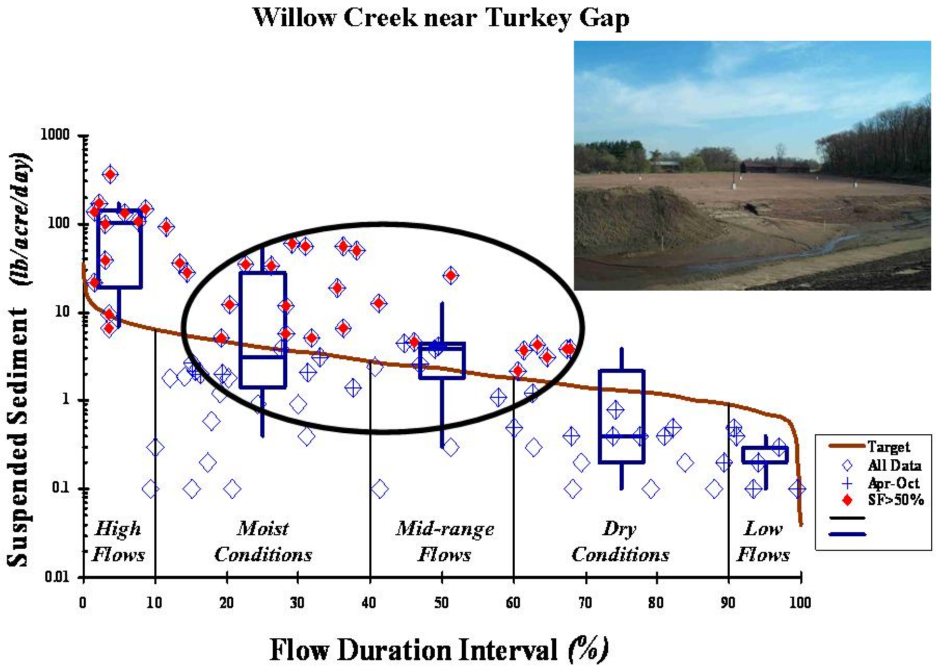
5. CONNECTING TO IMPLEMENTATION AND RESULTS

A major advantage of the duration curve framework in TMDL development is the ability to provide meaningful connections between allocations and implementation efforts. Because the flow duration interval serves as a general indicator of hydrologic condition (i.e., wet versus dry and to what degree), allocations and reduction targets can be linked to source areas, delivery mechanisms, and the appropriate set of management practices. The use of duration curve zones (e.g., high flow, moist, mid-range, dry, and low flow) allows the development of allocation tables, which can be used to summarize potential implementation actions that most effectively address water quality concerns.

In general, wasteload allocations from WWTPs exert a significant influence under low flows. For total sediments, high flow conditions may result in stream bank erosion and channel processes playing a greater role. For urban watersheds, water quality concerns during mid-range flows and moist conditions might be best addressed through low impact development techniques or site construction BMPs, as illustrated in Figure 5-1. For agricultural areas, appropriate implementation efforts might include activities under such provisions as the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Program (CREP).

Appendix C provides an expanded discussion on the utility of the duration curve framework in targeting potential solutions and connecting to implementation and results. Included is a form similar to Table 4-1, which could be used to assess and target the management options appropriate for the different flow conditions.

***Figure 5-1*.** Duration Curve with Contributing Area Focus



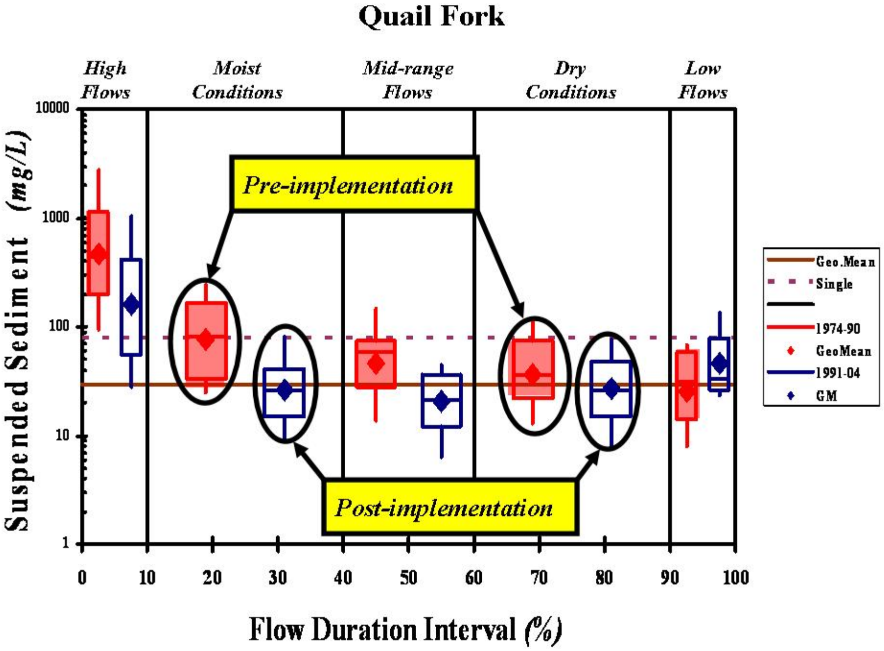
TARGETED Activities: *Construction Site Runoff Control*

A common challenge faced by TMDL practitioners is explaining how allocations translate into potential actions. Table 5-1 uses a duration curve framework to summarize TMDL targets in a way that highlights implementation opportunities. Figure 5-2 illustrates how a duration curve framework can be used to document results following implementation of erosion controls, showing those zones where *"on the ground"* efforts were most effective. These summaries can be combined with other basic elements of watershed planning to help guide problem solving discussions in a meaningful way.

***Table 5-1*.** Example TMDL Summary Using Duration Curve Framework

TMDL SUMMARY	**Loads expressed as *(tons per day)***				
	High	**Moist**	**Mid-Range**	**Dry**	**Low**
TMDL[1]	173.35	67.20	40.21	27.57	18.96
Allocations	118.32	48.24	34.47	21.83	6.90
Margin of Safety	55.03	18.96	5.74	5.74	12.06
Implementation Opportunities	***Post Development BMPs***				
	Streambank Stabilization				
	Erosion Control Program				
		Riparian Buffer Protection			
				Municipal WWTP	
Note:	1. Expressed as a *"daily load"*; represents the upper range of conditions needed to attain and maintain applicable water quality standards				

***Figure 5-2*.** Documenting Erosion Control Program Results



APPENDIX A

Load Duration Curve TMDLs -- Case Example

Pee Dee River Basin, South Carolina Fecal Coliform TMDL

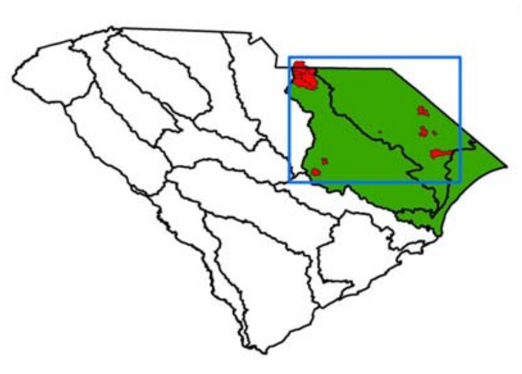
This appendix describes a case example where load duration curves were used to support TMDL development. The example is taken from a fecal coliform TMDL prepared by the South Carolina Department of Health and Environmental Control (DHEC), which was developed to address impairments in sixteen segments of thirteen waters in the Pee Dee River Basin (Hills Creek, Lynches River, North and South Branch of Wildcat Creek, Flat Creek, Turkey Creek, Nasty Branch, Gulley Branch, Smith Swamp, Little Pee Dee River, Maple Swamp, White Oak Creek, and Chinners Swamp).

The full TMDL document, available at:

http://www.scdhec.gov/environment/water/tmdl/docs/tmdl_peedee_fc.pdf

provides background information on the waterbodies, including water quality and pollutant source assessments. Sections 4 and 5 (titled *"Technical Approach and Methodology"* and *"TMDL Calculations"*) of the Pee Dee River Basin TMDL are excerpted into this technical appendix. These sections describe how the duration curve framework was used.

Section 4 provides an explanation of steps used to perform TMDL calculations. Section 5 describes the results of these calculations and how this information was used to address each component of the TMDL.



Pee Dee River Basin

SECTION 4
TECHNICAL APPROACH AND METHODOLOGY

A TMDL is defined as the total quantity of a pollutant that can be assimilated by a receiving water body while achieving the WQS. A TMDL is expressed as the sum of all WLAs (point source loads), LAs (nonpoint source loads), and an appropriate MOS, which attempts to account for uncertainty concerning the relationship between effluent limitations and water quality.

This definition can be expressed by the following equation:

$$\mathbf{TMDL = \Sigma\ WLA + \Sigma\ LA + MOS}$$

The objective of the TMDL is to estimate allowable pollutant loads and to allocate these loads to the known pollutant sources in the watershed so the appropriate control measures can be implemented and the WQS achieved. 40 CFR § 130.2 (1) states that TMDLs can be expressed in terms of mass per time, toxicity, or other appropriate measures. For fecal coliform, TMDLs are expressed as cfu per day where possible or as percent reductions, and represent the maximum one-day load the stream can assimilate while still attaining the WQS.

4.1 Using Load Duration Curves to Develop TMDLs

LDCs are graphical analytical tools that illustrate the relationships between stream flow and water quality and assist in decision making regarding this relationship. Flow is an important factor affecting the loading and concentration of fecal coliform. Both point and nonpoint source loads of pollutants to streams may be affected by changes in flow regime. Given an understanding of the potential loading mechanisms of fecal coliform, and how those mechanisms relate to flow conditions, it is possible to infer and quantify the major contributing sources of pollutants to a stream by examining the relationship between flow and pollutant concentration or load. Of critical importance is that the incremental watershed LDC approach makes effective use of existing data. The lack of instream flow data at most water quality monitoring locations would typically be identified as a significant data gap for application of watershed and water quality models. However, since the incremental watershed LDC approach makes use of drainage area ratio-based flow estimates, the lack of flow information at these locations is not limiting. The incremental watershed approach also allows for assessment of land use, soil, and source contribution differences between observation points. The fecal coliform TMDLs presented in this report are designed to be protective of typical flow conditions. The following discussion provides an overview of the approach used to develop LDCs and TMDL calculations. Results and calculations are presented in Section 5.

4.2 Explanation of Steps Used to Perform TMDL Calculations

The following discussion provides a summary of the steps involved in the calculation of the key components of the fecal coliform TMDLs presented in Section 5 of this report.

Step 1: Develop Flow Percentiles for each WQM Station. Direct flow measurements are not available for all of the WQM stations addressed in this report. This information, however, is vitally important to understanding the relationship between water quality and stream flow. Therefore, to characterize flow, in some cases flow data were derived from a flow estimation model for each relevant watershed. Flow data to support development of flow duration curves will be derived for each SCDHEC WQM station from USGS daily flow records (USGS 2005b) in the following priority:

i) In cases where a USGS flow gage coincides with, or occurs within one-half mile upstream or downstream of a SCDHEC WQM station and simultaneous daily flow data matching the water quality sample date are available, these flow measurements will be used.

ii) If flow measurements at the coincident gage are missing for some dates on which water quality samples were collected, gaps in the flow record will be filled, or the record extended, by estimating flow based on measured streamflows at a nearby gage. First, the most appropriate nearby stream gage is identified. All flow data are first log-transformed to linearize the data because flow data are highly skewed. Linear regressions are then developed between 1) daily streamflow at the gage to be filled/extended; and 2) streamflow at all gages within 93 miles (150 kilometers) that have at least 300 daily flow measurements on matching dates. The station with the strongest flow relationship, as indicated by the highest correlation coefficient (r-squared value), is selected as the index gage. R-squared indicates the fraction of the variance in flow explained by the regression. The regression is then used to estimate flow at the gage to be filled/extended from flow at the index station. Flows will not be estimated based on regressions with r-squared values less than 0.25, even if that is the best regression. This value was selected based on familiarity with using regression analysis in estimating flows. In some cases, it will be necessary to fill/extend flow records from two or more index gages. The flow record will be filled/extended to the extent possible based on the strongest index gage (highest r-squared value), and remaining gaps will be filled from successively weaker index gages (next highest r-squared value), and so forth.

iii) In the event no coincident flow data are available for a WQM station, but flow gage(s) are present upstream and/or downstream, flows will be estimated for the WQM station from an upstream or downstream gage using a watershed area ratio method derived by delineating subwatersheds, and relying on the Natural Resources Conservation Service runoff curve numbers and antecedent rainfall condition. Drainage subbasins will first be delineated for all impaired 303(d)-listed WQM stations, along with all USGS flow stations located in the

Step 2: Develop Flow Duration Curves. Flow duration curves serve as the foundation of LDC TMDLs. Flow duration curves are graphical representations of the flow regime of a stream at a given site. The flow duration curve is an important tool of hydrologists, utilizing the historical hydrologic record from stream gages to forecast future recurrence frequencies.

Flow duration curves are a type of cumulative distribution function. The flow duration curve represents the fraction of flow observations that exceed a given flow at the site of interest. The observed flow values are first ranked from highest to lowest, then, for each observation, the percentage of observations exceeding that flow is calculated. The flow rates for each 5th percentile for each WQM station are provided in Appendix D. The flow value is read from the ordinate (y-axis), which is typically on a logarithmic scale since the high flows would otherwise overwhelm the low flows. The flow exceedance frequency is read from the abscissa, which is numbered from 0 to 100 percent, and may or may not be logarithmic. The lowest measured flow occurs at an exceedance frequency of 100 percent, indicating that flow has equaled or exceeded this value 100 percent of the time, while the highest measured flow is found at an exceedance frequency of 0 percent. The median flow occurs at a flow exceedance frequency of 50 percent.

While the number of observations required to develop a flow duration curve is not rigorously specified, a flow duration curve is usually based on more than 1 year of observations, and encompasses inter-annual and seasonal variations. Ideally, the drought and flood of record are included in the observations. For this purpose, the long term flow gaging stations operated by the USGS are ideal.

A typical semi-log flow duration curve exhibits a sigmoidal shape, bending upward near a flow duration of 0 percent and downward at a frequency near 100 percent, often with a relatively constant slope in between. However, at extreme low and high flow values, flow duration curves may exhibit a “stair step” effect due to the USGS flow data rounding conventions near the limits of quantitation. The extreme high flow conditions (<10th percentile) and low flow conditions (>95 percentile) are not considered in development of these TMDLs. The overall slope of the flow duration curve is an indication of the flow variability of the stream.

Flow duration curves can be subjectively divided into several hydrologic condition classes. These hydrologic classes facilitate the diagnostic and analytical uses of flow and LDCs. The hydrologic classification scheme utilized in the development of these TMDLs is presented in Table 4-1.

Table 4-1 Hydrologic Condition Classes

Flow Duration Interval	Hydrologic Condition Class*
0-10%	High flows
10-40%	Moist Conditions
40-60%	Mid-Range Conditions
60-90%	Dry Conditions
90-100%	Low Flows

Source: Cleland 2003.

Step 3: Estimate Current Point Source Loading. In SC, NPDES permittees that discharge treated sanitary wastewater must meet the state WQS for fecal coliform bacteria at the point of discharge (see discussion in Section 2). However, for TMDL analysis it is necessary to understand the relative contribution of WWTPs to the overall pollutant loading and their general compliance with required effluent limits. The fecal coliform load for continuous point source dischargers was estimated by multiplying the monthly average flow rates by the monthly geometric mean using a conversion factor. The data were extracted from each point source's DMR from 1998 through 2004. The 90th percentile value of the monthly loads was used to express the estimated existing load in counts/day. The current pollutant loading from each permitted point source discharge as summarized in Section 3 was calculated using the equation below.

*Point Source Loading = monthly average flow rates (mgd) * geometric mean of corresponding fecal coliform concentration * unit conversion factor*

Where:

unit conversion factor = 37,854,120 100-ml/million gallons (mg)

Step 4: Estimate Current Loading and Identify Critical Conditions. It is difficult to estimate current nonpoint loading due to lack of specific water quality and flow information that would assist in estimating the relative proportion of non-specific sources within the watershed. Therefore, existing instream loads were used as a conservative surrogate for nonpoint loading. It was calculated by multiplying the concentration by the flow matched to the specific sampling date. Then using the hydrologic flow intervals shown in Table 4-1, the 90th percentile nonpoint loading within each of the intervals would then represent the nonpoint loading estimate for that interval. Existing loads have been estimated using a regression-based relationship developed between observed fecal coliform loads and flow or flow exceedance percentile.

In many cases, inspection of the LDC will reveal a critical condition related to exceedances of WQSs. For example, criteria exceedances may occur more frequently in wet weather, low flow conditions, or after large rainfall events. The critical conditions are such that if WQSs were met under those conditions, WQSs would likely be met overall. Given that the instantaneous fecal coliform criterion indicates that no more than 10 percent of samples should exceed 400 cfu/100 ml, it is appropriate to evaluate existing loading as the 90th percentile of observed fecal coliform concentrations. Together with the MOS, the reduction calculated in this way should ensure that no more than 10 percent of samples will exceed the criterion.

Existing loading is calculated as the 90th percentile of measured fecal coliform concentrations under each hydrologic condition class multiplied by the flow at the middle of the flow exceedance percentile. For example, in calculating the existing loading under dry conditions (flow exceedance percentile = 60-90%), the 75th percentile exceedance flow is multiplied by the 90th percentile of fecal coliform concentrations measured under the 60-90th percentile flows. The "high flow" or "low flow" hydrologic conditions will not be selected as critical conditions because these extreme flows are not representative of typical conditions, and few observations are typically available to reliably estimate loads under these conditions. This methodology results in multiple estimates of existing loading. However, TMDLs are typically expressed as a load or concentration under a single scenario. Therefore, these TMDLs will assume that if the highest percent reduction associated with the difference between the existing loading and the LDC (TMDL) is achieved, the WQS will be attained under all other flow conditions.

Step 5: Develop Fecal Coliform Load Duration Curves (TMDL). Load duration curves are based on flow duration curves, with the additional display of historical pollutant load observations at the same location, and the associated water quality criterion or criteria. In lieu of flow, the ordinate is expressed in terms of a fecal coliform load (cfus/day). The curve represents the single sample water quality criterion for fecal coliform (400 cfu/100 ml) expressed in terms of a load through multiplication by the continuum of flows historically observed at the site. The points represent individual paired historical observations of fecal coliform concentration and flow. Fecal coliform concentration data used for each WQM station are provided in Appendix A. The fecal coliform load (or the y-value of each point) is calculated by multiplying the fecal coliform WQS by the instantaneous flow (cfs) from the same site and time, with appropriate volumetric and time unit conversions.

TMDL (cfu/day) = WQS * flow (cfs) * unit conversion factor

Where: WQS = 400 cfu/100ml

*unit conversion factor = 24,465,525 ml*s / ft^3*day*

The flow exceedance frequency (x-value of each point) is obtained by looking up the historical exceedance frequency of the measured flow, in other words, the percent of historical observations that equal or exceed the measured flow. It should be noted that the site daily average stream flow is often used if an instantaneous flow measurement is not available. Fecal coliform loads representing exceedance of water quality criteria fall above the water quality criterion line.

Step 6: Develop LDCs with MOS. An LDC depicting slightly lower estimates than the TMDL is developed to represent the TMDL with MOS. An explicit MOS is defined for each TMDL by establishing an LDC using 95 percent of the TMDL value (5 percent of the 400 cfu/100 ml instantaneous water quality criterion) to slightly reduce assimilative capacity in the watershed, thus providing a 5 percent MOS. The MOS at any given percent flow exceedance, therefore, is defined as the difference in loading between the TMDL and the TMDL with MOS.

Step 7: Calculate WLA. As previously stated, the pollutant load allocation for point sources is defined by the WLA. A point source can be either a wastewater (continuous) or stormwater (MS4) discharge. Stormwater point sources are typically associated with urban and industrialized areas, and recent USEPA guidance includes permitted stormwater discharges as point source discharges and, therefore, part of the WLA.

The LDC approach recognizes that the assimilative capacity of a water body depends on the flow, and that maximum allowable loading will vary with flow condition. TMDLs can be expressed in terms of maximum allowable concentrations, or as different maximum loads allowable under different flow conditions, rather than single maximum load values. This concentration-based approach meets the requirements of 40 CFR, 130.2(i) for expressing TMDLs “in terms of mass per time, toxicity, or other appropriate measures” and is consistent with USEPA’s *Protocol for Developing Pathogen TMDLs* (USEPA 2001).

WLA for WWTP. Wasteload allocations may be set to zero in cases of watersheds with no existing or planned continuous permitted point sources. For watersheds with permitted point sources, wasteloads may be derived from NPDES permit limits. A WLA may be calculated for each active NPDES wastewater discharger using a mass balance approach as shown in the equation below. The permitted average flow rate used for each point source discharge and the water quality criterion concentration are used to estimate the WLA for each wastewater facility. All WLA values for each subwatershed are then summed to represent the total WLA for the watershed.

*WLA (cfu/day) = WQS * flow * unit conversion factor*

Where: WQS = 400 cfu/100ml

flow (mgd) = permitted flow or design flow (if unavailable)

unit conversion factor = 37,854,120 100-ml/mg

WLA for MS4s. Because a WLA for each MS4 cannot be calculated as an individual value, WLAs for MS4s are expressed as a percent reduction goal (PRG) derived from the LDC for nonpoint sources. The method for estimating the percent reduction of fecal coliform loading is described in Step 8.

Step 8: Calculate LA. Load allocations can be calculated under different flow conditions as the water quality target load minus the WLA. The LA is represented by the area under the LDC but above the WLA. The LA at any particular flow exceedance is calculated as shown in the equation below.

$$\mathbf{LA = TMDL - MOS - \sum WLA}$$

However, to express the LA as an individual value, the LA is derived using the equation above but at the median point of the hydrologic condition class requiring the largest percent reduction as displayed in the LDCs provided in Appendix E. Thus, an alternate method for expressing the LA is to calculate a PRG for fecal coliform. Load allocations are calculated as percent reductions from current estimated loading levels required to meet water quality criteria.

Step 9: Estimate WLA Load Reduction. The WLA load reduction was not calculated because it was assumed that the continuous dischargers (NPDES permitted WWTPs) are adequately regulated under existing permits and, therefore, no WLA reduction would be required. For the MS4 permittees, the percent reduction was assumed to be the same as the nonpoint load reduction.

Step 10: Estimate LA Load Reduction. After existing loading estimates are computed for the three different hydrologic condition classes described in Step 2, nonpoint load reduction estimates for each WQM station are calculated by using the difference between estimated existing loading (Step 5) and the LDC (TMDL). This difference is expressed as a percent reduction, and the hydrologic condition class with the largest percent reduction is selected as the critical condition and the overall PRG for the LA.

Results of all these calculations are discussed in Section 5.

SECTION 5
TMDL CALCULATIONS

5.1 Results of TMDL Calculations

The calculations and results of the TMDLs for the 303(d)-listed WQM stations in the Pee Dee River Basin are provided in this section. The methods for deriving these results are specified in Section 4. The Lynches River and various tributaries contributing to WQM station PD-113 are interstate water bodies. The TMDLs established in Section 5.7 of this report for WQM station PD-113 are achievable if WQS for fecal coliform are met at the state line.

5.2 Critical Conditions and Estimated Loading

USEPA regulations at 40 CFR 130.7(c) (1) require TMDLs to take into account critical conditions for stream flow, loading, and water quality parameters. Available instream WQM data were evaluated with respect to flows and magnitude of water quality criteria exceedance using LDCs. Load duration curve analysis involves using measured or estimated flow data, instream criteria, and fecal coliform concentration data to assess flow conditions in which water quality exceedances are occurring (SCDHEC 2003). The goal of flow weighted concentration analysis is to compare instream observations with flow values to evaluate whether exceedances generally occur during low or high flow periods (SCDHEC 2003).

To calculate the fecal coliform load at the WQS, the instantaneous fecal coliform criterion of 400 cfu/100 ml is multiplied by the flow rate at each flow exceedance percentile, and a unit conversion factor (*24,465,525 ml*s /* ft^3**day*). This calculation produces the maximum fecal coliform load in the stream without exceeding the instantaneous standard over the range of flow conditions. The allowable fecal coliform loads at the WQS establish the TMDL and are plotted versus flow exceedance percentile as an LDC. The x-axis indicates the flow exceedance percentile, while the y-axis is expressed in terms of a fecal coliform load.

To estimate existing loading, the loads associated with individual fecal coliform observations are paired with the flows estimated at the same site on the same date. Fecal coliform loads are then calculated by multiplying the measured fecal coliform concentration by the estimated flow rate and a unit conversion factor of *24,465,525 ml*s /* ft^3**day*. The associated flow exceedance percentile is then matched with the measured flow from the tables provided in Appendix D. The observed fecal coliform loads are then added to the LDC plot as points. These points represent individual ambient water quality samples of fecal coliform. Points above the LDC indicate the fecal coliform instantaneous standard was exceeded at the time of sampling. Conversely, points under the LDC indicate the sample met the WQS.

The LDC approach recognizes that the assimilative capacity of a water body depends on the flow, and that maximum allowable loading varies with flow condition. Existing loading, and load reductions required to meet the TMDL water quality target, can also be calculated under different flow conditions. The difference between existing loading and the water quality target is used to calculate the loading reductions required. Given that the instantaneous fecal coliform criterion indicates that no more than 10 percent of samples should exceed 400 cfu/100 ml, it is appropriate to evaluate existing loading as the 90th percentile of observed fecal coliform concentrations. Together with the MOS, the reduction calculated in this way should ensure that no more than 10 percent of samples will exceed the criterion.

Existing loading is calculated as the 90th percentile of measured fecal coliform concentrations under each hydrologic condition class multiplied by the flow at the middle of the flow exceedance percentile. For example, in calculating the existing loading under dry conditions (flow exceedance percentile = 60-90 percent), the 75th percentile exceedance flow is multiplied by the 90th percentile of fecal coliform concentrations measured under 60-90th percentile flows.

After existing loading and percent reductions are calculated under each hydrologic condition class, the critical condition for each TMDL is identified as the flow condition requiring the largest percent reduction. However, the “high flow” (<10th percentile flow exceedance) or “low flow” (> 90th percentile flow exceedance) hydrologic conditions will not be selected as critical conditions because these extreme flows are not representative of typical conditions, and few observations are available to reliably estimate loads under these conditions. In the example shown in Table 5-1 for WQM station PD-333, the critical condition occurs under “Moist Conditions,” when a 93 percent loading reduction is required to meet the WQS.

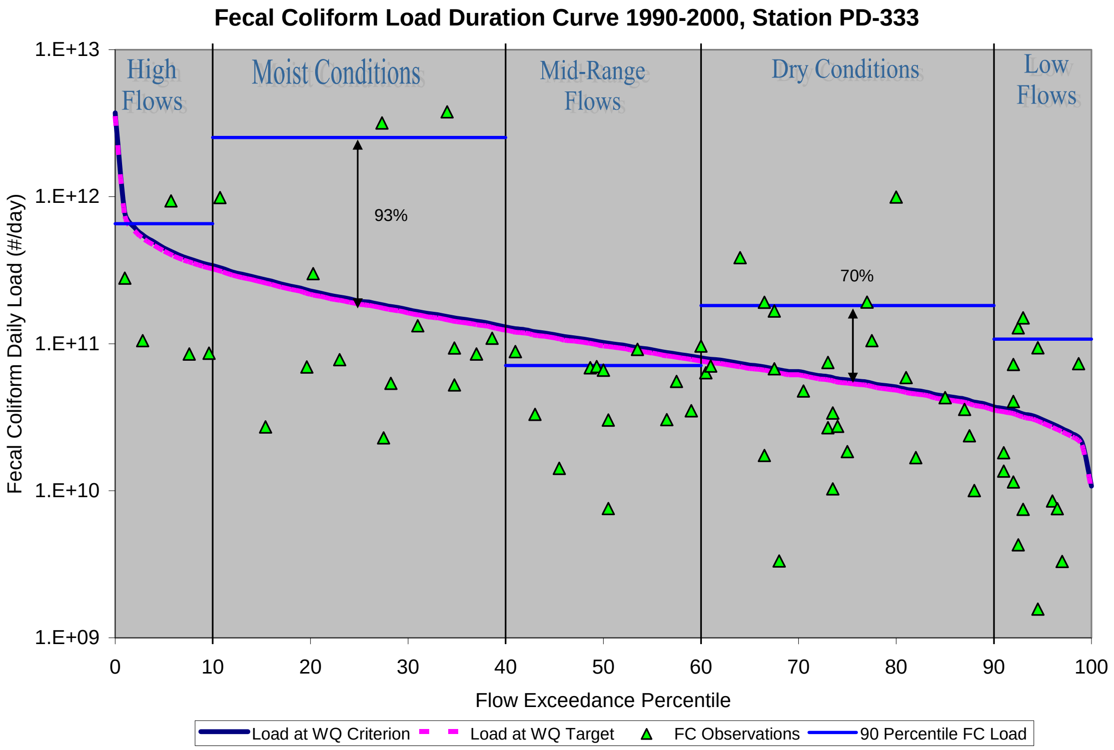
Table 5-1 Estimated Existing Fecal Coliform Loading for Station PD-333 (Hills Creek with Critical Condition Highlighted

Hydrologic Condition Class*	Estimated Existing Loading (cfu/100 ml)	Percent Reduction Required
High Flows	6.54E+11	NA
Moist Conditions	2.53E+12	93%
Mid-Range Conditions	7.10E+10	NA
Dry Conditions	1.82E+11	70%
Low Flows	1.08E+11	NA

* Hydrologic Condition Classes are derived from Cleland 2003.

The LDC for WQM station PD-333 shown in Figure 5-1 indicates actual fecal coliform loads are exceeding the instantaneous load of the WQS during “moist” and “dry” flow conditions. LDCs similar to Figure 5-1 for all of the 303(d)-listed WQM stations in this report used to estimate existing loading and identify critical conditions are provided in Appendix E. The LDCs were developed for the time period from January 1990 through October 2002 if data were available.

Figure 5-1 Estimated Fecal Coliform Load and Critical Conditions, Station PD-333 (Hills Creek)



The existing instream fecal coliform load (actual or estimated flow multiplied by observed fecal coliform concentration) is compared to the allowable load for that flow. Any existing loads above the allowable LDCs represent an exceedance of the WQS. For a low flow loading situation, there are typically observations in excess of criteria at the low flow side of the chart. For a high flow loading situation, observations in excess of criteria at the high flow side of the chart are typical. For water bodies impacted by both point and nonpoint sources, the “nonpoint source critical condition” would typically occur during high flows, when rainfall runoff would contribute the bulk of the pollutant load, while the “point source critical condition” would typically occur during low flows, when treatment plant effluents would dominate the base flow of the impaired water. Based on these characteristics, critical conditions for each WQM station are summarized in Table 5-2.

Table 5-2 Summary of Critical Conditions for each WQM Station as derived from Load Duration Curves

SCDHEC WQM Station	Moist Conditions	Mid-Range Conditions	Dry Conditions
PD-333			
PD-113			
PD-179			
PD-180			
PD-342			
PD-066			
PD-040			
PD-098			
PD-239			
PD-065			
PD-187			
PD-320			
PD-030A			
PD-030			
PD-037			
PD-352			

The existing load for each WQM station was derived from the critical condition line depicted on the LDCs described above and provided in Appendix E. Estimated existing loading is derived from the 90th percentile of observed fecal coliform loads corresponding to the critical condition identified at each WQM station identified in Table 5-2. This estimated loading is indicative of loading from all sources including continuous point source dischargers, leaking sewer lines, MS4s, SSOs, failing OSWD systems, land application fields, wildlife, pets, and livestock. The total estimated existing load for each station is provided in Table 5-3.

Table 5-3 Estimated Existing Loading at each WQM Station

SCDHEC WQM Station	90th Percentile Load Estimation (cfu/day)	Flow Exceedance Percentile
PD-333	2.53E+12	25
PD-113	3.15E+12	25
PD-179	7.76E+11	25
PD-180	2.31E+11	25
PD-342	3.72E+11	75

SCDHEC WQM Station	90th Percentile Load Estimation (cfu/day)	Flow Exceedance Percentile
PD-066	1.36E+13	25
PD-040	1.37E+11	50
PD-098	4.31E + 11	75
PD-239	1.63E+11	25
PD-065	1.51E+12	50
PD-187	2.54E+11	75
PD-320	1.33E+12	75
PD-030A	1.05E+13	75
PD-030	6.61E+11	50
PD-037	7.54E+11	50
PD-352	3.08E+11	75

5.3 Waste Load Allocation

Table 5-4 summarizes the WLA of the NPDES-permitted facilities within the watershed of each WQM station. The WLA for each facility is derived from the following equation:

WLA = WQS * flow * unit conversion factor (#/day)

Where: WQS = 400 cfu/100ml

flow (cfs) = permitted flow

unit conversion factor = 37,854,120 100-ml/mg

Table 5-4 Wasteload Allocations (WLA) for NPDES Permitted Facilities

Water Quality Monitoring Station / Permittee	NPDES Permit Number	Flow (mgd)	Load (cfu/day)
HUC 3050106020			
PD-333 Hills Creek at S-13-105			
Pageland Northwest WWTP	SC0021504	0.3	4.54E+09
HUC 3040202030			
PD-179 North Branch Wildcat Creek at S-29-39 1 Mile South of Tradesville			
Buford High School WWTP	SC0030210	0.035	5.30E+08
HUC 3040202050			
PD-066 Upper Lynches River			
Jefferson WWTP	SC0024767	0.15	2.27E+09
HUC 3040204030			
PD-030A Little Pee Dee River Below JCT with Maple SWP			
Dillon Little Pee Dee WWTP (Outfall 001)	SC0021776	4.0	6.06E+10

* Ceased Discharging in 1999.

When there are no NPDES WWTPs discharging into the contributing watershed of a WQM station, then the WLA for continuous point sources is zero. See Subsection 4/2 (Step 7) and Section 5.7 for an explanation of how the WLA for NPDES dischargers is depicted in a LDC.

The cities of Sumter and Florence are the only MS4s within the watersheds of this report. Because of insufficient data, it is not possible to express a WLA for MS4s as a load or concentration; therefore, the WLA is expressed as a PRG. Each MS4 was assigned a PRG equal to the PRG identified in the LA for each WQM station. The PRGs that will serve as a component of the WLA are provided in Table 5-5. When multiple WQM stations fall under one MS4 jurisdiction, multiple PRGs can occur. In these cases the highest PRG is selected as the overall reduction requirement incorporated into the TMDL of each station. For example, by reviewing the LDCs in Appendix E, Stations PD-098 and PD-040 have PRGs of 94 and 75 percent, respectively. Therefore, using a conservative approach, the highest reduction goal of 94 percent is selected and incorporated into the TMDLs (see Table 5-5) for WQM stations PD-098 and PD-040. The PRGs in this TMDL report apply also to the fecal coliform WLAs attributable to those areas of the watershed which are covered or will be covered under NPDES MS4 permits. Compliance by those municipalities within the terms of their individual MS4 permits will fulfill any obligations they have toward implementing TMDLs for fecal coliform.

Table 5-5 WLA for MS4 Entities in Turkey Creek and Gulley Branch Watersheds

MS4 Entity	WQM Stations	Percent Reduction Goal
Sumter	PD-098, PD-040	94
Florence	PD-065	99

5.4 Load Allocation

As discussed in Section 3, nonpoint source fecal coliform loading to the receiving streams of each WQM station originate from a number of different sources. For a select group of WQM stations (Table 3-3, Table 3-10, and Table 3-19) nonpoint sources of fecal coliform loading is the sole reason the primary contact recreation use is not supported. As discussed in Section 4, nonpoint source loading was estimated and depicted for all flow conditions using LDCs (See Figure 5-1 example and Appendix E). Figure 5-1, the LDC for PD-333, displays the relationships between the TMDL water quality target, the MOS, and the PRG that can serve as an alternative for expressing the LA. The data analysis and the LDCs demonstrate that exceedances at many of the WQM stations are the result of nonpoint source loading such as failing OSWD systems, leaking sewer lines, cattle in streams, and fecal loading from land application fields, wildlife and pets transported by runoff events. The LAs, calculated as the difference between the TMDL, MOS, and WLA, for each WQM station are presented in Table 5-6. Where MS4s are present then the LA is not calculated and is expressed as a PRG.

5.5 Seasonal Variability

Federal regulations (40 CFR §130.7(c)(1)) require that TMDLs take into consideration seasonal variation in watershed conditions and pollutant loading. Seasonal variation was accounted for in these TMDLs by using more than 5 years of water quality data (1990-2002) whenever possible and by using the longest period of USGS flow records when estimating flows to develop flow exceedance percentiles.

5.6 Margin of Safety

Federal regulations (40 CFR §130.7(c)(1)) require that TMDLs include an MOS. The MOS is a conservative measure incorporated into the TMDL equation that accounts for the uncertainty associated with calculating the allowable fecal coliform pollutant loading to ensure WQSs are attained. USEPA guidance allows for use of implicit or explicit expressions of the MOS, or both. When conservative assumptions are used in development of the TMDL, or conservative factors are used in the calculations, the MOS is implicit. When a specific percentage of the TMDL is set aside to account for uncertainty, then the MOS is considered explicit.

For the explicit MOS the water quality target was set at 380 cfu/100 ml for the instantaneous criterion, which is 5 percent lower than the water quality criterion of 400 cfu/100 ml. The net effect of the TMDL with MOS is that the assimilative capacity of the watershed is slightly reduced. These TMDLs incorporates an explicit MOS by using a curve representing 95 percent of the TMDL as the average MOS. The MOS at any given percent flow exceedance, therefore, can be defined as the difference in loading between the TMDL and the TMDL with MOS. For consistency, the explicit MOS at each WQM station will be expressed as a numerical value derived from the same critical condition as the largest load reduction goal at the respective 25th, 50th, or 75th flow exceedance percentile (see Table 5-6).

There are other conservative elements utilized in these TMDLs that can be recognized as an implicit MOS such as:

- The use of instream fecal coliform concentrations to estimate existing loading; and
- The highest PRG for nonpoint sources, based on the LDC used.

This conservative approach to establishing the MOS will ensure that both the 30-day geometric mean and instantaneous fecal coliform bacteria standards can be achieved and maintained.

5.7 TMDL Calculations

The fecal coliform TMDLs for the 303(d)-listed WQM stations covered in this report were derived using LDCs. A TMDL is expressed as the sum of all WLAs (point source loads), LAs (nonpoint source loads), and an appropriate MOS, which attempts to account for uncertainty concerning the relationship between effluent limitations and water quality. This definition can be expressed by the following equation:

$$TMDL = \Sigma\ WLA + \Sigma\ LA + MOS$$

For each WQM station the TMDLs presented in this report are expressed in cfus per day or as a percent reduction. The TMDLs are presented in fecal coliform counts to be protective of both the instantaneous, per day, and geometric mean, per 30-day, criteria. To express a TMDL as an individual value, the LDC is used to derive the LA, the MOS, and the TMDL based on the median percentile of the critical condition (*i.e.*, the median percentile of the hydrologic condition class requiring the greatest percent reduction to meet the instantaneous criterion which is the water quality target). The WLA component of each TMDL is the sum of all WLAs within the contributing watershed of each WQM station which is derived from each NPDES facilities' maximum design flow and the permitted 1-day maximum concentration of 400 cfu/100 ml. When MS4s do not exist in the contributing watershed, the LDC and the simple equation of:

$$\text{Average } LA = \text{average } TMDL - MOS - \sum WLA$$

can provide an individual value for the LA in cfu per day which represents the area under the TMDL target line and above the WLA line. Percent reductions necessary to achieve the water quality target are also provided for all WQM stations as another acceptable representation of the TMDL. Like the LA, the percent reduction is derived from the median percentile of the critical condition (*i.e.*, the median percentile of the hydrologic condition class requiring the greatest percent reduction to meet the instantaneous criterion which is the water quality target). Table 5-6 summarizes the TMDLs for each WQM station, and Figures 5-2 through 5-17 present the LDCs for each station depicting the TMDL, MOS, and WLA (if applicable).

Table 5-6 TMDL Summary for Select WQM Stations in Pee Dee River Basin (HUCs 03040202, 03040205, 03040201, 03040204)

SCDHEC WQM Station	WLAs (cfu/ day)	MS4 WLA (Percent reduction)	LA (cfu/day or % reduction)	MOS	TMDL (cfu/day or % reduction)	Percent reduction
Lynches River HUC 03040202020						
PD-333	4.54E+09	NA	1.80E+11	9.74E+09	1.95E+11	93
Upper Lynches River HUC 03040202030						
PD-113	0	NA	5.99E+11	3.15E+10	6.30E+11	81
PD-179	5.30E+08	NA	1.13E+11	5.97E+09	1.19E+11	85
PD-180	0	NA	1.12E+11	5.92E+09	1.18E+11	51
Upper Lynches River HUC 03040202040						
PD-342	0	NA	1.62E+11	8.51E+09	1.70E+11	57
Upper Lynches River HUC 03040202050						
PD-066	2.27E+09	NA	2.56E+12	1.35E+11	2.69E+12	81
Tributary to Pocotaligo River HUC 03040205080						
PD-040	0	94	3.44E+10	1.81E+09	3.62E+10	75
PD-098	0	94	2.70E+10	1.42E+09	2.84E+10	94
PD-239	0	NA	1.54E+11	8.12E+09	1.62E+11	5
Tributary to Pee Dee River HUC 03040201130						
PD-065	0	99	1.39E+10	7.34E+08	1.47E+10	99
PD-187	0	NA	8.74E+10	4.60E+09	9.20E+10	66
PD-320	0	NA	4.22E+11	2.22E+10	4.44E+11	68
Little Pee Dee River HUC 03040204030						
PD-030A	6.06E+10	NA	4.90E+12	2.61E+11	5.22E+12	53
PD-030	0	NA	2.51E+11	1.32E+10	2.64E+11	62
Little Pee Dee River HUC 03040204070						
PD-037	0	NA	7.16E+10	3.77E+09	7.54E+10	91
Little Pee Dee River HUC 03040204090						
PD-352	0	NA	1.90E+11	9.98E+09	2.00E+11	39

Figure 5-2 TMDL for PD-333 Hills Creek

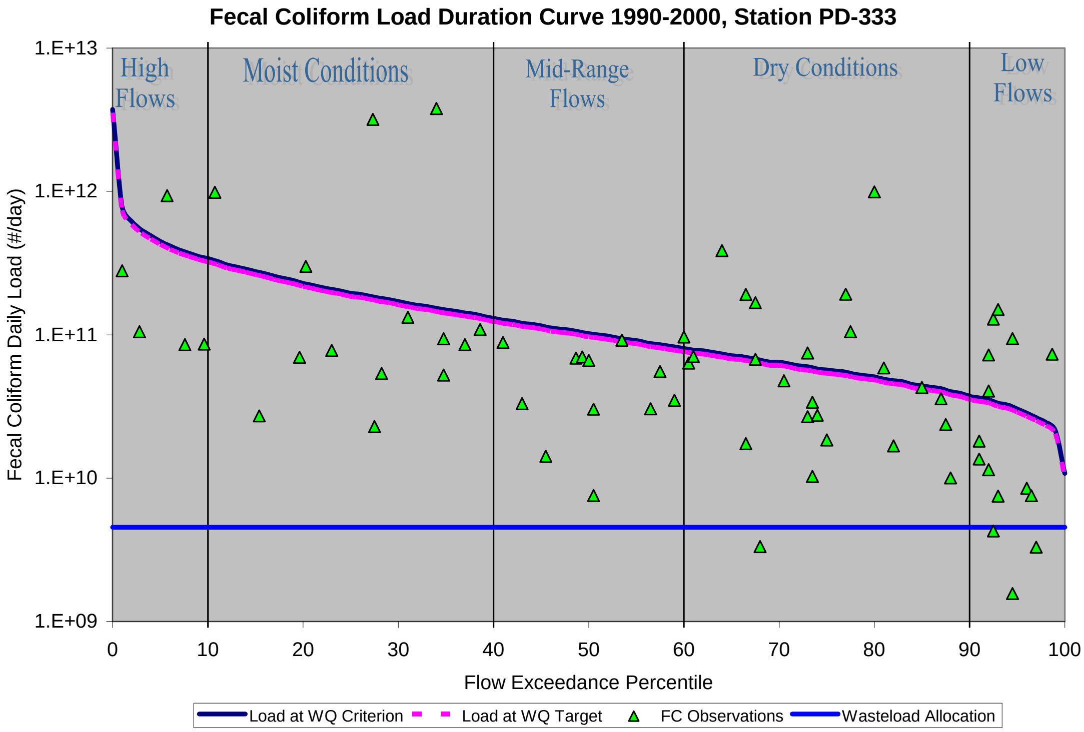
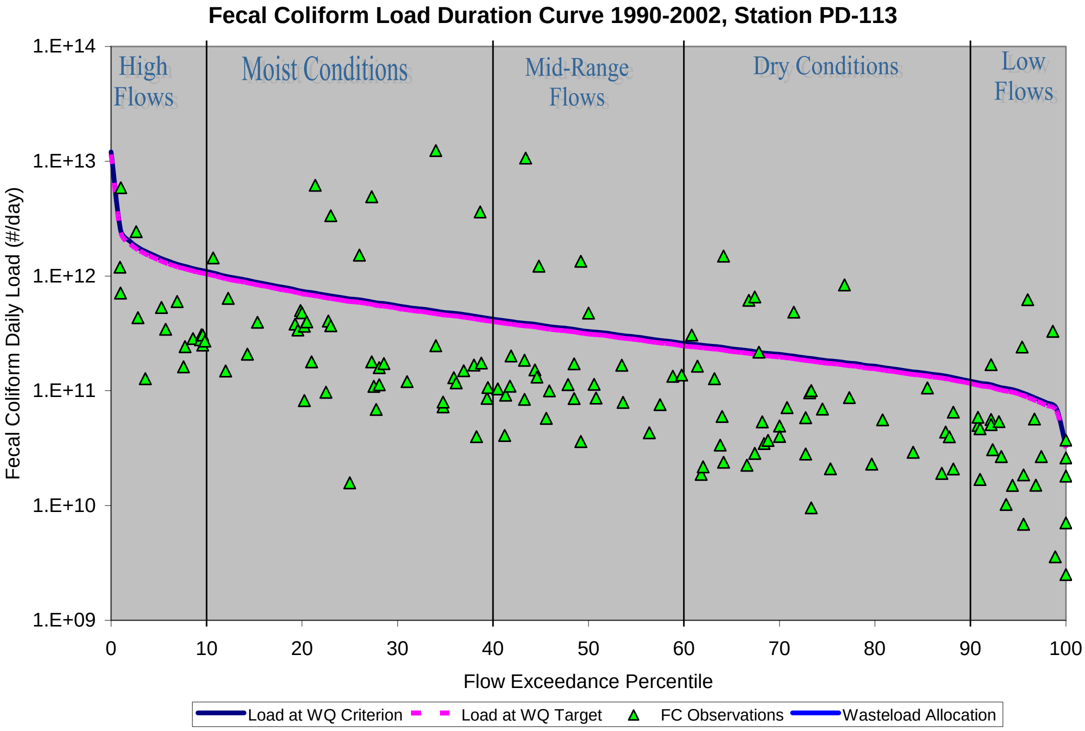


Figure 5-3 TMDL for PD-113 Lynches River



APPENDIX B

Additional Examples of Using Load Duration Curve Approach

This technical appendix discusses basic application of duration curves in TMDL development and provides several examples, including the derivation of loading capacities, wasteload allocations, and load allocations. The duration curve framework is well suited as a tool to support TMDL development because flow data is an important factor in the determination of loading capacities. This technical appendix also provides a discussion on ways the duration curve framework can be used to address different averaging periods (other than daily) in identifying loading capacities, particularly where a concentration-based target exists (expressed as monthly, seasonal, or annual average values).

B1. LOADING CAPACITY

Calculation of the loading capacity for impaired segments identified on the §303(d) list is an important first step in the TMDL development process. EPA's current regulation defines loading capacity as *"the greatest amount of loading that a water can receive without violating water quality standards"*. The loading capacity provides a reference, which helps guide pollutant reduction efforts needed to bring a water into compliance with standards.

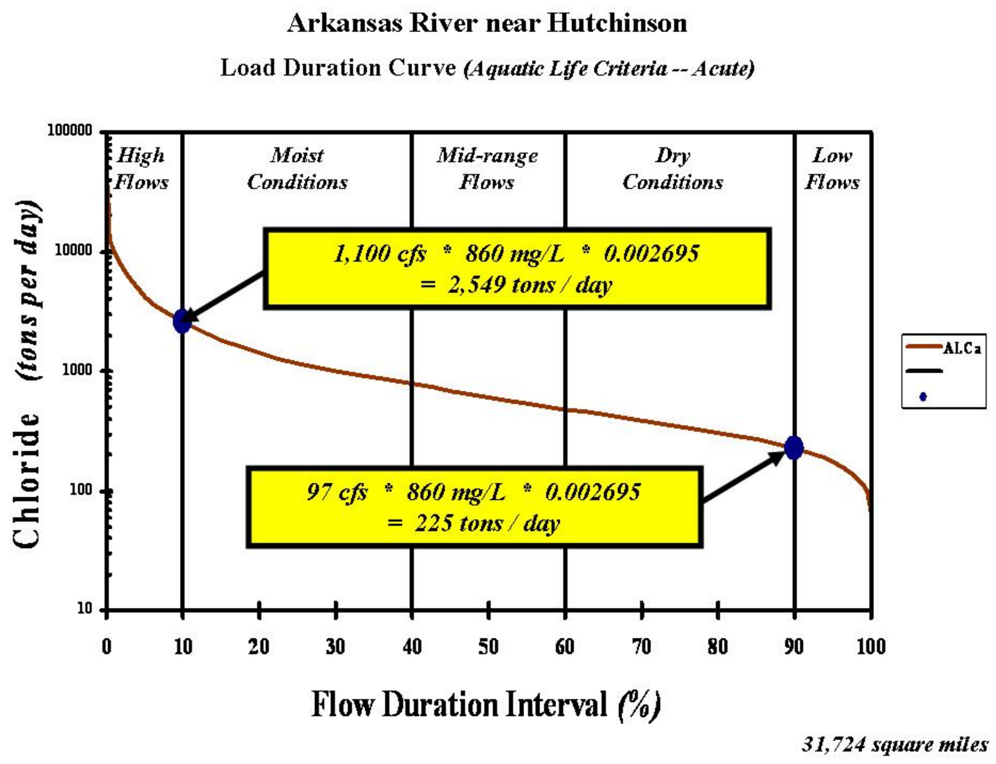
Chloride represents a good starting point to describe the use of duration curves in TMDL development because of its conservative nature as a pollutant. For example, Kansas has established 860 mg/L as the water quality criterion for chloride to protect aquatic life. To illustrate key steps, the flow duration curve for the Arkansas River (based on daily average stream discharge data) starts the process of identifying a loading capacity for chloride using the duration curve framework.

In-stream loads for chloride, expressed as tons per day, are calculated using the equation summarized in Table B-1. The loading capacity for the Arkansas River is shown in Figure B-1. It is derived directly from the water quality criteria (860 mg/L) and the duration curve using the *"flow to load"* calculation described in Table B-1 across the range of all daily average flows. Load capacity calculations for other parameters (e.g. nutrients, bacteria, sediment) are developed in a similar fashion.

***Table B-1*.** Calculation of Chloride Loads

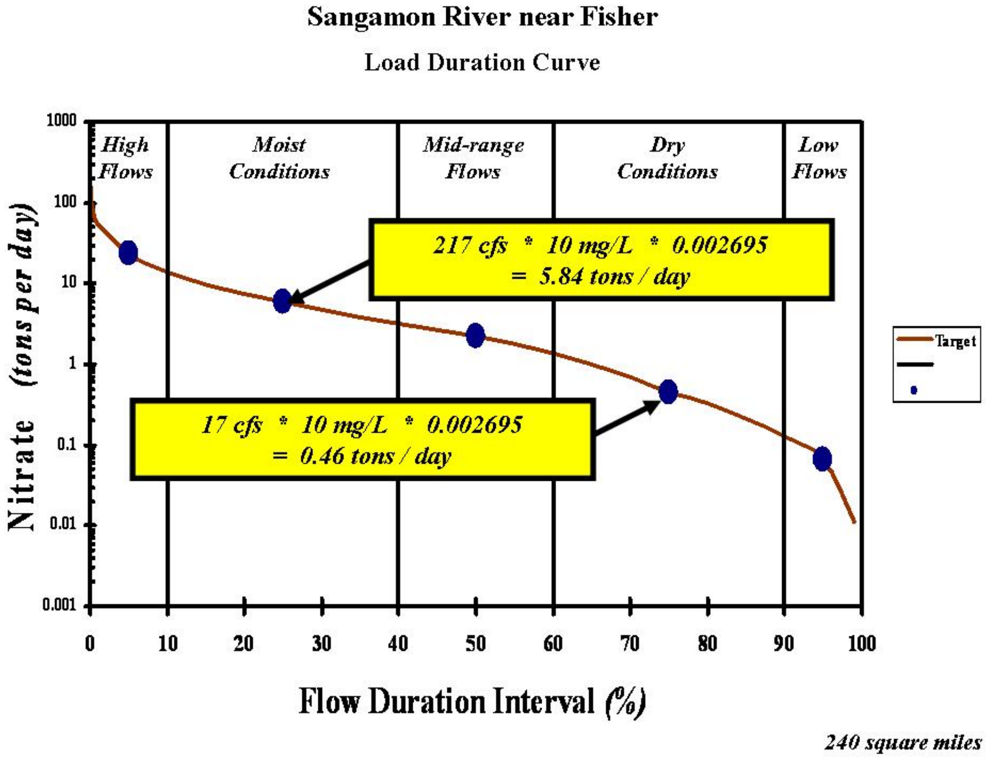
Load ***(tons per day)*** **= Flow** ***(cfs)*** *** Concentration** ***(mg/L)*** *** Factor**			
multiply by **86,400** *to convert*	seconds per day	→	ft^3 / day
multiply by **7.48** *to convert*	ft^3	→	gallons / day
divide by **453,592** *to convert*	mg	→	pounds
multiply by **3.7854** *to convert*	liters	→	gallons
divide by **2,000** *to convert*	pounds	→	tons
multiply by **0.002695** *to convert*	**(ft^3 / sec) * (mg/L)**	→	**tons / day**

***Figure B-1*.** Chloride Loading Capacity Using Duration Curve Framework



Nutrients have been the focus of TMDL efforts to address a variety of water quality problems including eutrophication, aquatic life impairments, and drinking water supply concerns. Duration curves can be used to support TMDL development where numeric targets exist for either nitrogen or phosphorus (similar to the chloride example). A loading capacity for nitrate in the Sangamon River is depicted in Figure B-2 using the drinking water maximum contaminant level (MCL) of 10 mg/L. It is derived directly from the MCL (10 mg/L) and the duration curve using the *"flow to load"* calculation described in Table B-1 across the range of all daily average flows.

***Figure B-2*.** Nitrate Loading Capacity Using Duration Curve Framework



*217 cfs * 10 mg/L * 0.002695 = 5.84 tons / day*

*17 cfs * 10 mg/L * 0.002695 = 0.46 tons / day*

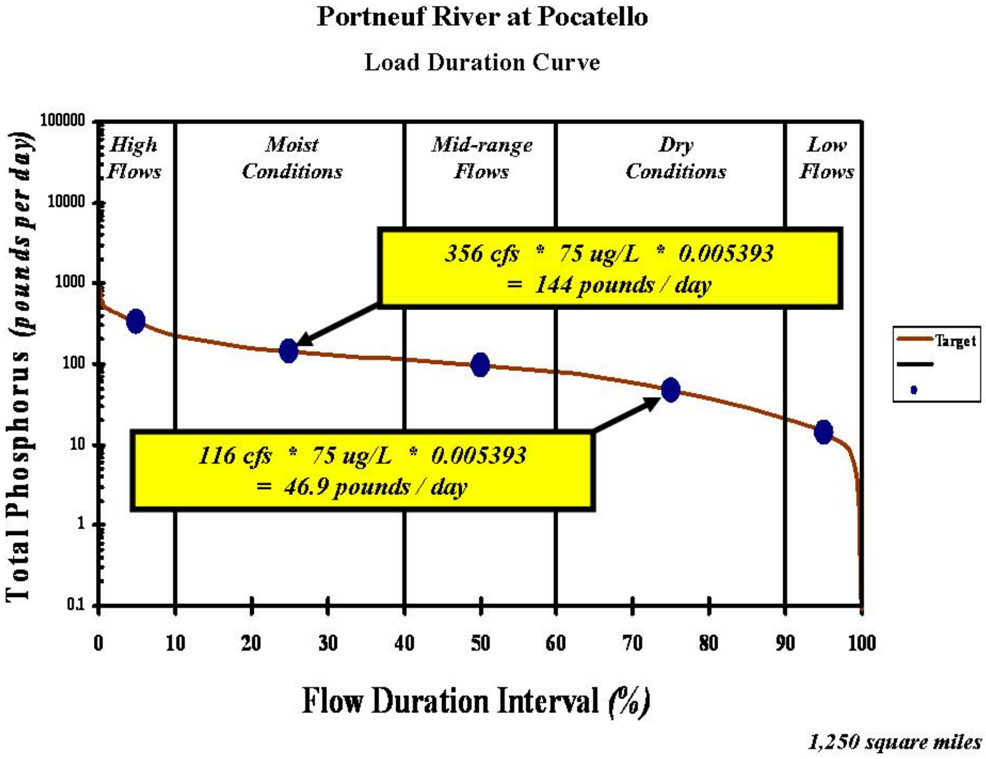
240 square miles

Figure B-3 shows the total phosphorus loading capacity curve for the Portneuf River using the TMDL target of 75 µg/L. In this example, loads are expressed as pounds per day (as described in Table B-2). Again, loading capacities developed using the duration curve framework provides information that adds a focus to discussions regarding allocations and implementation planning, particularly when used in conjunction with ambient water quality monitoring data.

***Table B-2*.** Calculation of Phosphorus Loads

Load *(tons per day)* = **Flow** *(cfs)* * **Concentration** *(µg/L)* * **Factor**			
multiply by **86,400** *to convert*	seconds per day	➔	ft^3 / day
multiply by **7.48** *to convert*	ft^3	➔	gallons / day
divide by **1,000** *to convert*	µg	➔	mg
divide by **453,592** *to convert*	mg	➔	pounds
multiply by **3.7854** *to convert*	liters	➔	gallons
multiply by **0.005393** *to convert*	**(ft^3 / sec) * (µg/L)**	➔	**pounds / day**

Figure B-3. Phosphorus Loading Capacity Using Duration Curve Framework

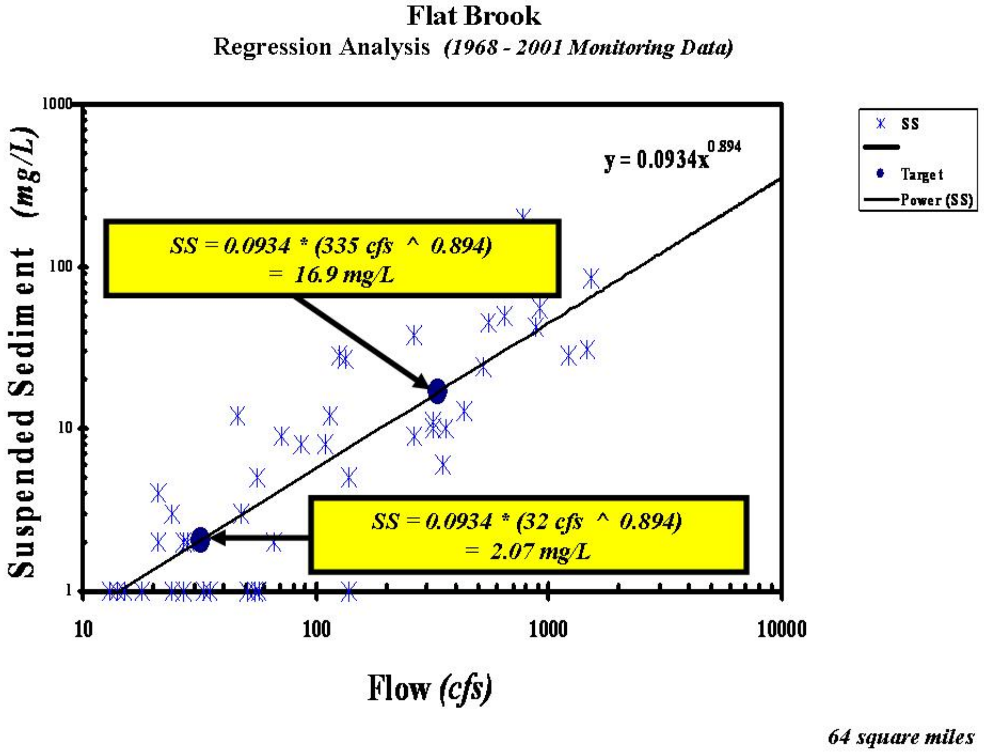


Sediment concerns have long challenged TMDL practitioners for several reasons. First, States typically do not have established numeric criteria for sediment, instead relying on narrative components of their water quality standards. Second, sediment problems can result from changes in processes that influence either surface or channel erosion. Sediment concerns are also associated with changes that affect the capacity of watersheds to store and transport sediment throughout the drainage network. TMDL assessments typically consider the influence of land management activities on changes in erosion processes, water discharge amounts and timing, as well as channel form (EPA, 1999).

There is a wide range in methods that have been employed towards sediment TMDL development. Some use fixed numeric targets, often based on values recommended by the European Inland Fisheries Advisory Commission (EIFAC), which could be used to establish categories of risk to fisheries. With this approach, the process outlined to generate loading capacities described for chloride, nitrate, and phosphorus *(Figures B-1 to B-3)* would be applied.

The *"Protocol for Developing Sediment TMDLs"* (EPA, 1999) indicates the suitability of using sediment targets, which relate concentrations to stream flow for reference streams that reflect unimpaired conditions. A target can be identified by developing a sediment rating curve for an appropriate reference stream based on the regression slope, by plotting flow against suspended sediment concentration. Figure B-4 illustrates an example rating curve for a reference stream.

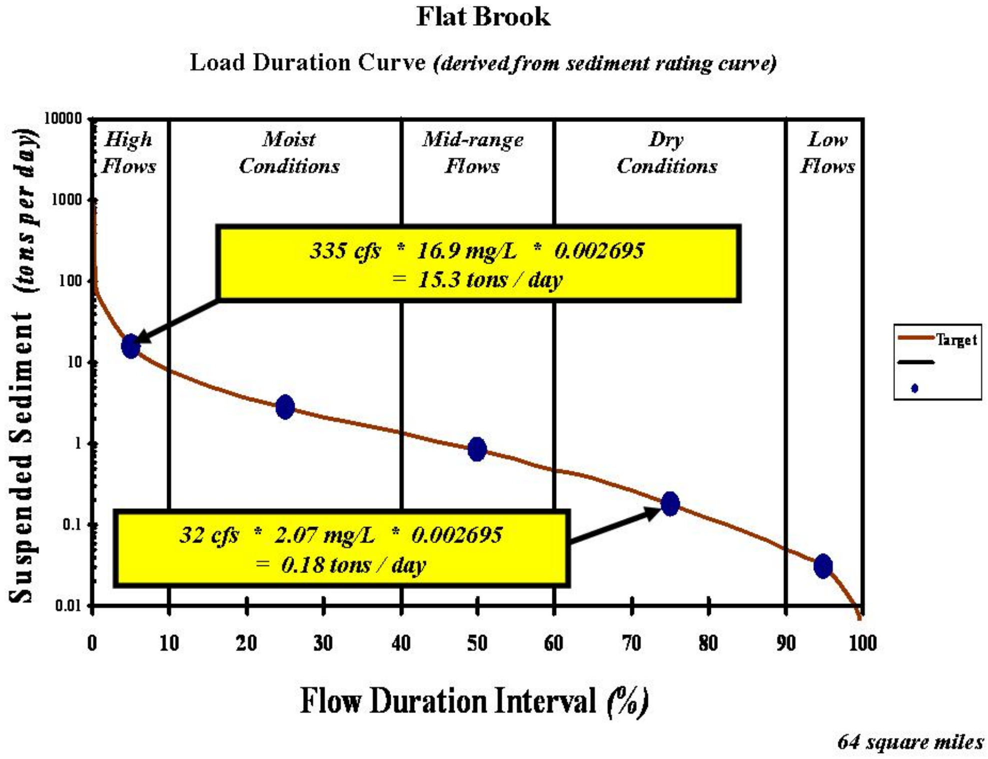
Figure B-4. Example Sediment Rating Curve



Duration curves provide a useful framework for TMDL development where there is an inherent relationship between stream flow and sediment. Rating curve methods can be used to adjust targets under higher flows, where sediment levels are expected to be elevated under natural conditions, as shown in Figure B-4. A key in using this approach is to ensure that regression curves are developed using appropriate reference streams. Simon (2004) describes a framework for sediment TMDLs where regression relationships are applied.

Again, a unique loading capacity for each duration curve zone allows the TMDL to reflect major watershed processes indicative of different flows *(Figure B-5)*. In-stream channel processes tend to dominate the sediment regime at high flows, while sediment delivered from surface erosion may be of greater concern under mid-range flows. A separate loading capacity for each zone allows the TMDL to guide implementation efforts uniquely associated with these conditions. The use of a discrete loading capacity for each zone also acknowledges the variability and uncertainty inherent in natural systems. The framework provides a focus for identifying targets that reflect expected patterns.

Figure B-5. Sediment Loading Capacity Using Duration Curve Framework



Bacteria is a major pollutant leading to §303(d) listings and subsequent TMDL development. Typically, loads are expressed as chemical mass per time, such as pounds per day. Given the nature of bacteria measurements (e.g., counts per 100 milliliters), an appropriate expression of loads for bacteria TMDLs is organisms per day. Table B-3 describes an approach used in TMDL development to calculate bacteria loads, which includes needed conversion factors.

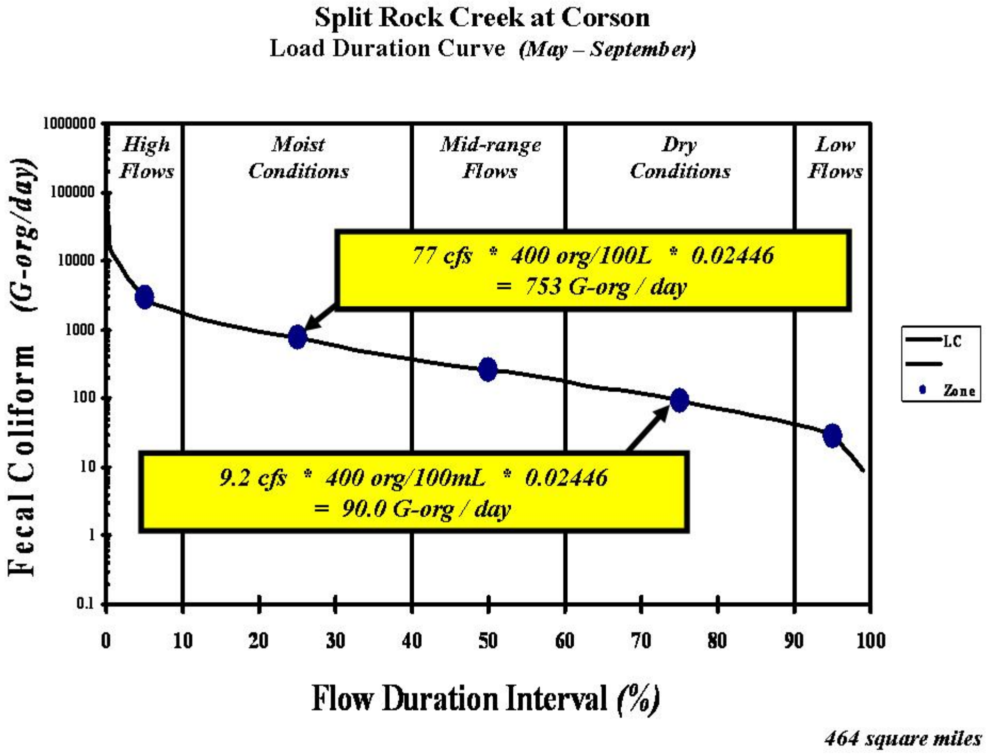
Loading capacities calculated in this manner result in extremely large numbers (i.e., numbers of organisms in the billions, trillions, or quadrillions per day). In order to avoid difficulties of communicating information associated with large counts (e.g., macro numbers of microorganisms), bacteria loading capacities are expressed as million organisms per day (mega- or M-org/day), billion organisms per day (giga- or G-org/day), or trillion organisms per day (tera- or T-org/day), similar to computer abbreviations of MB for megabytes, GB for gigabytes, or TB for terabytes.

As an example, waters designated for support of immersion recreation in South Dakota must achieve a daily maximum fecal coliform concentration of 400 cfu / 100mL between May and September. Figure B-6 shows an example *"daily maximum"* loading capacity curve for Split Rock Creek using the 400 cfu / 100 mL target and a duration curve derived with daily average flows. This load duration curve is based on daily average flows measured between May and September, in order to ensure consistency with the water quality criterion for fecal coliform.

***Table B-3*.** Calculation of Bacteria Loads

Load *(org/day)* = **Concentration** *(org/100mL)* * **Flow** *(cfs)* * **Factor**			
multiply by **3785.2** *to convert*	mL per gallon	➔	org / 100 gallon
divide by **100** *to convert*		➔	org / gallon
multiply by **7.48** *to convert*	gallon per ft^3	➔	org / ft^3
multiply by **86,400** *to convert*	seconds per day	➔	ft^3 / day
divide by **1,000,000,000**	billion	➔	G-org
multiply by **0.02446** *to convert*	**(org/100mL) * ft^3 / sec**	➔	**G-org / day**

***Figure B-6*.** Bacteria Loading Capacity Using Duration Curve Framework



Split Rock Creek at Corson
Load Duration Curve *(May – September)*

*77 cfs * 400 org/100L * 0.02446*
= 753 G-org / day

*9.2 cfs * 400 org/100mL * 0.02446*
= 90.0 G-org / day

464 square miles

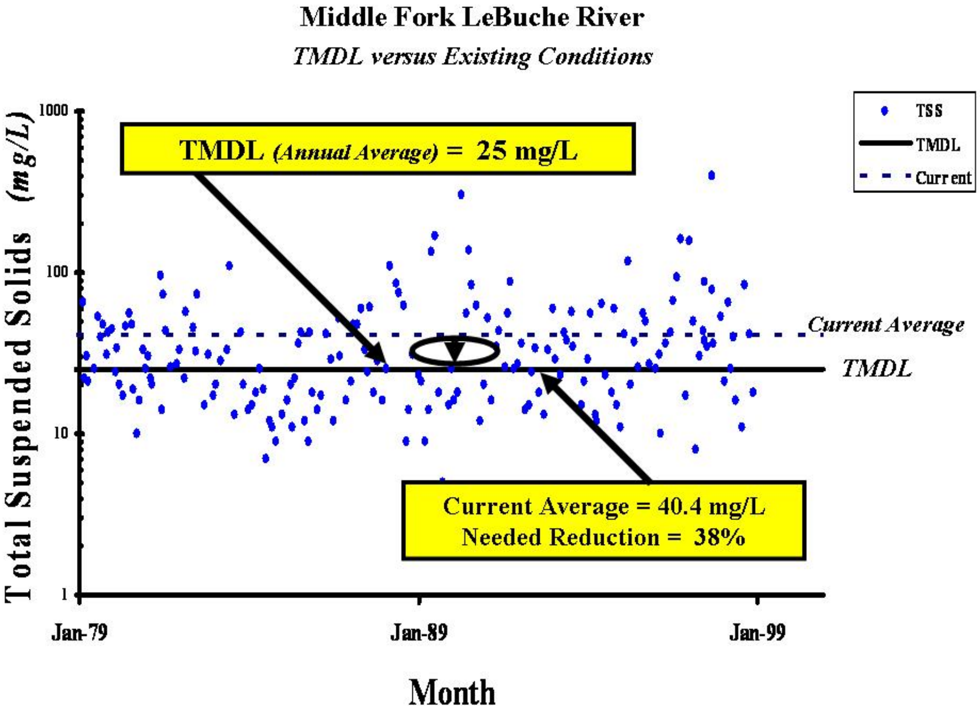
B2. MULTIPLE AVERAGING PERIODS

Connecting to "Non-Daily" Targets -- Sediment

The following sediment example represents one type of problem where an array of different approaches can bring multiple averaging periods into the technical analysis. The duration curve framework can accommodate different averaging periods (other than daily) in identifying loading capacities, particularly where a concentration-based target exists (expressed as monthly, seasonal, or annual average values).

Figure B-7 illustrates an example TMDL developed to attain the water quality criteria expressed as an annual average concentration of 25 mg/L total suspended solids (TSS). Figure B-7 portrays this TMDL in the context of existing conditions, both individual measurements and the current annual average (40.4 mg/L). Use of these *"non daily"* averaging period TMDLs is one way to account for variability.

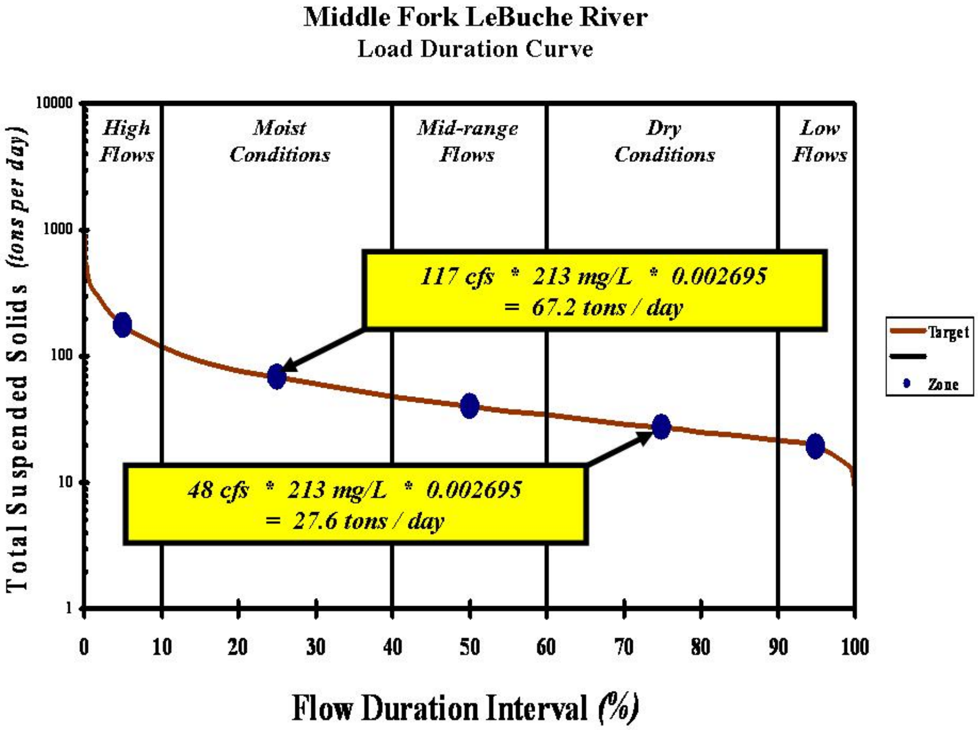
Figure B-7. Concentration-Based TMDL



Statistical methods, which consider patterns and variability in a consistent manner, offer a way to connect targets that use multiple averaging periods. Using an approach described in EPA's *"Technical Support Document for Water Quality-Based Toxics Control"* (1991 TSD), the maximum daily concentration for the Middle Fork LeBuche River is 213 mg/L total suspended solids (based on achieving an annual average of 25 mg/L with a coefficient of variation of 1.164). In-stream loads for TSS, expressed as tons per day, are calculated using the equation summarized in Table B-1. The loading capacity for the

Middle Fork LeBuche River is shown in Figure B-8. It is derived directly from the daily concentration target (213 mg/L) and the duration curve using the *“flow to load”* calculation described in Table B-1 across the range of all daily average flows.

Figure B-8. TSS Loading Capacity Using Duration Curve Framework



The maximum *“daily load”* and long-term (or *“non daily”*) average target work together. The *“non daily”* target serves as a benchmark that connects to the applicable water quality standards. Multiple averaging periods provide a way to achieve both long-term program objectives and focus implementation efforts while avoiding short term problems. In order to ensure consistency with applicable water quality standards, a load duration curve can be developed that reflects the long-term (or *“non daily”*) criterion.

Table B-4 provides another way to view the overall TMDL using a duration curve framework based on multiple averaging periods. The long-term average portion of the water quality criteria is identified as a benchmark, specifically the standard against which the overall performance of management control strategies is measured. Recognizing the variability associated with water quality conditions, the TMDL serves as the upper range needed to achieve the applicable standards. The TMDL is expressed as a *“daily load”*; it is the basis for developing the allocations and *“margin of safety”*.

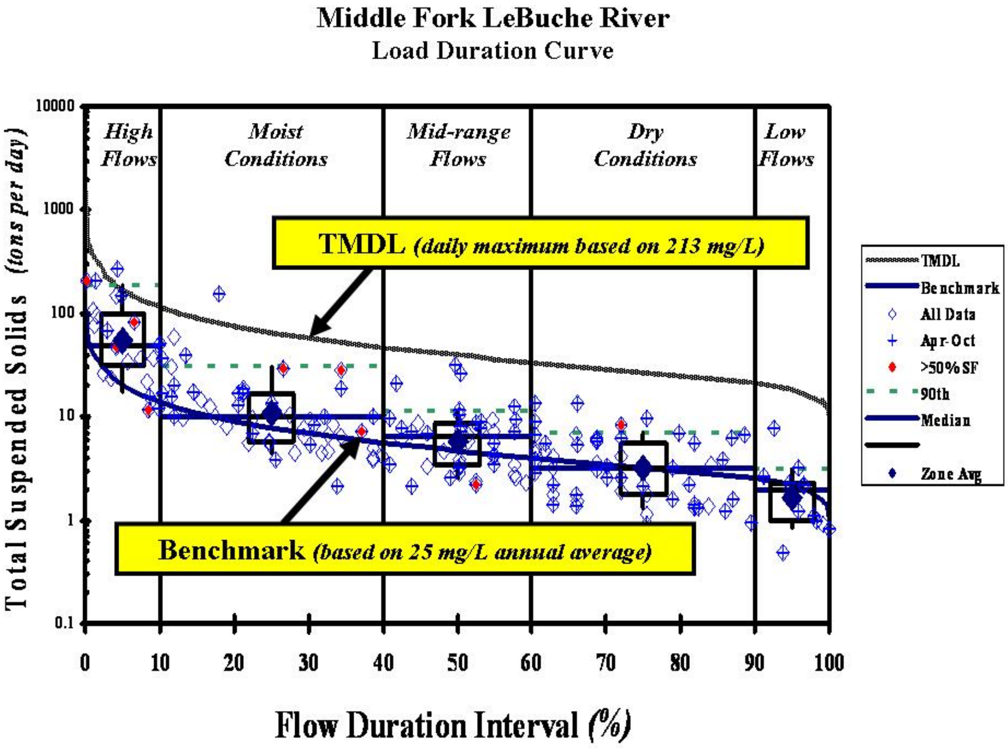
Figure B-9 illustrates the utility of the duration curve framework in connecting *“daily loads”* to benchmarks based on *“non daily”* averaging periods (both curves can be displayed on the same graph). Using actual monitoring data, critical conditions that the TMDL is exceeded can be identified (in the case of the M.F. LeBuche River, it occurs under high flows and moist conditions). This information enables planners to target appropriate source areas, delivery mechanisms, and water quality management control strategies to address short term problems. Similarly, average values within each zone can be calculated and compared to the long term average (or *"non daily"*) benchmark curve. In the case of the M.F. LeBuche TMDL, benchmarks are exceeded under high flows, moist conditions, and mid-range flows.

In addition to providing the needed linkage between the *"daily load"* and the applicable water quality standards, the duration curve framework provides the groundwork for the transition from the TMDL to implementation efforts. Reduction estimates can be developed for each duration curve zone benchmark, which serve to guide problem solving discussions on appropriate management strategies (based on knowledge associated with likely source areas, delivery mechanisms, and appropriate control measures that correspond to particular hydrologic conditions). As shown in Table B-4, implementation opportunities are highlighted that correspond to the flow conditions best suited for the array of control options.

Table B-4. Middle Fork LeBuche River TMDL Summary

<table>
<tr><th rowspan="2">TMDL SUMMARY</th><th colspan="5">Loads expressed as <i>(tons per day)</i></th></tr>
<tr><th>High</th><th>Moist</th><th>Mid-Range</th><th>Dry</th><th>Low</th></tr>
<tr><td>TMDL[1]</td><td>173.35</td><td>67.20</td><td>40.21</td><td>27.57</td><td>18.96</td></tr>
<tr><td>Allocations</td><td>118.32</td><td>48.24</td><td>34.47</td><td>21.83</td><td>6.90</td></tr>
<tr><td>Margin of Safety</td><td>55.03</td><td>18.96</td><td>5.74</td><td>5.74</td><td>12.06</td></tr>
<tr><td>Benchmark[2]</td><td>20.35</td><td>7.89</td><td>4.72</td><td>3.24</td><td>2.22</td></tr>
<tr><td>Reduction Estimate[3]</td><td>63%</td><td>27%</td><td>19%</td><td>0%</td><td>0%</td></tr>
<tr><td rowspan="5">Implementation Opportunities</td><td><i>Post Development BMPs</i></td><td></td><td></td><td></td><td></td></tr>
<tr><td><i>Streambank Stabilization</i></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3"><i>Erosion Control Program</i></td><td></td><td></td></tr>
<tr><td></td><td colspan="3"><i>Riparian Buffer Protection</i></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="2"><i>Municipal WWTP</i></td></tr>
<tr><td colspan="6">Notes:
1. Expressed as a <i>"daily load"</i>; represents the upper range of conditions needed to attain and maintain applicable water quality standards
2. Based on annual average target identified in the applicable water quality standards
3. Developed using long-term fixed station ambient water quality monitoring data</td></tr>
</table>

Figure B-9. Middle Fork LeBuche River TMDL Using Duration Curve Framework



Connecting to "Non-Daily" Targets -- Bacteria

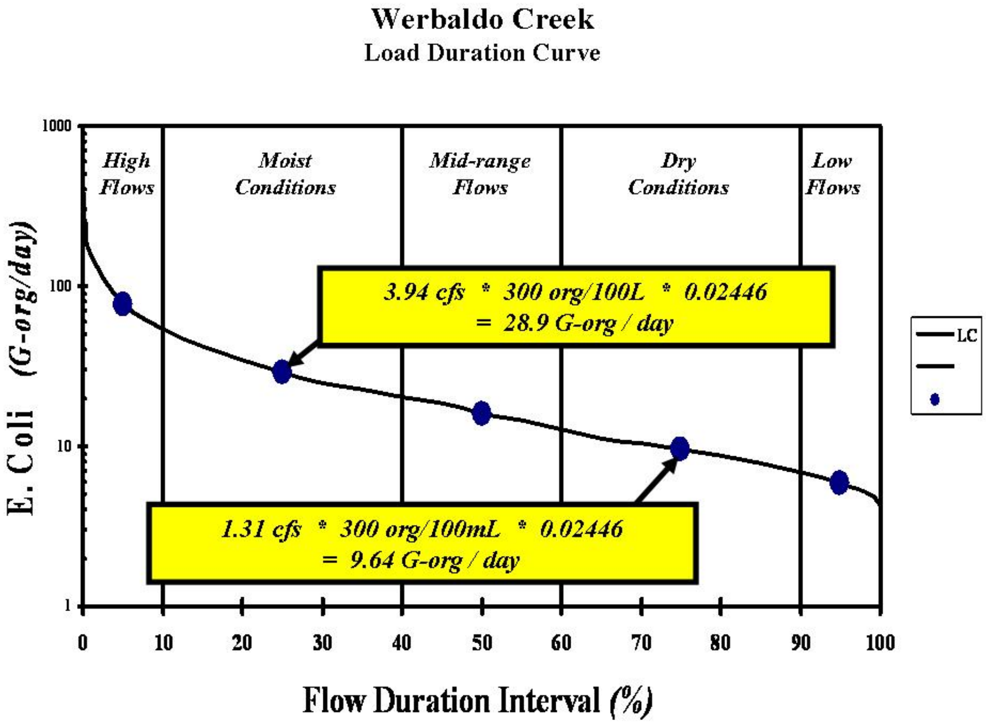
Many State water quality standards for pathogens include a 30-day or monthly geometric mean averaging period and an upper limit (either a single sample maximum or no more than a set percent exceedance value). A challenge facing TMDL practitioners is identifying the appropriate target that will protect both criteria values. Michigan's applicable water quality standards (WQS) for bacteria, for instance, focus on E. Coli and indicate that all waters be protected for total body contact recreation from May 1 to October 31. Target levels for TMDL development are derived from Rule 62 of the WQS, which state that:

> *"R 323.1062 Microorganisms.*
> *Rule 62. (1) All waters of the state protected for total body contact recreation shall not contain more than 130 E. coli per 100 milliliters (ml), as a 30-day geometric mean. … At no time shall the waters of the state protected for total body contact recreation contain more than a maximum of 300 E. coli per 100 ml."*

When the duration is expressed as a daily average or *"never to exceed"* value, the daily target is explicitly stated in the applicable water quality criteria (USEPA, 2007). For example, using Michigan's bacteria criteria, the *"daily"* value is the maximum of 300 E.

Coli per 100 mL to protect for total body contact recreation. Procedures described in Table B-3 and Figure B-6 are then used to develop the loading capacity using a duration curve framework. Another example is shown in Figure B-10.

***Figure B-10*.** Bacteria Loading Capacity Using Duration Curve Framework



TMDLs must be established at a level necessary to attain and maintain the applicable water quality standards. In the case of the Werbaldo Creek E. Coli example *(Figure B-10)*, this includes both a not to exceed value and a 30-day geometric mean of 130 per 100 mL. Material in EPA's November 2004 promulgation of water quality criteria for coastal recreational waters elaborates on the intended purpose behind each of the two criteria values. In particular, the preamble of the coastal recreational water rule states:

> *"the geometric mean is the more relevant value for ensuring that appropriate actions are taken to protect and improve water quality because it is a more reliable measure, being less subject to random variation"* (EPA, 2004).

The rule provides a context for multi-value bacteria criteria with respect to Clean Water Act implementation programs, such as TMDLs and NPDES permit requirements. This context is to meet the geometric mean criteria for bacterial indicators, such as E. coli, enterococci, or fecal coliform.

For this reason, a linkage analysis may be needed to demonstrate consistency between the not to exceed value used as the *"daily"* TMDL target and the 30-day geometric mean. EPA's development of ambient water quality criteria for bacteria, specifically E. Coli, defines the statistical relationship between these two criteria values. This relationship can be used to demonstrate that attaining the maximum daily target in the TMDL will also achieve the 30-day geometric mean criteria.

The concepts used to develop the *"not to exceed value"*, often referred to as the single sample maximum (SSM), are described in the *"Ambient Water Quality Criteria for Bacteria -- 1986"*. The method used to develop the SSM values for E. Coli in the 1986 document is based on a recognition of the inherent variability that occurs in water quality. In particular, the relationship between the 30-day geometric mean and the SSM is based on the assumption that bacteria data can be described using a log-normal frequency distribution. The method used to identify the upper target values in the 1986 document provides a way to develop a linkage analysis, which describes the connection between the *"daily"* value and the 30-day geometric mean.

Specifically, the log-normal distribution has been used to identify upper targets in conjunction with geometric mean and a measure of variability (in this case, a log standard deviation). Figure B-11 illustrates this concept for *E. Coli* bacteria. As shown in Figure B-11, upper targets are based on the assumption of a log-normal distribution using a log standard deviation of 0.4 centered on 130 cfu / 100 mL, i.e. the target geometric mean.

Figure B-11. Development of E. Coli Upper Targets

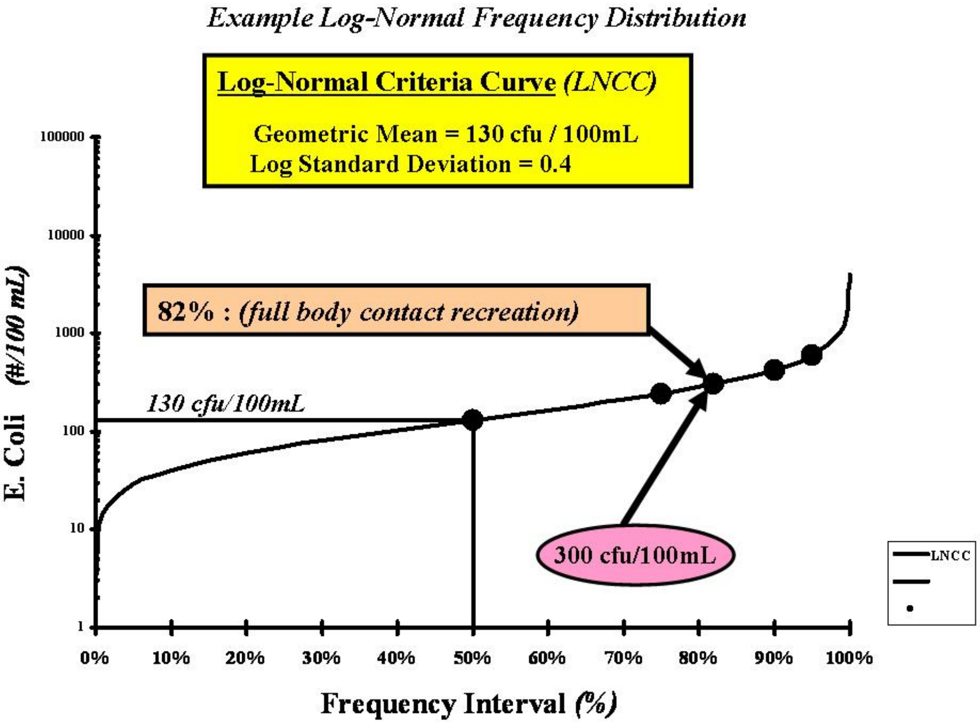
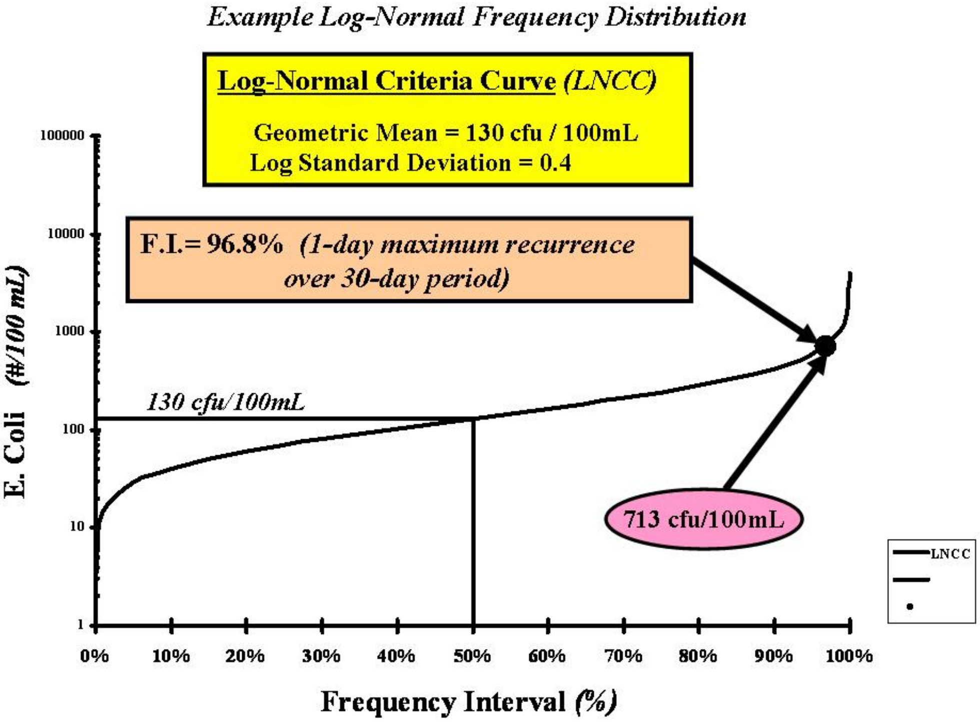


Figure B-12 illustrates the same concept for E. Coli bacteria where the applicable criteria is simply a geometric mean (no single sample maximum). As shown in Figure B-12, the 1-day monthly maximum is based on the same assumptions behind development of the E. Coli criteria, specifically a log-normal distribution using a log standard deviation of 0.4

centered on 130 cfu / 100 mL (i.e. the target geometric mean). The daily target is set at the recurrence interval associated with a 30-day averaging period using percentiles along the curve, specifically 96.8% [e.g., (30/31)%, or (k/k+1)% where k is the number of averaging period days]. Note that the *"daily"* target set in the Werbaldo Creek TMDL is much lower than one based solely on the 30-day geometric mean criteria using the same assumptions behind establishing the single sample maximum (e.g., 300 versus 713).

Figure B-12. Development of Daily Value Based on Monthly Target



Using a *"daily"* target of 300 organisms per 100 mL is more restrictive than one based on a geometric mean of 130 using the same assumptions behind development of the E. Coli criteria. The linkage analysis can also use these same assumptions to determine the 30-day geometric mean that corresponds to a *"daily"* target of 300 E. Coli per 100 mL. Figure B-13 shows the graphic results of this analysis, indicating that the resultant 30-day geometric mean will be 54.6. Thus, a daily target of 300 will be protective of the 30-day geometric mean in the water quality standards.

Table B-5 provides a summary of the Werbaldo Creek TMDL using a duration curve framework based on multiple averaging periods (similar to the sediment example in Table B-4). The 30-day geometric mean must be met before full compliance with the bacteria water quality standards is achieved in Werbaldo Creek. Based on the linkage analysis, the 30-day geometric mean component of the water quality criteria will be met provided the maximum daily target is met. If subsequent data or information demonstrates that, for some reason, the maximum daily target is met and the 30-day geometric mean is not met, the TMDL should be revised with allocations lowered to ensure attainment of both criteria values.

Figure B-13. Relationship Between 30-day Geometric Mean and Daily Target

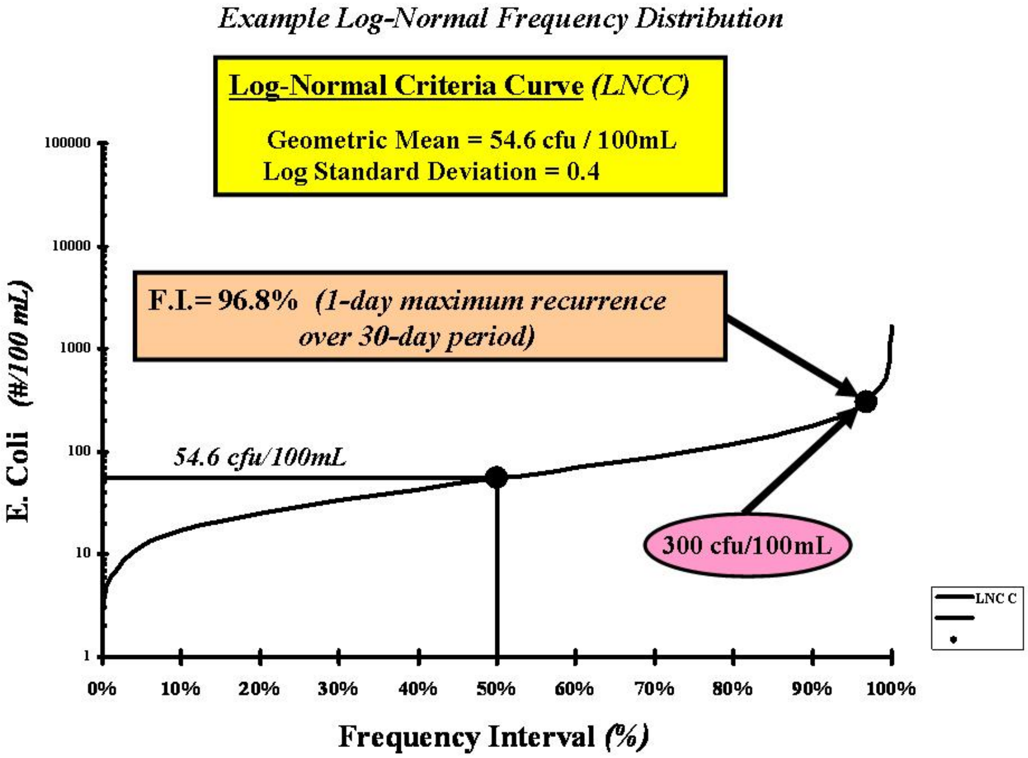


Table B-5. Werbaldo Creek TMDL Summary

TMDL SUMMARY	**Loads expressed as *(G-org per day)***				
	High	**Moist**	**Mid-Range**	**Dry**	**Low**
TMDL[1]	77.15	28.93	16.07	9.64	5.87
Allocations	53.84	20.09	12.86	6.91	4.26
Margin of Safety	23.30	8.84	3.21	2.73	1.61
Benchmark[2]	130	130	130	130	130
Reduction Estimate[3]	92%	90%	75%	40%	20%
Implementation Opportunities	***Long-term CSO Control Program***				
	Riparian Protection				
			Illicit Discharge Detection & Elimination		
				Address on-site wastewater disposal problems	

Notes:

1. Expressed as a *"daily load"*; represents the upper range of conditions needed to attain and maintain applicable water quality standards
2. Based on the 30-day geometric mean identified in the applicable water quality standards
3. Developed using ambient water quality monitoring data

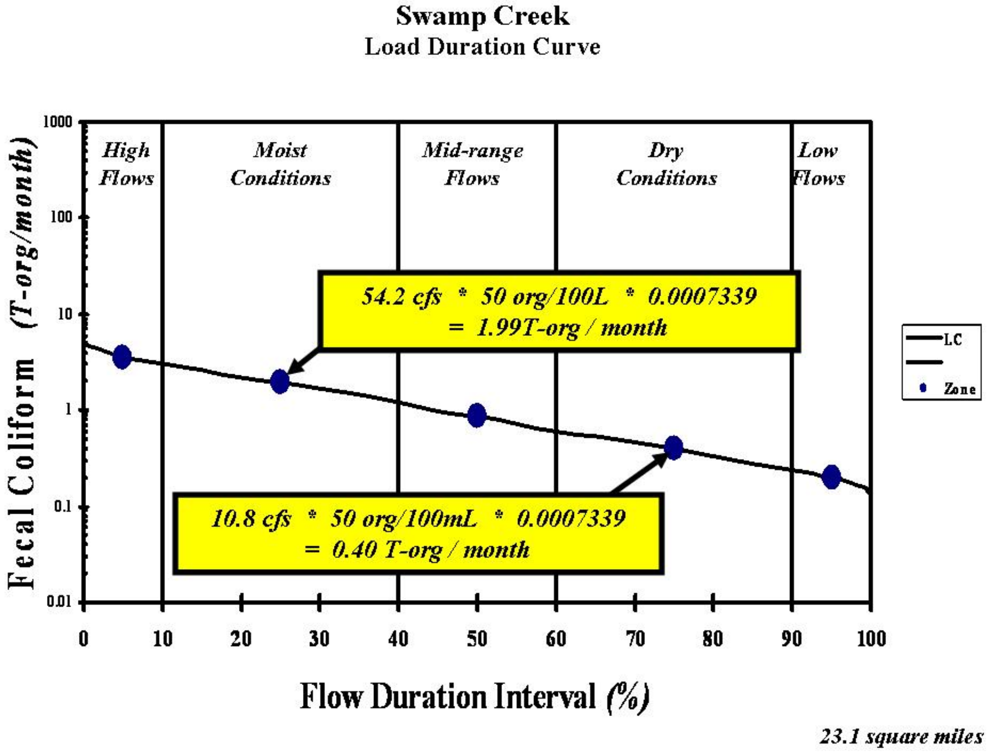
Use of Monthly Duration Curves. In order to ensure consistency with the geometric mean criterion, 30-day or monthly mean flows can also be used to identify loading capacities that supplement daily load targets. This approach offers another way to develop a quantitative analysis of seasonal variation indicative of the 30-day or monthly target in the water quality standards (i.e., larger loads in months with higher flows and smaller loads in months with lower flows). Table B-6 summarizes a portion of individual monthly mean flow values using USGS data for Swamp Creek near Kenmore, WA. Summary statistics for each month using the full record are included at the bottom of Table B-6.

As seen in Table B-6, seasonal patterns reflect higher flows in late fall and early winter (e.g., December, January) with a transition to lower flows in summer months. However, interannual variation is another factor to consider when identifying loading capacities. Average values for the same month can vary by as much as an order of magnitude due to varying weather conditions (e.g., an unusually dry December or an abnormally wet June), as shown in Table B-6 for the Swamp Creek. Flow duration curves developed using individual monthly average values (as opposed to daily average flows) provide a way to consider interannual variation. The duration curve framework uses a frequency distribution based on all individual months over the same period (such as all values in Table B-6). Figure B-14 shows the loading capacity curve for Swamp Creek using the frequency distribution of mean monthly flows.

Table B-6. Swamp Creek Monthly Mean Flows

	Individual Monthly Mean Flows *(cfs)*											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1978	27.1	79.2	33.2	39.0	11.0	5.7	6.0	5.5	7.5	14.4	14.9	86.5
1979	63.5	80.0	59.2	41.3	15.8	21.9	10.1	9.2	8.8	7.6	37.1	69.5
1980	42.5	57.3	30.3	34.6	22.5	20.8	14.0	6.9	15.4	53.9	74.2	131.2
1981	94.1	105.7	68.6	48.3	13.7	8.4	10.2	7.6	12.3	18.5	24.9	110.0
1982	87.7	89.8	57.5	28.8	17.8	12.2	13.5	12.5	13.0	10.3	91.1	59.2
1983	46.6	66.7	71.8	38.9	30.2	19.3	8.4	7.5	12.9	13.4	80.6	86.1
1984	24.8	40.9	29.0	31.1	19.9	26.7	6.7	7.4	10.0	35.1	26.1	23.8
1985	110.4	56.4	25.3	19.8	24.0	7.7	10.3	5.1	9.1	18.0	66.1	61.4
1986	80.0	59.9	79.0	25.9	15.6	7.8	6.8	6.4	6.0	5.8	13.1	54.1
1987	41.3	18.7	46.1	48.4	22.4	22.6	6.4	5.4	8.7	10.1	42.2	35.6
1988	58.5	53.1	74.8	23.1	17.4	10.8	7.0	6.6	5.1	22.1	26.3	42.2
1989	27.1	79.2	33.2	39.0	11.0	5.7	6.0	5.5	7.5	14.4	14.9	86.5
Maximum	140.5	105.7	115.1	50.7	30.2	26.7	14.0	13.0	22.8	53.9	91.1	131.2
Average	77.0	62.5	56.6	34.6	18.5	12.8	7.7	7.1	10.3	15.5	38.7	72.9
Median	83.5	57.5	54.3	34.6	17.4	11.3	6.7	6.7	9.6	12.7	26.3	69.5
25th %	55.5	51.5	38.2	29.7	15.5	8.0	6.0	5.3	7.0	9.1	24.4	55.6
10th %	35.6	35.4	29.8	22.2	14.0	6.5	5.0	4.3	5.4	7.2	14.7	39.1
Minimum	22.7	18.7	25.3	15.9	11.0	5.7	4.3	3.6	5.1	5.8	11.1	16.4

Figure B-14. Monthly Bacteria Loading Capacity Using Duration Curve Framework



B3. SUMMARY

The use of duration curves provides a technical framework for identifying *"daily loads"* in TMDL development, which accounts for the variable nature of water quality associated with different stream flow rates. Specifically, a maximum daily concentration limit can be used with basic hydrology and a duration curve to identify a TMDL that covers the full range of flow conditions. With this approach, the maximum *"daily load"* can be identified for any given day based on the stream flow. Identification of a loading capacity using the duration curve framework is driven by the flow duration curve and a water quality criterion or target value. The target may be constant across all flow conditions (e.g., chloride example) or the target may vary with flow (e.g., sediment rating curves).

Under the duration curve framework, the loading capacity is essentially the curve itself. The loading capacity, which sets the *"total maximum daily load"* on any given day, is determined by the flow on the particular day of interest. The use of duration curve zones can help provide a simplified summary through the identification of discrete loading capacity points by zone. Using a duration curve framework, an explicit *"margin of safety"* can be identified for each listed reach and corresponding set of flow zones. Allocations within the TMDL are set in a way that reflects dominant concerns associated with appropriate hydrologic conditions.

APPENDIX C

Targeting Potential Solutions and Connecting to Implementation

Traditional approaches towards TMDL development tend to focus on targeting a single value, which depends on a water quality criterion and design flow. The single number concept does not work well when dealing with impairments caused by NPS pollutant inputs *(Stiles, 2001)*. One of the more important concerns regarding nonpoint sources is variability in stream flows, which often causes different source areas and loading mechanisms to dominate under different flow regimes. Because NPS pollution is often driven by runoff events, TMDL development should consider factors that ensure adequate water quality across a range of flow conditions.

C1. *"BOTTOM UP"* APPROACHES

An important key to the success of the TMDL program, in terms of engaging the public, is building linkages to other programs, such as nonpoint source (NPS) management. Many successful efforts to develop TMDLs have involved the §319 program as a way to utilize local groups in data collection, analysis, and implementation. Watershed analysis has been used to build a *"bottom up"* approach, which defines one way to establish a meaningful, value-added framework linking water quality concerns to proposed solutions. TMDL development using a *"bottom up"* approach considers the interaction between watershed processes, disturbance activities, and available methods to reduce pollutant loadings, specifically BMPs.

A *"bottom up"* approach capitalizes on the networks of programs and authorities across jurisdictional lines. Information on management measures related to both source control and delivery reduction methods is linked to conditions for which specific restoration strategies may be most appropriate. This information can then be incorporated into the allocation part of TMDL development using a duration curve framework.

C2. PROBLEM SOLVING FRAMEWORK

The "two Ps" – *practical* approaches and *partnerships* – are critical to successful watershed planning and implementation. On the practical side, a *"bottom up"* approach must overcome the challenge of translating detailed technical concepts and information into "*plain English"*. On the partnership side, key stakeholders must be engaged in the process, so that meaningful results with measurable improvements are achieved.

A problem solving framework, constructed around a set of fundamental questions, can help focus development of practical approaches and encourage participation among key partners. A basic set of questions using a *"bottom up"* approach to address water quality problems often includes:

- * *WHY* the concern?
- * *WHAT* reductions are needed?
- * *WHERE* are the sources?
- * *WHO* needs to be involved?
- * *WHEN* will actions occur?

These simple, practical questions can be easily used to keep assessment efforts connected with implementation activities. Methods to communicate technical information, such as duration curves, can be an important part of the problem solving process.

C3. ENGAGING STAKEHOLDERS

Public involvement is fundamental to successful TMDL development and implementation. Duration curves provide another way of presenting water quality data, which characterizes concerns and describes patterns associated with impairments. As a communication tool, this framework can help elevate the importance of monitoring information to stakeholders.

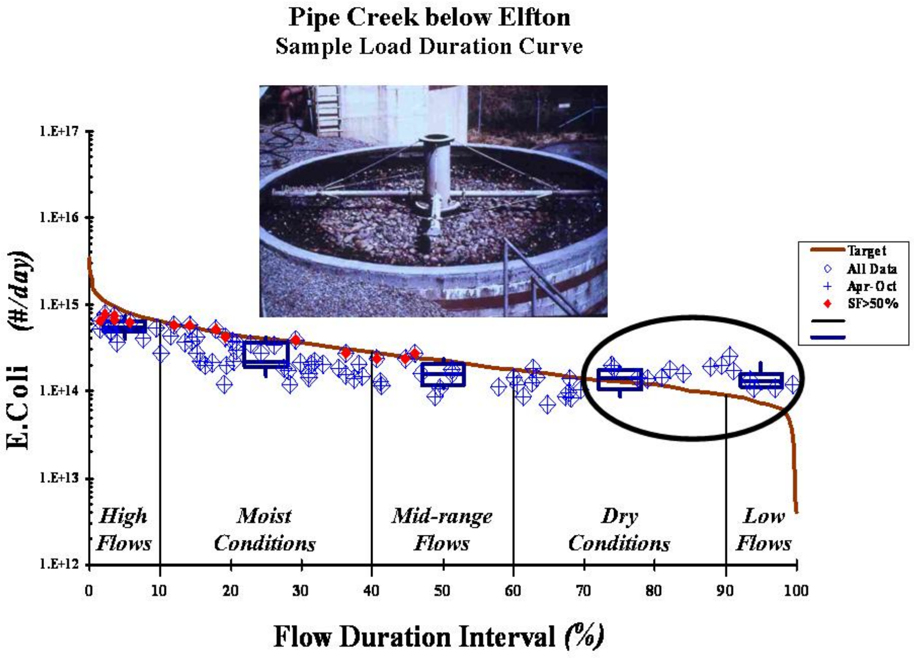
The extended use of monitoring information and the alternative way to present TMDLs using duration curves offers an opportunity for enhanced targeting, both in field investigation efforts and implementation planning. As an assessment and communication tool, duration curves can help narrow potential debates, as well as inform the public and stakeholders so they become engaged in the process. Duration curves offer an opportunity for enhanced targeting, both in TMDL development and in water quality restoration efforts. In particular, duration curves can add value to the TMDL process by identifying:

- targeted participants (e.g., NPDES permitees) at critical flow conditions;
- targeted programs (e.g., Conservation Reserve Program);
- targeted activities (e.g., conservation tillage or contour farming); and
- targeted areas (e.g., bank stabilization projects).

Figure C-1 represents the first of several hypothetical examples to illustrate the potential use of duration curves, both as a diagnostic indicator and as a communication tool for targeting in the TMDL process. The target curve in Figure C-1 is derived using flow duration intervals that correspond to stream discharge values and numeric criteria for E. Coli.

The area circled on the right side of the duration curve represents hydrologic conditions where the target is exceeded. In this example, wastewater treatment plants exert a significant influence at low flows. Duration curves support a *"bottom up"* approach towards TMDL development and restoration efforts by identifying targeted participants, in the case of Figure C-1, point sources. For urban watersheds, water quality concerns experienced during low flow conditions might involve detecting illicit connections under an MS4 stormwater program. In an agricultural setting showing similar patterns, potential solutions could include livestock management through riparian fencing or off-site watering BMPs.

***Figure C-1*.** Duration Curve as General Indicator of Hydrologic Condition



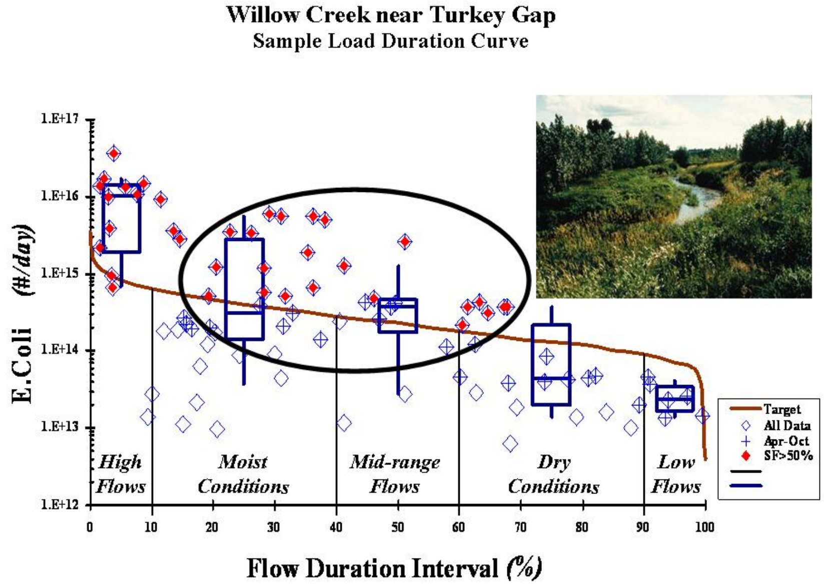
TARGETED Participants: *Point Sources*

Figure C-2 illustrates the added value duration curves can provide by highlighting potential contributing areas. As seen in this hypothetical example, the target is met when the hydrologic condition of the watershed is above a flow duration interval of 70 (generally low flow and dry conditions). Problems start to develop under mid-range flows and sometimes dry conditions, as indicated by the circled area.

Wet-weather events can range from high flows and moist conditions after severe thunderstorms to lower surface runoff volumes following light rains. Watershed conditions, land use, and proximity of source areas to streams should also be considered. For this particular watershed *(Figure C-2)*, the increased load may be the result of pollutant delivery associated with rainfall and runoff from riparian areas. In more urban watersheds, runoff from impervious areas could also contribute flow and pollutants in response to light rain, exhibiting a pattern similar to Figure C-2.

Duration curves can be used as a diagnostic tool, which supports a *"bottom up"* approach towards TMDL development and water quality restoration by identifying targeted programs, namely those focused on riparian protection. In agricultural areas, such as the Willow Creek example watershed *(Figure C-2)*, this might include activities such as the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Program (CREP).

***Figure C-2*.** Duration Curve with Contributing Area Focus



TARGETED Programs: *Riparian Buffers (e.g. CRP, CREP)*

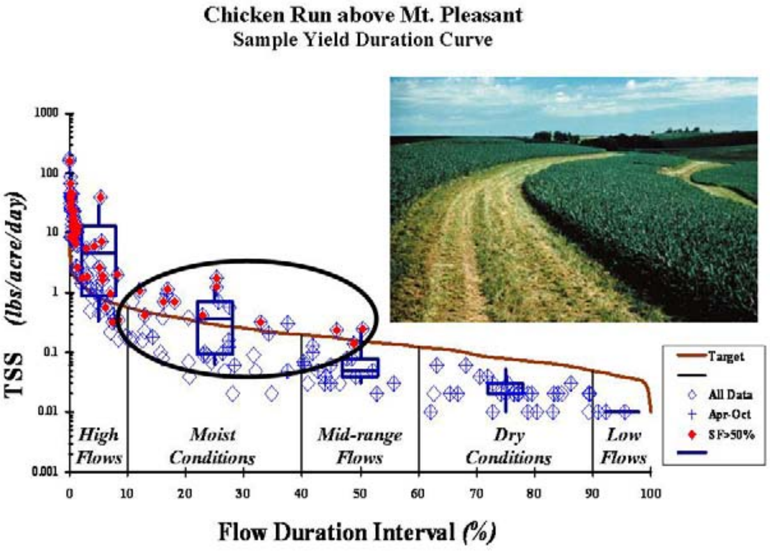
The focus on contributing areas is further illustrated with another hypothetical example, shown in Figure C-3, where total suspended solids associated with surface erosion is the pollutant of concern. Here, the duration curve is expressed in terms of yield to show how distributions derived from a flow duration curve can be extended to other measures, again as a simple targeting tool.

In the Chicken Run example *(Figure C-3)*, observed values only exceed the target when the hydrologic condition of the watershed is below 55 (generally higher flows). For the Chicken Run example watershed, duration curves can be used to support a *"bottom up"* approach towards TMDL development.

Chicken Run is also an agricultural watershed. Wet-weather events expected to deliver pollutants under moist conditions are generally associated with more saturated soils. In addition to riparian areas, a larger portion of the watershed drainage area is potentially contributing runoff.

In this case, consideration might be given to targeted activities such as conservation tillage, contour strips, and grassed waterways. For urban watersheds, water quality concerns experienced during mid-range flows and moist conditions might be best addressed through site construction BMPs under an MS4 storm water management program (SWMP). Critical area ordinances are another set of management measures that would address water quality concerns under these flow conditions. Thus, water quality data and a duration curve framework can help guide local implementation efforts to achieve meaningful results.

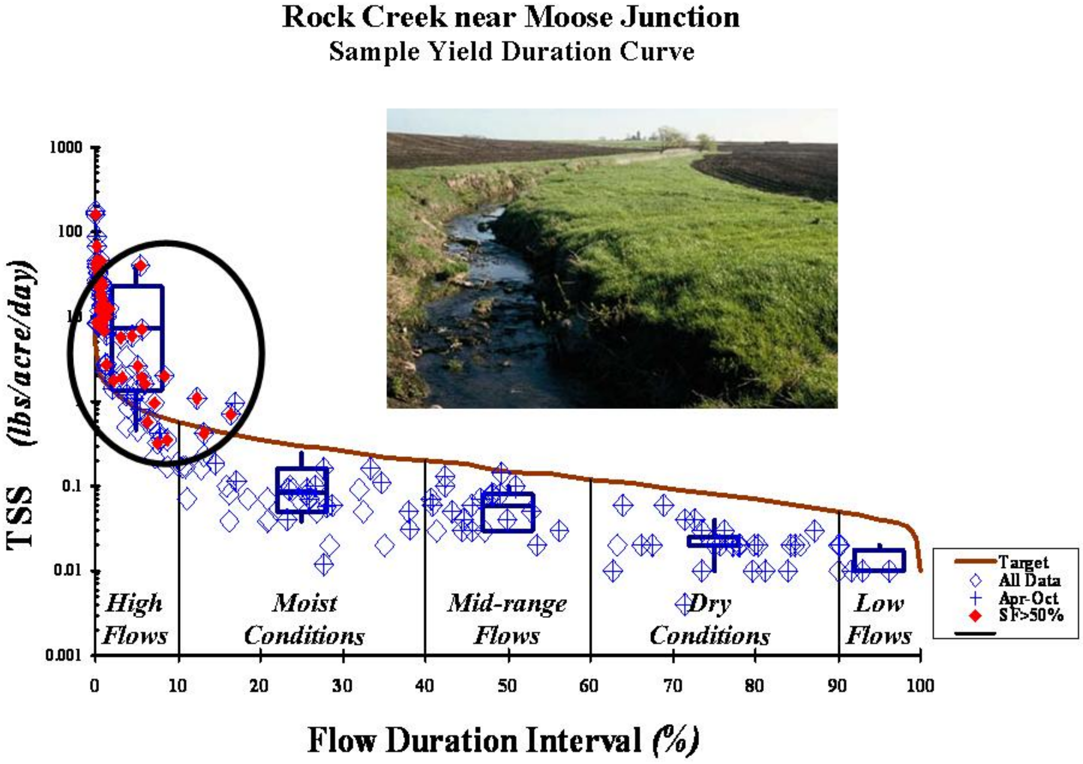
Figure C-3. Duration Curve with Targeted Activity Focus



TARGETED Activities: *Contour Strips, Conservation Tillage*

Figure C-4 illustrates another hypothetical example, where transport and delivery mechanisms that occur under high flow conditions typically include stream bank erosion and channel processes. Targeted areas for water quality improvement might consider bank stabilization efforts. For urban watersheds, targeted areas might involve post development BMPs intended to address channel protection.

Figure C-4. Duration Curve with Delivery Mechanism Focus



TARGETED Areas: *Streambank Erosion, Bank Stability*

CONNECTING TO IMPLEMENTATION AND RESULTS

A major advantage of the duration curve framework in TMDL development is the ability to provide meaningful connections between allocations and implementation efforts. Because the flow duration interval (FDI) serves as a general indicator of hydrologic condition (i.e., wet versus dry and to what degree), allocations and reduction targets can be linked to source areas, delivery mechanisms, and the appropriate set of management practices. The use of duration curve zones (e.g., high flow, moist, mid-range, dry, and low flow) allows the development of allocation tables, which can be used to summarize potential implementation actions that most effectively address water quality concerns.

Connections to Management Practices

Development of wasteload allocations for continuous point source discharges is relatively straightforward using a duration curve framework, when compared to either storm water or nonpoint sources. Consideration of pollution control measures is typically done in conjunction with NPDES permit development. Wasteload allocations (WLAs) can be expressed at one level across the entire duration curve, or WLAs may be tiered to specific flow levels and the corresponding flow duration interval. Storm water or nonpoint sources, on the other hand, present a much greater challenge because pollutants are transported to surface waters by a variety of mechanisms (e.g., runoff, snowmelt, groundwater infiltration). Best management practices (BMPs) generally focus on source control and / or delivery reduction. Table C-1 illustrates an approach, which could be used to assess the management options in a way that considers the potential relative importance of hydrologic conditions.

Documenting Results

Figure C-5 illustrates the advantage of the duration curve framework in documenting results using Charles River data. This location has been monitored since 1989. Based on this water quality information, significant reductions in bacteria loads to the river have occurred over the past ten years through CSO controls plus illicit discharge detection and elimination. These improvements are reflected in the data using a duration curve framework, particularly in the moist, mid-range, and dry zones. Individual allocations can help focus implementation efforts to address remaining problems that occur under high flow conditions.

Figure C-6 illustrates another example of the advantage of this framework using Big Sioux River data. This location has been monitored by the State of South Dakota since 1974. As noted in Figure C-6, significant reductions in bacteria loads to the river have occurred over the past fifteen years. These improvements are reflected in the data using a duration curve framework, particularly in the high, moist, mid-range, and dry zones. The duration curve framework can help focus efforts to address remaining problems with management strategies most appropriate for those flow conditions.

***Table C-1*.** Example Management Practice / Hydrologic Condition Considerations

Management Practice	**Duration Curve Zone**				
	High	**Moist**	**Mid-Range**	**Dry**	**Low**
Bacteria Source Reduction					
Remove Illicit Discharges					
Address Pet & Wildlife Waste					
Combined Sewer Overflow Management					
Combined Sewer Separation					
CSO Prevention Practices					
Septic System Management					
Managing Private Systems					
Replacing Failed Systems					
Installing Public Sewers					
Storm Water Infiltration / Retention					
Infiltration Basin					
Infiltration Trench					
Infiltration / Biofilter Swale					
Storm Water Detention					
Created Wetland					
Low Impact Development Practices					
Disconnecting Impervious Areas					
Bioretention					
Pervious Pavement					
Green Roof					
Rain Gardens					
Agricultural Management Practices					
Managing Manure Application					
Pasture / Grazing Management					
Managing Barnyards					
Managing Recreational Sources					
Designate No Discharge Areas					
Address Discharges from Boats					
Other					
Point source controls			*M*	*H*	*H*
Riparian buffers		*H*	*H*	*H*	
Pet waste education & ordinances		*M*	*H*	*H*	

***Note*:** Potential relative importance of management practice effectiveness under given hydrologic condition *(H: High; M: Medium; L: Low)*

Figure C-5. Documenting Program Results Using Duration Curve Framework

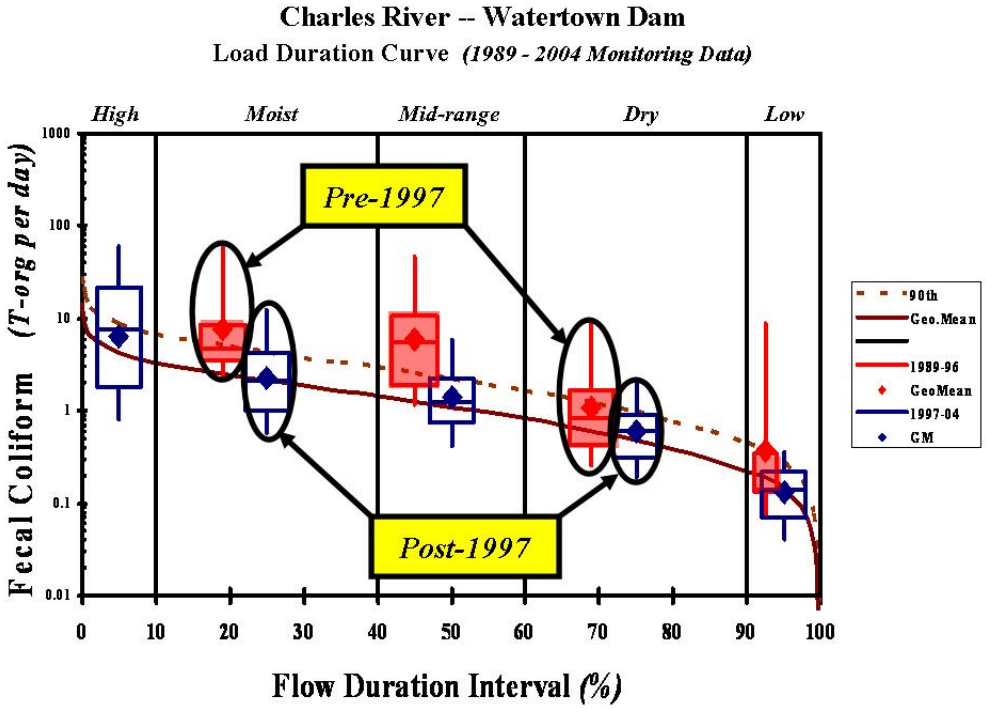
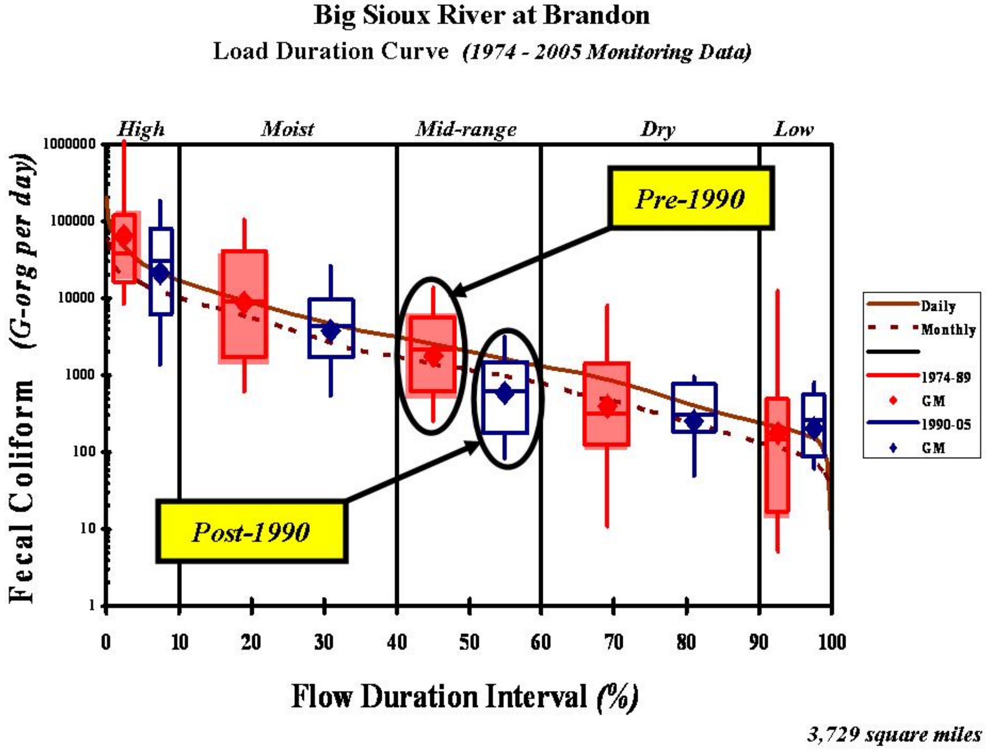


Figure C-6. Documenting Program Results Using Duration Curve Framework



APPENDIX D

Acronyms and References

ACRONYMS

7Q10	the 7-day average low flow occurring once in 10 years
90th	90th percentile
ALC	aquatic life criteria
ARA	antibiotic resistance analysis
BMP	best management practice
BST	bacteria source tracking
CFR	*Code of Federal Regulations*
cfs	cubic feet per second
cfu	colony forming units
C.L.	confidence level
cms	cubic meters per second
CREP	Conservation Reserve Enhancement Program (U.S. Department of Agriculture)
CRP	Conservation Reserve Program (U.S. Department of Agriculture)
CSO	combined sewer overflow
CWA	Clean Water Act
DC	duration curve
EIFAC	European Inland Fisheries Advisory Committee
EPA	U.S. Environmental Protection Agency
FDI	flow duration interval
F.I.	frequency interval
FR	*Federal Register*
geo. mean	geometric mean
GIS	geographic information system
GM	geometric mean
G-org	billion organisms
GWLF	generalized watershed loading function
HSPF	hydrological simulation program – FORTRAN
LA	load allocation
LC	load (duration) curve
LDC	load duration curve
LNCC	log-normal criteria curve
MCL	maximum contaminant level
MOS	margin of safety

MS4	municipal separate storm sewer system
NPDES	National Pollutant Discharge Elimination System
NPS	nonpoint source
org	organisms
PS	point source
Q-based	flow data–based
R. curve	regression (or rating) curve
SF	storm flow
SS	suspended sediment
SWAT	soil and water assessment tool
SWMP	storm water management program
TMDL	total maximum daily load
T-org	trillion organisms
TSD	technical support document
TSS	total suspended solids
USGS	U.S. Geological Survey
WLA	waste load allocation
WQ	water quality
WQS	water quality standard
WWTF	wastewater treatment facility (also referred to as a WWTP)
WWTP	wastewater treatment plant (also referred to as a WWTF)
Z-90th	90th percentile of a particular zone
ZMC	zone median concentration
7Q10	Lowest streamflow for 7 consecutive days that occurs on average once every 10 years

REFERENCES

Bonta, J.V. March 2002. *Framework for Estimating TMDLs with Minimal Data*. ASAE Proceedings of the Watershed Management to Meet Emerging TMDL Regulations Conference. Fort Worth, TX. pp. 6-12.

Cleland, B.R. June 2007. *TMDL Development From the "Bottom Up" -- Part IV: Connecting to Storm Water Management Programs*. National TMDL Science and Policy 2007 -- WEF Specialty Conference. Bellevue, WA.

Cleland, B.R. November 2003. *TMDL Development From the "Bottom Up" -- Part III: Duration Curves and Wet-Weather Assessments*. National TMDL Science and Policy 2003 -- WEF Specialty Conference. Chicago, IL.

Cleland, B.R. November 2002. *TMDL Development From the "Bottom Up" – Part II: Using Duration Curves to Connect the Pieces*. National TMDL Science and Policy 2002 -- WEF Specialty Conference. Phoenix, AZ.

Hornberger, G.M., J.P. Raffensperger, P.L. Wiberg, and K.N. Eshleman. 1998. *Elements of Physical Hydrology*. Johns Hopkins University Press. Baltimore, MD. 302 p.

Leopold, L.B. 1994. *A View of the River*. Harvard University Press. Cambridge, MA.

Linsley, R.K., M.A. Kohler, and J.L. Paulus. 1982. *Hydrology for Engineers (3rd ed.)*. McGraw-Hill. New York, NY.

Mehan, G.T. November 2001. Testimony on TMDL Program before Subcommittee on Water Resources and Environment – U.S. House of Representatives. Washington, DC.

Rosgen, D.L. 1996. *Applied River Morphology*. Wildland Hydrology. Pagosa Springs, CO.

Searcy, James, K. 1959. *Flow-Duration Curves; Manual of Hydrology: Part 2. Low-Flow Techniques*. U.S. Geological Survey Water-Supply Paper 1542-A. 33 p.

Sheely, L.H. July 2002. *Load Duration Curves: Development and Application to Data Analysis for Streams in the Yazoo River Basin, MS*. Special Project – Summer 2002. Jackson Engineering Graduate Program.

Simon, A and C.R. Hupp. March 1986. *Channel Evolution in Modified Tennessee Channels*. Proceedings of Fourth Interagency Sedimentation Conference. V.2, Section 5, pp. 5-71 to 5-82. Las Vegas, NV.

Simon, A., E. Langendoen, R. Bingner, R. Wells, Y. Yuan, and C. Alonso. 2004. *Suspended-Sediment Transport and Bed-Material Characteristics of Shades Creek, Alabama and Ecoregion 67: Developing Water Quality Criteria for Sediment*. USDA -- Agricultural Research Service, National Sedimentation Laboratory. Oxford, MS.

Sloto, R.A. and M.Y. Crouse. 1996. *HYSEP: A Computer Program for Streamflow Hydrograph Separation and Analysis*. U.S. Geological Survey Water Resources Investigations Report 96-4040. Lemoyne, PA. 46 p.

South Carolina Department of Health & Environmental Control. 2005. *Total Maximum Daily Load (TMDL) for Fecal Coliform for Hills Creek, Lynches River, North and South Branch of Wildcat Creek, Flat Creek, Turkey Creek, Nasty Branch, Gulley Branch, Smith Swamp, Little Pee Dee River, Maple Swamp, White Oak Creek, and Chinners Swamp of the Pee Dee River Basin, South Carolina*. SCDHEC Technical Report Number: 029-05.

Stiles, T.C. November 2002. *Incorporating Hydrology in Determining TMDL Endpoints and Allocations*. National TMDL Science and Policy 2002 -- WEF Specialty Conference. Phoenix, AZ.

Stiles, T.C. March 2001. *A Simple Method to Define Bacteria TMDLs in Kansas*. ASIWPCA / ACWF / WEF TMDL Science Issues Conference: On-site Program. St. Louis, MO. pp 375-378.

Sullivan, J.A. March 2002. *Use of Load Duration Curves for the Development of Nonpoint Source Bacteria TMDLs in Texas*. ASAE Proceedings of the Watershed Management to Meet Emerging TMDL Regulations Conference. Fort Worth, TX. pp. 355-360.

U.S. Environmental Protection Agency. 2007. *Options for Expressing Daily Loads in TMDLs*. Office of Wetlands, Oceans, & Watersheds. Washington, DC.

U.S. Environmental Protection Agency. 2004. *Total Maximum Daily Load (TMDL) for Siltation, Turbidity, and Habitat Alteration in Shades Creek -- Jefferson County, Alabama*. USEPA Region 4. Atlanta, GA.

U.S. Environmental Protection Agency. 1999. *Protocol for Developing Sediment TMDLs*. Office of Water. EPA 841-B-99-007. Washington, D.C.

U.S. Environmental Protection Agency. April 1991. *Guidance for Water Quality-based Decisions: The TMDL Process*. Office of Water. EPA 440/4-91-001. Washington, D.C.

U.S. Environmental Protection Agency. March 1991. *Technical Support Document for Water Quality-based Toxics Control*. Office of Water. EPA 505/2-90-001. Washington, D.C.

U.S. Environmental Protection Agency. 1986. *Ambient Water Quality Criteria for Bacteria -- 1986*. Office of Water. EPA-440/5-84-002. Washington, D.C.