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USE OF PROBABILISTIC INFORMATION IN THE WATER QUALITY BASED APPROACH

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16. ABSTRACT

During the past two decades, implementation procedures in wastewater management often resulted in a large margin of safety being incorporated into the use of water quality criteria for the protection of aquatic life and its uses. Wasteload allocation design conditions, such as the use of seven-day, ten-year low flow, gave assurances of instream concentrations well below the water quality criteria for a large percentage of time. Present-day economic conditions and the increasing cost of advanced wastewater treatment are necessitating a re-examination of how water quality criteria are being used in the water quality based approach for establishing effluent limitations.

The relationships between water quality criteria and other components of the water quality based approach are identified. The need for a better defined and more consistent use of statistical information is suggested not only in the development of water quality criteria but also for the entire water quality based approach. Intensity, duration, and frequency of occurrence (return period) appear to be three common statistical parameters of the six-step water quality based approach. Research is identified, which if successful, would allow water quality managers better insight in determining pollutant exposures that more adequately simulate receiving water conditions resulting from variable stream flows, wastewater discharge rates, and pollutant concentrations.

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ABSTRACT: During the past two decades, implementation procedures in wastewater management often resulted in a large margin of safety being incorporated in the use of water quality criteria for the protection of aquatic life and its uses. Wasteload allocation design conditions, such as the use of seven-day ten-year low flows, gave assurances of instream concentrations well below the water quality criteria for a large percentage of the time. Present-day economic conditions and increasing cost of advanced wastewater treatment are necessitating a re-examination of how water quality criteria are being used in the water quality based approach in wastewater management implementation procedures.

The interrelationships of water quality criteria and other steps of the water quality based approach are identified. The need for a better defined and more consistent use of probabilistic information is suggested not only in the development of water quality criteria but for the entire water quality based approach. Intensity, duration, and frequency of occurrence (return period) appear to be three common statistical parameters of the six steps of the water quality based approach.

Research is identified which, if successful, would allow water quality managers more insight into the better selection of pollutant exposure histories that more adequately simulate receiving water conditions, resulting from variable stream flows and wastewater discharge rates. It is also suggested that more aquatic toxicity research resources be focused on those areas where greatest variability and lack of knowledge currently exist, such as in species selection, incorporating fluctuating exposures, considering multi-pollutant effects, field applicability, etc.

Introduction

During the 1950's and 1960's, water quality criteria for the protection of aquatic life prescribed a maximum pollutant concentration for the receiving water. The criterion was usually presented as a "no-effect level" which would protect aquatic life and its uses under most ambient conditions. This was readily interpreted as applying to all stream flow and wastewater discharge conditions.

This "no-effect level" ambient concentration concept is analogous to a speed limit for our highways. That is, a posted highway speed limit is in essence a maximum "safe" speed for traffic under optimum road conditions. For both the water quality criteria and the speed limit applications, the "safe" limits have no time period restrictions. That is, the no-effect concentration can be maintained in the receiving water "forever"; likewise, one can drive forever at the maximum speed limit. The only safety factors incorporated are those asserted in developing the no-effect concentration or the maximum speed limit.

The early intended use of water quality criteria was, in general, to allow the determination of whether the concentration of a pollutant in the receiving water was above, and/or below a level deleterious to aquatic life; simply stated, "safe" or "unsafe".

The purpose of this paper is to demonstrate how the use of water quality criteria/standards has gone beyond the "speed limit" stage and its use expanded in the water quality based approach. The interrelationships of water quality criteria and other steps of the water quality based approach are identified. The need for a better defined and more consistent use of probabilistic information is suggested for the entire water quality based approach. Research areas that require further study are identified.

Expanded Use of Water Quality Criteria in the Water Quality Based Approach

A major departure from the early intent (safe or unsafe) occurred when water quality standards were used to establish wastewater treatment requirements as part of the water quality based approach. The water quality based approach, as envisioned today, encompasses many technical, socioeconomic, and judgmental issues which previously were not rigorously addressed. It consists of the following components:

1. Establishment of water quality standards, including:
    a. Use attainability analysis;
    b. Development of water quality criteria, including site-specific modification of the national criteria;
    c. Impact analysis.
2. Wasteload allocation process.
3. Development of wastewater discharge permit limits.
4. Design of wastewater treatment facilities.
5. Operation and maintenance of wastewater treatment facilities.
6. Compliance monitoring of both effluent and ambient receiving waters.

Water quality standards today take on more meaning, and therefore the use of standards needs to be better defined and be more consistent with the water quality based approach. In the establishment of water quality standards, both water quality criteria and use attainability analysis are integral aspects. In this interpretation, criteria and use attainability are linked through exposure and water-body use attainability analysis. Water quality standards, once established, are incorporated in the wasteload allocation process.

To illustrate this point, let us examine how receiving stream flow characteristics are utilized along with water quality criteria in the wasteload allocation process. One part of the wasteload allocation process includes a statistical analysis of hydrologic stream-flow discharge rates. This analysis was usually accomplished independently of the water quality criteria setting process. For example, for a wastewater discharge containing a toxic pollutant, the analysis can result in design conditions in which the "criterion" concentration is applied to a relatively severe hydrologic condition which may occur less than five per cent of the time. At all other times, the concentration in the receiving water will be much less than the prescribed "criterion" level. This use of water quality criteria in conjunction with the hydrologic analysis has led to the establishment of wastewater permits and the design and operation of waste treatment plants that are based on the "worst case" analysis.

The degree of rigor involved in hydrologic analysis in the late 1950's has greatly expanded through the use of operations research techniques. The use of advanced statistical techniques including synthetic hydrology has given the water quality planner greater insight into the sensitivity of stream-flow conditions and wastewater treatment requirements. Nevertheless, the two processes of development of water quality standards for the protection of aquatic life and analysis of hydrologic factors were done independently, and this has lead to the incorporation of unnecessarily large safety factors under some stream-flow conditions.

Stream Flow and Exposure Considerations

Let us further examine the selection of stream-flow design conditions. Historically, the water quality based approach has been based on the selection of stream-flow design conditions such as 7Q10, which is the lowest seven-day stream flow that occurs, on the average, once every ten years. The specification of a stream flow (intensity) for a seven-day period (duration) that occurs, on the average, once in ten years (frequency of occurrence or return period) was the basis for calculating the permit limitations. These three statistical parameters: intensity, duration, and return period, are major input variables in the six steps of the water quality based approach. However, many times the three parameters are either not well defined or not used in a consistent manner.

In many wasteload allocation processes [1] especially for BOD-DO analysis, there often is a coupling using relationships between stream flow characteristics and DO targets. Nevertheless, the basic design parameters are usually developed mainly from hydrologic considerations, not from toxicological, proposed use, or water quality criteria considerations.

Statistical analysis of the exposure of aquatic systems to toxic pollutants can bridge the gap between the development of standards and their use in wasteload allocation. Pollutant exposure analysis has three basic properties which are very analogous to precipitation analysis [2]. In precipitation analyses, one requires probabilistic information concerning the intensity of rain storms of various frequencies and for specific durations. From these analyses one can determine the average intensity of a given frequency of rainfall for any desired duration. The same probabilistic techniques can be used to develop the three pollutant exposure statistical parameters for a stream reach or lake segment. The three parameters are: intensity, as measured by the concentration of a pollutant; duration, as measured by the exposure period; and return period, as measured by frequency of occurrence. These parameters can facilitate the selection of design conditions for an ambient receiving stream's "pollutant exposure" which can be expressed, [illegible] ly to the stream flow design condition, as "7C10" where 7 is duration of exposure in days, C is the water quality criterion, and 1[illegible] retu[illegible] eriod in years. This simple analysis provides a mechanism f[illegible] he probability of events or exposure periods during which t[illegible] ng water concentration may be above or below the no-effect level. This ability to analyze these exposure periods or events during which the toxicity of a pollutant may be deleterious -- depending, of course, on the intensity, duration and frequency or return periods of the events -- adds greatly to our understanding of how toxicity can occur and thereby helps to ensure appropriate protection.

Water Quality Criteria Interrelationships

As our understanding of aquatic toxicological science became more sophisticated in the 1970's in the development of water quality criteria for the protection of aquatic life, there evolved a two number criterion. The criterion includes a maximum concentration, usually for protection against most acute toxic effects, and an average concentration for protection against most chronic toxic effects. The National Guidelines [3] for deriving water quality criteria, which were developed in 1978 and updated in 1980, reflected this refinement in establishing national water quality criteria.

To investigate the interrelationships of water quality criteria, wasteload allocation limits, return period, stream flow, statistics, time averaging periods, and pollutant toxicity information (acute/chronic ratio), a joint study was undertaken between the Environmental Research Laboratory-Duluth and Manhattan College [4]. Preliminary study results suggest the following:

1. For toxic chemicals with an acute/chronic ratio less than 100 and being discharged into a stream with high flow variability, the wasteload allocation limits are mainly controlled by the maximum water quality criterion with return periods having a major impact. For chemicals with an acute/chronic ratio above 100, the wasteload allocation is controlled by the average water quality criterion.
2. For toxic chemicals with an acute/chronic ratio less than 15 and being discharged into a stream with low flow variability, the wasteload allocation limits are mainly controlled by the maximum water quality criterion, with return and time averaging period being of lesser importance. For chemicals with an acute/chronic ratio greater than 15, the average water quality criterion is restrictive.
3. When the third condition is added to prevent significant excursions between the maximum and average concentrations, it becomes the most restrictive in the wasteload allocation process for toxic chemicals which have an acute/chronic ratio of about 8 or more, and stream flow variability and return period considerations have small impact on restricting wasteload allocations.

The preliminary analysis clearly demonstrates the interrelationships and the need to integrate fully the various processes of the water quality based approach.

Use Attainability Considerations

It is important to review how the water quality criteria are established. The basic building blocks for the criteria are laboratory tests--acute, chronic, and bioconcentration--at steady-state exposures, and generally in clean test waters. The algorithm that has been developed for the National Guidelines brings together the information required to derive criteria, including a maximum concentration and an average concentration, that must be maintained to protect aquatic life and its uses. The intent of the two-number criteria was to give the planner more information and degrees of freedom in the water quality based approach. A major question to be asked is: are use attainability considerations and analyses congruent with the entire water quality based approach?

If the analogy of the speed limit for traffic control is further examined, additional considerations arise. If the maximum concentration is analogous to the maximum speed limit that cannot be exceeded, the average concentration has no direct analogy in traffic control, unless we begin to distinguish between "maximum" or "safe" speeds. This distinction adds significantly to the process and involves other technical, socioeconomic, and judgmental issues. For example, how many accidents within a given time period and of what type are we willing to accept? Likewise, in the protection of aquatic life, how many exposure events and for what duration within a given time period and at what intensity are we willing to accept?

The current water quality based approach suggests that the amount of wastewater treatment provided should consider not only the establishment of a numerical water quality criterion for a given pollutant for the protection of aquatic life, but also "use attainability" considerations. Use attainability, including level of protection for a given site, can have a significant impact on the other component steps of the water quality based approach. For example, the selection of wasteload design conditions for duration and return period should be based more on the use attainability analysis than on hydrologic and exposure considerations alone. The selection of design conditions for return period, above a given design exposure concentration (intensity) and duration, should consider the assemblage of the aquatic organisms to be protected; that is, their biological value to the aquatic community and their ability to repopulate. One further point is worth mentioning here. If two deleterious events occur back-to-back, the impact of the two events may be additive. Therefore, we may need also to include an additional parameter for this effect, especially when small periods of return are considered.

Toxicological Considerations

In reviewing the National Water Quality Criteria Documents, one can readily see that for certain pollutants the slope of the ranked acute toxicity plot for the species tested is very steep, suggesting that all of the species tested with that chemical have similar toxicity responses. For other pollutants the species rank curve is relatively flat, suggesting that some species are greatly more sensitive than others. A key question here is how can we best take advantage of the information already known about the differences in species sensitivity to given pollutants? Can we take advantage of this information by treatment of these relationships in a more probabilistic nature?

Receiving stream data clearly demonstrate that the ambient concentration of pollutants can vary significantly, influenced mainly by effluent and stream flow variability. The preponderance of available toxicity data has been developed using clean water and constant toxicant concentrations. We are just beginning to study fluctuating exposures in the laboratory. Models [5] have been suggested for certain pollutants which can incorporate the toxification/detoxification process, mainly on an acute basis. Laboratory data for certain compounds, such as ammonia [6], suggest that even short exposure periods (hours) can have severe biological impact. With the high cost of data generation using existing laboratory test methods, the need exists to make better use of existing data bases by extrapolating from steady-state to fluctuating exposures. It is paramount in this extrapolation process to keep in perspective the receiving water pollutant exposure statistical parameters--intensity, duration, and return period.

All of the above items suggest more extensive and expensive testing and analysis requirements in the water quality based approach. Is this really true? Some preliminary studies [7] suggest that ecosystems may be more similar than dissimilar with respect to toxicological endpoints, when comparative toxicity analyses are made that couple the derivation of site-specific water quality criteria and analysis of use attainability requirements. If so, the process should collapse, not expand, into multi-toxicological endpoints. More extensive comparative toxicological analysis including probabilistic considerations in use attainability analysis should aid in answering this fundamental question.

Studies [8] have indicated that most wastewater discharges contain multiple pollutants near or above the concentrations required to protect against chronic effects of aquatic life. Many of the pollutants are not readily removed by wastewater treatment, and are persistent in surface receiving waters. The ability to incorporate multiple pollutant effects in wasteload allocation, even at steady-state conditions, is not well developed at the present time. The inclusion of multiple pollutants under fluctuating conditions is even more poorly understood. Although the use of laboratory toxicity tests on complex effluents is promising [9], much more research is needed in use of the complex effluent toxicity testing approach as an alternative to single pollutant testing in the water quality based approach, including incorporating appropriate intensity, duration, and return period considerations.

The selection of wasteload design conditions for intensity and duration of pollutant exposure should be based more on toxicological considerations (i.e., water quality criteria/standards) than on hydrologic conditions alone. The pollutant exposure design conditions should reflect both the characteristics of community assemblage to be protected and of the toxicological characteristics of the toxicant.

Need For An Integrated Approach

Inherent in all six steps of the water quality based approach are design conditions which contain time variables like intensity, duration of exposures, recruitment time, return period, permit limits, wastewater treatment design conditions and monitoring frequency. Although different terminology is often used in each of the steps, one can grossly aggregate time considerations into three parameters: intensity, duration, and return period.

Studies [10] have shown that the concentrations of pollutants in effluents and from non-point sources vary considerably but can be represented by a probability function. Likewise, studies [11] have shown the ambient stream concentrations of most pollutants vary considerably but also can be expressed by a probability function. Although the robustness of the functions is debatable, probability functions, for the most part, can be developed.

Such analyses suggest that most pollutants are "event" oriented with a determinable intensity, duration, and return period. In the development of this argument further, the need for aggregating common time units becomes more obvious as indicated below:

1. Water Quality Standards
   - What properties of the aquatic systems are to be protected or not protected, and to what extent?
   - What frequency and duration of impairment should be used for use attainability analysis?
2. Wasteload Allocation
   - What are the major factors that influence exposure and impact in receiving water: wastewater effluent variability, stream flow variability, or physical, chemical, and biological transport processes?
3. Wastewater Discharge Permit Limits
   - What are options for expression of loading, in terms of intensity (concentration), duration, and return period time units?
4. Wastewater Treatment Design
   - Are the design parameters such as hydrologic loadings and treatment removal effectively based on time parameters similar to those used in setting water uses?

5. Wastewater Treatment Operation and Maintenance

. Are the operational procedures resulting in effluents with the prescribed pollutant concentration expressed in intensity, duration, and return periods?

6. Monitoring

. Is the monitoring program of both effluent and ambient receiving water properly addressing time-event conditions?

What does this mean in terms of the state of the establishment of water quality criteria in the water quality based approach for the protection of aquatic life? The message is very clear. No longer can we consider water quality criteria for the protection of aquatic resources as a simple speed limit. We must better understand how it is used in the entire process of the water quality based approach. We have taken a major first step, in the authors' opinion, by developing a two number criteria; that is, maximum and average concentration numbers. However, these terms need to be better defined in relation to the entire water quality based approach. For example, what is maximum? What is average? What return periods do these two number criteria suggest in wasteload allocation, if any? Should the duration and return periods be the same or different for the maximum and the average concentration? Better defined and more consistent use of the probabilistic parameters are needed for all steps of the water quality based approach.

Safety Factor Considerations

The need for safety factors in the water quality based approach can be debated, but it is of paramount importance to determine when safety factors are being employed, either intentionally or unintentionally. If a better defined and more consistent use of probabilistic information were incorporated into the water quality based approach, it would be much easier to determine what safety factors are being employed and when the factors are or are not additive.

In the development of water quality criteria and standards, the speed limit concept does not incorporate any safety factors. The incorporation of safety factors for protection of aquatic life results in the selection of design conditions such as in wasteload allocation for calculating permit limitations from water quality standards.

In the authors' opinion, much of the margin of safety provided by these intentional or unintentional safety factors has provided a "cushion" for scientific uncertainty in developing water quality criteria for the protection of aquatic life. We should be well aware of the consequences to the environment when we begin to reduce these margins of safety in the water quality based approach.

Conclusions

In summary, intensity, duration, and return period of a pollutant exposure event appear to be the common statistical parameters also used in the other component steps of the water quality based approach. We need to understand better how these common statistical parameters can be utilized in the entire water quality based approach, so that consistency can be obtained and maintained; that is, consistency in criteria development, use attainabilty determination, wasteload allocation, impact analysis, wastewater treatment permitting, treatment design and operation, and monitoring compliance.

Specifically:

1. An approach for statistical defining receiving water pollutant exposure is suggested consisting of the parameters of intensity, duration, and return period.

2. More emphasis should be placed on the consistent use of intensity, duration, and return period, not only in defining acute and chronic toxicity and bioaccumulation required in developing the water quality standards, but in the entire water quality based approach.

3. It is well established that ambient concentrations fluctuate due to many reasons, as indicated earlier. We must be able to incorporate into our current aquatic toxicology research, either directly or indirectly, the ability to handle fluctuating exposures.

4. Most systems have more than one pollutant. We must begin to give more attention to chemical interactions of pollutants and to multi-pollutant toxic effects. Currently we have a very limited capability for handling multi-pollutant effects under both laboratory and ambient conditions. This could be improved in a number of ways: use of simple models, multi-pollutant models, or toxicity tests on complex effluents or instream toxicity determinations.

5. The species sensitivity comparative analysis must be coupled to use attainability--that is, what use are we trying to protect--not only the specific communities, but for what intensity, duration, and return period.

6. More rigorous comparative toxicological studies to determine species sensitivity differences for a range of organisms and compounds. These relationships should be examined probabilistically and if possible be incorporated into the water quality standards process.

The above indicates that although we have come a long way in aquatic toxicology research in support of the water quality based approach, there are many areas in which we can become more effective, efficient, and consistent in developing a scientific basis for the water quality based approach. We need to focus our research efforts on these areas. We need to determine what are the key parameters that have the greatest impact on the entire process and focus our research effort on answering the key unknowns for these parameters, so that the effectiveness of the water quality based approach can be maintained.

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