Advances in Water Pollution Control

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SYSTEMS ANALYSIS IN WATER QUALITY MANAGEMENT

Editor: M. B. BECK

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INTERNATIONAL ASSOCIATION ON WATER POLLUTION RESEARCH AND CONTROL

SYSTEMS ANALYSIS IN WATER QUALITY MANAGEMENT

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Editor

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IAWPRC Specialist Group on Systems Analysis in Water Quality Managment

FOREWORD

The resolution of today's complex issues of water pollution control requires a systems approach. Or so it is often said, for do we really know what is meant by this catch-phrase "a systems approach"? Indeed, do we even need to define it precisely? I have spent much time in reflecting on what might be meant by a systems approach, and have come to no succinct conclusion. Perhaps then it is that a systems approach is something that one will recognise when one sees it.

When the IAWPRC Specialist Group on Systems Analysis in Water Quality Management was formed in 1984 it had five fixed points by which to determine its subject area. These were (and still are) that:-

i. Systems analysis is a matter of the exchange and progression of ideas across traditional disciplinary boundaries.

ii. It is a subject whose very foundations are an antidote to the natural tendency of the educational process to increasing specialisation of interest.

iii. It frequently requires the development and use of a mathematical model, though it is by no means synonymous with mathematical modelling.

iv. It is very definitely concerned with the more formal, systematic analysis of decision-making situations, but it is also a subject whose objective may simply be the acquisition of a scientific understanding of a problem or a system's behaviour.

v. It seeks to distil from a variety of perhaps superficially quite different problems, principles of problem-solving of a more general, universal nature.

Specifically in the area of water quality management, systems analysis is concerned with all aspects of the water cycle and those facilities affecting and affected by the quality of that water. Its concerns range across the needs of planning and the needs of operational management.

There is an order to the sequence of papers that follow. Essentially it traces a path from the broader, longer-term matters of planning (for a "better future") to the more detailed, shorter-term considerations of the operational policies that will be necessary to satisfy and maintain these planned objectives. En route, special reference will be made to the topical issue of acid rain. And the proceedings will finish with a look forward to the potential of information technology - and to the re-assessment of long-held conventional views that this may eventually provoke.

In sum, I hope that the reader, on seeing this collection of papers, will recognise the "systems approach".

It is, of course, a pleasure to acknowledge those who have contributed to the making of these proceedings and of the Symposium from which they derive. First, the Group would like to thank all the authors for responding so generously with the submission of their papers. Second, I would like to thank the Group members for responding so well in defining the content and direction of the Symposium. On behalf of the Group, I would also like to thank Professor R.V. Thomann for accepting our invitation to give the keynote address to the Symposium. Third, I am most grateful to the members of the IAWPRC Secretariat for taking on all the organisational and administrative responsibilities of this meeting.

Finally, it amuses me how things acquire names; and it may amuse others too. I can reveal in this case that WATERMATEX owes its existence to Margaret Kitchingman and Tony Milburn of the IAWPRC Secretariat. It is definitely about water and for me it is also pleasingly suggestive of both mathematical modelling and automation. I believe all of us should be grateful to Margaret and Tony for this invention. We so nearly had to live with SAWQUAM.

M.B.Beck,
Secretary,
Specialist Group on Systems Analysis in Water Quality Management.

CONTENTS

SYSTEMS ANALYSIS IN WATER QUALITY MANAGEMENT— A 25 YEAR RETROSPECT

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ABSTRACT

A reflection is presented of the utility, credibility and application of water quality systems analysis techniques over the past several decades. The emphasis is on predictive water quality models and the U.S. experience. The complexity of the water quality questions and associated modeling has increased by orders of magnitude. Models of sediment interactions and effects of toxic substances are crucial to further development. Four criteria for judging performance and impact are discussed: usefulness, accuracy, serendipity and ownership. Models are widely used in decisions regarding alternative controls specifically to improve cost effectiveness. The results of systems techniques need to be detailed in a wide ranging effort of post audit analysis following implementation of environmental controls. Legislation and policies have incorporated, in a general way, the principles of water quality systems analysis, with the notable exceptions of a widespread reliance on technology based effluent programs and a general disregard of cost trade-offs using principles of optimization. It is concluded that the impact of systems techniques has been broad and significant. Increased quality assurance of model formulation and calculation is necessary to ensure frameworks that are rigorous and state of the art. A need exists for upgrading of understanding by users of water quality systems techniques and the time has arrived for a major world-wide effort to compile the economic advantages of using systems techniques for more informed and efficient decision making.

KEYWORDS

Water quality models; post audit; systems analysis; criteria for impact; model usefulness; model performance; dissolved oxygen; eutrophication.

INTRODUCTION

My dictionary (Webster's, 1963) defines a Retrospect as "a review of, or meditation upon past events" as opposed to a Retrospective which is "a generally comprehensive exhibition showing the work of an artist over a span of years." This paper is a reflection on our past, meditative perhaps at times, but not intended to be a comprehensive exhibition of our collective artistic works. That would be a task well beyond my own competence. So what I have to offer in this retrospect are my own thoughts, views, comprehensions and understanding of where we have been in the last 25 years in this (sometimes perceived) arcane practice of systems analysis applied to water quality management.

To review our past, to evaluate the impact, or lack thereof, of systems analysis in water quality management is essential, if we are to offer the decision making community a state-of-the-art understanding of comtemporary water quality issues. What effect has our work had on the decision making process? Does our work really matter or are we just talking and reporting to ourselves? What are our "successes"? Our "failures"? Indeed, what are the criteria that we can even suggest as useful for judging the significance of our work on the water pollution community at large? Finally, what does the future hold and what are the emerging issues?

NATURE OF SYSTEMS ANALYSIS IN WATER QUALITY MANAGEMENT

In the present context, we begin by offering a definition of systems analysis: "The engineering art of integrating and synthesizing the physical, chemical, biological and mathematical sciences with the social and economic sciences to construct frameworks that elucidate the consequences of alternative water quality and water use objectives."

The principal components of this definition are:

1. Engineering art of integration: implying (a), a focus that is practical in nature (the engineering), (b), a certain "flair" that tends to be personalized and less than totally scientifically rigorous (the art), and (c) a culling and rebuilding of key elements of diverse disciplines (the integration).
2. Synthesis of the natural and mathematical sciences with the social and economic sciences: implying that what we do is more than mathematical modeling of natural systems and incorporates policy, economic, social and cultural issues into the analysis.
3. Elucidation of consequences of alternatives: implying that water quality systems analysis has much to say in the process of decision-making including revelation of previously hidden behavior and formulation of new alternatives.

Within these broad components, the key steps are:

1. Evaluation of the Problem
    a. Residuals input determination
    b. Mathematical model construction
    c. Assessment of risk to human and ecosystem population without controls
    d. Specification of a range of feasible water quality/use objectives
2. Evaluation of Alternative Controls
    a. Determination of effectiveness of alternatives
    b. Optimal cost/benefit analysis
3. Decision and Promulgation of Control Program
    a. Water quality standard setting
    b. Determination of allowable risk
    c. Optimal control strategies
4. Implementation of Control Program
    a. Waste load allocation
    b. Negotiation and issuance of discharge permit
    c. Monitoring of Program
5. Post-Audit of Program
    a. Attainment of water quality standards
    b. Attainment of water use objectives
    c. Evaluation of costs and benefits
    d. Predictive capability of model framework

With no apologies for an obvious bias, at the heart of the entire sweep of these components and key steps is the construction of credible, defensible and predictively accurate mathematical modeling frameworks. Without such predictive capability, it is simply not possible to develop a firmly based water quality management program. It is for this reason that much of the effort in the past several decades has been in developing predictive mathematical models of water quality at a variety of different levels of complexity. All of these models are aimed first at calculating the expected concentrations of water quality variables. These concentrations then form the basis for risk assessment to the aquatic ecosystem and to the public health. Thus there have been intensive efforts in developing models that can be used with confidence in evaluation of alternative controls, cost/benefit analysis, risk assessment and optimal control strategies.

I would like to focus on this area of water quality models not to the exclusion of the socio-economic models (e.g. optimization of water quality) but simply to emphasize the central role that predictive models play in the decision-making process.

Historically, we have developed systems frameworks and more specifically water quality models for three broad classes of problem contexts: 1) Biochemical oxygen demand (BOD)/ dissolved oxygen (DO), 2) Aquatic plants and nutrients, and 3) Toxic substances. Within these contexts, attention has been variously placed on steady state and time variable deterministic frameworks to ensure credible inclusion of relevant mechanisms as well as incorporation of uncertainty and probabilistic concepts to insure consideration of stochastic elements in alternative evaluations. Models have grown from the two state variable BOD/DO models to multi-state variable (e.g. 20) models of phytoplankton/ nutrient models. Spatial detail has increased by orders of magnitude from simple stream calculations to finite difference models of 500 or more grid points. Time variable calculations have emerged extending from hour to hour calculations to long-term year to year calculations. Hydrodynamic circulation models are increasingly coupled to water quality models.

Reflection indicates some general observations:

1. The aquatic plant/nutrient problems are the most difficult models with which we have worked because of the complexity of the plant biology, the non-linear interactions between nutrients and aquatic plants and the interactions of the sediment.
2. The dissolved oxygen problems, connected intimately with primary productivity and sediment effects, in spite of the long history, tend to be considerably more complex than generally believed.
3. Sediment interactions are important to all water quality problem contexts and apparently credible interactive sediment models are only now appearing.
4. Toxic substances fate models, linear in nature, tend to be less complex than generally believed.
5. Past emphasis was on models of fate (i.e. concentration), future models must of necessity include prediction of effects on the aquatic ecosystem and to a degree on human health; toxic substances represent the most complex problem context experienced to date for prediction of effects of exposure concentrations.

With this background and observations, it is necessary to inquire to what degree water quality systems analysis has been "satisfactory" in some sense and the degree of impact on the larger decision-making process.

CRITERIA FOR JUDGING PERFORMANCE AND IMPACT OF SYSTEMS ANALYSIS IN WATER QUALITY MANAGEMENT

In this context, "systems techniques" are considered the entire process discussed earlier, within which are embedded predictive water quality modeling frameworks. The following criteria are offered for judging performance and impact of systems techniques:

1. The criterion of USEFULNESS, i.e. the degree of use of the frameworks in decision-making; does it really matter whether systems techniques are available?
2. The criterion of ACCURACY, i.e. the comparison of predicted water quality to actual water quality after a control program has been implemented; a post-audit analysis of the problem context.
3. The criterion of SERENDIPITY, i.e. whether systems techniques expose new, previously hidden interactions that are significant from a decision-making point of view.
4. The criterion of OWNERSHIP, i.e. the degree to which the community at large takes ownership of our principles through legislation, regulations and policies that reflect the insights of systems techniques.

Criterion #1 - Usefulness

There is little doubt that water quality modeling and system techniques are now used quite extensively in water quality management decision contexts. Negotiations for discharge permits, evaluation of varying alternatives, support for higher or lower degrees of treatment are all areas that now make extensive use of water quality modeling. On the other hand, the use of optimization planning models (e.g. cost minimization models) and optimal implementation programs (e.g. effluent charges) is apparently not as widespread. The relative extensive use of water quality modeling techniques has been justified on economic grounds, i.e. the belief on the part of regulatory agencies and dischargers that when properly applied, the application of the principles of predictive modeling is necessary but not sufficient to a rational decision. Tiemens (1986) reports that for the USEPA in Washington, D.C., about

100 projects have been reviewed over the past 8 years. In about one-half of these projects, the review, which included application of the principles of systems analysis in varying degrees, resulted in deferring the decision or a significant change in the proposed environmental control. The total capital costs of these projects impacted by the review was about $1 billion. Tiemens estimated that other smaller projects reviewed elsewhere at the state and regional levels may be an additional 200-300 in number but with a lesser overall total cost. So our techniques are useful and are being used in a variety of review contexts. A tributary to the Chesapeake Bay system serves as an illustration.

The Wicomico River. For this problem, (Salas and Thomann, 1975), data indicated a potential violation of a DO standard under low flow conditions due partly to a large diurnal variation of oxygen. Chlorophyll levels were high (e.g. 300 μg/l) in the vicinity of the input. The question was whether further removal of BOD was warranted. A detailed modeling analysis was conducted evaluating the various alternatives for control of the problem. Figure 1 shows the components of the DO deficit from this analysis. The maximum deficit

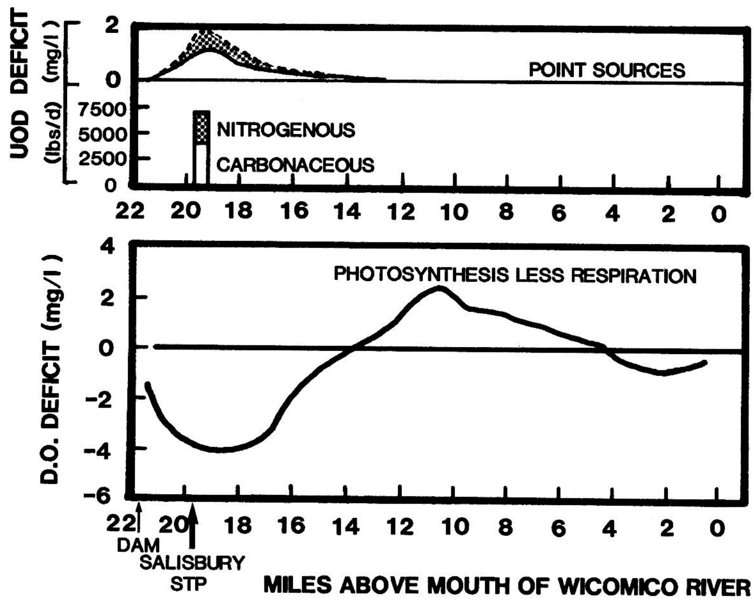

Fig. 1. Wicomico River, DO deficit components from water quality model indicating significance of phytoplankton respiration at mile 10 rather than point source carbon effects (Salas and Thomann, 1975).

(minimum DO) at site 10 is calculated to be due to phytoplankton respiration exceeding photosynthesis (together with the sediment oxygen demand) and not due to the point source of oxidizable carbon and nitrogen. It was therefore concluded that further reduction in these inputs would be only marginally effective and that emphasis should be placed on reducing the phytoplankton productivity through nutrient control. In the course of the decision making process, the conclusion was accepted by the regulatory authorities and a recommendation was made for construction of phosphorus removal facilities rather than additional carbon removal.

Criterion #2 - Accuracy

Since a predictive framework employing theoretical principles and past experience is at the heart of the water quality management system, it is crucial that our models be credible from an engineering point of view, but, equally important trustworthy and reliable from a management point of view. The forecasting ability of water quality models and uncertainties associated with predictions have been examined in detail elsewhere (see, for example, Beck and van Straten, 1983). Here a few simple examples are presented for illustration. Since DO analyses have such a long history, it is reasonable to evaluate how accurate our past analyses have been by examining the performance of DO models.

Post audit of DO models. Post audit is the evaluation of system performance following actual implementation of environmental control facilities. Three questions are addressed:

1. Do the actual DO data after a treatment upgrade is installed generally reflect the basic principles of DO models, i.e. does the DO go up when the BOD goes down?
2. To what degree are the DO models successful in predicting quantitatively the observed DO?
3. Does the accuracy of the DO models really matter in the decision regarding the treatment facilities to be installed?

In the work summarized here, an evaluation was made of 52 water bodies where some data were available on water quality conditions before and after treatment (HydroQual, 1983). Thirty seven states, five USEPA regional offices and six regional planning agencies were contacted, but in no case was there a complete compilation of water quality, biology, water use, cost or benefit data to perform a detailed post audit analysis. However, 13 water bodies did have some information for a review. The treatment changes included increases from primary to secondary and secondary to nitrification and advanced waste treatment.

Regarding the first post audit question, the data for the 13 cases indicated that the increase in DO normalized by the reduction in ultimate oxygen demanding (UOD) load was inversely proportional to river flow (Fig. 2).

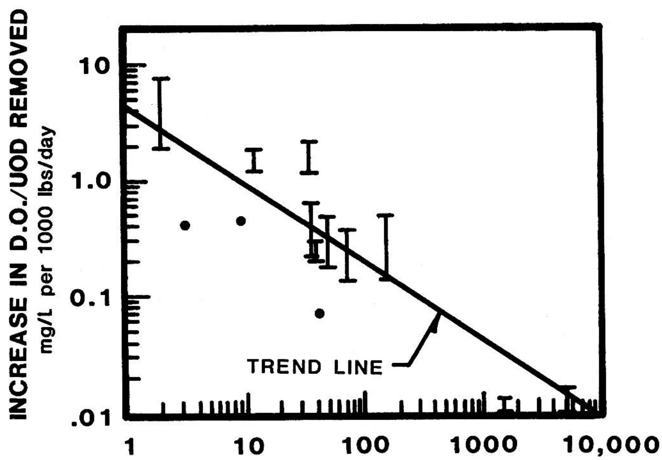

Fig. 2. Relation between actual DO increase (mg/ℓ) per 1000 lbs UOD/day removed and spatial average stream flow (cfs) - 13 water bodies. (From HydroQual, 1983)

At the very least, this is the simplest confirmation of the classical DO model framework. That is, from the basic DO sag equation we know that $\Delta DO/\Delta UOD$ reduction should be approximately inverse to the river flow.

To first approximation, then, our basic theory holds together and supports a fundamental tenet in DO systems analysis: the greatest DO improvement will result from facilities that provide the largest amount of UOD removal located on the smallest water bodies. The difficulty is that Figure 2 is a log-log plot, so the first approximation may not be all that satisfactory in a decision making context. Therefore, we need to take a closer look at the quantitative performance of DO models and address the second question.

Testing of six river models was performed by setting the conditions (i.e. river flow, temperature and effluent) for the appropriate "after treatment change". All model reaction rates were identical to those rates used in the original waste load allocation analysis. Root mean square (RMS) errors served as one quantitative measure of model accuracy in reproducing the data collected after a change in treatment. In post-improvement testing, RMS errors range from 0.0 mg/l to about 2.0 mg/l. The average error of 0.9 mg/l was somewhat larger than the RMS error of 0.7 mg/l associated with calibration of the six models.

Fig. 3 shows the correlation of observed to calculated mean DO concentrations for the calibration and post-improvement evalutions. The Figure clearly indicates that we do a good job in calibration partly because we have the data in front of us during this model calibration phase. On the other hand, the post-improvement comparisons, when we did not have the data <u>a priori</u>, indicate that the DO models tend to overestimate actual DO concentrations at levels less than 7 mg/l.

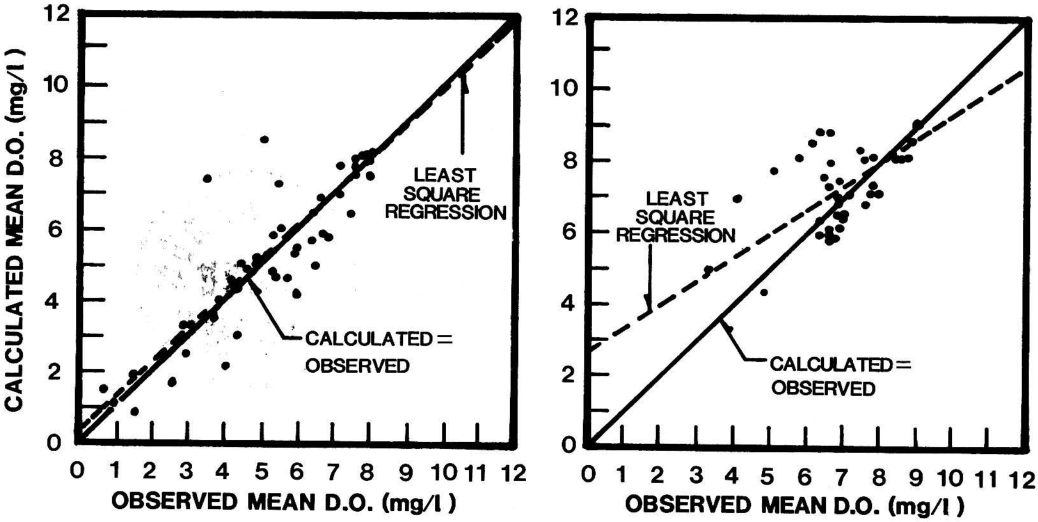

Fig. 3. Comparison of calculated and observed DO concentrations - 13 water bodies (a) from calibration stage of model, (b) from post-audit stage, after treatment upgrade. (From HydroQual, 1983)

Recognizing that many DO analyses are conducted without recourse to any data at all, it is important to also determine the credibility of the DO models where "simplified desk top" studies are conducted. Indeed, at least in the U.S., many more permits are probably issued by analysts who have never been within 100 miles of the river. The scenario therefore was as follows: an experienced water quality engineer was asked to analyze the DO in ten streams without looking at the DO data and only having available data on the river characteristics, e.g., flow and depth. Following the analysis, a comparison could then be made between the simplified analysis and the actual data. Quantitatively, the "simplified" models resulted in RMS errors that were 50% to 200% higher than the RMS errors developed from more complex data-available analyses. The average RMS error for the ten river analyses was about 2.0 mg/l.

The answer to the second question above is therefore somewhat sobering. With a detailed model construction and using reasonably extensive (and expensive) data sets, the RMS error in the actual subsequent comparison to DO levels after treatment upgrade is about 0.9 mg/l. Simplified, desk top analyses double that error. With these kinds of errors, one wonders about all the discussion that sometimes ensues in permit negotiations over a few tenths of a mg/l DO.

Now, to the third question, i.e. do these errors really make any difference in the decision-making phase? In the preceding discussion, there are two types of errors that may occur in the comparisons: the first error is overestimation of the water quality improvement for a given level of treatment. Therefore, water quality will be less than actually thought after treatment upgrade and a water use interference may occur that was not predicted. The second error is underestimation of the water quality improvement resulting in overdesigned treatment facilities and an overexpenditure of funds. The first error can be termed a water quality error (i.e. quality (use) will be less than projected). The second error can be thought of as a facilities error (i.e. the facility is overbuilt to meet target water quality.)

Comparisons for 10 rivers were made between the decisions reached using simplified desk-top techniques as compared to detailed modeling approaches. Simplified modeling could have potentially resulted in four water quality errors and two facilities errors. In four cases, the decision was identical. The comparison, of course, assumes that the more complex model analyses with available data results in "correct" decisions, which in fact is not always the case. With respect to an upgrade to nitrification facilities, the comparison indicated that the simplified models reached the same decision in nine of the ten cases. This is due principally to the step increases in UOD reduction with the installation of nitrification facilities.

One concludes from this post audit analysis that simplified DO models and to a lesser extent, more sophisticated DO models do not do very well in predicting actual values of DO after a treatment upgrade. RMS errors of 1-2 mg/l DO are the bad news. The good news is that from a decision-making point of view, it doesn't seem to make all that much difference especially for an upgrade to nitrification.

The Potomac Estuary Case. This estuary has been the subject of water quality management and modeling efforts for several decades. Freudberg (1985) has reviewed the history and the implications of the modeling work. In the late 1960's, extensive algal blooms developed in addition to a depressed oxygen condition in the Washington, D.C. vicinity. As a result of modeling efforts by people such as Jaworski et al. (1971) significant reductions in incoming carbonaceous and nitrogenous BOD loading was accomplished along with significant reductions in point source phosphorus loading. Considerable controversy surrounded the phosphorus reduction strategy since it was argued that nitrogen was the limiting nutrient and that nitrogen should be controlled. Concern was also expressed over the release of phosphorus from the sediment. The phosphorus removal strategy was founded on the notion that with sufficient reductions of phosphorus, that chemical could be made the limiting nutrient. Since it was considered cheaper to remove phosphorus than nitrogen, the phosphorus removal program was instituted. Fig. 4 shows the reductions in phosphorus during the late 1970's and early 1980's.

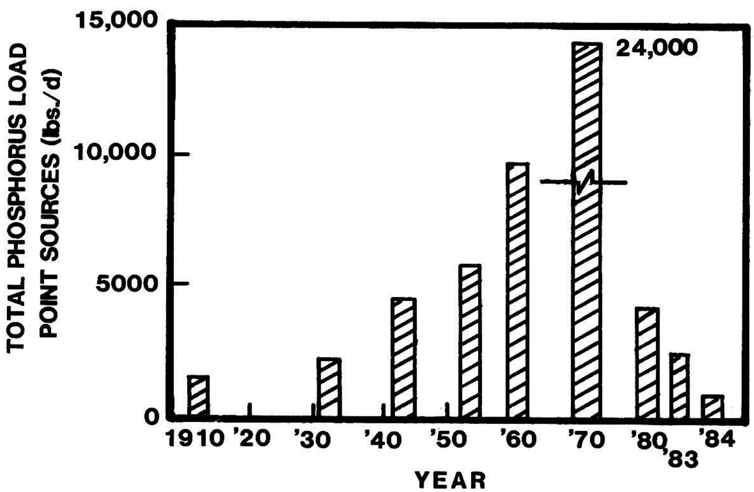

Fig. 4. Phosphorus loads, Potomac estuary (Jaworski et al., 1971; Thomann et al., 1985; Metro. Wash. Council of Govt's, 1985).

A major algal bloom occurred in 1977 following the first stage of the phosphorus reduction program. An intensive effort was then undertaken to update the modeling framework for