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DIFFICULTIES IN DETERMINING ALLOWABLE MAXIMUM DAILY POLLUTANT LOADS TO WATERWAYS UNDER PL 92-500*

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ABSTRACT

The legal background for water-quality-derived effluent limitations and total allowable maximum daily polluting loads under PL 92-500 is reviewed. Sophisticated techniques are often required to implement these provisions of the law. Nevertheless, the shortcomings of some techniques and the lack of experience with their use may lead to challenge of their results by those affected. Dissolved oxygen models for streams are dissected as an example of technical shortcomings. Recommended are the support of explicit and probabilistic accounts for the uncertainty of such models' predictions and standardized rules from the Federal government for making the conservative assumptions required by the law when uncertainty is present.

Introduction

Water pollution law has mainly taken two discrete approaches to the control of effluent quality from point sources. One, uniform

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technology-based standards by category of polluter, is favored for its administrative convenience and substantial equity. The other, standards based on the effects of the effluents in the receiving waterway, is favored for its emphasis on protection of waterway uses and for greater overall economic efficiency.

Prevailing Federal law now places primary emphasis on the latter course, though the former is included for minimum standards. The technical aspects of determining allowable pollutant inputs to a waterway segment have not yet been worked out into an airtight package, however. As such, those agencies responsible for implementing the law may find their requirements under legal attack by those polluters most heavily affected.

This paper explores an important dimension of water quality, dissolved oxygen, and attempts to point out the strengths and weaknesses of present methods for determining allowable pollutant inputs related to that parameter. The assessment is preceded by a bit of background on the present Federal water pollution control law and followed by recommendations on some possible ways of proceeding toward having an integrated body of techniques that may deal with some of the weaknesses outlined.

The Law

The Federal Water Pollution Control Act Amendments of 1972 (PL 92-500), hereafter referred to as the Act, contain a dual approach toward control of the quality of effluents from point sources of wastewater. Section 301 establishes uniform, national, minimum treatment requirements for categories of point sources, all based on levels of available technology. In addition to the minimum levels of treatment, Section 301 (b) (1) (C) requires that

> . . . there shall be achieved not later than July 1, 1977, any more stringent limitation, including those necessary to meet water quality standards, . . . established pursuant to any State law or regulations . . . or any other Federal law or regulation . . . .

Water quality standards begin a process required of the states to

> . . . establish for the waters [where effluent limits more stringent than the minima of section 301 are needed] . . . the total maximum daily load for those pollutants which the [EPA] Administrator identifies under section 304 (a) (2) as suitable for such calculation. Such load shall be established at a level necessary to implement the applicable water quality standards with seasonal variations and a margin of safety which takes into account any lack of knowledge concerning the relationship between effluent limitations and water quality.

Under subsequent EPA regulations pursuant to section 303 (e) of the Act [40 CFR 131] each point source of pollutants is to be allocated a portion of the total maximum daily load, with a gross allotment of such load reserved for "nonpoint sources."

Dealing With the Law

Estimation of total maximum daily loads requires in many cases that sophisticated mathematical models be developed. To plan to meet dissolved oxygen standards, one of the more important measures of the health of a waterway, several simultaneous biological, chemical, and physical processes must be accounted for in order to estimate allowable inputs of oxygen-demanding materials.

Total maximum daily loads are to be designed so that water quality standards will be met "during critical flow conditions," 40 CFR 131.11 (f) (1). Point sources have their largest impact at low flows when they are diluted least. Many states have specified the minimum, average, seven-consecutive-day flow with a ten-year recurrence interval as the critical low flow. Other factors associated with low flows also enter into defining criticality. One, high temperature, increases the rates of biochemical reactions and decreases the solubility of oxygen in water.

The multifacet critical conditions, the "margin of safety" requirement, and the strictness of water quality standards to protect indigenous species can combine to leave small allocable loads of oxygen-demanding substances for small streams. Meeting the resulting requirements can be a financial burden to treatment facility owners if federal aid is not available. Allocations for plant nutrients, heat, or other pollutants can add more to the burden.

Ample incentive exists, therefore, for challenges to the total maximum daily loads and allocations developed by the states. Thus, the technical basis for establishing loads and allocations must be strong enough to survive court challenges if there is to be hope of implementing water quality standards. Minimum technology standards have been costly to implement, but have been reasonably successful. Water-quality-derived effluent limitations have not yet been developed enough to speculate on their success.

Dissolved Oxygen Models for Freshwater Streams

It was mentioned that dissolved oxygen is one of the most important indicators of the health of a waterway. States like New Jersey consider it so important that they have oriented much of their

water-quality-management-planning programs exclusively toward this parameter at the expense of considering such other measures of quality as trophic state or nutrient enrichment, temperature, and toxin concentration. Such states wish to take advantage of the enormous amount of work that has gone into developing models of dissolved oxygen balance over the last twenty-years. Comparatively little work that can be applied by decision-makers with small budgets has gone into these other areas.

The fund source for establishing total maximum daily loads is of course EPA. Their old guidelines EPA [1], acknowledge the acceptability of the standard modeling techniques for doing so. Despite this official endorsement and the great body of investigative work behind dissolved oxygen system models, it is the thesis of this paper that they may still be questioned by those affected by conclusions based on their application. The remainder of this section examines some of the theoretical and empirical weaknesses of applied freshwater-stream-dissolved-oxygen modeling. Related issues, such as the specification of particular design critical conditions or quantitative dissolved oxygen standards, two key variables upon which total maximum daily loads are based, are ignored for the sake of brevity, though these are as open to technical scrutiny as the dissolved-oxygen models themselves.

MATHEMATICAL MODELS IN GENERAL

Rickert, Hines, and McKenzie described the array of water-quality-modeling techniques with a pyramid of complexity, total ecosystem models perched at the top and simple dissolved-oxygen and heat-balance models forming the broad base [2]. The pyramid analogy also describes the relative amount of use models in each category enjoys, for as one ascends the pyramid, costs and theoretical difficulties build up exponentially.

Imprecision and inaccuracy in modeling can be lumped together and called error or uncertainty, since it is difficult to separate the two in overall results. One type of error comes from model structure. Abendt postulated that model structure error decreases with increasing complexity [3]. Theoretically, a model paralleling all possible partial chemical and biochemical reactions and storages over time could be quite precise, and would also be quite impractical due to burdensome data requirements for its set-up. Simplified, lumped models, assuming steady-state conditions, first-order reaction kinetics, and simple component interrelationships are the most common used in government decision-making. Few time-variable or ecological models have come into significant use outside research projects.

The other source of error or uncertainty is a result of imprecise and inaccurate observations of the real systems. Incomplete space-time sampling and inaccurate observation procedures may lead to results unrepresentative of the system being observed. Imprecision in preserving and testing samples adds to this. Models calibrated against poor data can at best be poor, and at worst dangerous, if interpreted to represent the real waterway rather than the poor data set.

The basic equations of a dissolved-oxygen model for a stream correspond to those for a plug-flow biochemical reactor. A three-dimensional, time-varying transport equation is the basis for the mass transport of oxygen and oxygen demand. The equation is simplified by temporal and spatial averaging to one space dimension and a temporal steady-state. To achieve the simplicity of plug flow in the equations, an additional assumption of no longitudinal dispersion is often made.

Structural uncertainty is introduced in each simplifying step of the derivation of the integrated set of dissolved-oxygen and oxygen-demand equations. As a consequence, the potential error of the model's representations is increased. Interpretations of its predictions can only be thought of as approximations to long-term, cross-sectional averages of real system behavior.

Given these initial limitations, the following section discusses how the various mechanisms affecting dissolved oxygen in a stream are postulated to act in the context of a one-dimensional, steady-state model, with highlights on the uncertainty of each.

DISSOLVED OXYGEN SUBSYSTEMS

Beginning with Streeter and Phelps' work, there has been substantial effort to uncover processes affecting dissolved oxygen in streams, and to, fit predictive equations to them [4]. Dobbins presented an excellent summary of work to that date, which serves essentially as the present state-of-the-art review [5].

Dobbins broke the sources of oxygen deficit in a stream segment into six categories:

1. upstream oxygen deficit;
2. carbonaceous oxygen demand from point sources;
3. nitrogenous oxygen demand from point sources;
4. carbonaceous oxygen demand from diffuse, uniform nonpoint sources;
5. nitrogenous oxygen demand from diffuse, uniform nonpoint sources; and
6. plant respiration and in-place oxidation of bottom sediments.

Atmospheric reaeration due to equilibrium forces and plant photosynthesis are the two sources of replenishment of the withdrawn oxygen. All are addressed in the following sections.

Hydraulics — Flow and other characteristics of mass movement of water are obviously central to any water-quality model. Well-developed methods of hydraulics exist to measure and predict such accessory variables to flow as velocity, depth, and cross-sectional area. Given enough measurements, precise and accurate sets of physical data can be developed. This aspect of dissolved-oxygen modeling is limited only by the thoroughness of the investigation performed.

Atmospheric reaeration — Reaeration has long been postulated to act as a first-order process, as far back as the pioneering work of Streeter and Phelps [4]. The time rate of change of the concentration of oxygen due to this physical process is considered to be proportional to the oxygen deficit. Temperature affects the process by changing the saturation constant and the proportionality constant in the reaction. Saturation is also affected by atmospheric pressure and the concentrations of certain other substances found in low concentrations in fresh water.

Since the saturation value is a relatively well-predictable physical variable, the proportionality constant is the main source for prediction error. Since the constant is sometimes the most important in the stream for renewal of depleted oxygen, it has been given much study [6]. There have been many theoretical and empirical equations developed for prediction of the constant, relating the exchange of oxygen between the atmosphere and water to surrogates for turbulence, such as mean depth, mean velocity, channel gradient (energy slope), bed roughness, and other measures [7].

Rathburn used a large and reliable empirical data set in evaluating the statistical performance of a large number of these equations. He found the mean per cent errors to range from 2 to over 200 per cent of the values of the constant being predicted. Kothandaraman and Ewing found a standard deviation of 36 per cent of the predicted values when fitting an equation to another large data set on the TVA rivers [8]. Together, these results suggest that the predictability of the reaeration rate constant is somewhat poor relative to its importance.

Carbonaceous biochemical oxygen demand — instream — The five-day biochemical oxygen demand (BOD) test has become the

standard measure of the amount of oxidizable organic matter in water. "Complete" oxidation may take upwards of twenty days, but correlations between the five-day value and the long-term ultimate value have been made.

In the laboratory, after a period of some fifteen days (under standard conditions), oxidation or inorganic nitrogen compounds begins, concurrent with the continued oxidation of the organic (carbonaceous) matter. The nitrogenous fraction is usually considered separately in modeling (see below).

Oxidation of carbonaceous BOD has usually been modeled as a first-order process, considering the time rate of change of the BOD concentration due to oxidation to be proportional only to the concentration. The proportionality, or rate constant, is adjusted for temperature, as is often the initial ultimate BOD concentration value [9].

Besides temperature, the oxidation rate is affected by other factors. Foremost is the nature of the material being oxidized. Complex, persistent organics would have a low associated rate, and simple compounds, such as glucose, would have much higher ones. Domestic sewage treatment plant effluents would have an intermediate rate constant.

Another phenomenon affects the removal, but not the oxidation, of carbonaceous BOD. If some fraction of the substances making up the BOD is in particulate form rather than being dissolved, that fraction is subject to settling in addition to oxidation. Due to the complexity of the turbulent flow processes of some streams, it is almost impossible to predict the rate of settling deterministically. Nevertheless, settling of BOD is still often modeled as a first-order process [9]. Some qualitative information on settling can be gleaned from stream velocity and separate lab tests on soluble and particulate BOD.

Depth also has an indirect effect. Thomann suggested that the total rate of removal could be ten times higher in shallow creeks than deep rivers, due to the better firm substrate-to-volume ratio for oxidizing bacteria and the smaller depth for settling of small streams [10].

Overall, the physical and biological processes of BOD settling and oxidation are not as strongly understood as atmospheric reaeration and hydraulics. This may be partly a result of the high inherent error of the BOD test. It may also be due to the large stochastic influences on the oxidation rate constant. Kothandaraman and Ewing reported a standard error of over one-third of the mean value in measurements of the rate on the Ohio River [8].

Nitrogenous biochemical oxygen demand — instream — The secondstage surge in the laboratory BOD time curves is due to the oxidation of nitrogenous compounds by autotrophic nitrifying bacteria. Three separate reactions take nitrogen from organic molecules (largely as amine groups of amino acids) to ammonia, from ammonia to nitrite (by *nitrosomonas)*, and from nitrite to nitrate (by *nitrobacter*). The latter two steps consume oxygen, overall 4.57 milligrams of oxygen per milligram of ammonia-nitrogen converted to nitrate nitrogen [11].

Factors affecting the extent and rate of nitrification include [12]:

1. pH. An alkaline environment is needed to neutralize the acidic end products of the ammonia-to-nitrite reaction.
2. Presence of organic matter in high concentrations (not usually a significant factor in natural waters). Heterotrophic bacteria that process the organic matter appear to use most of the available nitrogen for their own nutrition, and can outcompete the nitrifiers.
3. Slow growth rate of nitrifying bacteria.
4. Surfaces for growth of nitrifying bacteria. Growth is best on firm substrates, such as rocky streambeds.

Temperature also has an accelerating effect on nitrification rates, as in the oxidation of carbonaceous BOD.

The overall nitrification process has been modeled in two ways. One treats the overall set of reactions in one lumped, first order equation [10]. The other uses separate routing equations for each of the four sets of nitrogen compounds [12].

The lumped, one-equation apprach requires far less data than its alternative, but it does not allow consideration of the uptake of nitrogen by plants, which can remove ammonia from the water without using up oxygen.

Predictability of the nitrification process is much poorer than that of the carbonaceous BOD oxidation process due to the stricter environmental requirements of the nitrifiers. Such factors as organic matter, algal nutrient uptake rates, and pH must be known to estimate nitrification rates with reasonable accuracy.

Point sources of oxygen demand — Wastewater treatment plants characteristically exhibit a highly variable effluent in both quantity and quality. Diurnal water use patterns in residential areas tend to peak in the afternoon and reach a minimum during early morning (2:00 to 3:00 AM), sending a variable amount of water to a domestic treatment plant. Concentrations of pollutants in raw wastewater also

vary during a day, but less extremely. This diurnal variability is passed on through the treatment plant unless it uses pretreatment equalization.

Weekly patterns may also be evident, caused by work force patterns that place more people at home on weekends than on weekdays. Annual patterns are also significant, particularly in areas with large seasonal populations.

The performance of treatment equipment also varies probabilistically. Bulkley found in one treatment plant in Michigan that removal efficiencies of selected substances were pretty much unpredictable, and that they even fit standard probability distributions poorly [13]. A change in equipment at the plant reduced the spread of the measured efficiencies for some parameters, but still performance was unpredictable. It would appear that the equipment used, operation and maintenance practices, hydraulic loading, and other highly variable factors have a strong effect on the stochastic performance.

Some rough correlations concerning effluent variability were made by Adams and Gemmell [14]. They postulated a power curve relationship between size of domestic treatment plants and the variability (as the coefficient of variation) of their effluent quantity and quality. They found their equations to explain more than half of the variation of their data sets in several cases.

Overall, though, it appears that most point source effluents are poorly represented by steady-state average numbers. Variability ranges of effluent quantity are reasonably well known due to their importance in plant design. Variability of effluent quality is poorly known.

Nonpoint sources of oxygen demand, benthal demand, and plant photosynthesis and respiration — These influences on oxygen in a waterway are much harder to quantify than those from point sources. Many vary with streamflow or solar radiation. Others vary with the concentration of oxygen or oxygen demand in the water.

Benthal deposits of organic matter, perhaps of decaying plants or sewage solids, undergo decomposition either anaerobically or aerobically. Aerobic decomposition takes up oxygen from the water above. Both processes take place in deeper sludge layers, with release rates to or withdrawal rates from the water column being related to the concentration of the released or withdrawn substance in the water column [15].

Swamp runoff can be high in organic matter. Acting as nutrient traps, swamps and marshes convert nutrients into biomass, a product that is exported to the surface drainage way.

Plants liberate oxygen as a by-product of photosynthesis, a process that follows a stochastic, periodic pattern coupled to the stochastic periodicities of solar radiation incident on the water surface.

Light is, of course, uneven throughout the day if there are clouds. The penetration of light below the surface depends on reflection at the surface and from the bottom, turbidity, and the concentration of algae and the thickness of rooted plants. Each of these factors, some of them stochastic or time-variable, can affect light penetration and consequently photosynthesis.

The largest source of error in predicting photosynthesis would appear to be from predicting algae and other plant abundance. Most of the factors involved in aquatic plant growth are exogenous to an oxygen model. Models for predicting algal abundance are considerably more complex (and probably more unreliable) than simple oxygen models.

Plant respiration is less affected by light and consequently is less variable with time. Its importance comes at night, when it continues while photosynthesis ceases. Of course, the problems of predicting plant abundance exist here as with photosynthesis.

The mathematical model terms related to these nonpoint phenomena often become lumped error terms when used to force-fit the model's predictions to observed in-stream concentrations. As such, they may reflect sampling and analytical errors in addition to actional nonpoint phenomena.

Conclusions and Recommendations

The simple conclusion of the preceding part of this paper is that there still exist large unexplored or undeciphered areas of the technical aspects of establishing total maximum daily loads of oxygen-demanding substances. Yet we cannot quantify how uncertain we are in total, particularly when a model is used in an extrapolative sense, to make predictions for driving forces substantially different from those upon which the model was originally based. The question still remains; how sure do we have to be to implement the limits based on our technical analyses? The courts ultimately will be the testing ground for this question.

Given that it will be impossible to eliminate all manner of uncertainties in a short time period, for the time being recommendations should deal with setting up methods for determining uncertainty and rules for what amount of uncertainty is allowable under what conditions.

The mathematical language of uncertainty is of course probability.

The literature has quite a few examples of probabilistic water quality modeling [14, 16—19]. Unfortunately, the expanded data requirements of such methods have meant limited real-world application. Further support for development and practical application of these approaches is needed, with the aim of developing methods for quantifying the uncertainty over entire models.

The development of rules for margins of safety as hedges against uncertainty is both necessary and difficult. One approach would be to base the margin on the total uncertainty predicted by a probabilistic model. Higher uncertainties (as higher variances, perhaps) would warrant higher margins of safety. Without probabilistic models, there are few objective bases for quantifying safety margins. Yet a standard consensus method would be a substantial improvement over unofficial and ad hoc methods used today. EPA should take this action at the nationwide level so as to provide uniform guidance to all of the states.

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