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COMPLEX SYSTEMS ANALYSIS OF WATER QUALITY DYNAMICS:  
THE FEEDBACK SYSTEMS STRUCTURE

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COMPLEX SYSTEMS ANALYSIS OF WATER QUALITY DYNAMICS:

THE FEEDBACK SYSTEMS STRUCTURE

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## SUMMARY

The institutional arrangements for management and control of a region's water quality are known to be greatly influenced by the way social, political, and economic conditions develop over time. Research into how these conditions have interacted with public attitudes, in a process that has evolved into present levels of stream water quality, focuses understanding on the basic causes of pollution rather than on problem symptoms. Thus the main purpose of the research has been to probe the basic system causes for deteriorating water quality in order to make it possible to recommend actions which will stabilize water quality at levels scientifically and ecologically compatible with long run human welfare. Important system components are public awareness of pollution through perceptions and traditions as to what is acceptable, water standards legislation, the funds and personnel allocated to enforce standards, and the delays and responses between these interrelated factors.

The results of the research include a systematic analysis of important feedback loops within the total complex system identified. Periodic water quality crises reflected by public awareness are shown to have a 15 year period. Each crisis only generates enough funds for additional abatement and treatment capacity to temporarily stabilize pollution concentration growth. Meanwhile during the construction interim, higher levels of pollution are slowly integrated into tradition, thereby allowing a "drift"

to higher pollution concentration levels.

Two basic changes are suggested to stabilize water quality and prevent drifts to higher pollution levels. First, control of technological and industrial wastes must be instituted. New technology is encouraged, but only when corresponding advances in pollution control technology are discovered and utilized. Secondly, the institutional system for managing water quality should be taken out of the social and political arena and based on scientific analysis. The agency selected to enforce standards must be relatively free of explicit or implicit pressures potentially imposed on it from political, industrial, or other special interest groups.

The methodology and philosophy of Industrial Dynamics is utilized in the system construction and later testing and experimentation. Using this methodology, time histories of important system variables are first isolated through the analysis of historical social, political, and economic factors as they affected the evolution of pollution in the Ohio River Basin. Secondly, controlling feedback loops accounting for the identified historical performance patterns are postulated and tested. Following construction of a model which generated similar performance patterns in identified variables, the model is tested under a wide range of policy parameters to illustrate system response and sensitivity to changes. Understanding of the system structure then allows the postulation of policy directions which will result in long term solutions to the problem of growing pollution concentrations.

## CHAPTER I

### INTRODUCTION

Water pollution is having an ever increasing impact on man's everyday life. Oil spills foul beaches and kill wildlife; fishing must be restricted along stretches of some rivers as mercury concentrations reach intolerable levels; water must be more thoroughly filtered and chemically treated to be suitable for drinking; seashore waters suitable for swimming are becoming limited; fishing and seafood industries are experiencing smaller catches of many high valued species. In response to these and an almost endless list of other problems, man is being forced to change, many would say degrade, his way of living to accommodate new manifestations of pollution.

During the past few years, an increasing number of lakes and river stretches have reached pollution concentration levels considered to be anaerobic. Under anaerobic conditions, free oxygen is not available to oxidize wastes in the water, resulting in the release of noxious odors and the substantial slowing of the biological stream self-purification process.\* When this happens, water withdrawn for industrial and municipal uses must be more extensively treated at increased cost to meet established health safety standards or industrial process requirements. The consequences

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\*The concepts of aerobic and anaerobic cycles are covered in Engineering Management of Water Quality by P.H. McGauhey, pp. 8-11.

of many new pollutants are not yet appreciated and standards and treatment methods are not yet developed. Therefore, the potential for disaster brought by these new pollutants multiplies. Aside from health safety problems, the removal of objectionable but not harmful tastes and odors increases past the point most communities are willing to pay, and the water user must consequently live with an aesthetically lower quality product.

Possibly much more important are the effects on the quality of the water for its value while still flowing in the stream. Anaerobic and other highly polluted streams release noxious odors, do not support desirable species of fish and wildlife, and are aesthetically repugnant and unfit for recreational use. The extent of the spillover effects through ecological linkages are not well understood and may be disastrous in some of their effects on human life support systems. Man can treat water from open sewers and make it suitable to drink healthwise, but he may suffer a profound aesthetic and ecologic loss if he is institutionally unable to prevent his streams from becoming open sewers.

Specific consequences of a continuing increase in water pollution are already observable on a limited scale, as some rivers and lakes are relatively more polluted than others. The Chesapeake Bay, long known as the seafood basket of the East Coast, has suffered a 60% drop in the total fish catch in the past 6 years (1). Lake Erie has been referred to as a "cesspool" and a "dying lake" (21). Drinking water in Detroit and Cleveland must be filtered and chemically treated. Even after these measures, the water still

smells and tastes poorly as the majority of the taxpayers seem unwilling to pay for further treatment. Water rate increases of 50% have been proposed in Atlanta, Georgia, in addition to a 300% increase in sewage costs - both increases being attributed to the need for cleaner water in the Chattahoochee River.

It seems apparent that the dire implications of these publicized cases have finally been perceived by the general public. Public awareness of water pollution problems has increased substantially over the past few years. Presently, corrections to the system which produced these problems are being proposed and implemented. Capacity to reduce the discharge of pollutants into natural waters is slowly being purchased, and governmental agencies are formulating new policies to control and more effectively manage the quality of our limited water supplies.

Even in the face of these corrections, however, pollution concentrations may continue to increase if the increased abatement capacity is unable to keep pace with an accelerating increase in the generation of pollutants. When pollution concentrations continue to rise, even greater corrections are sought, and the persistent lag of operational abatement capacity behind that needed must be explained to those who are harmed. Insufficient abatement technology has been offered as a possible cause, however, present political and institutional obstacles seem to create the controlling delays in the system (12). Delays exist in setting abatement standards, in obtaining binding enforcement orders for individual polluters, and in constructing new facilities. These accumulated

delays often total more than five years.

Multiple reasons exist for both the rapidly increasing pollutant generation rate and the lagging operational abatement capacity to control the problem. Two major factors contributing to the increasing generation of pollutants are: (1) population growth and concentration of the population in cities and (2) technological growth and industrial expansion. Similarly, two major factors appear to be influential in creating the lagging abatement response: (1) the attitudes of the general public and (2) the structure and policies of institutions responsible for controlling the level of pollution.

#### Increasing Generation of Pollutants

##### Population Growth and Concentration in Cities

An expanding population creates a proportional increase in the production of human wastes. The magnitude of the human waste disposal problem is growing exponentially just as the population is growing. For example, in the past 50 years population in the United States has doubled from 100 million to 200 million and is expected to double again to 400 million in another 50 years. For each doubling of the population, a similar increase in the tons of human wastes generated will occur. These increased absolute amounts of pollutants are coincidentally being amplified in terms of demands on water resources as a greater proportion of the population is becoming concentrated in cities. In these heavily populated areas, rural type septic tank facilities are unworkable, and consequently the local river serves as a common point of disposal.

### Technological Growth and Industrial Expansion

The increase in the rate of generation of human wastes is, however, relatively less significant than the increase in the rate at which industrial pollutants are being generated. These industrial wastes, by-products of highly technological processes, create greater demands on water supplies than do human feces and other household wastes. For example, industrial use and demands for water since 1900 have increased 11 times in contrast to a tripling in human waste demands. Industries now produce four times the tonnage of wastes which can be directly attributable to human and animal excrement. Ten years ago, the ratio of industrial pollutants to personal wastes was only 3 to 1. As far

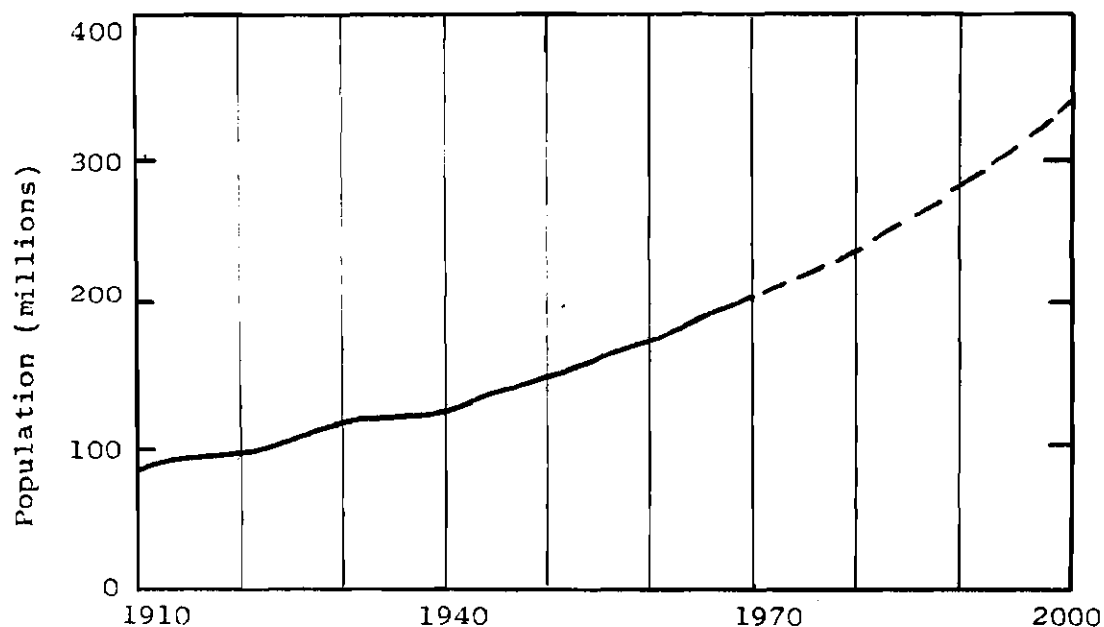


Figure 1. Population of United States, 1910-2000.\*

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\* Figures on population from past and projected values were taken from "The Nations Water Resources," published by the Water Resources Council, Washington, D. C., 1968, p. 1-1.



back as 1900, the ratio was 1 to 3.\*

The rapidly changing nature of these industrial pollutants and their relative weight in the mix of total pollutants poses special problems to traditional abatement processes. Abatement technology has been relatively stable for human wastes due to the essentially static nature of the pollutant. In contrast, industrial pollutants change in character as old processes are modified and new processes are developed. For example, a new chemical is created every 20 minutes. The life span of an industrial process producing a new pollutant may be far less than the time necessary to determine the impact of the pollutant on the stream ecology and to set relevant standards. As the rate of generation of new industrial pollutants continues to grow, satisfactory

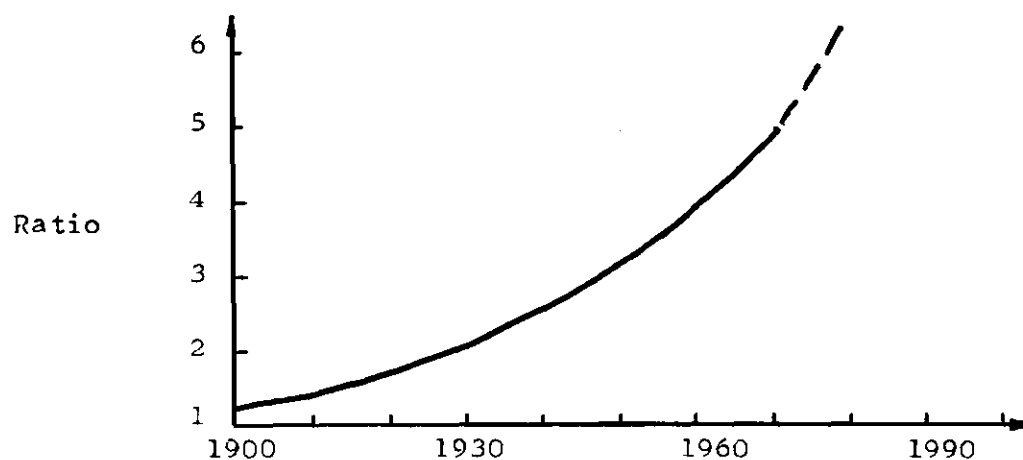


Figure 2. Ratio of Industrial Wastes to Human Wastes.\*

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\* Data for this graph was gathered from information contained in an article "Water Pollution" by Harvey Lieber published in Current History in July of 1970.

response by conventional institutional procedures in terms of creating satisfactory controls will become increasingly more difficult.

### Lagging Abatement Rate Problem

#### Attitudes of the Public

Two major factors appear to be prominent in causing the abatement rate to lag behind the generation rate of pollutants. First, the attitudes of the public are exploitation oriented (20). Throughout history, man has been utilizing his supposedly unlimited and free resources to produce more goods and services without sufficient regard for problems which may be created by the need to dispose of by-products or waste materials from his processes. Changing these deeply ingrained exploitation attitudes is difficult. Another relevant attitude of the public is its crisis orientation (17, 22). The public may only react to a problem which has already gone beyond acceptable bounds. When a situation is finally perceived as intolerable, corrective procedures frequently overreact. The delays caused by forces wishing to continue exploitation and the intervals required for crises to develop and be perceived, create a time lag between problem occurrence and willingness to commit resources to control it. This time lag becomes intolerable in a society based on a rapidly changing technology.

#### Structure and Policies of Institutions

A second major cause for the time lag to pollution abatement

is the structure of institutions which deal with socially oriented problems. Enforcement agencies are budgeted and subsequently staffed from tax funds which are allocated according to prevailing "priorities." These priorities are established in response to public interests. Thus, if attitudes are crisis oriented and lag the occurrence of a crisis creating the problem, funding and enforcement will also lag behind as they are somewhat dependent on public priorities. After further delays for the enactment of legislation and testing in the courts and for training of enforcement agency staff, the effectiveness of the enforcement agency increases, enabling the agency to force municipalities and private polluters to abate polluting according to prevailing standards.

In addition to the funding process, the enforcement agency has evolved as a balancer of competing pressures (3, 27). Standards are set, negotiated, and changed in response to desires of competing pressure groups, such as industrial lobbies and public conservation groups. Even if the agency establishes standards on paper and refuses to change them, the same result can be effectuated through increasing or decreasing enforcement efforts. The pure negotiability of the standards has often perpetuated compliance delays as polluters wait to determine at exactly what level standards will finally be set and likewise enforced.

Furthermore, our political system is structured with many checks and balances and consequently contains many long delays which in effect filter out many daily problems. Thus, long delays in budgeting, legal proceedings, and perceptions of public desires

have made the system concentrate on dealing with major lingering problems while short-term, minor problems are allowed to solve themselves.

#### Consequences of Continued Growth in Pollution Concentration

As long as the generation of new pollutants continues to outpace the acquisition rate of operational abatement capacity, the extent of water pollution problems can be expected to increase. Unfortunately, if the pollution concentration over a long reach of stream is allowed to reach threshold levels which arrest natural self-purification such as occurs in the formation of anaerobic conditions, pollution concentrations can potentially spiral upward. The oxygen deficiency resulting from anaerobic conditions tends to break down the ferric iron which holds large quantities of oxygen demanding nutrients in insoluble complexes at the river's bottom. If the anaerobic condition at the river's bottom persists for any extended period of time, the nutrients held in insoluble complexes are released to further pollute the water.

Pictorially, the pollution concentration level will accelerate when the threshold level is passed for any extended period of time. The explanation for the rapid pollution concentration increase can be explained by the circular causal relationships defining the character of the stream or lake. Thus, as the pollution concentration passes the threshold (anaerobic conditions), the level of free oxygen in the stream for assimilation purposes is depleted. As the level of free oxygen falls, the compound ferric iron begins to break down releasing even more oxygen

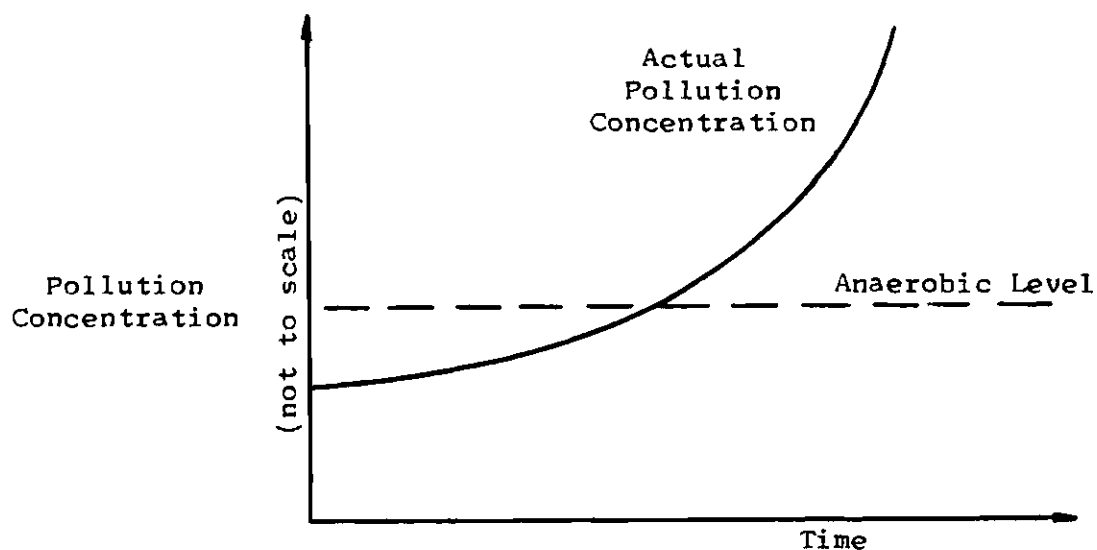


Figure 3. Rapid Pollution Concentration Growth as the Threshold Concentration (anaerobic conditions) is Reached.

demanding nutrients to the already overburdened stream. Such a set of circular relationships continues to feed on itself creating intolerable levels of pollution before any corrective action can

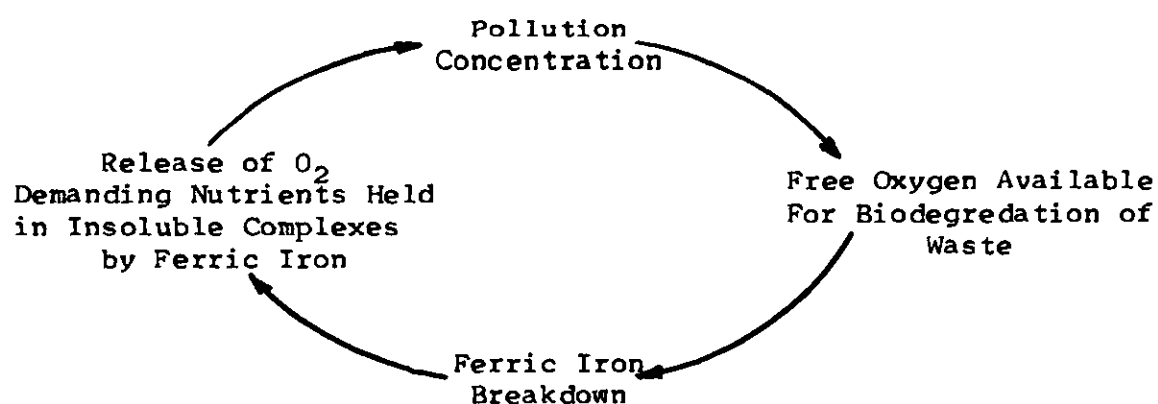


Figure 4. Circular Causal Relationships Responsible for the Acceleration of Pollution Concentrations Once the Threshold Concentration is Reached.

be taken. As a consequence of this cycle, the body of water now over-burdened with nutrients which are still undegraded will undergo accelerated eutrophication,\* eventually turning the lake or stream into a swamp.

The tragic consequences of the above process cannot be allowed to occur. If the process were triggered throughout a large river system, the aesthetic and ecologic values of our available water resources could be destroyed before correctional measures could be taken. The aesthetic values we associate with natural streams would be destroyed. Recreational use would be prevented. Substantial changes in dietary habits would be required. Ultimately, vital life processes could be threatened.

In light of the consequences of growing pollution concentrations, action must be taken. It appears now that we must manage water resources, and do so in a manner which is effective in both the short term and the long term. In order to develop managerial policies and structure institutions which would be most effective, greater understanding of the complex problem must be gained. This understanding must not be limited to technical considerations nor even to the problems of particular human participants in the control process. Rather, the high-level problem described requires understanding of the relationships between all important participants, including the public, the courts, the legislators, and enforcement agencies. When these interactions are more fully understood from a dynamic viewpoint, more effective and lasting managerial policies can begin to be developed.

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\*The process of eutrophication and its consequences is described in Chapter 11 of Engineering Management of Water Quality by P. H. McGauhey, McGraw Hill, N. Y., 1968.

### Motivation for the Research

The motivation for the research arises out of the need to understand water pollution control as an effort designed to resolve a series of interrelated problems - not a set of isolated problems. Thus, a system's viewpoint must be taken in order to more fully understand the complex nature of the interrelationships between related problem areas. The biologists and ecologists need to understand not only the problems and consequences of their work, but also they must appreciate the problems of enforcement agencies, the courts, and special interest groups. The total picture has often been neglected in the past as each group attempted to magnify their particular problem rather than understand its relationship to the total problem.

Studying the interactions of the various problem areas in a time oriented context helps to focus on the variables which control the process which is increasing water pollution in a constantly changing social, political, and economic environment. A lack of understanding and research into these time dependent interrelationships has allowed some problems to persist over time in a recurring manner thus obstructing adequate provision of long range solutions.

Thus, the motivation for this research deals with studying social processes in a time context to supplement past studies of physical processes in a time context. This understanding is then used to begin developing policies of management and institutional structures which will effectively deal with the changing nature

ang magnitude of the pollution problem. If understanding can be gained, new managerial policies and structures could be suggested and tested. Hopefully, these new policies would be more effective in dealing with the long term nature of growing pollution concentrations.

### Purpose and Objectives

The purpose of this research is to gain better understanding of social processes which control the use of technological processes through which people generate and react to water pollution. Related to this basic purpose is the desire to determine the structural aspects of the social and institutional system which seem to be most responsible for creating observed deterioration in water quality on an aggregate scale and in the long run.

Coinciding with this purpose is a set of objectives around which the research is structured and around which the results of the study must be evaluated. The specific objectives will be:

- (1) To identify the controlling social, political, and economic factors and structural relationships which systematically appear to create identified historical response patterns with respect to water quality. This objective will include the quantification of some variables which have previously only been qualitatively identified.

- (2) To use a complex mathematical model to demonstrate how the patterns are generated. The mathematical model will use descriptions of the identified controlling forces as feedback



information to control the problem better.

(3) To explain the reasons for and the consequences of past institutional structures and related managerial policies in relationship to our present day water pollution problem.

(4) To suggest alternative policies and institutional structures which would more effectively protect our limited water resources from further degradation in quality.

(5) To study implications of these new policies and structures on an operational scale.

#### Scope and Limitations

The research attempts to broaden the scope of understanding of water pollution problems to include explicit consideration for social, political, and economic factors and relationships which interact over time. In order to accomplish this objective, a mathematical model was developed which emphasizes systematic identification, description, and analysis of information sources which were used as feedback to generate historical pollution concentration patterns. The historical patterns were generally defined by analyzing historical literature and data from the Ohio River Valley.

Many of the identified model variables and relationships lack extensive empirical documentation. The lack of empirical justification is due in part to the paucity of historical data. In addition, where data were available, limited observations were made, or the observations were often of a qualitative nature. The lack of empirical documentation, however, was not deemed important

in a pilot approach designed to explore ways for more meaningful conceptualization of highly complex social processes. The collection and use, and where possible the quantification of the qualitative data, was therefore pursued, providing an analytical basis for manipulating the model.

It should be recognized that this study is but a beginning effort in the systematic identification and analysis of the general structure which is believed responsible for producing some of the dynamic response patterns. These patterns have characterized man's role in creating and fighting water pollution over the past years.

## CHAPTER II

### LITERATURE BACKGROUND

Literature from two areas of study needed to be examined, analyzed, and related in order to form the background of understanding necessary to study the social processes of water pollution control in a time history context. First, literature associated with information feedback models was investigated, second came an examination of literature dealing with water quality management, and the final step was an examination of literature which integrates these two areas.

#### Information Feedback and Control Literature

Information feedback and control literature has several branches. The branch which seemed most suitable for this study of social processes was that branch which has been developed by Jay W. Forrester and called Industrial Dynamics (7). This approach builds simulation models which interrelate information, policies, decisions, and actions by expressing key relationships within a set of difference equations. Simulation using these equations allows non-linearities and multiple feedback loops to be contained in the model. Traditional information feedback and control methodologies do not have such flexibility.

Utilizing the methodology of Industrial Dynamics, models of complex social and economic conditions can be constructed when the

problem can be pictured as a closed system. A closed system model can, within itself, produce the kinds of behavioral modes that are of interest in the particular study. The closed system consists of an interrelated set of information feedback loops. A simple feedback loop is shown in Figure 5. In the feedback system, the system state is observed and information about the state is used in making a decision which will eventually, after delays, alter the system state. The decision influences action which creates the actual change in the state. Thus, a continuous process is underway where the system state influences a decision, which subsequently alters action, which changes the system state.

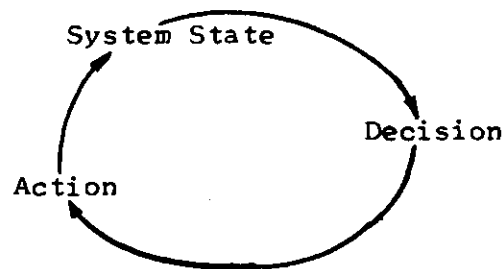


Figure 5. A Simple Feedback Loop.

Feedback loops can be classified in general by their polarity, positive or negative. Positive feedback loops act so as to reinforce any initial change in the system conditions in the direction initially disturbed. Such a feedback loop has exponential growth or decay characteristics. An example of a positive feedback loop has been discussed in reference to Figure 4.

Negative feedback loops act so as to correct any change of the observed system state away from that which would be desired

or needed. Thus the loop acts as a goal seeking type of mechanism. If the observed system state is too high, decisions and actions are taken so as to lower the system state. Also, if the observed system state is too low in relationship to that desired, decisions and actions are taken so as to increase the value of the system state.\* The simple thermostat which regulates the furnace to keep room temperature at a desired level is an example of such a feedback loop. A generalized formulation of a negative feedback loop is shown in Figure 6.

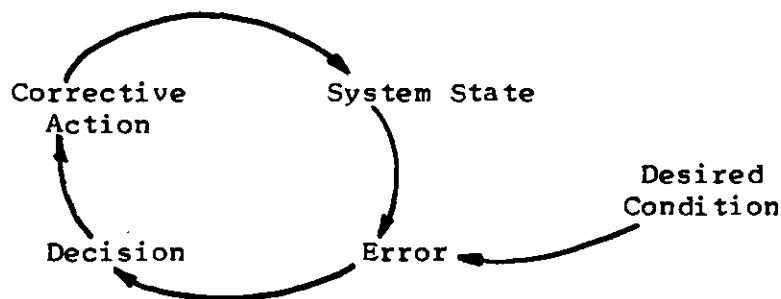


Figure 6. General Description of a Negative Feedback Loop.

#### Water Quality Management Literature

Writers on water quality management and control have often dealt with problems related to individual river basins. These case studies emphasize interactions which seem prominent in creating pollution control responses in that particular river basin. Other literature is devoted to utilizing the information from case studies as supplementary data in the formulating and testing of quality control systems utilizing generalized internal stream

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\*A comprehensive and mathematically simple discussion of feedback methodology can be found in "Modeling the Dynamic Processes of Corporate Growth" by J. W. Forrester, IBM Computing Symposium, N. Y., 1964.

relationships and treatment processes. Formulas, methodologies, and techniques which optimize based on the criterion of economic utilization of the water are continually being refined through this process for general application. For example, stream flow augmentation schedules and waste treatment schedules have become accepted water quality control techniques as their generality has been extended to varying conditions. Meanwhile, the systematic analysis of interactions between social, political, and economic factors has not been receiving commensurate emphasis. This condition was observed by Maass (14) who suggested that political and social scientists have become "too preoccupied with case studies and individual non-conformities, and have neglected analysis which attempts to discover normal structure and general principles."

Insufficient understanding of either the internal stream relationships or the social, political, and economic relationships will result in water quality standards being set too high or too low or will result in insufficient laws and enforcement powers to insure compliance to the standards. The understanding of each set of relationships is necessary. For example, stream analysis and technical relationships must be implemented and administered within the social, political, and economic framework. Alternatively, the social, political, and economic institutions must rely on sound engineering and research in order to utilize most effectively the limited amount of water.

With these thoughts in mind, the literature can be broadly classified into two major categories for purposes of analysis:

(1) historical documentation or analysis of social, political, and economic factors associated with control of water quality in particular watersheds, and (2) quantitative approaches focusing on establishment of treatment schedules consistent with water standards which "optimize" according to some economic return function. The qualitative, historical documentation literature places emphasis on many social-political-economic relationships, but the descriptions lack systematic analysis and interpretation of the factors which create and subsequently govern operation of the total system network. The quantitative approaches often assume that water standards are developed and enforced through the result of interactions among social, political, and economic factors. The process through which this result is obtained is assumed to be given for purposes of model simplicity and quantitative description.

Recently, the study of water quality problems has been examined using various techniques of "system analysis." Many of these systems studies continue to assume a given social, political, and economic context, but others are attempting to extend systems boundaries to eliminate the necessity for these assumptions.

The "complex system" studies attempt to include within the system boundary all important factors which can determine the performance of the system over time. Boundaries are not limited to factors which can be explicitly measured by empirical means but also include intuitive factors of known influence which may defy rigorous empirical documentation.

### Historical Literature

Historical descriptions of problems, factors, and responses within localized polluted watersheds provide a wealth of information regarding the social, political, and economic pressures involved in creating and fighting pollution. Close examination of these cases can lend insight into the delays involved, levels and times of "crises" in the system, and interrelationships which couple the system together. Although much information has been available for some time, little effort has been made to effectively integrate it into a system for determining general principles and basic system structure.

The combination of social, political, and economic conditions necessary to prompt water pollution control efforts have been experienced on localized geographical levels for at least a hundred years. For instance, in 1865, a Royal Commission on River Pollution was appointed in England, for the purpose of inquiring into methods of reducing stream pollution (26). Although the technology to reduce pollutants was available three years later, twenty five years later other authors continued to acknowledge the severity of the water pollution problem, thus illustrating that the social, political, and economic forces had system dominance over that extended period.

More recently, in the United States, the Ohio River has had serious pollution problems by 1900. From the time of Ohio's passage of the Benze Act to the present day, a constant effort has been made to insure cleaner water in the Ohio. These efforts were more



successful at certain times than others due to shifting social, political, and economic conditions. Also their success has been greater in the long run than that observed in other comparable programs. Edward J. Cleary in his book The ORSANCO Story: Water Quality Management in the Ohio Valley under an Interstate Compact (2), provides a clear historical documentation of the numerous publically perceived water crises, enforcement efforts, legislation, and levels of pollution which have been experienced. Further documentation on policies and programs implemented to control water pollution are provided in the book, illustrating program policies tested in the Ohio River Valley.

Other notable documentations exist for the Ruhr Valley (15) in Germany and the Mersey River (5) in Great Britain. Additional insight into the legislative process in water pollution control can be gained from Wisdom (28) and Murphy (15). With emphasis on public perception, enforcement efforts, legislation, and the pollution abatement success, careful examination of these localized problems can lend intuitive information for the construction of a general systems model of water pollution control.

Characteristic of these documentations in their localized geographical nature. The problem concerning millions of people today is a national and world-wide pollution crisis.

The extent of today's problem, however, represents only a change in scale of the physical effects of pollution, not necessarily a change in social, political, and economic policies and institutions formed to control water quality. Thus, analysis of these

past experiences for uncovering general principles and general systems structure should be emphasized. This emphasis can possibly reveal new understanding and insight for future program development.

Social reactions and responses to water pollution in a long term, time context have received little analysis but their importance has not been overlooked. Wantrup (25) suggests that social conditions "can be appraised only ordinally in terms of direction of changes, the relative speed of changes and the sequence of events in time." Spradlin (22) developed his model in this vein, and he further recognized that society generally reacted to "crises" conditions. He thus fashions corrective response from perception of severe capacity shortages in the face of high levels of pollution.

The political environment and response patterns have received more emphasis in the literature than sociological responses. Dea (3) proposes a single feedback control loop to monitor needed enforcement based on the difference between desired and actual water quality. However, his model assumed the setting of desired water standards as a result of social, political, and economic needs - similar to many mathematical programming models of recent years. Dea observes that

"water pollution control proceeds intimately with the political climate. Wide disturbances and sensitivity can be exerted through political decisions. Budgets and legislative intent in laws and regulations fluctuate with the parties in power, lobbying interest, and parochial interests." (3)

Kneese (11) also discusses the legislative process in addition to court proceedings and test of laws. He suggests that shortening of court delays in trial matters could lead to improved system response.

The economic questions and problems of water pollution control have probably received the most comprehensive analysis of all aspects of the pollution problem, both qualitatively and quantitatively. Qualitatively, the literature focuses on the problems associated with competitive disadvantages faced by potential pollution abators, on economic hardships created on special industries such as fishing, and on special interest groups such as conservationists. Quantitative analysis of economic factors affecting water pollution control has received even more extensive analysis and merits further discussion.

#### Quantitative Economic Analysis of Water Pollution Control

Quantitative approaches used in analyzing economic problems of water pollution control can be classified into two categories: the macroeconomics approach through the concept of technological external diseconomies, and the microeconomic approach to the development of water standards and treatment schedules for maximization of economic return.

The study of technological external diseconomies has been studied most intensively by Kneese and Bower (11). Kneese and Bower demonstrate how upstream waste discharges can, under present laws, neglect the cost of water pollution caused by their processes. Downstream users must subsequently bear the cost of treating the

water for reuse, and these deprived of values they once gained from high quality water flowing in the stream may in fact suffer a far greater loss. Kneese calls this the "basic element of the pollution problem." Institutional changes to make possible internalization of the externalities is suggested as the solution. This internalization can be achieved by regional water quality control; but the establishment of such control rests upon other social and political considerations. Loucks (13) also recognizes the effect of externalities in a quantitative model, and then seeks to maximize public welfare as a compromise between four competing political groups.

A substantial body of knowledge and expertise has been developed on water standards and treatment schedules based on maximization of economic returns. Thomann (24) has applied linear programming to determine treatment levels which would satisfy water standards at an economically optimum return. Dysart and Hines (4) used dynamic programming in attempting to minimize the cost of treating organic and thermal waste while satisfying multiple quality standards.

Even though these models have developed mathematically rigorous results, their implementation can only be effected through existing social and political institutions. Experience has shown that new approaches must wait for the institutions to become receptive. This often requires a deeper appreciation of the potential problem before results can be implemented. Therefore, understanding of the relationships controlling institutional decision making and

implementing processes in a dynamic, growing, and affluent urban and industrial society is required to reduce time lags in the implementation of economically optimum treatment schedules and water standards.

Complex Systems Approach to Social, Political, and  
Economic Conditions

Wantrup's observations of critical problems on a broad sociological level were perhaps indicative of the scope and direction of the needed research.

"For public policy to know whether a change sets in motion corrective counter changes tending over time toward a balance of the initial change, or whether it sets in motion other changes that are circular and cumulative and tend to reinforce the initial change,.... and,...

"For the pursuit of these objectives, benefit-cost analysis and related quantitative techniques must be supplemented by a type of analysis that takes cognizance of research in economic history, in the sociology of value systems and in the change of social institutions, especially by law." (25)

Since Wantrup's article in 1961, research effort in the direction of complex system problems have been promoted by Forrester using the methodology of Industrial Dynamics (7). Forrester's efforts have recently culminated in a complex systems study and book entitled Urban Dynamics (8). He describes a "complex system" as a "high order, multi-loop, nonlinear feedback structure." He further stresses that all social systems are of this type of structure. Included in the complex feedback system approach are considerations noted by Wantrup such as economic history and social values. The feedback loops in his model have either goal seeking, negative polarity, or cumulative, positive polarity. The complex

network of these loops, their couplings, delays, and interactions are very unintuitive in response and defy usual mathematical analysis. Within the urban environment of study, Forrester identified three important networks related through information feedback which can determine the growth, aging and stagnation of a city - these flows being labor, housing, and business. Simulation analysis of the system provided considerable insight into growth processes of cities, and the consequences of programs directed toward desired system behavior.

The analysis of the pollution problem using this same complex systems methodology was studied by Spradlin (22). Spradlin concentrated on solid waste pollution and its control through purchasing of disposal capacity (short term consideration). Using public awareness as a stimulating factor, model analysis reflected the long term cost reduction when the system is long term oriented toward technological investment rather than "crisis oriented" toward capacity acquisition.

The problem of research in this paper focuses on a similar keying mechanism (public awareness) but the level of pollution is basically changed through increased or decreased waste dumping in streams or increased or decreased compliance to water standards. The reduction in polluting occurs as a result of the acquisition of industrial and municipal treatment and abatement capacity. The increase in polluting results as cities and industrials delay or fail to adequately treat or control their discharges into the streams. Because of financial and economic conditions, many

industries and municipalities actively fight to avoid compliance to existing desired standards. As they begin to perceive increasing legal and enforcement powers by designated institutional control agencies, concessions are slowly made by the polluters and abatement facilities are built, but only after every alternative has been investigated. Factors of importance which finally control the acquisition rate of treatment capacity include the economics of abatement, resistance to abatement on the part of polluters, levels of existing legal water standards and enforcement, and non-legal motivating factors on the part of the human participants in the decision making process.

## CHAPTER III

## WATER QUALITY DYNAMICS

Synthesis of Performance Behavior from  
Historical Records

In order to hypothesize and synthesize an information feedback model describing and explaining time changes in a basin's water quality, the level at which the variables are best aggregated must be selected. The optimum level of aggregation depends on the relationships of importance which must be analyzed over time to determine their relative periods, phasing, and magnitude in producing the effects of interest.

In this research, variables were aggregated at a high level in order to extend the boundaries of the study to include social and political conditions, attitudes, and controlling institutional structures in addition to the water quality itself as reflected through pollution concentration levels. Other levels of study would have been possible, but it was thought that this research should be focused on the highest social, political and economic factors thought responsible for affecting water quality over time.

The choice of a basin for which data would be collected was influenced by the length of time a basin had experienced water quality problems and the length of time over which there had been attempts to control quality. Also considered was the availability



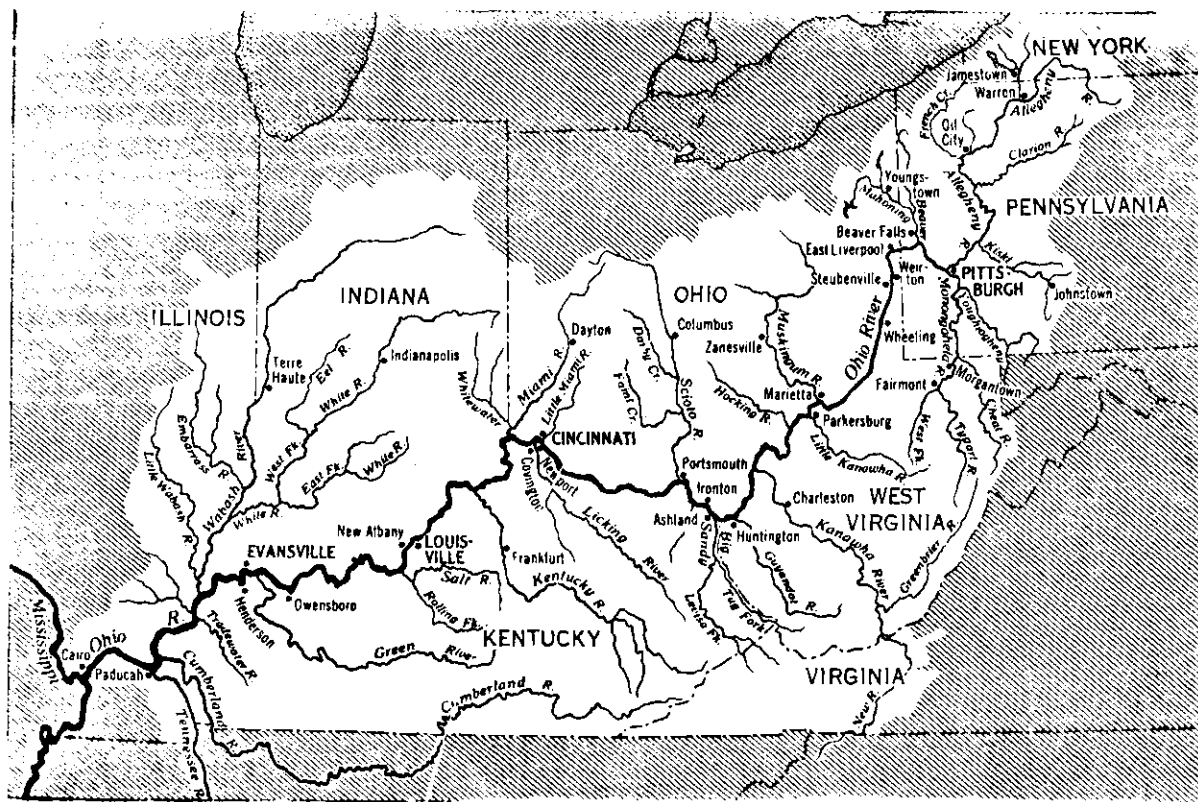


Figure 7. The Ohio River Valley.\*

of data from historical literature and documentations. Using these criteria as bases for selection, the Ohio River and its River Basin was selected.

Within the region drained by the Ohio River and its tributaries live almost 10% of the population of the United States. The Ohio River itself (the main channel) is 981 miles in length and stretches from the junction of the Allegheny and the Monongehela Rivers at Pittsburgh through Wheeling, West Virginia, past

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\* This picture was taken from The ORSANCO Story: Water Quality Management in the Ohio Valley under an Interstate Compact by Edward J. Cleary, The John Hopkins Press, Baltimore, Maryland, 1967. Page 5.

Cincinnati and Louisville, and finally meeting the Mississippi River near Cairo, Illinois. The river is characterized by having the greatest concentration of industry and population at the head of the river where dilution capacity of the river is least (See Figure 7). For example, the river from Pittsburgh to Wheeling, West Virginia is almost completely lined with industries, notably steel and coke industries. Similar types of industries are found downstream about two hundred miles in the region of Huntington, Ironton, and Portsmouth. Another 150 miles downstream lies the metropolitan area of Cincinnati at the approximate midpoint of the river as it flows to the Mississippi. The remaining portion is more sparsely populated and less industrialized, although the river has the greatest dilution capacity in this portion of the river basin.

The Ohio River Valley has experienced water pollution problems as far back as 1900. Documentation of laws, pollution levels, crisis conditions, and corrective response actions are more easily obtainable than comparable data from other river basins. For this reason, the Ohio river basin was chosen as a data source to study the problem of concern.

Much of the data from the earlier years is qualitative and general in its nature, but the use of more recent data to supplement the historical generalities allows one to construct a reasonable time-history behavior of selected variables of importance in the socio-political area. The results of the synthesis of data can be seen in Figures 8 and 9. A complete description of the

qualitative and quantitative situations which were used to generate the behavioral patterns can be found in Appendix A.

Emphasis must be placed at this point on the author's interpretation of historical conditions, attitudes, and responses. Much of the interpretation is based on limited amounts of quantitative and qualitative data. In addition, some of the factors which were examined (for example, public awareness) are difficult to measure on a quantitative scale. However, the author does feel that a reasonable interpretation of responses in this particular case has been made. If conflicts arise as to the particulars of interpretations, they must be evaluated in light of the purpose of the study. The author proposes to use this historical data only as a basis from which to extract common conditions and general principles relating to water pollution control on a broad social, political, and economic level. The underlying research goal was not to model specific interactions which took place in the Ohio River Basin. Variables and relationships were selected on the basis of their importance in this as well as other watersheds in general. The plots presented in the figures thus served merely as basic guidelines in the total overall identification effort.

#### Identification of Historical Performance Patterns

The attempt to draw a reasonable time history pattern of the factors of importance shaping the evolution of water quality change and water quality control measures in the Ohio River Basin began with the examination of the region's history. Graphs and plots

were constructed through interpretation of the relative importance of historical events as interacting causes and effects evolved over time. When numerical data were not available to represent a specific event, the interpretation was based on the best qualitative information available to assess the relative magnitude, direction of change, and speed of change in the variable.

For example, public awareness to water pollution was a variable selected for examination. The historical literature shows awareness to be greater in some years than in others. From 1920 to 1924, phenol concentration made river water unsuitable for drinking. The resulting magnitude of public awareness can be gauged by observing governmental and industrial changes to correct the problem. The public awareness of poor water quality in the 1920 to 1924 period resulted in the recognition that a problem needed to be corrected. The correction process precipitated agreement among the states on establishing water standards limiting phenol discharges. Coincidentally, steel industries undertook work to discover ways of eliminating the objectional discharges. Therefore, using the information about the concrete results which public awareness achieved, awareness was rated as 1 on a scale from 0 to 1, with 0 representing low public awareness and 1 representing public awareness of a degree capable of achieving substantial efforts to corrective action on the pollution problem.

After corrective action reduced the "high" public awareness of 1920 to 1924, public awareness reached another peak, although not as intense as previously, in 1937. The fact that there was

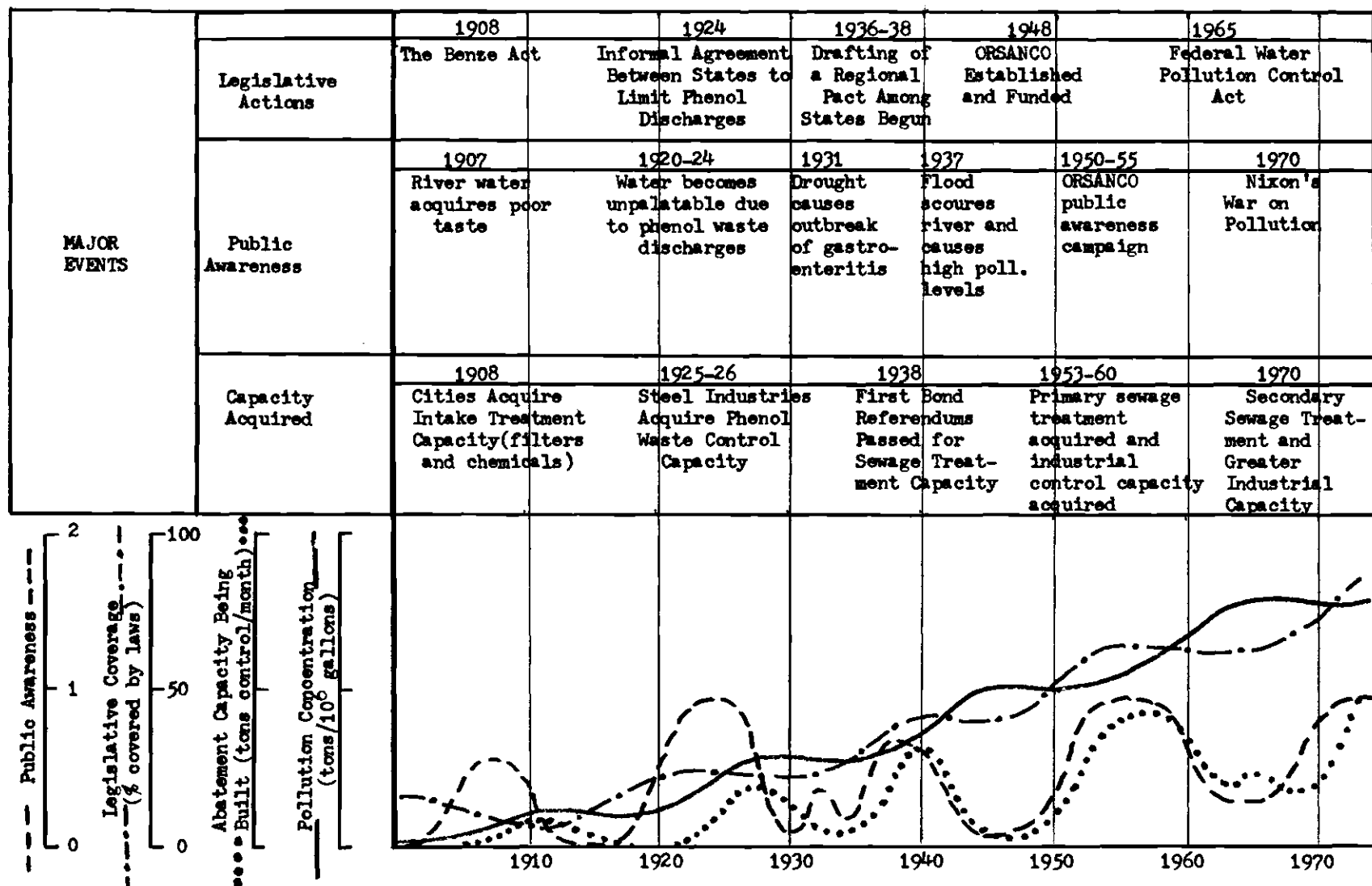


Figure 8. Long-Term Social, Political, and Environmental Response Patterns.

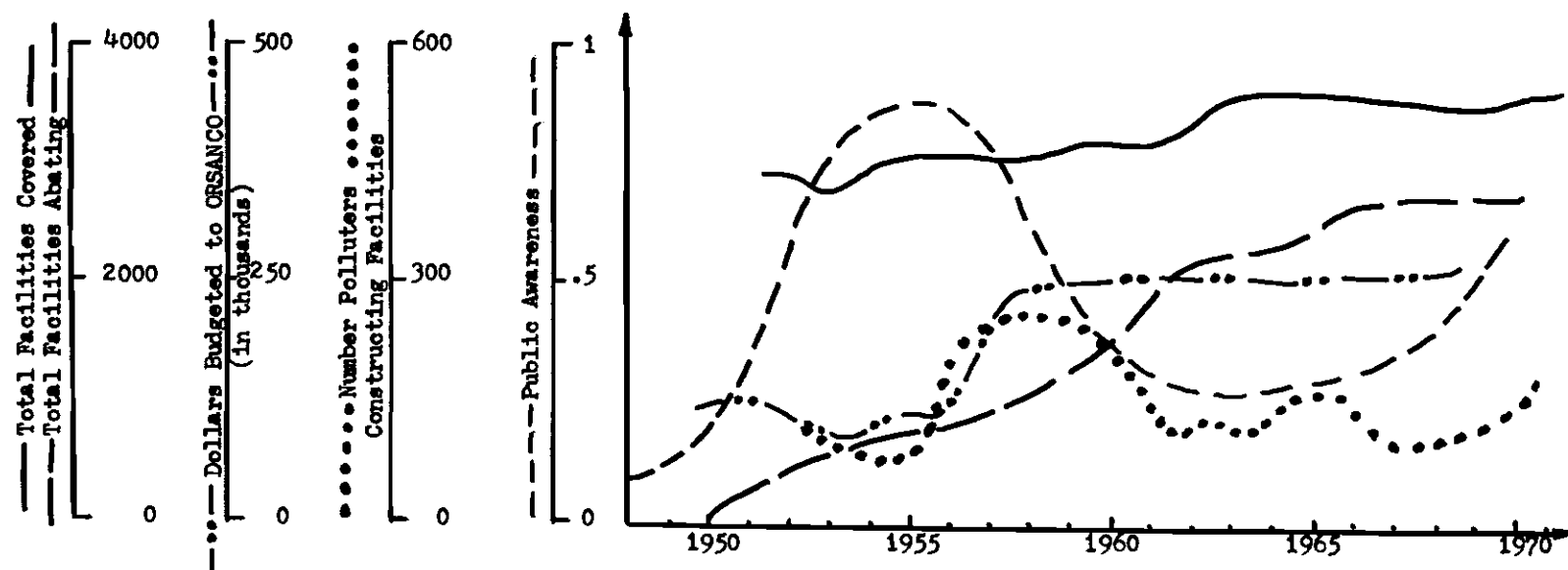


Figure 9. Recent Data Relating to Performance Behavior.

less public awareness of water quality as posing a problem which needed to be corrected can be evidenced by the relatively smaller achievements made toward legal controls and smaller achievements made in the acquisition of new abatement capacity. In 1937 flood water created excessive pollution concentration levels, creating public awareness and resulting in Cincinnati (a downstream city) passing bond referendums for pollution control facilities. Also, only the preliminary stages of a regional water quality control pact were drawn up, but the lack of intense and sustained awareness resulted in the plans laying dormant. Thus, due to the lack of definite action and continuing results, public awareness was judged to be less than before and reaching only the approximate relative value of .6, showing a moderate but not intense amount of public awareness (on a 0 to 1 scale mentioned previously).

Such evaluations, utilizing the tangible results of public awareness, led to a reasonable construction of the time history pattern of awareness and of other variables over time. During later years, more concrete data were available and could be utilized to supplement and check relationships which were found from the earlier periods of more qualitative data. Data used for this purpose is shown graphically in Figure 9 and was collected from ORSANCO Yearbooks from 1948 to 1970.

After describing the selected problem variables in a general manner, the description of events which led to the construction of the curves will be presented and examined.

### General Description of Constructed Performance Patterns

Public awareness (Figure 8) of the pollution problem was not constant nor steadily increasing over the period of years analyzed. Public awareness usually was high for a number of years associated with some "crisis" pollution condition and then returned to a state of general apathy following initiation and implementation of a pollution control program. The magnitude of public awareness generated was normally proportional to the limitations which the pollution crisis placed on the use of drinking and bathing water.

The pollution concentration level had not only a sinusoidal component but also an increasing trend. The general long term degradation of river water was often responsible for establishing the pre-conditions necessary to have a random event precipitate a "crisis" level of pollution in a particular pollutant. After public awareness rose in reaction to the crisis, popular feeling was strong enough to instigate acquisition of abatement capacity not only of a nature to correct the particular pollutant creating the immediate problem but also of a more general nature to deal with the overall problem. However, these efforts were not enough to prevent the general concentration level from continuing higher in the long run, although it did rise in stages rather than smoothly.

Legislative coverage represents the percentage of polluters throughout the entire river valley which fall under legal jurisdiction of a specific enactment. Thus, legislation such as the



Benze Act of 1908 which applied basically to Ohio has relatively less legal importance than do legislative compacts between states. Legislative coverage increases in the long run similar to pollution concentration, however, it generally increases in response to public awareness rather than in the form of preventive legislation passed before a pollution crisis caused renewed public awareness.

Finally, capacity being built represents a measure of restraint and control being imposed on various polluters - due to enforcement, legal, social, and sometimes economic pressures. The capacity acquired may be considered as processes which are capable of extracting or preventing so many tons of waste per month from remaining or being dumped into the stream.

#### Historical Events Describing Construction of Performance Patterns

The interrelationships of these factors over time seem to evolve in logical sequence. For example, in 1907 filters were first necessary to purify water for drinking purposes, especially for downstream water users. Immediately previous years had seen the taste and purity of drinking water fall. The public perception of pollution at this time was that it was higher than any tolerable level representative of tradition. The resulting awareness on the part of downstream users prompted immediate legislative response in that area. Acting on the stimulus of the public, the Ohio legislature passed the Benze Act as a measure of retaliation against upstream polluters. The act essentially exempted any city or town in Ohio from installing waste treatment facilities

until all upstream users had installed similar facilities. Although this form of legislation was negative in nature, it did point out a need for some type of legal compact which would insure equitable pollution abatement from all stream polluters - upstream and downstream. Due to the awareness generated downstream by the poor water quality, protests, litigations, and pleas of restraint directed toward upstream users alerted the upstream users and public of the deteriorating conditions of the river. Thus awareness spread from the downstream users to the upstream users. Subsequently, informal talks were begun between river basin states regarding the possibility of some mutually beneficial agreement.

Meanwhile, other forces were changing over time. Additional capacity (filter and chemical treatment) for purifying municipal water upon its withdrawal from the stream was being acquired through public funding at a rate fast enough to cope with increased concentrations of pollution in river water that threatened public health. This fact, in conjunction with growing tolerance for the taste of chemically treated drinking water, decreased the public's perception of pollution levels. The lack of continuous public arousal probably had the effect of keeping the legislative talks underway but informal; and of stymying other abatement projects which would have returned the water quality in the river to its former level.

Recapping, the following sequence of events was seen to occur. A perceived shortage of abatement and treatment capacity to cope with increased wastes occurred as the water quality provided to

the public decreased sharply. As a result of the decrease in water quality, public perception of the pollution problem became amplified. The increased public awareness sparked both legislative action and funding for some form of capacity to control the problem - in this instance the capacity was treatment plants for purification of waste waters before their discharge into the river. As the capacity became available, public awareness and concern over the problem subsided, thus lowering demands for legislative action and funding for additional capacity. Meanwhile, higher pollution concentration levels have become integrated into tradition, allowing for a higher tolerable level of pollution.

Further analysis of the historical literature reveals that similar responses occur at apparently fairly regular intervals. In 1920-1924 another crisis condition occurred sparking tremendous public awareness - an interval of 15 years following the earlier crisis. Another major crisis occurred during the flood in 1937 - an interval of 14 years. Public awareness again rose sharply around 1952-1954 following an intensive public awareness campaign of the ORSANCO group - an interval from 1937 of 15 years. In this case, the pre-conditions for a random event to set off a crisis were present. However, leadership of concerned community members (especially Cincinnati) was responsible for establishing information programs which informed the public of the actual problem before it was manifested as a precipitous event.

Recently new forecasts of future water and ecology threats are seen to be increasing public awareness again - approximately 15 years after the last crisis. Thus, some regularity of period

(timing) is seen in public awareness, as well as in other variables.

This regularity of timing can be observed by analyzing the responses over a longer time span. Thus following the 1908 crisis and its subsequent "solution," the rate of capacity acquisition and legislative actions decreased as public awareness to the problem decreased. However, industrial expansion, especially of steel mills, resulted in an ever increasing amount of pollutant production and discharge. By the early 1920's, waste discharges from steel plants began causing phenol concentration levels in the water which filter and chemical treatment was unable to adequately handle. Initial attempts were made to consider corrections in the system. As increases in steel production continued to outpace purification capacity to treat phenol discharges, the problem worsened. By 1924, the water became so poor in taste that downstream users found it hard to drink the water. Public awareness rose sharply. As a result of this crescendo of public outrage, two results were finally achieved. The informal talks between the states which had been lingering on for years with no concrete action, finally resulted in an informal agreement among the states which would set standards to limit the amount of phenol discharges. Coincidentally, the steel industries made concessions and agreed to find ways to eliminate the objectional discharges. Within a few years, the capacity to eliminate the phenol discharges was acquired and operating, thus reducing the offensive phenol in the drinking water. Public perception of the water pollution problem

soon decreased as a "solution" to the problem had been perceived.

Subsequently, little additional legislative action was taken nor was additional capacity to treat other types of waste acquired. Capacity was acquired merely to prevent discharge into the river of one pollutant which filtration and chemical treatment by those withdrawing water were unable to treat. Abatement capacity for growing numbers of other pollutants was neglected. Thus the stage was reset for industrial and municipal growth and their related waste production to outpace the growth of treatment capacity and treatment facilities. This situation did in fact reoccur in 1937 as flood water created excessive pollution levels at purification plants and throughout many low lying areas along the river. Some sewage treatment capacity was soon acquired, as bond referendums were first passed (see Appendix A). In addition, the preliminary stages of a regional water quality control pact were drawn up, although the lack of continued public awareness left the preliminary plans as merely plans rather than action. This lack of sustained public awareness was possibly due to the short duration of the crisis and also due to the World War II war effort.

Following World War II, the supply and demand situation began to reach critical proportions again. Technological demands of industrial production, growth of cities, and increased leisure time increased the demand for water usage. However, the supply was limited and growing smaller. Preparatory action was taken by the states, and in 1948 a regional pact for water quality control was established. Recognizing the necessity of public awareness

to provide the main stimulus for capacity funding and enforcement staffing, the ORSANCO group started an intensive public awareness campaign to enlighten the public of the pollution problem. The efforts of the campaign in combination with a critically polluted river created rising public awareness by the mid 1950's. This awareness led to the acquisition of capacity to treat the pollution problem (in this case both industrial and primary municipal waste treatment was acquired). Figure 2 gives a more detailed picture of the actual and hypothesized response of these factors during the last major awareness phase.

The public awareness in the 1950's prompted a series of actions. Funding was increased to the enforcement agency to carry out its water standards development program and compliance program. In addition, public susceptibility to bond referendums was increased, providing the necessary funds to buy "adequate" treatment facilities to meet the designated water standards.

As the additional treatment capacity became operative, and perceived pollution concentration levels decreased, public awareness again appeared to subside, creating an apparent leveling out of capacity acquisition by 1962-68. This capacity acquisition stagnation occurred even though approximately 30% of the facilities covered still had not acquired abatement capacities necessary to meet designated water standards. It must be pointed out, however, that these 30% of facilities in number probably constitute smaller plants or cities, and as such, do not contribute a corresponding amount of pollution.

### Generally Occurring Relationships

Using the above presentation and analysis as a background, a series of behavioral response patterns (Figures 10A to 10E) are hypothesized in an attempt to depict normally occurring relationships as they appear to change over time. The plots attempt to show the relative phasing and magnitudes of the different variables. In Figure 10A public awareness of the water pollution problem increases as a larger share of the populous perceives a level of pollution concentration surpass what it considers to be a tolerable level. In addition, this condition appears to occur periodically - once approximately every 15 years. During any one of these surges of public awareness, a chain of events is initiated which aims to return the perceived level of pollution concentration to a value below what is tolerable. This correction process is in response to multiple pressures brought on the government and industries which have resulted in these commonly occurring reactions, as substantiated in the historical data:

- (1) the demand for the establishment of legal guidelines which embrace general water quality standards,
- (2) the appropriation of sufficient funds and staffing for the enforcement agency responsible for implementing and administering the legislative guidelines,
- and (3) public funding to supplement the construction costs of treatment facilities.

This last category entails the appropriation of funds through public bond referendums, general taxes, and also a willingness to pay higher prices for products produced by industries.

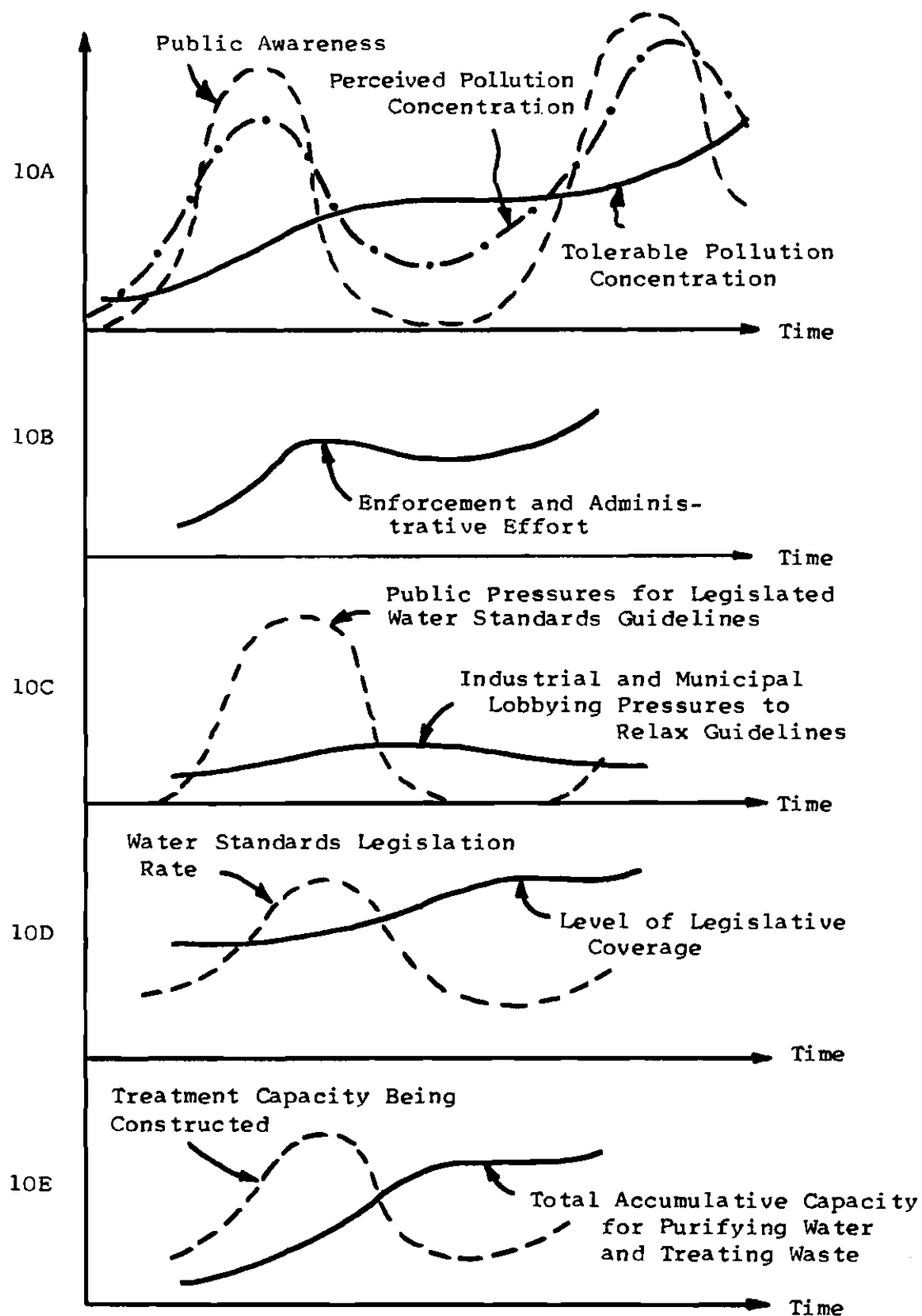


Figure 10. Short Term Hypothesized Interrelationships Which Produce Water Quality Dynamics.



Figure 10B illustrates what appears to be the time history of effective enforcement effort. Additional staffing requested by an enforcement agency would logically be considered most favorably by the legislature when public awareness is high. However, the delays involved in allocating these requests and in hiring and training additional staff would likely delay the peak of any enforcement effort until it lags the peak in public awareness. As public awareness eventually subsides, further allocations by the legislature to the enforcement agency would not be looked upon as favorably, especially in relationship to alternative public priorities. Thus, a leveling out or decrease in effective enforcement power is likely to occur.

Figures 10C and 10D depict the level of legislative guidelines as they respond to factors responsible for generating changes in the existing level of legislation and associated water standards. In Figure 10C emphasis is placed on describing how, in general, changes in legislative regulations are generated. The legislature (or legislatures, if a number of states are involved) acts in response to competing pressures. The two main competing pressures appear to be the public pressures and municipal and industrial lobbying pressures. Public pressures for more effective restriction of pollution through legislative guidelines and water standards develop in proportion to awareness of the problem. In addition, when this pressure reaches peak levels, the force seems to be much greater than opposing lobby pressures. However, opposing lobbying pressures, which ask for special exemptions

and relaxation of stringent controls, seem to be more constant over time.

The end result of the competing interaction can be seen in Figure 10D. Laws are passed as public awareness dominates the lobbying pressures in the legislative branch. Later as public awareness subsides due to decreases in perceived levels of the pollution problem, industrial and municipal lobbying pressures dominate the legislature, although not nearly sufficiently so as to bring so rapid a change. The long term pattern seems to be a surge of increased legislative laws passed, followed by an increasing legislative tolerance to industrial and municipality exemptions or postponements. After a long delay, the level of accumulated court rulings establishes the legal boundaries of the laws and associated water standards.

Figure 10E represents the purpose and end result of the other actions. Some type of capacity for treating or otherwise reducing waste discharges must be acquired in order to bring the perceived level of pollution back to a tolerable level. The rate at which this capacity is acquired is dependent on the effectiveness of the institutionalized process in working through the other described relationships. The majority of the capacity is acquired through motivating existing nonabators to adhere to designated water standards and treatment schedules. These non-abators will seldom abate out of a sense of concern for the public in the face of strong economic pressures. In the presence of other abators, they would be presently receiving an economic incentive to remain a

non-abator. For example, an industry avoiding payment of water treatment and waste treatment costs has lower operating costs than those of its competitors, thus allowing cheaper production and a competitive advantage. Municipalities can gain the same type of competitive advantage as they assess lower taxes.

In the face of these incentives, therefore, non-abators would not be highly motivated to implement an abatement program and consequently are likely in effect to delay compliance as they move along the path of least resistance. Thus, if water standards are set high through legislation, but enforcement staffing is low, abatement response would basically correspond to enforcement pressure. However, if enforcement staffing is high but insufficient legal boundaries are established, abatement response would essentially follow the perceived minimum allowed by law. Another interacting factor is the public's consent to supply completely external funds. For example, an industry does not mind acquiring abatement capacity if someone else pays the complete bill. In the case of cities, politicians would not mind acquiring abatement capacity if increased taxes did not threaten their political careers.

In summary, capacity acquisition and total accumulative capacity respond as a function of the three aforementioned interactions. The total response historically appears to show that total treatment capacity begins growing gradually during the period of public awareness and later peaks out as new treatment capacity being constructed falls due to decreased pollution levels, public awareness, and the related impacts on public awareness.

Comments Regarding the Identification  
of Normal Relationships

The preceding section developed the four principal components of water quality control programs as they have existed historically in the United States and postulated broad social, political, and economic processes interacting in their development as based on an analysis of a case history of the evolution of water quality management in the Ohio River Basin. These components as described were (1) public awareness, (2) legislated water standards, (3) enforcement efforts, and (4) waste treatment capacity. These factors do not always appear in identical form however, and they may appear in discrete events. Thus, a further examination of each factor as it changes in nature and magnitude over time may be helpful in demonstrating the generality of the relationships which have been isolated and described.

Public Awareness

Public awareness to water pollution problems seems to rise most rapidly when a significant deviation from recently prevailing or normal conditions of water quality occurs, especially when the deviation involves limitations on drinking water. When drinking water seems degraded as opposed to some traditional standard, the need for pollution control capacity is quickly and extensively realized by the public. This awakening is precipitous if the polluted water is distributed through a common usage system - the water supply system. Unless such conditions as these occur or seem eminent, the public is apathetic over water pollution,

especially in relationship to other problems which may be occurring simultaneously. In addition, it is reasonable to hypothesize that public awareness campaigns would have their greatest effectiveness when public water supplies seem endangered.

These statements reinforce the historical analysis previously discussed. In the example, the period of 1900-1910 showed river waters becoming increasingly polluted and intolerable as drinking water. Since raw river water was distributed in the downstream water supply systems, downstream public interaction with the pollution was high. Subsequent pressure on upstream users resulted in raising their awareness of downstream problems, eventually alerting much of the entire river basin. Corrective action was subsequently demanded and initiated. The result was the introduction of filtering and chemical treatment which insured purification of the water before distribution was made to the public. The resulting purification of drinking waters soon caused public awareness to subside.

Again in the early 1920's, intense public awareness resulted when phenol concentrations in the river water reached levels which even filters and chemical treatments were unable to adequately handle. Offensive odors and tastes appeared in the drinking water making it nearly unpalatable.

Another strain on the public water supply system occurred in the late 1930's when flood water washed stagnant organic wastes into the river. Awareness again spiraled. Similar strains on the water purification system occurred in the early 1950's as increased industrial discharges and added household discharges

such as nondegradable detergents were responsible for creating excessive water hardness. Although the problem did not precipitate into a crisis due to some natural disaster, the potential hazard became clear when citizens were fully informed. An intensive public awareness campaign was thus successful.

Public awareness does therefore seem to result from rather consistent factors over time. In each case, public awareness resulted from wide public interaction with the problem either through direct observation of degraded drinking water or through perception of eminent dangers to the public water supply system. Given certain prevailing conditions, public awareness campaigns to generate increased problem perception appear to be successful. Thus, some awareness crises are exclusively "natural" causes while others are relatively more man-made.

The public appears to be indirectly controlling the general level of water quality by allowing indiscriminant municipal and industrial usage of streams and rivers to carry away waste material until some notion of severe pollution is experienced. At that time public demand forces corrective actions to regulate waste discharge into the water resource. This corrective process usually results in rapid ordering of new abatement capacity.

These responses are currently observable in the technology versus ecology discussion. Society would like to most effectively utilize its resources to produce physical goods for its convenience, but society also desires clean water and air for recreational, aesthetic, and physical health reasons. Some balance must

be struck. Public awareness and its related impacts on funding, legislation, and enforcement and followed by subsequent reactions seek to define this socially acceptable balance.

#### Water Quality Legislation

Legal compacts and laws establishing water quality guidelines seem to evolve with consistent properties and with similar response patterns. Each stage of legislation has been characterized by increased requirements of waste treatment or control and by increased efforts to equitably distribute the capacity acquisition responsibility among all stream users - both upstream and downstream. For example, when the water became unpalatable due to phenol concentration, an informal agreement was signed among the states which set limits on discharges of phenol related wastes. The signatory states thereby agreed to increase waste treatment requirements at steel plants and also eliminate disproportionate responsibility for water pollution from downstream users and facilities. Additional control and regulation was legislated during succeeding waves of public awareness. During the 1937 period, the drafting of a formal regional pact among the states was begun. These efforts finally crystallized in 1948 when a regional water quality control agency was formally established.

In addition, each stage of legislation was evolved with a similar response pattern. Legislative action crystallized with a short time after public awareness developed to the point where pleas for legislation dominated the political scene. Eventually, as the perceived level of pollution had been lowered by increasing

pollution control capacity, increased legislative action stagnated. This stagnation resulted when public demands subsided while lobbying interests increased pleas for delays, exemptions, and special waivers. When the pressure from lobbying interests dominated the legislature, granting of delays and special exemptions slowly diluted some of the actual legislative guidelines earlier established.

#### Capacity Acquisition

Capacity acquisition to control the level of water pollution occurred in major stages in response to public awareness and its related influences. Filtration and chemical treatment of water withdrawn from the stream represented the first stage of capacity acquisition. Although this capacity did not decrease the level of pollutants actually in the stream, it did effectively reduce pollution in the public water supply system. Since there has been greater tolerance of polluted water for uses such as recreation or industrial uses, the stream was actually utilized more effectively (assuming purification and filtering costs were cheaper than waste treatment or source reduction costs).

By 1924, stream phenol concentrations had effectively become greater than purification or chemical methods could adequately handle. In order to solve the phenol pollution problem, waste discharge control capacity was achieved as steel and coke industries agreed to limit phenol discharges. At this point in time, the total capacity to treat or control waste was the combined water purification treatment capacity and facilities to limit



phenol discharge.

Total accumulative capacity continued to grow in stages coinciding with waves of public opinion. In 1937 the first major efforts to treat sewage discharge were spurred when Cincinnati passed a large bond referendum to build a sewage treatment facility. Similar capacity was probably acquired in limited quantities by other towns or cities.

Another stage of capacity acquisition appears to have occurred during the late 1950's and early 1960's when the regional commission in the Ohio River Valley (ORSANCO) developed water standards and treatment specifications, encouraged public and private funding, and pursued compliance activities. The goals which ORSANCO hoped to achieve included primary sewage treatment for all cities and towns and similar levels of waste treatment from industries.

Further increases in capacity, through secondary sewage treatment and further increases in industrial discharge control would seem logically to follow from the next surge of pollution awareness - possibly stemming from the Nixon Administrations' "War on Pollution."

As has been illustrated, public awareness appears to occur in waves due to perceived lack of availability of adequate personal usage water. Legislation appears to develop in response to public awareness. Capacity also appears to be acquired in recognizable stages following waves of public awareness.

#### Enforcement Agencies

One additional factor seems prominent in overall pollution

control efforts. Legal guidelines may play a major role in setting water quality standards, but they also must insure the specific regulations are adequately developed and enforced. Such enforcement usually stems from the establishment and staffing of a pollution control agency. This agency usually becomes more sophisticated and specialized as time passes. The original enforcement and administrative agencies were subsidiaries of local or state health departments. Later, state water quality control boards or some related specialized activity evolved. The regional water quality control commission was finally established in the Ohio River Valley as a means to insure equity among the states, their standards, and enforcement of standards. Although limited information is available regarding the size and powers of the control agencies during particular years, it does seem reasonable to assume that funding and staffing of the agency reaches the maximum level in rapid response to public awareness and subsequent budget allocations. Such response appears prevalent in the most recent data available (Figure 9). Funding to the ORSANCO agency reached its maximum level by 1958, three years after the hypothesized public awareness peak. Although the individual states then took over many of the enforcement and monitoring duties, subsequent enforcement may have effectively decreased. This decrease could help explain why the difference between total facilities covered and the total number with "adequate" facilities leveled out by 1964-1968.

### Summary

Much emphasis has been placed on isolation, description, and analysis of high-level social, political, and economic factors which characterize water quality control within any region. These efforts were made in order to extract normal relationships and general principles which resulted among the various interacting factors.

The final objective of the analysis was to identify the feedback and control mechanisms that promote the problem of periodic crisis conditions of water pollution in addition to the ever increasing "drift" to higher absolute pollution concentration levels. Understanding of these complex mechanisms should provide better insight into the specific nature of the total system behavior.

## CHAPTER IV

### SYNTHESIS OF A MODEL OF INSTITUTIONAL FACTORS AFFECTING WATER QUALITY

#### General Modeling Technique

The preceding chapter was devoted to identifying and describing the social, political, and economic factors which interact in the formation of individual and institutional behavioral response patterns to opportunities for using water to carry away waste and to subsequent quality degradation. Specific factors were noted as being of primary importance in determining the level of water quality in a region over time. From this information and the understanding of basic relationships that it imparts, an information feedback model of important relationships can be rationally developed. The remaining portion of this section will be devoted to the explanation and justification of the modeling process used and the resulting model.

The modeling process was guided by three important considerations. First, in attempting to extend system boundaries to include explicit recognition of social, political, and economic factors of importance, many relationships were considered. However, for purposes of the model, only those relationships which seemed to be controlling factors in producing the historical behavioral patterns identified were selected and incorporated into the model. The model therefore contains only those relationships

within social, political and economic sectors in response to environmental change which seemed highly instrumental in producing the response patterns observed historically. In this form the model lends added explicitness to the controlling relationships and couplings while retaining as much simplicity as possible.

Secondly, the model was developed so as to be amendable to some analytical process through which the information feedback loops and control loop mechanisms could be systematically analyzed. The philosophy and methodology of Industrial Dynamics (7) and its related simulation language DYNAMO (19) were especially well suited for this task and were therefore selected. Using this methodology, the model is developed as an interrelated set of states (level variables) and transitional relationships (rate variables). Equations describing these variables are derived and programmed on a digital computer, and they allow the analysis of the system through repeated simulations.

Thirdly, the model illustrates how observed historical behavioral response patterns associated with water quality control result from the complex interaction of multiple information feedback loops. Better understanding of the complex relationships provides a better basis for developing managerial policies and institutional structures which can more effectively control system behavior in critical variables.

#### The Systems Problem

The response patterns previously discussed point out the

cyclical pattern which seems to have been historically experienced in the process of acquiring waste treatment and control capacity to match the growing amounts of pollutants generated. Ohio River Basin records demonstrate an almost continuous historical increase in the production of pollutants and a capacity to control the pollutants that has been acquired in discrete stages. The result has been a series of episodes where pollution concentrations increase to unacceptable levels, public awareness becomes high, and abatement capacity is soon afterwards rapidly acquired. After the newly acquired capacity is able to handle the immediate problem, pollution concentrations drop to acceptable levels, the public loses awareness of pollution, and the rate at which additional abatement capacity is acquired drops to very low levels. Simultaneously with this repeating cycle, the long term trend has been toward growing pollution concentration levels. Thus it appears that the crises oriented efforts to control pollution in the short run have been insufficient to control the long term problem of rising pollution concentration levels and subsequent decreases in water quality.

#### Simple Control Process

A feedback control system of the process in its most simplified form would be helpful in understanding the basic system. In this or any other control system, basic controlling relationships usually exist. Figure 11 shows the relationships suggested as basic to the water quality control system. Society observes both

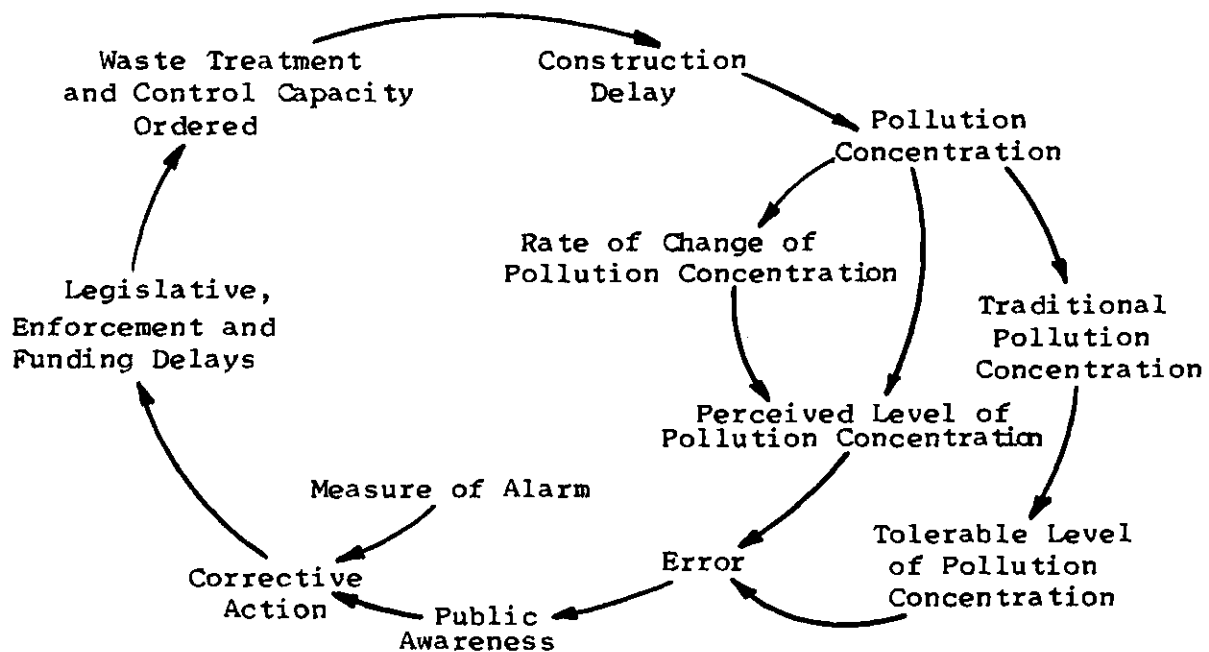


Figure 11. Simple Control Model Responsible for Basic Performance Patterns.

the present pollution concentration level and the changing rate of pollution concentration. The public then utilizes these two observations to establish a perceived level of pollution concentration. The perceived level of pollution is then compared to the acceptable state of the environment - the tolerable level of pollution. A judgement process determines the error, that is, the difference between the perceived and tolerable levels of pollution concentration. If the difference is perceived as making it worthwhile, corrective action is subsequently taken to realign conditions to remove the apparent error.

In addition to the perception of the error, the measure of alarm determines how quickly the error will be corrected. If

corrective action is perceived as desirable in light of the cost and effort required, delays follow because it takes time for laws to be passed, for monies to be appropriated, for enforcement agencies to be staffed, and for the judicial system to resolve related legal issues. After these delays, waste treatment and control capacity is ordered. Following a construction delay, the new abatement capacity helps reduce stream pollution, and the perceived pollution drops to better conform to the tolerable level of pollution.

In general, two loops can be seen in this simple diagram. The nature of these two loops explains the basic performance of the system. First, a negative feedback control loop exists through the perceived level of pollution which attempts to keep the perceived pollution concentration from growing too rapidly in relationship to the tolerable level. If the perceived level of pollution increases in relationship to the tolerable, public awareness is generated. Waste treatment and abatement capacity is then ordered in large quantities. After delays for construction, the additional abatement capacity becomes available and is responsible for decreasing waste discharges and hence pollution concentration in the stream, resulting in a decrease in public awareness. Thus, an initial increase in the perceived level of pollution traverses the loop after various delays to create a decrease in the same variable.

Secondly, a positive feedback loop exists through the tolerable level of pollution. If the tolerable level of pollution



increases while the perceived level of pollution is high, the difference between the tolerable and perceived levels of pollution grows smaller, resulting in decreased public awareness and less subsequent action to acquire new abatement capacity. The actual level of pollution in the stream edges higher as inadequate treatment and abatement facilities eventually result. These higher levels of pollution concentration are slowly integrated into tradition, and allow a still higher tolerable level of pollution. Thus, an increase in the tolerable level of pollution traverses the loop leading at a later time to still further increases in the same variable.

The negative feedback loop is therefore responsible for creating the goal seeking nature of the system, but the positive feedback loop allows the goal (tolerable level of pollution) to edge higher. In Figure 12, the results of these two coupled loops can be seen. The actual pollution concentration has two basic modes - an oscillatory pattern reflecting the negative feedback loop and a growing exponential pattern reflecting the positive feedback loop.

Some important points must be made concerning the above process. Water quality control involves multiple feedback and feedback control loops with many non-linearities. The matching of capacity available to capacity needed is difficult as both the tolerable level of pollution and the rate at which pollutants are generated continue to increase. Other difficulties occur because the correction process is highly dependent on public awareness

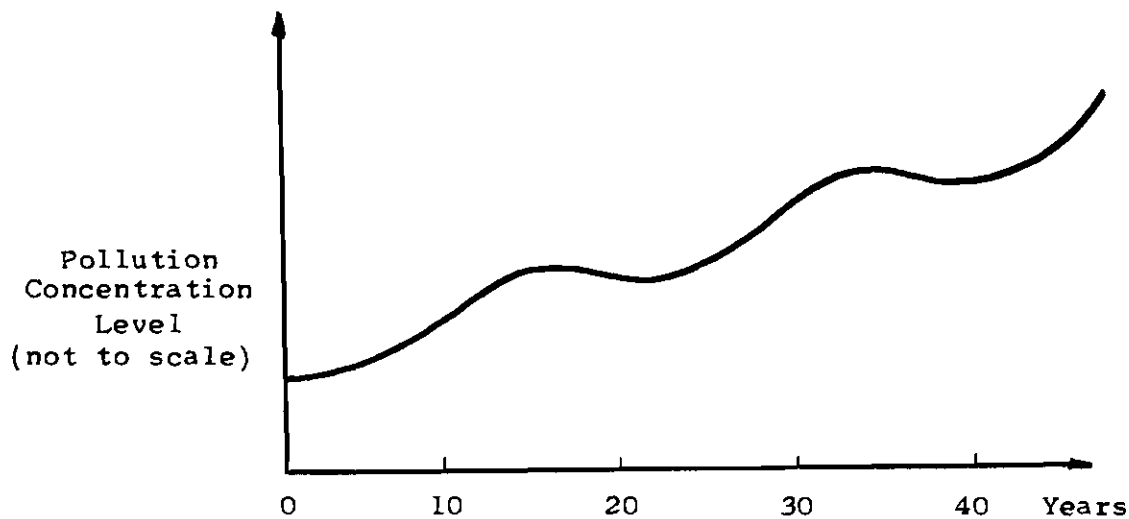


Figure 12. Results of Two Major Feedback Loops Being Coupled.

and its impact on funding, legislation, and enforcement. Without public awareness, these impacts are unable to make full problem corrections. Still further difficulties are created because the long delays necessary to activate abatement in some of the feedback loops create an atmosphere of negotiation, compromise, and even further delay. The totality of these considerations make the simple information feedback control model in Figure 11 seem unrealistic, but it does serve to depict the model at a level of more widespread understanding of control principles. A model which includes more complex considerations is developed in the following section.

#### A Water Quality Model

The composite flow diagram illustrated in Figure 13 inter-relates important feedback and feedback control loops among and within such model sectors as the environment, the legislature, the



enforcement agency, and the abatement capacity.

The model (Figure 13) is driven by an exponentially increasing generation of potential pollutants, created by the general growth in population and technological and industrial expansion.

The pollutants actually dumped in the stream, however, will be the difference between the pollutants which would potentially be generated if polluters were free to dump all wastes in the stream and the amount of operational abatement capacity available to restrict dumping or in fact generation. Thus, operational abatement capacity would include sewage treatment plants, cooling towers for hot water, any reconstitution or recycling processes for waste, and any modification to industrial processes which reduces pollution generation in the first place. Any potential generation rate of pollutants greater than this capacity will lead to the excess being deposited in the river.

The pollution concentration then builds as the polluting rate exceeds the natural ecological capacity of the stream to oxidize and assimilate the new waste load. In order to reduce this accumulating level of concentration, operational abatement capacity must be brought into alignment with the rate of pollutant generation.

Full corrective effort to align the operational abatement capacity with the rate of potential pollutant generation requires a high level of awareness. Awareness builds as the perceived level of pollution concentration approaches and then passes some tolerable level based on tradition (See Figure 11). Perception

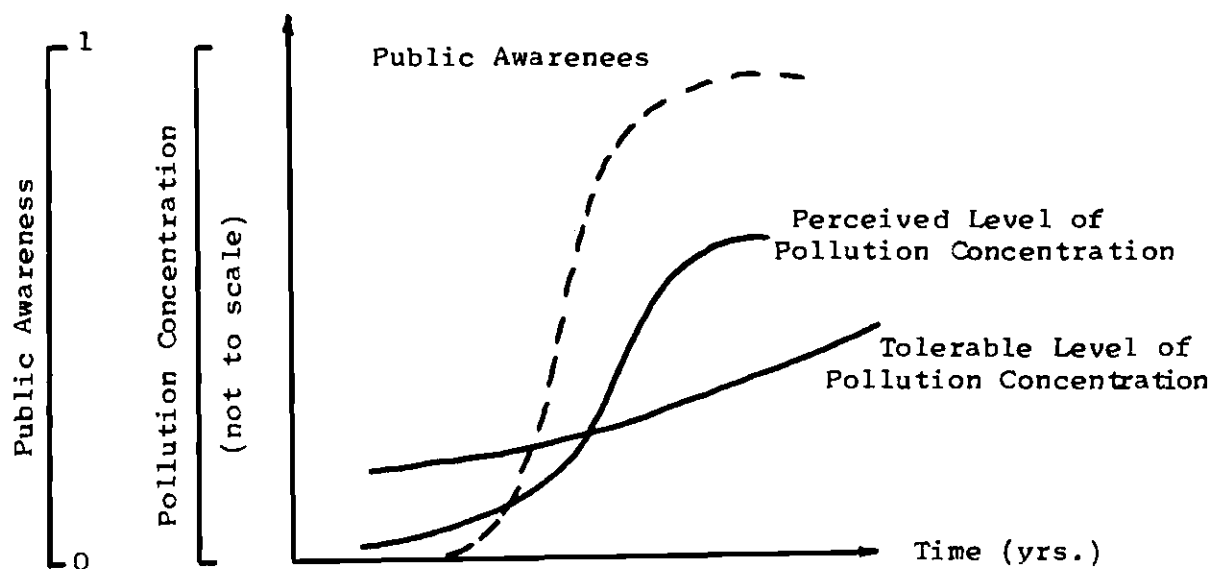


Figure 14. Perceived versus Tolerable Pollution Concentrations.

of pollution is normally damped below or amplified above this traditional level of pollution based on (1) how rapidly pollution changes occur and (2) the absolute magnitude of pollution. Slow changes in pollution concentration allow increased levels of pollution to be slowly integrated into tradition without apparent public notice. Rapid changes are more likely to create color and taste differences which become observable in the public water supply system. Such rapid changes are easily perceived by the public, regardless of the individual's technical sophistication or previous knowledge of the problem. Therefore if changes are more rapid, the perceived level surpasses the tolerable level, subsequently stimulating public awareness. In addition to the impact which the rate of change has on perception of pollution, the absolute magnitude of the pollution influences awareness. As the absolute level of pollution concentration edges higher, general

awareness to the problem grows proportionately.

Awareness eventually stimulates three interrelated responses - each aimed at reducing the pollution to a more tolerable level. The three interrelated responses include increases in (1) funding, (2) legislation, and (3) enforcement effort. Funding represents external monies raised to pay all or part of the facility construction cost. These external funds can be raised by municipalities through increased taxes or bond referendums or by industries through public willingness to pay higher prices for consumer products. Either way, funding requires a public willingness to pay for correcting the problem. However, the general public desires the particular publics served by pollution creating municipalities and industries to pay their fair share for correcting the problem; thus, the widely dispersed general public attempts through legislation and enforcement efforts to enjoin municipalities and industries from passing the cost on to those downstream.

Legislation follows as delayed response to public awareness and usually takes two forms - both aimed at providing the enforcement agency the legal framework under which to operate more effectively. Legislative acts usually attempt either (1) to set water standards for streams and lakes or (2) to prevent upstream polluters from taking unfair advantage of their location, where they can hurt those downstream but not be hurt in turn, through legislative pacts or arrangements among jurisdictional districts or states. Within the legal framework developed, the enforcement agency may then be able to prod polluters into generating internal

funds for the construction of pollution control facilities.

Finally, enforcement effort is dependent on staffing allocations dictated by the budget limitations imposed by the legislative branch responsible for the agency. This enforcement agency is responsible for not only monitoring pollution levels and individual polluters and for inspecting construction of new facilities, but also is responsible for forcing polluters to meet their abatement responsibilities as established by law.

As determined by the interrelationship among external funding, enforcement, and legislation, internal funds from industries and municipalities are raised in order to match public external funds which are available. The total funds generated are then converted into the construction of new abatement facilities, which after a delay, result in an increase in operational abatement capacity. This increased capacity then helps align capacity available with capacity needed.

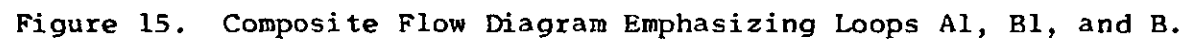
It should be noted that the interrelationships (timing and magnitude) among enforcement, legislation, and public funding are important in producing some peculiar system dynamics. That is, due to problems concerned with technological external diseconomies and competitive advantages it produces for non-abators, non-abators desire to delay compliance to abatement orders as long as possible. Thus, if no external funding stimulus is available, non-abators would naturally respond with the minimum possible compliance with water standards that they can get by with in the context of the enforcement pressures applied by the enforcement agency and

the success of those hurt downstream in obtaining redress through the courts. Subsequently abatement response would follow the minimum of the two pressures - legal or enforcement. However if external funding is available, internal funding will accelerate as polluters take advantage of the limited availability of external funding grants. Accordingly, the responsiveness of the system and resulting dynamic performance patterns could be altered.

#### Description of Individual Feedback Loops

Feedback loop A1 (Figure 15) describes how a large amount of the instability in the system behavior is created through cycles of change in public awareness. This loop represents the essential mechanisms through which society attempts to control water quality. Following an addition to the pollution load and after a perception delay, the perceived level of pollution concentration builds with respect to tolerable and perceived levels. Public awareness that something is wrong is subsequently generated and rises as the perceived level surpasses a tolerable concentration determined at least in part by the traditional pollution concentration. Awareness with time stimulates external funding for capacity construction cost supplements. As increased capacity becomes operational following a construction delay, the dumping of pollutants is better controlled, reducing the polluting rate and the level of pollution concentration. Loop A1 is a negative feedback control loop working to keep the perceived well below the





tolerable water pollution level. Thus an observed trend of the perceived to approach the tolerable level initiates a series of actions which subsequently reduce the perceived level with respect to the tolerable level of pollution concentration.

Feedback loop B1 is a positive feedback loop responsible for the long term growth in pollution toleration. The full explanation of the loop behavior was given as part of the simplified model given in the previous section.

Loop B (Figure 15) attempts to couple environmental needs with treatment and control capacities to meet those needs. The capacity needed is forecast from the time trends in pollutant generation rate. If total capacity to handle this pollutant generation rate falls below the needed level, funds are requested in order to build treatment facilities which would correct this error. However, funding may not be available due to lack of public awareness. When awareness is low, loop B does not have sufficient funds to buy all the capacity which is needed. Loop B is also a negative control loop, continually attempting to align capacity with capacity needed.

The coupling of loops A1 and B contribute significantly to the dominant behavioral patterns previously identified. Loop B determines needs for additional capacity, and these needs are filled at various rates, dependent on public awareness and previously established enforcement powers and legislation. The interaction of the two loops can be explained as follows. The capacity needed to deal with changing levels of pollutant

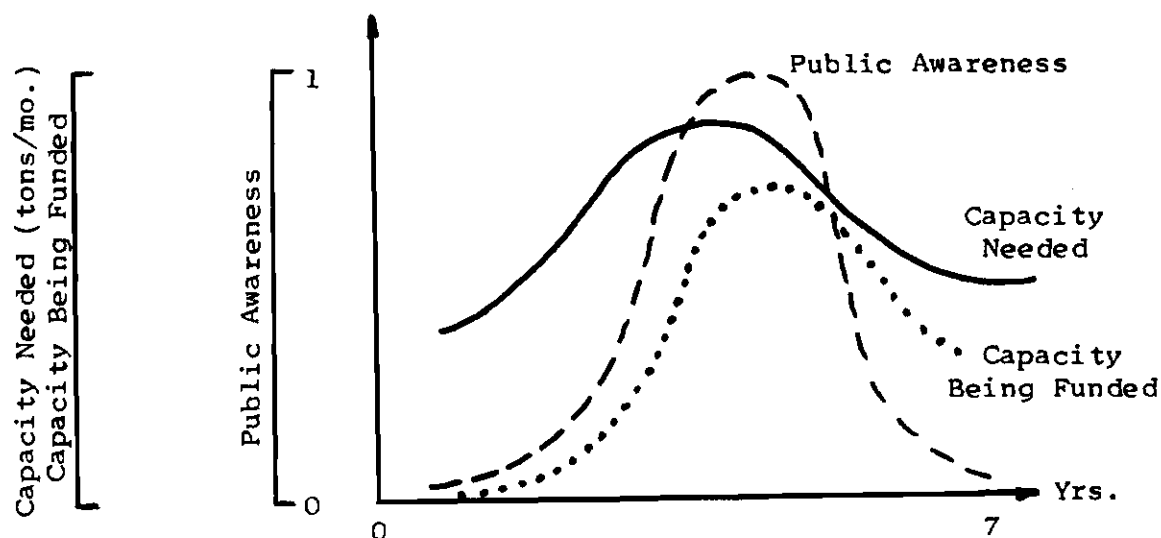


Figure 16. Behavioral Patterns Generated by Loops A1 and B.

generation is at first only partially funded due to the unwillingness of the public and industries to commit funds to a problem not clearly perceivable. As the problem worsens due to the lagging abatement rate and public awareness finally catalyzes, funding programs are instituted to fully correct the error between capacity needed and capacity available. The behavioral response patterns that these two loops generate are shown in Figure 16.

Loop C (Figure 17) represents attempts to maintain staffing at the enforcement and administrative agency at a level able to accomplish the three primary responsibilities of (1) administration and monitoring of present abating facilities, (2) inspection of new facilities being constructed, and (3) gaining compliance to water standards from non-abators through enforcement activities.



The staffing level necessary is determined by estimating the amount of effort needed in each area of responsibility. Staffing to police the discharge of pollutants to make sure that it is in compliance with established standards requires a proportionately greater effort. If staffing falls below the needed level, enforcement effort is adjusted upward, therefore allocating additional staffing to the agency. As enforcement effort increases, external funding is accelerated, increasing compliance, and subsequently reducing the need for additional staff. These considerations are included in the negative feedback loop D.

Corrections in staffing allocations are not always fully made. The extent to which the requested allocations are granted depends on public awareness and its impact on the legislative budgeting allocations. When public awareness is high, requests are normally fully granted. Loop A2 (Figure 17) provides for the full or partial allocation of staffing which is requested.

Public awareness of pollution problems fluctuates with time over a wide range. The lobbying pressures which favor going easy on industry to promote economic growth or to prevent the loss of jobs during hard times are comparatively constant. When public awareness is high, legislators find it politically necessary to establish tighter laws and regulations governing discharges of wastes into streams. Included in these laws would be pacts which insure equitable coverage and enforcement across jurisdictional boundaries. Feedback loop A3 (Figure 18) contains the essential elements representing the effects of legislation on internal

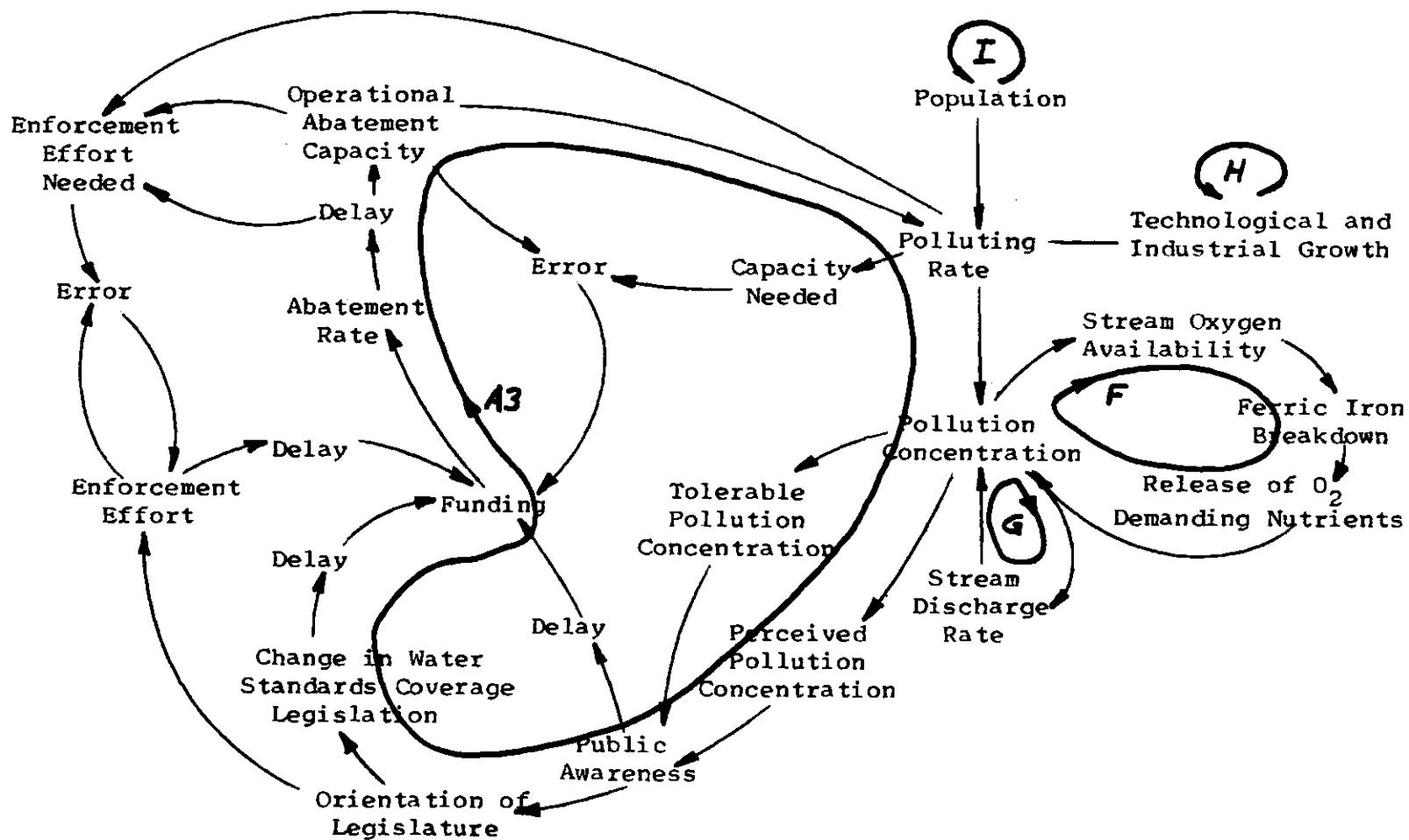


Figure 18. Composite Flow Diagram Emphasizing Loops A3, G, F, H, and I.

funding from cities and industries for the construction of pollution control facilities. Feedback loop A3 is a negative feedback loop as increases in the pollution concentration create awareness which causes a shift in the legislative orientation - from basically municipal and industrial interests to public environmental interests. When this shift occurs, tighter control laws are passed requiring polluters to build abatement facilities, thus increasing abatement capacity and finally decreasing the pollution concentration level.

Public awareness and public requests for laws, however, are not the only voices with which the legislature must contend. Lobbying pressure from both private and municipal sources are usually attempting to affect legislation for their benefit. These lobbying interests desire to utilize the water as a free resource. Thus when adequate abatement capacity has been apparently acquired, public awareness decreases allowing lobbying pressures to dominate the legislature. When the legislature is thusly dominated, exemptions, postponements, and waivers are granted - thus reducing through dilution some of the effectiveness of laws and water standards previously passed.

Feedback loop F (Figure 18) represents the description of the environment being controlled. The loop has positive polarity in that changes in any variable in the loop traverse the loop stimulating still further change of the variable in the same direction. The natural ecological capacity of the stream fits this description after certain threshold pollution concentration levels are passed.

As the pollution concentration level reaches excessive levels, stream oxygen for bio-degradation is unavailable. This lack of oxygen eventually creates a breakdown of the compound ferric iron which holds many oxygen demanding nutrients in insoluble complexes at the river's bottom. As the ferric iron breaks down, even more oxygen demanding nutrients are released, creating a still further rise in the pollution concentration level.

Feedback loop G represents the watershed's ability to eliminate excess levels of pollution through the natural flow of the stream. As the pollution concentration level increases, the magnitude of pollutants discharged by stream flow increases. Loop G thus has negative polarity.

Feedback loops H and I are the driving forces to the model. Both are positive feedback loops which are producing increasing amounts of wastes which must be controlled.

#### Summary

The feedback loops described are continually interacting, and the high order of the system, its non-linearities, and multiplicity of loops makes traditional systems analysis impractical. The system in total, due to these complex relationships, is difficult to deal with from an intuitive standpoint. Single feedback loop systems may be analyzed separately to determine their responses, but when placed in complex interaction with other loops, the total response is extremely difficult to predict or control. Therefore the remaining analysis will be made by viewing the system in its totality.



## CHAPTER V

### SYSTEM ANALYSIS

In the preceding Chapter, a complex information feedback system was hypothesized to explain the manner in which long term water quality dynamics evolved. This hypothesized feedback structure was then translated into a series of level and rate variables, as pictured in Appendix B. The resulting structure was further described as a set of difference equations (See Appendix C) and programmed for the Georgia Tech Rich Electronic Computer Center Burrough's 5500 digital computer.

The model structure and equations shown in the Appendices represent the culmination of extensive trial and error experimentation testing relevant relationships among physical events, subsequent decisions, and resultant policies. Water quality literature was examined to identify perspective important variables and hypothesize relationships among variables. Importance was defined in terms of influence on the dynamic pattern of interaction between pollution loads and water quality control measures. The hypothesized model structure was then used to simulate a time sequence of pollution loads and management measure changes. The simulated patterns were examined for similarity with historical patterns in respect to periodicity, phasing, and trends. Thus the model performance itself served as information feedback in the model building and evaluation process, so that the model variables, parameters,

loop gains, and loop couplings could be adjusted to insure similarity between modeled and historical conditions.

### Description of Model Behavior

The performance patterns generated by the basic model structure are shown in Figures 19 and 20. All of the simulation curves have time as their horizontal axis and cover 70 years (840 months) - the same time span examined in the historical literature. Each 60 time units represent 5 years. The vertical axis has scales for numerous variables - all of which are plotted and identified in time history patterns on the diagrams.

Throughout the analysis of the various simulation runs, the reader should be aware of the scales on the left of the diagrams as they may change from simulation to simulation. On the plots, the reader should especially note that the perceived and tolerable levels of pollution are on a scale separate from the variable representing the actual pollution concentration pattern. Variable B representing the pattern of pollution concentration is actually the mass of waste in the stream and the concentration is found by dividing that value by the relevant volume of water given by the constant WSC ( $WSC = 1 \times 10^9$ ).

The variables plotted on the simulation curves are represented by individual letters. The letters and variable names are equated below:

A = Public Awareness

B = Mass of Waste in Stream (Concentration found by dividing by  $1 \times 10^9$ )

C = Perceived Pollution Concentration  
 D = Tolerable Pollution Concentration  
 E = Effective Enforcement Staff  
 F = Level of Water Standards Legislation  
 G = Court Tested Water Standards Legislation  
 Z = Abatement Rate  
 H = Allocation of Funds to Capacity by the Public  
 I = Allocation of Funds to Capacity by Polluting Entities  
 J = Effective Enforcement Effort  
 K = Effective Laws on Water Standards  
 Y = Total Generation Rate of Wastes

### Long-Term Model Trends and Behavior

Examination of the long-term trends, magnitudes, and variable characteristics reveals that the model corresponds closely with the historical results.

For example, pollution concentration levels grow in much the same manner as shown in Figure 8 of Chapter III. The pollution concentration (Figure 19, variable B) grows in stages and, in the long run, seems to be growing higher at an accelerated rate. Other variables such as the staffing of enforcement agencies (Figure 19, variable E) and the level of legal water standards (Figure 19, variable F) also grow in magnitude over the simulation. These variables also experience a stage type growth and expansion impressed on the overall growth pattern. More significantly, the tolerable level of pollution concentration (Figure 19, variable D) related to the traditional value of pollution concentration is also growing in magnitude over time.

The general exponential growth in the model can be partially explained by viewing the performance pattern of variable Y in Figure 20. The variable Y represents the total tons of waste that are being produced per month through both industrially oriented processes and human and animal biological wastes. During the time

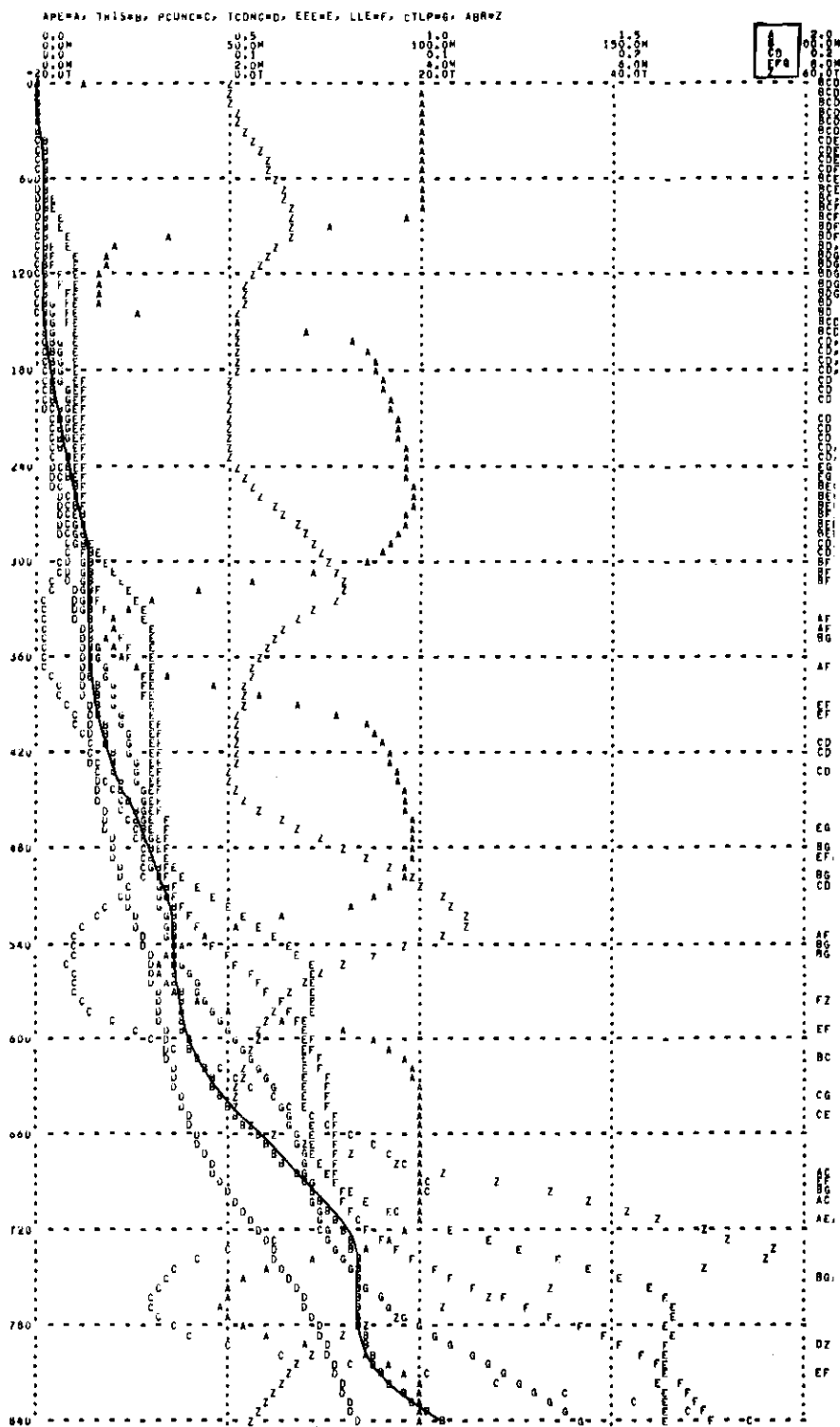


Figure 19. Basic Simulation Model - Plot A

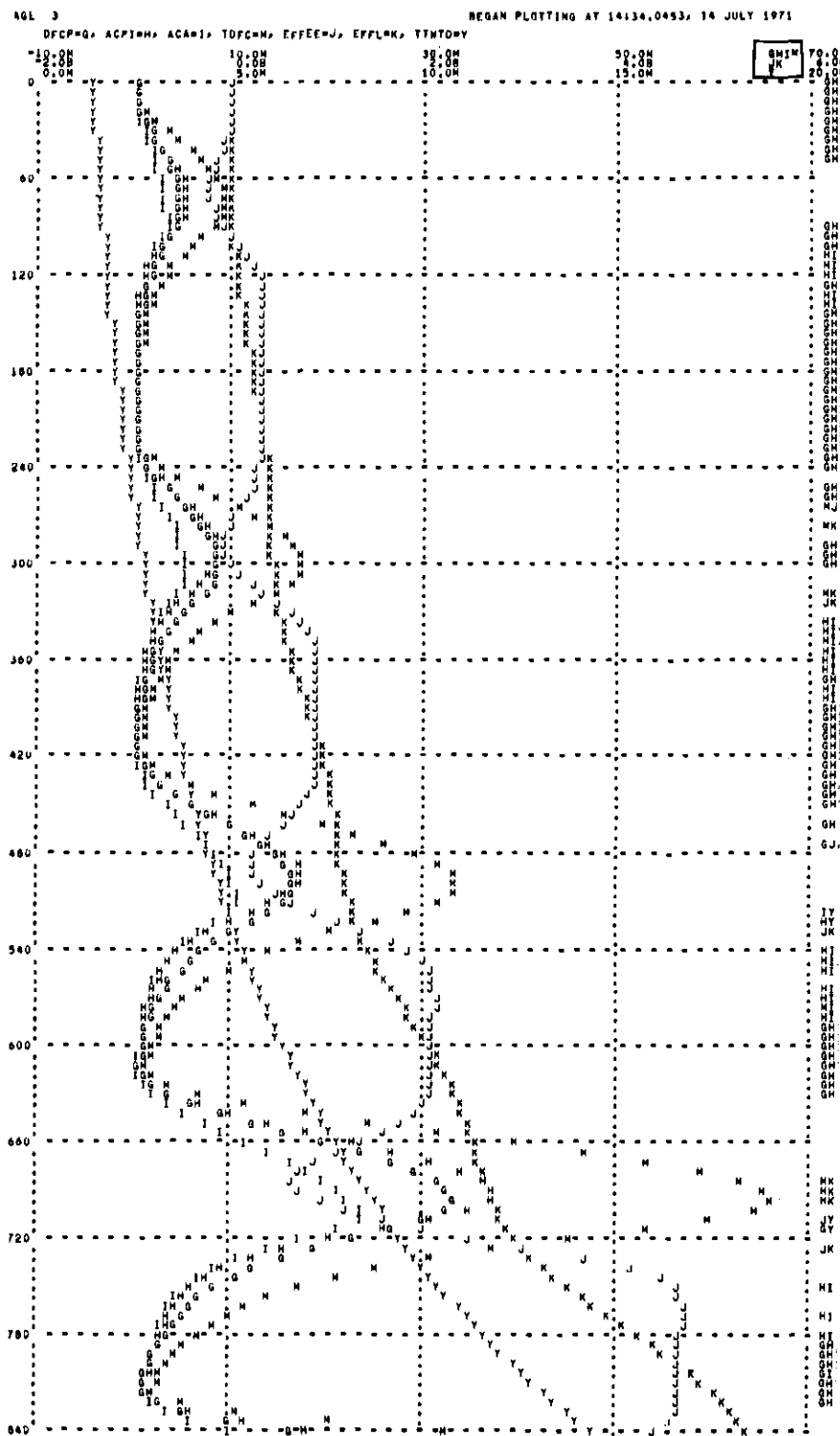


Figure 20. Basic Simulation Model - Plot B

period covered in the study, insignificant feedback loops existed between the actual environmental state (pollution concentration) and the generation of additional wastes. As a result, the production of wastes continues to dominate the system, forcing the rest of the system to attempt to buy abatement capacity to handle higher quantities of wastes.

Some of the model variables oscillate through time. For example, public awareness in Figure 19 (represented by variable A) peaks approximately every 15 years. These peaks are caused by the perceived level of pollution concentration approaching and passing the tolerable pollution level. In response to the surges in public awareness, abatement projects are begun after numerous delays (variable Z in Figure 19 representing the Abatement Rate) through funding programs of the public and private industries (variables H and I in Figure 20). All of these funding variables contain the basic 15-year cycle which was evidenced in public awareness.

In summary, the long-term performance patterns consist of a series of recurring conditions in the model variables with some variables being transient while others continue to grow in magnitude from stage to stage. The cyclical nature of the patterns experienced seem to point to the notion that the solution to the problem in the short run merely sets the stage for similar events to occur in the future, however, at an ever increasing scale of pollution. These long term model relationships do then coincide reasonably with observed and identified historical patterns.

### Short Term Model Behavior

In addition to the model generating historically similar, long-term variable trends and scales, the phase relationships of model variables also interrelate in historically identified patterns (refer to Figures 19 and 20 for the model simulation and Figure 9 for the short term, historical variable relationships).

The shorter term dynamics of the model depict the recurring actions taken by the public and its designated institutions to correct the pollution problem as it grows gradually worse. In general, the following series of cause and effect relationships seem responsible for creating these shorter-term cyclical patterns. First, the perceived level of pollution begins to increase as the rate of change of pollution concentration starts upward. As this perceived level of pollution begins to approach and surpass the tolerable level of pollution, public awareness grows. The results of this increased public awareness are manifested in additional laws for pollution control, increased enforcement efforts to insure compliance with the laws, and increased willingness of the public and some industries to abate polluting and build effective treatment capacity. After a delay which is necessary to gain cooperation or sufficient pressure polluters, abatement and treatment capacity are built. After the capacity has become operational and the rate of change of pollution concentration growth slows, the public senses that the problem is being controlled. However, as public awareness of the problem subsides, further allocations of funds needed to return the water quality to its original level are foregone. The public has, in the process of fighting higher

pollution concentration levels, learned to live with much of the present pollution concentration level as long as it does not go any higher. As a result of the lack of sustained awareness and perceived need for further pollution control projects, the generation of new levels of wastes later surpasses the capacity of the current treatment facilities. As capacity to treat the level of wastes falls behind generation rates, the excess pollutants are discharged in the stream creating another growth in the rate of change of pollution concentration. Another series of similar events are now set to occur as the underlying forces creating the original problem are already beginning to reappear.

A more detailed description of the forces creating the recurring set of events can be examined during one of the typical problem stages. One such stage exists between times 540 and 780 on the simulation plots in Figures 19 and 20.

Time 540 to 600. At time 540, the pollution concentration is being effectively controlled at a steady value. The perceived pollution concentration level is meanwhile less than the tolerable level as pollution perception is low due to the slow rate at which pollution is growing. Meanwhile only part of the total funds necessary to handle these wastes is not made. The results of failing to continue to fight the problem of pollution are now faintly noticed. The perceived level of pollution concentration starts to increase, resulting in the first signs of public awareness. by time 600, the pollution concentration rate of growth has increased, as has public perception of pollution, resulting in awareness levels



capable of stimulating definite legislative action toward correction of the problem.

Time 600 to 660. During the time between 600 and 660, the rate of pollution concentration growth reaches its maximum rate. The perceived level of pollution exceeds the tolerable level, and public awareness remains high throughout the entire period. Building of new treatment and abatement facilities is begun as public willingness to commit funds to abatement projects increases. Some of these public funds are matched by industrial organizations as these companies seek to enhance their public image and goodwill and also take advantage of these public grants offered to supplement construction costs. Thus the abatement rate begins to rise by time 630.

Meanwhile the awareness has also created responses in the enforcement and legal areas. Now enforcement agency staff is allocated by time 640, and after a training delay, these new employees become effective in pursuing enforcement activities. However, during their training period, the actual effectiveness of the entire organization falls as previously trained men must devote a portion of their time for training of new employees. The end result is an initial drop in the actual effectiveness of the agency due to the large increase in new untrained employees. This is followed by a rapid increase in the effectiveness of the organization, once training and reorganization of the enforcement agency is complete (time 690).

Laws dealing with pollution have meanwhile increased steadily,

but their effectiveness is limited by the inability of the enforcement agency to insure compliance to so many new and unfamiliar restrictions. Many marginally profitable firms and others interested in gaining competitive advantages from the postponement of abatement efforts respond to the perception of minimum enforcement effort and legal coverage effectiveness. Thus from time 630 to 660, the allocation of funds to pollution treatment by industrial firms and large municipalities falls behind the rate at which the public appropriates matching fund grants. Situations where grants are actually forfeited result.

Time 660 to 720. During these five years the abatement rate reaches its peak values, as public willingness to fund treatment projects remains high, and the effectiveness of the enforcement agency finally begins a rapid increase. Polluter's perceptions of the increased trend in enforcement effectiveness encourages their matching of all available funds for the construction of new facilities.

Other forces are also changing. The rate of pollution concentration growth has slowed by time 720, resulting in a drop in the perceived level of pollution concentration and in public awareness. The public perceives progress being made to correct the problem, that is, not allowing it to grow any worse than it presently is. Public willingness to support all funding necessary to continue full problem correction drops. Capacity needed is not fully funded by time 720.

Also changing during this time span was the trend of actual

enforcement effort effectiveness (time 690). Legal coverage meanwhile has also steadily increased and by time 720 is the restraining barrier to further enforcement of pollution standards.

Time 720 to 780. The pollution concentration growth levels out during the first part of this phase causing reduction in awareness, and falsely signalling the public that full and continued control of the problem is forthcoming. In contrast, it is this decrease in public awareness which is responsible for creating many of the dominating forces and situations capable of creating another pollution concentration crisis in the future. When public awareness drops, only partial allocations to further abatement projects are appropriated. Additionally, public willingness to pay higher consumer prices or restrict local industrial growth for pollution control projects decreases, putting pressure on legislators to grant special exemptions, delays, and postponements to some polluters. The end result is a decrease in acquisition of new abatement capacity when pollution concentration growth stops rising.

It is important to note that no absolute control is placed on the tolerable level of pollution. Rather, the tolerable level of pollution represents a traditional perception of the actual pollution concentration. As this actual level is in excess of the tolerable level much of the time, the high level of pollution becomes slowly integrated into tradition - leading to a higher tolerable level. As the tolerable level of pollution concentration

grows, pollution approaches critical concentration levels where catastrophies can result.

One stage of the pollution concentration growth has been completed. However, the forces and conditions to create another similar cycle of events have already been established and are at work. The model follows historical results and generates another crisis and crash building program. However, one must note the ever increasing amplitude and scale of the problem as the source of the problem (the generation rate of pollutants) and the tolerable level of pollution go essentially uncontrolled and continually move to higher values.

#### Significance of Historical Data and Model Building Perspective

Through focusing the model on major historical trends, emphasis is directed toward understanding the causes behind the evolution of water pollution and its management over time. True problem understanding must be based on causes rather than on symptoms reflected in day to day pressures and forces. In order to deal effectively with the problem in the long run, basic causes must be understood. Treating of problem symptoms merely perpetuates and reinforces the underlying causes allowing the actual problem to grow worse.

The present evolved as the accumulation of past experiences and responses. Thus the basic foundation of present water quality control institutions, policies, and laws have evolved from experiences in controlling past problems. These responses have proven to be at least moderately successful or they would not have been

perpetuated. Whether these same policies and procedures are successfully attacking today's problems is questionable as the problem has basically changed in nature. The absolute scale of pollution is the primary problem today as certain pollutants have begun to approach ecologically intolerable limits. Previous institutional structures and controls dealt with the pollution problem on a level where the margin of error between the actual pollution concentration and the intolerable limit was much less crucial.

#### Analysis of Historical Pollution Control Policies and Objectives

During the early stages of pollution concentration growth, the problem of concern was getting greater utilization of our water resources while at the same time preventing water borne disease or poisons to impose immediate health problems. Increased utilization of these free resources reduced production costs, of consumer goods, and services. However, the growth of pollution concentration, although acceptable economically, was not necessarily acceptable sociologically or psychologically - especially if the growth occurred too rapidly in relationship to traditional concepts of tolerable pollution concentrations. The controlling forces and pressures sought to keep the perceived pollution concentration below the tolerable pollution concentration level. These forces and pressures were generated because of people's slowness to assimilate deteriorating pollution levels into traditional concepts. Neither technological considerations nor

ultimate threats to the ecology seemed to be dominant problems of concern. Thus the problem and resulting pressures and activities for control were not necessarily directed toward the control of problem scale, but rather to the problem of excessive rates of pollution concentration change.

Pollution control programs in effect became concerned with balancing alternative and conflicting demands and acting in response to those demands. At times, demands for increased utilization of the free resource to produce more and cheaper goods were made by the public. These demands sought to keep the rates of change of pollution concentration within ranges which could reasonably be integrated into tradition. As history shows, society on the balance, demanded more convenience goods relative to tradeoffs for lower pollution concentration levels.

Society structured institutional policies which dealt with water pollution control so as to have slow response characteristics. Such a system allows abatement and treatment capacity that is requested or being built to be received slowly - meanwhile allowing the perception of higher pollution levels to be integrated into traditional concepts. Given that the true objective of the system was then greater utilization of free resources at the maximum, sociologically tolerable rate, the slowly responding system assured that the tolerable level of pollution would grow at a rate which would have minimum interference with industrial and economic expansion.

### Structural Analysis of the System

Additional insight into the system's characteristics can be gained by examining the basic system structure through sensitivity analysis of various model parameters. Through this analysis, alternative institutional structures can then be suggested and ultimately tested to determine their probable impact on real world system performance.

The analysis reveals that within the context of the present system, changes in certain model parameters result in improved model performance - given that the criteria for improvement is based on minimizing the long-term rate of pollution concentration growth. However, the analysis failed to reveal any changes in model parameters which would significantly alter the basic response character of the model. Crises were still generated and drifts to higher tolerable levels of pollution continued. No set of parameter changes were capable of producing a shift from the basic growth mode in pollution concentration to a steady state performance mode.

The parameters which were found to be significant in slowing the rate of pollution concentration growth are discussed below. The original parameter values and the parameter values which were used to generate the illustrated simulations are given in Appendix E.

### Results of Public Awareness Programs

In the basic model shown in Figures 19 and 20, public awareness depends on the perceived, less the tolerable level of pollution.

In the model yielding simulations for Figures 21 and 22, the sensitivity of public awareness to the difference is increased. Such increased awareness might be generated through publicity campaigns. In effect, public awareness begins to rise earlier during each cycle of capacity acquisition and is sustained for a longer period of time. By viewing variable A in Figure 21 which represents public awareness, it can be seen how the awareness maintains higher levels for longer periods of time than in the basic model.

Pollution concentration magnitudes in the model with increased sensitivity in public awareness grow approximately 15% slower in the long run as can be seen by comparing the magnitudes of variable B at time 840 in Figures 19 and 21. The explanation for the decreased rate of growth can be found by comparing Figure 20 of the basic model with Figure 22 of the revised model.

In the basic model, public awareness begins falling while significant funds for capacity are still needed. The decrease in awareness results in decreased public willingness to support abatement programs fully. As a result, the funds allocated to abatement programs by the public fall during the later stages of each capacity acquisition cycle. Thus variable H representing the actual allocation of funds by the public falls significantly below variable G representing the total desired public allocation to capacity acquisition.

In Figure 22 of the revised model, the sustained public awareness during the later stages of the capacity acquisition



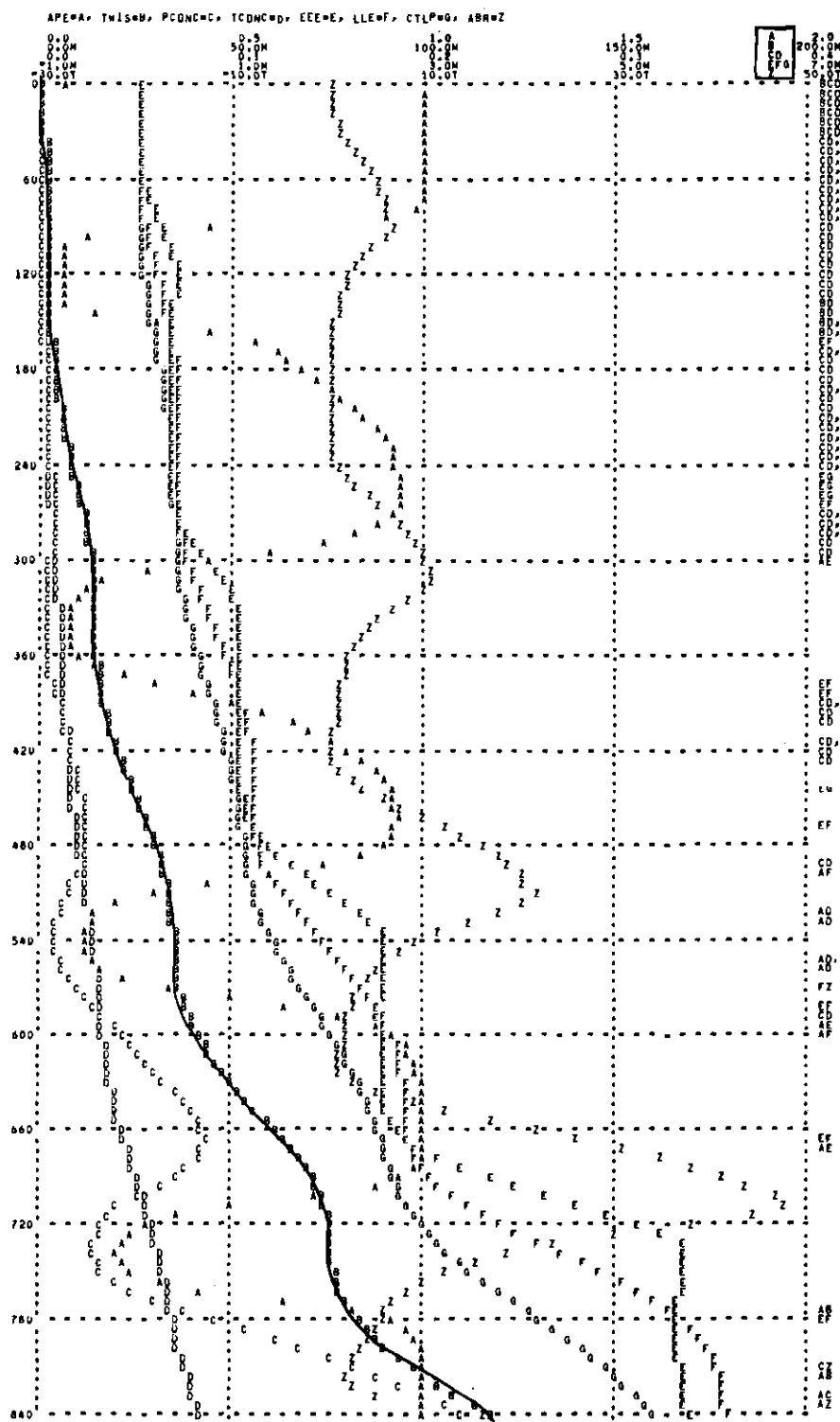


Figure 21. Increased Public Awareness Simulation - Plot A

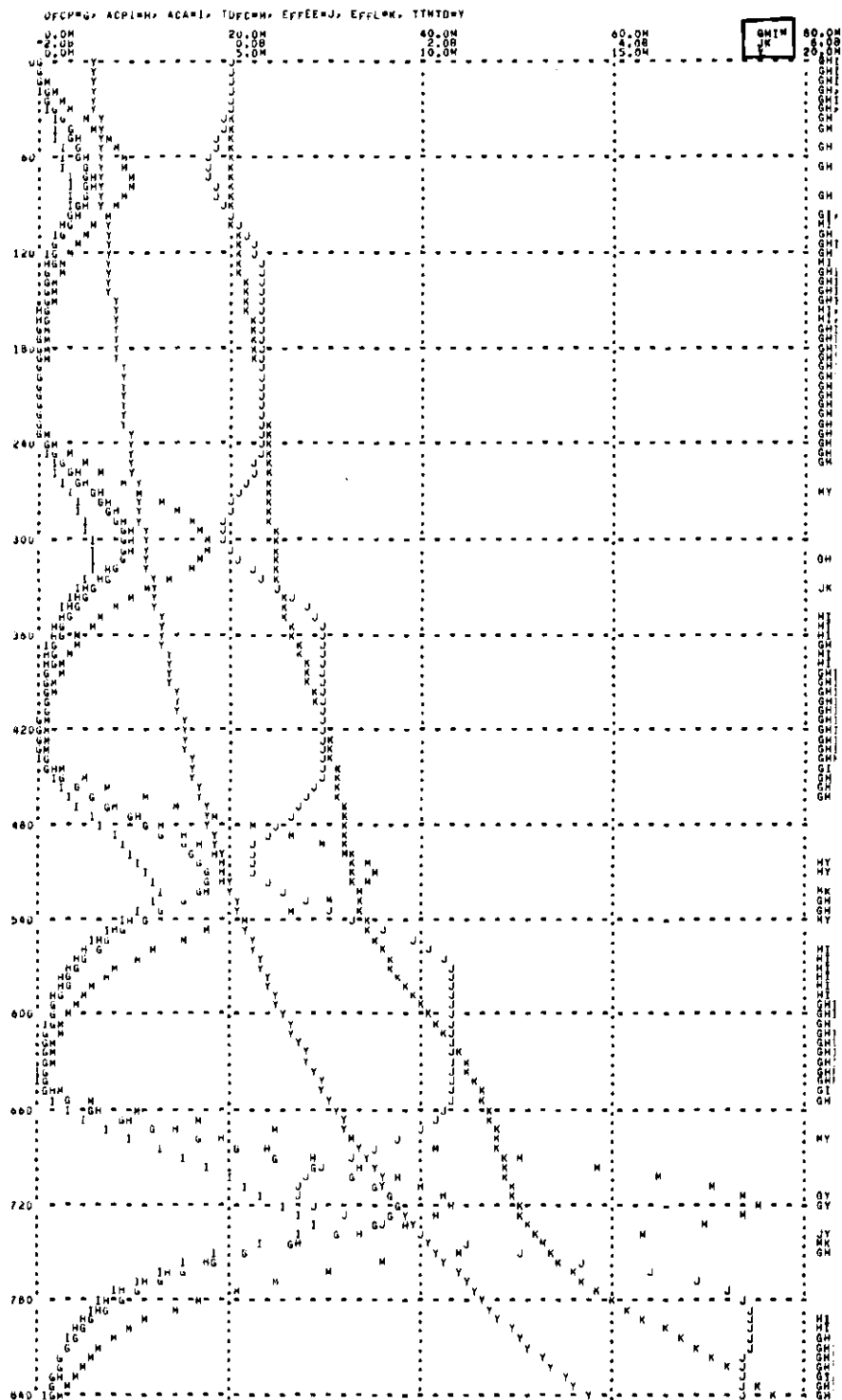


Figure 22. Increased Public Awareness Simulation - Plot B

growth result in public willingness to allocate funds as they are needed. Therefore, variables H and G do not drift apart as they did in the basic model.

The increased public awareness to the problem through awareness programs is successful in damping the long-term growth rate of pollution, however, its effects are unable to stop the basic growth mode and achieve a steady-state performance pattern.

#### Results of Rephasing and Increasing the Impact of Enforcement Effort

In Figure 20 of the basic model, industrial and municipal allocation of funds to pollution abatement capacity is well below the funds raised or appropriated by the public. Thus, during the initial periods of each stage of capacity acquisition, variable I representing the industrial and municipal allocation of funds to capacity fall significantly short of the funds raised by the public (variable H).

The explanation for the lag in funding is manyfold. As mentioned previously, the failure of polluters to consider adequately the technological external diseconomies means that some polluters will only desist polluting in the face of legal and enforcement pressures. The polluter will seek the path of minimum resistance and delay compliance as long as possible. Under these conditions, allocation of funds to fully match public grants is basically responsive only to building legal and enforcement pressures.

In Figure 20, variable J represents an estimate of the effective enforcement effort directed toward polluters and variable K represents an estimate of legal boundaries for standards enforce-

ment. The less restrictive of these two factors is responsible for the actual response in funding by the polluters. In the basic model the impact of the minimum pressure on funding was given moderate influence. Variable J representing effective enforcement effort directed toward compliance activities is the minimum restraining factor during the early stages of each capacity acquisition stage. After a change in the trend of effective enforcement effort is finally perceived by the polluters, industrial and municipal funds to match public grants are fully matched. Thus, during the later stages of each cycle, variables H and I follow each other more closely than during the earlier part of the acquisition stage.

In Figures 23 and 24, the results of changing the simulation relationships to give the enforcement agency greater powers to force polluters to fund abatement projects and also the effects of shifting effective enforcement forward can be seen. First the pollution concentration growth has been slowed approximately 25% and even at times falls from previous peak values. The decreases in pollution concentration growth occur because added capacity has been acquired. The increased capacity acquisition occurs as a result of increased industrial and municipal funding during earlier stages of abatement response. Thus variable I (representing industrial and municipal allocation of funds) rises to match public appropriation of funds earlier in each cycle. This occurs because the effective enforcement effort, the minimum of enforcement and legal pressures, is now phased forward. Subsequently, due to the

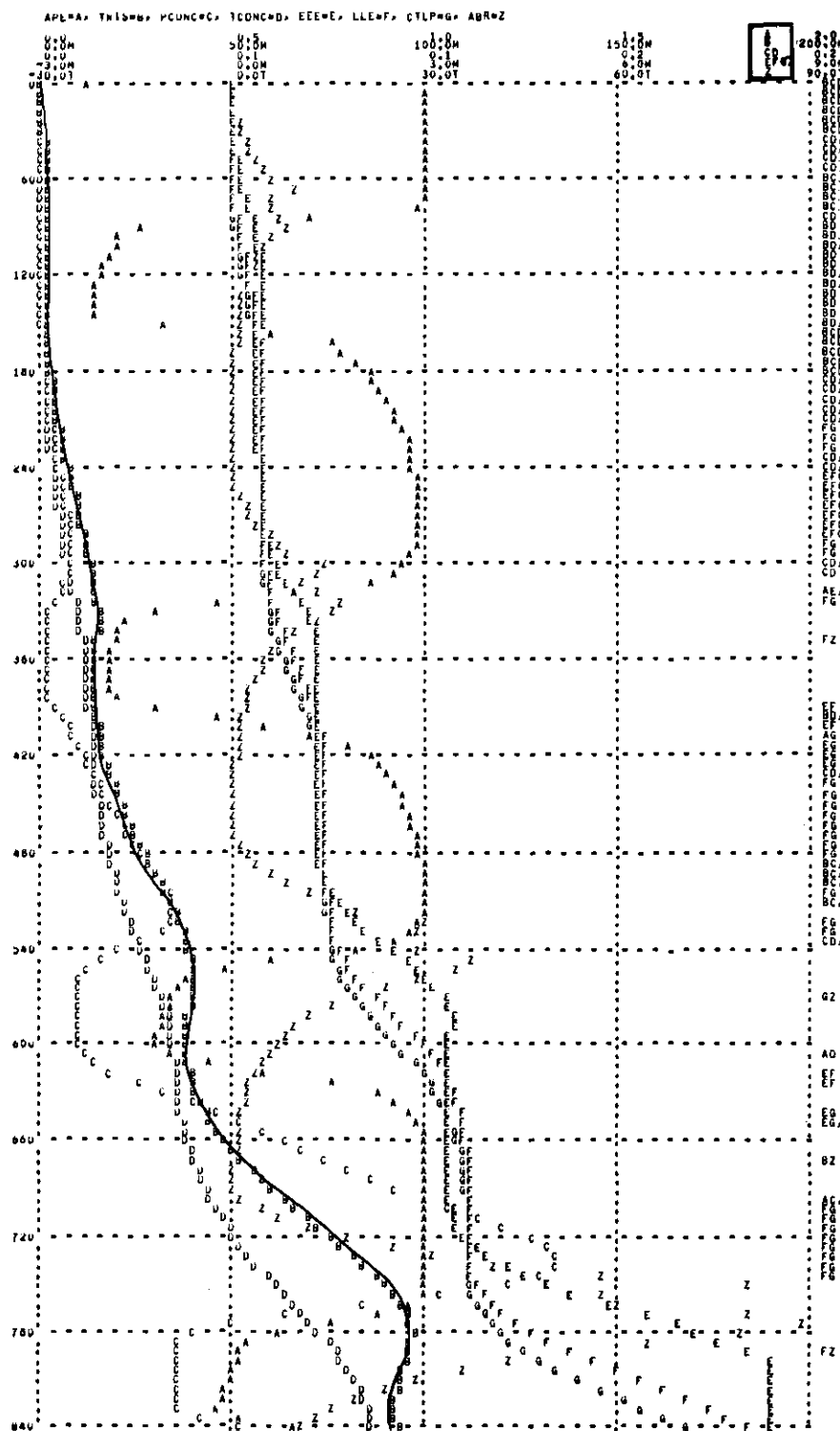


Figure 23. Rephased and Increased Impact of Enforcement Effort - Plot A

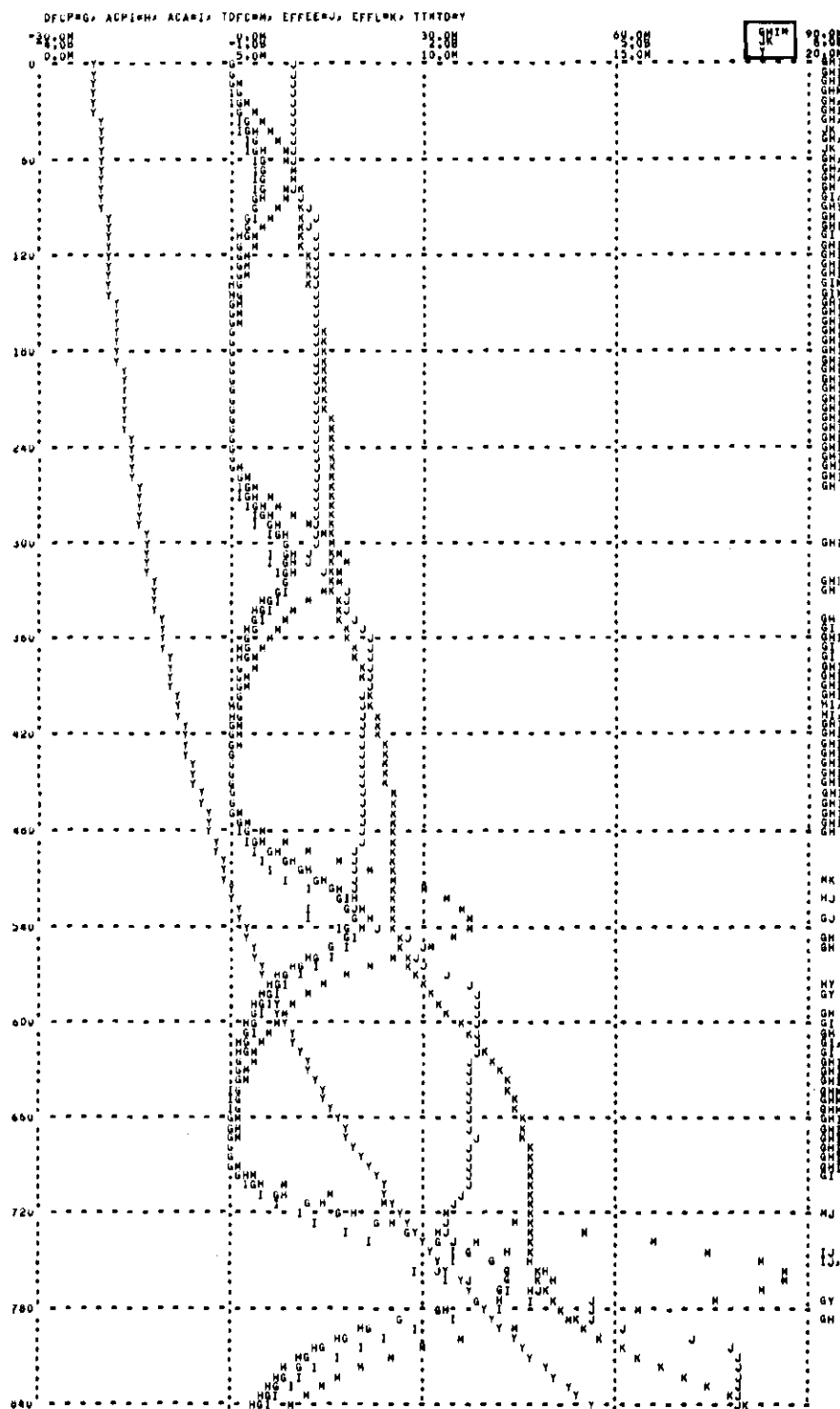


Figure 24. Rephased and Increased Impact of Enforcement Effort - Plot B

increased impact on funding and the rephasing, industrial and municipal funds even exceed those raised by the public for matching construction fund grants. Therefore variable I is greater than variable H during the later stages of each cycle.

The final results of the changes are that increased amounts of capacity are acquired while the public is still intensely aware and willing to fund additional abatement projects. Further, the residual effects of the increased enforcement effort and the impact of this effort on funding result in subsequent funding of some capacity even after awareness has subsided.

#### Effects of Decreased Generation of Technological Wastes

In the simulation used to develop Figure 25, the exponential growth in the generation of new and different technological and industrial wastes is eliminated. The exponential growth continues as in the basic model until time 300, but is then stabilized at the value existing at time 300.

Figure 25 shows that the pollution concentration (variable B) is decreased by approximately 70% over the value generated in the basic model. It seems readily apparent that the rate of generation of pollutants is sensitive to the magnitude of the pollution problem. However, the basic performance mode of the model remains unchanged. The pollution concentration still grows in stages as public awareness continues to key both the added capacity acquisition for increased human and animal wastes and new capacity to replace older, inefficient treatment capacity. Thus, the pollution concentration still grows in stages as inadequate

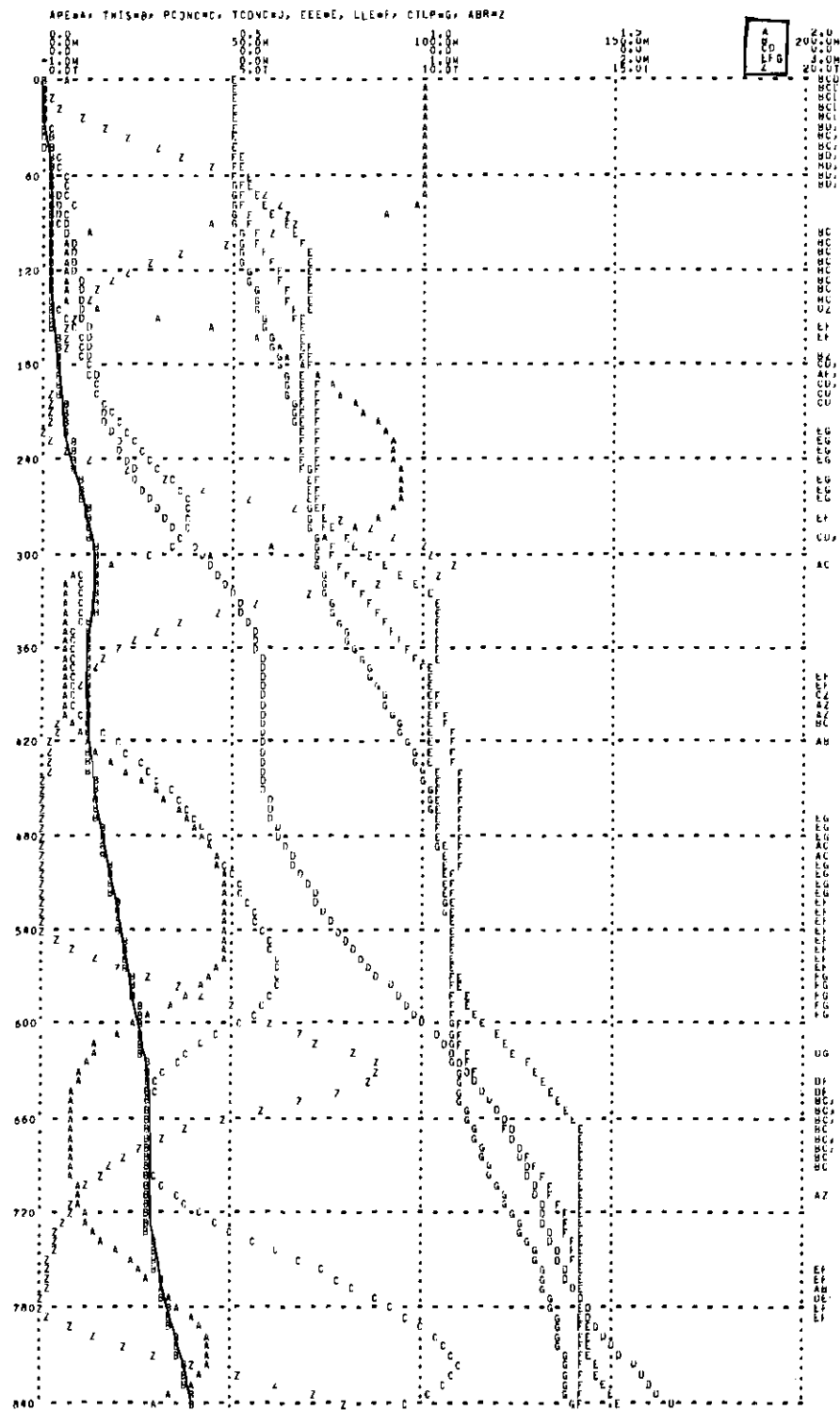


Figure 25. Effects of Decreased Generation of Technological Wastes



corrections are made to capacity acquisition. Also of note is the growing tolerable level of pollution. Although its value is far below the value in the basic model (note a change in scales at the left of the graph), it still continues to drift higher as no definite controls have been placed on the traditional goal.

#### Effects of Biologically Intolerable Limits Being Reached

As was mentioned in Chapter I, continued pollution concentration growth from present levels could create disastrous problems if the pollution concentration reached a threshold after which pollution could increase dramatically without much notice. Figure 4 diagrams the cause and effects which are involved.

Figure 26 represents the model behavior in a simulation which assumes that the biologically intolerable threshold is reached. Since the actual limit is unknown precisely, the model only represents the results if that point is reached. The results of the model show that the exact point is relatively important. The important point illustrated is that that limit must be avoided.

The pollution concentration in Figure 26 follows much the same pattern as the basic model until time 720. At this point, the gain in the positive feedback loop (Loop F of Chapter IV) begins to be activated. Before action can be taken to construct new facilities (variable Z), the pollution concentration has risen to levels much in excess of values produced in the basic model (about 5 times greater). Note the changed scale of variable B on the left of the diagram. Prediction of the results of the rapid

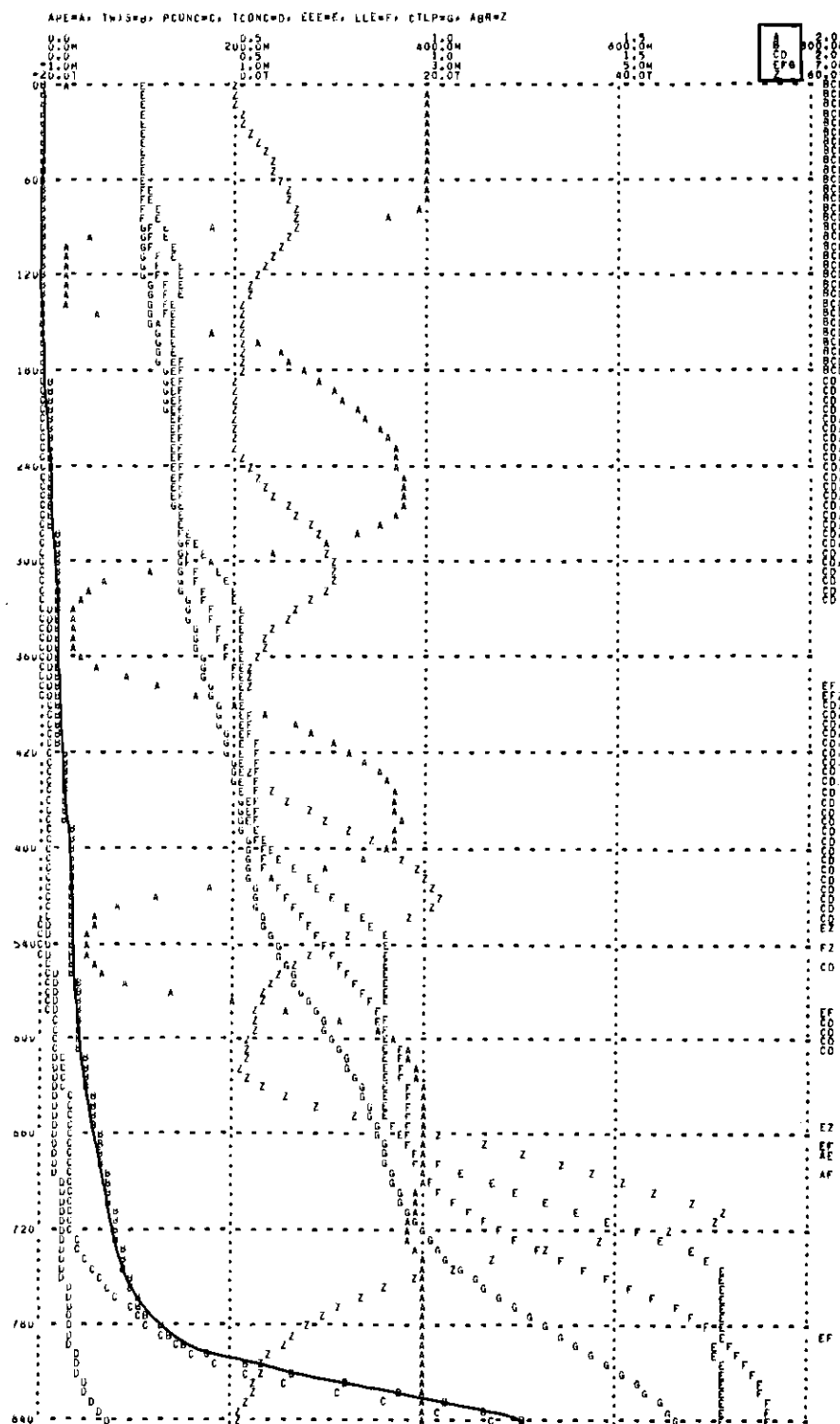


Figure 26. Effects of Biologically Intolerable Limits Being Reached

pollution increase on population and, subsequently, their production of additional wastes is not made here. However, Forrester (6) discusses such a possibility as occurring and gives its consequences.

#### Implications of Evolutionary Institutional Structures

The present institutions, laws, and broad water quality control policies and procedures have proven to be successful in controlling past water pollution problems with respect to some objectives. However, new problems exist; and the simulation results warn that these same institutions may be unable to control the new problems if they continue to perform in the traditional manner. The nature of the problem changes when society will no longer allow further environmental degradation. Institutions must then control the absolute level of pollution concentration rather than be responsive to rates of changes in pollution concentration growth. Water quality management systems must be devised which do not permit further water quality degradation. Political and social pressures, which invite the system to follow negotiated or traditional goals, must be avoided. Two major bases can be stated for these arguments.

First, the pollution concentration level is seriously depleting the free oxygen supply in many rivers. Continued dumping of more wastes than the river has the ability to degrade will release additional wastes lying on stream bottoms, which are now kept relatively inert by iron complexes. In order to avoid the consequences of reaching the threshold concentration of disaster (see

Figures 3 and 26), control of pollution concentrations at absolute levels must be exercised and exercised responsively. The control must be administered in a way which does not allow "drifts" to higher tolerable pollution levels.

Secondly, traditional institutions with historically oriented delays in funding, enforcement, and standards negotiation are only able to manifest major corrective efforts after a significant time lag. In the interim greater amounts of waste are discharged into the environment. These incremental amounts of pollutants are not significantly noticed or important when pollutants are at relatively low magnitudes. However, as the exponential growth of pollutants reaches later stages, the interim amounts of pollutants generated become highly significant. Figure 27 illustrates the exponential growth of pollutants as it has been historically experienced. As the exponential growth curve presently being experienced reaches its later stages (times B and B1), the time between problem recognition and problem control allows a rate increase of X2 tons of untreated wastes being dumped into the water during corrective problem phases. Therefore as the growth of pollutants continues, equivalent delays result in higher intermediary amounts of untreated wastes being dumped into the water before the problem correction measures can be manifested. In fact, during the later stages of the growth curve, shorter delays do not really solve the problem. For example, during later curve stages, a large reduction in traditional institutional delays for problem correction would still generate large intermediary amounts

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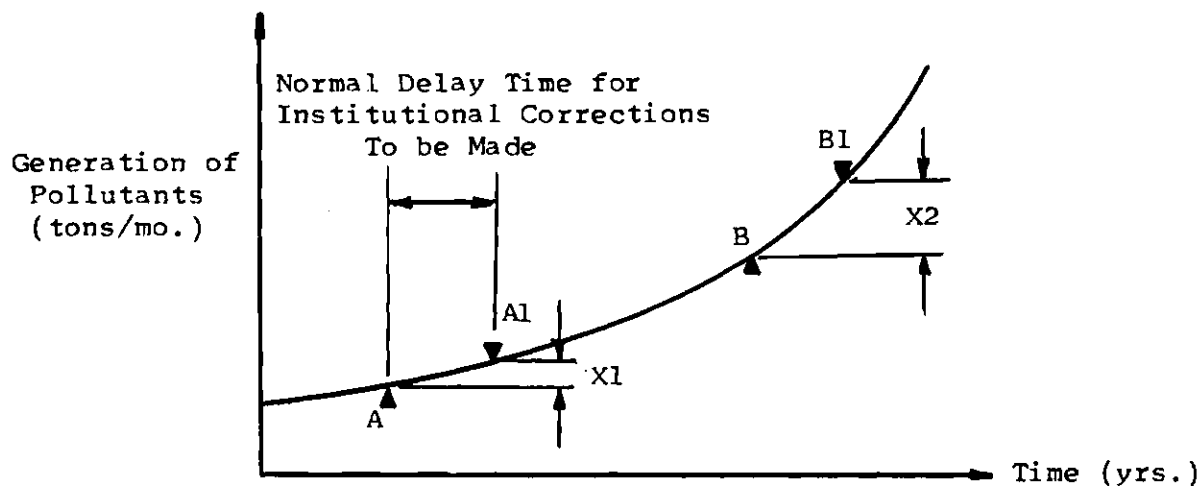


Figure 27. Implications of Exponential Growth of Pollutants

of untreated pollutants which must be assimilated. Thus, as one goes farther out on the curve of exponential generation of pollutants, it becomes apparent that shortening delays in the system (a traditionally suggested panacea for problem solution) will not bring lasting results. It merely puts off the time that dealing with the causes of the problem must be faced.

#### Summary

The hypothesized feedback loop model of Chapter IV was found to generate model performance patterns similar to historical responses. Most importantly, the pollution concentration level continued to grow in spite of periods of corrective efforts. Several policy changes were given to illustrate system performance under alternative policies. No changes were able to alter the basic growing pollution concentration performance mode, however,

some policies nominally reduced the absolute magnitude of the problem. It was emphasized through simulations that the scale of the pollution problem must be controlled or society may be faced with rapid increases in pollution concentrations. These increases would occur so rapidly that traditional institutions would be unable to respond adequately to the problem before disaster became widespread.

## CHAPTER VI

## CONCLUSIONS AND RECOMMENDATIONS

Desired System Performance

When inspection of the way an existing system is dealing with a problem shows unsatisfactory performance, planned change must begin with two steps. The forces controlling present system performance must be understood. The criteria for satisfactory performance must be defined. Present performance patterns and the causes behind them have been examined in the earlier chapters. The definition of desirable performance remains.

Many people believe that streams and rivers should not be allowed to lose their ecological, aesthetic, and recreational value. These and still others desire to keep rivers and streams from becoming a manace to public health or a financial burden for more expensive water treatment. Everyone feels that, in the long run, degredation of water quality must be stabilized at a safe standard which will not be allowed to "drift" higher. Secondly, the standard must be set to allow a reasonable margin of error in estimating the pollution concentration level which could create potential disasters.

Stabilization of pollution concentration at ecologically safe water quality standards will necessitate a change in the basic historical performance pattern. Up to the present, pollution concentration appears to have grown in stages impressed upon an

exponential growth curve. This pattern cannot continue to increase unbounded, or the environment will become overloaded with pollutants degrading our water resources to levels where vital ecological processes will be threatened. Thus a transition from growth in the performance pattern of pollution concentration to a steady-state performance pattern must occur if we are to avoid disaster. Such a shift in social control systems often imparts great stresses on the system and its individuals. These stresses, however, must be overcome to avoid even greater stresses from environmental loss.

The past performance pattern and the desired transition to a new performance pattern are shown in Figure 28. Up to time A, the performance pattern drawn describes the past evolution of the pollution problem. From time A on, a steady state control of the

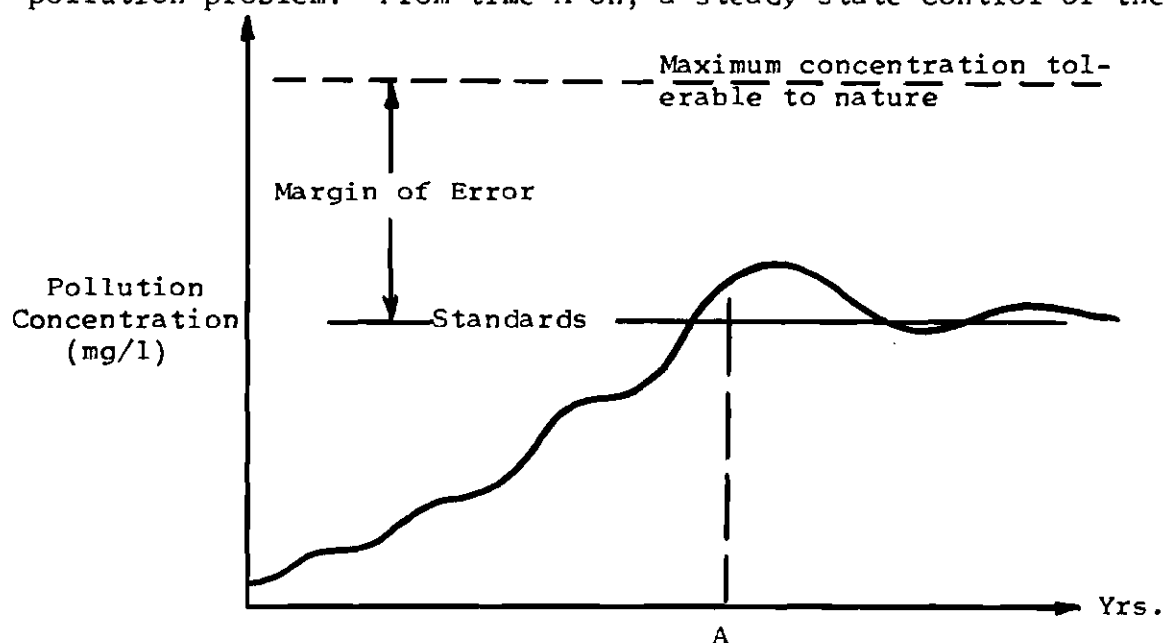


Figure 28. Desired Performance Pattern of Pollution Concentration.



pollution concentration is shown. The standard around which the system stabilizes will be set by engineering and ecological studies which allow a sufficient margin of error to exist between the standards and the pollution concentration which will create cumulative, growing pollution concentrations caused by breakdown of ferric iron complexes. The standards must be stable and definite in order to have fixed targets and goals for enforcement agencies to put into force. Additional waste discharges should be allowed only after extensive proof has been supplied by those potential polluters desiring to discharge pollutants not covered by or limited by the standards. They should definitely establish that their discharges will not infringe on the margin of error. Standards can no longer be subject to public whims nor can enforcement agency effectiveness be subject to legislative appropriations which are themselves subject to wide variations due to public and industrial lobbying pressures.

The standards must be established and maintained well within ecologically tolerable limits, even if it forces society to slow technological change until by-product waste production can be made compatible with the standards. These actions could possibly force a re-evaluation of the ultimate role of technology in many areas - and certainly encourage research in controlling waste by-products.

These re-evaluations of technology will be necessitated by realizing that positive, exponential loops cannot grow unbounded. The present pollutant generation rate is a case in point. Some non-linearity or other pressure will eventually bound the growth

of this rate. Forrester (6) has, in effect, said that the growth in pollution concentration will be bounded and controlled through population catastrophies where much of the population of the world will perish. It appears then that society must achieve safe water quality standards or other more drastic "control" measures will gain dominance in the system. Powerful leadership must be invoked. Standards must be established and lived with - even if they force a readaptation in some of our present living patterns.

#### Major Directions for Development of New System Structure and Policies

In order to achieve transition from growth to steady state, system restructuring will be necessary. The previous chapter illustrated the futility of creating significant changes in the basic growth mode of the pollution concentration with only changes in problem parameters. Some of the policies did have the effect of slowing the magnitude of growth of the problem - but none actually was able to stabilize the system to any steady state value. Slowing the gain in the exponential growth of the pollution concentration may be beneficial in the short term, but it merely delays the ultimate accounting.

Several policy directions can be suggested which will aim to stabilize the system at some desired steady-state conditions by actually changing the character of some of the feedback loops which now seem to control water quality dynamics. It has already been demonstrated that changes in model parameters will not change

the basic character of the performance patterns generated. Restructuring of loops will therefore be necessary.

#### Control of the Tolerable Level of Pollution Concentration

The first major policy direction would aim at eliminating the "drift" in the tolerable level of pollution. By not allowing tradition to set this value and selecting standards which have little flexibility, a feedback loop could be created where pollution concentration stabilizes around a desired goal. The present feedback loop (B1 in Chapter IV) which determines the tolerable pollution concentration limit is set by traditional values of past pollution concentration levels. Meanwhile the perceived level of pollution is essentially a publicly monitored variable, basically responsive to the rate of pollution concentration change and the absolute level of pollution concentration. The mechanism which attempts to provide for full correction is then a relationship between these two variables.

This controller mechanism allows "drift" to higher tolerable pollution concentration levels as discussed in Chapter IV. The control mechanism is not necessarily in direct relationship to actual environmental conditions.

An improved policy direction would have to take the general feedback loop form shown in Figure 29. In this loop, two major differences occur relative to the present structure. First, the tolerable level of pollution concentration is now a fixed, unchanging constant rather than a variable representative of tradition. Secondly, the perceived level of pollution concentration results from

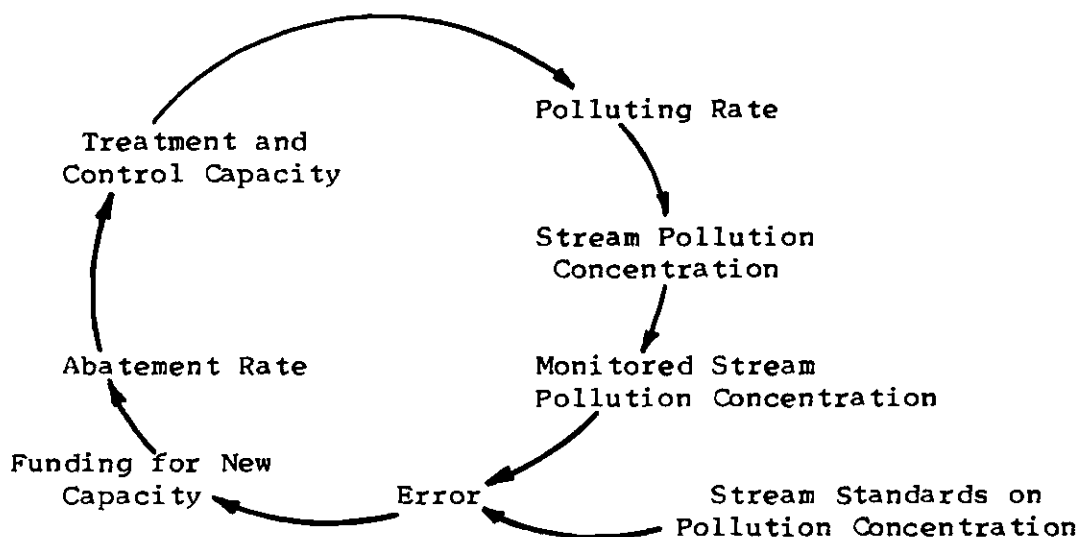


Figure 29. Restructured Feedback Loop for Controller Mechanism.

technical monitoring of stream conditions. Under this arrangement, the need for undertaking problem correction is directly and accurately shown by the error. Public awareness in terms of perceived pollution concentration levels - which are admittedly vague and may be out of phase with actual pollution conditions - is no longer the dominating influence on problem correction and, thus, system performance.

#### Control of Problem Source

The second major change in policy direction which would be necessary to transition from growth to equilibrium conditions involves control of the source of the problem, that is, the rate of production of potential pollutants. At the present time, production of pollutants is tied to two major factors - population and technology. In order to slow the exponential growth of potential pollutants from these contributing factors, several directions

are possible. One alternative would be to monitor and control population and technology at set desired values - admittedly, a politically "unpopular" policy direction. However, further analysis of the relative contribution to pollution of each factor reveals that technological and industrial wastes are far greater potential problems than are wastes attributable to human and animal life cycles - in both magnitude of pollutants generated and technology of disposal. Therefore, control of the variable lending the greater amplification to the positive feedback loop growth of potential pollutants would eliminate much of the problem. In addition controls on technological and industrial pollutants would be politically more acceptable - although again, still very unpopular.

The feedback loop required to control the exploding growth of technological and industrial wastes would involve structuring an effective counter feedback loop around the present technology responsible for pollutant generation. Present technology generates potential pollutants through production processes. Pollutants are either direct by-products or come by use and discarding of the output by the consumer. At present, the business emphasis is basically on production and sales of as much output as possible in order to maximize profit. Eventually each product must be retired. Many new product wastes cannot be treated effectively by existing abatement and treatment facilities, even if normal abatement type facilities have excess capacity. A detergent-type crisis may be created.

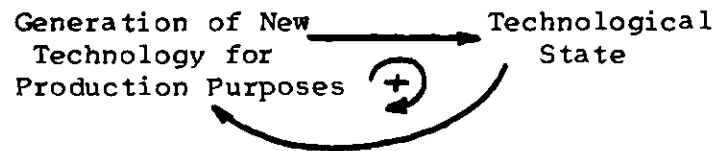


Figure 30. Positive Feedback Loop of Technology.

A new control orientation would involve a switch from quantity of sales to quality (durability and ease of repair) of the quantity sold. Emphasis would be on more efficient recycling of products and by-products. Pictorially, the feedback loop having present dominance is shown in Figure 30. In this loop, as the accumulation of technological knowledge permits the manufacture of new products, resultant demands in turn induce more sophisticated, different, and newer technological wonders.

This series of cause and effects, however, becomes a positive feedback loop responsible for creating the exponential growth of greater and more varied kinds of technological wastes. New control loops for problem stabilization would necessitate placing standards on the allowable technological state. Figure 31 gives an indication of the suggested loop structure. A standard is set again. When it is determined that the technological state is responsible for creating excessive per capita excesses of industrial wastes, major emphasis must be redirected from generation of new production technology to the technology of methods to control industrial wastes. Such methods could include reducing the rate of obsolescence of products, designing for product reuse at different levels of operating demand, and planning for reuse

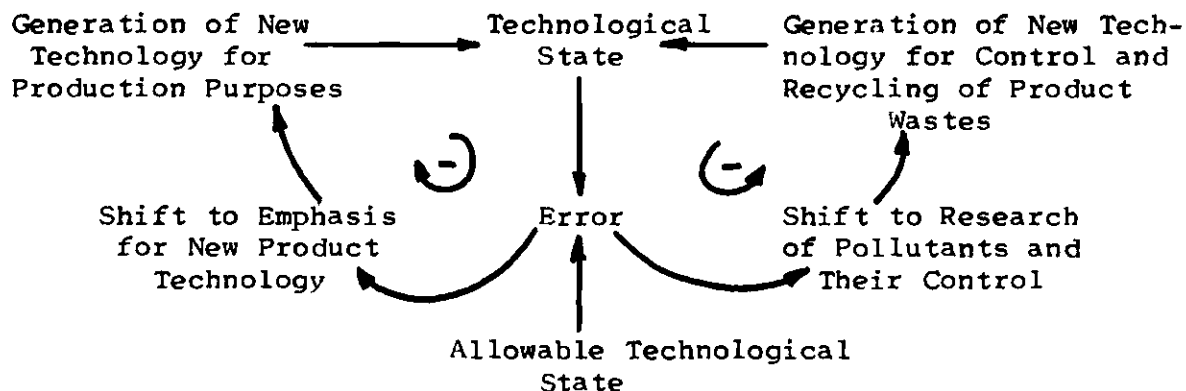


Figure 31. Control of Technological Generation of More and Different Potential Pollutants.

of parts or product sectors.\*

These feedback loops do not pretend to stop the growth of technology or knowledge - only to keep the technological state responsible for production of larger quantities and more varied types of pollutants in harmony with the technological state of recycling waste products. New production technology would only be permitted when corresponding increases in pollutant control were available.

With adequate controls on both the generation of pollutants and possible drifts in the tolerable pollution concentration, much of the present system structure which buys capacity to treat discharged pollutants could be retained. The revision in system structure would then have three major sectors: 1) an overall control of the problem scale (the tolerable concentration set at standards), 2) a sector to purchase and regulate treatment

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\* See Introduction to Design by Morris Asimow (Prentice Hall: Englewood Cliffs) 1962. pp. 16 and 17 for suggested ways to plan for product retirement.

and abatement capacity for pollutants discharged, and 3) a control sector on the rate and nature of pollutants being generated.

Operating Level Changes Necessary to Implement  
New Policy Directions

In order to implement effectively the suggested feedback loop mechanisms in a complex institutional framework that is largely governed by social and political considerations, several changes in the current approach to water quality management will be required.

First, comprehensive monitoring capability would have to be established for all streams, lakes, and other bodies of water where any chance exists of pollution reaching dangerous proportions. The monitoring capability should be designed so that measured pollution concentrations would be as free of human judgement as possible. Scientific data gathering needs to be freed from time trends in interpretation. Unless monitoring can be tied to time invariant procedures, polluting violations and slow incremental drifts away from standards would be undetectable.

Coinciding with the development of comprehensive monitoring capability would be the scientific establishment of stream standards well within the bounds of ecological tolerances. Further, prolonged research into establishment of environmental pollution capacities, ecological chains, and stream characteristics seems relatively unimportant in correcting the long term performance growth mode to one of steady-state conditions. Such



research merely postpones the time when some standard must be selected - possibly to a time when much less slack exists in the system for errors. Utilizing today's knowledge and understanding, safe standards well within tolerable ecological capacities could be established. Research could then concentrate on optimizing utilization of the water resources within these set limits from the long range viewpoint. If later extensive and exhaustive research shows that the absolute standards were initially set too low, then the standards could be changed and the research into understanding of stream-use optimization under set constraints would still be relevant.

The second major operating level change would entail freeing the monitoring and enforcement agency from almost all public, industrial, legislative, and civic pressures and counterpressures. Examination of the model performance patterns and historical data appears to support the contention that much of the problem of growing pollution concentration evolved because of the lack of effective enforcement effort at the proper times to insure compliance with standards. Staffing of enforcement agencies is now and has been highly dependent on legislative budgetary appropriations. The legislature primarily responds to public, industrial, and civic pressures. The conflicting pressures and subsequent legislative reactions have failed to provide a growth in budgetary appropriations in proportion to the enforcement effort needed to insure compliance with standards. Thus even if legal precedents are available to enforce standards, the ability of

the regulation agency to enforce these statutes has been hampered due to their lack of experienced staff and funds to legally pursue cases against violators.

Due to the instability caused by legislative and judicial reactions to shifting balances of pressures, the legislature and courts should divest themselves from roles of problem controllers. Legislatures should set definite guidelines which would fix enforcement agency responsibilities and would establish methods to fund these agencies in proportion to their costs for administering control through their monitoring facilities. For example, legislation could establish that funds for the agency should have the immediate authority to suspend dumping of pollutants in violation of standards. In order to insure that the enforcement agency can carry out these responsibilities, the judicial system must not preempt the enforcement agency in identifying violators and in their subsequent execution of punitive or remedial measures.

To establish each of the enforcement agency responsibilities through legislation, and court changes through precedent, would require tremendous courage and foresight on the part of legislative leaders and judges as great pressures will be generated on nearly all policies directed toward changing the system from growth to stability (6).

#### Directions for Continuing Research

Two major directions for additional research have been

perceived through the study of water quality dynamics. The first deals with the further verification and detailing of the present model and the use of the model to test suggested effective water quality control programs. The understanding subsequently gained will be helpful in guiding future water quality administrators in understanding the value of a dynamic outlook. Secondly, other problems on different aggregation levels have been perceived. For example, dynamic studies of interactions between streams could be undertaken as well as dynamic studies of ecological cycles. Through further study in these two directions, new insight into the dynamics of long term water quality change can be gained. Once the relationships among basic causes are more fully understood in a dynamic context, policies and decisions can be restructured to improve system performance.

In regard to further verification and detailing of the present model, a number of directions should be taken. This initial study was only able to collect and analyze data about historical response characteristics of people, laws, and pollution in one river basin. Studies based on empirical data from other river basins could be pursued with the intent of finding similarities in the responses to pollution. Comparison of different studies could more explicitly determine which relationships normally occur in most river basins. Such information could be used in the construction of a revised model even more useful for development and testing of prospective control policies.

Further, the policy and program directions suggested earlier in this chapter for pollution control should be pre-tested by restructuring the model to include the suggested feedback control loops. Only in this manner can long term solutions be found.

Other directions of study to verify and detail the present model could also be taken. The model could be further tested to provide more explicit statistical evidence on many of the model parameters and causal relationships. Important factors and measures such as public opinion, effectiveness of enforcement effort, and effectiveness of laws could be further researched. In addition, much more extensive analysis of the model itself could be undertaken to further provide directions for effective policy development. Lastly, research dealing with implementation of suggested new policies and procedures must be undertaken.

The second major direction for further research points to analysis of problems on other levels of variable aggregation. For example, water is often transported from one watershed to another in which it is either in short supply or where the available water is of poor quality. Special dynamic interactions could result as clean water is exported while additional amounts of wastes are still being dumped in the watershed. In the long run, possible equilization of pollution concentrations could pollute both areas to a dangerous level.

Other studies could focus on the dynamic interactions and changes in the actual states of the stream ecology. Imbalances

of various organisms, oxygen availability, and other factors could be examined to determine the response characteristics of stream life and man's ability to manage properly the stream ecology.

In summary, these suggested research directions illustrate the need to examine the entire problem in terms of dynamic properties. Causes of problems and responses must be determined before the basic problem can be handled. Dealing with symptoms can only postpone the time before crises will force our attention on these variables. The ground work in understanding problem causes and structuring policies to deal with their dynamic properties must be laid as soon as possible.



**APPENDICES**

APPENDIX A

HISTORICAL OBSERVATIONS AND INTERPRETATIONS



| DATE    | OCCURRENCE   | INTERPRETATION  |
|---------|--|---|
| 1907-15 | Filters were necessary to purify water for drinking purposes.  |   |
| 1908    | Ohio passes Benze Act as a measure of retaliation - the act exempted every Ohio village and city along the Ohio from installing sewage treatment plants until similar facilities were provided by all cities upstream. | The use of filters for the first time caused some public alarm as shown by Ohio's response to the problem - negative legislation but still indicative of mild concern for the problem.  |
| 1908-24 | Informal talks between the states concerning pollution problems but little action was taken.   | This period saw the first stage of legislation being formed - that stage, an informal regional pact. Meanwhile water treatment capacity has increased through use of chemicals to treat waters for public drinking and consumption. |
| 1920-24 | Industrial phenol wastes reached such a level that water became unpalatable.   | Public awareness to water pollution, especially phenol wastes, became intense because of the wide distribution of water to the general public. Meanwhile, demands for legislative and enforcement effort were high.                 |
| 1924    | Informal agreement among states was subsequently reached.  | The first stage of legislation - an informal agreement for regional control.  |
| 1924    | Industries agree to cooperate in eliminating phenol waste discharge. This agreement resulted in concerted action by industries in eliminating taste producing wastes.  | While the actual concentration of phenol was excessive, industries were responsive to clean-up efforts. Capacity for phenol treatment was obtained fairly soon, which subsequently reduced public awareness.                        |

| DATE    | OCCURRENCE  | INTERPRETATION   |
|---------|---|--|
| 1930    | Severe drought hits the Ohio Valley - river flow became so low that river pools became "open cesspools."  | First indications of an intolerable level of pollution. Public awareness however was not widespread since the river "cesspools" were not <u>carried to the public</u> at large except in drinking water, which in <u>most</u> cases was tolerable or not identifiable as the cause of the epidemic.  |
| 1930    | High levels of pollution concentration cause a few cases of gastroenteritis - said caused by drinking of polluted water and wide dissemination of polluted water.   |  |
| 1930-35 | Growing advocacy for Federal intervention in water pollution problems was noted, however, the states on constitutional grounds and industrial resistance discouraged congressional support. Public opinion was apathetic.     | Although signs of pollution problems were being forecasted, and thus the advocacy for federal intervention, the problem was not of "crisis" proportions as yet to overcome legal technicalities or to stimulate public interest. The prospects of increased legislation did however, influence industries resistance to any type of legislative action or enforcement. |
| 1935    | Water pollution has worsened since 1907-1915. Filters were doubled, chemical treatment doubled. Mr. H. M. Streeter concluded that future water purification through filtering and chemical treatment was becoming infeasible. | The margin of safety (in this case, intake treatment capacity) was being narrowed.   |
| 1935    | The Cincinnati Chamber of Commerce decided to awaken the public to the problem of water pollution, and also break the opposition of industries and municipalities to pollution control.                                       | Public awareness as reflected by the formation of a citizen's group - but industrial opposition and lobbying pressures created a stalemate.  |

| DATE      | OCCURRENCE   | INTERPRETATION   |
|-----------|--|--|
| 1935      | Industry against all types of pollution controls, either state or national. They claim such controls would hurt their competitive positions.   |  |
| 1937      | High flood waters cause water purification plants serving cities to be burdened with unusually high levels of pollution due to the scouring action of the rising waters.                               | Public becomes aware as flood waters carry the polluted waters to the <u>general</u> public through flooding and lower purity, personal usage water.   |
| 1936-1938 | Six state committees met to consider a regional water quality control commission.  | Public awareness stimulates consideration of new legislation for a regional control commission.  |
| 1936-1938 | Public awareness to pollution concentration levels resulted in the Chamber of Commerce Committee drumming up public support. Two years later a \$1 million bond issue for sewage treatment was passed. | Public funding also increases as awareness becomes more widespread. Capacity for treatment of wastes subsequently increases from actions such as this at several points throughout the valley. |
| 1940-1944 | War intervened and the drive for pollution abatement lessened.   |  |
| 1944      | Corps of Engineers and USPHS issued a report on pollution in the Ohio - indicating its excessive pollution concentration levels.   | War times allowed the tolerable level of pollution to be increased as sacrifices were considered important in the war effort.  |

| DATE      | OCCURRENCE   | INTERPRETATION  |
|-----------|--|---|
| 1946-1948 | Generally high pollution levels and ending of war switch peoples thoughts back to demand to clean up waters.   | High pollution levels caused by increased industrial wastes due to industrial expansion, technological demands, and general growth received increased emphasis and public concern as war effort subsided and tolerable pollution levels were lowered.   |
| 1948      | Governors of Ohio Valley States meet to establish ORSANCO.<br><br>ORSANCO starts intensive public awareness campaign.<br><br>Less than 1% of 2.8 million people along the river were provided with treatment facilities. Projection for compliance of communities estimated at 10 years.<br><br>First national water pollution control act passed, starting federal authority in such areas and supplying a commitment of <u>funds</u> . | Public awareness created by increased pollution levels created demands for legislative action.<br><br>Capacity in the form of sewage treatment (primary) was to be needed. Completion of capacity acquisition estimated at 10 years.<br><br>Federal intervention into the water pollution control problem, indicating the beginning of a new level or stage in legislation and funding. |
| 1949      | Sewage facilities standards drafted.   |   |
| 1956      | National water pollution control act ammended. Federal government instituted a grant-in-aid program.   |   |

| DATE | OCCURRENCE  | INTERPRETATION   |
|------|---|--|
|      | Treatment facilities in operation or under construction for 3/4 of the sewerred population. | Sewage treatment capacity acquisition response was the first 75% in 8 years, and last 25% in 17 years. |
| 1965 | More than 99% of sewerred population served by treatment facilities.                        |  |

## APPENDIX B

## MODEL STRUCTURE



## APPENDIX C

## LIST OF EQUATIONS



## POLLUTION GENERATION SECTOR

```

1L  PUP,K=PUP,J+(DT)(BR,JK=DR,JK)
6N  PUP=70E6
1L  TS,K=TS,J+(DT)(CTS,JK+0)
6N  TS=1
20R DR,KL=PUP,K/LD
C   LD=840
12R BR,KL=(PUP,K)(PEC)
C   PEC=.00245
12R CTS,KL=(TS,K)(CTSC)
C   CTSC=.00288
13A ITWG,K=(TPPW)(PUP,K)(TS,K)
C   TPPW=.005
12A TUG,K=(PPW)(PUP,K)
C   PPW=.015
7A  ITWTD,K=ITWG,K+TUG,K
14A PRI,K=ITWTD,K*((TACAP,K)(EFFCP,K))

```

## CAPACITY SECTOR

```

3L  ATGPM,K=ATGPM,J+(DT)(1/DATG)(PR,JK=ATGPM,J)
6N  ATGPM=1.4E6
C   DATG=6
15A FW,K=ATGPM,K+(FL)(PR,JK=ATGPM,K)
C   FL=2
7A  CN,K=FW,K-NEAR,JK
21A CORR,K=(1/ADJ)(CN,K-TC,K)
C   ADJ=10
20A ABR,KL=TEC,K/CU
C   CU=1000
1L  NFC,K=NFC,J+(DT)(ABR,JK=CFR,JK)
6N  NFC=0
20R CFR,KL=NFC,K/CD
C   CD=36
1L  LA,K=LA,J+(DT)(CFR,JK=DRA,JK)
6N  LA=0
20R DRA,KL=LA,K/DRLA
C   DRLA=160
1L  LALE,K=LALE,J+(DT)(DRA,JK+DRIA,JK)
51A DCIF,K=CLIP(0,TDFC,K,TDFC,K,0)
3L  DRIA1,K=DRIA1,J+(DT)(1/DRIA1D)(DCIF,J-DRIA1,J)
6N  DRIA1=0
20R DRIA,KL=DRIA1,K/CU
6N  LALE=0
C   DRIA1D=36
14A TC,K=(LA,K)(1)+(EFF)(LALE,K)+(XX)(NFC,K)
C   EFF=.85
C   XX=0
8A  SNSD,K=NEAR,JK+SDR,JK+SETR,JK
15A TACAP,K=LA,K+(EFF)(LALE,K)
51A CURRI,K=CLIP(CURR,K,0,CURR,K,0)
3L  ACURR,K=ACURR,J+(DT)(1/DACU)(CURRI,J-ACORR,J)
6N  ACURR=0
C   DACU=32

```

## ENVIRONMENTAL SECTOR

```

1L  TWIS,K=TWIS,J+(DT)(PR,J+ER,J-SETR,J-SUR,J-NEAR,J)
6N  TWIS=1
1L  TWSS,K=TWSS,J+(DT)(SETR,J-ER,J)
6N  TWSS=0
1L  U2,K=U2,J+(DT)(U2INC,J-U2DEP,J)
6N  U2=100
3L  ARNU2,K=ARNU2,J+(DT)(1/DARNO)(RNU2,J-ARNU2,J)
6N  ARNU2=0
C   DARNU=12
51R PR,KL=CLIP(PRI,K,0,PRI,K,0)
12R SUR,KL=(CONC,K)(NSFR)
C   NSFR=1E7
12R NEAR,KL=(NEAC)(IDU2,K)
6A  IDU2,K=1
C   NEAC=1.4E6
20A CONC,K=TWIS,K/WCS
C   WCS=1E9
12R U2DEP,KL=(U2,K)(FDPM,K)
58A FDPM,K=TABHL(1FDPM,CONC,K,0,.15,.03)
C   1FDPM*=0/0/0/0/0/0
51A U2INC,KL=CLIP(U2II,K,U2,K,100)
12A U2II,K=(U2,K)(U2EX)
C   U2EX=.0005
21A RNU2,K=(1/NU2)(NU2=U2,K)
C   NU2=100
12R ER,KL=(TWSS,K)(PEPM,K)
58A PEPM,K=TABHL(1PEPM,ARNU2,K,0,.15,.03)
C   1PEPM*=0/.003/.009/.03/.045/.05
20R SETR,KL=TWIS,K/SD
C   SD=24
58A EFFCP,K=TABHL(1EFF,ARNU2,K,0,.15,.03)
C   1EFF*=1/1/1/1/.98/.92

```

## PUBLIC AWARENESS

```

3L  ACUNC,K=ACUNC,J+(DT)(1/DACC)(CONC,J-ACUNC,J)
6N  ACUNC=.000000001
C   DACC=12
3L  TCUNC,K=TCUNC,J+(DT)(1/TD)(ACUNC,J-TCUNC,J)
6N  TCUNC=.000000001
C   TD=60
3L  AACUN,K=AACUN,J+(DT)(1/2)(CONC,J-AACUN,J)
6N  AACUN=.000000001

21A RCC,K=(1/CONC,K)(CONC,K-AACUN,K)
58A IRCP,K=TABHL(1IRCP,RCC,K,0,.02,.002)
C   1IRCP*=.3/.37/.5/.75/1/1.25/1.45/1.6/1.75/1.9/2
13A PCUNC,K=(ACUNC,K)(IRCP,K)(IALP,K)
58A IALP,K=TABHL(1IALP,ACUNC,K,0,.13,.01)
C   1IALP*=.3/.42/.54/.7/.85/.95/1.05/1.15/1.2/1.25/1.3/1.3/1.3
21A DPT,K=(1/TCUNC,K)(TCUNC,K-PCUNC,K)
58A APE,K=TABHL(1APE,DPT,K,1,1,.2)
C   1APE*=1/1/.98/.95/.9/.75/.55/.32/.15/.07/.05

```

## ENFORCEMENT SECTOR

```

12R EE1,KL=(DCE,K)(PRG,K)
1L EEIP,K=EEIP,J+(DT)(EE1,JK-EE2,JK)
6N EEIP=0
39R EE2,KL=DELAY3(EE1,JK,D EEIP)
C D EEIP=18
1L EEE,K=EEE,J+(DT)(EE2,JK-EE3,JK)
6N EEE=0
51A EE3,KL=CLIP(0,EE3T,K,DCE,K,1)
12A EE3T,K=(EEE,K)(RDA)
C RDA=.005
16A DREE,K=(LAL,K)(M1)+(LA,K)(M2)+(NFC,K)(M3)+(ACORR,K)(M4)
C M1=1
C M2=.5
C M3=1.5
C M4=3
21A DCEI,K=(1/ADJ2)(DREE,K-EEE,K)
51A DCE,K=CLIP(DCEI,K,0,DCEI,K,0)
C ADJ2=12
15A EEE1,K=EEE,K-(EEIP,K)(MHI)
C MHI=3

```

## LEGISLATIVE SECTOR

```

3L AA1,K=AA1,J+(DT)(1/DAAL)(APE,J-AA1,J)
6N AA1=.05
C DAAL=12
7A LS,K=AA1,K=LUBBY
C LUBBY=.25
3L AOL,K=AOL,J+(DT)(1/DAOL)(LS,J-AOL,J)
6N AOL=.2
C DAOL=12
58A PRG,K=TABHL(TPRG,AOL,K,.2,.8,.2)
C TPRG*=.6/.9/1/1/1/1/1.05
12R LP,K=(DCL,K)(ILS,K)
58A ILS,K=TABHL(TILS,LS,K,.2,.8,.2)
C TILS*=.6/.9/1/1/1/1/1.05
1L LLP,K=LLP,J+(DT)(LP,JK-LPR,JK)
6N LLP=0
20R LPR,KL=LLP,K/DPL
C DPL=12
1L LLE,K=LLE,J+(DT)(LPR,JK+0)
6N LLE=0
3L CTLP,K=CTLP,J+(DT)(1/CTD)(LLE,J-CTLP,J)
6N CTLP=0
C CTD=60
8A TCL,K=ACORR,K+TACAP,K+NFC,K
3L ATCL,K=ATCL,J+(DT)(1/DATCL)(TCL,J-ATCL,J)
6N ATCL=0
C DATCL=24
7A DLC,K=ATCL,K+0
21A DCL,K=(1/ADJ3)(DLC,K-LLE,K)
C ADJ3=18

```

## POLLUTERS ABATEMENT DECISION

```

12A  TDFC.K=CLIP(ABRI.K,ABRII.K,ABRI.K,0)
12A  ABRI.K=(ACURR.K)(CU)
13A  ABRII.K=(.2)(ACURR.K)(CU)
12A  DFCEP.K=(TDFC.K)(FCS)
C    FCS=.5
3L   AA2.K=AA2.J+(DT)((1/AFD)(APE.J-AA2.J))
6N   AA2=.05
C    AFD=10
58A  IAF.K=IABHL(IAF,AA2.K,0,1,.1)
C    IIAF*=.6/.6/.66/.72/.78/.84/.9/.95/1/1.07/1.15
12R  ACP.KL=(DFCEP.K)(IAF.K)
12A  EFFL.K=(CTLP.K)(CU)
44A  EFFEL.K=(EEEE1.K)(CU)/(AMPM)
C    AMPM=1.2
54A  MEE.K=MIN(EFFEL.K,EFFL.K)
51R  ERCP.KL=CLIP(ERCA.JK,ACPI.K,ACPI.K,ERCA.JK)
3L   AACP.K=AACP.J+(DT)((1/DAACP)(ACPI.J-AACP.J))
6N   AACP=0
C    DAACP=1
12A  MMA.K=(AACP.K)(FWE)
C    FWE=.0
51A  RCMEX.K=CLIP(1,0,RCMEE.K,0)
7A   RCMEE.K=MEE.K-MEE.J
3L   ARCME.K=ARCME.J+(DT)((1/DARC)(RCMEX.J-ARCME.J))
6N   ARCME=0
C    DARC=10
58A  IELFA.K=IABHL(IEL,ARCME.K,0,1,.5)
C    IIEL*=.9/1/1.5
12A  ACA.KL=(MMA.K)(IELFA.K)
12A  ACPI.K=(DFCEP.K)(IAF.K)
1L   LFCA.K=LFCA.J+(DT)(ACA.JK-ERCA.JK)
6N   LFCA=0
6A   ERCA.KL=LFCA.K
7A   TEC.K=ERCA.JK+ERCP.JK

```

```

PLDT  APE=A(0,2)/CUNC=B,PCUNC=C,ICUNC=D/EEE=E,LLE=F,CTLP=G/ABR=Z
PLUT  DFCEP=G,ACPI=H,ACA=I,TDFC=M/EFFEL=J,EFFL=K/ITWTD=Y
SPEC  DT=1/LENGTH=640/PRTPER=120/PLTPER=6

```

## APPENDIX D

## LIST OF VARIABLES AND PARAMETERS

List of Variable and Parameter Names

Pollution Generation Sector

POP - Population (number of people)  
 TS - Technological State (dimensionless)  
 DR - Death Rate (people/month)  
 LD - Life Span Average (months)  
 BR - Birth Rate (people/month)  
 PEC - Population Growth Constant (1/month)  
 CTS - Change in Technological State (1/month)  
 CTSC - Change in Technological State Constant (1/month)  
 TTWG - Tons of Technological and Industrial Wastes Generated  
       (tons/month)  
 TPPW - Per Capita Demand for Technological Products  
       (tons/month/person)  
 TOG - Tons of Organic Wastes Generated Per Month (tons/month)  
 PPW - Per Capita Generation of Organic Wastes  
       (tons/month/person)  
 TTWTD - Total Tons of Wastes Generated for Disposal (tons/month)  
 PRI - Polluting Rate Indicated (tons/month)

Capacity Sector

ATGPM - Average Tons of Wastes Generated Per Month (tons/month)  
 DATG - Delay to Average Generation Rate (months)  
 FW - Forecasted Wastes (tons/month)  
 FL - Forecast Lead (months)  
 CN - Capacity Needed (tons/month)  
 CORR - Correction Desired in Capacity (tons/month/month)  
 ADJ - Time to Correct Error Between Capacity and Capacity Needed  
       (month)  
 ABR - Abatement Rate (tons of capacity funded/month/month)  
 CU - Cost per Unit of Abatement Capacity (dollars/ton)  
 NFC - Number of Facilities Being Constructed (tons/month)  
 CFR - Construction Finishing Rate (tons/month/month)  
 CD - Construction Delay (months)  
 LA - Level of Efficient Abatement Capacity (tons/month)  
 DRA - Decay Rate of Efficient Abatement Capacity (tons/month/  
       month)  
 DRLA - Time for Abatement Capacity to Lose Peak Efficiency  
       (month)  
 LALE - Treatment Capacity of Inefficient Abatement Facilities  
       (tons/month)  
 DCIF - Decrease in Available Funds to Revamp Inefficient  
       Facilities (dollars)  
 DCIAI - Decay Rate of Inefficient Abatement Capacity Indicated  
       (tons/month/month)  
 DCIA - Actual Decay Rate of Inefficient Abatement Capacity  
       (tons/month/month)

TC - Total Treatment and Control Capacity (tons/month)  
 EFF - Efficiency Factor of Inefficient Capacity (dimensionless)  
 TACAP - Total Treatment and Control Capacity (tons/month)  
 CORRI - Indicated Correction Desired in Capacity (tons/month/month)  
 ACORR - Average Correction Ready for Funding (tons/month/month)  
 DACO - Delay to Appropriate Funding for New Capacity (months)

#### Environmental Sector

TWIS - Tons of Waste in Stream (tons)  
 TWSS - Tons of Waste Settled on Stream Bottom (tons)  
 O2 - Dissolved Oxygen Level in Stream (Base of 100)  
 ARNO2 - Average Ratio of Normal to Actual Oxygen Level  
 (dimensionless)  
 DARN0 - Delay to Monitor Sustained O2 Level (months)  
 PR - Polluting Rate (tons/month)  
 SDR - Stream Discharge Rate (tons/month)  
 NSFR - Normal Stream Flow Rate (billion Gallons/month)  
 O2DEP - Dissolved Oxygen Depletion Rate (units/month)  
 FDPM - Fractional Decrease in O2 Level Due to Pollution (1/month)  
 O2INC - Dissolved Oxygen Increase Rate (units/month)  
 O2II - Dissolved Oxygen Increase Indicated (units/month)  
 O2EX - Re-oxygenation Rate (1/month)  
 RNO2 - Ratio of Normal to Actual Dissolved Oxygen Levels  
 (dimensionless)  
 NO2 - Normal Dissolved Oxygen Level (Base of 100)  
 ER - Escape Rate of Settled Pollutants (tons/month)  
 PEPM - Percent Excapage Per Month (1/month)  
 SETR - Settling Rate of Suspended Solids (tons/month)  
 SD - Settling Delay (months)  
 EFFCP - Effectiveness of Capacity Due to O2 Depletion  
 (dimensionless)

#### Public Awareness

ACONC - Average Concentration of Pollutants (tons/billion gallons)  
 DACC - Delay to Average Concentration (months)  
 TCONC - Tolerable Concentration (tons/billion gallons)  
 TD - Tradition Delay (months)  
 AACON - Two Month Average Pollution Concentration (tons/billion  
 gallons)  
 RCC - Rate of Change of Pollution Concentration (percentage)  
 IRCP - Impact on Perception of Rate of Change of Pollution  
 Concentration (dimensionless)  
 PCONC - Perceived Concentration (tons/billion gallons)  
 IALP - Impact on Perception of Absolute Pollution Concentration  
 Level (dimensionless)  
 DPT - Difference Between Perceived and Tolerable Pollution  
 Concentration Levels (dimensionless)  
 APE - Public Awareness (dimensionless)

Enforcement Sector

EE1 - Hiring Rate of Enforcement Agency Staff (men/month)  
 EEIP - Enforcement Staff in Training (men)  
 EE2 - Employees Finishing Training (men/month)  
 DEEIP - Delay to Train and Organize New Enforcement Staff (months)  
 EEE - Experienced Enforcement Staff (men)  
 EE3 - Actual Enforcement Staff Leaving (men/month)  
 EE3T - Enforced Staff Resigning (men/month)  
 DREE - Desired Enforcement Effort (men)  
 RDA - Rate of Attrition of Staff (percent/month)  
 M1 - Staff Time Necessary for Monitoring of Inefficient Facilities (man-months/ton)  
 M2 - Staff Time Necessary for Monitoring Efficient Abators (man-months/ton)  
 M3 - Staff Time Necessary to Inspect New Facilities Under Construction (man-months/ton)  
 M4 - Staff Time Necessary to Enjoin Standards on Polluters (man-months/ton)  
 DCEI - Desired Change in Enforcement Effort Indicated (man/months)  
 ADJ2 - Time to Adjust Difference Between Desired and Actual Enforcement Effort (months)  
 EEE1 - Effective Enforcement Effort (men)  
 MHT - Man Months Training Required by Experience Staff (man-months/man)

Legislative Sector

AA1 - Public Awareness Affecting Legislation (dimensionless)  
 DAAL - Delay for Public Awareness to Affect Legislation (months)  
 LS - Orientation of Legislature (dimensionless)  
 LOBBY - Lobbying Pressure for Decreased Legislation (dimensionless)  
 AOL - Average Orientation of Legislation (dimensionless)  
 DAOL - Delay to Average Orientation of Legislature (months)  
 PRG - Percent of Requests Granted in Laws and Enforcement Staff  
 LP - Law Proposal Rate (tons of coverage/month/month)  
 ILS - Impact on Law Passage of Legislation Orientation (dimensionless)  
 LLP - Laws Being Studied (tons of coverage/month)  
 LPR - Law Passage Rate (tons of coverage/month/month)  
 DPL - Delay to Pass Laws (months)  
 LLE - Level of Legal Coverage (tons/month)  
 CTLP - Court Tested Legal Coverage (tons/month)  
 CTD - Court Testing Delay (months)  
 TCL - Total Coverage of Laws Needed (tons/month)  
 ATCL - Average Coverage Perceived (tons/month)  
 DATCL - Delay to Perceive Need for Additional Coverage (months)  
 DLC - Desired Legal Coverage (tons/month)  
 DCL - Desired Change in Legislation (tons/month/month)  
 ADJ3 - Time to Correct for Additional Coverage (months)



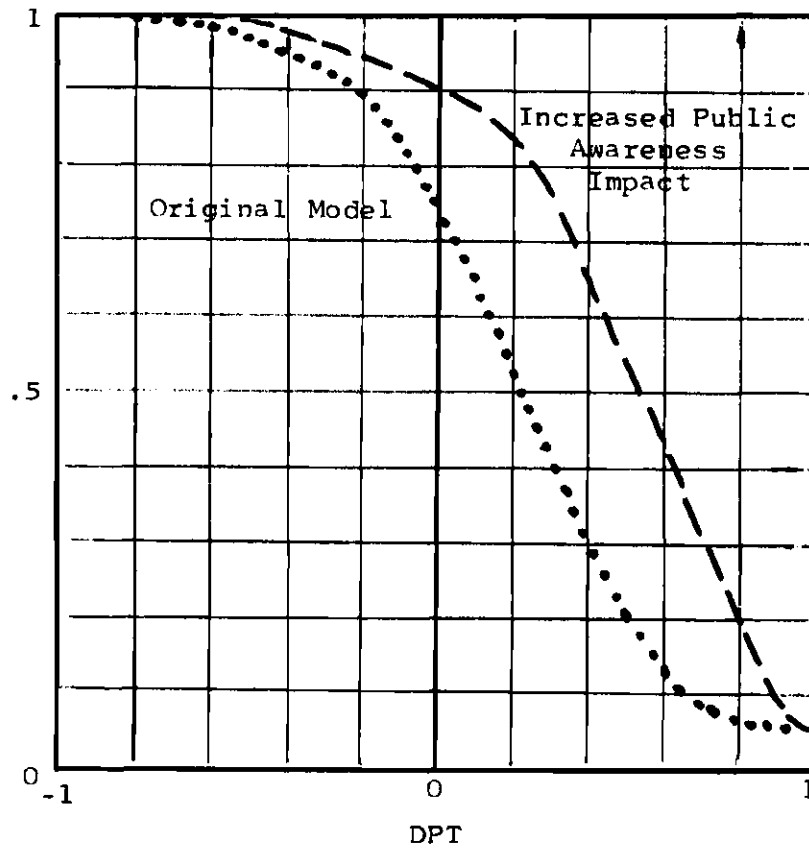
Polluters Abatement Decision

TDFC - Total Desired Funds for Capacity (dollars/month/month)  
 ABRI - Abatement Rate Indicated (dollars/month/month)  
 ABRII - Abatement Rate of Slack Indicated (dollars/month/month)  
 DFCP - Desired Funds for Capacity From Public (dollars/month/month)  
 FCS - Fraction of Cost Supported Directly By Public (fraction)  
 AA2 - Public Awareness Affecting Funding (dimensionless)  
 AFD - Delay for Funding Awareness (months)  
 IAF - Impact of Awareness on Funding (dimensionless)  
 ACP - Allocation of Funds from Public for Capacity (dollars/month/month)  
 EFFL - Effectiveness of Legal Coverage (tons/month)  
 EFFEE - Effectiveness of Enforcement Effort (tons/month)  
 AMPM - Average Man Months per Month (man-months/month)  
 MEE - Minimum of Enforcement or Legal Powers (tons/month)  
 ERCP - Expenditure Rate for Capacity at Public (dollars/month/month)  
 AACP - Average Allocation of Capacity from Public (dollars/month/month)  
 DAACP - Delay to Average Allocation from Public (months)  
 MMA - Matching Funds by Polluters Without Enjoinment (dollars/month/month)  
 FWE - Fraction of Public Funds Matched (fraction)  
 RCMEX - Rate of Indicated Change of Minimum Enforcement and Legal Powers (tons/month)  
 RCMEE - Trends of Minimum Rate of Change (tons/month)  
 ARCME - Average Rate of Change Minimum (tons/month)  
 DARC - Delay to Perceive Change in Direction of Minimum Power to Enforce Standards (months)  
 IELFA - Impact of Minimum on Funding at Polluters (dimensionless)  
 ACA - Allocation to Treatment Capacity at Polluters (dollars/month/month)  
 ACPI - Allocation to Treatment Capacity at Public Indicated (dollars/month/month)  
 LFCA - Level of Funds for Capacity at Polluters (dollars/month)  
 ERCA - Expenditure Rate for Capacity at Polluters (dollars/month/month)  
 TEC - Total Expenditure for Treatment Capacity (dollars/month/month)

APPENDIX E

ORIGINAL AND REVISED PARAMETER VALUES OF  
ILLUSTRATED SIMULATIONS

1. Basic Model versus Model of Increased and Sustained Public Awareness



Basic Model: C TAPE\*=1/1/.98/.95/.9/.75/.55/.32/.15/.07/.05  
 Revised Model: C TAPE\*=1/1/1/.98/.95/.91/.85/.65/.45/.2/.05

2. Basic Model versus Model with Rephased and Increased Impact of Enforcement Effort

Basic Model: C TIEL\*=.9/1/1.5  
 C CTD=60  
 C DEEIP=18  
 C ADJ2=12

Revised Model: C TIEL\*=.9/1/2.5  
 C CTD=18  
 C DEEIP=9  
 C ADJ2=6

3. Changes from Basic Model to Show Effects of Decreasing Gain in the Generation of Pollutants

Revised Model: 51A CTSC.K=CLIP(.00288,0,300,TIME.K)  
 12A CTS.KL=(TS.K)(CTSC.K)

4. Changes from Basic Model to Show Effects of Reaching Biologically Intolerable Limits

Revised Model: C TFDPM\*=0/0.0005/.001/.002/.004  
 Basic Model: C TFDPM\*=0/0/0/0/0/0

OTHER PERTINENT DETAILED MODEL ANALYSIS

| Basic Model Conditions |  | New Conditions   | Pollution Concentration Results                              |
|------------------------|--|--|--|
| 1.                     | C DACO = 32<br>C CD = 18   | DACO = 16<br>CD = 36   | No change in ultimate magnitude                              |
| 2.                     | C ADJ = 15   | ADJ = 10   | Slightly worse   |
| 3.                     | C FL = 2   | FL = 18  | Reduction of approximately 20%                               |
| 4.                     | C TIEL*=.9/1/1.5   | TIEL*=.9/1/2.5   | Reduction to approximately .1 from basic model value of .125 |
| 5.                     | C TIEL*=.9/1/1.5<br>C CTD = 60<br>C DEEIP = 18<br>C ADJ2 = 12<br>C MHT = 3 | TIEL*=.9/1/2.5<br>CTD = 18<br>DEEIP = 6<br>ADJ2 = 6<br>MHT = 2.8 | Reduction from previous model of another approx. 8%          |

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## VITA

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