White Paper (l): Advantages and Disadvantages of Using Load Duration Curves to Estimate Existing and Allowable Loads for the Development of Nutrient TMDLs

Introduction

Section 303(d) of the Clean Water Act and the U.S. Environmental Protection Agency's Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop total maximum daily loads (TMDLs) for waterbodies that are not meeting applicable water quality standards/guidelines or designated uses under technology-based controls. TMDLs specify the maximum amount of a pollutant which a waterbody can receive and still meet water quality standards. Based upon a calculation of the total allowable load, TMDLs allocate pollutant loads to sources and a margin of safety. Pollutant load reductions are allocated among the significant sources and provide a scientific basis for restoring surface water quality. In this way, the TMDL process links the development and implementation of control actions to the attainment and maintenance of water quality standards and designated uses.

One of the technical challenges associated with the development of TMDLs is estimating both existing and allowable pollutant loads for a waterbody. There are two basic options for estimating existing and allowable loads in a stream or river: (1) applying a computer model to simulate conditions within the watershed, and (2) using the available water quality and flow data in a statistical analysis.

A computer model is essentially a series of algorithms applied to watershed characteristics and meteorological data to simulate naturally occurring land-based processes over an extended period of time, including hydrology and pollutant transport. Many watershed models are also capable of simulating in-stream processes using the land-based calculations as input. Once a model has been adequately set up and calibrated for a watershed it can be used to quantify the existing loading of pollutants from subwatersheds or from land use categories. Models can also be used to assess the potential benefits of various restoration scenarios (e.g., implementation of best management practices).

Challenges are often associated with effectively setting up and applying a computer model, however, including having the necessary time, expertise, data, and resources. Some watersheds are also difficult to model because the available tools do not fully address key environmental factors such as extensive hydromodifications (e.g., irrigation diversions or tiling) or complex geology (e.g., karst). Faced with these challenges, some TMDL developers have explored the possibility of using statistical techniques to estimate existing and allowable loads. This white paper discusses one such technique, the use of load duration curves, for estimating nutrient loads in streams and rivers. Much of the discussion also applies to the development of non-nutrient TMDLs, as well.

Methodology

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. Generally, the percentage of time during which specified flows are equaled or exceeded may be compiled in the form of a flow duration curve. This is a cumulative frequency curve of daily mean flows without regard to chronology of occurrence (Leopold, 1994). The flow duration curve includes all flows observed at the gage for the applicable period of record; flow rates are typically sorted from the highest value to the lowest. For each flow value the curve displays the corresponding percent of time that flow value is met or exceeded–the flow duration interval (FDI). (A FDI can also be referred to as a flow recurrence interval.) Extremely high flows are rarely exceeded and have low FDI values; very low flows are often exceeded and have high FDI values.

Figure 1 presents a flow duration curve using data from the Sevier River near Gunnison, UT (U.S. Geological Survey (USGS) gage 10217000). The figure illustrates that the highest observed flow value at this gage for the period of record is 5400 cubic feet per second (cfs) and the lowest observed flow is 6 cfs. The median flow (the 50 percent FDI) is approximately 200 cfs.

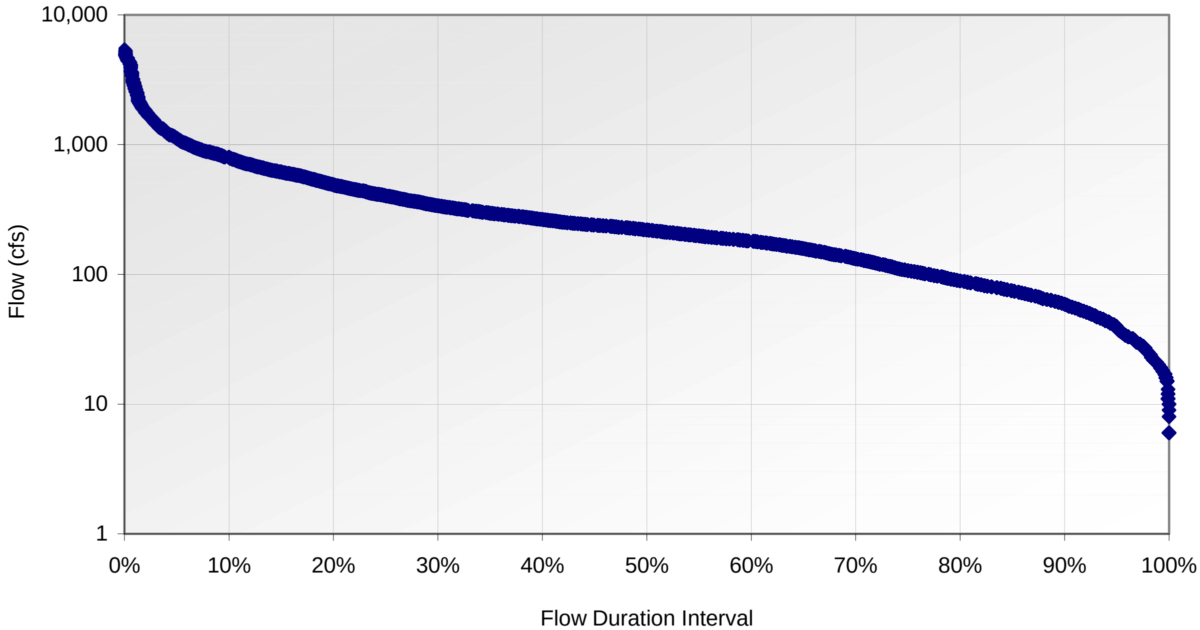


Figure 1. Flow duration curve for the Sevier River near Gunnison, UT, covering the period January 1, 1977 to September 30, 2002.

A load duration limit curve can be created from a flow duration curve by multiplying the flow values by the applicable water quality criterion or target and a conversion factor. The independent x-axis remains as the FDI, and the dependent y-axis depicts the load at that point in the watershed (rather than the flow). The limit curve therefore represents the allowable load (or the TMDL) at each flow condition. A load duration curve for the Sevier River is shown in Figure 2, using a target of 0.05 mg/L total phosphorus. Figure 2 also displays the observed loads, which are calculated by multiplying the sampled total phosphorus concentration by the instantaneous flow associated with the sample (the daily mean flow can be used if the instantaneous flow is not available). Points plotting above the curve represent exceedances of the target and are therefore unallowable loads. Those plotting below the curve represent compliance with the target and allowable daily loads.

From Figure 2 the reader may infer that application of the method requires both gaged flow and pollutant concentrations. Sufficient flow data are needed to establish return frequencies, and a significant amount of concentration data should be available to compare to the limit curve.

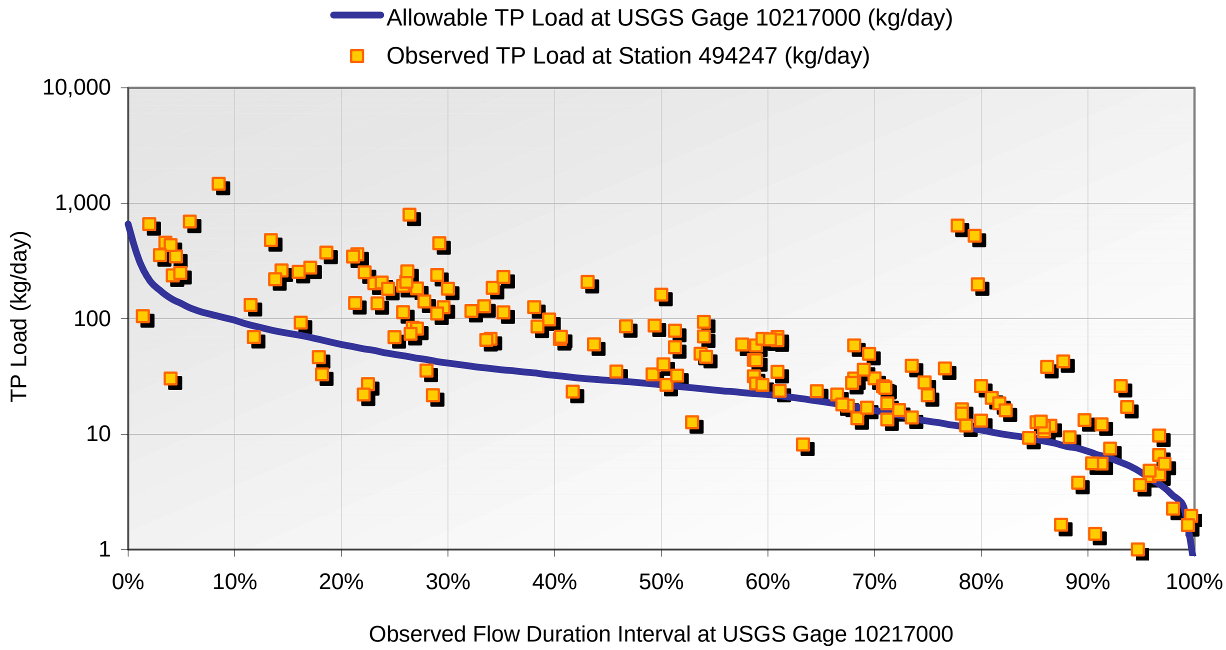
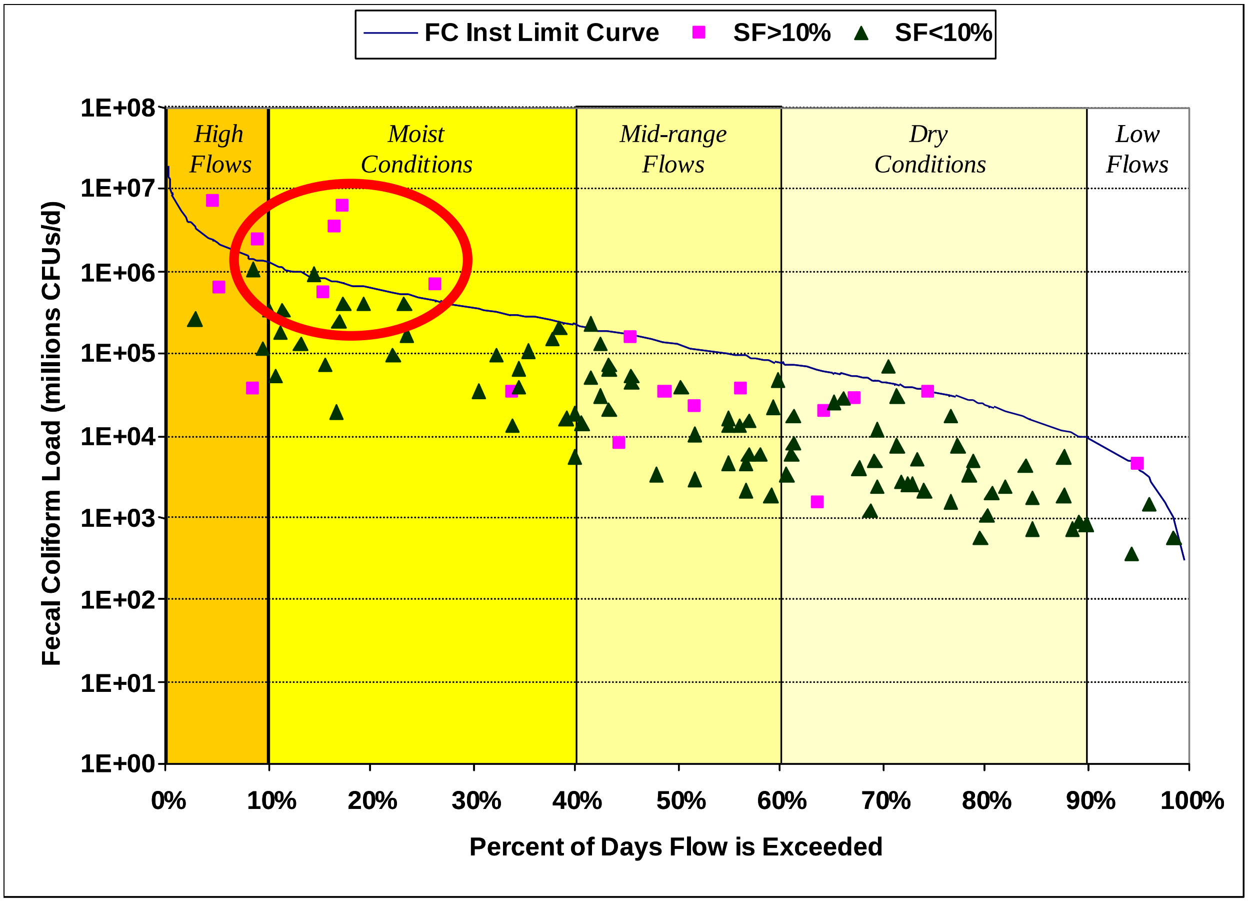


Figure 2. Load duration curve for the Sevier River near Gunnison, UT, covering the period January 1, 1977 to September 30, 2002.

Interpretation of Results

Important information can be interpreted from a load duration curve. First, the extent of the impairment can be visually assessed based on the number of loads that are above or below the allowable loading curve. Figure 2 indicates that most observed loads in the Sevier River are above the allowable limit. Secondly, the nature of the impairment can be inferred based on when the loads occur (Cleland, 2003). Loads that plot above the curve during flow duration intervals of 85 to 99 (low flow conditions) are likely indicative of constant discharge sources such as wastewater treatment plants, irrigation return flows, or dry weather flows. Those plotting above the curve between flow duration intervals of 10 to 70 reflect wet weather contributions associated with sheet and rill erosion, washoff processes, and, potentially, streambank erosion. Some combination of the two source categories lies in the transition zone of 70 to 85 percent. Those loads plotting above the curve at flow duration intervals greater than 99 or less than 10 percent reflect extreme hydrologic conditions of drought or flood, respectively. Figure 2 illustrates that allowable total phosphorus loads in the Sevier River are exceeded during all flow ranges, indicating that multiple sources contribute to the impairment. These sources include irrigation return flows, livestock, land erosion, and wastewater lagoons (UDEQ, 2004).

A case with a clearer interpretation is shown for fecal coliform bacteria in Chicod Creek, NC in Figure 3. Excursion of the standard occurs primarily during moist conditions with a higher fraction of surface runoff contribution (estimated by a baseflow separation filter). This suggests that excursions of the fecal coliform standard in Chicod Creek are primarily associated with nonpoint washoff events.



Notes: SF = Surface runoff fraction. Circle indicates conditions at which the criterion is most likely to be exceeded.

Figure 3. Load-duration curve for fecal coliform in Chicod Creek, NC, 1997-2003

Information from load duration curves can be summarized in table format in a variety of ways. Table 1 below presents the results of determining existing and allowable loads in the Sevier River based on the median values in each of the ten flow duration intervals. For example, an observed load of 354.8 kg/day is presented for the 0 to 10 flow duration interval because that is the median observed load for the 11 observations in that interval. It should be noted that the method by which the data in each interval are summarized can have significant impacts on the resulting values (e.g., the <u>average</u> observed load for the Sevier River 0 to 10 FDI is 458 kg/day).

Table 1. Total phosphorus observed and allowable loads for the Sevier River at Gunnison.

Flow Duration Interval	159-Sample Distribution	Median Observed Flow (cfs)	Allowable Load (kg/day)	Observed Load (kg/day)	Estimated Reduction (kg/day)	Estimated Reduction (%)
0-10	11	1,108.50	135.6	354.8	219.2	61.8%
10-20	11	612.00	74.9	219.4	144.5	65.9%
20-30	28	401.25	49.1	161.3	112.2	69.6%
30-40	10	295.00	36.1	115.0	78.9	68.6%
40-50	11	239.00	29.2	66.7	37.4	56.1%
50-60	18	197.00	24.1	48.2	24.1	50.0%
60-70	17	157.00	19.2	27.8	8.6	30.9%
70-80	19	106.00	13.0	25.2	12.2	48.5%
80-90	15	74.00	9.1	12.7	3.6	28.6%
90-100	19	38.15	4.7	4.8	0.2	3.3%

Advantages and Disadvantages

There are a number of advantages associated with using load duration curves in the TMDL development process. First, assuming sufficient data are available, the method accurately identifies the allowable and existing loads at the point in the stream where the data were collected. The calculated loads are the result of a straightforward mathematical exercise that does not require any assumptions regarding loading rates, stream hydrology, land use conditions, etc. The approach also allows one to use all of the available flow and water quality data and provides easy insight into the critical conditions. This is superior to very simplified TMDLs that are expressed as an average daily load based upon one average long-term flow and one average long-term concentration value.

Assuming that permitted point source loads are known, load duration curves also provide the information necessary to meet the basic minimum regulatory requirement of a TMDL (i.e., existing loads, loading capacity, load allocations, and wasteload allocations). The allowable load (column 4 in Table 1) is the loading capacity and load allocations can be determined by subtracting the permitted point source loads (wasteload allocations) from the loading capacity. A margin of safety can also be factored in explicitly by reserving a portion of the loading capacity.

Load duration curves are also relatively easy to develop once one has an understanding of how they work. Most resource management personnel with a background in hydrology and water quality should be able to develop and interpret load duration curves with relatively little training. Similarly, explaining the results of a load duration curve to the public can be easier than explaining other technical approaches, such as modeling. This can promote effective communication between TMDL developers and those responsible for implementation (Cleland, 2002).

A number of disadvantages are also associated with applying the load duration curve to develop TMDLs. First among these is the limited information they provide regarding the magnitude or nature of the various sources. Although the relative importance of low flow point sources versus wet weather nonpoint sources can often be identified, no information is provided regarding what types of point or nonpoint sources exist in the watershed. This might not be a problem if there are few sources that contribute the pollutant or if the major sources are already known; however, this is often not the case. A significant advantage of a modeling exercise is its ability to quantity the magnitude of sources, both by subwatershed and source type (e.g., specific wastewater treatment plants, row crop agriculture, urban runoff). Such information can be critical to effective implementation and management, especially in California where implementation plans are required for TMDL approval.

Load duration curves also do not allow simulation of scenarios evaluating the impact of various restoration options, as can be done with watershed models. Load duration curves do not provide any "linkage" between sources and water quality response and therefore such "what if" scenarios are impossible to analyze. This lack of a linkage can also be a problem if conditions in the watershed have significantly changed over time. Because load duration curves require a fair amount of data over a range of flow conditions, there is a tendency to include as many sampling results as possible. However, using observed data that are twenty years old might mistakenly "skew" the results if conditions in the watershed have changed (e.g., wastewater treatment plants have expanded or upgraded or land use conditions have altered runoff patterns).

Another potential disadvantage of applying load duration curves is their inability to allow a direct comparison to TMDL targets. TMDL targets, like numeric water quality criteria, typically have three components:

- *Magnitude:* How much of a pollutant, expressed as a concentration, is allowable.
- *Duration:* The period of time (averaging period) over which the in-stream concentration is averaged for comparison with target concentrations. This specification limits the duration of concentrations above the target.
- *Frequency:* The number of times an event occurs over a fixed time interval.

Applying the duration and frequency components to a load duration curve is difficult because, as described above, the curve is developed without regard to the chronology of the observed values. One therefore does not know (simply from reviewing the curve), for example, whether unallowable loads happened within the same month or ten years apart. This can be particularly problematic for the development of nutrient TMDLs because often the appropriate averaging period is a month or longer. For example, the target might be expressed as an average monthly concentration of 1.5 mg/L nitrate+nitrite. This means that values greater than the target are allowed, so long as the average for the month is less than the target. Such intricacies of TMDL targets are difficult to apply with load duration curves, but can be easily addressed when one has daily predictions of pollutant concentrations, such as are available from a watershed model.

Finally, load duration curves only apply to the point in the stream where the data are collected. This can be a problem in large watersheds where the station with the most data is frequently located at the mouth. If significant nutrient sources are located far upstream, the loss of nutrients in transit (due to plant uptake, settling, and denitrification) can lead to underestimating the extent of the impairment in upstream segments. For this reason it is recommended that multiple curves be developed throughout the watershed to evaluate how conditions might vary spatially.

Examples

Numerous TMDLs have been developed with the use of load duration curves. The approach was first used extensively by the Kansas Department of Health and Environment from 1999 to 2001 when more than 1,000 TMDLs were developed and approved (USEPA, 2004) to address a consent decree requirement. More than one-half of these TMDLs were for fecal coliform and involved the use of a standardized technique based on load duration curves.

Several nutrient TMDLs developed using load duration curves were found during an Internet search conducted for this paper and are briefly summarized here to provide perspective on different types of impairments. One of these was for the James River in Missouri (MDNR, 2001). The goal of the James River TMDL was to reduce the frequency of benthic algal blooms in excess of 100 mg/m^2 chlorophyll *a* through in-stream nutrient limits on total phosphorus and total nitrogen. In-stream daily nutrient limits of 0.075 mg/L TP and 1.5 mg/L total nitrogen were set based on a review of the available data and literature. Load duration curves were then used to determine existing and allowable loads. The results indicated that 82 and 43 percent reductions in annual TP and TN loads are required, respectively. Wastewater treatment plants were found to be the most significant sources and effluent limits of 0.5 mg/L TP were put in place as a result of the TMDL. (New nitrogen limits were not initially set as a result of the TMDL.)

Load duration curves were also used to develop total phosphorus (and fecal coliform) TMDLs for the lower Cuyahoga River in Ohio (OEPA, 2003). A total phosphorus target of 0.12 mg/L was used based on a statewide study relating biological quality to nutrient concentrations. One load duration curve was developed for the Cuyahoga River at Independence because almost daily chemical grab samples and instantaneous flow readings were available at this station for the period 1985 through 2002 (a total of 7202 in-stream phosphorus data points). The results of the load duration analysis indicated that the target nutrient concentration is exceeded during all flow duration intervals and that the necessary reductions range from 76 percent for high flow conditions to 28 percent for low flow conditions. The contribution of various sources to existing loads was made using a variety of techniques including observed data and a variety of modeling tools (Table 2). The results of the separate source estimation exercise were displayed graphically along with the load duration curve to provide perspective on the importance of various sources during different conditions (Figure 4).

Table 2. Methods used to estimate total phosphorus loads from various sources in the Cuyahoga River TMDL (after OEPA, 2003)

Source Category	Method to Estimate Existing Loads
Wastewater Treatment Plants	Actual Data
Reservoir Releases	Actual Data
Combined Sewer Overflows	Actual Data and Storm Water Management Model (SWMM) Modeling
Septic Systems	Actual Data and Extrapolation; GIS
Groundwater	Calculated using Hydrologic Separation (HYSEP) Model and Actual Data
Runoff	Export Coefficients
Instream Loss	Difference between total known input load for days without runoff and observed load downstream

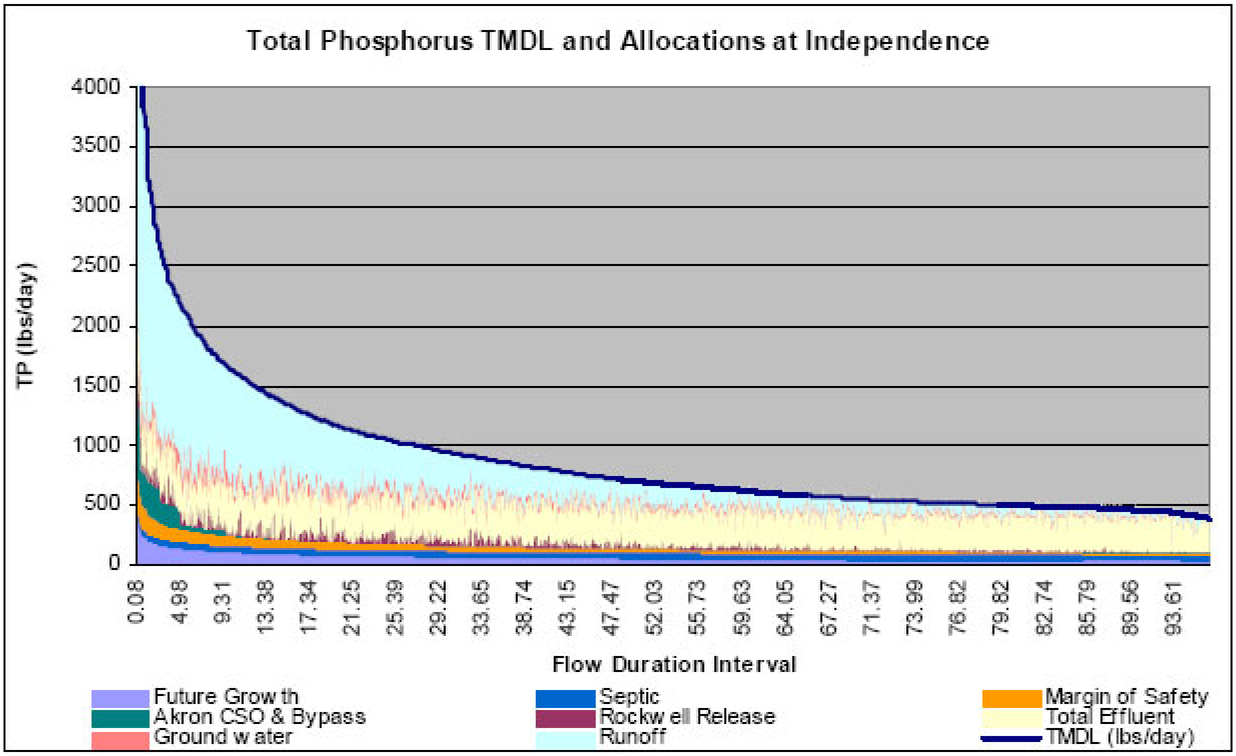


Figure 4. Allocations of lower Cuyahoga River total phosphorus TMDL.

Recommendations

Load duration curves offer a simple method by which to derive the minimum necessary requirement elements of a TMDL. Used appropriately, they can provide important insight into water quality conditions and potential sources. In some cases, where sufficient data are available and the most important sources are already known, they might be used independently to develop a nutrient TMDL. However, it is suggested that load duration curves be used in combination with other tools or techniques that are better able to evaluate source contributions or the effects of various restoration and implementation options. Combining load duration curves with continuous model results may be of particular value. Overplotting model output ranges for each flow interval on the load duration curve for ambient data provides a useful visual check on the representativeness of model results, and can help guide future sampling to flow regimes in which excursions of limits are anticipated.

References

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