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COMPUTING TMDLs FOR URBAN RUNOFF AND OTHER POLLUTANT SOURCES

by

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Abstract

Under the Clean Water Act, states are required to compute Total Maximum Daily Loads (TMDLs) for their priority water bodies. A TMDL determines the maximum pollutant loading from both point and nonpoint sources that a receiving water can accept without exceeding an allowable frequency of water quality excursions. Computing a TMDL is difficult because point source loadings are continuous in time while nonpoint source loadings occur only intermittently. A framework for determining a TMDL and its allocation among sources is developed, based on a modified form of continuous simulation. The approach is applied to an example problem of lead toxicity control within an urban catchment. Results show that it is possible to define the TMDL in an operationally useful way for simple receiving water systems, that the computed TMDL value depends on the level of nonpoint source control selected, and that multiple combinations of equally effective point and nonpoint source control levels are possible.

Introduction

The U.S. Environmental Protection Agency (EPA) has established the "TMDL process" to satisfy the requirements of section 303(d) of the Clean Water Act (Guidance for Water Quality, 1991). A TMDL, or Total Maximum Daily Load, establishes the allowable loadings from all pollutant sources (both point and nonpoint) to a waterbody so that water quality standards are attained. Developing a TMDL typically involves the following kinds of activities: (1) selecting the type of water quality impact to analyze, (2) identifying the pollutant loadings from all types of sources that affect the selected water quality impact, (3) determining the total amount of pollution that the waterbody can accept without exceeding water quality standards, (4) allocating this allowable pollutant load to the various sources.

These activities mirror the commonly accepted approach to water quality management as described in textbooks (Pavoni, 1977) and even in federal guidance issued two decades ago (Guidelines, 1971). What makes the TMDL process especially pertinent today is the programmatic emphasis it places on coordinated control of both point and nonpoint pollution sources, including urban runoff. This emphasis is enforced through EPA's Water Quality Planning and Management Regulation (40 CFR Part 130) which requires that States develop TMDLs for their priority water bodies and submit these for EPA approval.

Planning for coordinated control of both point and nonpoint pollution sources is made difficult by the fundamentally different nature of the two sources. Point sources discharge continuously while most nonpoint pollution occurs only intermittently. Pollution loads from nonpoint sources, such as urban runoff, are influenced greatly by rainfall and other stochastic phenonema (e.g., the effectiveness of street sweeping) and are therefore not predictable in any deterministic sense. The receiving water impacts of both types of sources are affected by many other stochastic factors as well. These include stream flow, temperature, pH, alkalinity, hardness, and light intensity. Thus a fundamental question to ask is how can the statistical variability of all these factors be taken into account so that a TMDL and its allocation among sources reliably meets water quality standards.

This paper illustrates one approach for making the TMDL an operationally useful concept. It demonstrates how the TMDL should be interpreted in light of the various sources of variability that affect receiving water impacts. And it shows how a TMDL can be quantified and allocated between point and nonpoint sources so that water quality standards are met.

Background

EPA guidance (Guidance for Water Quality, 1991) defines the TMDL for a waterbody segment with the following equation:

$$TMDL = WLA + LA + MOS \quad (1)$$

where WLA (wasteload allocation) is the portion of the TMDL allocated to existing or future point sources, LA (load allocation) is the portion allocated to existing or future nonpoint sources or to natural background sources, and MOS (margin of safety) is a portion that accounts for the uncertainty in the relationship between pollutant loads and receiving water quality (or a portion reserved for future growth within the watershed).

The TMDL itself is the maximum pollutant loading that a water body can receive without violating water quality standards. It can be expressed in units of mass per time, toxicity, or other appropriate measures that relate to a State's water quality standard (Guidance for Water Quality, 1991). EPA guidance does not address the issue of how the loadings from both continuous (point sources) and episodic (nonpoint sources) can be reconciled into a single number nor does it recognize the fact that when interpreted literally, as an allowable daily load, the TMDL varies from day to day as a receiving water's capacity to accept pollutant loads varies.

EPA recommends that numeric water quality standards be stated in terms of magnitude, duration and frequency, i.e., a standard is a receiving water concentration occuring over a given averaging period allowed to be exceeded with a specified frequency (Technical Support Document, 1991). In theory, the standard can be stated in terms of some quantitative measure of water quality impact that can be related to pollutant source loading. These include limits on specific chemical concentrations (e.g., lead), ambient toxicity (e.g., a dilution necessary to achieve a specific endpoint for an aquatic species in a toxicity test), and biological criteria (biological community indices, amount of suitable habitat). We will focus on chemical-specific standards because the predictive linkages between loadings (and pollution reduction measures such as BMPs) and aquatic toxicity and biological indicators are not as well developed.

Viewing water quality standards in these terms, a TMDL could be set to a water body's loading capacity whose frequency of not being exceeded equals the allowable excursion frequency of the water quality standard. For example, if one excursion above water quality limits were allowed every 3 years, then the TMDL would equal the daily water body loading capacity whose frequency of not being exceeded is once in 3 years. Taking this concept one step further, suppose the magnitude of the water quality standard is a constant concentration C_{WQS}, and the x-day average stream flow is Q, where x is the averaging period used in the water quality standard. Then for any x-day period, the water body loading capacity is $Q \cdot C_{WQS}$, and a TMDL could be found by solving the following equation for TMDL:

$$\text{Freq}\{Q \cdot C_{WQS} < \text{TMDL}\} = E \quad \text{.......(2)}$$

where Freq{X} is the frequency at which condition X occurs and E is the allowable excursion frequency of the water quality standard. This concept is displayed visually in Figure 1.

Because stream flow is the only quantity that varies in Eq. 2, the TMDL can be set to $Q_{des}C_{WQS}$ where Q_{des} is a design flow, equal to the flow whose frequency of not being exceeded is E. This has been the traditional approach used for simplified waste load allocations for point sources (which ignores background and nonpoint sources) wherein

$$\text{WLA} = Q_{des}C_{WQS} \quad \text{.......(3)}$$

and

$$C_{PS} = \text{WLA} / Q_{PS} \quad \text{.......(4)}$$

with C_{PS} = point source effluent concentration limit and Q_{PS} = point source flow rate.

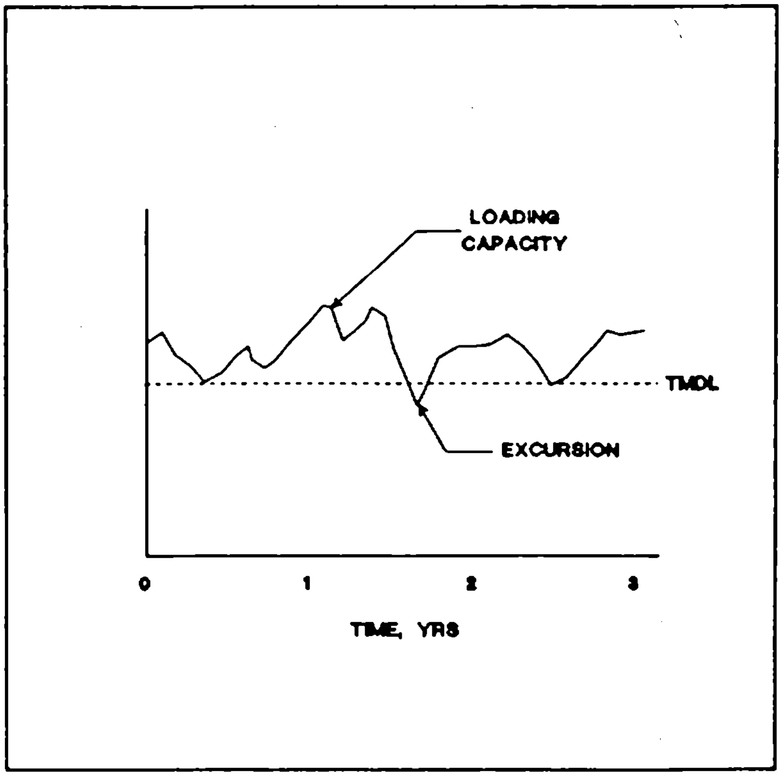

Figure 1. One Possible Interpretation of the TMDL

When background sources and nonpoint sources (such as urban runoff) are included the picture becomes more cloudy. First, the argument above assumes that the TMDL is a constant load that the waterbody sees every day. This might be true for point sources (if variability in discharge flow and treatment efficiency were ignored) but certainly would not be the case with intermittent nonpoint source loadings. Second, nonpoint source controls, such as detention basins or porous pavement, will alter runoff flow and therefore change the stream flow statistics. Thus the TMDL and any design flow will become a function of the nonpoint source control program chosen. Finally, there are many other sources of variability, besides stream flow, that can affect a TMDL. For example, C_{WQS} could be a function of other water quality parameters, such as hardness in the case of heavy metals or pH and temperature in the case of ammonia (Quality Criteria, 1986). These parameters will vary, both seasonally and randomly, over time. Likewise, background source levels of a pollutant might display a random variation as would effluent levels of a pollutant being discharged from a point source's treatment process. How might these additional sources of variability be taken account of when computing a TMDL?

Computational Approach

Figure 2 illustrates the nature of the problem being addressed. Given a time-varying, uncontrollable source of background pollutant loading, determine the mixture of controls on point and nonpoint pollutant sources and the corresponding TMDL whose resulting frequency of water quality excursions meets the limit set in the standard. The following questions seem particularly relevant: (1) what are the relative contributions of different source categories to the TMDL, (2) which type of source most influences water quality excursions, (3) as nonpoint source loads are reduced, how much can point source loads be increased, and (4) what is the most cost-effective mix of point and nonpoint source controls?

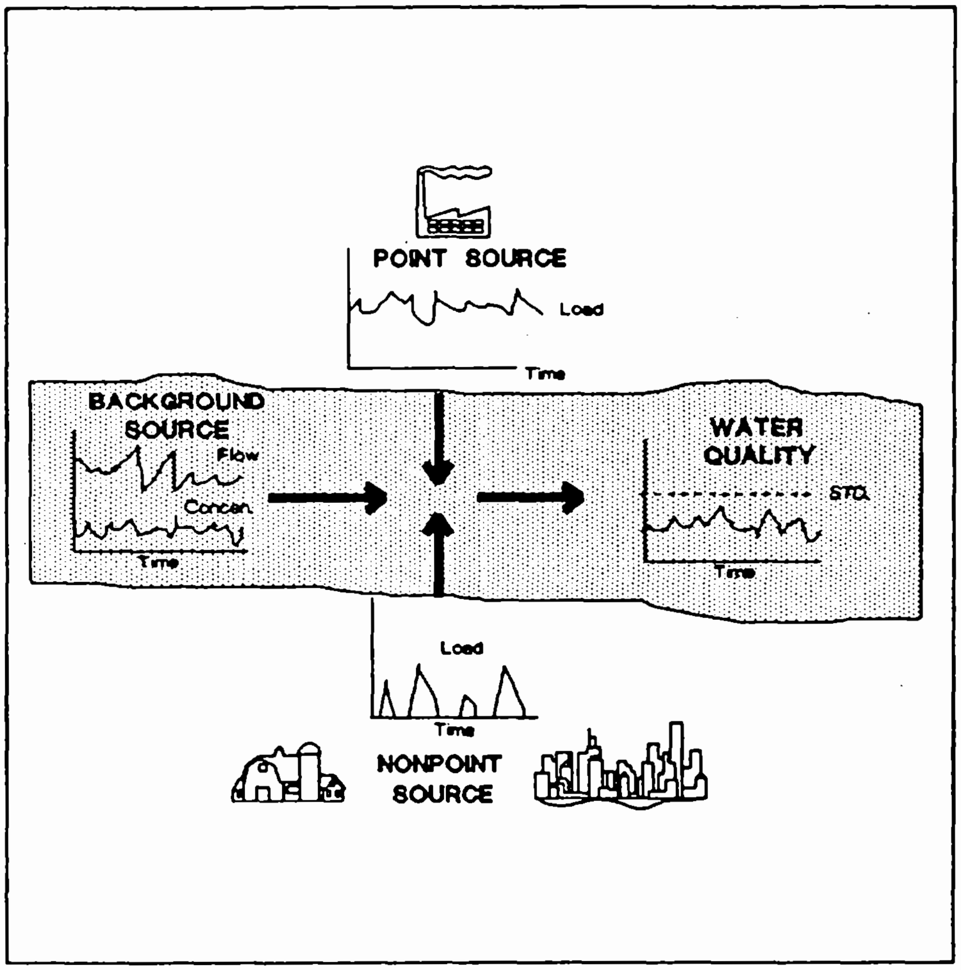

Figure 2. Definitional Sketch of a Receiving Water System

We have shown that a direct determination of a TMDL based on the concept of loading capacity will not allow us to find a meaningful allocation of this load between point and nonpoint sources. An alternative approach is to use continuous simulation modeling (Singh et al., 1982). A set of point and nonpoint control actions is specified and a long-term record of all pertinent flows, source loadings, and supplemental water quality input variables are accumulated, either from historical measurements or from statistical models. A water quality response model is then used to predict a time series of water quality conditions. A frequency analysis of these conditions is made to determine the frequency of water quality excursions. Based on these results, source loadings are adjusted and the simulation process is repeated until the desired excursion frequency is acheived.

An alternative way for computing TMDLs is available that avoids the need to do repetitive continuous simulation. The approach is best suited for screening level analyses on free-flowing rivers where point sources and runoff outfalls are in close proximity to one another. It does not consider fate and transport phenomena within the receiving water, but focuses instead on meeting water quality standards at the edge of a mixing zone between all source inputs. This makes it only applicable to situations where the water quality conditions at a mixing point are determined only by source loadings occuring during the averaging period used to evaluate water quality standards. Examples would be episodic events, such as heavy metal toxicity or bacteriological contamination, and algal bloom problems which can be correlated with annual or seasonal loadings of nutrients. Sediment deposition, transport and resuspension or nutrient recycling within benthic deposits are problems which cannot be handled at this time.

This alternative approach can accommodate several complicating factors. Water quality standards can be functions of supplementary parameters, such as temperature and pH. Speciation of materials at the point where sources mix can be considered. Statistical variability of all relevant factors can be accounted for, using a variety of different distributional assumptions. Lastly, the method can show how for a given allowable excursion frequency, different nonpoint source control actions give rise to different levels of point source controls.

As we noted earlier, runoff controls can alter stream flow statistics and therefore the frequency of water quality excursions. We account for this by analyzing candidate nonpoint source control strategies one at a time. For each strategy, we determine what the long-term mean point source loading must be so that water quality excursion frequencies are met. From this we can establish a TMDL and, as each nonpoint control option is examined, generate a trade-off curve between point and nonpoint control efforts.

In general terms, the steps of the approach go as follows:

1. Select a nonpoint source control option.
2. Simulate a long-term daily record of:
   a. background stream flows (Q_{BS}), contaminant concentrations (C_{BS}), and, where relevant, supplementary water quality variables (such as temperature, pH, or hardness)
   b. nonpoint source flows (Q_{NPS}) and pollutant concentrations (C_{NPS})
   c. point source discharge flows (Q_{PS}), variations in point source treatment efficiency (V), and, where relevant, supplementary water quality variables.
3. If water quality standards (C_{WQS}) are functions of supplementary water quality variables, then compute these standards for conditions occurring over each day of the record.
4. For each x-day period of the record (where x is the duration specified in the water quality standards), use a rearrangement of the simple mass balance equation to compute the point source discharge concentration (C_{PS}) that just meets water quality standards:

$$C_{PS} = \frac{\langle C_{WQS} \rangle_x - \langle Q_{BS}C_{BS}/Q \rangle_x - \langle Q_{NPS}C_{NPS}/Q \rangle_x}{\langle Q_{PS}V/Q \rangle_x} \qquad (5)$$

   where $Q = Q_{BS} + Q_{PS} + Q_{NPS}$ and $\langle X \rangle_x$ denotes the x-day average of the quantity X.
5. From the collection of computed C_{PS} values, find C^*_{PS}, the value whose frequency of not being exceeded equals the allowable water quality excursion frequency.
6. Evaluate the following quantities:

$$\begin{aligned} WLA &= C^*_{PS} LTA(Q_{PS}V) \\ LA &= LTA(Q_{BS}C_{BS} + Q_{NPS}C_{NPS}) \\ TMDL &= WLA + LA \end{aligned}$$

   where LTA(X) is the long-term average value of X over the simulation.
7. Evaluate the costs and any other criteria associated with the point and nonpoint source controls used in the analysis (such as land requirements and implementability) and repeat the analysis for another choice of nonpoint source control.

In step 6 we interpret the TMDL as the sum of the long-term average loadings from each source category that achieves water quality standards, with the understanding that the variability associated with each source loading has been taken into account to insure compliance with water quality standards. This allows us to add together quantities (long term average loads) defined over equivalent time frames. This view of the TMDL differs from that in the previous section, where it was interpreted as a water body loading capacity with a certain frequency of not being exceeded. Also note that the third element of a TMDL as defined in Eq. 1, the MOS (margin of safety), is not explicitly considered here. One way to include it in the calculations is to reduce C_{WQS} by a given amount.

A computer program was written to implement steps 1-6 of this TMDL procedure. Some notable features of the program are:

1. Water quality standards for heavy metals can be functions of stream hardness while standards for ammonia can be functions of pH and temperature.
2. Any external rainfall-runoff model can be used to generate runoff events as long as its output includes the start time, duration, flow, and contaminant concentration for each event generated.
3. Daily background stream flow is taken from historical flow records. This avoids the problem of having to identify a statistically correct stream flow probability distribution, including the proper autocorrelation structure between successive daily flows.
4. Daily concentrations of background water quality parameters are generated by an equation containing two terms: The first term is a daily deterministic seasonal pattern that repeats each year; the second term adds randomly generated perturbations to the annual pattern. A similar equation is used to generate daily point source flows and supplemenatry water quality variables (pH, temperature, etc.).
5. The V factor in Eq. 5 is computed by modeling the daily variability in contaminant concentration discharged from the point source as a lognormally distributed, first order Markov time series. It can be fully described by means of a coefficient of variation and an auto-correlation coefficient.

<u>Example Application</u>

We present an example TMDL analysis that illustrates how the questions asked at the beginning of the previous section can be answered. The problem involves controlling acute aquatic toxicity caused by lead discharges within an urban catchment area. The data are summarized in Table 1. Note that the lead standard increases with increasing water body hardness and can only be exceeded once every three years. Historical stream flow data from the Quinnipiac River in Connecticuit are used along with rainfall statistics from Boston. We assume that no lead is present from background sources and that its mean concentration in uncontrolled runoff is 100 ug/L. A simple statistical rainfall-runoff model (Areawide Assessment, 1976) is used to generate runoff events.

Table 1. Data Used in Example TMDL Calculation

Data Category	Value
Water Quality Standards	
Type	US EPA CMC (Acute)
Averaging Period	1 day
Concentration Limit	34 ug/L at 50 mg/L Hardness 82 ug/L at 100 mg/L Hardness 137 ug/L at 150 mg/L Hardness
Excursion Frequency	1 in 3 years
Stream Flow	
River	Quinnipiac near Wallingford CT
Period of Record	1932 - 1978
Mean Flow	205 cfs (6 m^3/sec)
7-day, 10-year Low Flow	32 cfs (1 m^3/sec)
Background Source	
Lead Concentration	0 ug/L
Hardness	$87 \cdot SF + 15 \cdot N(0,1)$ $0.86 < SF < 1.15$
Point Source	
Flow	3 cfs (0.08 m^3/sec)
Hardness	100 mg/L
Lead Variability	CV = 0.7
Nonpoint Source	
Rainfall Statistics	Boston, MA
Catchment Area	1310 acre (531 ha)
Runoff Coefficient	0.38
Lead Concentration	Mean = 100 ug/L CV = 0.7
Hardness	Mean = 100 mg/L CV = 0.5

Notes: CV = coefficient of variation; N(0,1) is a normally distributed random variable with zero mean and unit variance; SF = seasonality factor.

Table 2 presents TMDL results for the case of no runoff controls. The mean point source lead limit (C^*_{PS}) must be 54 ug/L to achieve the 1 in 3 year excursion frequency. On a long-term average basis, the receiving water can accept 687 g/day of lead of which 58 percent comes from the point source and the rest from urban runoff. Table 3 shows during what periods of the historical record excursions of the lead standards would have occurred under the assumptions of our simulation. Note that every excursion is caused primarily by runoff.

Table 2. TMDL Results for No Runoff Control

Mean Point Source Concentration	54 ug/L
Total Maximum Daily Load	687 g/day
Point Source Waste Load Allocation	392 g/day
Background/Nonpoint Source Load Allocation	295 g/day

A second run was made using 15 acre-ft (18450 m^3) of detention storage runoff control. Table 4 shows the TMDL that results under this scenario. The allowable point source discharge limit has increased more than three-fold, the nonpoint load has almost halved, and the TMDL has more than doubled. An excursion table like Table 3 would show that there are just as many events as before, because the allowable excursion frequency has not changed. But now the point source becomes the dominant cause in 20 percent of the events.

It is interesting to compare the magnitudes of the point loads, nonpoint loads, and load capacities over time for these two runs. Figures 3 and 4 do this for a portion of 1944, a year containing several water quality excursions. These excursions show up very clearly in the figures where the sum of the two loads exceeds the load capacity curve. The figures also show that runoff storage has reduced the magnitude of all but the highest runoff loads and has permitted a higher level of point source loading to occur.

Table 3. Water Quality Excursions Under No Runoff Control

Date	Duration (Days)	Magnitude[1]	% Caused by Runoff
09/24/31 10/23/31	1 1	1.78 1.22	99.2 95.1
07/16/35	1	1.61	98.8
07/20/44 09/08/44	2 1	1.06 1.30	95.5 91.6
08/01/47	1	1.56	98.3
06/27/49	1	2.59	99.2
08/24/56	1	1.46	98.2
07/29/57	1	1.14	98.3
12/18/62	1	1.56	99.4
10/27/63	1	2.92	96.6
04/03/66	1	1.76	99.2
01/21/67	1	2.57	99.4
10/28/77	1	1.45	99.8

[1]Ratio of actual load to load capacity.

Table 4. TMDL Results for 15 Acre-Ft of Detention Storage

Mean Point Source Concentration	174 ug/L
Total Maximum Daily Load	1439 g/day
Point Source Waste Load Allocation	1281 g/day
Background/Nonpoint Source Load Allocation	158 g/day

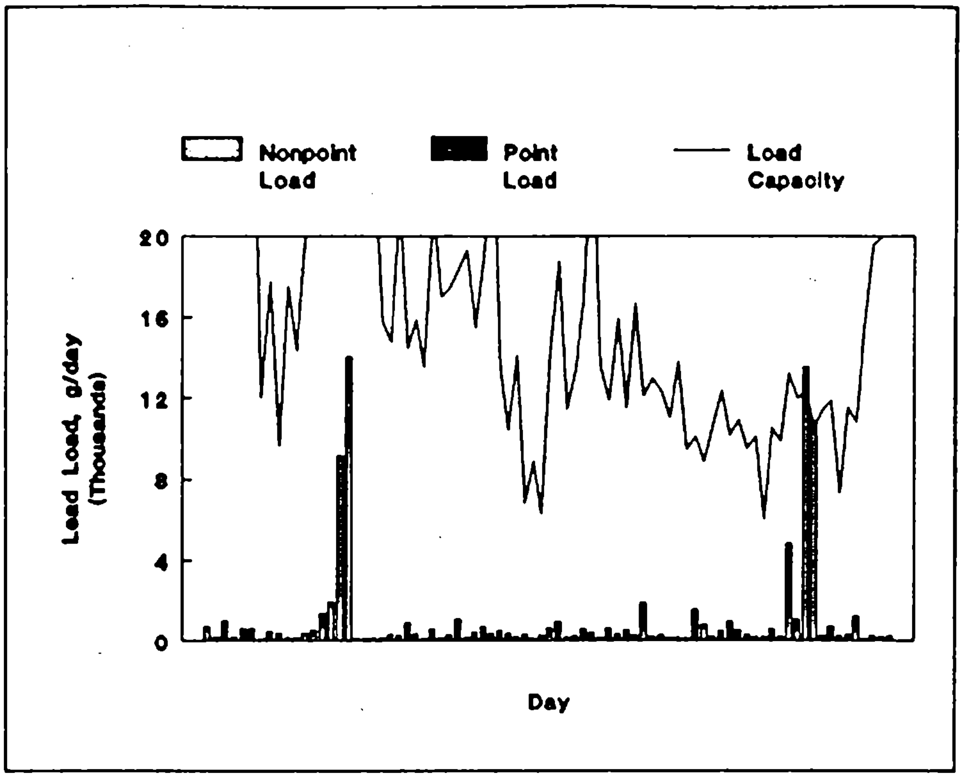

Figure 3. Lead Loadings for Portion of 1944 - No Nonpoint Controls

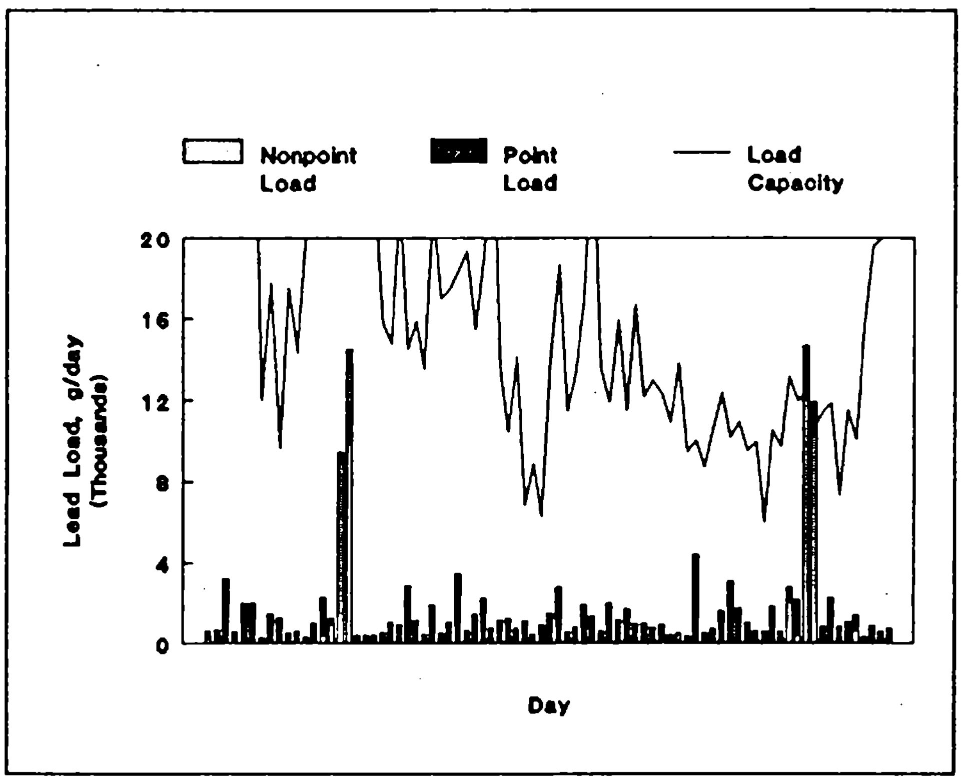

Figure 4. Lead Loadings for Portion of 1944 - 15 Acre-Ft of Storage

Table 5 shows the results of computing TMDLs for a variety of different storage levels. As additional increments of storage are added, the TMDLs and point source loads rise at a diminishing rate. Figure 4 compares detention storage with treatment as a nonpoint source control. A 50 percent lead removal in the runoff is equivalent to 30 acre-ft (36900 m^3) of storage and allows a fourfold increase in the point source lead loads. By computing the costs of these various allocations of lead between point and nonpoint sources we could determine the most cost-effective mix of controls that meets our water quality objective.

Table 5. TMDLs for Different Volumes of Detention Storage

Storage acre-ft[1]	TMDL g/day	Point WLA g/day	Nonpoint LA g/day	% Nonpoint Excursions[2]
0	687	392	295	100
3	895	627	268	100
6	1269	1028	241	100
15	1439	1281	158	80
22.5	1689	1588	101	40
30	1725	1659	66	20

[1]1 acre-ft = 1230 m^3

[2]Percentage of excursions caused primarily from runoff.

Conclusions

This paper has provided an operational meaning to the TMDL concept. The TMDL is contingent upon the method of nonpoint source control used and should be calculated as the sum of long-term average loads. A modified form of continuous simulation was developed to compute its value and its allocation between pollution sources for simple receiving water systems. In general, the TMDL will increase as tighter levels of nonpoint source control are applied. Many different combinations of point and nonpoint source controls that meet water quality standards can be generated. Further economic analysis could then determine the most cost-effective combination of controls. These ideas were illustrated through a numerical example involving the control of acute lead toxicity.

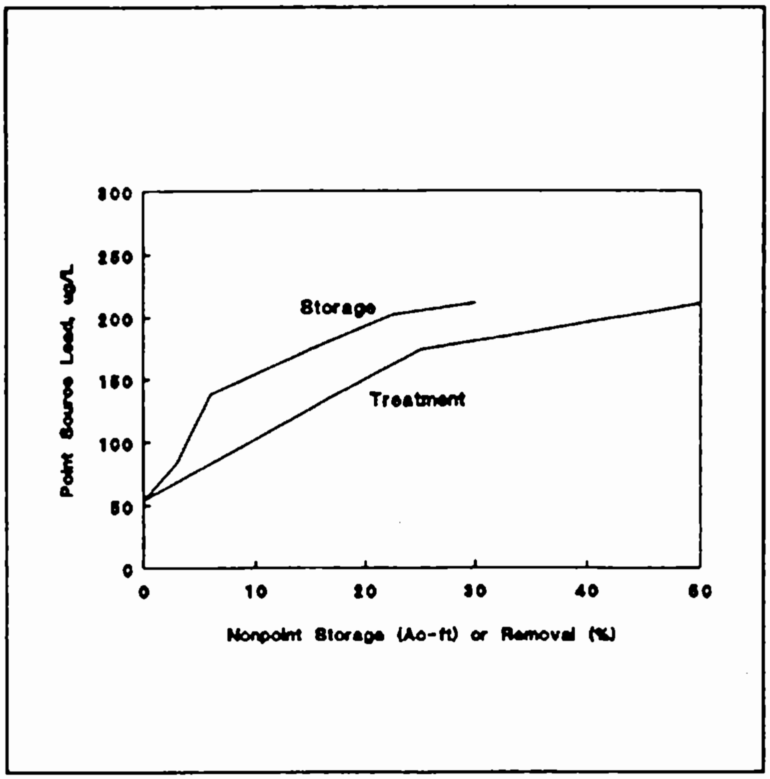

Figure 5. Effect of Runoff Controls on Point Source Discharge Limits

Several questions remain regarding the computation of TMDLs. Can the concepts used here be extended to consider larger scale watersheds where considerable distances exist between discharge points? How can more complex water quality impact phenomena, such as interactions between sediments and overlying waters, be handled? In these situations the effects of settleable solids in runoff may not be observed until months later, after sediment processes have released nutrients or created an oxygen demand in the overlying waters (Novotny and Bendoricchio, 1989). Finally we need to explore how the approach would work with alternative ways of defining water quality impacts and protection, such as ambient toxicity, biological indices, physical habitat protection, and riparian restoration.

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