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THE UNCERTAIN SEARCH FOR ENVIRONMENTAL POLICY: SCIENTIFIC FACTFINDING AND RATIONAL DECISIONMAKING ALONG THE DELAWARE RIVER *

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TABLE OF CONTENTS

I.	INTRODUCTION	421
	A. <i>Structuring Decisionmaking on Environmental Questions</i>	422
	1. The Political Model	423
	2. The Technocratic Model	424

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	3. The Legal-Administrative Model	425
	4. The Common Law Model	427
	B. <i>Mixed Models and the Delaware Experience</i>	429
II.	FROM THEORY TO PRACTICE	431
III.	DEFINING THE "POLLUTION PROBLEM"	436
	A. <i>Water Quality and Dissolved Oxygen</i>	436
	B. <i>Sources of BOD</i>	441
	C. <i>Shortcomings of the DO Index</i>	444
	D. <i>Playing the Environmental Numbers Game</i>	447
IV.	THE THOMANN MODEL'S BASIC STRUCTURE	449
	A. <i>Overview</i>	449
	B. <i>The Problem With Estuaries</i>	451
	C. <i>The Steady State Assumption</i>	455
V.	THE THOMANN MODEL: SOURCES OF ERROR	457
	A. <i>The BOD Equation</i>	457
	1. Treatment of Decay Rates	457
	2. Combined Sewers and Raw Sewage	460
	3. Loads Imposed by non-Estuarine Branches of the Delaware Basin	464
	4. The Data Base Sources for Error	465
	5. The BOD Equation: The Proof of the Pudding ..	466
	B. <i>The DO Equation</i>	467
	1. Reaeration	467
	2. Benthic Demand	470
VI.	APPRAISING THE UTILITY OF THE MODEL	472
VII.	ASSESSING THE DECS ANALYSIS OF PROPOSED POLLU- TION PROGRAMS	478
VIII.	BEYOND THE STEADY STATE: THE TIME VARYING MODEL	482
IX.	BEYOND 1966: FOLLOWING THROUGH ON THE DECS WORK	484
	A. <i>The Regional Failure to Follow Through</i>	484
	B. <i>The Federal Failure to Follow Through</i>	489
X.	THE ADMINISTRATIVE PROCESS AND THE PURSUIT OF SCIENCE	489
XI.	CONCLUSIONS	495
XII.	APPENDIX	498

I. INTRODUCTION

When the members of the Delaware River Basin Commission (DRBC) met at Dover on March 2, 1967 to adopt a massive pollution control program for the river, the event had significance not only for environmentalists, but for every student of American institutions. For the decision seemed to vindicate the American faith in the power of men to create both new modes of thought and novel organizational forms that promise to control the problems of a rapidly changing industrialized society.

On the organizational level, the Basin Commission itself was an innovative attempt to construct a regional government that proceeded from the perception that the coherent development of the Delaware River's resources would be impossible if left to the uncoordinated decisions of each of the four riparian states—New York, Pennsylvania, New Jersey, and Delaware—as well as the large number of powerful federal agencies, especially the Army Corps of Engineers, that had an interest in the river. To accommodate both state and federal interests, the Delaware Basin Compact, approved in 1961,¹ broke new ground by providing that the federal government, as well as each riparian state, would have a voting member on the Commission.² Moreover, unlike so many earlier interstate compacts, the signatory governments were not niggardly in granting broad—though not unlimited—powers to the Commission, which seemed to give the agency a realistic opportunity to effectuate a comprehensive plan that concerned itself with water quality, as well as the development of hydroelectric power, recreational areas, wildlife conservation, flood protection, and water supply.³

The DRBC's pollution control program is significant, however, not only for what it revealed about the viability of regional government, but also because it was grounded in a conceptual approach that promised to enhance dramatically the rationality of decisions affecting environmental quality. An agency embarking upon a water pollution program must, in one way or another, resolve three basic issues. First, it must determine the level of water quality that is desired. Secondly, it must determine the amount of pollutant that must be removed from the stream in order to achieve the water quality standard selected. Thirdly, the

¹ The Compact and formal acts of consent to the Compact by the signatory governments may be found at: Act of Sept. 27, 1961, Pub. L. No. 87-328, 75 Stat. 688; DEL. CODE ANN. tit. 7, §§ 6501-13 (Supp. 1970); N.J. STAT. ANN. §§ 32:11D-1 through 32:11D-110 (1963), as amended, N.J. STAT. ANN. §§ 32:11D-111 through 32:11D-115 (Supp. 1971); N.Y. CONSERV. LAW §§ 801-12 (McKinney 1967); PA. STAT. ANN. tit. 32, §§ 815.101-815.106 (1967).

² Delaware River Basin Compact § 2.5.

³ *Id.* arts. 4-10; see Grad, *Federal-State Compact: A New Experiment in Cooperative Federalism*, 63 COLUM. L. REV. 825 (1963).

agency must determine the way in which the burden of cleaning up the river to the desired level will be allocated among the polluters: should *A* treat his effluent more than *B* because it is cheaper for *A* to do so, or should a uniform percentage treatment be required of all polluters regardless of cost, or should each polluter's effluent be of equal purity, or should some other means of apportioning the burden be selected? The Commission was not obliged to resolve these issues in a completely capricious manner, but instead had the benefit of a pioneering study made by the Department of the Interior, in which an expert staff had constructed a mathematical model that simulated the impact of pollutants discharged by the industries and cities bordering upon the river. Using the model, the Interior study attempted to quantify the costs and benefits of embarking upon a variety of cleanup programs that were under consideration by the Commission.

This is the first of a series of essays attempting to deal with the institutional and conceptual novelties involved in the Delaware decision. In each of the essays, we shall be assuming the perspective of a hypothetical social engineer charged with the task of designing a set of institutions that promises to handle "best" the complex problems of environmental regulation posed by a major interstate river. We shall ask: what does the Delaware's experience teach the Engineer? To respond to this question coherently, it is necessary to attempt a statement of the basic issues the Engineer may be expected to confront in his adventure in institution building. Without a notion of the problems faced by the Engineer, it would be fruitless for us to attempt to act as interpreters of the Delaware's experience. Thus, while complexities may be deferred, the nature of the general inquiry will be clarified considerably if from the outset we indicate our understanding of the basic problem confronting the Engineer, and thereby locate in a larger context the particular concerns of the present Article.

A. Structuring Decisionmaking on Environmental Questions

The basic problem confronting the institution-builder can best be understood by contemplating for a moment an extremely simple model to which a pollution control agency could conceivably conform. Imagine that, during the course of their deliberations, one of the Engineer's apprentices suggests that the power to select a pollution control program for the river be placed in the unchecked discretion of a single citizen of the Delaware Valley selected by lot. In proffering the Lottery Model, the Apprentice explains further, he is not suggesting that it necessarily be adopted: rather, its principal analytical utility lies in its challenge to his associates to justify their preference for a different

decisionmaking model, to which the Apprentice would gladly adhere if he is persuaded that the proposal is superior to the Lottery.

In responding to the Apprentice's challenge, it would appear that the Engineer and his assistants are faced—at first blush—with an embarrassment of riches. Not one, but at least four, models may be plausibly invoked, each offering a different approach to the decision-making problem. At this early stage in the discussion, it will suffice to characterize each of the models in highly generalized terms, at the same time noting the basic grounds upon which the doubting Apprentice may question their utility to the Engineer in the case at hand.

1. The Political Model

It is not necessary here to explore the Ultima Thule of democratic political theory to assert that decisions generated by the political process are generally accorded legitimacy in the contemporary polity. Moreover, we do not argue here that there is something peculiar to pollution control policy that renders the complex play of forces set into motion by the political process an inappropriate mechanism for decision-making. Rather, the principal difficulty in invoking the Political Model in the present case lies in the obvious fact that no well developed set of regional political institutions exists at present that can be expected to deal coherently with the problems of the Delaware Basin or any other major interstate river. In addition, embarking upon the difficult task of constructing a full fledged political system for a river basin would make sense only if the basin were the geographic locus of a large number of problems of common concern to the citizens of the basin. It is not clear that typically this will be the case. Other problems of greater importance than river development—transportation, housing, employment, air pollution—may define a more appropriate set of regional boundaries cutting across watershed lines.⁴ Organizing regional government by watersheds would, for example, have the unfortunate consequence of placing much of New Jersey in one regional unit, and the City of New York in another. Thus, even if regional government were a reality, the regions in all likelihood would not be drawn in a way that would easily solve the Engineer's problem. The Engineer's principal difficulty, therefore, in designing a set of institutions along the Political Model will simply be: how can decisionmakers be held politically accountable in the absence of regionally organized

⁴ For a sensitive introduction to the problem of constituency definition with an emphasis upon the particular difficulties involved in organizing river basin pollution control authorities, see Roberts, *Organizing Water Pollution Control: The Scope and Structure of River Basin Authorities*, 19 PUBLIC POLICY 75, 83-113 (1971), which also contains a comprehensive review of previous work in the area.

political parties, regular elections, interest groups and other sources of public opinion that discipline and legitimate the politician's attempt to articulate and effectuate public policy on the local, state, and national levels? The obvious (perhaps only) response to this question would be to select the river basin agency's policymakers from local, state, or national officeholders who have successfully manipulated the political process at other levels of government. But if this move were taken, would there be any reason to believe that these politicians, responding to pressures from their non-regional constituencies, would make the decision that, in any intelligible sense, corresponds to the best interests of the residents of the river basin? What institutional structures can be devised that promise to deal with this problem? Without this promise, is it really quite clear that the Political Model is significantly superior to the Lottery Model? Thus, the doubting Apprentice.

2. The Technocratic Model

But let us escape from politics. Using contemporary welfare economics as a conceptual base, professional economists have over the past generation sought to develop the techniques of cost-benefit analysis to permit the resolution of complex public policy issues in more familiar market terms.⁵ Just as—under perfect competition—the firm that sets production at the point where its marginal cost is equal to marginal revenue is acting in the public interest in facilitating the efficient allocation of resources, so too a pollution control agency should select those water quality goals at which the marginal cost of abatement equals the marginal benefit to society. In doing this, the agency will be furthering the public interest in efficient resource allocation. Thus (says the Technocrat), if it is possible to quantify accurately the marginal costs and benefits implied by various levels of water quality, the “marginal cost = marginal benefit” test permits the resolution of the pollution problem in the most efficient way without the need to worry overmuch about the relationship between regional decisionmakers and the political systems existing upon local, state, and national levels.

⁵ Water resource development has been one of the principal fields in which leading economists have attempted to apply “cost-benefit” techniques developed over the past generation. See, e.g., S. BAIN, R. CAVES & J. MARGOLIS, *NORTHERN CALIFORNIA'S WATER INDUSTRY* (1966); R. DORFMAN & H. JACOBY, *MODELS FOR MANAGING REGIONAL WATER QUALITY* (forthcoming); A. KNEESE & B. BOWER, *MANAGING WATER QUALITY: ECONOMICS, TECHNOLOGY, INSTITUTIONS* (1968); A. KNEESE & S. SMITH, *WATER RESEARCH* (1966); J. KRUTILLA, *THE COLUMBIA RIVER TREATY—ECONOMICS OF AN INTERNATIONAL RIVER BASIN DEVELOPMENT* (1967); J. KRUTILLA & O. ECKSTEIN, *MULTIPLE PURPOSE RIVER DEVELOPMENT* (1958); A. MAASS, M. HUF-SCHMIDT, R. DORFMAN, H. THOMAS, S. MARGLIN & G. FARR, *DESIGN OF WATER RESOURCE SYSTEMS* (1962).

Needless to say, the doubting Apprentice would not be rendered speechless by the Technocratic argument suggested above: To what extent can one accurately quantify benefits and costs? What is the relationship between cost-benefit analysis and the corpus of welfare economics that allegedly provides the basis for its claim to legitimacy? What institutional structures may be devised to induce an agency to engage in a disciplined analysis of costs and benefits, and to choose the optimal water quality level in the manner prescribed by the economics scholar?

3. The Legal-Administrative Model

Advocates of either of the first two models attempt to gain adherence without ascertaining whether the Engineer himself prefers certain pollution control programs to others. The standard political theory supporting the Political Model does not seek to justify itself by arguing that the Model will generate decisions the Engineer personally considers wise; in order to render a particular pollution decision legitimate, it is enough under the Political Model that the environmental standard has been set through the democratic process. Similarly, under the Technocratic Model, it is quite irrelevant whether the Engineer believes that the Delaware "ought" to be clear as crystal or an open sewer; it is enough that the Model selects the program cost-benefit analysis indicates will most efficiently allocate society's finite resources, whatever concrete substantive outcome is thereby prescribed. It is possible, however, to embark upon the Engineer's journey in quite a different spirit: the Engineer could instead choose to immerse himself in the substance of the particular problem of water pollution control at hand in an effort to develop a coherent set of policies that, in his best judgment, define the wisest way to deal with the conflicting interests at issue. If a preferred set of substantive policies can be established, perhaps the problem of institution building will be simplified considerably. If, for example, the Engineer decided that sound social policy required that the polluted waters of the Delaware be cleansed "to the highest degree technology permits,"⁶ it would be a *relatively* simple matter to design an institution that would carry the policy out effectively and that would give concerned groups in the river basin a fair opportunity to explain to the agency the manner in which the standard should be applied in the particular river system in question. Indeed, once the standards have

⁶ See, e.g., the Muskie Bill presently under consideration by the Congress, which requires all point source polluters to install by 1976 "the best practicable control technology currently available." S. 2770, 92d Cong., 1st Sess. § 301(b)(1)(A)(i) (1971).

been articulated, it is possible that an administrative agency of the kind familiar to our post-New Deal polity would prove a satisfactory institutional vehicle for the Engineer's purposes. Agencies of the kind enshrined by the federal Administrative Procedure Act are designed in theory to fulfill the Engineer's basic requirements: an adequate opportunity is generally provided interested groups to argue the concrete implications of the general statutory policy; the agency is provided sufficient expert assistance to evaluate the probable success of alternative methods of achieving the statutory objective; and, finally, a corps of legally trained generalists in the judiciary may be relied upon to check an agency that attempts to embark on a course of action not substantially justified by the statute.⁷ Doubtless, the federal Administrative Procedure Act could be improved substantially by an Engineer who wished to design an institution conforming to the Legal-Administrative Model; nevertheless, the Engineer would use the A.P.A. as one of the starting points for his deliberations.

And that is precisely the trouble with the Model in the eyes of the doubting Apprentice. We have had enough of New Deal failure, he would suggest. Unless the statute mandates a *coherent set of relatively unambiguous policies*, there is every reason to believe that history will repeat itself: the pollution control agency will prove unequal to the task of developing a coherent set of policies on its own initiative, and will instead respond principally to the pressures of those polluters who in theory it is supposed to regulate in the public interest.⁸ Thus, before considering the important matters of detail involved in the use of the Legal-Administrative Model, it is critically important to inquire: (a) whether it is possible to develop one or more approaches to pollution control policy that will yield a set of standards sufficiently clear and coherent to serve as an appropriate statutory basis for agency action; and (b) even if it is possible, whether there is reason to believe that the legislature would refuse to make the hard choices necessary for a coherent pollution policy and would instead respond to conflicting political pressures by enacting a statute framed in purposefully ambiguous language, thereby delegating the task of basic policy formulation to an agency unable to rise to the high challenge of statecraft.

⁷ See generally, K. DAVIS, ADMINISTRATIVE LAW TREATISE (1958, Supp. 1970).

⁸ For different perspectives on this problem, see H. FRIENDLY, THE FEDERAL ADMINISTRATIVE AGENCIES: THE NEED FOR BETTER DEFINITION OF STANDARDS (1962); H. HART & A. SACKS, THE LEGAL PROCESS: BASIC PROBLEMS IN THE MAKING AND APPLICATION OF LAW 1144-1242 (tent. ed. 1958); R. NADER, J. ESPOSITO & L. SILVERMAN, VANISHING AIR (1970); R. NADER & R. FELLMETH, THE INTERSTATE COMMERCE COMMISSION (1970); R. NADER, D. ZWICK & M. BENSTOCK, WATER WASTELAND (prelim. draft 1971); Hector, *Problems of the CAB and the Independent Regulatory Commissions*, 69 YALE L.J. 931 (1960); Posner, *The Federal Trade Commission*, 37 U. CHI. L. REV. 47 (1969).

4. The Common Law Model

What if the defects of each of the previous models prove irremediable? What if we find that no feasible mechanism can be devised that promises to vindicate the Political Model in a regional context devoid of developed political institutions; that cost-benefit analysis is not sufficiently developed to justify the Technocratic Model; that no statute enacted at present can be expected to incorporate a coherent set of pollution control policies, as required by the Legal-Administrative Model? What then is to save us from the Lottery Model? When all else fails, perhaps it is the judiciary upon whom the Engineer must rely to serve as the "fourth-best" institutional mechanism for generating societal pollution policy. In theory, at least, the common-law judge seems to have a good deal to recommend him: the ideal judge would strive to be impartial, seek to explicate the complex values of our legal tradition in an effort to formulate a sensitive response to the novel aspects of the pollution problem, respond to reasoned arguments advanced both by the lawyers in the case before him and by academic critics writing in the law reviews. It is true, of course, that the common law process will proceed slowly on a case-by-case basis, but in the absence of a satisfactory alternative, the Common Law Model at least seems to assure that these incremental decisions will be made in a conscientious, disinterested, and sensitive fashion.

Let us concede—for purposes of argument—that the judicial process will in fact substantially conform to the idealized picture suggested by the Common Law Model. Nevertheless, the sceptical Apprentice could still properly doubt the propriety of the Model's claim to even "fourth-best" status. First, since water quality at any point in the river is generally a function of the effluent discharged by a considerable number of polluters, it will be necessary to embark upon a complex multiparty litigation our court system handles only with much time consuming effort. Secondly, rational river planning requires a lengthy scientific investigation of river conditions that the judge has neither the expertise, nor the financial resources, to launch. Of course, it would always be possible for the judge to require either plaintiffs or defendants to embark upon the elaborate scientific studies necessary for an informed judicial decision. Few private plaintiffs, however, would be able to afford the millions of dollars and the substantial expenditure of time that would be required either to initiate an ambitious series of studies or even to rebut the "expert scientific inquiry" launched by the defendant polluters.⁹ Even if the required studies and counterstudies

⁹ Krier, *Environmental Litigation and the Burden of Proof*, in M. BALDWIN & J. PAGE, *LAW AND THE ENVIRONMENT* 105 (1970); Sive, *Securing, Examining and*

were proffered, the fact remains that the judge would ultimately be obliged to evaluate the inevitably conflicting analyses. This is no task for the typical law-trained professional, who bid a grateful farewell to integral calculus thirty years previously and who looks at the prospect of manipulating a computer program with undisguised terror. How is such a man to decide between the rival scientific analyses proffered by defendant and plaintiff: by the cut of the expert's jaw?¹⁰ Thirdly, courts will often select an extremely expensive strategy for achieving whatever water quality goals they ultimately select. A judge will typically seek to effectuate his policy by issuing orders to each defendant-polluter specifying the amount the discharger is to treat its waste. The fact may be, however, that the cheapest and surest way of attaining the judicially determined environmental standard will not require that each discharger treat its own waste on an individual basis but will instead involve the construction of regional treatment plants and substantial dams as well as other measures that treat waste *after* it has been discharged into the stream.¹¹ Nevertheless, the judiciary would properly refuse to adopt any of these strategies requiring courts to assume an intimate role in the on-going management of the river system. Finally, assuming these considerable obstacles were somehow overcome, and a plausible pollution control program were initially articulated, the court would be incapable of sustaining the scientific inquiry *beyond the time of the original decision* so that policies could constantly be modified as

Cross-Examining Expert Witnesses in Environmental Cases, in *id.* 48. The government could bear the litigation expenses either through a subsidy arrangement for private plaintiffs or by directing state employed attorneys to bring legal action on behalf of environmental interests. In either case, it would be necessary to develop guidelines determining the situations in which government resources would appropriately be invested in environmental litigation, and this would raise, in a somewhat different context, the principal issues canvassed under the Legal-Administrative Model. If a corps of government lawyers developed substantial sophistication in environmental matters, it is quite possible that courts would begin to give substantial weight in deciding the merits to the government's decision to bring legal action, thereby transforming the Common Law Model to one more closely conforming to the Legal-Administrative Model. Such a phenomenon would parallel developments in the ongoing relationship between the Antitrust Division of the Department of Justice and the federal judiciary.

¹⁰ The judiciary may seek to avoid these difficulties by appointing special masters with substantial expertise in these matters to evaluate the evidence in the first instance, thereby transforming the Common Law Model into a kind of Legal-Administrative proceeding, raising the problems associated with this Model in a particularly acute form.

¹¹ For example, the problem posed by dissolved oxygen depletion, to be considered in detail in the body of the text, may sometimes be most efficiently solved by installing apparatuses in the river itself that introduce dissolved oxygen in those locations where it is required. See *FEDERAL WATER POLLUTION CONTROL ADMINISTRATION, U.S. DEP'T OF INTERIOR, DELAWARE ESTUARY COMPREHENSIVE STUDY: PRELIMINARY REPORT AND FINDINGS* 68-69 (1966) [hereinafter cited as *DECS*]; Roberts, *supra* note 4, at 77. Courts would, however, be severely taxed if they were required to devise a formula that would assess each polluter's financial contribution to the fund necessary to purchase and maintain these "in-stream aeration" devices.

experience accumulated. It is possible that one of the parties would at some future point seek to reopen the initial decree or that a new plaintiff would demand reconsideration of the original judicially imposed program. But there is no assurance that the parties would be willing to make the substantial expenditures necessary for these continual court tests; there is even less assurance that these episodic court battles would occur at the points in the river basin's future at which wise planning would demand that substantial strategy changes be considered. In short, the judicial process is geared toward the resolution of an isolated dispute between a small number of parties that can be understood by the intelligent generalist after a relatively brief study; it is irremediably distorted when it is called upon to undertake a long-term effort at reconciling the conflicting claims imposed by a large number of conflicting activities upon a natural resource whose character is best understood as a result of an on-going scientific enterprise.¹² Perhaps even the random decisionmaker selected by the Lottery could design a pollution control system that would take into account the complex nature of the problem far more satisfactorily than even the most inspired judge constrained by the Common Law Model, or so the Apprentice would suggest.

B. Mixed Models and the Delaware Experience

Each of the four Models is, of course, capable of very sustained elaboration. Doubtless the determined theorist would find that each of the basic archetypes discussed above embraces a wide variety of sub-models, differing in important respects from their brothers and cousins subsumed under the same Model. Equally important, an adequate theory of social engineering would explore the implications of an almost infinite variety of mixed models, seeking to remedy the irremediable defects in one mode of institutional design by complementing it with features drawn from another archetype. Our crude treatment here is sufficient for our purposes, however. For we believe that before more abstract theory can be fruitful, it is necessary to explore concrete cases with the needs of the theorist in mind. Instead of attempting a more

¹² As befits an Apprentice, the argument presented in the text is somewhat overstated. Courts have engaged in complex on-going enterprises, notably those involving school desegregation and legislative reapportionment. Similarly, judges have sometimes exercised on-going control of complex business firms undergoing reorganization, although here the reorganization trustee will generally function as the first-line decisionmaker, with the judge reviewing the decisions made by others in the manner contemplated by the Legal-Administrative Model. Even those (like the present authors) who have generally applauded the judiciary when it has taken an activist, quasi-managerial role in the vindication of constitutional rights should recognize the possibility, however, that the managerial role in river basin management could well be of an order of magnitude too demanding for a lay judge, however conscientious.

reticulated theoretical statement at the outset, we shall move immediately to consider the manner in which the Delaware's experience enlightens certain parts of our primitive conceptual framework.

From this perspective, the importance of our case study centers around the lessons it can teach about the operation of the Political and the Technocratic Models of pollution policy formulation in contemporary America. As we have already suggested, the voting members of the Delaware River Basin Commission are high level political actors: on matters of primary importance like the question of the water quality goals to be selected for the polluted sectors of the river, the Governors of the four riparian states and the Secretary of the Interior each *personally* cast equal votes on the Commission, with a simple majority carrying the day in case of disagreement. Before the politicians made their final decision, however, one of the most careful technocratic analyses in the history of American pollution policy had been attempted, with the aim of clarifying the costs and benefits implied by selecting each of five different water quality objectives for the river. Now it happens that the water quality objectives selected by the Political decisionmakers and the objective suggested by the Technocratic analysis did not coincide: while the Technocrats recommended a moderately ambitious quality improvement program, the Politicians selected a much more expensive cleanup goal. Thus, by contrasting the Technocratic analysis with the dynamics of the Political decision, we shall gain an insight into the strengths and weaknesses of each of the two Models. In addition, by considering the way in which Technocrats and Politicians dealt with the concrete problems of pollution control on the Delaware, we shall also be gaining an insight into the potential relevance of the Administrative-Legal Model to the Engineer. For we shall ultimately argue that along the Delaware (and other rivers) both Technocrats and Politicians are developing basic pollution policies that would be rejected by most thoughtful citizens *if their premises were made explicit*. Moreover, once the premises of present policy are made explicit, it may be possible to develop a set of standards sufficiently explicit to serve as the basis of a Legal-Administrative process that has some chance of shaping environmental policies more wisely than will the mixed Political-Technocratic model exemplified by the Delaware's experience.

But all this is prologue. The present essay does not attempt a definitive comparison between Political, Technocratic, Legal-Administrative and Common Law Models, but simply lays a foundation for an analysis of that ultimate question in a subsequent article. It is our purpose here to focus attention upon the way in which the "facts"

about the river's "pollution problem" were presented to the decision-makers on the Delaware. We have taken this course for three reasons. First, the way in which the "facts" about the "pollution problem" are presented has a profound impact upon the kind of policy options decisionmakers will consider seriously. Thus, if the "factual description" invites decisionmakers to ignore certain dimensions of the "pollution problem" that seem of great importance, a Model is rendered suspect to the extent there is reason to believe that the Model's policymakers will be especially prone to accept the "facts" uncritically. Secondly, since sound policymaking requires a sophisticated understanding of the factual context, it is necessary to consider whether any of the Models make effective fact gathering difficult or impossible. Thirdly, at the end of this study, the reader will be called upon to understand the nature of the policy choices open to our society in situations epitomized by the polluted Delaware. In order to equip him for this task, he must be furnished with the necessary data.

Given these concerns, three questions seem of fundamental importance: (a) to what extent does the structure of contemporary scientific descriptions of the "water pollution problem" invite decisionmakers to ignore variables that seem important in the satisfactory formulation of policy; (b) even when considered on its own terms, how reliable is the information the contemporary factfinder can provide; (c) how can institutions be structured to facilitate effective factfinding? The importance of the first two questions to our larger goals should be clear: if the "facts" presented by the "expert" factfinders are unreliable or ignore crucial dimensions of the "pollution problem," each of the models must be designed with an eye toward sensitizing decisionmakers to the inadequacies of the "facts" proffered to him. Similarly, the third question raised here, exploring the problem of optimal institutional design for effective factfinding, has obvious importance to the Engineer choosing between the four models.

II. FROM THEORY TO PRACTICE

It would be a great mistake to assume that a discussion like the one we have imagined in the Engineer's conference room preceded the decision to combine elements of the Political and Technocratic Models in the special mixture they exhibited on the Delaware. Indeed, it is more truthful to say that nobody ever consciously decided that the complex decisionmaking mechanism that evolved was the best one for the job at hand.

For at the very beginning of our story, we encounter a problem that will complicate it to the end: the fractionation of governmental

planning and decisionmaking authority made it difficult (if not impossible) for any single man or organization to consider the problem of institutional design from the Engineer's perspective. When the DRBC became a functioning entity in September of 1961, it found that a scientific study of the water pollution problem in the Delaware was already gathering steam under the aegis of the federal Public Health Service, which subsequently came under the control of the Federal Water Pollution Control Administration in the Department of the Interior. Indeed both the Interior study and the DRBC itself were the products of the same natural disaster that changed the face of water policy along the river. In the mid-1950's, the valley had experienced a series of disastrous floods that had focussed local and state attention upon the river with an unaccustomed intensity, catalyzing the energies of a broad range of groups.

The way in which the floods of the 1950's generated political pressures leading to the establishment of the DRBC has been adequately detailed by others.¹³ The history of the Department of the Interior's study, however, is less well known. Within a relatively short time after the floods, the Army Corps of Engineers was requested by the concerned states to make a comprehensive study of the Delaware watershed. Given the Corps' own institutional biases, together with the fact that floods had precipitated its investigation, the Engineers were principally concerned with devising a plan for building a series of dams for flood control. The Corps believed, however, that water quality, as well as water quantity, was within its mandate, and asked the Public Health Service (PHS) to conduct a study in this area as part of the over-all effort. Thus, when the Engineers' report was published in the late 1950's it included a chapter containing primitive data on the pollution problem in the valley.¹⁴

Matters might have been left in this primitive condition but for developments within the Public Health bureaucracy in Washington. Cost-benefit analysis was a relatively new idea in Washington during the waning Eisenhower years and the PHS was eager to apply the new learning to the solution of water quality problems. Given the fact that some work had already been undertaken on the Delaware, the river basin was selected as the testing ground for the new techniques. Thus, by 1962, the Service's plans had matured to the point where it could

¹³ R. MARTIN, G. BIRKHEAD, J. BIRKHEAD & F. MUNGER, *RIVER BASIN ADMINISTRATION AND THE DELAWARE* 3-61 (1960); F. ZIMMERMAN & M. WENDELL, *New Horizons on the Delaware*, 36 STATE GOVERNMENT 157, 162 (1963).

¹⁴ 3 U.S. ARMY ENGINEER DISTRICT, PHILADELPHIA, CORPS OF ENGINEERS, *REPORT OF THE COMPREHENSIVE SURVEY OF THE DELAWARE RIVER BASIN: APPENDIX C*, H.R. Doc. No. 522, 87th Cong., 2d Sess. 91-189 (1962) (prepared by the U.S. Dep't of Health, Educ. & Welfare, 1960).

launch its Delaware Estuary Comprehensive Survey (DECS), which undertook a pathbreaking scientific analysis of the Delaware's pollution problem at a cost of \$1.2 million over the next four years.¹⁵ During the earlier years of the study, the DECS proceeded on its way with very little assistance or guidance from the DRBC, the political agency with ultimate decisionmaking authority on the matter of pollution in the Delaware. In part, DECS's independence was explained by the capriciousness of nature. No longer was the valley victimized by severe floods; instead, the early and middle 1960's was an era of ever-deepening drought along the Delaware. As drinking water became scarce, New York City and Philadelphia became enmeshed in one of their periodic clashes over their respective rights to tap the Delaware for water supplies, and the infant DRBC's prime concern was to mediate the conflict between these cities, as well as among other concerned communities.¹⁶ Water quality seemed of relatively small importance when compared with the consequences of inadequate water quantity.

The preoccupation of the DRBC was not the only reason for the independence of DECS. At its inception, the DECS investigators understood their task principally in academic terms. DECS's research director, Robert Thomann, was a young sanitary engineer whose doctoral thesis had proposed a new mathematical model for dealing with the physical impact of pollutants upon estuaries like the Delaware.¹⁷ It was his intention to demonstrate his model's utility in actual practice, and it was easy to recruit a youthful staff who shared this exciting goal. The DECS staff, driven by their desire to vindicate the new scientific methodology, would not have taken kindly to "guidance" by an agency like the DRBC, which at that time did not contain engineers with similar mathematical competence. Given the DRBC's preoccupation with other matters, however, no substantial conflicts along these lines occurred, and the DECS was permitted to go along its own way.

All this began to change dramatically with the passage of the Federal Water Quality Act of 1965,¹⁸ which for the first time required

¹⁵ Interview with James F. Wright, Executive Director of the Delaware River Basin Commission, Dec. 1970; Interview with Blair Bower, Resources for the Future, Nov. 1970; Interview with Walter Lyon, Director of Bureau of Sanitary Engineering, Department of Environmental Resources, Commonwealth of Pennsylvania, Aug. 1970; Interview with Professor Matthew Sobel, Yale Univ., Dec. 1971.

¹⁶ R. Hogarty, *The Delaware Water Emergency*, 1966 (unpublished manuscript, on file in Biddle Law Library, Univ. of Pa. Law School).

¹⁷ R. Thomann, *The Use of Systems Analysis to Describe the Time Variation of Dissolved Oxygen in a Tidal Stream*, Feb. 1963 (unpublished thesis in General University Library, New York University).

¹⁸ Water Quality Act of 1965, Pub. L. No. 89-234, 79 Stat. 903 (codified at 33 U.S.C. § 466 (1970)).

the states to submit water quality standards for federal approval, with the deadline for submission set for June 30, 1967.¹⁹ Suddenly, the DECS study was perceived from a more practical perspective. It was no longer basically a research operation that might inform decision-makers in the indefinite future. Rather, it became an action-oriented project promising a suitable basis for establishing regional pollution control objectives. By this point, however, the DECS staff had developed enough momentum so that it would have been even more difficult for the DRBC—still in the midst of the water shortage crisis—to significantly affect the shape of the DECS study. Thus, it was the DECS, not the DRBC staff itself, which was principally responsible for the critical task of *framing the alternatives* that would be presented to the political decisionmakers on the DRBC. In response to the 1965 act, the expert Interior staff accelerated the pace of its work, issuing a “preliminary” report in the middle of 1966, in time for use by the DRBC in its efforts to develop water quality standards.²⁰ This is not to say that the DECS staff framed the alternatives in a vacuum. The staff perceptively organized a complex set of advisory committees incorporating interested industrial, governmental, and citizens groups, so that important political constituencies would define their own positions fully armed with the facts as the DECS understood them, and so that the DECS could incorporate ideas from concerned groups into its definition of alternative water quality strategies.²¹ Nevertheless, it is fair to consider the DECS staff itself as the principal entity that articulated the nature of the basic choices confronting the citizens of the Delaware Valley.

The core of the DECS preliminary report analyzed the quantifiable costs and benefits involved in attaining five hypothesized water quality programs of widely different magnitudes. The least ambitious plan considered took as its goal the prevention of further degradation in river quality (Plan V); the most ambitious program contemplated the greatest possible effort consistent with the limitations of existing technology (Plan I); Plans II through IV contemplated water quality improvements of descending magnitude. When presented in tabular form, the DECS computer print-out provided information that promised to be of the highest utility to decisionmakers. Thus, under the regulatory

¹⁹ *Id.* § 5(c) (1), 33 U.S.C. § 466(g) (c) (1970).

²⁰ DECS, *supra* note 11.

²¹ These committees played an important role in the political process that ultimately defined the river's water quality objectives. Consequently they will be discussed in more detail in a subsequent essay.

system the DRBC was most seriously considering,²² the DECS cost-benefit analyses generated the following figures:

TABLE I²³
COST-BENEFIT ANALYSIS OF DECS POLLUTION PLANS

<i>Program</i>	<i>Cost</i>	<i>High estimate-low estimate of benefits</i>
I	\$460 million	\$355-\$155 million
II	250 million	320- 135 million
III	120 million	310- 125 million
IV	80 million	280- 115 million

In a sense, all that follows is a commentary upon this table from the perspectives suggested by the three questions advanced at the end of our earlier excursion into the theory of Social Engineering. To be precise, we shall ask:

(1) To what extent did the basic concepts used in the DECS analysis of the "pollution problem" influence the way in which the policy options were framed? Did the analysis invite the decisionmaker to ignore certain fundamental aspects of the problem and emphasize others unduly? (Section III)

(2) Within its own terms of reference, how reliable was the information the DECS sought to provide about each of the plans it presented for the consideration of the political actors on the DRBC? (Sections IV-VIII)

(3) To what extent did the institutional division between the DECS, a technocratic arm of the federal government, and the DRBC, a political body of regional scope, impede or advance the effort to generate an expert analysis of maximum utility in the decisionmaking process? (Sections IX-X)

²² As will be described in a subsequent article, this system required different polluters to treat their wastes in different degrees depending upon the polluter's geographic location on the river.

²³ The chart is derived from information to be found in DECS, *supra* note 11, at 66, 77. The benefit figures represent the dollar value of the recreational opportunities generated by improving water quality beyond Program V. In other words, the value of the existing uses of the water as of 1964 is not included in the statistics provided by the study. Similarly, the future costs of keeping the river at its present quality level were estimated by the DECS in a complicated manner, whose nature will be described in a subsequent article. For present purposes, it will be best to ignore these complexities by omitting Program V from the cost-benefit chart, as we have done.

III. DEFINING THE "POLLUTION PROBLEM"

A layman taking a slow boat trip down the Delaware as it flows through the densely populated conurbation stretching from Trenton, New Jersey, through Philadelphia, to Wilmington, Delaware, is offered an unusual perspective upon contemporary urban industrial civilization.²⁴ As he looks up from his boat, he sees enormous factories lined up one after another belching smoke into the air and dumping stuff of various kinds into the river; giant tankers and other vessels steam by, perhaps the ultimate source of the occasional small oil slick that can be observed; the river is extremely cloudy, with little in the way of aquatic life visible (although even if the fish were there, it would be difficult to see them). Despite all this, the number of "pleasure boats" on the river is surprisingly large, though it is very rare to see a person hardy enough to dare to swim in what is obviously a "polluted" stream.

There is, doubtless, much in this scene that would disturb a citizen concerned with the "pollution" problem; there is even more that does not meet the eye. Indeed, the problem with the "pollution problem" is that the label subsumes too many discrete issues that must be understood individually before their interrelationships can be mastered in an intellectual synthesis. And in this perception lies the importance of the first of the three questions with which this essay is concerned: in its efforts to "describe the facts" in a systematic way, which aspects of the "pollution problem" did the DECS staff emphasize and which did they ignore? To answer this question, we must explore the premises and character of a mathematical model that was the principal analytical tool used by the DECS to describe the factual relationships obtaining between various "pollution sources" and the river's "water quality."

A. *Water Quality and Dissolved Oxygen*

To write an equation relating "waste" discharges to a river's "water quality," it is first necessary to define the meaning of "waste" and "water quality" *in terms susceptible of quantification*. Since "waste" may properly be defined as anything that impairs "water quality," it will be sufficient at the outset to concentrate on defining the latter term: how, then, are we to *measure* "water quality"?

DECS answered this threshold question by taking recourse to the received wisdom of the sanitary engineering profession. Traditionally, the amount of dissolved oxygen (DO) in the water has served sanitary engineers as the principal benchmark of water quality, and DECS adopted this indicator to serve as the focus of its analysis. DO had

²⁴ Both of the authors did in fact take such a journey during the summer of 1970.

several advantages for the DECS. First, and most important for model building purposes, DO can be measured. Secondly, the amount of DO in the stream has an impact upon several important river uses. Fish need dissolved oxygen to breathe. If DO sags below a certain level—at best ill defined, but between three and four parts per million (ppm) of water—they will have increasing difficulty breathing. And if oxygen deficiencies are substantial and sustained, the fish will die.²⁵ If DO sags yet further to levels approaching zero for substantial periods of time, a group of microorganisms attack many organic wastes and degrade them in a way that throws off offensive odors, notably those associated with the rotten egg smell of hydrogen sulfide.²⁶ Needless to say, the presence of these odors makes the river an unpleasant place in which to boat or swim; nor is picnicking (or even travelling) nearby an attractive prospect.

Given these facts, it is obviously important to determine the extent to which the pollutants discharged into a river like the Delaware affect the stream's DO level, and it is precisely this problem that the DECS model sought to solve. The pollutants of greatest concern here include almost all organic compounds like those present in human feces and many industrial effluents. Perhaps the best way to understand the essential aspects of the impact of these wastes is to imagine an experiment in which a small lump of sugar is added to a bottle of clean water. If the amount of oxygen consumed by the microorganisms in the bottle as they decompose the lump of sugar is measured, a curve similar to the one in Figure 1 is obtained as time passes.²⁷ In the shorthand of engineers, the curve depicted in Figure 1 indicates the Biochemical Oxygen Demand²⁸ (BOD) exerted by the sugar over time.

²⁵ C. Tarzwell, *Water Criteria for Aquatic Life*, 1957 (unpublished paper), cited in T. CAMP, *WATER AND ITS IMPURITIES* 119 (1963). Camp indicates that:

for a well-rounded warm-water fish population, the dissolved oxygen must not be below 5 ppm for more than 8 hours of any 24-hour period and at no time should it be below 3 ppm. For the maintenance of a coarse fish population, the dissolved oxygen should not be below 5 ppm for more than 8 hours of any 24-hour period and at no time should it be below 2 ppm.

Id. Similar standards may be found in NATIONAL TECHNICAL ADVISORY COMMITTEE TO THE SECRETARY OF THE INTERIOR, *FEDERAL WATER POLLUTION CONTROL ADMINISTRATION, WATER QUALITY CRITERIA* 44 (1968), which suggests that at 3 ppm many species, especially game fish, suffer a significant retardation of normal growth and activity. For the approach of the DECS, see Morris & Pence, *Quantitative Estimation of Migratory Fish Survival Under Alternative Water Quality Control Programs* (unpublished manuscript under imprint of Federal Water Pollution Control Administration, U.S. Dep't of the Interior, Edison, N.J.).

²⁶ Hydrogen sulfide is produced by microbial decomposition of organic matter in the absence of air (anaerobic decomposition). T. CAMP, *supra* note 25, at 64.

²⁷ This figure is derived from one appearing in *id.* 246.

²⁸ *Id.* 243-51. BOD is defined as the number of pounds of oxygen that will be consumed in the biochemical oxidation of the organic impurity present. *Id.* 243.

As the shape of the curve indicates, the more concentrated the pollutant, the greater the rate at which it is decomposed,²⁹ and the faster DO is depleted.

FIGURE 1

OXYGEN CONSUMPTION VS. PERIOD OF INCUBATION FOR A CARBONACEOUS MATERIAL

Now suppose that a polluter discharges a lot of waste into a river. Since the consumption of dissolved oxygen is a function of the concentration of pollutant present, it follows that the concentration of DO will initially fall off rapidly at the pollutant's point of entry. As time passes, a given sample of polluted water will move downstream and the concentration of pollutant will decrease. As the concentration of pollutant decreases, DO consumption diminishes. Another effect also takes place. As the concentration of DO decreases, oxygen diffuses into the river from the air. This process is called reaeration. As the DO deficit increases, increasingly large amounts of oxygen diffuse into the river. The combined actions of the microorganisms consuming the pol-

²⁹ The correct differential equation describing the decomposition process is simply:

$$\frac{dx}{dt} = -kx$$

where k represents the "decomposition rate constant;" x represents the concentration of BOD; and t represents time. It should be noted that while k is a constant, the rate at which BOD is consumed over time $\left(\frac{dx}{dt}\right)$ is proportional to the negative of the concentration of BOD (x).

lutant in the water, the water flowing downstream, and the reaeration effect, result in a DO profile as shown in Figure 2.³⁰

FIGURE 2

A TYPICAL OXYGEN SAG CURVE

This curve is known, appropriately enough, as the oxygen sag curve. To complicate matters, the DO sag is also affected by water temperature (the warmer the water, the less oxygen it can dissolve and the faster the microorganisms consume oxygen), by changes in the river's flow rate (the faster the current, the further downstream the oxygen sag), and by the river's cross-sectional area (which affects the rate at which a waste discharge diffuses across the river).³¹

Even when all these factors are taken into account the student of the Delaware will not observe a DO curve precisely resembling the simple shape depicted above. The Delaware is endowed with a hundred or so significant dischargers, each at a different point in the river, each making its own contribution to the DO profile. Moreover, the impact on the river of many wastes is complicated by the fact that many pollutants contain elements other than the oxygen, carbon, and hydrogen which are the constituents of sugar. Most wastes con-

³⁰ This figure is derived from one appearing in T. CAMP, *supra* note 25, at 294. In this introductory explanation, we are assuming away the problems posed by the fact that the Delaware is an estuary experiencing tidal action. These problems will be discussed in detail at notes 48-91 *infra* & accompanying text.

³¹ The relationship between the factors and the DO profile was first systematically articulated by Streeter and Phelps in an equation reproduced at note 49 *infra*.

tain nitrogen as well, and in these cases the biological oxygen demand (BOD) of the material is a two-stage affair, as is shown in Figure 3.³²

FIGURE 3

OXYGEN CONSUMPTION VS. PERIOD OF INCUBATION FOR A HYDROCARBON CONTAINING NITROGEN

Under laboratory conditions, the nitrogen in untreated wastes begins oxidation approximately fifteen days after the test begins, in contrast to carbonaceous activity, which begins at once. Thus nitrogenous demand begins at a time when approximately ninety percent of the carbonaceous activity has been exerted; this explains the hump in the curve. It should be noted, however, that about ten percent of the carbon oxidation is yet to occur when nitrogenous decomposition begins even in the case of untreated waste. Nevertheless, sanitary engineers are accustomed to describing BOD in terms of "carbonaceous oxygen demand" (often called "First Stage Ultimate Oxygen Demand" or FSUOD) and "nitrogenous oxygen demand" ("Second Stage Ultimate Oxygen Demand" or SSUOD), although FSUOD and SSUOD cannot be precisely measured since carbonaceous demand has not ended when nitrogenous begins.³³

³² This figure is derived from one appearing in T. CAMP, *supra* note 25, at 245.

³³ *Id.* After the fifteenth day, when both nitrogenous and carbonaceous materials are decaying simultaneously, the carbonaceous contribution is calculated by extrapolating the curve based on the first 2 weeks of data, a period during which nitrogenous activity is almost absent. The remaining excess oxygen demand prevailing after the fifteenth day is attributed to nitrogenous activity. Interview with G.D. Pence, Jr., Delaware Estuary Comprehensive Survey Staff, in Edison, N.J., July 1970. Moreover, it is an oversimplification to assert that nitrogenous activity does not commence until the fifteenth day. In fact the lag before the onset of nitrogenous demand is a function of other variables as well, including the degree of treatment of the waste before it is dumped into the river.

B. Sources of BOD

In addition to the discharges emitted by treatment plants owned by riparian cities and industries, substantial loadings are imposed upon the estuary from three other sources. Large portions of the river bottom are endowed with thick sludge deposits continually in the process of being consumed by microorganisms that require oxygen for subsistence. The oxygen demand from this source (called benthic oxygen demand) accounts for about twelve percent³⁴ of the total demand imposed upon the estuary. In addition, the major cities of Trenton, Camden, Philadelphia, and Wilmington each possess combined sewer systems serving as conduits for both sewage and storm water run-off from the cities' streets. This means that the sewer pipes transmit dramatically larger volumes of waste water during and after heavy storms. Municipal treatment facilities, alas, are not constructed to cope with these inundations, but, rather, are built to treat the volumes associated with sewage flows without the rain. Consequently, the four major cities are obliged, on an average of ten rainy days a year,³⁵ simply to divert raw sewage cum rainwater directly into the Delaware itself without any treatment whatsoever. These discharges account for approximately four percent of the total annual load upon the river.³⁶ Finally, some twelve percent of the total load is contributed by the Upper Delaware above Trenton, as well as the hundred or so tributaries feeding into the estuary itself.³⁷

Despite the complex interaction of BOD from industry, municipal treatment plants, river sludge, storm sewer run-off, and the estuary's tributaries, a well defined DO profile, complete with oxygen sags, may be discerned by a student of the estuary. It is depicted in Figure 4.³⁸ For purposes of this analysis the river below Trenton has been divided into thirty sections, some 10,000 feet in length and some of 20,000 feet: At Trenton, just above the estuarine portion of the river, DO levels are high, and indeed approach saturation. The "sag" begins immediately below Trenton, where the combined effects of tidal action, a rapid increase in depth, a decrease in velocity, and the presence of polluting matter result in oxygen being consumed by microorganisms at a greater

³⁴ Porges & Selzer, *Allocation of Stream Capacity in the Delaware River Estuary*, in PROCEEDINGS OF THE SECOND MID-ATLANTIC INDUSTRIAL WASTE CONFERENCE 71, 80 (Nov. 18-20, 1968).

³⁵ Unpublished chapter of DECS Final Report (on file in Biddle Law Library, Univ. of Pa. Law School).

³⁶ Porges & Selzer, *supra* note 34, at 80.

³⁷ *Id.* 80.

³⁸ This figure is based upon one presented by G. Schaumburg, *Water Pollution Control in the Delaware Estuary* 44, 1967 (unpublished thesis on file at Harvard College Library).

FIGURE 4

PROFILE OF AVERAGE SUMMER DISSOLVED OXYGEN

rate. The sag at Burlington, however, is followed by a slight increase in DO, which has never been adequately explained. Up to section 7 (twenty-two miles from Trenton), just north of Philadelphia, the total FSUOD discharge from municipal and industrial sources is relatively small, amounting to 20,000 pounds per day for all seven sections combined. At Philadelphia, however, FSUOD inputs dramatically increase, averaging 75,000 pounds per day in each section through section 22 (sixty-five miles from Trenton), which is just beyond Wilmington, the last major city bordering the estuary. The three major treatment plants operated by Philadelphia contribute the lion's share of these wastes, discharging 450,000 pounds of FSUOD daily in 1964, which represented forty-five percent of the total FSUOD discharged by cities and industries along the estuary. During the same year, Camden's two plants discharged 62,250 pounds of FSUOD; Wilmington dumped 87,000 pounds; the chemical plants located along the heavily industrialized shore dumped 210,000 pounds; oil refineries, 95,000; paper plants, 30,000.

As a result of this series of discharges, DO drops precipitously in sections 7 through 11, a distance of merely six miles, from $5\frac{1}{2}$ ppm to $1\frac{1}{2}$ ppm and remains roughly constant for about the next thirty miles through section 19, which is a bit beyond the Pennsylvania-Delaware state line. DO begins to recover at this point since the river is increasing in size as it nears the Delaware Bay, diluting the waste to a greater degree as well as permitting accelerated reaeration. With the virtual cessation of substantial industrial and municipal loadings at Wilmington,³⁹ six miles beyond the state line, DO levels recover rapidly. Thus,

³⁹ The only sizeable discharge beyond this point is contributed by an oil refinery owned by the Getty Oil Co., located in section 26 of the river, 70 miles from Trenton. In 1964, the DECS estimated that the refinery was discharging 2500 pounds of

the DO level in section 25 (seventy miles from Trenton) is equal to the DO level in section 7 (twenty-two miles from Trenton); indeed, DO reaches near-saturation levels as the river meets the bay at Liston's Point.⁴⁰

Although this sketch of the relationship between waste discharges containing BOD and the resulting DO profile has been oversimplified, it suggests the magnitude of the task the DECS undertook in attempting to explain the shape of the Delaware's DO profile. Even more important for our purposes, it permits the beginning of an answer to the first of the three questions to which this essay is addressed: to what extent did the DECS attempt "to describe the facts" about DO emphasize

FSUOD per day. See Pence, Jeglic & Thomann, *Time-Varying Dissolved-Oxygen Model*, 94 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 381, 393 (1968).

⁴⁰ Our description of the river is based upon the DECS measurements of BOD loadings and DO profile obtaining in 1964. For a more precise description of the BOD loads imposed in each section of the river, we have provided the following chart taken from *id.*:

1964 WASTE LOADING IN THE DELAWARE ESTUARY, IN
POUNDS PER DAY OF CARBONACEOUS BIOCHEMICAL
OXYGEN DEMAND

Section	Municipal	Industry	Tributary	Storm Water Overflow	Total BOD Source	P, Total DO Sink
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	3,570	0	2,869	1,360	7,799	22,280
2	2,100	2,750	4,107		8,957	8,622
3	3,380	1,635	982		5,997	4,140
4	2,720	2,850	1,078		6,648	2,700
5	900	1,400	2,047		4,347	4,800
6	1,075	435	5,798		7,308	5,040
7	0	0	1,875	230	2,105	890
8	520	0	4,309	1,580	6,409	2,125
9	795	35	3,095	8,570	12,496	2,250
10	128,610	7,550	3,146	4,390	143,695	2,250
11	720	1,570	3,189	16,780	22,259	5,760
12	0	0	1,105	4,480	5,585	1,350
13	62,080	13,925	1,800	7,410	85,215	3,240
14	174,520	19,670	1,566	2,080	197,836	3,960
15	3,330	39,550	17,649	18,860	79,389	14,700
16	158,070	25,650	3,761		187,481	6,750
17	14,575	42,420	8,678	1,950	67,623	11,475
18	10,185	14,535	6,003		30,723	7,200
19	1,820	64,360	1,668		67,848	16,200
20	0	0	1,071		1,071	15,750
21	87,400	8,480	6,848	8,320	111,048	6,930
22	0	116,755	294		117,049	6,000
23	1,870	0	306		2,176	13,050
24	0	370	421		791	11,000
25	0	0	855		855	9,300
26	0	2,500	1,416		3,916	12,000
27	660	0	322		992	15,000
28	1,730	0	9,078		10,808	15,000
29	0	0	5,011		5,011	0
30	0	0	5,509		5,509	0
Totals	660,630	366,440	174,719	76,010	1,277,799	229,762

certain aspects of the "pollution problem" at the expense of other dimensions of equal or greater importance?

C. Shortcomings of the DO Index

We have said enough to explain why a policymaker would want to know the DO levels prevailing at various locations along the stream with which he is concerned. Nevertheless, a decisionmaker would be extremely myopic if he were to adopt DO as the exclusive touchstone of water quality. DO has little impact upon the ability of modern treatment plants to process water for human consumption, so long as anaerobic conditions producing serious odor problems are avoided.⁴¹ Turning next to a river's potential recreational uses, it is clear that DO is far from a sufficient indicator of water quality. Although a DO near zero indicates that a river cannot be used for swimming, fishing, or boating because of the "river-stink" resulting from complete oxygen depletion, a higher DO does not necessarily indicate that the river is suitable for these uses. That a river has a relatively high DO does not necessarily mean that the water will "look clean" to the typical swimmer, boater, or fisherman. At present, the Delaware is an extremely turbid river: over large sections, sunlight does not penetrate more than two feet beneath the surface.⁴² Reducing BOD loads upon

⁴¹ The DECS recognized that increasing DO will not result in substantial monetary savings for the major water treatment plant on the estuary, located at Torresdale, Pa., which provides half of Philadelphia's water:

The major source of municipal supply that may benefit from improved quality is the Torresdale Water Treatment Plant of Philadelphia. The fact that this plant is able to produce a potable water from an estuarine source of the present quality at a relatively low cost obscures the benefits picture for water supply. It is probable that the net monetary benefits in terms of dollar savings in treatment costs at Philadelphia's Torresdale plant will be relatively small at the alternative levels of water quality enhancement. What may result, however, after pollution abatement is carried out, will be a reduction in the taste and odor problem; and therefore an increase in Philadelphia's ability to produce a more palatable drinking water.

DECS, *supra* note 11, at 71.

No evidence is advanced to support the assertion that Philadelphia's water "may" become more palatable by improving the DO curve. Philadelphia's Water Department denies that this will occur, arguing that chlorination will still be a necessity to eliminate disease carrying organisms, and thus whatever taste problems arise from occasional over-chlorination will still exist. Interview with Samuel Baxter, Philadelphia Water Commissioner, Aug. 1970. Thus the claim that the plant's ability to produce high quality water "may" be enhanced seems a pious hope, rather than a well-founded estimate.

⁴² DECS studies indicated that, in the mid-1960's, the average depth to which only 1% of sunlight penetrated the Delaware was 3 feet, ranging from 7 feet at Trenton to 2 feet in the "critical regions" in the Philadelphia area. Letter from Professor R. Thomann, Nov. 1971. More recent data are difficult to obtain, indicating the professional pollution control community's continuing failure to transcend its preoccupation with BOD and DO as the primary water quality parameters. During a year in the mid-sixties, for example, the U.S. Geological Survey monitored turbidity levels around Philadelphia. This practice was discontinued, however, both because of uncertainty concerning the quality of the data collected and because no individual or organization had evinced any interest in the information the USGS compiled. Tele-

the stream will not necessarily change this dreary reality substantially since the river's turbidity is explained in large part by tides stirring up the river bottom, dredging operations required for large scale shipping, and the introduction of large quantities of sediment from the river's banks and tributaries. Thus, to understand the impact a cleanup of industrial and domestic waste will have upon swimming and boating in the Delaware, it is not sufficient to have a DO model of the river. A model must be available that calculates the impact a cleanup will have upon river turbidity.

It is even unclear that swimmers and boaters would benefit if an increase in DO did in fact indicate a dramatic reduction in turbidity.

phone communications with Richard W. Paulson, U.S. Geological Survey, Harrisburg, Pa., Sept. 1970, Apr. 1971. We have obtained informal estimates from experts who have done substantial research on turbidity levels in the Delaware Valley. An engineer who is the turbidity expert for the region's Army Corps of Engineers has informed us that in most parts of the river it is impossible to see an object 2 feet below the surface. Interview with Mr. Paul Hartzell, May 1971. Similarly, Professor Robert E. Ricklefs, of the University of Pennsylvania's Department of Biology informs us that along the lower Schuylkill, near the point where it joins the Delaware, the intensity of sunlight is attenuated by 10% to 30% per centimeter. Even assuming the lower value, this means that the intensity of sunlight 1 foot below the surface would be less than 1% of surface levels. While Professor Ricklefs has not done similar research on the main stem of the Delaware, he ventures to guess that results would be comparable along large sections of the river. Personal communications with Professor Robert E. Ricklefs, Aug. 1970, Apr. 1971. Finally, our own visual inspections of the estuary, particularly on boat trips that extended along its entire length, lead us to concur completely with Messrs. Hartzell and Ricklefs.

Data on present levels of photosynthetic activity are also incomplete and contradictory. Dr. C. Hull, now head of the DRBC's Program Planning Branch, did extensive studies of this problem, and concluded that despite high turbidity levels, significant photosynthesis was occurring. Hull, *Photosynthetic Oxygenation of a Polluted Estuary*, in 3 ADVANCES IN WATER POLLUTION RESEARCH: PROCEEDINGS OF THE (FIRST) INTERNATIONAL CONFERENCE HELD IN LONDON SEPTEMBER 1962, at 374 (E. Pearson ed. 1964). The DECS study, however, concluded that the net production of oxygen by photosynthetic activity was negligible. See Thomann, *Time-Series Analyses of Water-Quality Data*, 93 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 1 (1967). Even assuming that Dr. Thomann is correct and Dr. Hull completely mistaken, the present state of the Delaware is not our fundamental concern. We are concerned about the future: when Mr. Hartzell was asked whether the DRBC's projected cleanup would make algae bloom, he stated that neither he nor anyone else he knew was in a position to say. He indicated, however, that if the DRBC were not only to limit industrial and municipal discharges but also storm sewer overflow, it could happen that turbidity might decline sufficiently to allow significant algae growth in the shallow portions of the river along the shore.

Our conversations with various staff members of the DRBC indicate that they do not believe algae is presently a problem and refuse to consider the question seriously until it becomes one. The risk is made clear, however, by another view presented by A. Morris, a member of the DECS study group:

The Delaware Estuary above the Bay is an example of a relatively deep estuary where the nutrients are ten to one hundred times the concentrations theoretically necessary to cause a bloom; yet blooms don't occur. In this case, the euphotic zone is approximately four feet, but the average depth [of the river] is about 25'. Thus, it is hypothesized that photosynthesis is inhibited by insufficient radiant energy.

Unpublished remarks delivered to Manhattan College Summer Institute in Water Pollution Control, in R. Thomann, Teaching Materials 3 (1970) (on file in Biddle Law Library, Univ. of Pa. Law School).

At present, the cloudy Delaware is a relatively inhospitable home for algal growth precisely because the high turbidity prevents algae from photosynthesizing nutrients like phosphates and nitrates that are abundant in the water. If turbidity is reduced as a result of a BOD cleanup campaign, the algae may be in a perfect position to multiply. Increasing DO may simply mean that the valley is trading a brown river for a green one.⁴³ Per contra, if turbidity is not substantially reduced as a consequence of a BOD cutback, the impact of an increase in DO beyond the "river-stink" level will probably not be significant.

While aesthetics is probably the chief concern for boaters, swimmers are also concerned with the presence of disease-carrying organisms and toxic chemicals, whose existence—once again—is not dependent upon DO levels. In contrast, DO levels are of greater importance to fishermen, assuming they are willing to fish despite aesthetic affront. Here too, however, an adequate analysis would require an understanding of the impact of heat and toxic substances upon aquatic life.

What is true of a sophisticated understanding of the recreational uses of a river is even more true when a policymaker wishes to take into account the longer range ecological consequences of the alternative pollution programs he is considering. Once again, while adequate DO levels are a necessary condition for the survival of various forms of aquatic life, they are not a sufficient condition. Nor does the DO profile provide an adequate basis for determining the impact the Delaware has in the larger ecological balance upon which man ultimately depends for his survival.

Paradoxically, it is only with respect to one activity that DO serves as a relatively adequate indicator of water quality. Industries bordering upon the river use vast quantities of water for cooling as well as other industrial purposes. From their point of view, the DECS's use of DO as an indicator of "water pollution" is perverse for the simple reason that oxygen rich water corrodes piping systems at a more rapid rate.⁴⁴ The more "polluted" the water is (as measured by DO), the *better* it is for industrial water users. As soon as one moves beyond industrial processes, however, to consider the relationship between water and life, human or otherwise, the DO profile serves as an extremely imprecise measure of "water quality": generally speaking, a high DO is a necessary, but far from a sufficient, condition for beneficial water use.

⁴³ And one that will smell when the algae begin to die. Rotting matter creates high BOD, eventually resulting in depletion of DO leading to anaerobic decomposition. For the practical consequences to the man on the street of this same phenomenon occurring on the Potomac, see Kohn, *Warning: the Green Slime Is Here*, N.Y. Times, Mar. 22, 1970, § 6 (Magazine), at 26.

⁴⁴ DECS, *supra* note 11, at 72.

D. *Playing the Environmental Numbers Game*

All this means that the use of DO as an index for "water quality" facilitates a way of thinking about the "pollution problem" that is fraught with danger. Once a simple number is provided as a "proxy" for water quality, it may take on a life of its own, tempting all concerned to evaluate alternative programs in terms of the numbers, without asking more fundamental questions. Thus, a policymaker guided by the DO numbers will have little difficulty locating the portion of the Delaware River experiencing the most acute "pollution problem." For such a policymaker, it would be "obvious" that the region between Philadelphia and Wilmington suffering the most acute oxygen sag has the most urgent claims on public concern. For is not water quality "worse" there than at any other place? Is not this as "obvious" as the fact that a DO of one ppm is lower than a DO of seven ppm? And is it not equally obvious that society should first attempt to "solve" its "most serious" pollution problems before moving on to solve its less serious ones?

But *why* is the "pollution problem" most serious in the "critical region" characterized by severe oxygen depletion? Is it really clear that raising the DO level from 1 ppm to 3 or 4 or 5 ppm on the average in the "critical sections" between Philadelphia and Wilmington will substantially improve the quality of life of the inhabitants of the Delaware Valley? Will such a numerical triumph, for example, permit the urban masses to swim in the river? As we have suggested, there is no reason to think so. It is even possible that increasing DO will merely serve to transform the Delaware's color from a turbid brown to an even more unattractive green. And what of the nasty habit indulged in by municipalities who are obliged to discharge raw sewage into the river whenever there are heavy rains? If achieving a DO goal of 3 or 4 or 5 ppm permits the cities to continue this practice (as is in fact the case), will it be *healthy* for anyone to swim in the river for a substantial period after each rainstorm? Regardless of the health question, will people *want* to swim in the river after they have learned about the raw sewage? Putting all this aside, how *easy* will it be for people to swim in the Delaware in the "critical" region after it is "cleaned up," given the fact that at present heavy industry occupies much of the shoreline in the urban areas? Moreover, even if access were assured at convenient places, how many people would *want* to bathe on a beach bordered on one side by a belching chemical plant and on the other by a sewage treatment facility? And what about the large boats that ply the river supplying heavy industry with raw materials? Will swimmers enjoy their sport quite as much when they encounter the wake of the latest

intercontinental oil tanker steaming by? All these problems (and more) must be resolved successfully before a decisionmaker intent upon providing new swimming areas would consider the region characterized by intensive oxygen depletion important for his plans. Indeed, instead of developing the most polluted segment of the river for this purpose, it may be far wiser to develop one (or more) of the river's major tributaries *in all of the ways necessary to ensure an attractive body of water in which people would enjoy swimming and other water-based recreation activities*. To achieve this goal might cost a great deal of money, but it may well be far less than achieving even a numerical triumph in the so-called "critical region."

For other water uses, of course, DO has greater utility as an indicator. If fish are unable to live in the "critical region," we should be concerned, and DO helps to indicate whether the fish will die. But even here, keeping score by the numbers is far from sufficient. We still must ask: why is it important to reclaim the "critical region" for the fish? If it is to sustain a complex and variegated aquatic life system, the absence of certain aquatic species from the river near Philadelphia, while important, may be far from the most "critical" ecological threat facing the valley. As we have suggested, raising DO levels to 3 or 4 or 5 will not in and of itself transform the ecological consequences of twentieth century urban industrialism. Some fish will survive in, and others will more successfully migrate through, the highly deoxygenated stretch. But to imagine that the original ecological complexes displaced by industrialism will thereby be restored is simply folly. In contrast, forty miles downstream from the "critical" DO zone lies one of the few remaining major ocean-front areas in the Northeast yet to be significantly affected by heavy industry and concentrated population centers. In the marshes of the lower river and (even more importantly) the Delaware Bay, the complex interactions between land and water characteristic of relatively untouched areas still continues in a way whose fundamental ecological importance is only now being appreciated. Yet without sophisticated planning, the Bay may be transformed by urban industrialism in an all too familiar way in the coming decades. Which, then, was the more significant problem facing a pollution control policy in 1967: the nonexistence of fish near Philadelphia or the preservation of the fundamental character of the Bay? Paradoxically, it may be that the most "critical" ecological problem arises in an area, like the Bay, which at present contains *oxygen rich* water rather than in the DO sag region.

It would be premature to argue here that a sounder pollution strategy for the Delaware would have deemphasized the importance of

the problems generated by the oxygen poor area around Philadelphia in order to free resources to achieve goals of the kinds suggested in the preceding paragraphs. To make out this case persuasively will require an extensive discussion of both the theory of cost-benefit analysis and the attempt to apply the cost-benefit methodology by the DECS to the Delaware. This will be the goal of the second article in this series. Our point here is much simpler: unless great care is taken, a "successful" effort at charting the DO profile may predispose decision-makers to emphasize certain river uses at the expense of others; certain ecological risks at the expense of others. It is even conceivable that a decisionmaker can be so insensitive to the limitations of DO as a policy indicator that he will be led to select a program that would have been summarily rejected if the nature of the environmental control problem had not been so dramatically simplified as a result of a "successful" technocratic effort to chart the Delaware's DO profile.

IV. THE THOMANN MODEL'S BASIC STRUCTURE

A. Overview

Given the concerns of the model builders, it should prove no surprise that the most important difference between each of the programs they proffered to the politicians on the DRBC was the DO level that was set as the policy goal: the less ambitious programs were content with relatively oxygen-poor water, while the more ambitious insisted on higher DO levels. Moreover, it should be clear from our previous discussion that policymakers would "naturally" be concerned with the DO levels obtaining in the most polluted areas between Philadelphia and the Pennsylvania-Delaware state line, for it is in this region that river-stink and fish-kills pose the greatest dangers. Consequently, the cost-benefit chart presented earlier in this essay may appropriately be amended to indicate the DO levels contemplated by each of the proposed programs within the "critical" oxygen sag region below Philadelphia:⁴⁵

TABLE 2

<i>Program</i>	<i>Average DO in Most Polluted Region</i>	<i>Cost</i>	<i>High estimate-low estimate of benefits</i>
I	4.5	\$460 million	\$355-\$155 million
II	4.0	250 million	320- 135 million
III	3.0	120 million	310- 125 million
IV	2.5	80 million	280- 115 million

⁴⁵ This chart is derived from information to be found in DECS, *supra* note 11, at 56-58, 66, 77. For a caveat regarding the cost and benefit figures appearing in the chart, see note 23 *supra*.

In our sequel, we will have a good deal to say about the accuracy of the cost and benefit estimates presented in the Table as well as the subsequent estimates generated by the DECS after the DRBC had reached its decision to accept a variant of Program II listed above. Even when one considers the DECS's own figures, however, they reveal the nature of the challenge confronted by the builders of the DECS DO model when they sought to put their scientific expertise at the service of practical men of affairs. The chart demonstrates that a small improvement in the DO profile represents a substantial additional expenditure in pollution control. Thus, Program I achieves a one-half ppm improvement in DO at twice the cost of Program II, which in turn attains a one ppm increase at twice the cost of Program III.

This means that a relatively small error in the DO model predictions will be of great importance to decisionmakers. Imagine, for example, that instead of making perfect predictions, the DO model has a "standard error" of one ppm. This means that there is about a two-thirds chance the model's prediction will be within one ppm of actual river conditions existing after any particular program is effectuated.⁴⁶ Even this relatively small error would indicate that Program II, similar to the one ultimately adopted by the DRBC, could result in DO levels as high as Program I (costing twice as much) or as low as those contemplated by Program III (costing half as much). Of course, by selecting Program II instead of Program III, the agency *increases the chances* that a DO level of 4.0 ppm will be attained. Nevertheless, the intrusion of even a relatively small error into the DO predictions introduces a very significant new dimension into the decisionmaker's problem: how should he orient himself to the fact of uncertainty? Should he be risk-averse or risk-prone or risk-neutral? And as the error in the model's prediction increases, this latter question becomes increasingly important in policy formulation, dwarfing in significance the particular cost and benefit figures generated by the model.

In short, the second question advanced earlier in this essay,⁴⁷ inquiring into the reliability of the model's predictions, has great importance in an ultimate assessment of the scientific factfinding process in the present stage of its development. If the model's error is very substantial, the Engineer may properly act with a good deal of annoyance when the model builder proffers his information as to the consequences of adopting one or another of the programs under consideration. He may exclaim: "Any reasonable man already knew very

⁴⁶ For a discussion of the term "standard error," see P. HOEL, INTRODUCTION TO MATHEMATICAL STATISTICS 141 (3d ed. 1962).

⁴⁷ See text immediately preceding sections II & III *supra*.

well that if he ordered polluters to cut back their wasteloads a great deal (as required by Program II) the water would be somewhat 'better' than if he ordered them to cut back less (as required by Program III). What the scientific factfinder promises is a more precise estimate of the impact, so that policymakers can more precisely understand the benefits to be gained by imposing a more costly program instead of a less costly one. Yet the model's standard error is so great that it has not appreciably aided the decisionmaker in this task." More important than the Engineer's anger, however, the model's potential for error also raises an important problem in institutional design. For if a policymaker were to accept cost-benefit figures that did not take into account the risk that the promised benefits will be under- or over-fulfilled, cost-benefit analysis would obscure a critical dimension of the issue to be resolved. And it may be as grievous a flaw to present the illusion of certainty as to present to the decisionmaker an incomplete or inaccurate account of the known facts. Thus, the Engineer should be especially concerned with the importance of designing a set of institutional controls that will induce the model builder to reveal in a clear and unambiguous fashion the error his predictions may contain.

In addition to considering the institutional implications of the size of the "standard error" involved in the model's predictions, it is equally important to determine whether the model is systematically biased so that its predictions are consistently optimistic or pessimistic. While a detailed examination of the model reveals elements both of optimism and pessimism, it appears to us that the model's predictions have, in the aggregate, a significantly overoptimistic bias. Unfortunately, we have been unable to undertake the extensive theoretical, empirical, and computational work to form a precise estimate of the extent of the bias. All we can do here is to delineate the factors underlying our rough appraisal.

B. *The Problem with Estuaries*

The principal conceptual obstacle that rivers like the Delaware (below Trenton) pose to sanitary engineers is that they are estuaries and are therefore influenced by ocean tides. This means that BOD not only flows downstream, but upstream as well, complicating all calculations immensely. Thus, a systematic effort at predicting the DO profile had to await the development of the modern digital computer. Most of the elements necessary to run a computer program, however, had been developed much earlier in the study of nonestuarine rivers. In 1925, Streeter and Phelps, in a classic study of the Ohio River,⁴⁸ de-

⁴⁸ H. STREETER & E. PHELPS, A STUDY OF THE POLLUTION AND NATURAL PURIFICATION OF THE OHIO RIVER: 3 FACTORS CONCERNED IN THE PHENOMENA OF OXIDATION AND REAERATION (PUBLIC HEALTH SERVICE BULL. No. 146, 1925).

veloped an equation quantifying the relationships between DO, BOD, and the diverse factors we have already discussed.⁴⁹

Nevertheless, a systematic attempt to deal with the problem of tidal action was delayed until the 1960's, when the advent of the computer made the work seem worthwhile. In 1960, O'Connor developed the mathematical concepts that permitted the quantitative description of the manner in which a substance discharged in a tidal estuary would be distributed along its length over time.⁵⁰ Armed with O'Connor's contribution, Robert Thomann, then a graduate student, synthesized this work with that of Streeter and Phelps, and developed in his doctoral dissertation⁵¹ the first systematic mathematical treatment of an estuary with multiple pollution sources and varying temperature and flow rate along the length of the river. Thomann then became Technical Director of the DECS and attempted to put his model to the empirical test.

Thomann's contribution is of classic simplicity.⁵² The eighty-six mile estuary is divided into thirty sections, some of 10,000 and some of

⁴⁹ The original Streeter-Phelps equation is:

$$\frac{dD}{dt} = 2.3(-k_2 D + k_1 L) - a,$$

where D is the oxygen deficit in ppm, L is the first stage demand in ppm, t is the time of flow in days, k_2 is the atmospheric reaeration coefficient in reciprocal days, k_1 is the deoxygenation constant in reciprocal days, and a is the oxygen production by photosynthesis in ppm per day. In the original equation a was equal to 0. T. CAMP, *supra* note 25, at 295.

⁵⁰ O'Connor, *Oxygen Balance of an Estuary*, 86 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 35 (1960). As is normal in such enterprises, O'Connor was obliged to make a major simplifying assumption in order to achieve his theoretical advance. His description of tidal action assumes both that DO measured one foot below the surface is equal to the DO at the river's bottom and that DO levels are essentially uniform across the width of the river. In other words, O'Connor assumes away the river's breadth and depth. This oversimplification, while not inherent in the Thomann model, was used in its application to the Delaware Estuary.

⁵¹ See note 17 *supra*.

⁵² Although his Ph.D. thesis remained unpublished, the model developed there and subsequent elaborations are described in a substantial literature. Some of the significant references are: L. HETLING, *THE POTOMAC ESTUARY MATHEMATICAL MODEL* (1968); R. BUNCE & L. HETLING, *A STEADY STATE SEGMENTED ESTUARY MODEL* (Federal Water Pollution Control Administration Technical Paper No. 11, 1967); L. HETLING, *SIMULATION OF CHLORIDE CONCENTRATIONS IN THE POTOMAC ESTUARY* (Federal Water Pollution Control Administration Technical Paper No. 12, 1968); QUIRK, LAWLER & MATUSKY, *HUDSON RIVER WATER QUALITY AND WASTE ASSIMILATIVE CAPACITY STUDY* (1970) (a report done for the Div. of Pure Waters, N.Y. Dep't of Environmental Conservation); G. Schaumburg, *supra* note 38; WATER RESOURCE ENG'RS, INC., *A WATER QUALITY MODEL OF THE SACRAMENTO-SAN JOAQUIN DELTA* (1965) (a report conducted for the USPHS, Div. of Water Supply and Pollution Control, Region E); Hetling, *Water Quality Models of the Estuary*, in R. DAVIS, *THE RANGE OF CHOICE IN WATER MANAGEMENT; A STUDY OF DISSOLVED OXYGEN IN THE POTOMAC ESTUARY* (1968) (appendix A); Mamelak & Radziul, *Time-Varying Dissolved-Oxygen Model, Discussion*, 95 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 365 (1969); Morris & Pence, *supra* note 25; O'Connor, St. John & Di Toro, *Water Quality Analysis of the Delaware River Estuary*, 94 PROCEEDINGS OF THE AMERICAN SOCIETY

20,000 feet in length. The DO level in each section is calculated by the use of two equations—one computes the BOD load on the section; the other describes the amount of DO both entering and leaving each section. To determine the BOD load in each section, the model requires data that accurately describe the amount of BOD dumped by each pollution source on the river. This information alone, however, is insufficient for the purposes at hand. Even if we knew, for example, that industrial and municipal sources discharge 50,000 pounds of BOD per day in section 3, we must know several other facts before we can predict the amount of BOD that section 3's discharge contributes to section 4. First, it is necessary to determine the rate at which the 50,000 pounds per day of BOD are being oxidized: if 10,000 pounds are oxidized in section 3, only 40,000 pounds will move on to section 4. Indeed, as we have already indicated, it is overly simple to use a single rate of oxidation (often called the "decay rate") for all BOD materials, since the rate at which nitrogenous oxidation occurs differs from carbonaceous. Even after we have determined the decay rates for FSUOD and SSUOD, however, our task will still not be completed. To know the impact of the pollution discharged into section 3 upon water quality in section 4, one must determine the rate at which BOD is moving from one section to the others. The rate of movement in turn is a function of two different factors: first, the faster the flow downstream the faster BOD will flow in that direction; secondly, if BOD is more concentrated in section 3 than section 4, there will be a natural tendency for it to diffuse into section 4. (Engineers call this latter process "advective transport."⁵³) Thus, it is necessary both to know the flow rate and to have some measure of the speed at which advective transport is taking place between sections. Using FSUOD and SSUOD decay rates, as well as stream flow rates and a coefficient measuring advective transport, the Thomann model not only predicts

OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 1225 (1968); Pence, Jeglic & Thomann, *supra* note 39; Pence, Jeglic & Thomann, *Time-Varying Dissolved-Oxygen Model, Closure*, 96 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 179 (1970); Thomann, *Mathematical Model for Dissolved Oxygen*, 89 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 1 (1963); Thomann, *Systems Analysis and Simulation in Water Quality Management*, in PROCEEDINGS OF THE IBM SCIENTIFIC COMPUTING SYMPOSIUM ON WATER AND AIR RESOURCE MANAGEMENT 223 (1968).

Despite this documentation, however, many substantial problems have never been canvassed in the published literature. The lack of complete documentation has made our task more difficult than it should have been. The failure to present a systematic and complete analysis of the Delaware stands in stark contrast to the 609 page report issued by a similar contemporaneous investigation of the Thames Estuary. See HER MAJESTY'S DEP'T OF SCIENTIFIC AND INDUS. RESEARCH, EFFECT OF POLLUTING DISCHARGES ON THE THAMES ESTUARY (1964) [hereinafter cited as the THAMES REPORT].

⁵³ The rate at which pollutants move between sections via advective transport is affected by tidal action within the estuary, and this effect is taken into account in the construction of the model.

the BOD impact that polluters in section 3 will have on section 4, but also predicts the BOD impact these polluters will have on each of the other sections in an analogous way. Similarly, using these same four factors, the model predicts the BOD load polluters on the other sections of the river will place on section 3. By doing all this simultaneously, a set of BOD concentrations in the river can be predicted, given discharges from municipal and industrial sources. Similarly, if BOD loads from storm sewers and tributaries, as well as their oxidation rates, are known, an analogous calculation can be made, and the concentration of BOD in each section can then be determined by summing the contributions from each of the four sources—municipalities, industries, tributaries, and storm sewers.⁵⁴

From this description, it should be reasonably clear that the following inquiries are necessary for an assessment of the accuracy of the model's first equation predicting BOD concentrations. How does the theoretical formulation deal with:

- (a) FSUOD and SSUOD decay rates?
- (b) storm sewer run-off and tributary loads?
- (c) flow and advective transport?

If the model deals with any of these factors improperly, it will systematically mis-estimate the impact of BOD discharges on the DO profile.⁵⁵

As we have already indicated,⁵⁶ the model's prediction of BOD concentrations in each of the thirty sections is only a preliminary step in the larger task of estimating the DO profile that can be expected from a given set of BOD loads. To move from BOD concentrations to DO profile, the DECS model must consider three factors that were irrelevant in the BOD prediction, and that are considered in the model's second equation concerning itself with DO inputs and outputs in each section. First, the DECS model must calculate the saturation level of oxygen at a given temperature; secondly, it must calculate the rate at which oxygen will diffuse into the river as BOD creates a DO deficit in the section; thirdly, it must take into account the fact that the sludge

⁵⁴ In the earlier discussion of BOD sources, a fifth source, benthic oxygen demand, was included. See text preceding note 34 *supra*. In Thomann's model, however, this source is considered in the second equation, which deals with DO levels, and so we shall discuss it at a later stage.

⁵⁵ In addition to the factors mentioned in the text the model also contains a term that attempts to account for the impact on the DO curve of oxygen generated by photosynthetic activity. The DECS, however, proceeded on the premise that no net oxygen demand was exerted by this force. We have already suggested, however, that this resolution of the problem is subject to serious question. See note 42 *supra*.

⁵⁶ See text accompanying note 52 *supra*.

deposits on the bottom of each section of the river continually consume oxygen in the way we have described.

There is little difficulty in measuring the solubility of oxygen in water, and hence the model's value for the saturation concentration of dissolved oxygen at a given temperature poses no serious problem. The same cannot be said for the other two steps by which the model moves from BOD concentration to DO prediction, and thus we shall consider the treatment of (a) reaeration and (b) benthic demand in detail.⁵⁷

C. The Steady State Assumption

Using the DECS BOD-DO model, it is *in principle* possible to predict the Delaware's DO profile at any point in time. Of course, if the policymaker wishes to predict the DO profile for a particular day (say the July 4 peak vacation day), extensive data will be required by the model. Not only will it be necessary to hypothesize the flow, temperature, and BOD conditions prevailing on July 4, but it will also be necessary to assume that during the month before July 4 river conditions developed in a particular way, since the July 4 DO profile will in large measure depend on the pattern of temperature, flow-rate, and BOD discharges prevailing during the previous thirty days. Moreover, an effort to predict the way in which DO will vary with time requires a relatively high expenditure on computational facilities—for example, an attempt to trace the way the Delaware's DO profile varies over the year as a result of hypothesized *weekly* changes in temperature, flow rate, and BOD inputs will occupy a highly sophisticated "third generation" IBM 360/75⁵⁸ some thirty minutes. And, of course, before the policymaker could gain a modest insight into the probable effects over time of a given pollution control policy, a very large number of computer runs simulating a broad range of recurring river histories would be demanded.

To reduce the data base and computational resources required for a "time-varying analysis" the DECS primarily attempted to predict the DO curve on the hypothesis that the *relevant river conditions remained constant over time*. This approach is so common to modelling efforts of diverse kinds that it has its own name: the "steady state" approach. Unfortunately, things are far from steady on the estuary. First, BOD loads vary substantially from day to day and throughout the year. Secondly, so does the flow-rate. Thirdly, DO varies over the course of

⁵⁷ For those readers who would prefer a mathematical description of the model, we have provided an Appendix in which the matters discussed in the immediately preceding pages in an intuitively plausible manner are presented in a mathematical format.

⁵⁸ Interview with G. D. Pence, Jr., Delaware Estuary Comprehensive Survey Staff, in Edison, N.J., Oct. 1970.

the year, as the river's temperature moves from near-freezing to as high as 80°F. during the summertime. As the river gets colder, oxygen becomes increasingly soluble in water—for example, at 40°F. fully saturated water contains thirteen ppm of oxygen, while at 80°F., it contains eight ppm.⁵⁹ Thus, an oxygen-rich stream can oxidize much greater quantities of BOD during the winter without endangering aquatic life or generating noxious odors. Even if DO levels momentarily drop to a relatively low level, the river's capacity for recovery is much greater in the wintertime. This is because the farther away water is from saturation, the faster oxygen diffuses into the river to redress the imbalance. Thus, if DO is four ppm and saturation is sixteen ppm, oxygen will diffuse three times more rapidly into the river than if the saturation level of DO is eight ppm,⁶⁰ as it is during the summer. Finally, the microorganisms that consume BOD are much less active as water temperature declines. As a consequence, discharges of BOD are oxidized more slowly in the colder months, thereby permitting the increased rate of reaeration then prevailing to more rapidly counterbalance the oxidation process. For this reason the Delaware estuary has no substantial DO depletion problem during the wintertime. The oxygen sag is most acute from July through September, since these summer months are characterized by high water temperatures, low oxygen saturation levels, maximum biological activity, and minimum reaeration.

This situation permitted the DECS to attempt a "steady state" approach in analyzing important pollution problems. While it is fruitless to indulge in "steady state" thinking to predict DO levels prevailing *over the year*, if the model builder is willing to ignore all differences between any particular summer day and the average day for the summer, it is plausible to apply a "steady state" approach in an effort to predict average DO *throughout the summer*. Although this technique simplified the DECS factfinding problem, it inevitably introduced an

⁵⁹ See T. CAMP, *supra* note 25, at 292. The saturation solubility of oxygen in water is also a function of the water's salinity, though, according to DECS measurements, salinity effects are minimal in the Delaware. Letter from Prof. R. Thomann, Nov. 1971. See also THAMES REPORT, *supra* note 52, at 438.

⁶⁰ The appropriate differential equation may be written

$$\frac{d(C_s - C)}{dt} = -k_2(C_s - C)$$

where C_s represents the saturation concentration of DO, C represents the actual concentration of DO, and t represents time. In words, the equation states that the rate of change of the oxygen deficit ($C_s - C$) with respect to time is proportional to the negative of the difference between the saturation concentration of DO and the actual concentration of DO.

element of imprecision in the "steady state" model.⁶¹ As our analysis of the DECS equations proceeds, it shall become clear that "steady state" thinking has important policy implications that can be easily neglected by the factfinder anxious to reduce his own problem to manageable proportions. It is to the high credit of the DECS, however, that it did not (like so many other studies) simply ignore the limitations of the "steady state." In spite of the difficulties, the staff applied Thomann's general model in an effort to explore the implications of changing river conditions in those cases in which this seemed important to the rational formulation of policy. We shall assess the success of these efforts in our exploration of the model's structure and performance, which follows.

V. THE THOMANN MODEL: SOURCES OF ERROR

A. The BOD Equation

1. Treatment of Decay Rates

DRBC officials, using DECS data, report that in 1964 carbonaceous oxygen demanding materials dumped by industries and cities accounted for fifty-three per cent of the total BOD in the estuary, while nitrogenous oxygen demand from these sources represented twenty-two percent of the total BOD load.⁶² With the adoption of the new DRBC control program, however, the relative importance of carbonaceous demand (FSUOD) and nitrogenous demand (SSUOD) will shift dramatically since, under DRBC requirements, each of the firms and cities bordering on the estuary will be required within the near future to build "secondary treatment" facilities that reduce FSUOD by eighty-seven to ninety-three percent but that reduce SSUOD to a much smaller degree.⁶³ We must therefore scrutinize with special care the

⁶¹ The DECS reports that the standard day to day deviation around the summer average in a typical section of the river is 0.3 ppm. That is to say, if the DECS predicted the summer average DO concentration, the actual concentration would be within 0.3 ppm of this value on approximately 2 days out of 3 and would be within 0.6 ppm of this value on 95% of the days. Thomann, *supra* note 42, at 22. Given the methodological frailties in the DECS "verification" analysis, to be considered at text accompanying notes 115-29 *infra*, we have, however, little confidence in the reliability of this DECS estimate.

⁶² See Porges & Selzer, *supra* note 34, at 75, 80.

⁶³ Most "primary" and "secondary" treatment plants are designed primarily for the purpose of removing FSUOD. Measurements of the efficiency of SSUOD removal by 5 different treatment plants may be found in Barth, Mulbarger, Salotto & Ettinger, *Removal of Nitrogen by Municipal Wastewater Treatment Plants*, 38 J. WATER POLLUTION CONTROL FEDERATION 1208-18 (1966). The following table summarizes the results (in some cases, 2 test periods were selected):

manner in which the model predicts the impact SSUOD will have upon DO after the cleanup program is completed.

As we have explained, laboratory tests indicate that no substantial nitrogenous demand is exerted by untreated waste until approximately fifteen days after the substance is introduced into the water,⁶⁴ because a substantial period of time is required before nitrogen consuming bacteria reproduce in such numbers that a significant oxygen demand ensues. To take into account the delayed response time, the DECS treated the nitrogenous component of a discharge as if it occurred at a place farther down the river than its actual point of entry.⁶⁵

This procedure suffers from several important defects. First, unlike the laboratory, large numbers of nitrogen consuming micro-organisms already exist in the river before a given BOD sample is dumped, since they have been feasting upon prior nitrogenous discharges. Thus, it does not follow that the fifteen day nitrogenous lag observed in the laboratory will also take place in the river.⁶⁶ Moreover, subsequent investigators have explained the nitrogen lag phenomenon on more plausible grounds, with which the DECS model altogether

Plant	Period	Efficiency of Nitrogen Removal in %		
		Primary Treatment	Secondary Treatment	Overall Removal
A	I	9	57	61
B	I	-27	34	16
	II	2	20	22
C	I	5	8	13
	II	28	42	58
D	I	0	30	30
E	I	17	25	38
	II	19	8	25

The data indicate that treatment plants containing both primary and secondary phases removed from 13% to 61% of SSUOD, with the average removal being 33%.

⁶⁴ See text preceding note 33 *supra*; *id.* 1217 (Table V).

⁶⁵ The THAMES REPORT, *supra* note 52, at 212, provides a good statement of accepted doctrine concerning the delayed response of nitrogenous oxygen demand:

This [delayed response] is believed to be because the concentration of nitrifying bacteria initially present is usually small and because the rate of growth of these organisms is slow, especially when compared with that of the heterotrophic bacteria which oxidize carbon; the rate of oxidation of nitrite to nitrate is particularly slow in the initial stages since it tends to be limited by the rate of formation of nitrite from ammonia.

⁶⁶ Indeed, subsequent unpublished course materials prepared by Professor Thomann indicate that this assumption was faulty:

In the BOD test, there is a pronounced lag between the carbonaceous oxidation and the nitrification step, the latter following by as much as ten days. The lag is less for the treated samples and is on the order of one or two days for highly treated effluents. In the stream, the two stages frequently proceed simultaneously, although there may be lags in the nitrification stage in highly polluted streams, or those with low dissolved oxygen.

R. Thomann, Reactions, at 24, undated (section of untitled, unpublished materials on file in Biddle Law Library, Univ. of Pa. Law School).

fails to deal. O'Connor, in a 1966 study of the DECS model,⁶⁷ argues persuasively that the microorganisms that oxidize nitrogenous waste do not thrive in conditions in which large carbonaceous loads deplete oxygen levels greatly. Consequently, when carbonaceous loadings are reduced, nitrifying bacteria—whose growth was formerly frustrated—will flourish and generate substantial oxygen demand *in precisely those areas in which the DO deficit is currently most critical*. This means that as the current DRBC program succeeds, the predictive powers of the model will progressively deteriorate, since the nitrogenous share of total load will be increasing and the distribution of this load will be altered and move upstream into the area between Philadelphia and the Pennsylvania-Delaware state line, the area of maximum oxygen deficit, in ways that the model was powerless to predict at the time of the DRBC decision.⁶⁸

There is, then, not only a source of error in the model's structure but one that will systematically yield overly optimistic predictions as to the consequences of ambitious cleanup programs upon the DO profile, especially in the most polluted river sections. We have not attempted to develop alternative modes of dealing with SSUOD in an effort to determine precisely the degree of error involved in the DECS model, since such an attempt would require very extensive theoretical and empirical investigation. Nevertheless, the importance of even a moderate error cannot be underestimated when it is recalled that the model is being used to delineate the costs and benefits of alternative water quality programs that may differ by hundreds of millions of dollars in their cost but that differ only by one ppm in their impact on the DO curve in the most polluted sections of the Delaware.⁶⁹

In addition to the structural failures in the treatment of SSUOD decay, the DECS also utilized a questionable procedure in its attempt to measure the rate at which both FSUOD and SSUOD decayed in each section. The decay rate in each section was estimated from laboratory experiments upon samples of Delaware River water from that section.⁷⁰ This indeed seems to be a sound method for estimating decay rates as of 1964 (before the cleanup) except for a caveat we shall discuss in a

⁶⁷ D. O'Connor, *Water Quality Analysis of the Delaware River Estuary* 45, 1966 (an unpublished report made for the Industrial Subcommittee of the Technical Advisory Committee, Delaware Estuary Comprehensive Study, on file in Biddle Law Library, Univ. of Pa. Law School).

⁶⁸ *Id.* 51-52.

⁶⁹ Further work on this problem has been attempted subsequent to the publication of the "preliminary" DECS Report of 1966 and the DRBC decision of 1967. See text accompanying note 154 *infra*. Our concern at this point in the essay, however, is to analyze in detail the validity of the information provided to the decisionmakers at the time they made their decision.

⁷⁰ Interview with G. D. Pence, Jr., Delaware Estuary Comprehensive Survey Staff, in Edison, N.J., July 1970.

footnote.⁷¹ But what of the situation after cleanup? There is no reason to believe that a decay rate for a given section in 1975, after cleanup measures are taken, will equal the decay rate in 1964. The best evidence available indicates that the more treatment wastes receive before entering the river, the slower they will decay thereafter.⁷² Thus, as pollution loads on the river decrease, the decay rates will probably be less than those found formerly. The effect of this will be to shift the oxygen sag downstream, though to what extent we cannot guess.

2. Combined Sewers and Raw Sewage

Four percent of the total BOD discharged into the river during the year is contributed by the raw sewage discharged during heavy rains by the combined sewer systems operated in Trenton, Camden, Philadelphia, and Wilmington.⁷³ The relatively small annual contribution from this source, however, grossly understates its importance in policy formulation. For the sewers do not discharge relatively small amounts of effluent continuously, but enormous quantities sporadically. Since the sewers overflow about ten days a year,⁷⁴ the four percent *annual* percentage means that the total BOD contributed by raw sewage during and after a stormy period can exceed the BOD from all other sources combined.⁷⁵ Moreover, the bulk of these untreated wastes will be emitted by Philadelphia and Camden, thereby threatening oxygen reserves at the core of the "critical area" already characterized by severe oxygen depletion. Thus, it is of prime importance to a decisionmaker to understand the impact raw sewage will have on DO on those occasions on which it is present in quantity. Indeed, if the model builder only provided the summer *average* DO to be anticipated in the critical region, in the manner conveyed by Table 2, the information could be profoundly misleading. For example, Table 2 reports that pollution Program II (costing \$250 million) will achieve an *average* DO of four ppm during the summer, while Program III (costing \$120 million)

⁷¹ The caveat centers upon the DECS assumption that the river water samples measured in the laboratory decay in the same manner as they would under river conditions. Two leading authorities point out that the assumption that the rate of consumption of organics in laboratory equipment is equal to the rate of consumption in natural waste "overlooks the fact that the biophysical as well as the biochemical environment of BOD bottles cannot possibly be like that of every kind of stream, even when the temperature of incubation of the bottles is that of the stream water." G. FAIR & J. GEYER, *WATER SUPPLY AND WASTE-WATER DISPOSAL* 835 (1954). Nevertheless, these authors claim that, in general, there seems to be a relatively good correlation between river and lab decay rates, as well as between laboratory and river BOD consumption rates. *Id.* 835-36.

⁷² THAMES REPORT, *supra* note 52, at 216, 226.

⁷³ Text accompanying notes 35-36 *supra*.

⁷⁴ Text accompanying note 35 *supra*.

⁷⁵ See detailed discussion to be found in notes 80-81 *infra*.

will achieve an average DO of three ppm. Thus, on the surface, the more expensive program seems to promise more varied forms of aquatic life even in the heavily polluted region. If, however, the intermittent discharge of raw sewage will for sustained periods reduce DO levels to two ppm under Program II and one ppm under Program III, the more expensive program's promise of a more extensive aquatic life will in large part be illusory, since living things must breathe all of the time, not most of the time. On the other hand, it *may* be that Program II will assure varied aquatic life even during the intermittent inundations of raw sewage while Program III will not. But if there is a real difference between the two programs in this respect, it surely is not obvious. It is precisely issues of this kind that led decisionmakers to search for expert factfinders in the first place.

Despite its importance for the rational formulation of policy, the DECS "steady state" model was incapable of treating the storm overflow problem in a way that would clarify its dimensions. For it should be recalled⁷⁶ that the fundamental limitation of a "steady state" model lies precisely in its assumption that river conditions remain constant over time. Given this framework, the "steady state" model builders, in making their predictions, were forced to assume that the sewers were *constantly* emitting a BOD flow equal to four percent of the total loading. Consequently, the "summer average" DO level DECS associated with each of the proposed programs slightly understates the DO that could be anticipated during dry spells but grossly overstates the impact of pollution control during and after heavy rains. Thus, "steady state" thinking could easily induce policymakers to overestimate the benefits of embarking upon any of the programs under consideration: it obscures the probability that *none* of the programs under consideration would significantly alter environmental conditions *unless the sewer problem were resolved*. Once this possibility is raised, its policy implications can be seen to have critical importance. If it is necessary to eliminate the storm sewer problem in order to generate substantial environmental improvements in the "critical sections," the costs of "meaningful" pollution control become enormous. "Solving" the raw sewage problem would require a city like Philadelphia to rip up most of its busy streets and replace the present sewer piping system with one that would prevent raw sewage from sweeping into the Delaware during heavy rains. To accomplish this objective, it would be necessary to segregate sanitary sewage from rain water runoff by placing wastes in a completely separate piping system from the one used to transport

⁷⁶ Notes 60-61 *supra* & preceding & accompanying text.

rainwater. In this two pipe system, which is common in more recently developed communities, municipal treatment plants are not overloaded with rainwater for the simple reason that the rain pipes conduct the relatively unpolluted runoff to the river directly. Since the water in the pipe carrying domestic and industrial waste does not expand during the stormy periods, it is perfectly feasible for the city plant to treat the waste on foul, as well as fair, days before discharging it into the river. While installing a two-pipe system would "solve" the raw sewage problem, such a solution would not only cause Philadelphia's inhabitants substantial inconvenience but would cost the public fisc a sum in excess of a billion dollars.⁷⁷ Are costs of this magnitude worth the benefits to be gained when even after the sewer problem is "solved," it is far from clear that the river's "critical" section will be a pleasant place for swimming, let alone a refuge for the sensitive man seeking communion with nature, undisturbed by the vulgar evidence of urban industrialism? If, however, the costs of installing new piping systems far exceed the benefits, what is the justification for embarking on *any* of the cutback programs tendered by DECS to DRBC? Is there any reason to believe that, *absent the elimination of raw sewage*, the reduction of BOD from other sources contemplated by Programs I or II or III or IV will significantly improve the bleak environmental picture in the "critical" region? Unless there is a thoroughgoing effort to clean up the Delaware, will half-measures, however expensive, make a real difference? When faced with the costs of a thoroughgoing effort, do we still want to clean up the "critical" region? These fundamental questions can be avoided only by remaining within the confines of "steady state" thinking; for once the intermittent flood of raw sewage is treated as if it were a constant trickle, the policy problems evaporate.

While the cost-benefit analysis presented in Table 2 does not transcend the "steady state" approach and hence fails to consider these basic questions, the DECS scientific staff, led by Dr. Thomann, attempted some "time varying analyses," which cast light on the importance of the storm run-off problem. For example, the staff's model predicted that a sudden temporary impulse of 200,000 pounds of BOD introduced into section 15 (in the middle of the river's "critical region") would induce a temporary decline of .15 ppm of DO in that section dur-

⁷⁷ The costs of separating the combined sewer systems presently serving some 60 million Americans are enormous, with estimates seeming to cluster around the \$50 billion figure. See 2 COUNCIL ON ENVIRONMENTAL QUALITY, ANNUAL REPORT 145 (1971); Starr & Carlson, *Pollution and Poverty: The Strategy of Cross-Commitment*, PUBLIC INTEREST, Winter 1968, at 104, 122. While no solid estimates for Philadelphia have been developed, we have encountered no knowledgeable observer who would dispute the billion dollar price tag suggested in the text.

ing the following week.⁷⁸ The DECS staff, however, nowhere suggests that storm run-off will be limited to a mere 200,000 pounds when it occurs.⁷⁹ Rather, as we have suggested, DECS data indicate that a heavy storm may induce *an impulse far in excess of 1.2 million pounds of FSUOD per day in the "critical region."*⁸⁰ Thus, if the four ppm *summer average* predicted for the "critical region" by the DECS "steady state" model *had been correct in all other respects*, a "time varying" analysis would imply that during the week after a heavy storm, DO in the Philadelphia metropolitan area could plummet to three ppm or even less.⁸¹ Unfortunately, while the DECS "time varying" effort itself suggested the seriousness of the storm sewer problem, the implications of its analysis were not articulated in the "preliminary" report tendered to decisionmakers in 1966.

⁷⁸ DECS, *supra* note 11, at 41 (Figure 29). The maximum decrease in DO is predicted to occur some 2 or 3 days after the 200,000 pounds is introduced into the system. Of course, the discharge in section 15 also has a significant impact in other sections. For example, the maximum decrease in DO in section 18 is .1 ppm and occurs 5 days after discharge; while in section 24 (downstream from the "critical zone" of oxygen depletion) the maximum impact is about .02 ppm some 2 weeks after the discharge.

⁷⁹ In discussing these findings in its 1966 Report, the DECS does not even refer to the problem posed by raw sewage runoff. Rather, its calculation of a .15 ppm DO decline is premised upon the analysis of a "short duration discharge such as an accidental spill." *Id.* 41.

⁸⁰ We arrive at this conclusion by 2 different complementary routes. DECS indicates that, at present, Philadelphia's 3 major plants discharge 450,000 pounds of FSUOD per day *after the waste is treated by presently existing processes* that remove approximately half of the FSUOD. Thus, when a major rainfall requires the plants to dump their wastes without treating them, it is reasonable to expect an added impulse of 450,000 pounds of FSUOD per day to be imposed upon the system. Moreover, the organic debris on the city's streets will also be swept into the river without treatment, adding an unknown but surely very substantial BOD input. Similarly, Camden's 2 plants, after treatment (of about 50%), discharged 62,250 pounds in 1964 and so can be expected to impose an extra impulse of 62,500 pounds during storms, together with a substantial addition contributed by street debris. Thus, *under 1964 conditions*, BOD well in excess of 600,000 pounds of FSUOD will be introduced by Philadelphia and Camden. Under the pollution control program adopted by the DRBC (a variant of Program II in Table 2), however, both cities will be required to reduce FSUOD by 85% to 90% instead of 50%. Thus, when treatment is made impossible by storm overflow, these cities will contribute each day of the storm an added impulse of *1.2 million pounds of FSUOD plus the very considerable quantity of street debris flushed into the river by the rain.*

An even more depressing conclusion can be reached by considering another set of DECS data. Since it is reported that storm overflow accounts for 4% of the annual load on the estuary, and since it is also reported that overflow occurs approximately 10 times a year, Porges & Selzer, *supra* note 34, at 75, 80, simple mathematical calculation indicates that the impulse of untreated sewage for an average storm will be 2.5 to 3 million pounds of BOD. Since the vast majority of these wastes will be contributed by Philadelphia and Camden, the consequences of the storm sewer problem seem more serious than even the prior discussion suggests.

⁸¹ Since the model's equations are linear, *see Appendix infra*, there is no difficulty in assuming, as does the text, that if 200,000 pounds of BOD depresses DO by .15 ppm, 1.2 million pounds will depress DO by exactly 6 times that amount.

It is also true that not all of the storm overflow will be imposed in only one of the estuary's "critical sections;" nevertheless, it is clear that the bulk will be imposed over no more than a 6 or 7 mile stretch of the river, and it is equally clear, *see note 78 supra*, that this distance will not substantially ameliorate the storm runoff's impact on DO.

3. Loads Imposed by non-Estuarine Branches of the Delaware Basin

A similar defect afflicts the DECS treatment of the loads imposed on the estuary by the Upper Delaware⁸² and the tributaries to the main stem. DECS reports that in 1964 twelve percent of total FSUOD was contributed by these sources.⁸³ Once again, however, these loads do not remain constant over time; there is a periodic cycle in which BOD inputs reach an annual peak between April and June as a result of the normal springtime thaw. Thus during April of 1964 the Upper Delaware dumped an average of 168,500 pounds of FSUOD each day; during the month of August only 40,200 pounds was discharged.⁸⁴ Nevertheless, the DECS used an annual average to express the load placed on the river in its mathematical model. The significance of ignoring seasonal variations of such substantial dimensions can be appreciated when it is recognized that the entire city of Philadelphia, which contributed some forty-five percent of the carbonaceous load dumped by all of the cities and firms along the estuary in 1964, is limited to 131,500 pounds of FSUOD under the allocation plan adopted by the DRBC.⁸⁵ Similarly, "steady state" thinking assumed away the fact that BOD discharges from the tributaries can be expected to be especially severe during stormy periods when debris from city streets and rural countryside is flushed into the river system.

The DECS treatment of the tributaries and Upper Delaware was defective in yet another respect. Our inspection of unpublished DECS documents reveals⁸⁶ that the study assumed that in this case SSUOD was equal to FSUOD. From all that appears from even the unpublished documentation—which is inadequate—no data exist to support this

⁸² It is not clear exactly what figure was used by the DECS to represent the average load imposed by the upper Delaware upon the estuary at Trenton. While the published literature indicates that 22,000 lbs. was used as the FSUOD loading, *see* table at note 40 *supra*, there has clearly been an omission of a large load of approximately 86,000 lbs. in the tributary inputs listed in the table, since the individual loads do not sum up to the total load. Contradicting the published work, an unpublished chapter of the final DECS Report indicates the existence of an FSUOD load at Trenton of 84,993 lbs. and an SSUOD load at Trenton of 84,593 lbs. When we inquired at the DRBC concerning this substantial discrepancy we were told that the initial loadings used were corrected upward. It is unclear, however, whether any effort has been made to chart the DO consequences of this substantial adjustment of BOD inputs.

⁸³ Note 37 *supra* & accompanying text.

⁸⁴ FEDERAL WATER POLLUTION CONTROL ADMINISTRATION, U.S. DEP'T OF THE INTERIOR, DECS REPORT NO. BDZ (basic stream quality data sheets nos. 27 & 28) (estimates based on unpublished data from Water Resources Div., Geological Survey, U.S. Dep't of the Interior, undated (available in file no. 4639, Trenton, New Jersey)).

⁸⁵ Unpublished table of waste load allocations provided by the DRBC, on file in Biddle Law Library, Univ. of Pa. Law School.

⁸⁶ These documents have been made available to us by an anonymous non-governmental source.

assumption.⁸⁷ Thus, once again, the DECS treatment of nitrogenous demand appears to suffer from an overly large dose of simplification.⁸⁸

4. The Data Base Sources for Error

To test the reliability of its model, the DECS staff attempted to "predict" the then existing DO profile on the basis of the BOD inputs being exerted upon the estuary. To undertake this task, it was necessary to embark upon a systematic monitoring program of the BOD loadings imposed by cities, tributaries, the Upper Delaware, and the sludge. While we do not have adequate information to permit a fair assessment of the way in which the DECS monitored the BOD levels from many of these sources, we can consider the effectiveness of the program that measured the FSUOD and SSUOD dumped by the cities and municipalities along the river during 1964.⁸⁹

The DECS selected forty-four of the largest polluters, whose waste-loads accounted for more than ninety percent of all industrial and municipal effluent, for sustained analysis. DECS did not carefully measure the BOD loads of middle-sized and small municipalities included in their sample but, rather, derived their imputed BOD loads by using a rule-of-thumb formula, which as we shall see in a subsequent essay, was extremely imprecise.⁹⁰ Moreover, in addition to biochemical oxygen demand, certain large plants discharge large quantities of chemicals that

⁸⁷ Professor Thomann explains that the 1:1 ratio of FSUOD to SSUOD is "generally supported" by available sanitary engineering literature. Letter to the authors, Nov. 1971. However this may be, the ratio is not supported by empirical study of the relevant tributarial conditions, and it does not seem consistent with the FSUOD-SSUOD ratios that were generated by measurements on the Delaware's main stem, which suggested that SSUOD played a smaller role than is implied by the 1:1 relationship.

⁸⁸ The reader will recall that the model also attempts to relate flow and advective transport to the distribution of BOD concentrations on the estuary. Text accompanying notes 53-54 *supra*. So far as flow is concerned, no significant conceptual or measurement problems arise. Although many problems arise in the treatment of advective transport, these problems may safely be ignored by the average reader, since DO predictions are insensitive even to large changes in the advective transport coefficient. Telephone conversation with R. A. Norris of Quirk, Lawler, and Matusky, Consulting Engineers, N.Y., N.Y., Aug. 1970; interview with N. Jaworski, Middle Atlantic Region FWQA, in Annapolis, Md., Aug. 1970; interview with G. D. Pence, Jr., Delaware Estuary Comprehensive Survey Staff, in Edison, N.J., July 1970. For a more detailed discussion, see L. HETLING, *SIMULATION OF CHLORIDE CONCENTRATIONS IN THE POTOMAC ESTUARY* (Federal Water Pollution Control Administration CB-SRBP Technical Paper No. 12, 1968); *Dispersion Coefficient in the Delaware River Estuary as a Function of Fresh Water*, 6 WATER RESOURCES RESEARCH 516 (1970); R. Paulsen, *The Longitudinal Diffusion Coefficient in the Delaware River Estuary as Determined from a Steady-State Model*, 5 WATER RESOURCES RESEARCH 59 (1969).

⁸⁹ The program is explained in DECS, *supra* note 11, at 20-23.

⁹⁰ Unpublished documents indicate that the formula was: (number of inhabitants within service area) (0.286) = FSUOD.

react directly with dissolved oxygen in the water, thereby causing an additional depletion of DO. This factor was not taken into account.⁹¹

5. The BOD equation: The Proof of the Pudding

Our discussion of the defects in the basic BOD equation, in the DECS estimation of the decay coefficients, and in its measurement of BOD inputs leads us to the conclusion that the model's estimation of BOD loads in each section will have a very substantial error when it attempts to predict the summer average BOD concentrations prevailing at the time of the DECS study. While there are elements in the DECS approach that may overestimate the amount of BOD afflicting the estuary during the summer months,⁹² the BOD analysis as a whole is unduly optimistic in its appraisal of the possibilities of cleanup. Especially in its treatment of nitrogenous demand and the raw sewage discharged by combination sewers the analysis conceals highly important factors that may well erode substantially (or entirely) the benefits anticipated from the various program options proffered by the DECS to the political actors on the DRBC.⁹³ Given the limited resources at our command, we have been unable to undertake the substantial work required before a precise estimate of the model's error could be attempted. We are aware, however, of one study in which a skilled investigator has attempted to determine the extent to which the DECS model accurately predicts BOD. When Professor O'Connor considered this question in a 1966 paper, DECS provided him with all their data, thereby permitting him to determine in a reliable way the power of the model's BOD equation. When O'Connor compared the predicted and actual BOD profiles, he found extraordinary disparities between DECS estimates and the river's realities. We reproduce, opposite, the graph that best demonstrates the extreme discrepancies.

O'Connor's data demonstrate a consistent tendency of DECS to understate the magnitude of BOD concentrations in the estuary, providing additional evidence of the overoptimistic tendency we have adduced.⁹⁴

⁹¹ This is termed chemical oxygen demand. While this type of waste is not present in discharges from most plants, in at least 2 plants there is a large chemical oxygen demand; in some others there is a significant chemical oxygen demand. These statements are based on interviews with polluters along the estuary and from our inspection of files available at the Dep't of Environmental Resources in Harrisburg, Pa., and the Dep't of Environmental Protection in Trenton, N.J.

⁹² We refer to the likely change in decay rate after the DRBC's treatment program is effectuated, *see* text accompanying note 72 *supra*, and the use of an *annual* average to depict the impact of BOD introduced by the Upper Delaware on *summer* DO, *see* text accompanying notes 82-85 *supra*.

⁹³ *See* Table 2, text accompanying note 45 *supra*.

⁹⁴ O'Connor, *supra* note 67, Fig. 11. O'Connor notes that "The correlation of BOD data is observed to be unsatisfactory." *Id.* 48. He then adds, "However, if a background level of 2.0 mg/l, a value frequently observed above known sources of pollution at Trenton, is assigned to the system, better agreement would be realized."

FIGURE 5
COMPARISON OF ACTUAL AND PREDICTED BOD FOR AUGUST 1964

B. *The DO Equation*

Thus far, our analysis has focused on the first of the two equations used in the DECS model, whose purpose was to predict BOD concentrations along the estuary. On the basis of these BOD concentrations, the model's second equation calculates the DO concentrations to be expected. An analysis of this second equation (called the "DO equation") reveals two important additional sources of error.

1. Reaeration

In a river suffering an oxygen deficit, oxygen begins to move through the air-water interface, reducing the deficit over time until the saturation point of DO is reached in the river. One of the major tasks of the DECS DO equation is to describe accurately the rate at which this reaeration process takes place. Two major difficulties arise with the model's estimation of reaeration rate—one is of fundamental conceptual importance; the other involves the way in which reaeration is

Id. These 2 short sentences constitute the complete discussion of the discrepancy involved. Given the importance of ascertaining the reliability of the model's BOD predictions, this laconic discussion is extraordinary. Moreover, the suggestion that the model's predictive powers would be improved by adding an arbitrary constant of 2 ppm is advocating the use of a "fudge" factor well known in engineering circles. Such factors have 2 notable defects. First, they represent unexplained behavior in the system; it is more productive to recognize this harsh reality than to gloss over it. Secondly, fudge factors may not remain constant over time as O'Connor assumes. Even if one were to assign the 2 ppm background level as O'Connor suggests, one would have no way of knowing whether an identical constant should be assigned after cleanup activities have been completed. Thus, it is evident that the model predicts BOD behavior very badly, and the introduction of "assigned" factors, as suggested by O'Connor, would only make the problem worse. The way to handle "background BOD," if empirical data prove this concept tenable, would be to explicitly include it as a term in the model's predicting equations.

measured. As is often the case, the error in conception and the error in measurement are closely related.

The technical literature contains numerous proposed equations for the prediction of reaeration coefficients (constants reflecting the rate at which oxygen is replaced by aeration), yielding values that vary substantially from one another. DECS used values, for example, that were derived from a 1958 paper by O'Connor and Dobbins⁹⁵ and vary considerably from those proposed by more recent researchers.⁹⁶ We have provided the reader with a footnote illustrating these substantial differences in tabular form.⁹⁷

The differences in measurement, however, only suggest a fundamental conceptual problem. Overwhelming evidence developed by British investigators supports the intuitive notion that wind velocity at

⁹⁵ O'Connor & Dobbins, *Mechanism of Reaeration in Natural Streams*, 123 TRANSACTIONS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 641 (1958). The inference that the equation used by DECS was the one derived in this paper may be drawn from the fact that it was the reaeration equation used for the time varying model. See Pence, Jeglic & Thomann, *supra* note 39, at 381.

⁹⁶ P. Krenkel, *Turbulent Diffusion and the Kinetics of Oxygen Absorption* (unpublished dissertation, Univ. of Calif. Berkeley); Churchill, Elmore & Buckingham, *The Prediction of Stream Reaeration Rates*, 88 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 1 (1962). See also Krenkel & Orlob, *Turbulent Diffusion and the Reaeration Coefficient*, 88 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 53 (1962).

⁹⁷ As the following chart indicates, the reaeration rate is a function of channel depth and flow rate, among other factors.

Values of Reaeration Coefficients			
	O'Connor and Dobbins	Churchill	Krenkel- Orlob
For a deep channel (40')			
Velocity 1'/sec.	0.051	0.024	0.063
2	0.072	0.048	0.125
3	0.088	0.072	0.188
4	0.102	0.096	0.250
For a shallow channel (5')			
Velocity 1'/sec.	0.407	0.249	0.250
2	0.577	0.498	0.500
3	0.706	0.747	0.750
4	0.814	0.996	1.000

U.S. PUBLIC HEALTH SERVICE, A WATER QUALITY MODEL OF THE SAN JOAQUIN DELTA 44 (1965). The complexity of the process of estimating reaeration rates will be appreciated when it is noted that the depth of the Delaware Estuary varies from 16 to 34 feet. See Pence, Jeglic & Thomann, *supra* note 39, at 390. Flow velocities in the Delaware, at the Delaware Memorial Bridge, moreover, vary from -3 ft./sec. to +3 ft./sec. as a consequence of tidal action. See DECS, *supra* note 11, at 13. This further complicates the analysis.

Dr. Clifford Russell, of Resources for the Future, in his extremely useful written commentary upon an earlier draft of this essay, suggests that our criticism of the DECS's reliance on the O'Connor-Dobbins reaeration coefficients ignores the fact that the values for deep channels like the Delaware generally fall between the values given by the other 2 equations. While this is true, we do not find it overly comforting. Although the values do fall between the other 2 sets, there remains a very substantial disparity between the 3 equations, which remains extremely important given the admitted sensitivity of the DECS DO prediction to the particular reaeration coefficients selected.

the water's surface is a critical determinant of reaeration rate. When the wind was blowing at twenty miles per hour, oxygen entered the Thames more than five times as rapidly as when there was no wind.⁹⁸ Yet none of the estimates cited above consider wind velocity. Moreover, the O'Connor-Dobbins equation was derived principally from a study of non-tidal rivers.⁹⁹ Since "[i]n an estuary the adjustment for the effects of waves is likely to be of greater importance than in fresh-water streams,"¹⁰⁰ because of increased wind velocities and tidal action, the accuracy of the O'Connor-Dobbins equation in the context of the Delaware seems doubtful.

More is involved than the question whether the DECS equation is correct. At stake is the validity of the DECS assumption that reaeration can be described properly by the use of an equation not containing wind velocity as an independent variable. The Thames study, which was available to DECS, demonstrates that this assumption is untenable,¹⁰¹ and we are frankly at a loss to understand why the DECS never confronted the problem. Once the issue is articulated, it is apparent not only that wind velocity should be included but that no single reaeration coefficient can be expected to prevail in a given section at all times. Instead, a sophisticated approach would first attempt to determine the range of probable values associated with varying wind velocities on each section of the Delaware. Then, at a minimum, it would develop a co-

⁹⁸ THAMES REPORT, *supra* note 52, at 357-58.

⁹⁹ The equations for predicting the reaeration coefficient were based on theories of water circulation applicable only to non-estuarine rivers that experience neither tidal action nor heavy wave motion. Although nearly all verification of the reaeration coefficients predicted by the equation was based upon data from non-estuarine rivers, some data were used from San Diego Bay, and agreed with the predicted values rather well. An examination of the Thames Report on this problem suggests that the agreement between San Diego Bay data and the estimating equation is probably a coincidence. THAMES REPORT, *supra* note 52, at 569. A recent paper makes the DECS methodology appear even more vulnerable. Juliano, *Reaeration Measurements in an Estuary*, 95 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 1165 (1969), reports:

Extensive measurements and investigation of the reaeration constant and its controlling mechanisms suggests [*sic*] that surface reaeration in the Sacramento-San Joaquin Delta does not lend itself to mathematical definition. . . . [T]he writer feels that reaeration is best determined by methods which take into account each system's unique environmental conditions.

. . . .
Surface turbulence proved to be the most important factor controlling diffusion. Wind velocity is the most significant parameter causing surface turbulence. A specific wind velocity will result in varying degrees of surface turbulence depending on channel size and configuration, tidal phase, levee height, and wind direction. This accounts for the appearance of a more or less random variation in reaeration.

. . . The magnitude of surface reaeration is best determined by in situ measurements which consider the complex action and interactions of environmental factors effecting the reaeration constant.

Id. 1176-77.

¹⁰⁰ THAMES REPORT, *supra* note 52, at 569.

¹⁰¹ *Id.*

efficient based upon the average wind speed in the particular section under consideration. In fact, it would be possible to develop a more sensitive approach that would explicitly make reaeration a function of wind velocity. If this were done, one could give the administrator an indication of the range in which DO would fluctuate as wind speed changes. The importance of the DECS failure to conceptualize the reaeration problem properly, which led to the use of a questionable coefficient, is recognized once one takes into account the candid admission by the DECS staff, supported by the testimony of other experts who have worked with similar models, that the model's predictions are extremely sensitive to changes in the reaeration value.¹⁰²

2. Benthic Demand

The final component in the DO equation deals with the benthic oxygen demand resulting from sludge deposits on the bottom of the river. The model assumes that a pollution control program that reduces BOD loads from other sources does not affect the level of benthic demand. The load was 230,000 pounds in 1964, and it is assumed that it will remain so indefinitely.¹⁰³ While this is obviously a simplification, its speculative character is revealed by both the *Thames Report* and students of the Delaware who have worked independently of DECS. The English report reveals that sludge samples containing large numbers of a common worm ("tubificid" worms to be precise) exert an oxygen demand ten times that of an identical sample without worms.¹⁰⁴ At present, these worms exist in large numbers in the Delaware; they are plentiful enough to support the activity of local entrepreneurs who harvest the worms and sell some 600 gallons per day (272 million worms) to tropical fish stores as feed.¹⁰⁵ It would appear likely, therefore, that a substantial portion of the benthic demand may ultimately be traced to the oxygen requirements of the worms, which are one of the organisms that can live at extremely low DO levels. As oxygen levels increase as a result of the cleanup program, the number of worms may be expected to multiply, thereby radically increasing the benthic demand levels. As oxygen levels increase, the worms' natural predators may

¹⁰² Telephone conversation with R. A. Norris, Quirk, Lawler & Matusky, Consulting Eng'rs., N.Y., N.Y., Aug. 1970; interview with N. Jaworski, Middle Atlantic Region FWQA, in Annapolis, Md., Aug. 1970; interview with G. D. Pence, Jr., Delaware Estuary Comprehensive Survey Staff, in Edison, N.J., July 1970; Letter from R. Thomann, Nov. 1971.

¹⁰³ See note 40 *supra*.

¹⁰⁴ THAMES REPORT, *supra* note 52, at 205-06.

¹⁰⁵ G. Cox, The Role of *Limnodrilus spp.* (Oligochaeta) With Regard to Sediment Degradation and Secondary Pollution in the Delaware Estuary 91 (unpublished thesis, in Drexel University Library, Philadelphia).

also multiply in the area, killing off some of the worms and creating a new ecological equilibrium at which benthic demand will assume some new value, but even this is speculative.¹⁰⁶ Thus, the model's simplistic assumption that the benthic load will remain immutable is suspect. We are especially concerned that neither the DECS nor the DRBC has ever seriously considered the question despite the possibility that the worms will multiply exponentially to the detriment of the oxygen sag.¹⁰⁷

There is reason to believe that the DECS's failure to confront the worm problem not only has led to a faulty prediction as to the Delaware of the future, but has also permitted a misestimate of benthic demand in the river of today. Research by one of Professor Zemaitas' doctoral students, Dr. Geraldine Cox, indicates that the DECS staff measured benthic demand in samples containing no live worms.¹⁰⁸ This means that the 230,000 pounds of oxygen demand attributed to benthic demand by the federal study could be a serious underestimate of present conditions. The problem is made even more complex by the fact that, according to Dr. Cox, the worms are not distributed evenly throughout the river bed,¹⁰⁹ making a sophisticated biological survey a necessity if one is to have an accurate view of the problem.¹¹⁰

¹⁰⁶ Dr. Russell, of Resources for the Future, reports to us that an ecologist serving on the RFF staff, when questioned concerning the problem posed in the text, responded that, "If one is talking about increases in DO from near zero to, say, 2 or 3 ppm, it may be that the worm population would increase substantially. If, on the other hand, the expected increases are from 2 or 3 ppm to something higher, it is very likely that the growth of a predator population will result in a significant decrease in the worm population." Letter to the authors, Aug. 1971. We do not, of course, suggest that this is anything more than a guess, made without the intensive analysis that would justify even a modestly confident prediction. Nevertheless, the guess does seem to suggest the merit of further consideration, since—as we have suggested—it is far from clear whether DO will be higher or lower than 3 ppm after the present pollution program is effectuated.

¹⁰⁷ Professor Zemaitas of Drexel University believes this likely. Personal communications with Dr. Zemaitas, in Philadelphia, Pa., Aug. 1970, Sept. 1970, and Mar. 1971.

¹⁰⁸ Cox, *supra* note 105, at 70.

¹⁰⁹ *Id.* 70. This would help explain the fact that in the DECS samples the worms were not even considered a problem. Indeed, it is claimed that they were not present. Interview with G. D. Pence, Jr., Delaware Estuary Comprehensive Survey Staff, Dec. 1970. In his written comments on an earlier draft of this study, Professor Thomann, disagreeing with his DECS colleague, G. D. Pence, Jr., recollects that sludge worms were present in some of the sludge samples collected. Letter to the authors from G. Pence, Jr., Nov. 1971. It is not clear from Professor Thomann's commentary whether these worms were dead or alive when the oxygen demand of the samples was ascertained. However this may be, it remains clear that the DECS did not investigate the problem seriously.

¹¹⁰ In a memorandum to the Industrial Subcommittee of the DECS, one of the attachments summarizing a presentation delivered to the group by Dr. Thomann reported that the oxygen uptake rates of bottom material on the Delaware Estuary measured by the DECS were about half those reported in the literature. Memorandum from L. Falk, DECS, Technical Advisory Committee, Industrial Representative to U.S. Public Health Service, DECS, Technical Advisory Committee, Industrial Subcommittee, Sept. 30, 1965, at Exhibit B (minutes of Technical Advisory Committee meeting for Sept. 8, 1965).

VI. APPRAISING THE UTILITY OF THE MODEL

We have attempted in the preceding pages to give the reader a lively sense of the complex reality with which the model builders had to deal in their ambitious attempt to understand the Delaware and the many compromises they were obliged to make to complete their job within a reasonable amount of time. Our discussion of the limitations of DECS methodology and data should not be taken to deny the great scientific value of the project. After all is said and done, a relatively small staff at relatively low cost (\$1.2 million) within a relatively short time (four years from the beginning of actual study in 1962 to the first public report in 1966) constructed a model that was an effort at comprehensive understanding and has served as the basis of models developed for such estuaries as the Hudson,¹¹¹ the Potomac,¹¹² and the San Joaquin.¹¹³ Indeed, it is precisely the pathbreaking character of the investigation that gives importance to our question: given the fact that DECS represented the frontier of scientific research in 1966, to what extent did it help or hinder the decisionmaker in defining policy?

Apart from indicating the sources of error in the model's construction and in its data base, we have taken special care to focus upon those features that tended to lead the DECS to be either overly optimistic or pessimistic in their assessment of the impact alternative cleanup programs will have upon the river's DO profile. Our discussion of the DECS treatment of nitrogenous oxygen demand, raw sewage emitted by storm sewers, and benthic oxygen demand leads us to conclude that, in the aggregate,¹¹⁴ the DECS analysis substantially underestimated the difficulty of improving environmental quality in the so-called "critical region" of the estuary. Particularly troublesome is the fact that, at least so far as benthic and nitrogenous demand is concerned, the model's predictive powers will deteriorate with a substantial change of the status quo. Thus, the degree to which the model successfully explains the present DO profile does not constitute an entirely adequate indication of its utility to a policymaker who is principally concerned with the degree to which the model will successfully predict the future conditions that will result from the implementation of far-reaching pollution control measures. Nevertheless, the model's ability

¹¹¹ Telephone Communication with R. A. Norris, Quirk, Lawler & Matusky, Consulting Eng'rs, N.Y., N.Y., Aug. 1970.

¹¹² L. HETLING, *THE POTOMAC ESTUARY MATHEMATICAL MODEL* (1968); Hetling, *Water Quality Models of the Estuary*, *supra* note 52; Interview with N. Jaworski, Chesapeake Technical Support Laboratory, Middle Atlantic Region, FWQA, in Annapolis, Md., July 1970.

¹¹³ U.S. PUBLIC HEALTH SERVICE, *A WATER QUALITY MODEL OF THE SAN JOAQUIN DELTA* (1965).

¹¹⁴ For the countervailing factors, see note 92 *supra*.

to describe present conditions provides some indication of its trustworthiness as to the future, and so we shall investigate this matter in some detail.

DECS attempted to "verify" its model by comparing the actual DO profiles observed on the Delaware each week during the summers of 1964 and 1966 with the DO profile the model predicted would occur during these two summers.¹¹⁵ At no point in the DECS 1966 Report, however, was there any precise indication of the degree to which the model's 1964 predictions were erroneous.¹¹⁶ In our conversations with both state and DRBC officials, though, there seemed a broad consensus that the model's predictions had a "standard error" of .5 ppm.¹¹⁷ This means that the *predicted* summer average DO in each of the thirty sections would not diverge more than .5 ppm from the *actual* summer DO in about two out of three summers.¹¹⁸ On the basis of unpublished information provided us by the DECS staff, we have calculated the

¹¹⁵ To calculate the average DO profile on the river during 1964 and 1966, the DECS took weekly readings of the DO level prevailing in most of the river's 30 sections. It was then possible to derive a summer average for each section simply by calculating the arithmetic mean of the weekly samples tested. Unfortunately, the DECS definition of a summer changed between 1964 and 1966. In 1964, data collected during the months of June, July, and August were used for the verification analysis. In 1966, however, data collected during the months of July, August, and September were used.

We do not know for certain why the DECS definition of a summer changed over so short a time. However, as the following table shows, June 1966 was a relatively rainy month, in which the flow of the Delaware was quite high:

Flow Rate at Trenton (cfs)

	June	July	August	September
1964	4437	3102	2472	2136
1966	6215	2554	2484	2726

WATER RESOURCES DIVISION, U.S. DEP'T OF THE INTERIOR, GEOLOGICAL SURVEY, SURFACE WATER RECORDS OF NEW JERSEY 88 (1964); WATER RESOURCES DIVISION, U.S. DEP'T OF THE INTERIOR, GEOLOGICAL SURVEY, WATER RESOURCES DATA FOR PENNSYLVANIA: PART 1. SURFACE WATER RECORDS 47 (1966).

Given the DECS model's use of a steady state approach, if the DECS had tested its predictions in 1966 for the same months (June-August) as in 1964, the dissimilarity between the flow in June 1966 and that in July and August of 1966 would probably have dramatically increased the error in the model's predictions. Thus the shift in definition could conceivably have its source in a desire to put the model's reliability in its best light.

¹¹⁶ The clearest statement concerning verification to be found in the DECS Report states that the comparisons between predicted and actual results "indicate that the model can be used with a *sufficient* degree of accuracy." DECS, *supra* note 11, at 40 (emphasis added).

¹¹⁷ Interviews with state and DRBC officials who wish to remain anonymous.

¹¹⁸ The most common measure of error used by engineers to evaluate the validity of this sort of model is the "root mean squared error," or "standard error." It is defined as the square root of the sum of the squares of the differences between the predicted and actual values divided by the number of differences. For example, suppose we are examining a phenomenon that has successive average values of 1.0, 2.0, 3.0, 4.0, and 5.0. If our model predicts successively 1.0, 1.5, 3.2, 5.0, and 6.5, the differences are 0, -0.5, 0.2, 1.0, and 1.5. The squares of the differences are 0, 0.25, 0.04, 1.0, and 2.25. The sum of the squares of the differences is 3.54. And $3.54/5$ is approximately 0.71. Thus, the square root of 0.71, or about 0.84, is the "root mean squared error" for this example.

error with somewhat greater precision. The data provided by DECS indicates that during the summer of 1964, the staff took a weekly measurement of DO concentrations at virtually every one of the estuary's thirty sections. On the basis of these fifteen to twenty weekly samples, it was possible to calculate an average DO concentration prevailing during the summer at each of the thirty sections.¹¹⁹ When we compared the observed average with the predicted average, we found that the model's predictions had a "standard error"¹²⁰ of .46 ppm. In other words, if DECS predicted a DO level of 4.0 ppm in a section, the observed DO was between 3.5 and 4.5 about two times out of three. A graphic presentation of the data is given below.

The model's error is of the same order of magnitude if one concentrates exclusively upon the accuracy with which it predicted the summer average prevailing in sections 12-19, which experience the most acute oxygen shortage. Over these sections the model's standard error was .43 ppm.

For these "critical" sections, however, this value appears to overstate the model's accuracy. The key fact here is that it is physically impossible for DO to go any lower than zero ppm. Imagine, for example, that the model predicted a DO concentration of .5 ppm in section 18 and that the summer average in that section was observed to

¹¹⁹ Personal Communication with G. D. Pence, Jr., Delaware Estuary Comprehensive Survey Staff, in Edison, N.J., Aug. 1970.

¹²⁰ For a definition of this term, see note 118 *supra*.

be zero ppm. This does not imply that the error is only .5 ppm. For it may be that the section is so overloaded with BOD that even if some BOD is removed, the section will still register a zero DO level, despite the model's prediction that section 18 "should" have a DO concentration far greater than .5 ppm. Turning to the case at hand, a glance at the 1964 data indicates that the model has systematically overestimated the DO concentrations prevailing in the "critical" sections, and that many times, the DECS investigators observed a DO approaching zero in these areas. Thus, the model's .43 ppm error could well understate the extent to which its predictions diverge from reality.¹²¹

Up to the present point, we have assumed that the DO profile predicted by the model in 1964 constitutes an appropriate starting point for testing the accuracy of the model's predictions. This assumption must be discarded once the procedure DECS used to predict the 1964 DO profile is assessed. For the fact is that the DECS staff distorted its verification procedure in a way that deprived the "standard error" of .46 ppm of any significance to a decisionmaker attempting to assess the model's reliability. Instead of testing the model's predictions by comparing them with real world observations, the DECS staff *changed* the model's original predictions so that they would best *conform* to the observed DO data. When the DECS staff first compared their 1964 predictions with the actual results observed in 1964, before any "adjustments," they found a far greater disparity between predicted and actual DO, whose precise dimension we cannot report because the necessary data were not provided to us by the DECS and are not available in the published literature. The substantial disparity, however, did not convince the DECS that the basic structure of the model was misconceived or in any way incomplete. Nor was any attempt made to remeasure those independent parameters for which measurement errors could have been substantial.¹²² Rather, the DECS concerned itself exclusively with the possibility that the coefficients that related the variables to each other had been mis-estimated. Indeed, the concern was even narrower than this. As we have suggested,¹²³ the

¹²¹ Moreover, even if .43 were the correct figure, it would only establish that the average *weekly* deviation from the predicted *summer* average was .43 *for that summer*. This is a long way from the claim that the model will err by only .43 ppm in its prediction of a summer average *in 2 years out of 3*. For example, if a model predicts law school class attendance in 1964 to be 50 percent and actual average weekly attendance is between 45 and 55 percent approximately two-thirds of the time, it does not follow that this degree of accuracy will hold over the decade of the 1960's, particularly when law school conditions change substantially.

¹²² Examples are storm sewer overflows, *see* text accompanying notes 73-81 *supra*; benthic demand, *see* text accompanying notes 103-10 *supra*; tributarial loadings, *see* text accompanying notes 82-88 *supra*; and loadings from municipalities and industries, *see* text accompanying notes 89-91 *supra*.

¹²³ *See* text accompanying notes 64-72 *supra*.

coefficients used for the decay rate of nitrogenous oxygen demand (SSUOD) and the reaeration rates were both plagued with substantial uncertainty. Nevertheless, the DECS chose simply to determine whether the model's accuracy would be improved if the reaeration coefficients in the different sections were varied, ignoring SSUOD decay entirely.¹²⁴

Moreover, the DECS engaged in this effort in a highly imprecise way. If precision had been desired it would have been possible to determine the degree to which the reaeration rate had actually varied in the experiments that formed the basis for the DECS's original reaeration estimates. Then, DECS could have defined accurately the range over which the reaeration coefficient could be plausibly permitted to vary. Instead of undertaking this task, however, a large number of computer runs were made in accordance with the staff's intuitive notions as to the "reasonable" range of the coefficient involved in each of the estuary's thirty sections. From this quantity of computer printout, the staff chose the set of predictions that "best fit" the observations and adopted the coefficients that were a consequence of this selection.¹²⁵ Once again, however, the selection of the "best fit" was completely intuitive and without reference to standard statistical techniques.

These deficiencies in detail reflect an utter lack of sophistication in statistical analysis. There is no justification for arbitrarily selecting one of the large number of parameters—reaeration coefficient, SSUOD decay rate, benthic demand, municipal and industrial discharges, tributarial load—all of which must have a significant error attached to their measurement. For all one knows, the original reaeration coefficients chosen were the best possible set, and the entire error could be best explained by suitable variations in the other parameters. Indeed, it will not do simply to fiddle with any or all of the variables or coefficients in an effort to have the 1964 predictions closely fit the 1964 observations. There are countless combinations that would do this trick. A change in one coefficient can be offset by an equivalent and opposite change of another. To detect the correct relationship between all the coefficients in each of the thirty sections by observing the river, it would be necessary to have a very large number of observations that would permit the use of standard statistical techniques to estimate each of the coefficients with a tolerably small standard error. Even if this task were accomplished the results obtained would be biased since there are probably substantial errors in the measurement of independent variables

¹²⁴ Personal communication with G. D. Pence, Jr., Delaware Estuary Comprehensive Survey Staff, July 1970.

¹²⁵ Interviews with G. D. Pence, Jr., E. Smith, and A. Morris, all members of the DECS staff, June 1970; interview with G. D. Pence, Jr., Nov. 1970.

that represent the numerous BOD inputs into the system. That the DECS obtained a moderately close fit of the 1964 data by unscientifically adjusting a single coefficient does not in any way suggest that the model will predict with the same degree of accuracy DO levels prevailing in another year with another flow rate and another set of BOD loads.

In its second effort at "verification," the DECS staff attempted to determine the degree to which its model could successfully predict the DO profile in 1966.¹²⁶ Unfortunately, DECS had not attempted to conduct a systematic monitoring of BOD influents from point sources, tributaries, and sludge in 1966. Consequently the staff had little choice but to use their 1964 BOD inputs to predict the 1966 DO profile. This introduced an error of unknown dimensions into the analysis: even if the model had predicted the 1966 profile perfectly, one would not know how to assess this feat unless one were certain that BOD loads had remained constant. Even more important than this, the DECS staff was unable to test the accuracy of the model along the dimension that is most important to the policymaker. By using 1964 BOD loads, DECS disabled itself from reporting how well the model could predict DO under BOD conditions somewhat different from those in 1964. Yet this is the question in which the administrator is most interested since, after all, he wants the model to assist his decision on how much he should force polluters to cut back on their BOD discharges. While a model's ability to accurately predict the impact of small BOD changes on one occasion does not necessarily mean that it will similarly predict the impact of large changes in the DO profile resulting from an ambitious pollution control plan, it is at least a small step in the right

¹²⁶ The DECS has never explained why it did not also use 1965 data to test the model. It seems particularly important that this be done since one of the major parameters in the model is the flow rate, and flows differed markedly in 1965 from those that prevailed in either 1964 or 1966. In 1964, the average flow rate at Trenton for July and August was 2787 cubic feet per second (cfs). WATER RESOURCES DIV., U.S. DEPT OF THE INTERIOR, GEOLOGICAL SURVEY, SURFACE WATER RECORDS OF PENNSYLVANIA 41 (1964). In 1965, it was 1678 cfs. WATER RESOURCES DIV., U.S. DEPT OF THE INTERIOR, GEOLOGICAL SURVEY, WATER RESOURCES DATA FOR PENNSYLVANIA: PART 1. SURFACE WATER RECORDS 42 (1965). In 1966, however, average flow was 2519 cfs, closely resembling 1964. WATER RESOURCES DIV., U.S. DEPT OF THE INTERIOR, GEOLOGICAL SURVEY, WATER RESOURCES DATA FOR PENNSYLVANIA: PART 1. SURFACE WATER RECORDS 47 (1966). Thus a proper "verification" run on 1964 and 1965 data would have been far more revealing than a verification for 1964 and 1966. Similarly, verification runs on the three years following 1966 would have been illuminating since the average flow rates at Trenton for the months of July and August were 7859 cfs in 1967, 5745 cfs in 1968, and 4821 cfs in 1969. (The 4821 cfs given for 1969 is for the first 20 days of the period. After that, a deluge raised the average flow rate for the entire period to 13,320 cfs.) WATER RESOURCES DIV., U.S. DEPT OF THE INTERIOR, GEOLOGICAL SURVEY, WATER RESOURCES DATA FOR PENNSYLVANIA: PART 1. SURFACE WATER RECORDS 47 (1967); WATER RESOURCES DIV., U.S. DEPT OF THE INTERIOR, GEOLOGICAL SURVEY, WATER RESOURCES DATA FOR NEW JERSEY: PART 1. SURFACE WATER RECORDS 99 (1968); Water Resources Div., U.S. Dep't of the Interior, Geological Survey (unpublished figures on file in Biddle Law Library, Univ. of Pa. Law School).

direction. The DECS use of 1964 BOD data in its 1966 "verification" prevented it from making even this first small step. Moreover, other river conditions prevailing during the summer of 1966 happened to resemble quite closely those that had obtained in 1964,¹²⁷ when the equations were fiddled to obtain the "best possible" results. Thus, it should prove no surprise that the typical error in the model's predictions was only somewhat greater in 1966 than in 1964, with a "standard error"¹²⁸ of .63 ppm when all sections are reported¹²⁹ and with a smaller .47 ppm error when the comparison is limited to the model's predictions of DO concentrations prevailing in the zone of maximum oxygen depletion.

VII. ASSESSING THE DECS ANALYSIS OF PROPOSED POLLUTION PROGRAMS

All this means that if the decisionmaker was to gain any sense of the model's accuracy, it would have been necessary for him to move beyond the DECS presentation and insist that the staff report the disparity it found between actual and predicted DO profiles before it began distorting its procedures to obtain the set of predictions that "best fit" the observed data. Whatever the defects in the original coefficients (and we have shown that they are substantial) at least they were not manipulated for the purpose of putting the model in the best possible light.

Even if this disparity were known, however, it would not be of much significance to the policymaker wishing to chart the future course of pollution control on the Delaware. As we have seen, the model's power to predict the consequences of adopting ambitious cutback plans will be significantly worse than its ability to predict conditions like those presently prevailing on the river. Thus, given the various kinds of

¹²⁷ For flow rate comparisons, see note 126 *supra*. Temperature of the water at Trenton during the 2 years follows:

Delaware River Water Temperature—Trenton

	June	July	August	September
1964	72	78	75	72
1966	73	79	77	70

WATER RESOURCES DIV., U.S. DEP'T OF THE INTERIOR, GEOLOGICAL SURVEY, WATER QUALITY RECORDS IN PENNSYLVANIA 24 (1964); WATER RESOURCES DIV., U.S. DEP'T OF THE INTERIOR, GEOLOGICAL SURVEY, WATER RESOURCES DATA FOR PENNSYLVANIA: PART 2. WATER QUALITY RECORDS 27 (1966).

¹²⁸ For a definition of the term "standard error," see note 118 *supra*.

¹²⁹ The 1966 exercise is further compromised by the comparison of the model's predictions to the actual facts in only the central portion of the estuary, between sections 6 and 19. No attempt was made to determine the extent to which the model could predict accurately the conditions prevailing between Trenton and Burlington, and between Marcus Hook and the Delaware Bay. Since the 1964 verification indicated that the model's error was greatest in sections 1 and 7 (between Trenton and Burlington), graph following note 120 *supra*, it is likely that the error indicated in the text is an understatement.

error afflicting the model's predictions, it would not at all be surprising that the DECS forecasts of the DO impact of pollution control programs in the "critical" sections could have a "standard error" that was in excess of one ppm rather than the .46 ppm generated by the 1964 "verification" analysis.¹³⁰ The model's predictions not only contain a substantial error, but there is reason to believe that its predictions will consistently err toward an overly optimistic assessment of the impact of the pollution control programs under consideration.¹³¹ A reader sensitive to these factors will look with new insight at the table, reproduced for a third time, which best capsulates the DECS analysis:

TABLE 3

<i>Average DO in Most Polluted</i>		<i>High estimate-low estimate of benefits</i>	
<i>Program</i>	<i>Region</i>	<i>Cost</i>	
I	4.5	\$460 million	\$355-\$155 million
II	4.0	250 million	320- 135 million
III	3.0	120 million	310- 125 million
IV	2.5	80 million	280- 115 million

Instead of a set of predictions that nowhere indicate substantial uncertainty as to whether a given program of BOD cutbacks *will* lead to a given DO objective, would not the DECS effort have been far more useful to decisionmakers if the staff had appended the following caution to its presentation?

WARNING TO DECISIONMAKERS. When we report that Program II will lead to an average DO of 4.0 ppm during the summer in the "critical" sections of the river, we wish to emphasize that during periods of heavy rain, DO levels will be far lower for substantial periods as a result of the discharge of raw sewage from Philadelphia and Camden. It may well be that forcing cities and firms to reduce their output of FSUOD will not improve the DO profile as much as we expect because more SSUOD will then be exerted in the "critical" sectors; also, it may well be that the worms inhabiting the river sludge will increase in population and consume much of the oxygen that the BOD cutback program is intended to restore to the Delaware's waters; also, despite the fact we botched our "verification" procedures, decisionmakers should recognize that the model consistently predicts a higher DO concentration for the critical sections than the observed data

¹³⁰ We can only rest this claim on intuition, given the absence of data. For a somewhat more precise, but far from adequate, manner of assessing the model's reliability, see Appendix *infra*.

¹³¹ Text accompanying note 114 *supra*.

indicate, thereby suggesting again that our predictions have an overly optimistic bias.

Even if none of these tendencies toward overoptimism materialize, you should know that we would not be surprised if Program II, which promises a DO level of 4.0 ppm, will in fact during most summers achieve an average DO concentration of only 3.0 ppm or even less. On the other hand, it may be 5.0 ppm or even more.

Even if the program "succeeds" in achieving its DO goal, the result may simply be that the river will turn from a turbid brown to an unattractive green, thanks to algae bloom. We have not studied this.

Similar caveats are appropriate in considering our predictions concerning the DO consequences of the other programs.

For more caveats and qualifications, see our detailed report.

When confronted with this precis, the reader is doubtless tempted to conclude that the DECS exercise, when properly understood, contributed nothing of value to a more precise understanding of the problems confronting the sensitive decisionmaker. But this would be a mistake—for it is only as a result of our effort to trace the DECS investigations that it has been possible to obtain a perspective upon the probable consequences of the costly program of "pollution control" which the DRBC has adopted. Our basic complaint does not go to the wisdom of the effort at sustained understanding of river dynamics but to the way in which the DECS staff chose to *translate their insights into language comprehensible to decisionmakers*. After all, the WARNING we have written could easily have been made clear by the DECS in its 1966 Report.

Rather than describing the problems it had confronted, however, the DECS instead chose to transmit its work product primarily in the form of a set of quantitative predictions. Indeed, since the DECS analysis was conspicuously devoid of efforts to caution decisionmakers of the limitations of its predictions, it invited a decisionmaker to avoid a confrontation with the unpleasant realization that even relatively expensive programs could not be counted upon to ameliorate significantly, let alone cure, the environmental degradation characteristic of the darkest corners of our urban civilization. The Report's manner of presentation itself constituted an assurance to laymen that they should be confident that the experts had found DO to be a convenient index of "water quality" and that the experts had predicted that alternative pollution control programs will raise the DO index in the "critical

reaches" from 1 to 2.5 or 3 or 4. Given this setting it is but a short step for laymen involved in the political process to limit themselves to haggling whether the pollution control goal "should be" 2.5 or 3 or 4, never facing the more troubling issues that lie submerged below the numerical facade: Is our society willing to make the enormous expenditures required to revolutionize environmental conditions next to the industrial plants on the Delaware River? If not, why are we willing to spend a quarter of a billion dollars (or more) to take half measures that may well not improve matters significantly? Even if the DO goal is fulfilled, could more pressing environmental goals have been achieved with more certainty elsewhere at much lower expenditures? Considering the immense number of demands for social justice properly advanced by blacks and other deprived minorities, is it appropriate to divert substantial social resources to ameliorate marginally the admittedly undesirable conditions in the Delaware's "critical sections"?

While we have already intimated our own view on these questions,¹³² which we intend to elaborate in a subsequent article under preparation, we do not suggest that there is any one "correct answer" to them. Our point here is simply that the style of the DECS's analysis did not invite the policymaker to confront these fundamental questions and that this failing is a matter of substantial concern. This failing is particularly unfortunate since *if the DECS had taken pains to articulate the factors that made the achievement of meaningful environmental improvement uncertain, its analysis would have induced decision-makers to explore the basic premises of pollution control policy in a far more probing way than in fact was attempted on the Delaware.*

In saying this, we do not, however, wish to overemphasize the points we have made. Even though the DECS DO model did not raise the basic questions involved in an effort to rid the Delaware of BOD, these questions could have been raised at other stages in the decision-making process: the DECS's own cost-benefit analysis could have forced these issues to the surface; the complex political process could have done so as well. And we shall, in our subsequent efforts, seek to explore the reasons why these processes failed to surface the issues of critical importance. We have focused on the DO model only because clear analysis requires the student to understand each dimension of the policy problem with sophistication before attempting a higher synthesis of all the factors at work, and because when a higher synthesis is finally attempted, it seems to us that the style of the DECS effort played a significant role in the ultimate policy outcome, under which

¹³² See, e.g., text accompanying notes 41-45, 73-81 *supra*.

enormous sums of money will be committed to a program that will yield meagre environmental returns.

VIII. BEYOND THE STEADY STATE: THE TIME VARYING MODEL

As we have suggested, the DECS decision to put first priority on generating a set of "steady state" DO predictions made a good deal of sense from the scientific perspective. Thomann's basic model was, after all, untested on an estuary; thus, it was wisest to assess the model by simplifying the real world as much as possible without so departing from reality that the model's predictive powers could not be ascertained at all. Since during the summer months river flow rates and temperatures were relatively constant¹³³ it was desirable to use a "steady state" approach to predict the summer average DO profile, as a first attempt to test the reliability of the Thomann construction.

We have, however, demonstrated that especially in its treatment of storm sewer run-off and the loadings imposed upon the river by the Upper Delaware beyond Trenton, as well as the tributaries of the main stem, "steady state" methodology served to conceal important policy dimensions from the decisionmaker.¹³⁴ Equally important, "steady state" thinking proved inadequate when it was recognized that the estuary's pollution problems were not completely restricted to the summertime. Each spring, Atlantic Ocean shad swim through the polluted estuary on their way to their spawning grounds in the upper reaches of the Delaware; each fall, the shad swim back through the estuary and out to the sea. During these migration periods, temperature and flow conditions on the estuary fluctuate dramatically. In the beginning of April 1964 (when the shad began their move upstream)¹³⁵ the river's temperature was 49°F.¹³⁶ while the temperature in early June 1964 (when the last of the shad left the estuary for the upstream waters)¹³⁷ was 72°F.¹³⁸ Similarly, the flow at Trenton in April was 15,000 cubic feet per second (cfs) while by June it had fallen to between 4000-5000 cfs.¹³⁹ Analogous changes occur during the fall months

¹³³ We have, however, already explained that the DECS encountered serious problems even in finding an intra-summer steady state condition for such a simple variable as flow rate. See note 125 *supra*.

¹³⁴ See, e.g., text accompanying notes 73-88 *supra*.

¹³⁵ Morris & Pence, *supra* note 25, at 5.

¹³⁶ Pence, Jeglic & Thomann, *supra* note 39, at 392.

¹³⁷ Morris & Pence, *supra* note 25, at 5.

¹³⁸ Pence, Jeglic & Thomann, *supra* note 39, at 392.

¹³⁹ *Id.*

when the shad return to the ocean.¹⁴⁰ When the survival of the shad became an important issue in the political process defining the water quality objectives for the Delaware, the model builders were invited to define more precisely the degree to which adoption of each of the five competing quality programs would protect the shad in their struggle up and down stream.

In undertaking this task, it was apparent to the DECS that given the wide variations in flow rate and temperature during the migration periods it would be pointless to use a "steady state" approach. Instead, the staff attempted to develop a "time varying" model that could take into account the impact of changing conditions. In its basic conceptual structure, this model is identical to the one we have already analyzed: it deals with the lag in nitrogenous oxidation, FSUOD and SSUOD decay rates, advective transport, reaeration and benthic demand in the same way as did the "steady state" model.¹⁴¹ And all our criticisms of that model's use of these basic concepts apply here with equal force.¹⁴² Moreover, in moving to a "time varying" analysis, the DECS staff did not desert its "steady state" thinking with regard to a fundamental factor, and thereby further undermined the reliability of its conclusions. While the model builders did vary temperature and flow conditions to mirror typical patterns obtaining during the spring and fall migrations, the shad studies failed to take into account the way in which the DO profile varied with the temporal variation in BOD loadings, assuming instead that throughout the spring and fall all BOD inputs remained constant at their average annual level. This assumption was especially hazardous because the model attempted to describe transient conditions. Most important, it is quite untenable to treat storm overflow and BOD loadings from the Upper Delaware as if they were constant over time. Furthermore, our interviews with polluters reveal that a substantial number of them expect their secondary treatment plants to be less effective in the colder months than in the summer.¹⁴³ All this was ignored by the DECS in estimating the impact each cleanup level would have upon the survival of shad. Instead, using the model with all these

¹⁴⁰ In 1964, the flow rate at Trenton stayed fairly constant at about 2200 cfs throughout the fall until late December. The temperature fell rapidly from 78°F. in late August, to 63°F. in late September, to 60°F. in late October, to 50° in late November. See Morris & Pence, *supra* note 25. Apparently river conditions for shad survival are most critical in the spring months. *Id.*

¹⁴¹ Pence, Jeglic & Thomann, *supra* note 39, at 383-84.

¹⁴² See text accompanying notes 62-110 *supra*.

¹⁴³ The effectiveness of sewage treatment plants is heavily related to the rate of biological activity of the microorganisms that consume BOD in the treatment facility before the waste is discharged into the river. The rate of this activity drops significantly as temperature decreases, thereby reducing the percentage of BOD removed in the plant.

defects, the staff provided the DRBC with a chart that attempted to delineate the shad's prospects under alternative BOD cutback regimes:

TABLE 4 ¹⁴⁴

ESTIMATED TOTAL UPSTREAM SHAD PASSAGE

Program	Minimum % Survival		
	1 in 10 yrs.	5 in 10 yrs.	24 in 25 yrs.
II	95	95	90
III	85	85	80
IV	65	60	20

We do not mean to flail a dead horse. We shall only say that we think it remarkable that at no point in the DECS 1966 Report is there any indication of the limited value of these predictions.¹⁴⁵

IX. BEYOND 1966: FOLLOWING THROUGH ON THE DECS WORK

A. *The Regional Failure to Follow Through*

Our analysis of the pioneering DECS model should not be misinterpreted to mean that it is *impossible in principle* to construct a mathematical model of the river that would be accurate enough to be of great assistance to decisionmakers. While the model supporting the DECS 1966 Report to the DRBC did not meet this test, much could have been done since 1966 to improve the reliability of the model's predictions. Advances along several fronts were possible: first, improvements in the model's structure could have been attempted; secondly, the relevant coefficients (like those describing the reaeration rate and the decay of SSUOD) could have been remeasured with greater sophistication; thirdly, the BOD loadings imposed by the diverse pollution sources could have been constantly monitored to test the ability of the model to relate changing BOD loadings to the resulting DO profile. In the following pages, we consider the extent to which these and similar tasks have been attempted, thereby providing a framework for a consideration (in section X) of the last of the three questions set out early in the essay: which forms of administrative structure facilitate the on-going pursuit of scientific factfinding essential for sophisticated river management?¹⁴⁶

While the BOD monitoring program seems in some ways the most prosaic of tasks, it is nevertheless critical to a sustained advance in the

¹⁴⁴ DECS, *supra* note 11, at 60.

¹⁴⁵ Nor is there any such indication in a paper on this subject written by 2 DECS staff members. See Morris & Pence, *supra* note 25.

¹⁴⁶ Text immediately preceding sections II & III *supra*.

art of understanding rivers in quantitative terms. It is only by maintaining a reliable data base that innovations in the model can be tested empirically. Unfortunately, this basic task has been poorly discharged since 1966. Indeed, it is fair to say that the concerned agencies have less satisfactory data on BOD loadings at the time of this writing (February 1971) than the DECS possessed in 1966.

To understand the source of one of the principal data problems it is necessary, once again, to take into account the customs of the sanitary engineering profession. Engineers have been wont to measure the BOD content of waste samples by determining the quantity of oxygen the waste consumes at a standard temperature of 20°C. during a five-day period. (This value is often written BOD₅.) Since carbonaceous oxygen demand is still exerted after the first five-day period a constant is used that permits the engineer to "extrapolate" to FSUOD in a highly imprecise way;¹⁴⁷ SSUOD is not even measured under traditional practice. As we have noted, DECS revolutionized measurement practices, attempting to calculate FSUOD and SSUOD more satisfactorily. DECS strongly recommended a continuation of its sophisticated measurement techniques.¹⁴⁸ Since 1965, however, the main task of measurement has passed from the DECS to the DRBC, which, in turn, negotiated contracts with the three states bordering the estuary. We have inspected the data collected by the states with some care,¹⁴⁹ and it indicates unequivocally a relapse into the traditional defective measurement procedures. Almost all of the data sent by the states to the DRBC is expressed in terms of traditional BOD₅.

Even more remarkable is the manner in which the states collect BOD samples from the dischargers. There are clear dangers when an inspector arrives at a plant and merely takes a sample of the untreated waste and the treated effluent at a single point in time. First, given the extreme variability of the wasteloads, a one-shot "grab sample" is not representative; secondly, the procedure permits polluters who are dishonest to cheat quite easily if they have cause to expect the investigator to arrive on the premises at a particular time; thirdly, since there is a substantial error in the BOD test¹⁵⁰ several samples should be taken at the same time to allow an averaging of results. Instead of

¹⁴⁷ See T. CAMP, *supra* note 25, at 243.

¹⁴⁸ DECS, *supra* note 11, at 83-85.

¹⁴⁹ Members of the study group, working under Professor Ackerman's supervision, collected the state reports concerning industrial and municipal discharges made available by the state authorities of Delaware, New Jersey, and Pennsylvania. The data, at present, are on deposit in the project's files in Professor Ackerman's possession.

¹⁵⁰ Personal communication with G. D. Pence, Jr., Delaware Estuary Comprehensive Survey Staff, in Edison, N.J., July 1970.

relying on a single "grab sample," a more expensive "composite sampling" technique is necessary if reliable wasteload estimates are to be expected. Under the "composite" method, several samples are taken hourly over a twenty-four hour period, and an average of the test results is used as a measure of BOD load.

Our inspection of the state reports makes it clear that all three states rely principally upon grab samples. Moreover, when composite samples are attempted, the manner of execution undermines one's confidence in the results obtained. The twenty-four hour procedure is relatively expensive since it requires an inspector to be at a single plant both day and night. Our interviews with Pennsylvania staff personnel indicate that in order to save their time and the State's money, the polluter is called in advance and told to start collecting hourly samples; the inspector arrives on the scene later, and leaves before the sampling is completed.¹⁵¹ Obviously, this practice undermines the neutrality that a state sampling program is intended to obtain. Equally extraordinary is the Pennsylvania bureaucracy's acceptance of the demand made upon them by several large industrial firms that require the inspector to call the company before he arrives to take even a grab sample.¹⁵² We do not know whether similar practices obtain in Delaware and New Jersey.

Sampling frequency presents another problem. At present both New Jersey and Delaware sample major industrial and municipal plants monthly; Pennsylvania samples major plants once every second month at best. Since sampling is expensive, a trade-off must be made between accuracy and cost: in judging whether the monitoring is too frequent, the critical factor must be the variability in the results obtained. Our inspection of the state reports indicates, unfortunately, that in both industry and municipal facilities the variability is significant: often samples reveal a fifty percent variation from observation to observation. Similar variances are revealed when samples from the same month of consecutive years are compared. These variances should not be surprising, given the grab samples upon which they are based. What appears to be a year to year variation may actually be a variation of waste concentration from hour to hour. Thus, the chaotic condition of the reports may simply reflect the inspector's arriving at 9:00 a.m. on one visit and, on another, at 5:00 p.m. Nevertheless, the record suggests that a more frequent monitoring schedule would be required at least for certain polluters before data of sufficient reliability could be gathered to justify the confident use of even an improved mathematical model.

¹⁵¹ Interviews with state officials who prefer to remain anonymous, summer 1970.

¹⁵² *Id.*

Finally, a substantial number of the reports show obvious incompetence. Often reports fail to indicate the rate at which effluent is pouring through the outfall, noting only the phrase "meter broken" in the few cases in which any explanation for the failure is vouchsafed at all. This makes the report worthless, since it is impossible to determine a plant's daily BOD load without knowing both the concentration and the volume of effluent, and volume can only be determined if one knows the flow rate. Similarly, a substantial number of the reports indicate that daily volume has been "estimated" but do not describe the manner of estimation. Even worse, reports sometimes indicate that the BOD concentration of the treated effluent was found to be *greater* than the BOD of the raw waste. The anomalous readings may be the result of careless mislabeling of bottles or, on the other hand, it may be the result of the grab sample practice if, at the time of sampling, the raw waste entering the treatment plant exerted less BOD than the partially treated, but initially more heavily polluted, wastes leaving the plant. In any event, it is deplorable that, when the laboratory BOD analysis is received, such data are placed in the file without any indication of their intrinsic implausibility or any attempt to rectify the apparent mistake.

The DRBC staff is aware of these failings and has thus far unsuccessfully tried to induce the state pollution control bureaucracies that collect the BOD data to adopt more elaborate and expensive procedures. When DRBC staff members meet with their state counterparts at regular meetings of the Water Quality Advisory Committee, frequent pleas are made to supply data that will permit the accurate calculation of FSUOD.¹⁵³ Even here, however, we have found no indication that the DRBC has put any substantial pressure on the states to provide data on nitrogenous demand. This vacuum is significant now and will become increasingly important over time. We have already noted that the DECS model is deficient in its treatment of nitrogenous demand; yet data is not being collected that could serve as the basis for reliable theoretical work on the problem. Moreover, as traditional "secondary treatment" facilities of the sort being constructed under the DRBC cleanup primarily eliminate carbonaceous demand and only incidentally remove nitrogenous, SSUOD's share of the total will increase dramatically after the anticipated cleanup. In short, the DRBC is not now receiving the data on municipal and industrial treatment plants that either permit it to have a sophisticated understanding of the Delaware of

¹⁵³ DRBC Water Quality Advisory Comm., Minutes of meetings of Mar. 18, 1969, Oct. 2, 1969, and Apr. 16, 1970 (unpublished, available at Delaware Dep't of Natural Resources & Environmental Control).

today or enable it to make a more accurate prediction as to the impact its program will have on the Delaware of the future.¹⁵⁴

Turning to the DRBC's efforts to measure other BOD inputs, the results are similarly disappointing. No significant work has been attempted on the measurement of benthic demand or upon the analysis of BOD entering the estuary from the river's tributaries. In contrast, the agency has been taking important steps to expand its scientific knowledge of conditions prevailing in the relatively unpolluted waters of the Delaware above Trenton. Members of the staff are presently collecting data that will permit the application of a Thomann-type model to this region, and the information gathered in this study should illuminate the impact the Upper Delaware has upon the estuary below Trenton, thereby improving the quality of the data used by the DECS model in this single respect.

Just as the data collection effort has proceeded at a crawl, so too has new theoretical work sponsored by the DRBC. No explorations of reaeration rates have been attempted by the agency, despite the inadequacy of the DECS treatment and their importance to the model's predictions. Nor has there been a significant effort to better understand turbidity or the dynamics of benthic demand. On the other hand, a substantial amount of theoretical work has been attempted to better define the impact nitrogenous demand will have upon the estuary after the anticipated cleanup has been attempted. It is difficult, however, to determine the validity of such theoretical work without the assistance of detailed data on nitrogenous loadings, which the DRBC has failed to collect.

Given the failure of the agency to move substantially beyond the DECS's work, it should not be surprising that little has been done to determine the extent to which the DECS model successfully predicts the DO profiles prevailing along the estuary since DECS's final "verification" analysis of 1966. To run even a moderately satisfactory analysis it would be necessary to obtain reliable data on BOD loadings that are more recent than those DECS obtained in 1964. Since this essential work has not been attempted, meaningful verification efforts are impossible. Thus, while members of the DRBC staff attempted a "verification analysis" on the basis of fragmentary 1968 BOD data,¹⁵⁵ we have

¹⁵⁴ This is particularly unfortunate since river conditions during these years differed substantially from those prevailing in 1964 and 1966, *see* note 126 *supra*; thus a "verification" run on newer data would have provided extremely revealing information regarding the model's utility.

¹⁵⁵ MacEwen & Tortoriello, *Forecasting of Water Quality Data in the Delaware River Estuary*, PROCEEDINGS OF THE NATIONAL SYMPOSIUM ON DATA AND INSTRUMENTATION FOR WATER QUALITY MANAGEMENT 99 (J. KERRIGAN ed. 1970).

reason to believe that the DRBC staff itself considers this endeavor to be of no real significance.¹⁵⁶

B. The Federal Failure to Follow Through

At the time it published its "preliminary report" for use by the DRBC in the summer of 1966, the DECS promised a much more detailed and definitive "final" document by the end of 1967. At the time of this writing (February 1971), however, this report has not yet been published. While a number of the final report's chapters have been circulated informally, it does not appear that significant progress is now being made that would ensure the publication of a complete report within the foreseeable future. Even if the document should ultimately see the light of day, its utility will be limited since the DECS staff apparently has not integrated post-1966 data into its work,¹⁵⁷ for the simple reason that adequate data do not exist.

Indeed, at present the DECS staff has basically ceased to function as a unit. Only three of its members remain with the regional office of the Federal Water Quality Administration at Edison, New Jersey, and they are devoting only a small fraction of their time to the Delaware, working instead upon projects the FWQA considers to be of greater immediate importance.

X. THE ADMINISTRATIVE PROCESS AND THE PURSUIT OF SCIENCE

In sum, we have presented an understandable, yet depressing, tale. An admirable scientific endeavor in river dynamics was transformed by the force of events into a decisionmaking tool before it was sufficiently developed. After the short-term pollution control decisions had been made the scientific enterprise lost its vitality. Decisionmakers charting the course of the Delaware five or ten years from now will be constrained once again to activate a crash research program, which, with inadequate data and analysis, will nonetheless crank out predictions of limited value to the decisionmaking process. Moreover, policymakers and scientists on other rivers will not be able to use the Delaware's experience for their own profit.

While this dismal cycle may in part be attributed to the innate shortsightedness of mankind, an explanation that relies exclusively upon individual human frailties is incomplete. In large part the scientific

¹⁵⁶ Personal communication with an anonymous member of the DRBC staff, Oct. 1970.

¹⁵⁷ If the full report had been published in 1967, as scheduled, others might have been able to proceed with further research on the basis of the DECS pioneering work. Instead, other workers in the field have been deprived of a good data base, and the original DECS workers have been deprived of full recognition for their contributions to an understanding of estuarine pollution.

failure was a foreseeable result of the type of administrative structure that prevailed along the Delaware during the 1960's. The source of the problem rests with the institutional division of responsibility between the DECS, a creature of the federal agency charged with water pollution control, and the DRBC, a regional agency formed by the concerned states and the federal government. To divide the "thinkers" (DECS) from the "doers" (DRBC) in this way is to ask for several kinds of trouble. The "thinking agency" has little incentive to stay with the problem over the long haul. Instead, it may well maximize its bureaucratic prestige by publishing a preliminary report which loudly claims to be "relevant" to the decisionmakers' problems, prematurely leaving the area in search of new problems that are capable of "innovative" solutions. A pure "thinking" agency may be expected not only to plan episodically, but also to justify its existence by overselling the accuracy and importance of its preliminary reports by underemphasizing the uncertainties underlying its predictions.

In overselling its innovative enterprises, the thinking agency is aided by the action agency for several reasons. First, the action agency does not possess large numbers of personnel equipped with the necessary analytical skills to both understand the model and take steps to improve the model's structure and data base. Since agency funds are always limited, there is a natural tendency for the available money to be allocated for uses the existing action officials understand, to the prejudice of those they do not. Secondly, the action agency, after it adopts one of the competing pollution programs delineated by the thinkers, will have a natural tendency to seek to prove that the plan it has selected is the one the thinkers' report supports most persuasively. In short, even if the report in fact played a relatively unimportant role in the minds of the decisionmakers, the action agency will seek to legitimate its decision by proclaiming that it is rooted in the expert analysis provided by the thinkers, who have themselves sought to proclaim its importance for the reasons outlined above.¹⁵⁸ After this public episode in

¹⁵⁸ A tendency evident in the DRBC experience.

The DECS study played an important role in official statements legitimating the DRBC's decision:

A U.S. Public Health Service Report issued in 1966 found the river's overburdened estuary—the 86 mile stretch from below Wilmington to Trenton—to be "a polluted waterway which depresses esthetic values, reduces recreational, sport and commercial fishing, and inhibits municipal and industrial water use."

This important if uncomplimentary document, *probably more than anything*, represented the turning point for the polluted, oxygen-shy lower Delaware. Its findings of degraded conditions and extensive options for improving them (and surprisingly even for not improving them) startled the three-state area and spurred it into a solemn cleanup commitment.

7 DRBC ANN. REP. 6 (1969) (emphasis added). See also 5 DRBC ANN. REP. 6-8 (1967).

which the action agency seeks to legitimate its decision by relying upon the model-builders' expertise, efforts to launch a systematic effort to move beyond (or even update) the DECS model become something of an embarrassment. If it is necessary to improve the DECS model, does not this suggest that something was seriously wrong with the original analysis already publicly proclaimed to legitimate the original decision? Thirdly, after the basic pollution control program has been selected, the action agency's bureaucracy can be expected to concentrate its energies on enforcing the decision rather than engaging in the more basic research that will ultimately be needed for future planning efforts on the Delaware and elsewhere. After all, the action agency has yet to make its bureaucratic reputation, and, over the short term, rewards will be governed by successfully implementing the program already adopted rather than conducting experiments and collecting the data necessary for future planning along the estuary.

All this, of course, does not mean that an action agency is not correct in placing first priority upon implementing the pollution control program selected by decisionmakers. We simply argue that powerful bureaucratic forces will induce such an agency to ignore the necessity of following through upon the planning work initiated by others. In contrast, if both thought and action had originally been within the province of a single agency, the chances of an effective follow through on the research effort would have been improved *somewhat*. While the agency would have had the same tendency toward public self-praise of its planning sophistication in an attempt to legitimate its ultimate decision, the public praise would in this case probably strengthen the hand of the planning part of the agency in its efforts to maintain its share of agency funds for the further support of the scientific effort. Similarly, since the model-builders would already be well entrenched within the agency bureaucracy, they could be expected to sufficiently appreciate the informal patterns of power prevailing within the administrative structure to make their influence felt.

Having discerned the significance of the division of responsibility between DECS and DRBC, it is necessary to inquire more deeply into the reasons that brought separation about. From the legal viewpoint, nothing was foreordained about the division of the planning and decisionmaking roles. The DRBC's charter provides ample authority for sponsoring planning efforts of this magnitude.¹⁵⁹ As we have seen, the development of an institutionally separate DECS effort had much to do with two accidents of history: the interest of the Public Health Service in novel forms of cost-benefit analysis; the infant DRBC's concern with

¹⁵⁹ Delaware River Basin Compact, art. 13 (1961).

the pressing issues emerging from the deepening drought along the river.¹⁶⁰ Nevertheless, the same institutional bifurcation might have resulted even if the DRBC had not been diverted by the water shortage away from pollution control research. For the administrative pattern revealed along the Delaware is a fundamental aspect of the "cooperative" federalism, which, in increasingly complex forms, is playing a central role within the contemporary polity: a federal "task force" providing "technical" assistance to local "decisionmakers," who "implement" decisions with substantial federal oversight.¹⁶¹ And it is doubtful that the DRBC could have transcended this pattern. The agency, after all, had no legal authority to veto the federal study, nor to require that its own personnel undertake the work;¹⁶² nor would it have made sense to institute a parallel effort of its own that would only replicate much of the same ground at additional cost. It was only if the federal authorities had delegated the project to the regional body that the bifurcation could have been avoided. But this result was most unlikely: first, the Public Health Service would have been reluctant to abandon a project likely to redound to its bureaucratic prestige; secondly, given the prevailing philosophy of "cooperative federalism," which legitimates federal "technical" assistance, it is most unlikely that anyone within the federal bureaucracy would have thought it incongruous for a federal task force to investigate a regional problem in lieu of the regional agency established for the purpose.

Nonetheless, this structural division was of substantial significance for the future of regional government along the Delaware. A regional authority must develop its staff's planning capacities if it is to become anything more than a loose confederation in which representatives of the federal and state bureaucracies compromise their differences without any substantial effort to view the Delaware River's problems from a regional perspective. And the failure to develop planning resources feeds upon itself: it was in large part because the DRBC was not

¹⁶⁰ See text accompanying notes 13-17 *supra*.

¹⁶¹ A systematic legally-oriented analysis of the premises underlying the numerous patterns along which federal-state relationships have been structured has yet to be written, although the importance of the problem has been perceived by political scientists, AREA AND POWER (A. Maass ed. 1959), historians, D. ELAZAR, *THE AMERICAN PARTNERSHIP* (1962); Elazar, *Federal-State Collaboration in the Nineteenth Century United States*, 79 POL. SCI. 248 (1964), economists, G. BREAK, *INTERGOVERNMENTAL FISCAL RELATIONS IN THE UNITED STATES* (1967); *ESSAYS IN FISCAL FEDERALISM* (R. Musgrave ed. 1955), as well as legal academics, F. MICHELMAN & T. SANDALOW, *MATERIALS ON GOVERNMENT IN URBAN AREAS* 970-1212 (1970).

¹⁶² Indeed, § 1.5 of the Compact reads:

It is the purpose of the signatory parties to preserve and utilize the functions, powers and duties of existing offices and agencies of government to the extent not inconsistent with this compact, and the commission is authorized and directed to utilize and employ such offices and agencies for the purpose of this compact to the fullest extent it finds feasible and advantageous.

obliged to undertake a DECS-type study with its own personnel that it was poorly equipped to follow through on the task when the federal innovators left the scene.

Since the regional agency lacked an active research component, it was only natural that the essential task of data collection was delegated to the respective states, whose agencies have responded in such an unsatisfactory manner. Once again, it is too easy to explain the states' poor data collection practices by invoking the well-worn notion that state bureaucrats are more incompetent than their counterparts at other levels of government. However this may be, a more compelling explanation exists for the case at hand. Since the states' officials are not responsible for maintaining the model's accuracy, they have little incentive to collect data useful to run the model, if that effort requires them to change their cheap and easy grab-sampling technique for BOD₅. In short, one of the important reasons that the data is not being collected properly is that the states are responsible for data *collection* while the DRBC is responsible for data *manipulation*. Since state officials are not dependent upon the DRBC staff for their promotion or job security, DRBC personnel have no sanction to impose when the relevant data do not arrive. Moreover, since the DRBC staff does not even work in close geographic proximity with most of their state counterparts, even informal sanctions are relatively ineffective.¹⁶³ The DRBC staff's primary recourse is an occasional plea for better data at the regular meetings of DRBC personnel with their state counterparts.

The relationships between federal, regional, and state authorities we have charted should serve as a caution that the vague notion of "cooperative federalism" is in need of much more precise analysis than it has yet been given. At least in decisions requiring a significant scientific input of a continuing nature, it will not suffice to place bits and pieces of the scientific enterprise in different bureaucratic structures at different levels of government. The course of events along the Delaware eloquently warns the Social Engineer against placing the federal "thinkers" in one bureaucratic box, then shifting the responsibility for scientific follow through to the regional "decisionmaking" agency, simultaneously consigning the task of "data gathering" to yet another set of state agencies. In such a structure each component is prone to lose sight of the function it should be performing to enhance the rationality of the pollution control scheme that ultimately is the product of all the sound and fury.

¹⁶³ The Commission's staff works in Trenton, New Jersey, close to their New Jersey counterparts, but far from Albany, Harrisburg, and Dover.

The values of decentralized authority implicit in "cooperative federalism" would be better served by a more discriminating analysis. Given the continuing nature of the enterprise, the task of understanding the state of the river should be unambiguously assigned to a single agency for the long haul. Moreover, the Social Engineer should be reluctant to assign this task to an entity divorced from final decision-making responsibility, unless special steps are taken to assure that the "thinking" agency is committed to the project for the long haul. Thus, if there were a way to commit agency funds for a specific project over a twenty year period or if the research project was contracted out to a private firm for a similar term, the problems arising from an institutionalized bifurcation between thought and action might be controlled reasonably well. If, however, explicit steps to deal with the problem are not taken, the Delaware's experience suggests the wisdom of assigning the fact-finding function to the agency charged with ultimate decisionmaking authority over the river's future. Doubtless, there are substantial disadvantages implied by this joinder of functions, but at least there is some assurance—for the reasons previously suggested—that sophisticated research and planning will not be condemned to the episodic existence it has led on the Delaware River. Unfortunately, our case study does not permit us to explore the important questions going to the way an agency which embraced both decisionmaking and fact-finding functions should be structured to ensure an ongoing research effort. Our study can only serve as a warning to the Engineer that he refrain from repeating past errors in the future.

To make matters worse, it is not at all clear to us that these warnings will be heeded in the world of American institutions. A regional agency like the DRBC enters a world already occupied by well established institutions on the state and federal levels, which are unlikely to surrender meekly even so humdrum an activity as data collection. Except in the unlikely event that the regional compact grants exclusive jurisdiction to the regional agency in such matters, the effective pursuit of science will be sacrificed because established institutions refuse to defer to the new agency. Unless there is a greater sensitivity, especially on the part of the federal officials, to the need to foster the development of research activities in infant regional structures, "cooperative federalism" will be no more than a slogan concealing ineffective and sporadic scientific research. Indeed, if the outlook for successfully transferring the *factfinding* function to the regional agency is poor, it may well be wisest to consider the desirability of transferring the *decisionmaking* function to the federal level. It would then be possible to coordinate research and decisionmaking within a single agency

structure. Of course, the effective pursuit of science is not the only consideration in passing judgment upon the ultimate desirability of federal, as opposed to regional, decisionmaking control. Nevertheless, it should not be ignored in the inevitably complex task of constructing the optimal governmental structure for the control of water pollution.

XI. CONCLUSIONS

We have had four major purposes in writing this essay. The first is severely practical: studies similar to the DECS are being pursued around the country and if lawyers and other policymakers are to understand their significance and validity, they must learn the questions they should ask of the experts. Up to the present time, the basic concepts involved in model building have been presented in a mathematical language forbidding to most law trained professionals; this essay attempts to bridge the gap. A policymaker, attempting to evaluate a DECS-type study, should not blithely assume that it shares the same frailties as the models we have analyzed. Nevertheless, at least he will have a starting point for an intelligent scrutiny of the numbers placed before him. Secondly, just as law reviews have traditionally criticized the rationality of judicial opinions, we have attempted to perform a similar function for a less familiar aspect of the administrative process. If anything, criticism here is even more important, given the failure of DECS and DRBC staff members to document their analyses fully. If this essay prompts a rejoinder that reveals more of the inner workings of the DRBC and DECS scientific effort, its value will have been fully vindicated. Thirdly, an understanding of the frailties of DO as a policy indicator and the uncertainty concealed by the DECS DO predictions will provide an important perspective from which to evaluate the Political and Technocratic Models on the Delaware. Was the political process organized in a way that would surface the basic policy issues concealed by the proffer of DO as a criterion of water quality? Would the politicians accept the DECS definition of the policy options without recognizing the chance that the program selected would not accomplish its goal? If uncertainty was recognized, what were the implications drawn? Analogous questions should be asked of the Technocratic effort to quantify costs and benefits. Finally, if neither Technocrat nor Politician responded to these questions in a satisfactory way, we shall be obliged to investigate the sources of their failure, and in doing so better understand the questions of basic policy and institutional design that must be confronted before an industrial civilization can come to terms with the environmental consequences of its continued existence.

Fourthly, this essay is intended as an invitation to the legal profession to liberate itself from the conventional categories already afflicting the infant study of "environmental law." Despite the fact that lawyers (and law school professors) pride themselves in being "generalists" open to the peculiarities of new problems, the truth is that, like all human kind, the profession tends to convert new problems into familiar concepts. Thus "environmental law" turns out to be an occasion for canvassing once again some basic questions in administrative law, the traditional law of torts, and the received wisdom concerning water rights. The rapidly expanding literature seems full of discussions of the law of standing, "substantial evidence," and occasionally the more general questions concerning the extent to which courts should defer to administrative expertise in the formulation of environmental policy. Similarly, we are inundated with discussions of the law of nuisance and riparian rights.

All this is fine; but it suffers from the important defect that it myopically concentrates upon the law as it is applied by courts. If the legal community contents itself with such analyses, it will remain at the periphery of policymaking since policy in most areas will be made and enforced primarily by administrative agencies. In the case before us, for example, it should be clear that no court could handle the scientific enterprise even half as well as the DECS and the DRBC have done: courts are even less capable of assuring sustained and long term scientific effort than even the disorganized administrative process we have described. Thus if lawyers are to understand the genesis of pollution control policy, they must begin to understand the alternative ways the administrative process may be structured to find the "facts;" how the "facts" condition the policy options perceived to be open; how the decisionmaker must go beyond the numbers to probe the reliability of the experts' predictions.

The terrain is unfamiliar, but the tale presented here suggests that the sophisticated legal professional has a significant contribution to make in each of the three areas we have considered. First, consider whether it is wise to expect that the typical engineer will, *on his own initiative*, raise the first of our three questions¹⁶⁴ and inquire into the extent to which his work on the DO profile improperly diverts public attention from more pressing environmental concerns. For once this question is raised seriously, the answer may be far too threatening to the engineer's self-esteem. What if he concluded that an ecological study of the Delaware Bay was far more important than an effort to chart the DO profile of the polluted estuary? Would that not suggest

¹⁶⁴ Text immediately preceding sections II & III *supra*.

that he and other engineers must take a back seat to other professionals? In contrast, the legally trained policymaker can regard with equanimity the rise and decline of various species of expertise—he has no vested interest in any of them (except his own). It is precisely the goal of legal training to force the lawyer to assess the policy implications of the “expert information” all too eagerly proffered as a “valuable input” into the “decisionmaking process.”

Similarly, it is utopian to expect that an engineering team will take great pains to reveal all of the uncertainties threatening the accuracy of the DO predictions generated by a model they have spent years building, and thus raise the second major issue that has occupied our attention.¹⁰⁵ It is not merely that all human beings wish to emphasize the affirmative aspects of their achievements; even more important is the manner in which the DECS Report understands the very idea of “achievement.” The DECS “succeeded” insofar as it developed a set of equations defining a system that will achieve a predetermined purpose. Thus, in emphasizing its “achievement,” the research staff emphasized the accuracy of the numbers its model generated. In contrast, the lawyer is predisposed by his education to doubt that any simple structure can adequately “explain” an important piece of reality. Indeed, from his first day in professional school, the lawyer is taught that to be “successful,” he must worry about contingencies laymen are apt too readily to discount, and thereby “complicate needlessly” situations that seem “simple” to others. It is the lawyer’s delight in contingency, complexity, and ultimate scepticism that predisposes him to ask basic questions as to the model’s reliability that the engineer would otherwise insufficiently emphasize in presenting his “success.” Finally, there is even less reason to believe that the engineering profession will, on its own initiative, raise our third question and consider the structures that will facilitate the effective pursuit of science. Thus if lawyers and legal scholars ignore these issues and preoccupy themselves exclusively with judicial questions, it is likely that these issues will remain slighted by those professionals most intimately involved in the factfinding process, to the substantial prejudice of the ultimate environmental policies our institutions select. There is, alas, a substantial difference between Engineering and Social Engineering, and the legal community can make a substantial contribution to the development of the latter science.

¹⁰⁵ Text immediately preceding sections II & III *supra*.

APPENDIX

Model Formulation

The DECS mathematical model is based on a materials balance analysis of a hypothetical segment of the river. Repeating the same analysis for a large number of sections of the river results in a set of simultaneous differential equations.¹

Since the concentration of DO is directly related to BOD, it is necessary to model, for each section of the river, both DO concentration and BOD concentration. Thus there are twice as many differential equations as there are sections. In the DECS model of the Delaware River 30 sections were used, requiring 60 differential equations. In writing the differential equations, it is necessary to include all "sources" and "sinks" (*i.e.*, withdrawals) of BOD and DO. For example, BOD and DO "sources" and "sinks" in section *i* of the river are as follows:

Sources of BOD to Section <i>i</i>	Sinks of BOD from Section <i>i</i>
1. Current flowing downstream (and upstream, since we are dealing with an estuary).	1. Current flowing downstream (and upstream, since we are dealing with an estuary).
2. A contiguous section having a higher BOD concentration.	2. A contiguous section having a lower BOD concentration.
3. Municipal and industrial sewage outfalls in the section (including material from combined storm sewers).	3. Consumption by microorganisms.
4. Suspended solids resulting from either scouring action of the river bottom by high flows, stirring up of worms living in the sludge, or Corps of Engineers dredging activity. (Not included in DECS model.)	
5. Tributaries.	

¹ This technique is solidly rooted in the general theory of transport phenomena. For a clear presentation of a number of applications of the method, see R. FRANKS, *MATHEMATICAL MODELING IN CHEMICAL ENGINEERING* 228-58 (1967).

Sources of DO to Section i	Sinks of DO from Section i
1. Current flowing downstream (and upstream).	1. Current flowing downstream (and upstream).
2. A contiguous section having a higher DO concentration.	2. A contiguous section having a lower DO concentration.
3. Reaeration (this is the major source of DO to the section).	3. Consumption by microorganisms in consuming BOD.
4. Photosynthetic activity in the river. (Not included in DECS model.)	4. Consumption by benthic demand.
5. Tributaries and plant outfalls.	5. Consumption by chemical oxygen demand.
	6. Industrial water intake streams. (Not included in DECS model.)

From the enumeration above, the equations for section i are as follows:²

(1) For BOD:

$$V_i \frac{dL_i}{dt} = Q_{i-1,i} [e_{i-1,i} L_{i-1} + (1 - e_{i-1,i}) L_i] \\ - Q_{i,i+1} [e_{i,i+1} L_i + (1 - e_{i,i+1}) L_{i+1}] \\ + E_{i-1,i} (L_{i-1} - L_i) + E_{i,i+1} (L_{i+1} - L_i) - d_i L_i V_i + f_i$$

(2) For DO:

$$V_i \frac{dc_i}{dt} = Q_{i-1,i} [e_{i-1,i} c_{i-1} + (1 - e_{i-1,i}) c_i] \\ - Q_{i,i+1} [e_{i,i+1} c_i + (1 - e_{i,i+1}) c_{i+1}] \\ + E_{i-1,i} (c_{i-1} - c_i) + E_{i,i+1} (c_{i+1} - c_i) + V_i r_i (c_i^s - c_i) \\ - d_i L_i V_i + P_i$$

Where:

- V_i represents volume, liters,
- Q represents net flow, liters/day,
- L_i represents BOD level in the section, mg./liter,
- e represents tidal mixing parameter, dimensionless,
- E represents eddy exchange coefficient, liters/day,
- d_i represents decay rate, day⁻¹,
- f_i represents BOD discharged to the section, mg./day,

² Thomann, *Mathematical Model for Dissolved Oxygen*, 89 PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, SANITARY ENGINEERING DIVISION 1, 9 (1963).

c_i represents dissolved oxygen level in the section, mg./liter,
 r_i represents reaeration rate, day⁻¹,
 c_i^s represents saturation level of DO, mg./ liter,
 P_i represents other sources or sinks of DO action on the section, mg./day.

Explanation of Terms

1. The terms

$$Q_{i-1,i} [e_{i-1,i} L_{i-1} + (1 - e_{i-1,i}) L_i]$$

$$Q_{i,i+1} [e_{i,i+1} L_i + (1 - e_{i,i+1}) L_{i+1}]$$

and the corresponding terms in the DO equation, deal with the rate at which material (item 1 in the sources and sinks tables above) enters and leaves the section because of net advective flow into or out of the section. This is termed advective transfer and e is termed the advective coefficient. The advective coefficient is merely a proportionality constant used to express the effective concentration at the boundary between the sections.³

2. The terms

$$E_{i-1,i} (L_{i-1} - L_i) + E_{i,i+1} (L_{i+1} - L_i)$$

and the corresponding terms in the DO equation, deal with the rate at which material (item 2 in the sources and sinks tables above) enters and leaves the section because of diffusion between sections, *i.e.*, they represent material transported between sections due to the driving force of concentration differences.

3. The term

$$d_i L_i V_i$$

which occurs in both the BOD and DO equations represents the rate at which BOD leaves the section by oxidation, *i.e.*, by aerobic biochemical reaction. It occurs in both the equations because the rate at which BOD is consumed must equal (by definition) the rate at which oxygen is consumed during the oxidation of the BOD.

4. The term f_i represents the rate at which BOD enters the section from external sources.

5. The term P_i represents other sources and sinks of DO acting on the section. These are two types, the first being benthic oxygen demand and the second being chemical oxygen demand.

³ For a detailed discussion of this, see R. BUNCE & L. HETLING, A STEADY STATE SEGMENTED ESTUARY MODEL (Federal Water Pollution Control Administration Technical Paper No. 11, 1967).

6. The term $V_i r_1 (c_i^s - c_i)$ represents the rate at which DO enters the section by reaeration.

7. The terms $V_i \frac{dL_i}{dt}$ and $V_i \frac{dc_i}{dt}$ represent, respectively, the rate of change in the amount of BOD in section i and the rate of change in the amount of DO in section i .

Steady State and Time Varying Models

While the equations are linear in the independent variables, some of the coefficients vary with time (or with temperature, which in turn varies with time). It is possible to work with the equations by either (a) simplifying them in some way, or (b) utilizing a simulation technique to make their solution feasible. Both of these techniques were used. In the first case a steady state solution was sought for the summer months when DO values were at their annual average low. In the second case simulation allowed calculation of BOD and DO response on a year round basis.

The Problems Resulting From Small Errors in the Parameters

Consider a highly simplified situation for purposes of illustrating the difficulties involved. Suppose we consider a section i that has the same level of DO and BOD as sections $i - 1$ and $i + 1$. Moreover, suppose that $e_{i-1, i}$ and $e_{i, i+1}$ are equal, that the flow rate $Q_{i-1, i} = Q_{i, i+1}$ and $E_{i, i-1} = E_{i+1, i}$. Moreover, assume a steady state condition. Equations (1) and (2) reduce, under these conditions, to

$$(3) \quad V_i \frac{dL_i}{dt} = 0 = -d_i L_i V_i + f_i$$

$$(4) \quad 0 = V_i r_1 (c_i^s - c_i) - d_i L_i V_i + P_i$$

It follows that:

$$(5) \quad c_i = c_i^s + \frac{1}{V_i r_1} (P_i - f_i)$$

This equation, while admittedly being a rough approximation, allows us to think about the significance of some of the terms more easily than if we try to grapple with equations (1) and (2).

First of all, note that P_i is usually negative, that is, P_i represents an oxygen demand on the system, either from benthic demand or from chemical oxygen demand. Let P'_i represent oxygen demand, that is, $P'_i = -P_i$. Then

$$(6) \quad c_i = c_i^s - \frac{1}{V_i r_i} (P'_i + f_i)$$

This simple equation asserts that the equilibrium concentration of DO (c_i) is linearly related to the total load on the section.

It is clear that the assurance with which we can predict DO is directly related to the confidence that can be placed in the values of r_i , P'_i and f_i (the value of V_i is known quite accurately).

Consider equation (6). Under Plan II devised by the DECS, we would like c_i to be 4.0 ppm and c_i^s is about 8 ppm. Evidently

$$\frac{1}{V_i r_i} (P'_i + f_i) \sim 8.0 - 4.0 = 4.0$$

Since the values of P'_i , f_i , and r_i are all open to much question, the problem we address here is how much of an error in the parameters would make a significant difference in the results. Suppose V_i and r_i are exactly as estimated, but the sum of P'_i and f_i are 10% higher or 10% lower than anticipated. In the former case c_i will be 3.6 ppm, in the latter 4.4 ppm. Now suppose f_i and P'_i are exactly as anticipated but the value of r_i is either 10% higher or 10% lower than anticipated. If 10% higher, the level of DO will be about 4.4 ppm, if 10% lower, the level of DO will be about 3.6 ppm.

From the arguments in the main text, it would be unusual if the errors involved were of the order of a mere 10%. This simple illustration, then, demonstrates the hazards of (a) not determining both probable values of all parameters and probable values of their errors, and (b) not running sensitivity analyses on the model, utilizing the probability distribution data on the parameters, to determine what level of certitude is being proffered to the decisionmaker by the model.