

AN APPROACH FOR USING LOAD DURATION CURVES IN DEVELOPING TMDLS

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This guide provides an overview on the use of duration curves for developing Total Maximum Daily Loads (TMDLs). The guide describes basic steps needed to develop duration curves, which identify loading capacities, load and wasteload allocations, margin of safety, and account for seasonal variations. The guide also discusses some considerations in using the approach, and includes a fact sheet on developing daily loads using this method as well as 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 flow data 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.

Applying duration curves in TMDL development provides a framework to evaluate dynamic systems (i.e., flow variable) and is unlike a mass balance approach, where the waterbody is assumed to behave as a steady state system. A simple mass balance approach may be more appropriate for situations where the critical condition has been determined to occur consistently during low flow conditions. An underlying premise of the mass balance approach or a steady state system is that if the TMDL is designed to attain water quality standards during a single time period representative of the critical conditions (typically identified as 7Q10), then the TMDL should be sufficiently protective of the designated uses during all other times. In contrast, the duration curve approach is most effective when the entire flow regime of a system needs to be considered in determining appropriate loading capacities and allocations.

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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. For instance, it may be appropriate to use flow data of a similar and 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.

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 approved for the Pee Dee River Basin in South Carolina. Appendix A contains a step-by-step approach in calculating load and waste load allocations, as well as the margin of safety.

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. This is especially true for the majority of States that have not yet adopted numeric sediment and/or nutrient criteria. One way, specific to sediments, to address this issue could be the use of a sediment rating curve to derive appropriate TMDL endpoints. Another option is to use a reference watershed approach as a way to interpret and quantify narrative criteria for TMDL development. Using this method, the loading of a similar, representative attainment watershed serves as the TMDL endpoint for an impaired watershed.

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.

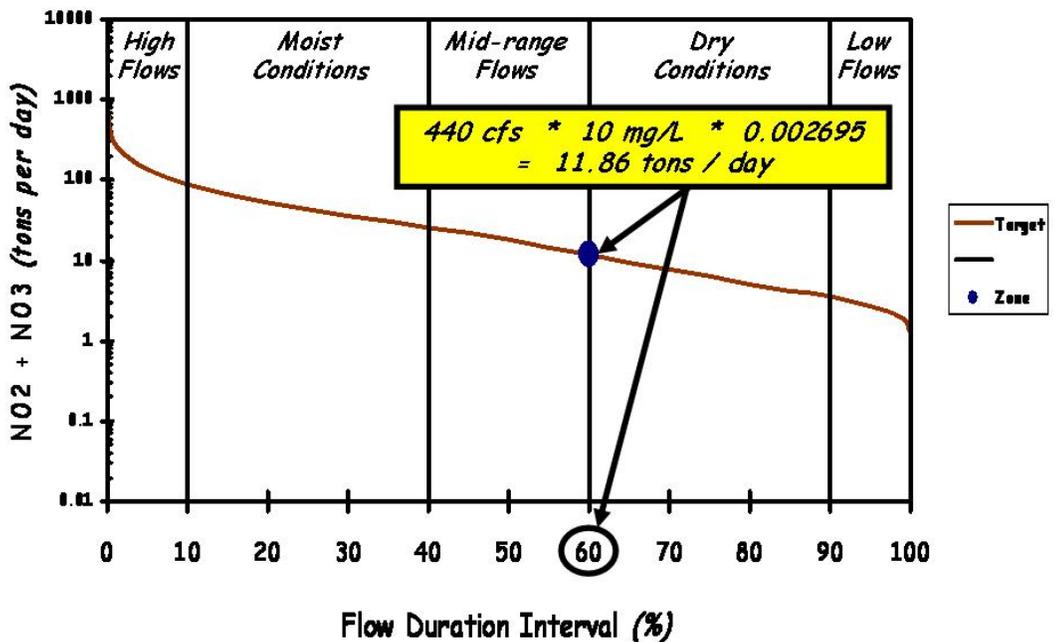
Numeric water quality standards or targets have a duration component, typically expressed as a specific average concentration or value that should not be exceeded at any time. When the duration is expressed as a daily average or “*never to exceed*” value, the daily target is explicitly stated in the applicable water quality criteria. Additional considerations are necessary to set daily TMDL targets for numeric water quality criteria with averaging periods other than daily (e.g., 30-day geometric mean for bacteria). Appendix B describes a technical framework for development of “*daily loads*”, which accounts for the variable nature of water quality that results from different flow conditions, seasonality, and source inputs.

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. Appendices C and D provide specific details on how loading capacity duration curves are developed for use in TMDLs.

Figure 2-1. Nitrate Loading Capacity Using Duration Curve Framework
Salt Creek near Greenview, IL
 Load Duration Curve



1,804 square miles

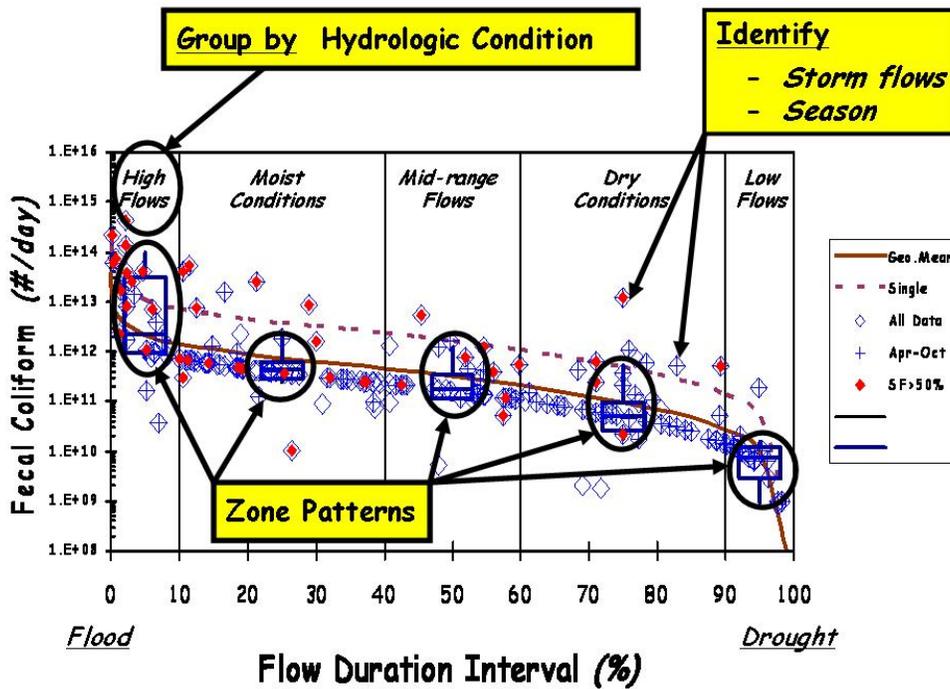
2b. Interpreting Load Duration Curves to Assess Water Quality

When using the duration curve framework in the context of developing a TMDL, it is important to keep in mind EPA’s view 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.

Table 2-1. Approaches for Developing TMDL “Margin of Safety”

Type of Margin of Safety	Approaches
Explicit	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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, an explicit “margin of safety” can be identified for each listed reach and corresponding set of flow zones. For example, the MOS can 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.

Because the allocations are a direct function of flow, accounting for potential flow variability is an appropriate way to address the “*margin of safety*”. Minimum flows over long periods of record at the USGS gage sites must be considered when defining the MOS for the low flow zone.

In summary, 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

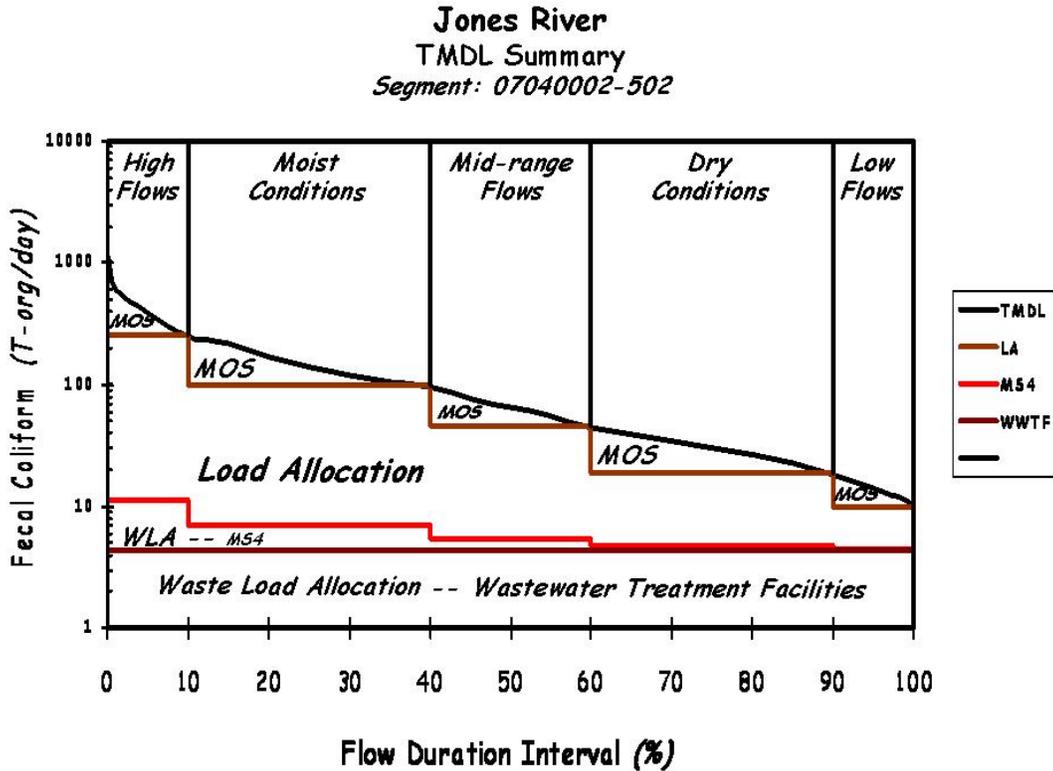
Segment ID	Name	TMDL Component	Duration Curve Zone (Expressed as T-org/day)					
			High	Moist	Mid	Dry	Low	
Q21-01	Quepote Brook							
		TMDL	19.87	9.37	4.09	2.20	1.29	
		MOS	4.31	3.92	0.76	0.66	0.77	
		LA	9.18	3.10	1.88	0.79	0.35	
		Korston DPW (WWTP)	WLA	0.12	0.12	0.12	0.12	0.12
		Loburn (WWTP)	WLA	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. Allocations have been “capped” at the minimum flow in each zone. The difference between the total allocation and the loading capacity (or TMDL) in each zone is the “margin of safety”.

For each zone, the amount available for load allocations and the storm water MS4 waste load allocation is the total allocation “cap” for that zone minus the WLAs for WWTFs. 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.

Figure 2-3. Example TMDL Using Duration Curve Framework

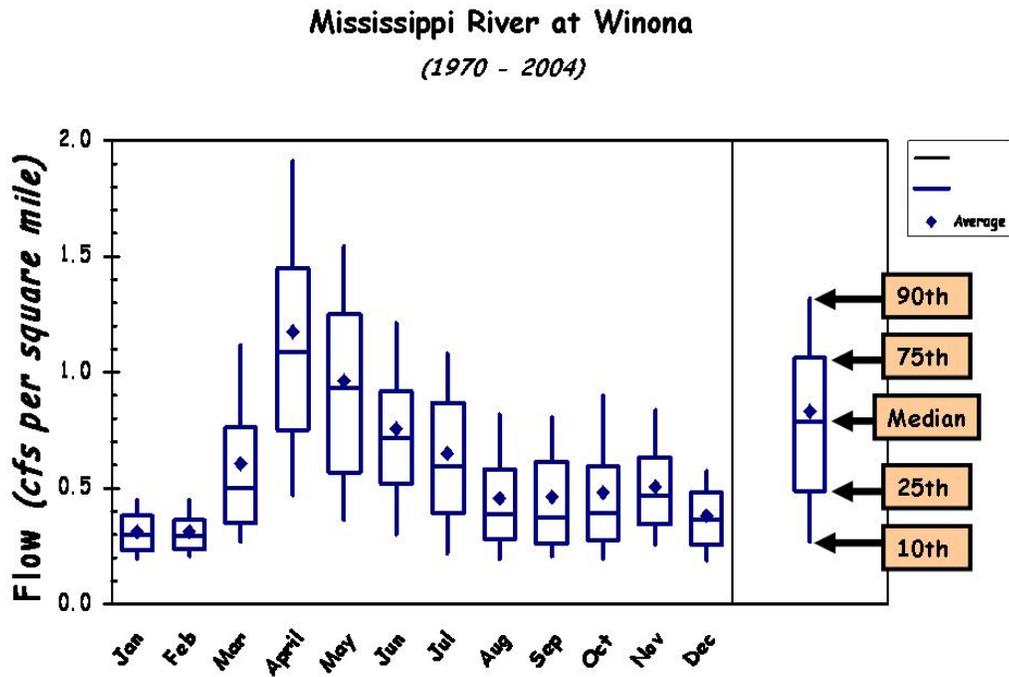


2e. Seasonal Variation

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.

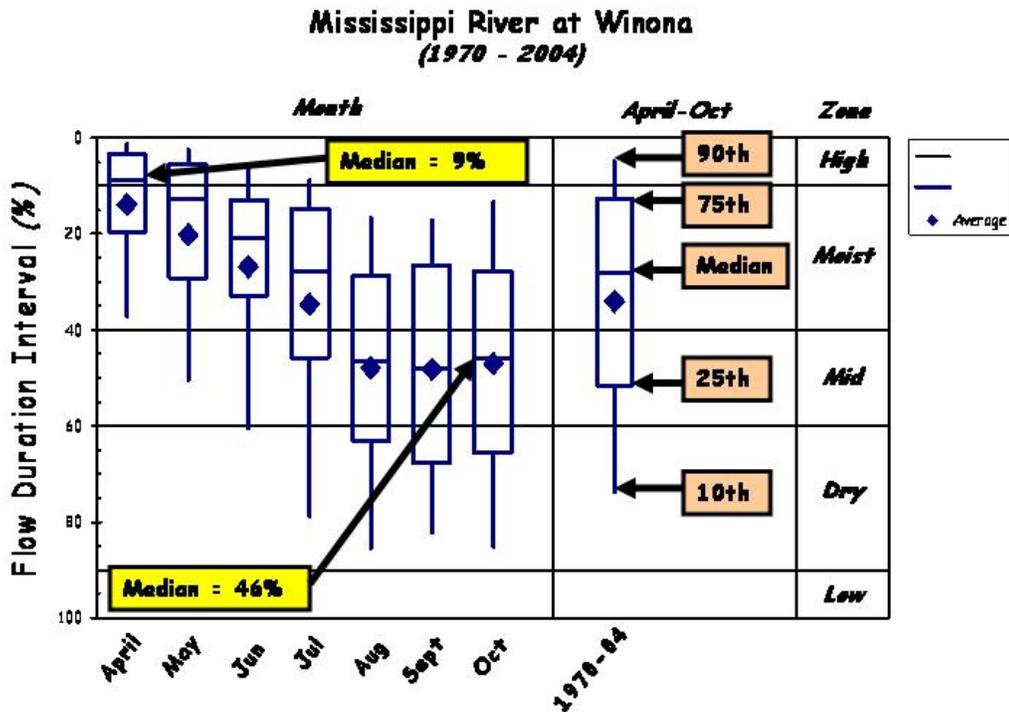
Another way to view seasonal variation is through the use of flow duration curves. Figure 2-5 illustrates monthly flow data expressed as duration curve intervals for the Mississippi River at Winona. The “box and whisker” format allows analysis of general patterns by conveying information on the distribution 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



Watershed Size: 59,200 square miles

Figure 2-5. Mississippi River Monthly Variation



USGS Data

59,200 square miles

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 C provides a “*Fact Sheet*”, which summarizes the use of the duration curve method for developing daily load expressions in TMDLs. Appendix C includes example calculations for chloride and total suspended solids. The duration curve framework is also well-suited for other parameters, such as nutrients and bacteria. Appendix D provides some additional example loading capacity calculations that address these other situations.

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 use 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. 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 (i.e., construction zone versus agricultural area) or individual sources of a similar source category (i.e., 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 are on the same playing field (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 Situations

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 provide some illustration as to when this might be necessary relative to source contributions, isolating impaired waters, or addressing spatial variation.

- *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.
- *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 and somewhat unrealistic, 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. EPA recommends that States 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.

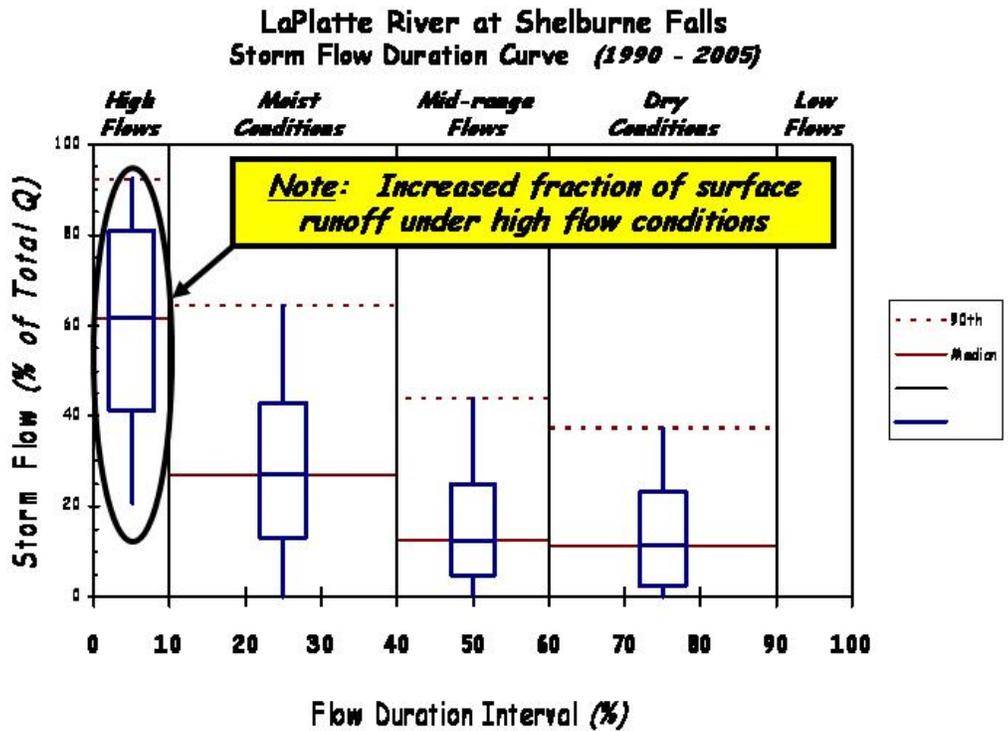
4d. Storm Events and Hydrograph Separation

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 Areas

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				<i>M</i>	<i>H</i>
On-site wastewater systems			<i>H</i>	<i>M</i>	
Riparian Areas		<i>H</i>	<i>H</i>	<i>H</i>	
Storm water: Impervious Areas		<i>H</i>	<i>H</i>	<i>H</i>	
Combined sewer overflows	<i>H</i>	<i>H</i>	<i>H</i>		
Storm water: Upland	<i>H</i>	<i>H</i>	<i>M</i>		
Bank erosion	<i>H</i>	<i>M</i>			

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

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.

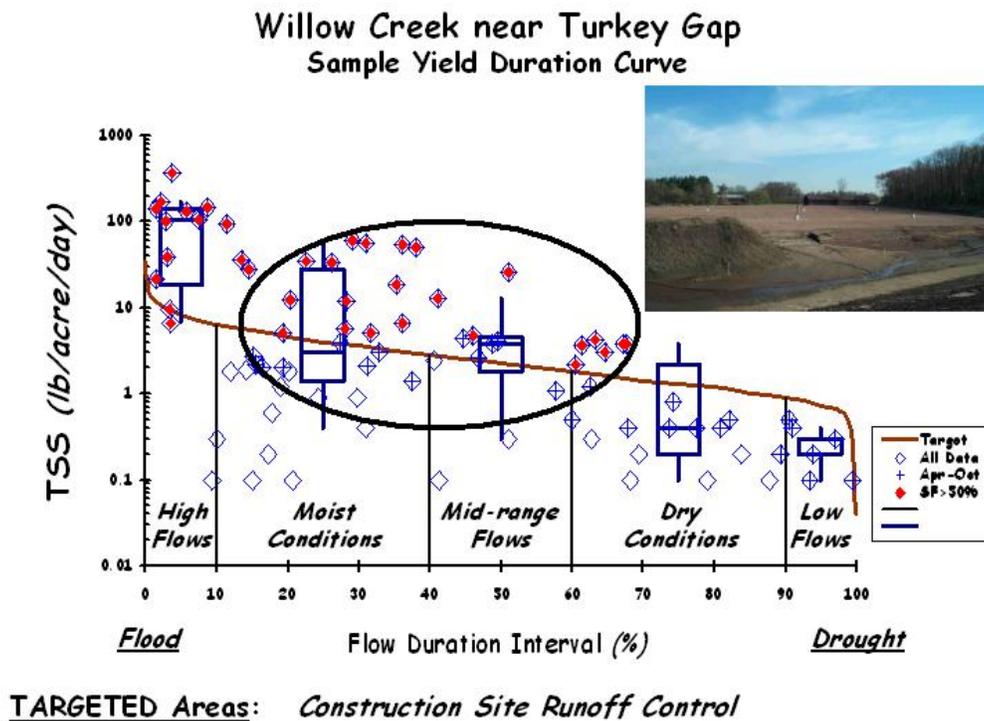
5. CONNECTING TO IMPLEMENTATION AND RESULTS

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 WWTP 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 site construction BMPs, as illustrated in Figure 5-1. For agricultural areas, appropriate implementation efforts might include activities such as the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Program (CREP).

Appendix E 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



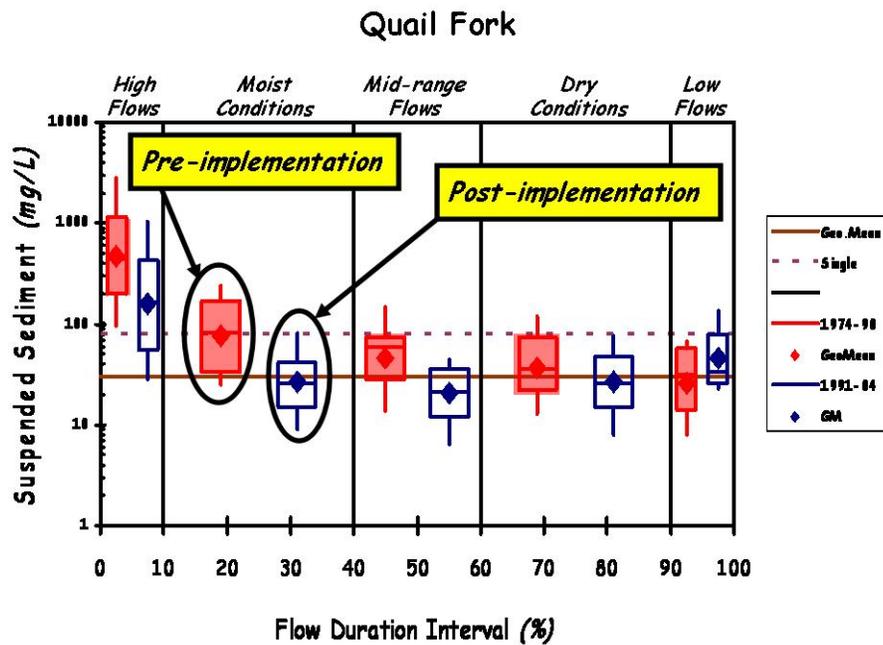
A common challenge faced by TMDL practitioners is explaining how allocations translate into potential actions. Table 5-1 uses a duration curve framework to summarize TMDL targets in a way that highlights implementation opportunities. Figure 5-2 illustrates how a duration curve framework can be used to 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	

Notes: 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 Chinnners Swamp).

The full TMDL document, available at:

http://www.scdhec.net/eqc/water/tmdl/pubs/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.

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:

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

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

8-digit HUCs with impaired streams. All USGS gage stations upstream and downstream of the subwatersheds with 303(d)-listed WQM stations will be identified.

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.

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

Where:

$$\text{unit conversion factor} = 37,854,120 \text{ 100-ml/million gallons (mg)}$$

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.

$$WLA \text{ (cfu/day)} = WQS * flow * unit \text{ conversion factor}$$

$$\text{Where: } WQS = 400 \text{ cfu/100ml}$$

$$flow \text{ (mgd)} = \text{permitted flow or design flow (if unavailable)}$$

$$unit \text{ conversion factor} = 37,854,120 \text{ 100-ml/mg}$$

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.

$$LA = TMDL - MOS - \sum WLA$$

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 ($24,465,525 \text{ ml*s} / \text{ft}^3*\text{day}$). 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 $24,465,525 \text{ ml*s} / \text{ft}^3*\text{day}$. 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.

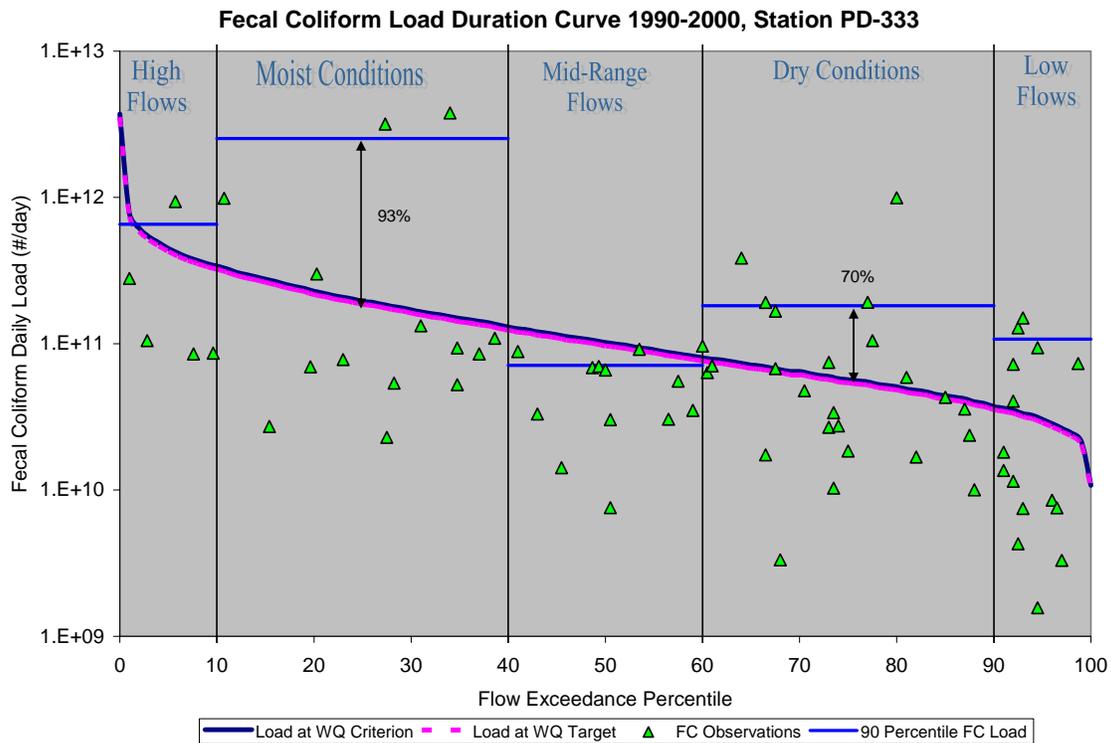
Table 5-1 Estimated Existing Fecal Coliform Loading for Station PD-333 (Hills Creek with Critical Condition Highlighted)

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: $WQS = 400\ cfu/100ml$

$flow\ (cfs) = permitted\ flow$

$unit\ conversion\ factor = 37,854,120\ 100\text{-}ml/mg$

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 OSD 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 incorporate 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:

$$Average LA = average TMDL - MOS - \Sigma WLA$$

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 Pocatigo 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

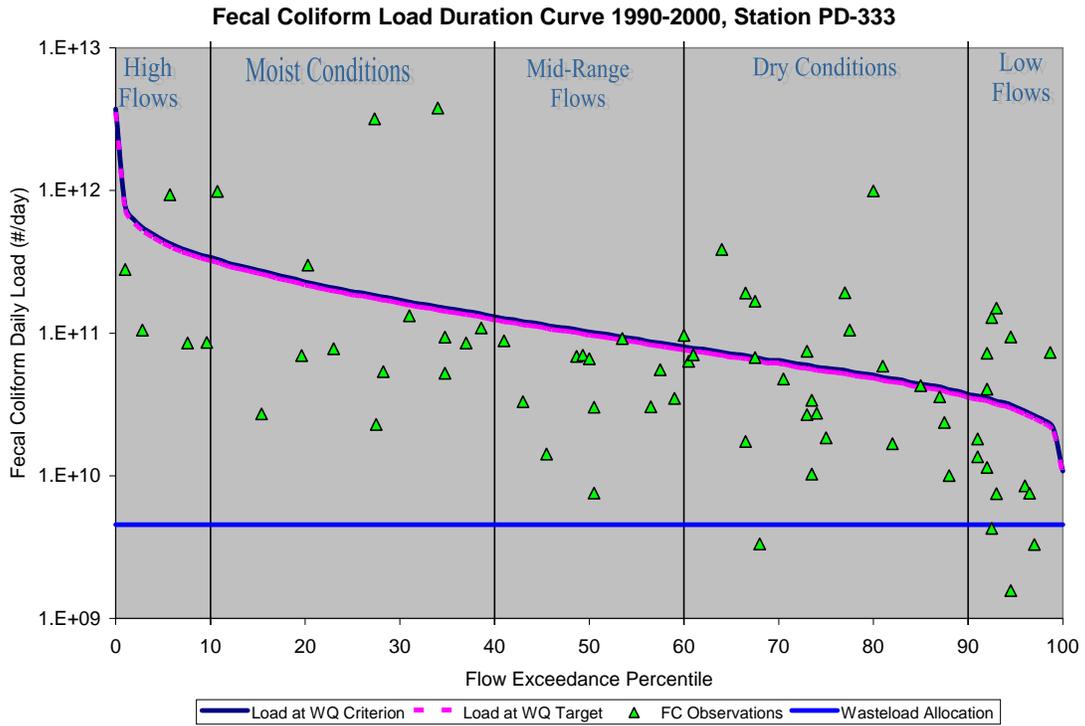
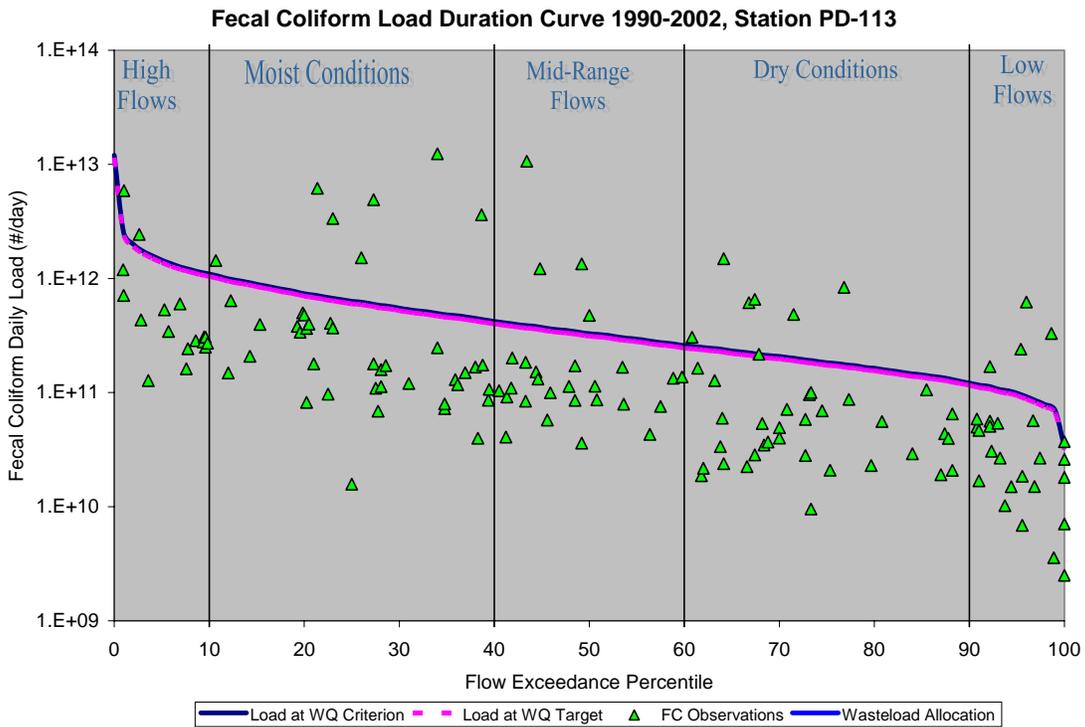


Figure 5-3 TMDL for PD-113 Lynches River



APPENDIX B

**Approaches for Developing a Daily Load Expression
for TMDLs Computed for Longer Term Averages**

FACT SHEET

Concentration Based Total Maximum Daily Loads

WATERBODY TYPE	Non-tidal rivers, streams, creeks and lakes
POLLUTANTS	Bacteria, sediments, phosphorus, nutrients and metals
WATER QUALITY CRITERIA	Narrative, never to exceed, etc.
MINIMUM DATA NEEDS	Water column observations, hydrology, bathymetry / land use

B1. OVERVIEW

The objective of the Total Maximum Daily Load (TMDL) program is to quantify the pollutant load that can enter an impaired waterbody and assure that all applicable water quality standards are attained and maintained. This pollutant load must be expressed as a “*daily load*.” The initial choice of an analytical approach to the calculation of this “*daily load*” is dependent upon a number of factors:

Considerations for Selecting an Approach for Daily Load Calculation

- How is the water quality standard expressed (e.g., never to exceed, an average, etc.);
- What is the specific averaging period selected (e.g., annual, seasonal, monthly, etc.);
- What is the availability and quality of data being used to develop the TMDL;
- What are the sources of the pollutant entering the waterbody (e.g., point, non-point);
- Which The analytical tool (e.g., empirical methods, reference watershed approach, duration curve, steady state model, deterministic model, etc.) used for developing a particular type of TMDL.

Consideration of the analytical tool is critical, because certain analytical/modeling methods may not be applicable to a translation approach (for instance, those simpler modeling approaches that do not easily lead to some form of a quantitative “*daily*” analysis).

The purpose of this series of fact sheets is to provide a technically sound approach TMDL practitioners can use to develop “*daily load expressions*” from TMDLs (completed or in process), which were calculated using averaging periods greater than daily (e.g., annual, monthly, seasonal, etc). Linkages with longer (“*non-daily*”) averaging periods may be needed to demonstrate consistency with the applicable water quality criteria. Additionally, “*non-daily*” calculations may be needed to provide a meaningful connection with implementation efforts, such as permits or nonpoint source Best Management Practices (BMPs), where other averaging periods provide the primary basis for water quality-based control strategies. However, all final TMDL submissions must contain a “*daily load*” component. This fact sheet presents an approach for translating allocations developed in concentration based TMDLs computed for non-daily averaging periods to a daily load expression.

Numeric water quality standards have a duration component, typically expressed as a specific average concentration or value that should not be exceeded at any time. 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. As an example, waters designated for support of semi-permanent warm water fish life in South Dakota must not exceed a daily maximum of 158 mg/L total suspended solids (TSS).

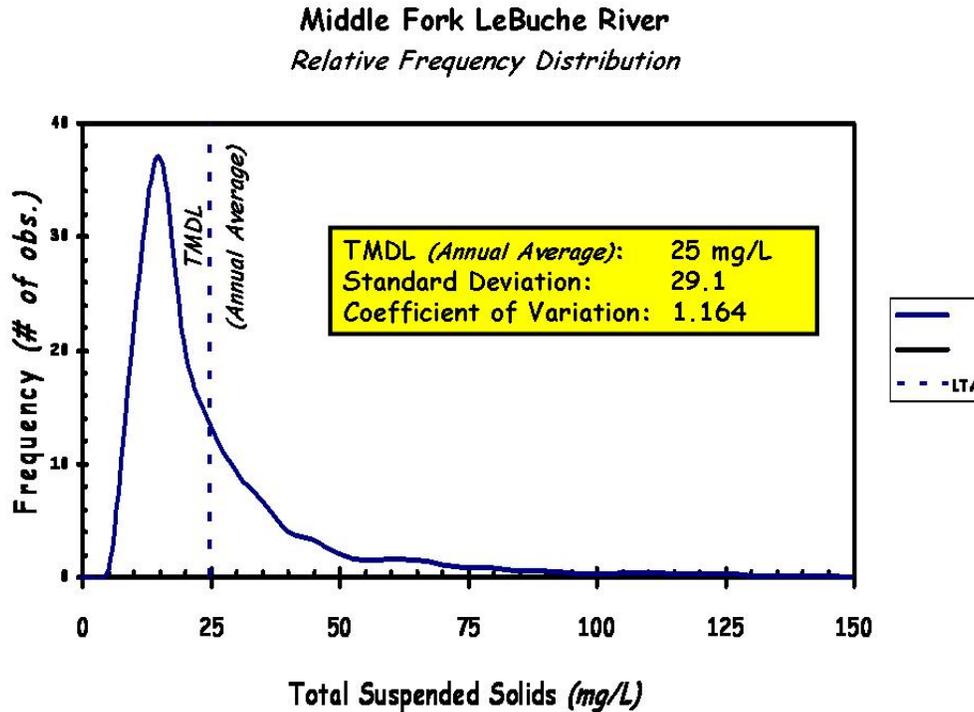
Additional considerations are necessary to set daily TMDL targets for numeric water quality criteria with averaging periods other than daily (e.g., 30-day geometric mean for bacteria). These considerations include TMDLs based on narrative standards that do not specify any unit measure or averaging period.

The following sections describe a technical framework for development of “*daily loads*”, which accounts for the variable nature of water quality that results from different flow conditions, seasonality, and source inputs. The framework starts with a discussion of concentration-based TMDLs, where statistical methods that consider patterns and variability can be used to make connections. The framework then expands into other potential methods to develop “*daily load expressions*.”

B2. BASIC PRINCIPLES

One approach towards TMDL development relies on concentration-based targets expressed as monthly, seasonal, or annual average values. Figure B-1 illustrates an example TMDL developed to attain the water quality criteria of an annual average concentration of 25 mg/L total suspended solids (TSS). Figure B-1 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-2. Frequency – Concentration Display of WQS Attainment Conditions



Based upon the shape of the frequency-concentration curve, data can be described in terms of a particular type of statistical distribution. Choices often include a normal distribution (bell-shaped), log-normal distribution (positively skewed), or other variations on the log-normal distribution.

The use of log-normal frequency distributions with environmental data is not a new concept. Air quality analysts have applied log-normal distributions for years in assessing patterns. Similarly, hydrologists have employed log-normal distributions in evaluating stream flow data. EPA’s “*Technical Support Document for Water Quality-Based Toxics Control*” (1991 TSD) utilizes log-normal distributions to determine maximum daily and monthly average effluent limits, based on achieving a long-term average (LTA) target and an understanding of variability.

B3. CONNECTING LONG-TERM AVERAGE TARGETS TO DAILY LIMITS

TMDLs can be developed using a variety of methods. Depending on the applicable water quality standards, the primary target for a particular TMDL may be expressed using a “non daily” time frame. Monthly, seasonal, or annual averaging periods may be entirely appropriate to ensure that beneficial uses are protected and water quality standards attained. However, a daily expression of the pollutant allocation must also be computed and included in the final submission to EPA.

To demonstrate an approach for translating a “*non-daily*” concentration based TMDL allocation to a daily expression, this fact sheet will present an example for a TMDL developed for Total Suspended Solids (TSS).

Impairments due to sediment represent approximately eight percent of all §303(d) listings in the nation. Because problems associated with excessive sediment loading are often long-term or chronic, such as degraded fish habitat or decreased reservoir capacity, sediment targets are not often developed for a daily time frame. Examples of commonly used sediment targets include monthly or annual sediment loading rates or a monthly average in-stream TSS concentration.

Sediment loading is highly variable with daily loads sometimes differing by orders of magnitude. Often, a large portion of a long-term sediment load is the result of a limited number of infrequent but major erosion-producing events carrying large amounts of sediment to the receiving water. Providing longer-term allocations such as monthly or annual loads provides an “*averaging period*” to allow for the variability of sediment loads. TMDLs also rely on longer-term allocations to account for the inherent complexity of sediment behavior and the associated difficulty of analyzing and modeling the processes. Because sediment erosion, delivery and in-stream transport processes are difficult to simulate, cumulative loads estimated over longer time frames by modeling or other analyses are more reliable than estimated daily loads.

Using a statistical framework, such as a log-normal or other distribution, a set of values covering the entire range can be projected from the data. Correspondingly, limits can be set at a specified probability of occurrence (e.g., a 1-day recurrence interval).

The 1991 TSD provides one approach, which illustrates a way to identify a target maximum daily concentration based on a coefficient of variation and the assumption of a log-normal distribution. The equation for determining the maximum daily limit (MDL) described in the TSD (Section 5-4, Box 5-2, Step 4) is as follows:

$$MDL = LTA * e^{[z\sigma - 0.5\sigma^2]}$$

where:

- MDL:** Maximum daily limit
- LTA:** Long-term average
- z:** z-score associated with target recurrence interval
- σ^2 :** $\ln(CV^2 + 1)$
- CV:** Coefficient of variation

Details regarding the mathematics used to derive this equation are described in the TSD. The z-score is sometimes called the “*standard score*” for normal distributions because it provides a useful way to compare sets of data with different means and standard deviations.

The z-score for an item (or a particular recurrence interval) indicates how far and in what direction that item deviates from its distribution’s mean (expressed in units of its distribution’s standard deviation). For instance, a z-score of +1.0 indicates that item (or recurrence interval) is one standard deviation in the positive direction from the mean. Z-scores are published in basic statistical reference tables and are often included as a spreadsheet function [e.g., NORMSINV(y) in Excel[®]].

Using this relationship, the TSD constructed a table of “LTA to MDL” multipliers for several recurrence interval / coefficient of variation combinations. Table B-1 provides a summary of these multiplier values for several averaging periods used in TMDL development (e.g., 30-day, 60-day ...365-day).

These averaging periods are also expressed as a recurrence interval in order to identify the appropriate z-score for use in the TSD equation. For example, the daily maximum of a 30-day averaging period equates to a 96.8% recurrence interval [e.g., (30/31)% or (k/k+1)% where k is the number of averaging period days] with a corresponding z-score of 1.849. If the coefficient of variation for a parameter is 1.0, the multiplier to convert the long-term average (LTA) to a maximum daily limit (MDL) is 3.30 (*Note*: key boxes for this combination are shaded in Table B-1).

Table B-1. Multipliers – Long-Term Average to Maximum Daily Limit

Averaging Period (days)	Recurrence Interval	Z-Score	Coefficient of Variation								
			0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8
30	96.8%	1.849	1.41	1.89	2.39	2.87	3.30	3.67	3.99	4.26	4.48
60	98.4%	2.135	1.50	2.11	2.80	3.50	4.18	4.81	5.37	5.87	6.32
90	98.9%	2.291	1.54	2.24	3.05	3.91	4.76	5.57	6.32	7.00	7.62
120	99.2%	2.397	1.58	2.34	3.24	4.21	5.20	6.16	7.06	7.89	8.66
180	99.4%	2.541	1.62	2.47	3.51	4.66	5.87	7.06	8.20	9.29	10.3
210	99.5%	2.594	1.64	2.52	3.61	4.84	6.13	7.42	8.67	9.86	11.0
365	99.7%	2.778	1.70	2.71	4.00	5.51	7.15	8.83	10.5	12.13	13.7

B4. SUMMARY

Statistical methods offer a way to connect targets that use multiple averaging periods. The 1991 TSD provides one approach, which considers patterns and variability in a consistent manner. The method is based on the assumption that water quality data follow a log-normal distribution. Identification of a maximum daily value is based on the recurrence interval associated with the long-term averaging period and a coefficient of variation that reflects the data.

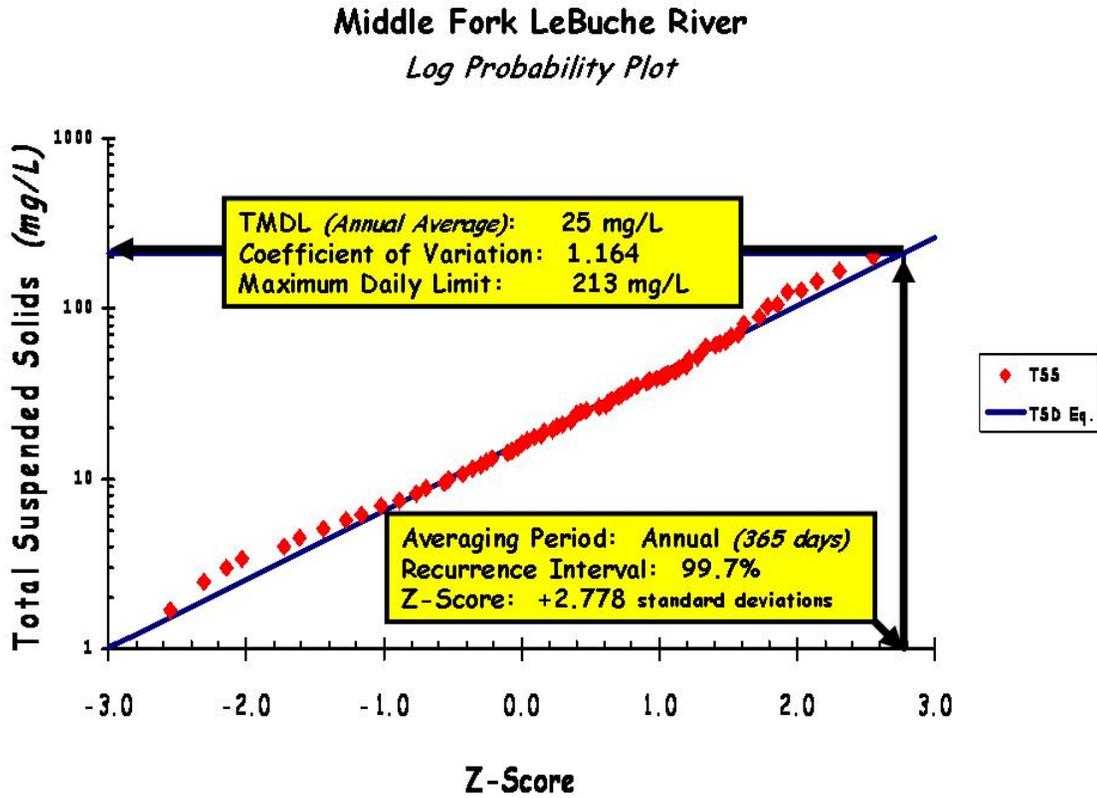
Figure B-3 graphically illustrates a “*log probability plot*” of the TSD equation using data that reflects conditions associated with attainment of the water quality standards and the TMDL. The x-axis is expressed as the z-score of a normal probability distribution; the y-axis displays concentrations on a logarithmic scale. A probability plot is one method that can be used to check the assumption of log-normality. If the data follow the pattern of a log-normal distribution, they will fall approximately along a straight line, as shown in Figure B-3.

Figure B-3 also shows translation of the recurrence interval for an annual averaging period (e.g., 365 days) to the corresponding maximum daily concentration limit. Identification of the multiplier is depicted in tabular form below the graph. The format is similar to Table B-1 with the last column modified to reflect the coefficient of variation associated with attainment conditions for the Middle Fork LeBuche River.

The last step is to convert the maximum daily concentration limit to a “*daily load*.” This can be accomplished in several ways. The simplest approach is to use the flow data alone. For instance, the Middle Fork LeBuche River annual daily average flow is 107 cubic feet per second (cfs) with a 1-day maximum recurrence flow of 907 cfs. Using appropriate conversion factors, the total maximum daily load for TSS is 521 tons per day at the 1-day maximum recurrence flow. While this approach requires less data and analysis, practitioners should recognize that it is intended to only address one set of critical conditions. Similar to use of the 7Q10 to address low-flow concerns, this method is most appropriate for TMDLs intended to solve problems associated with high flow situations.

Note that the maximum “*daily load*” and annual average concentration target work together. Multiple averaging periods provide a way to achieve both long-term program objectives and focus implementation efforts while avoiding short term problems.

Figure B-3. Log Probability Display – TMDL Target Conditions



Averaging Period (days)	Recurrence Interval	Z-Score	Coefficient of Variation								
			0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.164
30	96.8%	1.849	1.41	1.89	2.39	2.87	3.30	3.67	3.99	4.26	3.61
60	98.4%	2.135	1.50	2.11	2.80	3.50	4.18	4.81	5.37	5.87	4.70
90	98.9%	2.291	1.54	2.24	3.05	3.91	4.76	5.57	6.32	7.00	5.43
120	99.2%	2.397	1.58	2.34	3.24	4.21	5.20	6.16	7.06	7.89	5.99
180	99.4%	2.541	1.62	2.47	3.51	4.66	5.87	7.06	8.20	9.29	6.84
210	99.5%	2.594	1.64	2.52	3.61	4.84	6.13	7.42	8.67	9.86	7.19
365	99.7%	2.778	1.70	2.71	4.00	5.51	7.15	8.83	10.50	12.13	8.53

APPENDIX C

**Approaches for Developing a Daily Load Expression
for TMDLs Computed for Longer Term Averages**

FACT SHEET

Duration Curve Total Maximum Daily Loads

WATERBODY TYPE	Non-tidal rivers, streams, creeks and lake tributaries
POLLUTANTS	Bacteria, sediments, nutrients and metals
WATER QUALITY CRITERIA	Narrative, never to exceed, etc.
MINIMUM DATA NEEDS	Water column observations, hydrology

C1. OVERVIEW

The objective of the Total Maximum Daily Load (TMDL) program is to quantify the pollutant load that can enter an impaired waterbody and assure that all applicable water quality standards are attained and maintained. This pollutant load must be expressed as a “*daily load*.” The initial choice of an analytical approach to the calculation of this “*daily load*” is dependent upon a number of factors:

Considerations for Selecting an Approach for Daily Load Calculation

- How is the water quality standard expressed (e.g., never to exceed, an average, etc.);
- What is the specific averaging period selected (e.g., annual, seasonal, monthly, etc.);
- What is the availability and quality of data being used to develop the TMDL;
- What are the sources of the pollutant entering the waterbody (e.g., point, non-point);
- Which analytical tool (e.g., empirical methods, reference watershed approach, duration curve, steady state model, deterministic model, etc.) is used for developing a particular type of TMDL.

Consideration of the analytical tool is critical, because certain analytical/modeling methods may not be applicable to a translation approach (for instance, those simpler modeling approaches that do not easily lead to some form of a quantitative “*daily*” analysis).

The purpose of this series of fact sheets is to provide a technically sound approach TMDL practitioners can use to develop “*daily load expressions*” from TMDLs (completed or in process), which were calculated using averaging periods greater than daily (e.g., annual, monthly, seasonal, etc). Linkages with longer (“*non-daily*”) averaging periods may be needed to demonstrate consistency with the applicable water quality criteria. Additionally, “*non-daily*” calculations may be needed to provide a meaningful connection with implementation efforts, such as permits or nonpoint source Best Management Practices (BMPs), where other averaging periods provide the primary basis for water quality-based control strategies. However, all final TMDL submissions must contain a “*daily load*” component. This fact sheet describes the duration curve method and its utility as a tool to translate TMDLs computed for “*non-daily*” averaging periods to a daily load expression.

Numeric water quality standards have a duration component, typically expressed as a specific average concentration or value that should not be exceeded at any time. When the duration is expressed as a daily average or “*never to exceed*” criterion, the daily target is that value explicitly stated in the applicable water quality standards. As an example, waters designated for support of semi-permanent warm water fish life in South Dakota must not exceed a daily maximum of 158 mg/L total suspended solids (TSS). Additional considerations are necessary to set daily TMDL targets for numeric water quality criteria with averaging periods other than daily (e.g., a 30-day geometric mean for bacteria or a growing season average for phosphorus). These considerations also apply to TMDLs based on narrative standards that do not specify any unit measure or averaging period.

A number of approaches towards TMDL development result in a single value. Several are designed to address only a single flow condition (e.g. a one-day high flow or 7Q10 low flow). Other methods are derived from an analysis of aggregated data (e.g. annual average flow conditions), and may be of limited value in guiding implementation efforts. The following sections describe a technical framework for development of “*daily loads*”, 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.

This fact sheet starts with an overview of the duration curve method. Basic application of duration curves in TMDL development is then discussed with a focus on several key elements, notably the loading capacity, allocations, and margin of safety (MOS). In using the duration curve method, it is important to keep in mind EPA’s view that States *apply the entire duration curve* in the context of a TMDL, thus providing “*daily load expressions*” based on flow conditions.

C2. BASIC PRINCIPLES

States and EPA have used flow duration curves to support water quality assessments and the development of TMDLs, including the derivation of loading capacities, wasteload allocations, and load allocations. The duration curve framework relies on hydrologic conditions as a general indicator to provide information on water quality patterns, relevant watershed processes, important sources or contributing areas, and key delivery mechanisms. This allows for enhanced targeting, both in TMDL development and implementation.

Flow and Load Duration Curves

Flow duration curves use hydrologic data from stream gages to look at the cumulative frequency of historic flow data over a specified period. A 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. The full range of stream flows is considered. Low flows are exceeded a majority of the time, whereas floods are exceeded infrequently. Duration curve analysis thus identifies intervals, which can be used as a general indicator of hydrologic condition (i.e., wet versus dry and to what degree). A basic flow duration curve typically uses daily average discharge rates, which are sorted from the highest value to the lowest (*Figure C-1*).

Using the convention illustrated in *Figure C-1*, flow duration intervals are expressed as a percentage along the x-axis. Zero corresponds to the highest stream discharge in the record (i.e., flood conditions), while 100 corresponds to the lowest (i.e., drought conditions). Thus, a flow duration interval of ten associated with 1,100 cubic feet per second (cfs) implies that ten percent of all observed daily average stream discharge values equal or exceed 1,100 cfs. Similarly, a flow duration interval of ninety associated with 97 cubic feet per second implies that ninety percent of all observed daily average stream discharge values equal or exceed 97 cfs.

Load duration curves depict relationships between flow and water quality. Load duration curves identify critical hydrologic conditions (e.g., high flows, mid-range flows, low flows) during which the waterbody does not meet water quality standards for a particular pollutant. This information can then be used to define the TMDL loading capacity, load allocations and wasteload allocations. Load duration curves also provide water quality managers with information about potential pollutant loading mechanisms, enabling them to examine the major sources of pollutants for a particular waterbody.

The duration curve framework is particularly useful in providing a simple display that describes flow conditions under which water quality criteria are exceeded. Ambient water quality data, taken with some measure or estimate of flow on the sampling date, can be used to compute a daily load. By displaying these loads calculated from ambient water quality data and the flow on the sample date (expressed as a flow duration curve interval), a pattern develops that describes characteristics of the impairment. Loads that plot above the curve indicate an exceedance of the water quality criterion, while those below the load duration curve show compliance, as illustrated in *Figure C-2*.

C3. DURATION CURVE USE IN TMDL DEVELOPMENT

The duration curve framework is well suited as a tool to support TMDL development for several reasons. The use of flow data is an important factor in the determination of loading capacities. In addition, precipitation and 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). Recognizing the dynamic nature of stream systems, duration curves also provide a useful way to approach development of allocations and “margin of safety”, which are major components of a TMDL.

Loading Capacity

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. The following examples illustrate how flow duration curves are used to identify a loading capacity.

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. The flow duration curve for the Arkansas River based on daily average stream discharge data (shown previously in Figure C-1) 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 C-1. The loading capacity for the Arkansas River is shown in Figure C-3. 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 C-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.

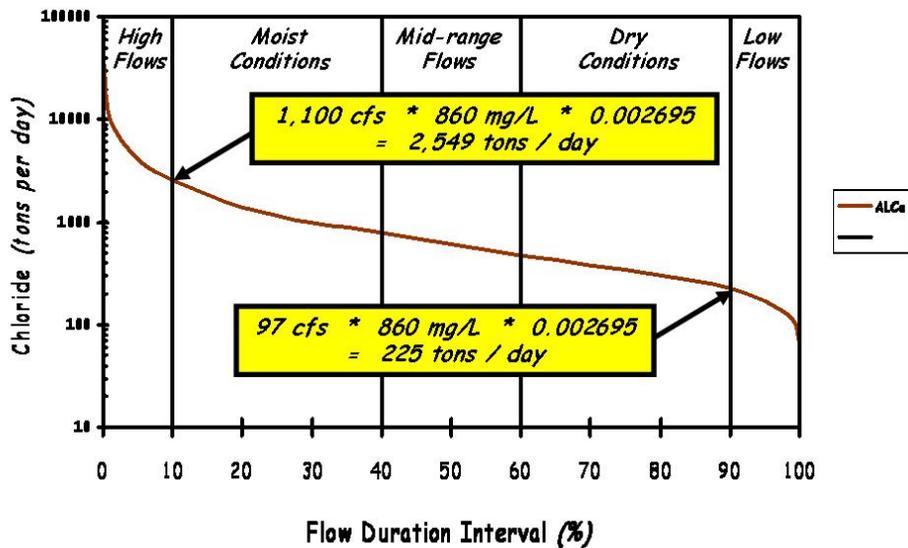
Table C-1. Calculation of Chloride Loads

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 C-3. Chloride Loading Capacity Using Duration Curve Framework

Arkansas River near Hutchinson

Load Duration Curve (Aquatic Life Criteria -- Acute)



USGS Gage 07143330 Duration Interval

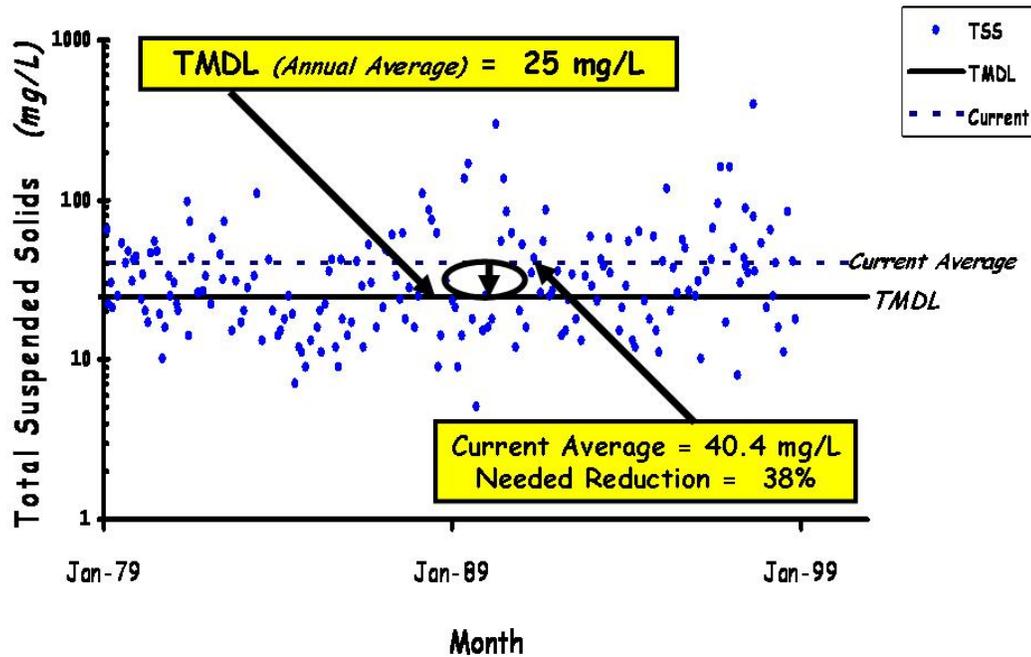
31,724 square miles

Sediment and Multiple Averaging Periods. Sediment concerns, which have long challenged TMDL practitioners, represent the type of problem where an array of different approaches can bring multiple averaging periods into the technical analysis. First, States typically do not have established numeric criteria for sediment, instead relying on narrative components in 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. These factors can vary due to the range of diverse landscapes found across the country. TMDL assessments must also 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) that could be used to establish categories of risk to fisheries. Alternatively, the “Protocol for Developing Sediment TMDLs” (EPA, 1999) indicates the appropriateness of using sediment or turbidity targets, which relate concentrations to stream flow. A target can be identified, based on the slope of a regression curve by plotting flow against concentrations or loads.

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 C-4 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 C-4 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 C-4. Concentration-Based TMDL
Middle Fork LeBuche River
TMDL versus Existing Conditions



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 C-1. The loading capacity for the

Middle Fork LeBuche River is shown in Figure C-5. 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 C-1 across the range of all daily average flows.

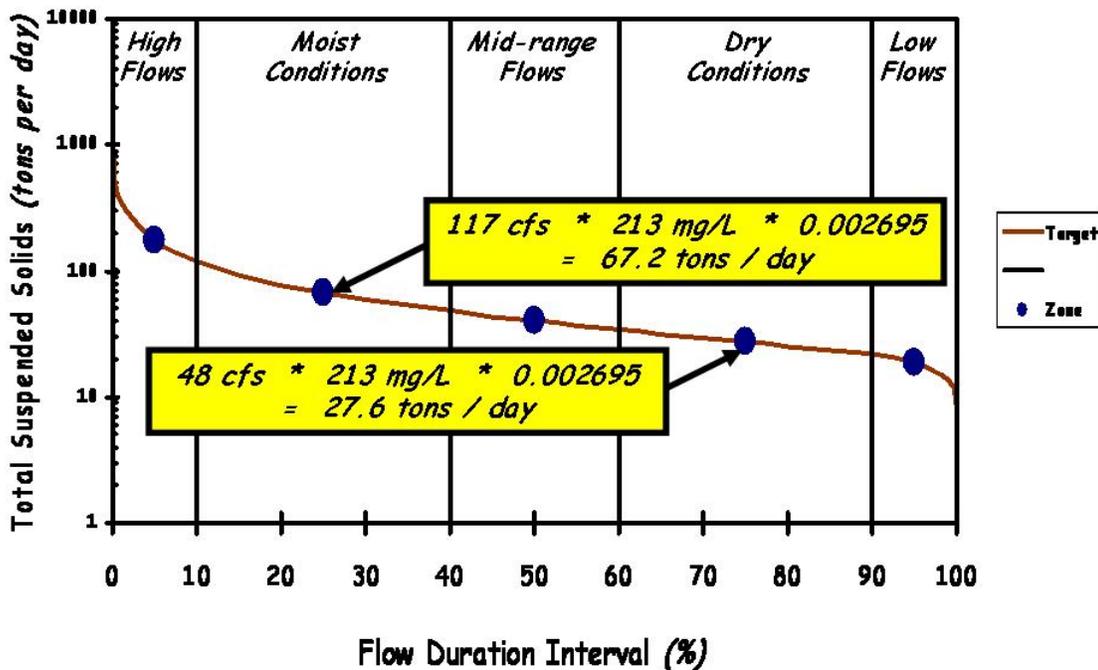
A continuous curve that represents the loading capacity has some logistical drawbacks. It is often easier to communicate information with a set of fixed targets. For this reason, critical points along the curve can be used as an alternative method to quantify the loading capacity, such as the mid-point of each zone (e.g., the 5th, 25th, 50th, 75th, and 95th percentiles).

A unique loading capacity for each duration curve zone allows the TMDL to reflect changes in dominant watershed processes that may occur under different flow regimes. For example, wastewater treatment plants or illicit discharges tend to exert a greater influence at low flows. A separate loading capacity for the low flow zone allows the TMDL to guide implementation efforts uniquely associated with these conditions. Similarly, combined sewer overflows (CSOs) may be of greater concern at high flows. A separate loading capacity enables the TMDL to serve as a meaningful guide for development and implementation of long term CSO control plans.

Figure C-5. TSS Loading Capacity Using Duration Curve Framework

Middle Fork LeBuche River

Load Duration Curve



Margin of Safety

Using a duration curve framework, an explicit MOS can be identified for each listed reach and corresponding set of flow zones. For example, a “margin of safety” can 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 MOS is provided. The MOS ensures that allocations will not exceed the load associated with the minimum flow in each zone. Because the allocations are a direct function of flow, accounting for potential flow variability is an appropriate way to address the “margin of safety”.

In summary, 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).

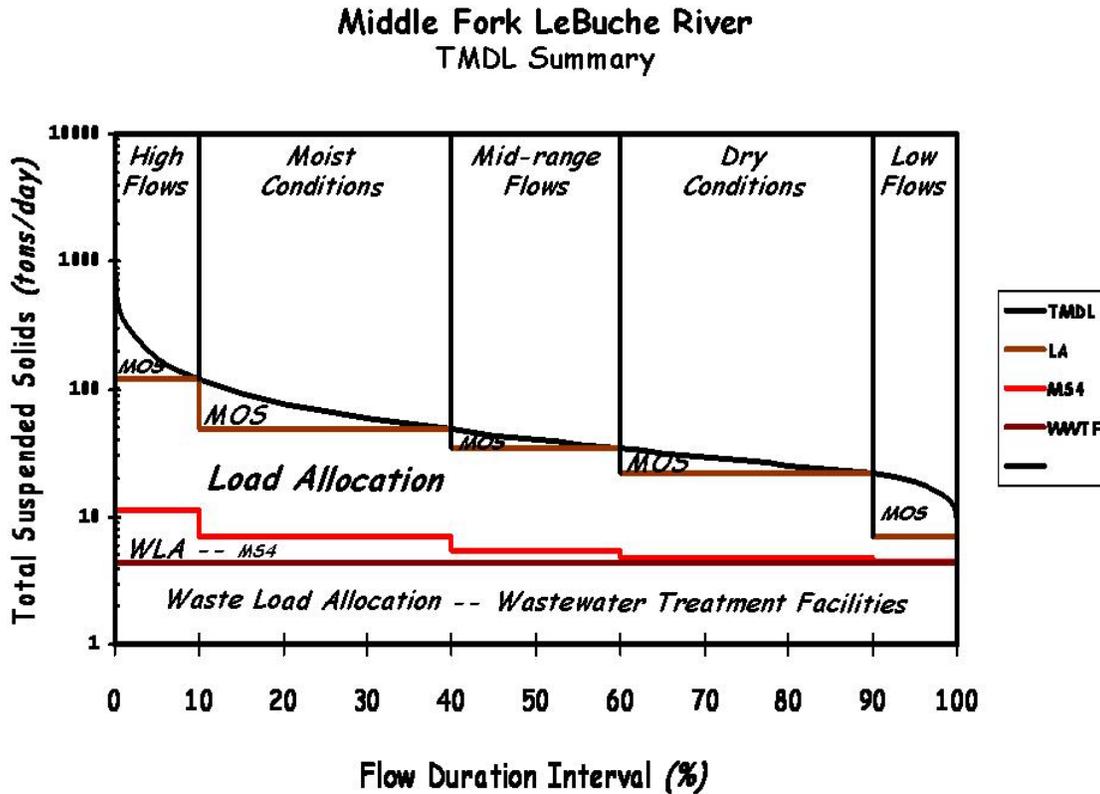
Allocations

Table C-2 summarizes the Middle Fork LeBuche TMDL 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). Figure C-6 illustrates the Middle Fork LeBuche River TMDL using a duration curve framework. Waste load allocations are specified for municipal treatment plants that reflect permit limits. In many cases, these WLAs are constant across all flow conditions. WLAs are also identified for MS4 storm water, which reflect increased loads under higher flow conditions. Similarly, loads allocations also increase with higher flows.

Table C-2. Middle Fork LeBuche River TMDL Using Duration Curve Framework

Segment ID	Name	TMDL Component	Duration Curve Zone <i>(expressed as tons per day)</i>					
			High	Moist	Mid	Dry	Low	
MFL-05	Middle Fork LeBuche River							
		TMDL	173.35	67.20	40.21	27.57	18.96	
		MOS	55.03	18.96	5.74	5.74	12.06	
		LA	106.19	41.35	29.08	17.07	2.38	
		City of Remdorf (WWTP)	WLA	3.92	3.92	3.92	3.92	3.92
		Village of Tulost (WWTP)	WLA	0.45	0.45	0.45	0.45	0.45
		City of Remdorf (MS4/P1)	WLA	5.51	1.68	0.65	0.26	0.10
	Village of Tulost (MS4/P2)	WLA	2.25	0.84	0.37	0.13	0.05	

Figure C-6. Middle Fork LeBuche River TMDL Using Duration Curve Framework



Connecting to “Non-Daily” Targets

The maximum “daily load” and long-term (or “non daily”) average target work together. The “daily load” portion of the TMDL addresses statutory language in §303(d); 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 C-3 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” required by §303(d).

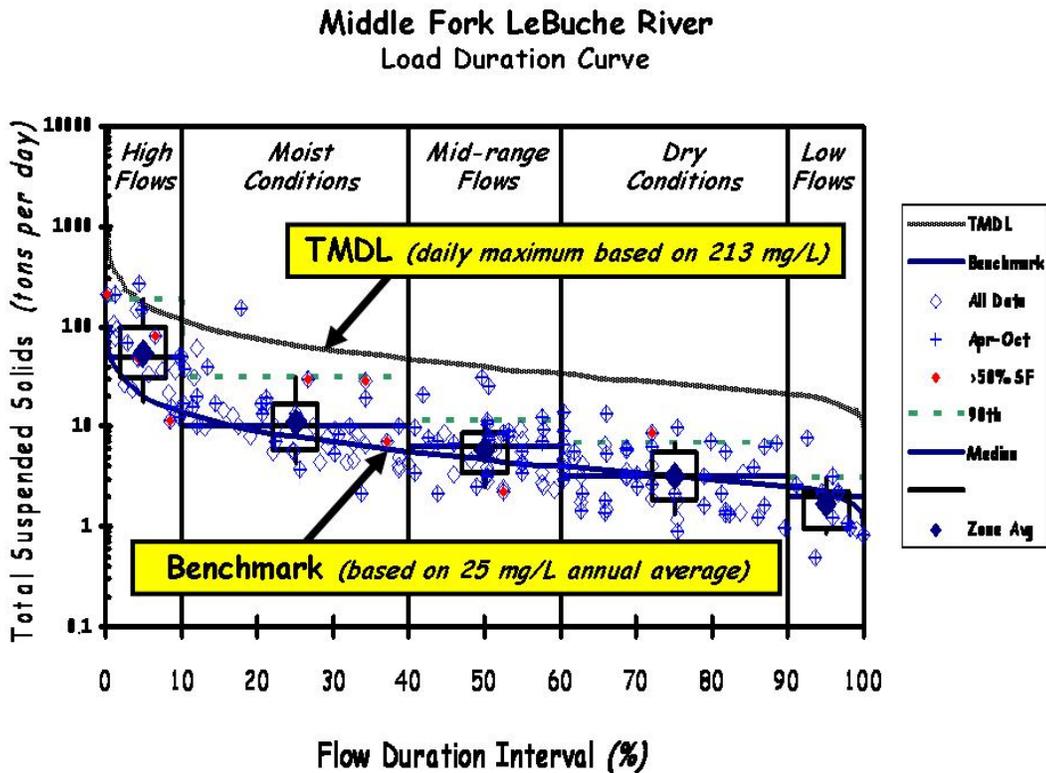
Table C-3. Middle Fork LeBuche River TMDL Summary

TMDL SUMMARY	Loads expressed as (<i>tons per day</i>)				
	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
Benchmark ²	20.35	7.89	4.72	3.24	2.22
Reduction Estimate ³	63%	27%	19%	0%	0%
Implementation Opportunities	<i>Post Development BMPs</i>				
	<i>Streambank Stabilization</i>				
	<i>Erosion Control Program</i>				
	<i>Riparian Buffer Protection</i>				<i>Municipal WWTP</i>
<p>Notes:</p> <ol style="list-style-type: none"> Expressed as a “<i>daily load</i>”; represents the upper range of conditions needed to attain and maintain applicable water quality standards Based on annual average target identified in the applicable water quality standards Developed using long-term fixed station ambient water quality monitoring data 					

Figure C-7 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 C-3, implementation opportunities are highlighted that correspond to the flow conditions best suited for the array of control options.

Figure C-7. Middle Fork LeBuche River TMDL Using Duration Curve Framework



C4. 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 D

Additional Examples of Using Load Duration Curve Approach to Develop Loading Capacity

Nutrients, Sediment, Bacteria

The duration curve framework is well suited as a tool to support TMDL development for several reasons. The use of flow data is an important factor in the determination of loading capacities. In addition, precipitation and 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). This technical appendix discusses basic application of duration curves in TMDL development with a focus on loading capacity.

Calculation of the loading capacity for impaired segments identified on the §303(d) list is an important first step. 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.

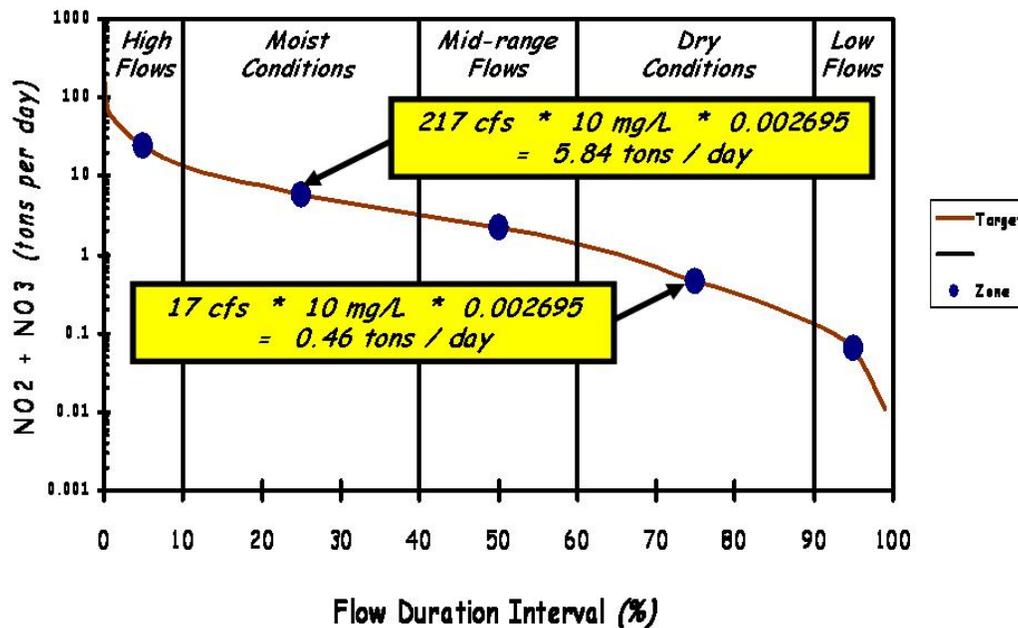
Flow patterns play a major role when considering loading capacities in TMDL development, regardless of the technical approach used. Duration curves, however, provide the added benefit of looking at the full range of flow conditions. The following examples illustrate how flow duration curves are used to identify a loading capacity.

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 in Appendix C). A loading capacity for nitrate in the Sangamon River is depicted in Figure D-1 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 D-1 across the range of all daily average flows.

Table D-1. Calculation of Nitrate 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 D-1. Nitrate Loading Capacity Using Duration Curve Framework
Sangamon River near Fisher
 Load Duration Curve



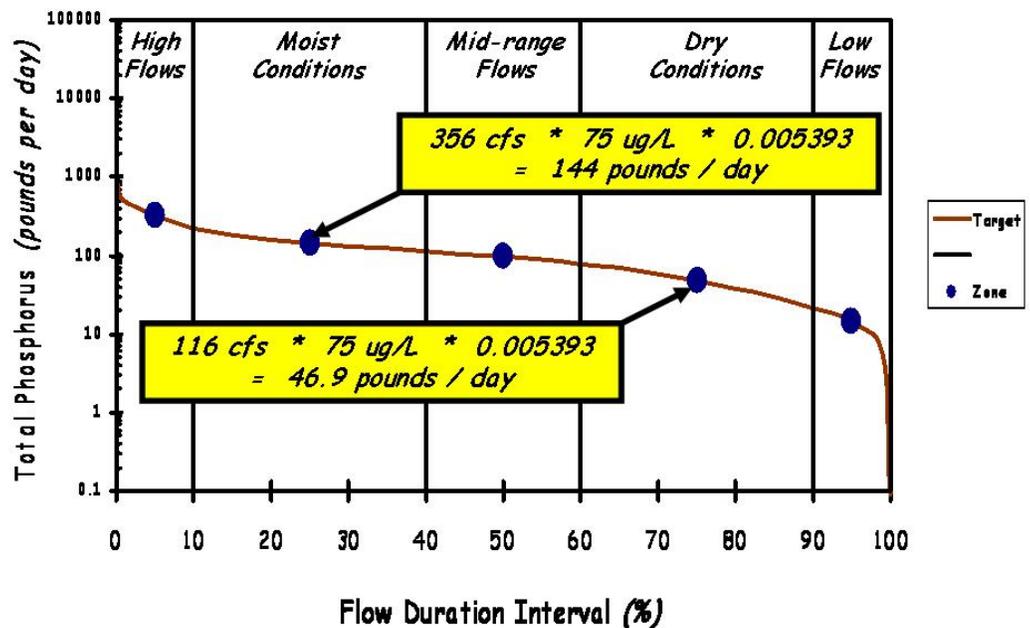
240 square miles

Figure D-2 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 D-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 D-2. Calculation of Phosphorus Loads

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

Figure D-2. Phosphorus Loading Capacity Using Duration Curve Framework
Portneuf River at Pocatello
 Load Duration Curve



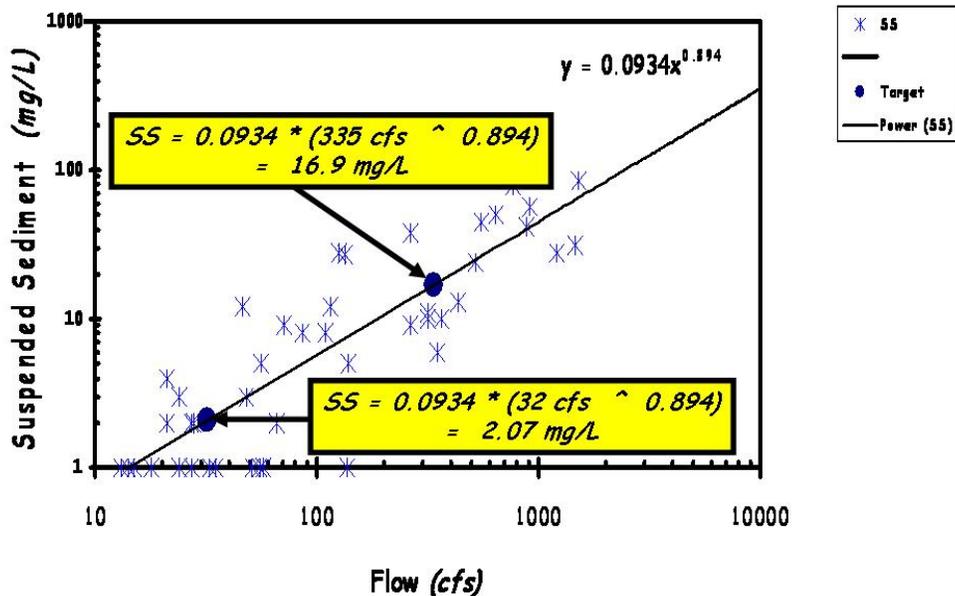
1,250 square miles

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 in 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. These factors can vary due to the range of diverse landscapes found across the country. TMDL assessments must also 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) that could be used to establish categories of risk to fisheries. With this approach, the process outlined to generate loading capacities described for nitrate and phosphorus (Figures D-1 to D-2) would be applied.

As an alternative, the “Protocol for Developing Sediment TMDLs” (EPA, 1999) indicates the appropriateness of using suspended sediment or turbidity targets, which relate concentrations to stream flow for appropriate reference streams to 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 D-3 illustrates an example rating curve for a reference stream.

Figure D-3. Example Sediment Rating Curve
Flat Brook
 Regression Analysis (1968 - 2001 Monitoring Data)

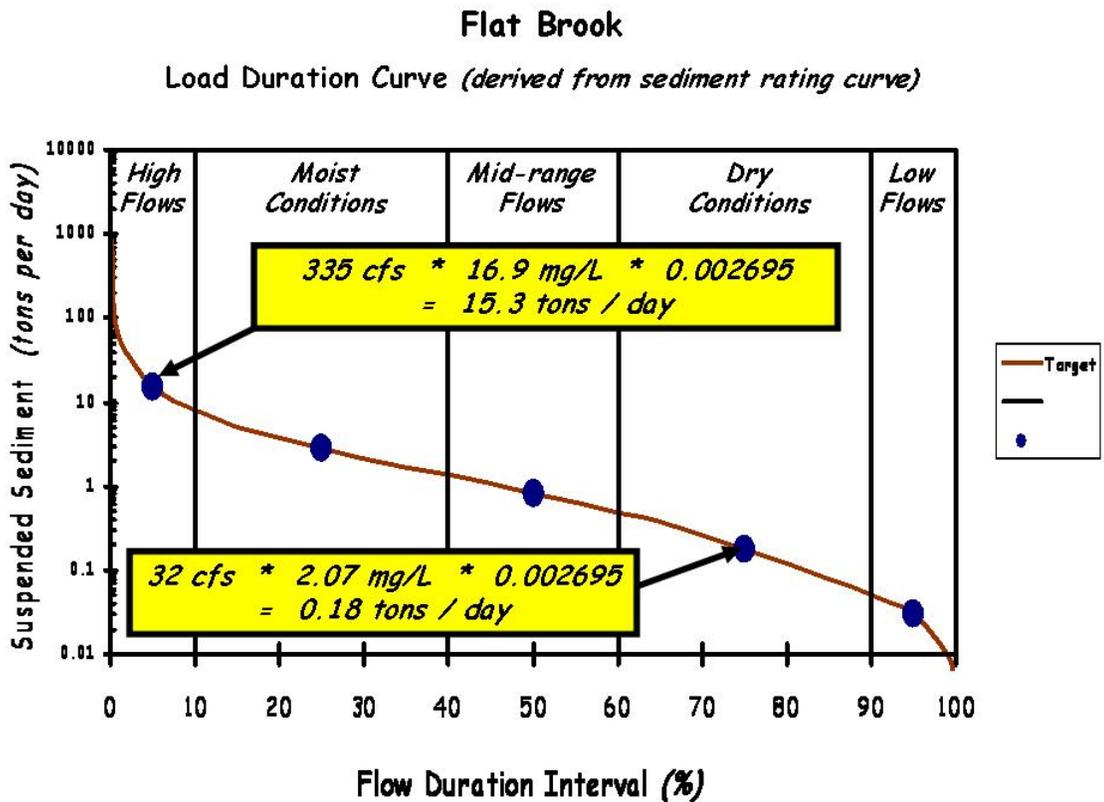


64 square miles

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 D-3. 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. 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 D-4. 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 D-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.

Table D-3. Calculation of Bacteria Loads

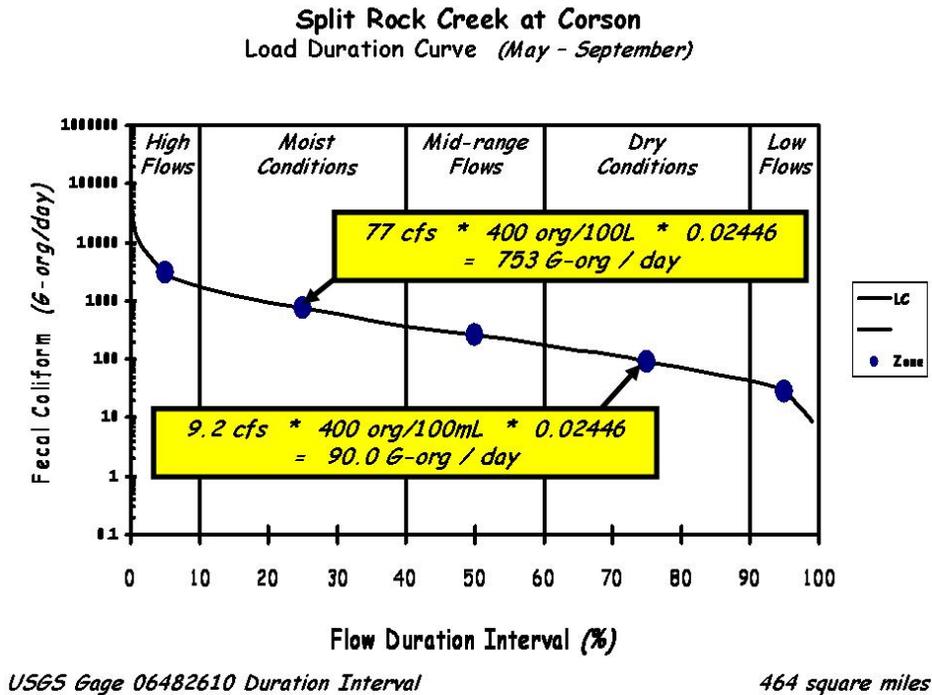
Load (org/day) = Concentration (org/100mL) * Flow (cfs) * Factor			
<i>multiply by 3785.2 to convert</i>	mL per gallon	→	org / 100 gallon
<i>divide by 100 to convert</i>		→	org / gallon
<i>multiply by 7.48 to convert</i>	gallon per ft ³	→	org / ft ³
<i>multiply by 86,400 to convert</i>	seconds per day	→	ft ³ / day
<i>divide by 1,000,000,000</i>	billion	→	G-org
<i>multiply by 0.02446 to convert</i>	(org/100mL) * ft³ / sec	→	G-org / day

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 September and May. Figure D-5 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.

The nature of the water quality criteria for bacteria presents a small challenge in terms of averaging periods. Many State water quality standards for pathogens consist of two criteria values: a 30-day or monthly geometric mean and an upper threshold to advise beach managers on closure decisions. 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).

Figure D-5. Bacteria Loading Capacity Using Duration Curve Framework



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.

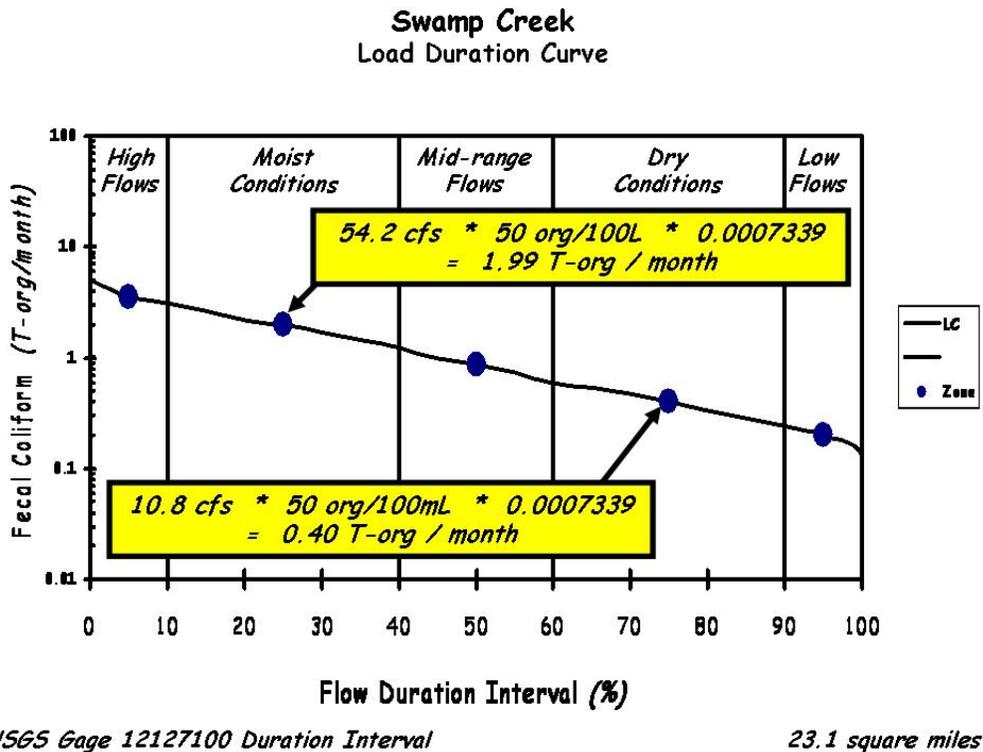
In order to ensure consistency with the geometric mean criterion, 30-day or monthly mean flows can also be used to identify loading capacities that supplement daily load targets. This approach offers a way to develop a quantitative analysis of seasonal variation indicative of the 30-day or monthly target in the water quality standards (i.e., larger loads in months with higher flows and smaller loads in months with lower flows). Table D-4 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 D-4.

As seen in Table D-4, 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 D-4 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 D-4). Figure D-6 shows the loading capacity curve for Swamp Creek using the frequency distribution of mean monthly flows.

Table D-4. 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
25 th %	55.5	51.5	38.2	29.7	15.5	8.0	6.0	5.3	7.0	9.1	24.4	55.6
10 th %	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 D-6. Bacteria Loading Capacity Using Duration Curve Framework



APPENDIX E

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.

E1. “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.

E2. 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.

E3. 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 permittees) 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 E-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 E-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 E-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 E-1. Duration Curve as General Indicator of Hydrologic Condition

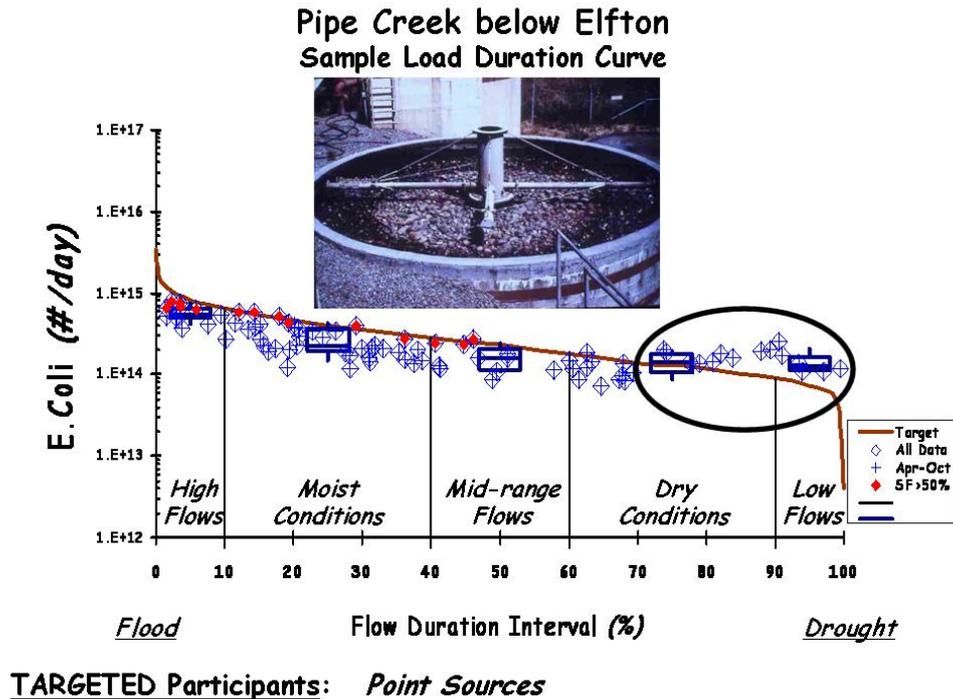


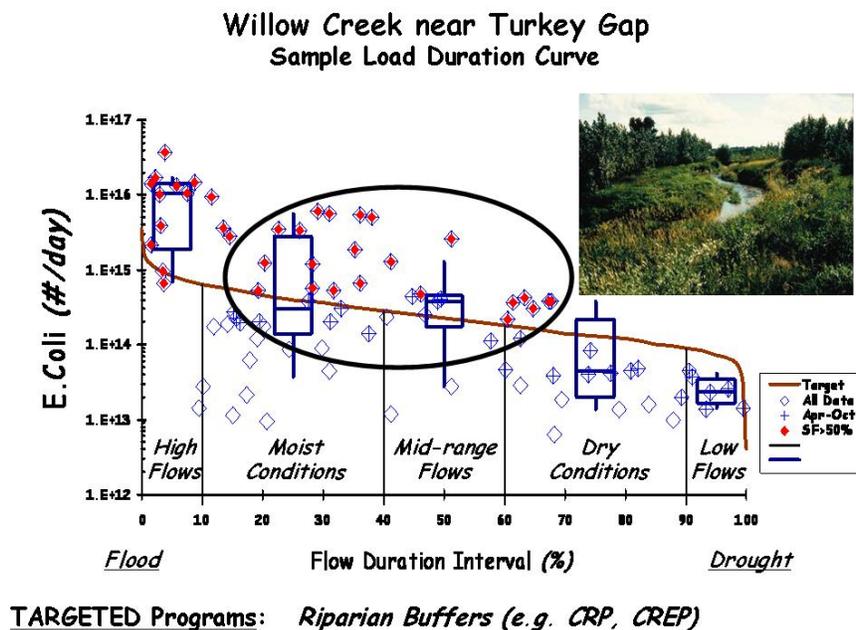
Figure E-2 illustrates the added value duration curves can provide by highlighting potential contributing areas. As seen in this hypothetical example, the target is met when the hydrologic condition of the watershed is above a flow duration interval of 70 (generally low flow and dry conditions). Problems 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 E-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 E-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 E-2), this might include activities such as the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Program (CREP).

Figure E-2. Duration Curve with Contributing Area Focus



The focus on contributing areas is further illustrated with another hypothetical example, shown in Figure E-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 E-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 E-3. Duration Curve with Contributing Area Focus

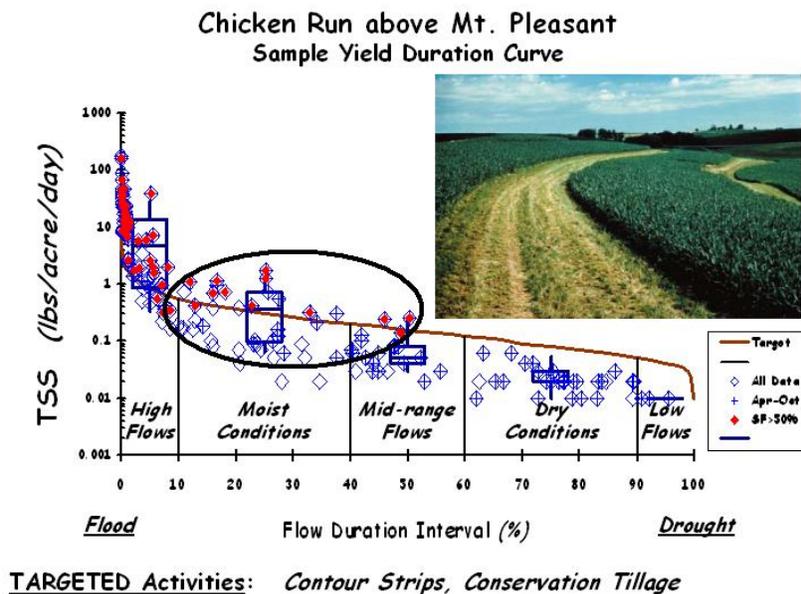
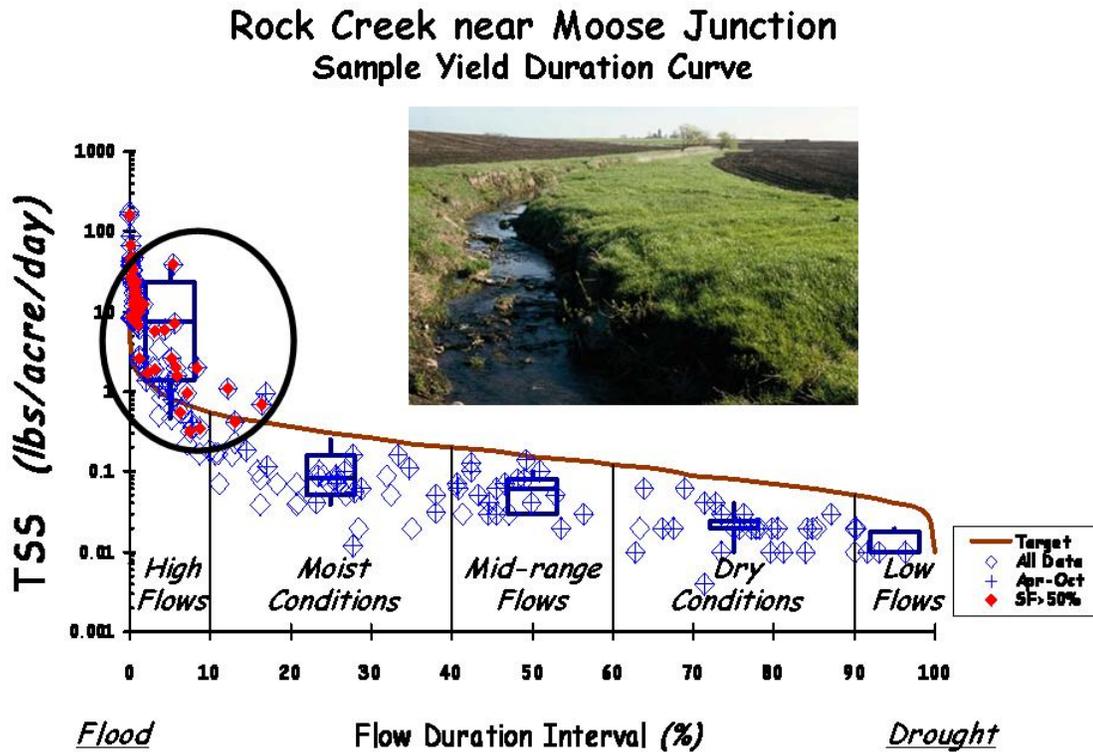


Figure E-4 illustrates another hypothetical example, where transport and delivery mechanisms that occur under high flow conditions typically include stream bank erosion and channel processes. Targeted areas for water quality improvement might consider bank stabilization efforts. For urban watersheds,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



Figure E-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 E-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 E-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 E-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 E-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 E-1. Example Management Practice / Hydrologic Condition Considerations

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

Figure E-5. Bacteria Loading Capacity Using Duration Curve Framework

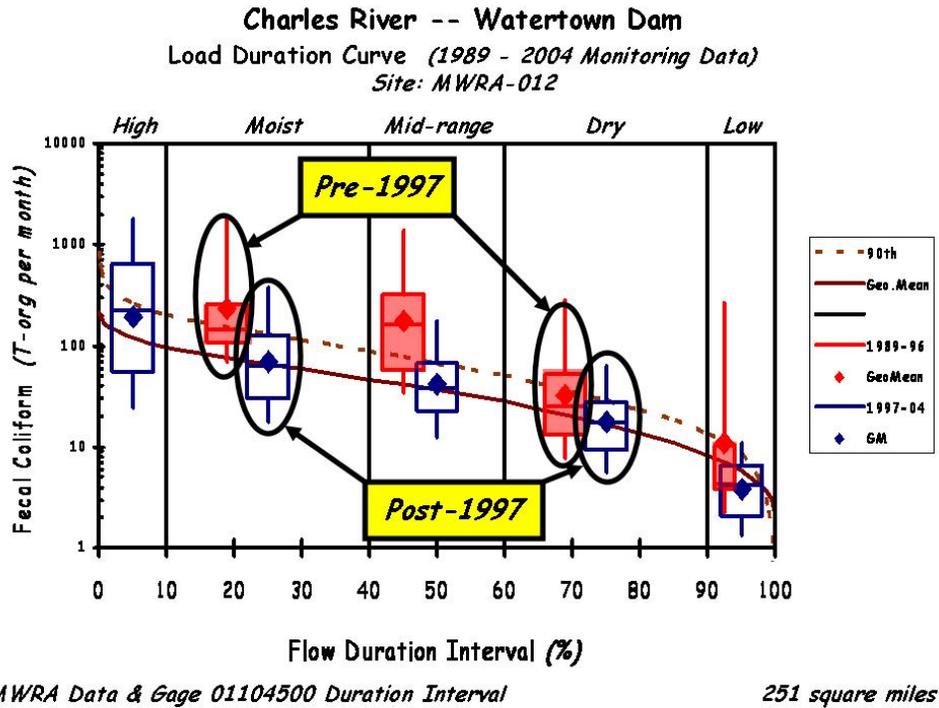
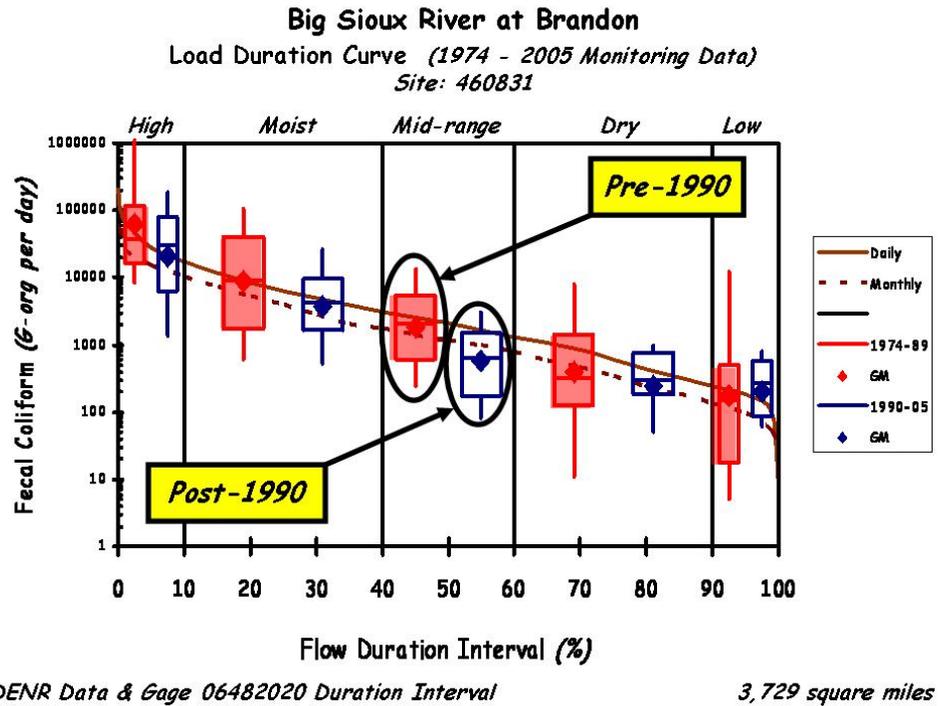


Figure E-6. Bacteria Loading Capacity Using Duration Curve Framework



APPENDIX F

Acronyms and References

ACRONYMS

7Q10	the 7-day average low flow occurring once in 10 years
90 th	90 th percentile
ALC	aquatic life criteria
ARA	antibiotic resistance analysis
BMP	best management practice
BST	bacteria source tracking
CFR	<i>Code of Federal Regulations</i>
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	<i>Federal Register</i>
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-90 th	90 th percentile of a particular zone
ZMC	zone median concentration

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