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RESEARCH BRIEF

Methods of Analysis for Waste Load Allocation

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Abstract

This research has addressed several unresolved questions concerning the allocation of allowable waste loads among multiple wastewater dischargers within a water quality limited stream segment. First, the traditional assumptions about critical design conditions for waste load allocation were shown to be true (except for some highly uncommon situations) in multi-discharger settings—namely, that lower streamflows and higher temperatures lead to more stringent allowable loads. Second, a method was developed for aggregating dischargers together into discrete groupings so that the water quality interactions between groups was minimized. This allows waste load allocations to be made separately for each grouping, thereby simplifying the overall computational process. Third, the issue of setting aside unallocated waste load capacity as a reserve against future growth or modeling uncertainty was examined. A case study illustrated the unique relationships that might exist between this reserve capacity, the frequency of water quality excursions, and the cost of wastewater treatment. Finally, a method was developed for designing multi-discharger seasonal waste load allocations. It determines seasonal discharge limits for each discharger that minimizes the degree of treatment necessary to provide the same risk of water quality excursion as would exist under a nonseasonal waste load allocation.

This Research Brief was developed by the principal investigators and EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in the reports and publications listed at the end.

Introduction

Waste load allocation is the process of determining allowable levels of pollutant discharges that will maintain acceptable receiving water quality. Several factors can complicate this task. The presence of multiple pollutant sources, including the need to find an economic and equitable allocation of allowable load among these sources, is one such factor. Another is the need to account for natural variations in receiving water conditions such as streamflow and temperature when determining the effects of a proposed load allocation on water quality. Additional concerns may involve accommodating possible future discharge sources and uncertainty in water quality modeling predictions when conducting a waste load allocation.

This project has addressed several previously unresolved questions related to allocation of waste loads to dischargers along a stream segment. The questions are:

1. Parameters that affect water quality, such as reaeration coefficient, and travel time, change with streamflow and temperature in a manner that sheds doubt on the traditional assumptions of low flow and high temperature as the "worst-case" conditions for decaying pollutants. What are the limitations for the validity of these assumptions?
2. On a large river there is usually an unmanageably large number of dischargers. Is there a way to

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split them into groups that can be analyzed separately thereby reducing the computational burden?

3. How should part of the allowable load capacity be reserved and how will this affect the goals of a waste load allocation program?
4. Seasonal (or periodic) discharge limits are used by many states to reduce the costs of water quality control programs. How can this approach be applied in an economically and environmentally sound manner to multiple discharger settings?

A brief discussion of the research findings related to each of these questions follows.

Critical Water Quality Conditions

The assumption that the worst water quality occurs at the lowest streamflow may not always hold in instances involving multiple discharges of nonconservative pollutants. The additional dilution resulting from increased streamflow may be offset by adverse changes in the parameters that govern water quality and in decreased travel time, which allows the stream less time to recover from the effect of one discharge before receiving another.

The question is whether, with multiple sources of nonconservative pollutants, water quality might worsen with increasing streamflow. This can be examined by finding the pattern of discharge that maximizes the rate of change of critical pollutant concentration (i.e., the concentration at the location where the quality standard is binding) with respect to streamflow. If that rate is positive, the standard will be violated with an increase in streamflow. If, regardless of the loading pattern, the rate is negative, then it is impossible to have such a situation and it may be assumed that the lowest streamflow is the worst streamflow.

Under constant temperature conditions, a linear programming model showed that this discharge pattern is a uniformly distributed load along the entire length of stream. This suggests that streams receiving a large number of discharges may be more susceptible to concentration increasing with decreasing flow than are streams receiving a small number of discharges [Eheart, 1988].

For substances that decay according to first-order kinetics, such as biochemical oxygen demand (BOD), whether the maximum value of the rate of change of critical concentration with respect to streamflow is positive or negative depends on the value of the exponent in the power law that relates stream velocity to streamflow. For dissolved oxygen (DO) deficit, the exponent relating reaeration coefficient to streamflow is also important. Results indicate that the rate is negative for most natural streams for both types of water quality parameters. Thus, the traditional assumption that the lowest streamflow is the worst from a water quality perspective will usually be valid. Exceptions, however, could occur in highly polluted backwater (impounded) stream reaches for which depth decreases as velocity increases.

For first-order pollutants, low temperature is the most pessimistic condition, since the pollutant decays more slowly and is hence present in larger concentration. For DO, however, the question is more complicated. The classical assumption that the lowest DO occurs at the highest temperature may not always hold. The DO saturation concentration decreases monotonically with increasing temperature, lowering the DO, but the reaeration coefficient increases monotonically with increasing temperature, tending to raise it. The BOD decay coefficient increases monotonically with increasing temperature, lowering the DO for single discharges but not necessarily for multiple discharges. (Lower decay rates attending lower temperatures could result in low DO at the point where the effect of one discharge meets that of another.)

The question of whether DO might under some circumstances worsen with decreasing temperature has been addressed [Eheart and Park, 1989]. A linear programming model showed that, for a uniform stream at constant streamflow, the discharge pattern that maximizes the rate of change of critical DO with respect to temperature is a uniformily distributed load along the entire length of stream. This suggests that streams receiving a large number of discharges may be more susceptible to DO increasing with decreasing temperature than are streams receiving a small number of discharges.

The maximum rate of change of critical DO with respect to temperature depends on temperature, the DO standard (C^*), and the temperature adjustment factor for the reaeration coefficient (ϕ). It does not depend on the BOD decay coefficient or its temperature adjustment factor. For the maximum reported value of ϕ of 1.047, the assumption that DO decreases monotonically with increasing temperature is valid for C^* greater than about 6 mg/L. This assumption breaks down, however, for ϕ values just above the range reported in the literature and for C^* values just below the normally chosen range of 5 to 6 mg/L.

Discharger Grouping

In developing programs for regulating waste discharges into water bodies, it is often convenient and, in many cases, necessary, to subdivide the dischargers into independently administered groups. If each group of dischargers is to be responsible for the water quality at a particular group of checkpoints, the groups should be chosen so that the effect of the dischargers of one group on the checkpoints of another is minimal.

A heuristic method was developed that groups dischargers on the basis of minimizing the effects of the dischargers included in a group on checkpoints associated with other groups of dischargers [Eheart et al., 1989]. The method was illustrated with the use of data for several river basins, viz., the Lower Fox River in Wisconsin, the Willamette River in Oregon, and the Mohawk River in New York. Several different grouping criteria were chosen to represent the effect of the excluded dischargers, and it was observed that, for the selected rivers, as examples, the groupings are somewhat insensitive to the choice of this criterion when the excluded effect is low, but not when it is high.

Reserve Capacity

To act as a hedge against any potential errors or inaccuracies in the predictions made with the water quality model and/or to allow for future growth in waste discharges, some of the river's allowable load capacity can be set aside and made unavailable for use by the dischargers. Depending on how the reserve capacity is actually incorporated into the waste load allocation process, however, the effects on water quality could vary.

To include reserve capacity in such a process, several criteria should be considered and evaluated. Acceptable levels of water quality should be maintained at an acceptable probability and an acceptable cost. In addition, the methods for including reserves should be equitable in terms of the distribution of required treatment levels and costs.

Approaches have been examined for including a reserve capacity in the waste load allocation process, and methods have been developed for analyzing these approaches in a given application [Michels, 1987]. Relationships among reserve capacity, frequency of water quality excursions, and total cost have been examined. It was found that, depending on how reserve is incorporated into a waste load allocation, these relationships may be quite different and the effect on overall water quality may vary. The relationships were illustrated quantitatively with the use of linear programming models for three load allocation programs employing Lower Fox River data.

Seasonal Waste Load Allocation

Water quality management programs that allow different waste discharge rates during different times of the year are an innovative approach for reducing the cost of waste treatment. Under such programs, referred to as periodic or seasonal discharge programs, the rate of waste discharge allowed at a given time is based on the assimilative capacity of the receiving water body during that time, the water quality goals of the river basin authority, and the acceptable risk of water quality violation. The number and length of the seasons are typically chosen considering the physical conditions of the stream, the waste treatment limitations of the dischargers, and the estimated administrative burden and treatment cost savings associated with each potential combination of season number and length.

An important criterion of seasonal discharge programs is that the degree of water quality protection achieved under such programs should be the same as that achieved under an accepted or existing nonseasonal discharge program for the same river basin. One expression of this criterion is referred to as risk equivalency [Rossman, 1989] because it requires that the risk of violating a given water quality standard under the seasonal discharge program be no greater than that allowed under an existing nonseasonal discharge program. Rossman [1989] describes an approach for designing risk equivalent seasonal discharge limits for single discharger stream segments. Under this approach, risk is defined as the probability of incurring one or more water quality violations in any given year, and the level of risk allowed may be related to the return period of the design streamflow used in an existing nonseasonal discharge program. For example, the 10-year return period associated with the annual 7-day, 10-year (7Q10) low flow would correspond to a 10% risk of water quality violation in any year. The seasonal discharge limits for a single discharger under this approach are designed to maintain risk equivalency with a nonseasonal discharge limit while minimizing the waste treatment effort of that discharger.

In this research, risk equivalent seasonal waste discharge programs for stream segments with several dischargers were examined [Lence et al., 1989]. Although this approach is similar to that proposed by Rossman [1989], it was modified to accommodate river segments with several dischargers. Two management objectives were proposed as substitutes for minimizing waste treatment effort, the minimum average uniform treatment (UT) and the maximum total discharge (TD) objectives. Under the UT objective, a seasonal set of uniform percent removal levels is designed such that the average percent removal over the year is minimized and a limit on the frequency of water quality violations is satisfied. Under the TD objective, the total design waste load in each season (i.e., the sum of the waste loads for the individual dischargers) is determined such that the TD over all seasons is maximized and a limit on the frequency of water quality violations is satisfied.

The seasonal waste discharge programs that meet these objectives were demonstrated for managing BOD discharges on the Willamette River. Streamflow and temperature data for the middle fork of the Willamette River, the stream segment on which the 10 major dischargers are located, were obtained from the United States Geological Survey. The dischargers' locations, waste load characteristics, design flows, and treatment cost data were taken from Kilgore [1985]. Alternative risk equivalent discharge programs for the dischargers on the Willamette River were compared with each other and were evaluated with respect to the resulting total waste discharge, water quality, and total treatment cost. A nonseasonal and a two-season discharge schedule was examined for both the UT and TD objectives. The DO standard was to be achieved with an annual risk of water quality violation of 10%, and the alternative standards considered varied from 5.0 to 7.5 mg/L.

The results of this analysis show that, when compared with nonseasonal discharge schedules, substantial potential reductions in waste treatment effort and cost were possible under a seasonal discharge schedule for the Willamette River. The two-season discharge programs, which allowed between 0 and 66,500 lb/day more waste discharge than the nonseasonal TD programs, resulted in treatment cost savings of between 0.0 and $22.0 million/yr, (0% to 48%) with respect to the nonseasonal discharge schedule.

To evaluate the dependence of cost on the relative lengths of the seasons under the two-season discharge schedule, the length of the critical season (i.e., the season in which the average streamflow is the lowest) was varied. For a given DO standard and critical season length, the total treatment costs of both the UT and TD management programs were obtained. For both of these discharge programs, the optimal critical season length ranges from 2 to 5 months, depending on the DO standard. The total cost of waste treatment is more sensitive to the critical season length for high values of the DO standard than for low values. The results for the UT allocation follows the same trend, but the UT allocation is generally less expensive than the TD allocation.

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