Operational Water Quality Management: Beyond Planning and Design

Executive Report 7, based on research
conducted at the International Institute
for Applied Systems Analysis (IIASA)

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Foreword

Developing effective means of managing water quality operationally is now both desirable and necessary, particularly for water resource systems that are used intensively.

Two factors make this an opportune time to assess the desirability and feasibility of such management: the convergence between theory and practice, and the changes affecting water pollution problems. These changes include the

- Growing scale and increasingly complex infrastructure of water quality management
- Transition from single, independent objectives to interacting multiple objectives
- Growing concern for preventing transient occurrences of pollution and for handling such events when they do occur
- Changing role of treatment plants
- Introduction of more complex and comprehensive standards for water quality
- Increasingly difficult economic climate

Traditionally, we have tended to consider the individual components of a water quality system – abstraction, purification, and supply of potable water; the sewer network; wastewater treatment; and the receiving water body – as separate entities requiring largely independent management policies and practices. Even where operational water quality management exists, it often lacks integration and coordination. In the past it was largely a matter of long-term planning and design.

A review of current practice in operational water quality management reveals the potential for further improvement. There are also new approaches and techniques for assessing and implementing operational management. These include

- Advances in economic analysis, which can now consider fixed and variable costs jointly
- New insights into aspects of reliability and risk
- Progress in the synthesis of process control systems, where the study of design and operating interactions is especially important
- Use of support services in making operational decisions
- On-line monitoring, estimation, and forecasting
- Computing and on-line control

The first three items concern analyzing problems before establishing operational practices, the second three deal with day-to-day practice. Underlying the latter are three requirements: accepting the human element in the control loop, exploiting all available operating data as fully as possible, and making good use of past empirical operating experience.

The central thesis of this report is that managing water quality through day-to-day operations is both desirable and necessary. Good management of this sort must be adaptable, flexible, integrated, and coordinated; must take into account the trade-offs between and interactions among multiple objectives; and must include planning for contingencies, so as to fail as safely as possible. We have grouped recommendations aimed at achieving these ends into five categories.

1. Institutional, dealing with integrated regional management authority, funding mechanisms and cost allocation, and legislation about standards
2. Economic, dealing with cost and performance data and with aggregated criteria
3. Technical, dealing with civil engineering innovations, design–operation interactions, and the roles of conventional and unconventional controls
4. Reliability, dealing with operational monitoring and with pertinent operating information
5. Professional, dealing with man–machine interaction and with education and research

Taking the courses of action mapped in this report is not expected to result in radical changes over the short term, but it should produce a significant improvement in water quality management in coming decades.

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Note on Organization

Operational Water Quality Management: Beyond Planning and Design is essentially two reports.

Introduction and Summary sketches the essence of the analysis and discusses its conclusions and recommendations, thus providing an overview of the findings and the path that led to them. The five subsequent sections add detail to this overview. Each includes an introductory abstract that links the steps of the analysis to the points summarized in Section 1.

A Point of Convergence describes how theory, practice, and the changing character of problems related to water pollution make this an opportune time to assess the feasibility and desirability of managing water quality operationally.

The Problems: Changing Emphasis for Management discusses the changes strengthening the need for managing water quality operationally.

A Review: Current Practice in Operational Management deals with current practice in each of the subsystems of a water quality management system.

The Approach: New Potential for Operational Management describes the growing scope of possibilities for operational water quality management.

Guidelines for the Future describes what we can expect of water quality management in the future.

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Introduction and Summary

Of all areas of consideration involved in the planning, design, and construction of wastewater treatment facilities, operation and maintenance (O and M) is the fundamental measurement of a facility's performance; this is also many times the area most overlooked during the planning phase. That only half of all treatment facilities in the US are meeting their design standards for biochemical oxygen demand and suspended solids clearly exemplifies the result of poor O and M.

The US Water Pollution Control Federation (WPCF) opened its 1979 White Paper on Operation and Maintenance of Water Pollution Control Facilities (Hill et al. 1979) with these words. They support the observation that management of water quality in river basins traditionally has been interpreted as long-term strategic planning. Predominant emphasis has been on problems related to capital investment and to the design and construction of treatment facilities for water and wastewater.

The WPCF White Paper leaves little room for doubt: if we do not look beyond planning and design, the management of water quality will suffer. In particular, we shall be unable to achieve the objectives of management, both because short-term operating policies are inadequate and because solving problems related to planning and design does not guarantee that operational problems will be solved. Developing an effective means of *operational water quality management* (defined here as the management of problems that cannot be managed by planning and design alone) has therefore become a desirable and necessary objective. This report discusses preliminary steps toward achieving this objective.

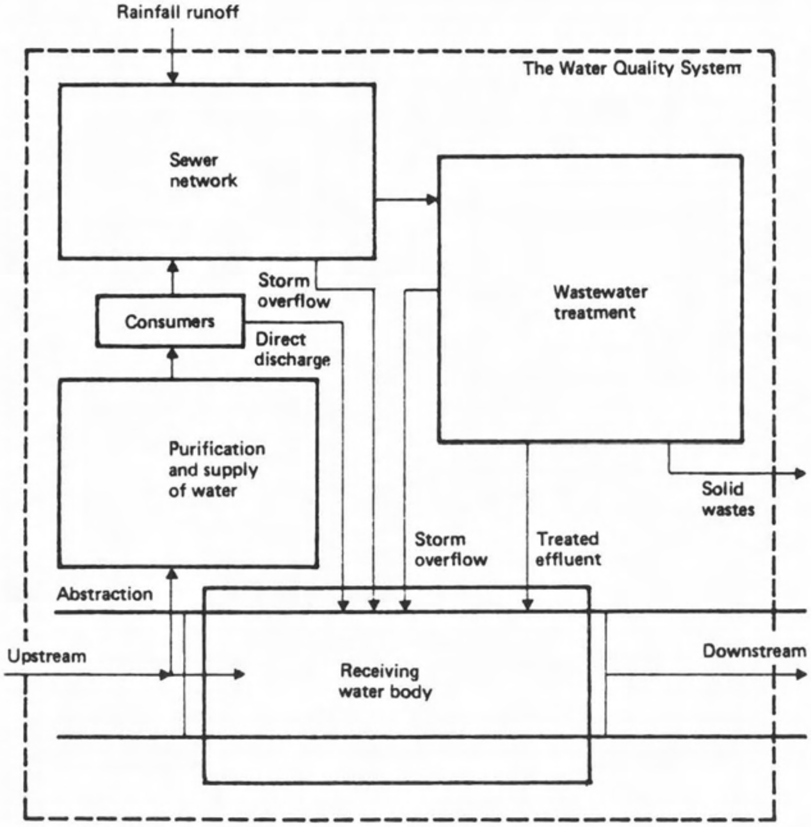

Figure 1. The water quality system comprising the following components: abstraction, purification, and supply of potable water; the sewer network; wastewater treatment; and the receiving water body.

The management of water quality, however, is not merely a matter of wastewater treatment. If our analysis is to be thorough, all the components in the system of Figure 1 are relevant; let us call this therefore the water quality system. Likewise, the feasibility of operational water quality management is not merely a technical matter of automation, computers, and instrumentation. Past research on wastewater treatment plant control, for example, has tended to overlook the possibilities for regulating stream discharge as a means of managing water quality. Detailed exercises in automatic control system design have not given due consideration to the economics of operational management. And economic studies, while yielding minimum-cost solutions under certain criteria, have probably not analyzed the costs of equipment failure and of accidental, transient pollution events. The scope of this report is thus determined by the need to integrate and coordinate, not only river basin management itself, but also the many perspectives that influence the desirability of operational management. These include economics, technological innovation, risk and reliability, and institutional arrangements.

The publication of the WPCF White Paper, with its key psychological role in promoting "problem recognition," suggests that there is no time like the present. Both a convergence between theory and practice and the changing character of problems related to water pollution have made this an opportune time to assess the desirability and feasibility of operational water quality management. Section 2 of this report, therefore, examines the present as a *point of convergence.* With respect to practice, there have been rapid developments in the past two decades: for example, in applying computers and automation to water and wastewater treatment facilities and installing telemetered, on-line networks to monitor river quality. In theory, we have deepened and focused more appropriately our understanding of the part played by control and systems analysis in developing operational management.

Creating the conditions under which operational management can be exercised is a start, but it carries no guarantees. Only when problems cannot be solved along conventional lines does the motivation for change become irresistible. Section 3 of the report thus builds from the sometimes-forgotten truism that nothing remains constant with time. This is a time of *changing emphasis for the management of water quality*; we see this change as a function of several factors.

First, the growing scale and increasingly complex infrastructure of water quality management in developed river basins will progressively curtail the freedom to manage one activity in a basin without affecting other activities there.

Second, the pollution problems to be managed are changing over the long term. We can expect our concern with single objectives (such as the regulation of easily degradable organic matter) to be replaced by the need to deal with interacting and conflicting multiple objectives. The focus on restoring acceptable yearly-average conditions will probably shift markedly toward increased concern with preventing the short-term crises that result from accidents or from the failure of equipment.

Third, the role of treatment facilities is changing. The pertinent questions for a developed river basin now deal, not with building a new system of facilities to achieve a standard, but rather with adapting an existing system to meet changes in problems and standards.

Fourth, instrumentation and monitoring technology have been radically influenced by innovations in electronic engineering. The new technology has created new opportunities for the specification and surveillance of water quality standards. Standards may not only become more stringent; they may also become more complex and may be referred to time scales that are much shorter and more varied than previous ones were.

And fifth, we have entered a period in which a difficult economic climate prevails. After enjoying the relative luxury recently afforded to environmental protection, those concerned with managing water quality will be forced to address much more difficult economic questions. Increasingly, these questions will deal with improving or changing the operation of existing facilities (rather than with constructing new facilities) and with the rapid rise to significance (from virtual obscurity) of operating costs.

In short, the conditions are ripe, and the needs exist, for more widespread applications of operational water quality management. Section 3 discusses the problems that will shape the potential for these applications.

Advocating more widespread applications does not imply that applications of operational water quality management do not exist. In general, however, they represent individual solutions to individual problems; they often lack integration and coordination. Section 4 reviews *current practice in operational management,* treating each subsystem of Figure 1 separately: abstraction, purification, and supply of potable water; the sewer network; wastewater treatment; and the receiving water body. It identifies and examines three types of innovative applications: those oriented to equipment (hardware); those geared to the degree of understanding of process behavior (software); and those concerned with the attitudes and education of managerial staff (man–machine interaction).

We should not underestimate the importance of the last type of application. As the authors of a recent survey of factors limiting wastewater treatment plant performance found, "The highest ranking factor contributing to poor plant performance was operator application of concepts and testing to process control." (Hegg et al. 1978). They also noted that " . . . present plant personnel are an untapped source for achieving improved plant performance."

Our analysis of past achievements provides insights into what we might achieve in the future. Section 5 looks at the *new potential for operational management* in the light of the changing problems and objectives discussed in Section 3. The six principal components of the approach are

1. Advances in economic analysis, which can now accommodate joint considerations of fixed and variable (operating) costs and can incorporate assessment of the effects of transient crises, failures, uncertainty, and meteorological variability
2. Analysis of interactions and reliability (in the sense of achieving multiple objectives within a complex infrastructure of activities, and including the sensitivity of operational management to accidents and failures)
3. Process control system synthesis, with special reference to analyzing subsequent operating policies in the planning and design stages of management (i.e., design–operation interactions)
4. Use of support services in operational decision making, including use of mathematical models
5. On-line monitoring, estimation, and forecasting, in the context of management's requirements for information on which to base operating decisions
6. Computing and on-line control, where we focus on microprocessor-based developments and on the appropriate deployment of both conventional and unconventional control system applications

The first three components concern procedures for analyzing problems before operational management is implemented in practice. They relate to the planning and design stages of management and are aimed at changing the conditions that have so far prevented or hampered wider application of operationl management. The other three components deal with problems of day-to-day operating practice. Three key requirements are characteristic of the approach underlying these components: accepting the human element in the control loop (in response to the findings of Hegg et al. 1978); exploiting all available operating data as fully as possible; and making good use of past empirical operating experience. They thus recognize, and respond to, the challenge of synthesizing solutions that will work in spite of ever-present practical constraints. How best to achieve all these aims is, however, a matter of policy.

Conclusions and recommendations

The final section of the report turns to the policy implications of the problems and the potential solutions to them. Section 6 offers *guidelines for the future*; it addresses the question of what our analysis leads us to expect of water quality management in the future.

We can draw some general conclusions about the desirable attributes of water quality management and can make some more specific recommendations about steps to take toward achieving the full potential of the approach discussed in Section 5. But just how specific can we be in making these recommendations? Our purpose in this analysis was, after all, to bring together many perspectives to provide a broad view of the overall problem. We did not restrict ourselves to a single country, with its own particular institutional structure, to a single type of pollution problem, or to a specific part of the water and wastewater industry.

Our recommendations are consistent with the broad sweep of the analysis. In general, operational water quality management is, and must be, feasible. In some cases, the problems themselves – whether transient crises or the definition of water quality standards by reference to shorter time scales – will force the pace of the change toward operational management. In other cases, desired changes – especially those related to innovations of an electronic engineering nature – are likely to occur at such a rate that further stimulation will be unnecessary, while cautionary recommendations may be needed. In yet other cases, for which most of our recommendations will be relevant, we can perceive undesirable constraints on developing and implementing operational management.

From our analysis we conclude first that good management should be adaptable, flexible, integrated, and coordinated. These virtues may be self-evident, but they will be increasingly necessary in managing complex problems.

A second desirable attribute of water quality management is an understanding of the trade-offs between and interactions among multiple objectives and problems. In other words, we need to recognize and classify the advantages and disadvantages of interactions among the components and management activities of the water quality system.

Third, we must include planning for contingencies. Failures (of many different kinds) will certainly occur, and hence we must plan for corresponding operational measures that will minimize the damaging effects of these failures.

Advocating these ideals is of course far different from achieving them, or even determining whether they are being achieved in practice. But we argue that the ability to exercise operational management, despite its appearance of concern with short-term problems, enhances the adaptability of water quality management over the long term. The problems as described in Section 3 and the review of Section 4 point toward the desirability of these attributes. For demonstration purposes, we need a case study that allows a detailed application of the approach outlined in Section 5; the nitrate pollution problem and the Bedford-Ouse (UK) river system – recurring topics in this report – provide suitable material for such a case study.

The recommendations arising from the analysis can be characterized as institutional, economic, technical, reliability, or professional.

The institutional recommendations concern

- An integrated, regional water management authority. Without such a body, coordinated operational management is unlikely to be as effective as it could be (which reiterates the point made by Okun 1977)
- Funding mechanisms and cost allocation. Separating the source of funds for design and construction costs from that for operating costs obstructs meaningful translation of the results of a fixed/variable-cost economic analysis into practice. Construction and operating costs cannot be traded against each other.
- Legislation. We may adopt the maxim "innovation with spare capacity." Standards that continually force management to operate at the limits of technical capabilities may stifle rather than stimulate innovation by fostering the fear of making mistakes.

The economic constraints on the more rapid development and justification of operational water quality management must also be relaxed. These pertain to

- Performance–cost data. Economic analysis geared to operational management relies on data on operating costs as a function of various pollutant removal efficiencies (for example, costs for operating at 75 percent, 80 percent, and 85 percent biochemical oxygen demand (BOD) removal rates). Such data are generally unavailable or considered irrelevant because treatment plants have always been operated at their maximum efficiencies. Yet when more than one type of pollutant must be removed, not all pollutants can be removed at maximum efficiency, and trade-offs among operations at less-than-maximum efficiencies must be evaluated.

- Aggregated criteria. New criteria for assessing the benefits of operational control must be developed if we are to evaluate these benefits within a broad economic framework. These criteria should, in particular, be capable of aggregating detailed features – such as the control scheme's performance in a wet or dry season and its ability to modify the probability of occurrence of a transient crisis.

With respect to technical recommendations, we are concerned partly with removing constraints and partly with stimulating the rate of innovations in civil engineering to match electronic engineering. Our technical recommendations thus relate to

- Civil engineering innovations. Such innovations relate to new process designs, including the exploitation of "new" physical, chemical, and biological processing mechanisms; biological fluidized bed treatment of water and wastewater is an example. These innovations improve management's "capacity to act" and to implement control decisions, while electronic innovations that facilitate communication and information retrieval are improving the complementary "capacity to observe". Given the stimulus expected from development of biotechnology in other fields, the required civil engineering innovations may be imminent.
- Design–operation interactions. We need to assess the influence of process designs (both new and old) on operating policies.
- Conventional/unconventional control applications. The primary aim of conventional control applications in operational water quality management should be to free the manager from routine business to enable him to concentrate on coordination, evaluation of trade-offs, and management of contingencies. In particular, we can then use unconventional approaches to assist the manager in achieving these aims.

The problems of communication and information retrieval have been much alleviated by innovations of electronic engineering equipment, as already noted. There are both advantages to be exploited and pitfalls to be avoided as a result of these developments, developments that have raised questions about reliability, particularly with respect to the following:

- Operational monitoring. The information requirements of operational decision making differ from those of planning and of supervising compliance with standards. The needs of operational monitoring should be defined according to the three principles discussed in Section 5: (1) Because all variables of possible interest cannot be measured, those that can be measured should be measured reliably; (2) what we wish to know for operational purposes is not necessarily the same as what can be measured; (3) the potential for deriving more useful information from existing monitoring systems has not been fully explored. To some extent, these principles shift the burden of providing operating information away from relying on sensor hardware and toward relying on computing device software.
- Pertinent operating information. An operational monitoring network is ultimately only as effective as the managerial response to the information provided. A monitoring system that encourages too great a dependence on the infallibility of instruments and computers and that submerges pertinent details of operation in an excess of irrelevant information is certainly unreliable.

These recommendations do not cover requirements for personnel responsible for operational management, yet this, too, is crucial. Two recent feature articles in the Journal of the US Water Pollution Control Federation highlighted the problem. Wubbena (1979) noted that "Billions of dollars are spent on complex facilities to ensure safe drinking water and to treat wastewater, but recruiting, training, and retention of competent operators has not kept pace with advancing technology." Sherrard and Sherrard (1979) argued that "One of the most pressing and immediate problems facing the water pollution control field is the recruitment, employment, training, and retention of a highly motivated and dedicated work force." Our professional recommendations therefore deal with

- Man–machine interaction. The convergence between theory and practice, our review of current practice, and the new potential for operational water quality management all point toward the critical importance of man–machine interaction. Plant automation and computerization should neither merely assume the passive role of recording plant performance nor aim toward eliminating the human element from the control function. Rather, technological innovations should be used to encourage active interaction between man and computer in operational management.

- Education and research. To the list of recommendations concerning operator training given elsewhere, we merely add that man–machine interaction implies an increasing demand for skilled personnel who are familiar with the use of computerized support services for operational decision making. With respect to research (and with important implications for education), two areas merit more concerted effort. First, we should improve our understanding and classification of interactions among components of the water quality system, interactions among pollutant problems, and interactions among the control actions taken to resolve these problems. This will accelerate satisfaction of the need for integration and increase appreciation of the interdisciplinary character of water quality management. Second, we should study design–operation interactions systematically. Such study will add a wider appreciation of process dynamics to existing strengths in civil engineering research.

Expectations

Innovative change does not occur rapidly. All systems exhibit dynamic behavior with characteristic response times, and some observers suggest that the system of water quality management has a response time of about 10 years. Certain observations support this hypothesis. For example, in 1975 the Committee on Public Works and Transportation of the US House of Representatives reported (in reviewing the effects of the 1972 amendments to the Federal Water Pollution Control Act, as embodied in Public Law 92-500) that " . . . where [improved water quality] is being achieved, along Lake Erie beaches, in the Hudson River, the Willamette River, and other lakes and streams, it is the result of earlier state and federal legislation, and particularly the 1965 Federal Act." (Committee on Public Works and Transportation of the US House of Representatives 1975). The same committee noted that "In the minds of too many professionals, PL-92-500 is a law to build waste treatment facilities in the same manner that they have always been built. It is vital that these key persons seek to apply the visionary concepts of PL-92-500 without repudiating the practicality of the past. [Wastewater treatment facilities] should be operated in a manner that is consistent with total environmental protection. Conventional thinking must be altered."

Given such observations, we have few illusions about the pace of change. Our expectations will be measured on a scale of decades rather than years.

2

A Point of Convergence

There is no time like the present; a convergence between theory and practice has made this an opportune time to assess the feasibility and desirability of operational management. In practice, we have in the past two decades seen a progressive increase in both the scope and ease of acquisition of water quality data. The electronic age has enhanced the capacity to observe in water quality management, a property that is central to operational management. In theory, on the other hand, we have seen a growing appreciation of the practical constraints on operational water quality management. We have come to recognize the key role of the manager as decision maker in the control loop.

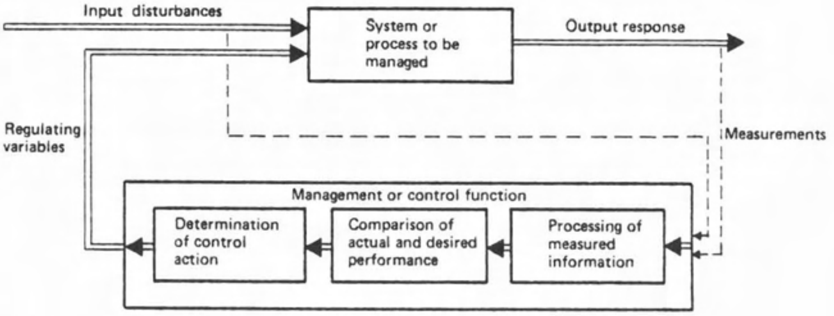

Figure 2. The simplified operational management system.

Practice

Figure 2 shows the three primary elements of a simple management system: (1) processing measured information, the results of which can be used for (2) comparing the system's performance with the desired objectives, the results of which can in turn be used for (3) determining a regulatory action if the performance

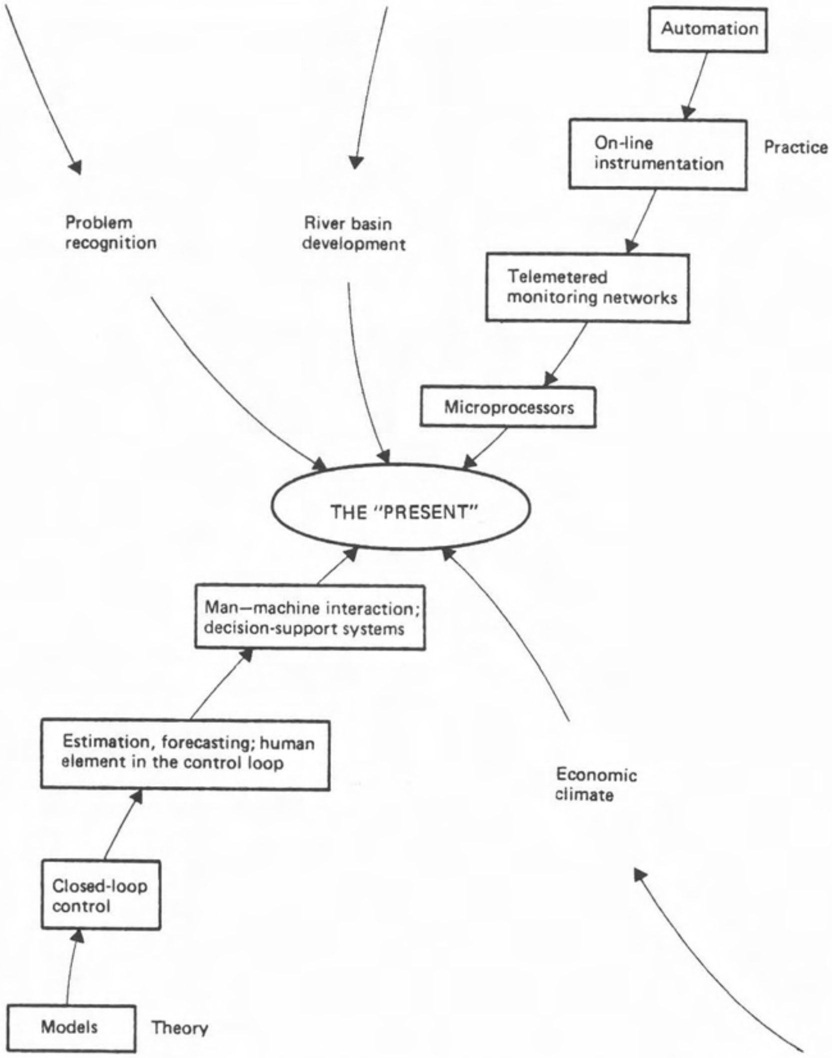

Figure 3. The present: a point of convergence between practical and theoretical developments.

does not meet the objectives. Thus, in practice, the success of management – at the planning, design, or operational stage – depends on the capacity to acquire pertinent and reliable information and to implement regulatory action.

During the past two decades significant changes have occurred in the technological facilities for observation and action in operational water quality management. Figure 3 shows some of these developments. Automation* in water quality management became particularly popular during the late 1960s and early 1970s. (The International Association for Water Pollution Research has convened three workshops – in 1973, 1977, and 1981 – on this topic.) Developments resulting in new and more reliable on-line instrumentation have been closely coupled with the movement toward automation. Equally significantly, but more recently (within the past four or five years in the United Kingdom, for example), several regional telemetered networks for monitoring water quality have been installed. And like every other area of industrial activity, water quality management currently is confronted with the need to evaluate the real and appropriate potential of small-scale computing applications – particularly microprocessors.

It is difficult to assimilate the full importance of all these rapid developments in practice, although a comparison of past and possible future practice indicates their potential. Manual collection of a water sample followed by laboratory analysis was (and still is) the common practice for measuring the variables that characterize water quality. Such practice meant that all data would have a relatively low frequency of sampling (probably less than once per day at the maximum). The data thus assembled were available for retrospective analysis only; they were collected for the purposes of acquiring basic knowledge and accumulating records for planning, design, and research – that is, for nonoperational activities. If, in the past, river basins were not particularly highly developed (with but few interactions among different activities), it may well have been possible to argue that today's computers and mathematical models would not have been required for the data to be

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* By *automation* we mean the automation of information retrieval (e.g., on-line sensors) and of implementation of control actions (e.g., turning pumps, blowers, and scrapers on and off). *Management/control,* on the other hand, refers to the set of activities linking these two functions. Because of this distinction, it is misleading to assume that automation necessarily implies better management – although one would expect it at least to create a greater potential for better management.

processed into information suitable for decision making. Moreover, the information derived from the data was probably not so copious or complex as to threaten to confuse and overwhelm this decision-making function. With current technology, however, we may contemplate the transfer of 300 pieces of data (for example, 30 monitoring stations with 10 measuring instruments each) from an on-line water quality monitoring network to a central computer once every five minutes. These are data received at a frequency orders of magnitude greater than previously imagined possible. Thus we have in a single step created an information system potentially capable of supporting operational management.

The increase in the capacity to observe brought about by the electronic age is, then, centrally related to the needs of operational management. Enhancement of the capacity to act, however, has been less spectacular – perhaps because of the closer relationship between this aspect of management and the "built" civil engineering features of the river basin.

Theory

Theory tells us that operational process control schemes will be successful

- If a valid and accurate model of process dynamic behavior exists
- If a reliable, robust monitoring system for rapidly collecting information about process performance is available (there is little point in implementing actions if they are decided on too late)
- If, for mass transfer processes, the capacity to store flows and substance masses is available (this concerns the capacity to implement actions)
- If the ability to specify clear, precise, unambiguous targets for good process performance exists

A conventional objective, after these conditions have been satisfied, would be to eliminate the human element from the feedback loop of the basic management system shown in Figure 2; this would be termed fully automatic, closed-loop control.

The areas in which the four conditions listed above are largely satisfied (such as the aerospace, nuclear power, chemical process, and paper and pulp industries) are areas in which automatic operational control has become indispensable. However, the assumption that these four points would hold in practice has lent an air of unreality to some early theoretical studies of operational water quality management. For example, numerous models of the relationships among water quality variables have existed since the mid-1960s. There has been no shortage of hypothetical models, but rather a shortage of evidence that the models reasonably represent reality. Six or seven years ago, articles about river water quality control began to appear in control theory literature. It was a relatively easy exercise to show that, in principle, many aspects of river water quality – although, more truthfully, river water quality models – are amenable to the methods of operational control system synthesis. Control in theory and automation in practice, as indicated in Figure 3, were at that time poles apart.

A compromise was clearly necessary. Why should we assume that the problems of operational water quality management are conventional problems requiring the application of conventional process control schemes? The conventional profit motives and reliability considerations of other industrial activities, which stimulated applying operational control in those areas, have not been strongly evident in the management of water quality. (There is, however, every reason to believe that they will become evident here, as we shall see in Section 3.)

The compromise of theory emerged in the form of concentration on developing and applying on-line estimation and forecasting algorithms. Accepting the manager as an integral component of the control loop, this compromise approach views models and information-processing algorithms as a support service in the day-to-day decision making of operational management. The models and algorithms are not replacements for the manager. Automation and computerization should neither merely assume the passive role of recording plant performance nor aim for eliminating the human element from the control function. To pursue this argument, active man–machine interaction should be the ultimate objective. Control theory itself now formally recognizes qualitative, empirical operating experience as a legitimate means of control system design.

Theory, then, shows a growing appreciation of the practical limitations on operational water quality management. It has come to recognize the key role of the manager as a decision maker in the control loop and it is especially well placed to examine the feasibility of microprocessor-based models and estimation, forecasting, and control algorithms. This does not mean that all the problems have been solved. For example, while improvements in instrumentation, monitoring, and automation are evident, wastewater treatment plants still use less instrumentation and automation than do related industries. Typical wet chemical process plants report investment in instrumentation and automation of 8 to 15 percent of construction costs, whereas water purification and wastewater treatment plants subscribe to a figure of 3 to 6 percent of construction costs for similar investments (Guarino and Radziul 1978).

Problem recognition and the economic climate

This is a time of convergence. The number and variety of technological facilities for practical application of operational management have increased, and the theoretical understanding of how best to exploit these new opportunities has improved. The prerequisites for introducing operational water quality management have been met. But having created the conditions under which operational management can be exercised does not guarantee that it will be; the prevailing economic climate and recognition of the problem are also essential factors that motivate change and merit our consideration.

3

The Problems: Changing Emphasis for Management

Operational water quality management must be seen as necessary and desirable in order to be accepted and used. There is no doubt, as the WPCF White Paper shows, that the problem of operation and maintenance is recognized in wastewater treatment. When problems cannot be solved along conventional lines, the motivation for change becomes difficult to resist.

This part of the report is a reference section about the changes and problems that make operational water quality management not only possible, but also necessary and desirable. Here we discuss

- The growing complexity of river basin management – activities in the river basin become intensive, and an increasing number of management objectives makes trade-offs among conflicting objectives necessary
- The changing character of pollution problems – from a concern with restoring acceptable average conditions to a desire to maintain such conditions while preventing damaging transient crises
- The changing role of treatment facilities – the pertinent questions for a developed river basin now deal, not with building a new system of facilities to achieve a standard, but rather with adapting an existing system to meet changes in problems and standards
- More complex standards resulting from better instrumentation and monitoring capabilities, which enable measurement of more variables in greater detail and more frequently and thus the revision of standards in like terms
- The more difficult economic climate, when operating costs are rising more rapidly than other costs and we are likely to inherit

plants that are expensive to operate owing partly to a lag in innovative design changes and partly to unwillingness to consider operational problems during the design process

Nothing remains constant with time. We are at a pivotal point in developing and applying operational water quality management.

Growing complexity of river basin management

In its early stages, river basin development consists merely of providing a reliable, unpolluted supply of water to users located within the catchment. The collection, treatment, and disposal of sewage are usually the responsibility of a management authority different from the authority supervising the supply of water; coordinated development and management are almost non-existent.

As development within the basin continues, water conservation measures (such as surface storage), water supply, and effluent disposal become increasingly interactive. The effects of all these activities must be monitored: the introduction of a monitoring system marks the initiation of formal, albeit passive, river management. Accordingly, legislation to preserve an "acceptable" river water quality may be required. The appropriate institutional structure for management is a single (regional) authority responsible for the growing number, scale, and complexity of activities within the basin.

In the final stages of development, the water resources of the river basin are used intensively, and the activities to be managed within the basin involve an increasing number of conflicting objectives. Rather than waiting passively and reacting to development *ad hoc,* river basin managers must now act in an integrated fashion, in terms of both planning and operation; they must exert positive control over activities within the basin. Rather than continuing to separate the parts from the whole, managers must consider together not only the constituent elements of the water quality system of Figure 1 but also the multiple combinations of such systems in the basin.

The management structure evolves with time, first permitting considerable development without coordination, gradually becoming more complex, finally requiring considerable coordination in managing development and managing the developed river basin in an operational sense. Independence of action in managing the activities of the basin is gradually lost in a kind of implosion of interactions. The objectives of management multiply and become more complex; focusing attention single-mindedly on, for example, the traditional problem of easily degradable organic wastes and their effects on dissolved oxygen becomes impossible. Inevitably, conflicts among multiple objectives lead to decisions that have to be made on the basis of more or less imponderable trade-offs.

The immediate concern of operational water quality management is with the intensively used water resource systems that characterize developed river basins.

Changing character of the problems

How have water pollution problems changed, thus changing the emphasis of management? We might conclude from recent surveys and reviews (see, for example, Organization for Economic Co-operation and Development 1979) that water quality in the rivers and lakes of several industrialized nations (as characterized by suspended solids and easily degradable organic matter) is improving. Assuming that an industrial society generates as much or more potentially polluting matter today as it did ten or twenty years ago, this is a fortunate situation; a bad environmental condition has been restored to a more or less acceptable one.

Management of water quality over the past decade has correctly been interpreted as a curative strategy. And there may well be a growing awareness among the public that, on a long-term average basis, the quality of river water is indeed improving. Between the beginning and the end of the past decade, governments invested in widespread construction of wastewater treatment facilities. Now, a greater amount of effort is being devoted to preventing a larger proportion of the potentially polluting matter from being discharged to receiving waters.

One consequence of such long-term changes is that water quality management in developed river basins is shifting from a curative to a preventive strategy. We now see greater concern for preventing failures in the system of pollution control because, on the one hand, a greater number of treatment facilities and complex processes need to be operated in order to maintain the control effort and, on the other hand, any failure will be more apparent and "damaging." If the thrust of legislation to control the discharge of toxic substances is prevention of release into the environment (source regulation), then management must create a form of control that is responsive to highly discontinuous events of inadvertent release. This, too, tends to shift emphasis away from the management of continuous discharges with essentially steady characteristics and polluting loads.

Assuming, for example, that water quality can be measured by an all-embracing index Q, we can postulate a simplified picture of past and future performance in water quality management (see Figure 4). In this picture, the average level of water quality achieved in the future will be better than the average level of water quality maintained in the past. Yet there remains the problem of transient crises – caused by accidental spillages or equipment failures at treatment plants, indicated in Figure 4 by P_A, P_B, F_A, and F_B. In the past, with rivers receiving a higher pollutant load, the relative effects of P_A and P_B might have passed virtually unnoticed, as minor perturbations in performance. In the future, however, the relative effects of similar crises will be significantly greater. As public awareness of improved water quality becomes well established, the responsibility of management to avoid such crises increases.

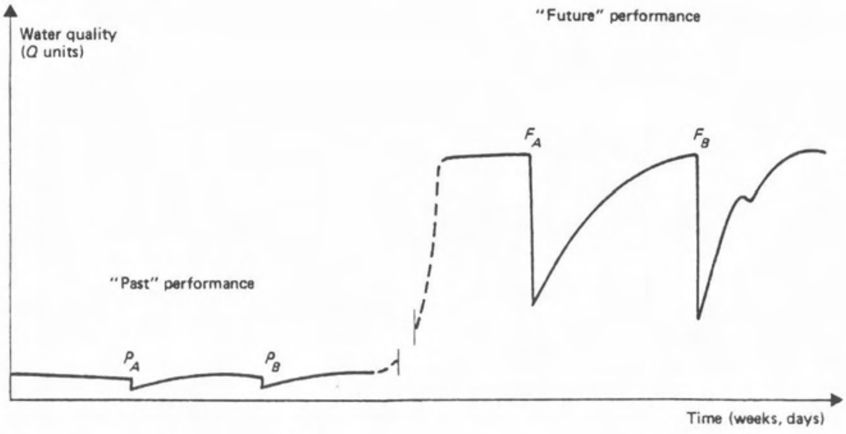

Figure 4. Past (P) and future (F) performance in water quality management, where P_A, P_B, F_A, and F_B represent transient pollution events.

Changing role of treatment facilities

What are the implications of the shift from curative to preventive management strategies in terms of treatment facilities? Figure 5 shows a scenario for long-term trends in water quality management over the three phases associated with the stages of river basin development discussed previously. During the first phase (no standards), there is an increasing load of polluting matter discharged to the receiving water body whose quality is steadily deteriorating. The objective in this phase is clearly to introduce standards and to ensure that they are met.

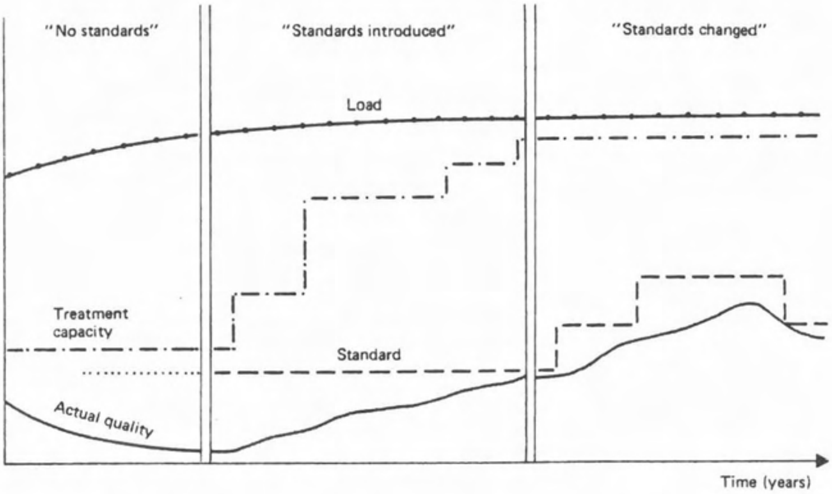

Figure 5. A scenario for long-term changes in total potential pollution load before treatment, treatment capacity, standards, and actual water quality in a developed river basin, where —•—•— shows the total potential load before treatment; —·—·— the treatment capacity; – – – the standard, and ——— the actual quality.

In the second phase (standards introduced), the progressive construction of treatment facilities (for example) may reduce step by step the load discharged to receiving waters, resulting in overall improvement in water quality.

For a river basin currently in transition from the second to the third phase, the recent past is characterized by a management strategy in which the installed capacity for treating wastewater is increased until a constant specified standard is achieved. Such a strategy emphasizes the need to plan and design facilities to treat a larger percentage of the polluting matter generated by industries and municipalities. The key to the strategy is contained in terms such as capacity, percentage, and volume. In the third phase of Figure 5 (standards changed), the predominant future management strategy is likely to be determined by the need to respond to changes in the desired standards for water quality under conditions of a more or less fixed capacity for wastewater treatment. In other words, the pertinent question for a developed river basin is not how to build a completely new system of facilities to achieve a standard but rather how to adapt an existing system to meet a change in the standard. Thus, the treatment system in the third phase is oriented to the type and flexibility of performance rather than to capacity.

Such questions of adaptability and the changing role of treatment facilities are intertwined with the changing nature of pollution problems. Precisely because of management's success in the widespread construction of wastewater treatment plants, the day-to-day operational management of water quality has assumed greater significance. Managers must deal with an already existing system of facilities. Maintaining the performance of this system, or changing its performance in the face of changing problems, is a continuing responsibility. Preventing equipment failures, detecting transient crises, and the associated managerial responses – in short, the reliability of performance and the sensitivity of one part of the system shown in Figure 1 to failure and perturbations in another part of the system – cannot be dealt with by planning and design alone. These are matters requiring operational management. The availability and practice of short-term, operational management may enhance the ability to adapt to changing problems and objectives over the long run.

As an illustration, a dominant concern of water quality management in Sweden has been to control lake eutrophication by removing phosphorus compounds from wastewater. Generally, little effort is made to obtain consistent nitrification in wastewater treatment, and standards concerning removal of nitrogen compounds are not widely applied. Inevitably, therefore, a significant portion of oxidizable nitrogenous matter passes through the treatment system. If attached to suspended solids, this matter eventually settles into the sediments of the receiving lake. Managing eutrophication in this manner might appear to be quite effective, but significant nitrification of the settled waste material may actually occur, with subsequent anaerobic conditions being temporarily established in the lake sediments. These anaerobic conditions may in turn give rise to releasing to the overlying water column additional phosphorus in a form suitable for uptake by algal populations. What then occurs in the lake – the oxidation of waste nitrogenous matter – should clearly be encouraged to take place in the wastewater treatment plant; this indeed is the case for the Akeshov-Nockeby plant near Stockholm. Yet how can an existing plant be adapted at minimal cost, and preferably through a change in operational management, to satisfy the revised objectives?

More complex standards

Standards for water or effluent quality do not change simply in becoming more stringent or in altering the focus of attention from one pollutant to another. Changes in instrumentation and monitoring technology create new opportunities for the specifying and surveying of standards. If more variables can be measured in greater detail and more frequently, standards can be revised similarly. The standards may therefore assume a more sophisticated and complex structure.

For example, certain regulatory agencies in the US, such as the Texas Department of Water Resources, may now impose instantaneous, 7-day average, and 30-day average constraints on the permissible concentration of ammonia in a municipal treatment plant effluent. Consider, then, the following possible dilemma. There is a spillage of toxic material into a sewer network that threatens to kill the nitrifying organisms. If the treatment plant manager acts to avoid process failure, the plant effluent may violate the instantaneous ammonia limit. If he does not take such action, the process may indeed fail, and several weeks may be required for the growth of a new nitrifying culture – weeks during which the probability of a violation of the 7-day or 30-day average limit will be high. A change, then, in the capabilities of the monitoring system toward observing shorter-term variations permits a corresponding change in the reference time scale for specifying standards. Standards of such a complex nature are strongly coupled to operational management of water quality; the flexibility of performance demanded by such standards is not assured simply by an appropriate plant design configuration.

A variation on the topic of changing standards is the situation in which a standard remains fixed, but the means of meeting it change fundamentally. As an example, we can look at the nitrate problem, a problem to which we shall return throughout this report.

In many rivers in the UK, the lower reaches of the River Thames included, nitrate concentrations have been steadily increasing over the past 15 years. Figure 6 presents a scenario for this trend (it does not show actual conditions on a specific river). The three main sources of nitrate in the Thames, for instance, are sewage effluents, groundwater, and local surface runoff from agricultural land. Conventional practice is to separate these sources into point and nonpoint categories. In terms of "problem recognition," it is also conventional to argue that as point-source discharges of pollutants become increasingly well managed, nonpoint-source pollutants are perceived as an increasingly significant problem.

Figure 6 is therefore unconventional, for in it we make a conceptual distinction between "direct" and "indirect" sources of nitrate in river waters. The nitrate problem can be (but does not have to be) viewed as a problem in which time is of the essence. The distinction made in Figure 6 is based on this view because the key problem for water quality management in the immediate

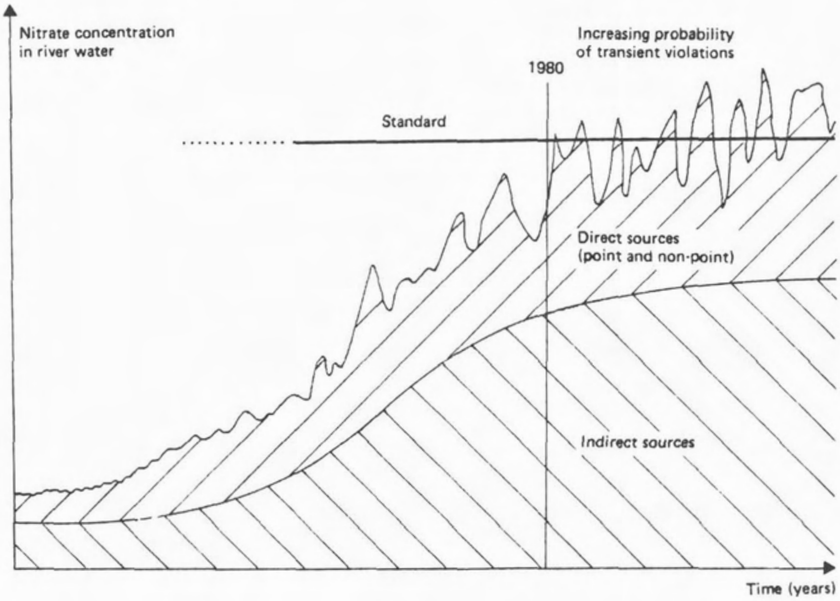

Figure 6. Long- and short-term changes in river nitrate-nitrogen concentration, showing the increasing probability of transient violations.

future will be the increasing probability of transient violations of the World Health Organization standard for permissible nitrate concentrations. These transient, higher-frequency variations are related to (among other factors) seasonal and day-to-day fluctuations in weather conditions, which affect both runoff from agricultural land and the effluents from wastewater treatment plants – that is, the direct sources of nitrate. In other words, fluctuations in river nitrate concentrations are a function of short-term changes in these direct sources, whether from point or nonpoint discharges, and such variations are determined by events of the recent past.

That the probability of transient violations is increasing is admittedly a function of the steadily increasing "base" level of river nitrate concentration deriving from indirect sources – that is, from groundwater flows. But, although the cause of increasing nitrate levels in groundwater and in local runoff is the same (most experts would point to increasing application of fertilizer), the effects on the quality of river water are quite different. Because a groundwater system has a slow response time, the effect perceived is probably related to a cause that occurred 10 to 20 years ago, and the indirect source of nitrate is unlikely to exhibit short-term variations of any relative significance.

In this situation managers are committed to a short-term management issue because of a long-term problem. Their response to this predicament might well be a prudent mixture of planning and operational functions. The latter might be proposed on the grounds that transient violations will occur and contingency control action will be taken to compensate for their effects. A network for operational monitoring and forecasting of water quality in order to protect potable water abstractions might serve as such a solution. It could be viewed as an interim solution, which will eventually become redundant, for managerial action to regulate the causes of excessive base-level nitrate concentrations is a matter of long-term strategy.

The more difficult economic climate

Few, if any, aspects of industrial activity have remained impervious to the effects of the oil price rises of 1973. Wastewater treatment is no exception. In the course of long-term changes in the economic climate, we note growing pressure for the emphasis of management to move toward shorter-term operational matters.

During the 1960s and early 1970s it became popular to design increasingly energy-intensive wastewater treatment plants. Such process designs were promoted because they offered opportunities both to reduce land requirements, capital costs, and operation and maintenance requirements and to increase the levels of pollutant removal. With the 1973 oil price increases and emerging awareness of the "energy problem," the trend reversed. Roughly speaking, however, the lead time between designing and commissioning wastewater treatment facilities is 10 years; that this gap is so large is a point worth considering in more detail later. Figure 7 shows that the delayed repercussions of the "energy problem" are surfacing in an awkward manner. Today, in 1981, many agencies responsible for managing water quality have either recently commissioned or are about to commission a greater number of energy-intensive treatment facilities.

But not all repercussions of the oil price increases have been so slow in coming. Before 1973, and for some time thereafter, one might have been informed, when inquiring about the significance of operating costs in wastewater treatment, that such costs were negligible. Annual operating costs might have

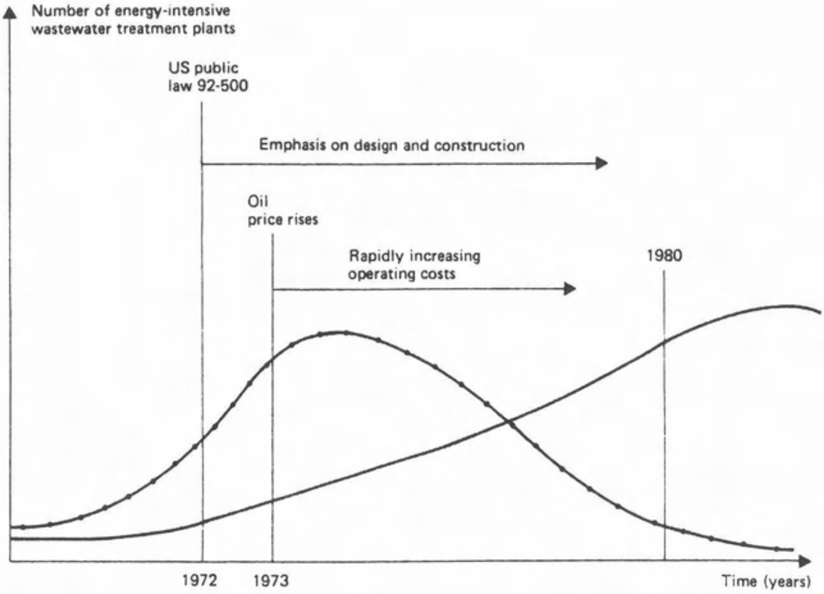

Figure 7. A scenario for the number of energy-intensive wastewater treatment plants at design stage (—•—•—) and at commissioning stage (———).

amounted to perhaps 3 percent of capital costs. However, a survey of the (US) Engineering News Record (Anonymous 1977) brings into sharp focus the radical change in this situation. The survey showed that the average number of years elapsed from the time a plant was put into operation to the point at which operation and maintenance costs totaled more than the initial investment was just 6.1 years. Similar changes are evident in Sweden: in 1971 the operating cost of treating one cubic meter (m^3) of wastewater was 1.0 Swedish krona; by 1978 this cost had risen to 3.5 kronor. Thus, at a time when operating costs are rising rapidly there is also the prospect of an inheritance of plants that are especially expensive to operate.

This predicament is hardly likely to be eased by (for example) some of the unexpected consequences of the US Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500). Observers looking back on the effects of the act have noted that large amounts of freely available construction funds led to instances of poor design and construction of plants that would subsequently make adequate operational management difficult to achieve. Moreover, the difference between the source of funds for design and construction and that for operating costs has tended to reinforce the conventional separation of design and operational considerations.

These matters concern innovation in a non-profit-making industry. To the quotation from the Committee on Public Works and Transportation of the US House of Representatives in Section 1 we may add the following observations from a special report of the UK Institution of Chemical Engineers (1974):

> The responsibility for designing plant often rests with firms of consulting engineers only a few of whom employ staff qualified to appraise novel equipment. In addition the system of remuneration can be considered to act as a disincentive. A consulting engineer has to spend extra time and money to devise or to appraise new equipment which, if it results in a lower capital cost for the works, will result in a smaller fee for the consulting engineer.

The incentive to build an optimally designed plant or process is small, and an analysis of economic trade-offs between design and operation is seldom, if ever, carried out. A wastewater treatment plant will not fail to survive economically even if the responsible authority neither demands, nor is offered, the most recent design configuration. From these circumstances derives a major part of the lag between design and commissioning and, to a lesser extent, the differential rates of electronic engineering and civil engineering innovations in water quality management.

Operational management in a long-term context

Nothing remains constant with time. The problems to be managed are changing over the long term. The objectives of management and the ways in which standards can be specified are also changing, as is the economic climate. Against the background of these long-term changes, then, we can look at the present as a pivotal point in the development and application of operational water quality management. Because of technological developments in monitoring and data processing, the success of past management strategies, and the rapid rate of increase in the cost of operating treatment plants, it is becoming increasingly important to devote attention and resources to operational management. Practicing operational management should enhance our ability to respond to future changes in water pollution problems.

4

A Review: Current Practice in Operational Management

At a time when so many things are changing so quickly, it is difficult to summarize the state of the art in operational water quality management. At best we can present only a sample of the most advanced existing practical applications. Table 1 shows the applications that we shall discuss in this section as we review achievements in solving the problems discussed in Section 3. The purpose of our review is to examine innovative applications that are oriented to equipment (hardware), geared to the degree of understanding of process behavior (software), or concerned with the attitudes and education of managerial staff (man–machine interaction). These points are related to the developments in theory and in practice that we discussed in Section 2. We also examine briefly some of the reasons underlying these innovative changes and turn finally to the largely unresolved matters of the integration, coordination, and adaptability of management activities. The nitrate problem, which we introduced in Section 3, exemplifies the type of problem likely to stimulate the changes needed to resolve these key issues of operational management.

Abstraction, purification, and supply of potable water

In 1975 the Bureau of Waterworks for the city of Yokohama, Japan, commissioned the Nishiya Water Purification Plant. The plant has a capacity of 400,000 cubic meters per day and is part of an integrated water supply system operating at a maximum daily supply of 1,350,000 cubic meters. Raw water is abstracted at three locations from adjacent rivers. In addition to the Nishiya

TABLE 1 Examples of applications of operational water quality management.

Subsystem	Applications
Abstraction, purification, and supply of potable water	Yokohama (Japan) Helsinki (Finland)
Sewer network	Seattle, Washington (USA) Cleveland, Ohio (USA)
Wastewater treatment	Norwich (UK) Hiroshima (Japan)
Receiving water body	Bedford-Ouse (UK) Ruhr (FRG)

facility, there are three other purification plants in the system; one of them, Tsurugamine (which has a smaller treatment capacity of 100,000 cubic meters per day), has been operated since 1976 with complete direct digital control for the entire plant. Since 1977 the Nishiya plant has also been operating with a fully integrated, centralized computer control system. Operational management

TABLE 2 Illustrative classification of types of operational management in the abstraction, purification, and supply of potable water (based on the Yokohama, Japan application).

Fully closed-loop control facilities (hardware)	Operational models (software)	Man–machine interaction
Chemical dosage control (coagulation) Sludge treatment control Pump operation	Prediction of source-stream discharge and quality Off-line simulation for control of rapid sand filter backwashing Prediction of potable water demand On-line scheduling model for distribution of supply	Interaction with the scheduling model during transient, accidental pollution of intake raw water

similar to that in Yokohama has been applied on the island of Okinawa and for the city of Tokyo.

Table 2 shows some of the important features characteristic of operational management in these applications; they are illustrative rather than exhaustive. Much of the system for abstraction, purification, and supply is fully automated under normal operating conditions but relies strongly on the human element in the management/control loop for decision making under abnormal conditions. For example, temporarily low-quality river water passing one of the abstraction points in the Yokohama system prompts decisions aimed at increasing the rates of abstraction at the other two locations. Models are used primarily to assist in stabilizing the operation of the system during short-term fluctuations in the input (raw water quality) and desired output (consumer demand); these inputs and outputs are defined by the fluxes ν_{01} and ν_{1c}, respectively, in Figure 8.

The sewer network

At the beginning of the 1970s most major cities in the US were facing the problem of pollution of receiving waters from combined sewer network overflows. In January 1971, as part of a six-year demonstration grant study with the US Environmental Protection Agency, the Municipality of Metropolitan Seattle commissioned an operational sewer network control facility. Similarly, throughout the 1975–1977 period, the city of Cleveland was assessing the performance of automatic regulators suitable for minimizing combined sewer overflows. The automatic regulators consisted of a control gate at the entrance of an interceptor sewer line and an inflatable dam placed adjacent to the control gate in the trunk sewer.

Table 3 summarizes some of the most important features of current practice in the operational management of sewer networks. The main stimulus for innovation in this part of the water quality system has come from the need to prevent overflows (flux ν'_{24} in Figure 8) from combined sewers. The problem of dealing with abnormal (rainfall-related) operating conditions is thus the basis for operational management. In practice, managing normal operating conditions is hardly considered at all, in contrast to the operational control strategy for the water supply network discussed in the preceding subsection. Clearly, it would be possible to use the existing control facilities for regulating the variations in the influ-

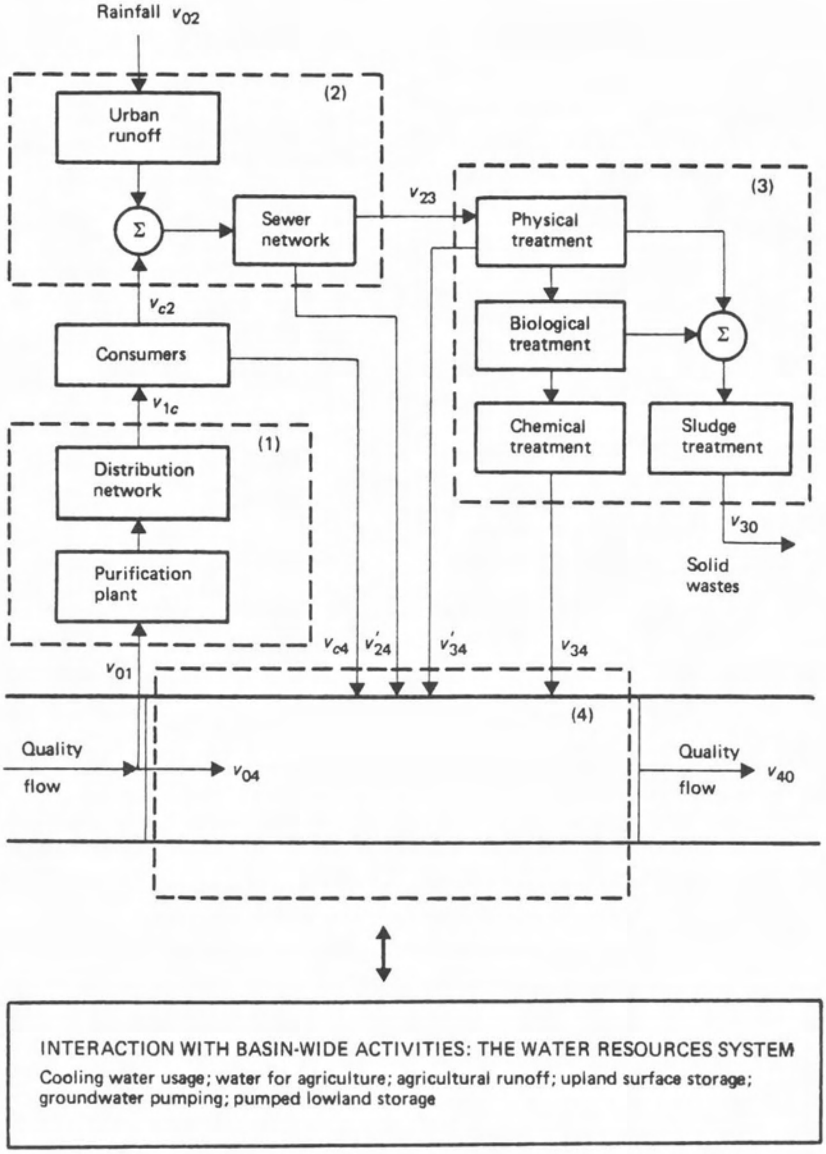

Figure 8. A more detailed definition of the water quality system (Figure 1) as an abstracted feature of river basin management: (1) abstraction, purification, and supply of potable water; (2) the sewer network; (3) wastewater treatment; and (4) the receiving water body. The notation v_{ij} indicates the flow of material from subsystem i to subsystem j, with subscript 0 denoting fluxes into and out of the system; v'_{24} and v'_{34} represent overflows (e.g., due to a storm event) from the sewer network and wastewater treatment plant respectively.

TABLE 3 Illustrative classification of types of operational management of sewer networks (based on the Cleveland, Ohio (USA) and Seattle, Washington (USA) applications).

Fully closed-loop control facilities (hardware)	Operational models (software)	Man–machine interaction
Inflatable dam in sewer for diversion of overflow	Prediction of quantity and quality of runoff entering the network	Interaction with the decision model
Gate for regulation of interceptor sewer flow	Routing of sewer flows	
Pump operation	Decision model for determination of the location, treatment, and diversion of overflows	

ent to the wastewater treatment plants connected to the network (i.e., flux ν_{23} in Figure 8). This is, however, generally regarded as a secondary objective of management. Operational management of the sewer network is therefore not subordinated to the requirements of wastewater treatment facilities. The operating strategy is geared to regulating abnormal conditions; thus interaction between the decision maker (operator) and computer support services (models) is integral.

Wastewater treatment

For the past 10 to 15 years a large proportion of research and development effort in water quality management has been allocated to designing and operating wastewater treatment facilities. We have chosen to look at two of the many applications of automation and process computers in wastewater treatment plants. In 1973 the computer control system of the Norwich Sewage Works in eastern England, our first example, was first placed on line. This is a medium-sized plant with a design dry-weather flow capacity of 55,000 m^3 per day. Our second example, the Asahimachi plant of the Bureau of Sewage for the city of Hiroshima, Japan, has a much larger operating capacity of 520,000 m^3 per day. It was commissioned in 1976.

Table 4 lists important aspects of automated control loops, on-line models, and man–machine interaction that are typical of

TABLE 4 Illustrative classification of types of operational management in wastewater treatment (based on the Norwich, UK, and Hiroshima, Japan applications).

Fully closed-loop control facilities (hardware)	Operational models (software)	Man–machine interaction
Dissolved oxygen control (activated sludge)	Model for the activated sludge process (prediction of effluent quality one week in advance)	Set-point coordination Interaction with the activated sludge model
Recycle flow or mixed liquor suspended solids control (activated sludge)		
Total sludge quantity control (activated sludge)		
Chlorination plant control		
Screen speed operation (preliminary treatment)		
Desludging (primary sedimentation)		
Pump operation		
Sludge blanket level (secondary clarifier)		
Additional screen operation during high flow conditions		

the installations at Norwich, Hiroshima, and elsewhere. Many items of equipment (such as pumps, screens, and scrapers) and several unit process operations (such as desludging and chlorination) can be fully automated or placed under closed-loop control. One process in particular, the activated sludge process of biological treatment, has attracted much attention in the development of operational control schemes. According to current practice, this process can be operated with closed-loop control of dissolved oxygen and mixed liquor suspended solids concentrations in the aeration tank. In turn, these individual control loops can be coordinated to satisfy the requirement of an overall closed-loop controller for total sludge quantity in the aeration tank and secondary clarifier.

Most of the items listed in the first column of Table 4 refer to operation of a wastewater treatment plant under normal conditions. In contrast to operational management of sewer networks, considerations of the control of abnormal events and circumstances, such as minimizing of overflows from the plant (flux ν'_{34} in Figure 8), have not been dominant innovative forces in changing management practice. This does not imply, however, that abnormal operating conditions are not managed. Some of the excessive influent disturbances (flux ν_{23} in Figure 8) are handled during preliminary sewage treatment – by using standby screens, for instance, or by installing screens that can operate at more than one speed. Other types of internally generated disturbances to normal plant operation – problems related to sludge settling in the secondary clarifier, for example – can be temporarily regulated by an automated control response to the detection of a rising sludge blanket level. Yet while many aspects of wastewater treatment operations can be managed without human decision making, coordination of the individual control loops remains essentially the plant manager's responsibility. In general, this responsibility does not involve a high level of active man–machine interaction; individual control-loop coordination, when it is practiced, is usually based entirely on the manager's previous empirical operating experience. All too frequently, installations of process computers seem to be confined to passive data-logging activities. Thus the reference in Table 4 to man–machine interaction in connection with an operational model of the activated sludge unit is quite exceptional (it refers, in fact, to the Asahimachi plant).

The receiving water body

During a severe drought in 1965, the salt water "front" in the Delaware estuary had moved considerably further upstream than normal and thus posed a threat to the abstraction supplying the city of Philadelphia at Torresdale. A model for chloride distribution in the estuary was used once every three or four days to make forecasts for the coming thirty-day period; presumably, operational management decisions depended on this information. Artificial in-stream aeration devices were also installed during the mid-1960s in an impounded section of the Ruhr river in Germany. These devices were – and still are – operated by being switched on or off when prescribed values for dissolved oxygen concentration were recorded on an associated monitor.

Since these two early cases, however, there have been few advances in operational management of receiving-water quality. As we have mentioned, a number of telemetered networks for monitoring the quality of river water have been installed in the past three to four years. Such developments clearly represent a considerable increase in the capacity of managers to observe the behavior and response of a river system. However, the use of on-line models and the capacity to implement control actions remain limited, as indicated by the relatively few entries in Table 5.

Figure 9 shows the telemetered monitoring network (commissioned in 1978) of the UK's Bedford-Ouse river. This is one of the most sophisticated applications to date. One of the motivations for constructing this network was the need to protect downstream abstractions of river water from excessively high transient variations in nitrate-nitrogen or ammonium-nitrogen concentrations. The region of the Bedford-Ouse catchment shown in Figure 9 is predominantly agricultural, although there are significant discharges of municipal effluent to the river from the cities of Milton Keynes and Bedford. As only limited bankside storage is available for water abstraction at Bedford, operational decisions to stop abstraction temporarily are required when stream water quality is unsuitable. Under such circumstances, supply is maintained by using other (more costly) sources of raw water.

TABLE 5 Illustrative classification of types of operational management of river reaches (based on the Bedford-Ouse, UK, and Ruhr, Germany, applications).

Fully closed-loop control facilities (hardware)	Operational models (software)	Man–machine interaction
Artificial in-stream aeration	Model for dissolved oxygen–biochemical oxygen demand (DO-BOD) interaction, ammonia, nitrate, and conductivity variations	Communication of impending poor stream quality

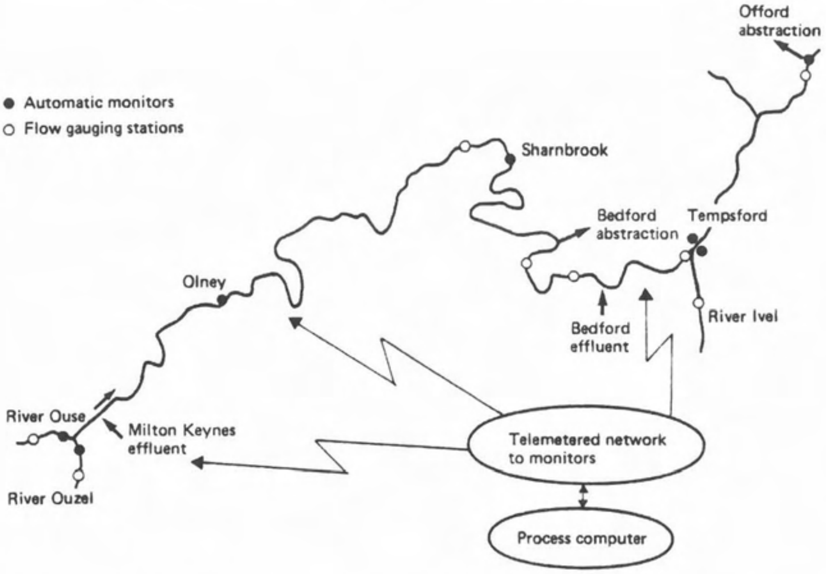

Figure 9. The telemetered monitoring network of the Bedford-Ouse river system.

Addressing and resolving the problems: achievements and outlook

Examination of Tables 2–5 leads to the observation that operational management of the potable supply network and of the sewer network has benefited from a relatively well-balanced development of hardware and software innovations. As both types of innovation are needed for the third type of innovation, this has clearly created a favorable potential for man–machine interaction, if and when it is necessary; ultimately, theory and practice are converging on this point, as we indicated in Section 2. The reasons underlying innovation in the two cases have been different: in the potable supply network, for operating more efficiently under normal conditions; in the sewer network, for managing transient crises under abnormal conditions. However, even though operational management of the potable supply network arose from a desire for more efficient normal operation, man–machine interaction becomes operative notably when transient crises occur.

The wastewater treatment and receiving-water subsystems exhibit somewhat asymmetrical, yet complementary, trends in innovative changes. The former can claim a relatively high level of innovative hardware applications yet only a low level of software applications; the latter has no lack of potential software innovations (witness the many models already available), but – at least until recently – has suffered from a dearth of hardware innovations. In both cases, therefore, the capacity for man–machine interaction has been limited.

The high number of new hardware applications in wastewater treatment stems from at least two causes. The first is the obvious desire to reduce costs. Roesler et al. (1978) quote figures from their survey showing overall savings of between 14 and 22 percent of annual operating costs with an automated treatment plant. Within these overall figures, savings in energy and material costs would amount to between six and 14 percent, and manpower savings associated with operation and maintenance would be approximately 30 percent. Second, the wastewater treatment industry is not immune to fashion; to some extent, the process computer has proved an irresistible force behind innovative change.

Against the background of these developments, we need to look again at the problems discussed in Section 3:

- Growing complexity of river basin management
- Changing character of pollution problems
- Changing role of treatment facilities
- More complex standards
- More difficult economic climate

How many of these problems are being addressed in current practice? Which are as yet unresolved?

Our conclusion is that integration and coordination of operational management among the subsystems shown in Figure 8 (including the broader aspects of water resources management) are not widely exercised – yet complex river basin management demands these features in particular. We do not even have an example of integration and coordination. In many river basins, such coordination may not have been necessary. On the other hand, the lack of an example may reflect a traditional division of the "water industry" into the distinct administrative and professional domains of water supply engineering, sanitary engineering, and river chemistry, hydrology, and hydraulics. Solutions to problems have tended to be made according to these divisions and as if the problems were separate. For example, manipulating the output from the sewer network as a function of wastewater treatment operations has been considered as, at most, a secondary objective of sewer network operational management. And it has been almost unthinkable until recently (see UK Department of the Environment, National Water Council 1981) to suggest that wastewater treatment plant management should be subordinated to short-term variations in the ambient conditions of the receiving water and, by extension, to the needs of a downstream abstraction.

In the early stages of river basin development, a primary (almost singular), unambiguous objective is to reduce the level of easily degradable organic material discharged to receiving waters. This goal allows for preservation of a relatively high degree of independence among the operational management activities of the individual subsystems. As long as this independence is preserved and water supply sources are not developed along moderately polluted water courses, one can argue that coordination and integration are neither necessary nor obviously desirable, partly because BOD and DO are not vitally important measures of the adequacy of water for potable supply. But the problems change – the definition of "moderately polluted" is not constant with time (we uncover and appreciate different problems) – and the objectives multiply. Compliance with standards becomes more difficult to evaluate, and balancing the satisfaction of multiple objectives may mean different and more substantial interactions and trade-offs among the subsystems. Matters such as these depend more strongly on operational decisions; in turn, they suggest the desirability of increasing integration and coordination.

Integration and coordination are admittedly no longer severe problems from the point of view of information retrieval and communication, as the improving capacity to observe pointed out in Section 2 shows. Like the computer, these other types of electronic engineering innovations have been irresistible. Once appropriate information has been obtained, however, determining and implementing the required (coordinated) control actions is problematic.

In a petrochemical complex, coordinated control of the individual unit processes is planned from the beginning; in contrast, coordination and integration have not been natural features in the evolution of water quality management. Adaptability of water quality management strategies is essential precisely because of the evolution in problems, objectives, and standards; many of the problems in our agenda call for this intangible quality.

Stimulus needed for change

If integration and coordination are desirable but generally lacking, and if the ability to adapt is limited, it would seem that

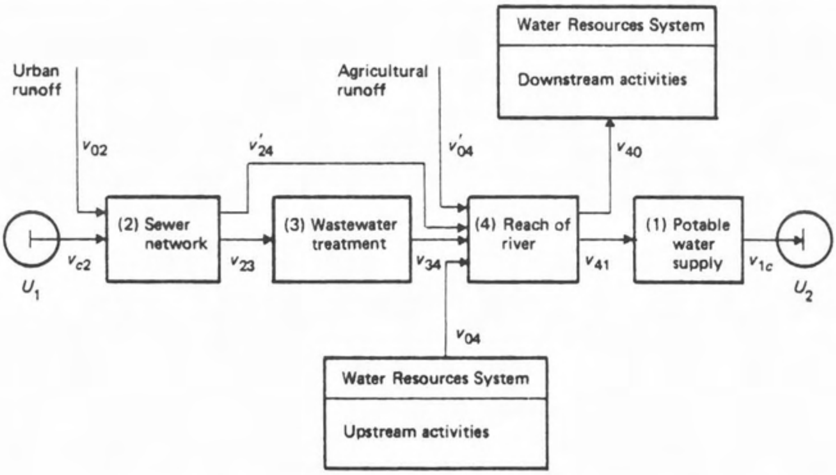

Figure 10. Integration and coordination of operational management: a hypothetical rearrangement of the water quality system shown in Figure 8. The notational convention is as used in Figure 8.

some stimulus is needed to bring about change. We may view the nitrate problem as such a stimulant issue.

Consider again the Bedford-Ouse river system shown in Figure 9. We can look at the river system (either between Milton Keynes and Bedford or between Bedford and the Offord abstraction) in terms of Figure 10, which is merely an appropriate rearrangement of the components of Figure 8 (the water quality system). How many of the components of Figure 10 affect or are affected by the nitrate problem?

First, nitrate-nitrogen is produced as an "optional" part of the biological treatment of wastewater (subsystem 3). As nitrification requires additional aeration in operating an activated sludge unit, it involves a definite cost. There are also trade-offs between the added costs of increased energy consumption for nitrification and the reduced costs of chemicals for phosphorus precipitation (nitrification removes ammonium-nitrogen, thus affecting the alkalinity of wastewater, which in turn affects the conditions for precipitation).

Second, nitrification of any residual ammonium-nitrogen in the wastewater discharge can occur in the receiving water body (subsystem 4). In the case of the Bedford-Ouse river, the preferred operational management response to excessive levels of nitrate-nitrogen in the river is to stop the abstraction at the Bedford supply intake. This, too, has a cost associated with it, because other, more "expensive" sources of raw water must be substituted for the river water.

Third, ammonium-nitrogen interacts with the performance of unit processes (primarily breakpoint chlorination) for water purification (subsystem 1).

Hence any study of the nitrate problem involves understanding the interactions among at least three of the subsystems (3, 4, and 1 in the sequence of Figure 10) of the overall water quality system. For two of these subsystems – the wastewater treatment plant and the water abstraction and purification plant – tangible operating costs can be associated with the consequences of management decisions. Trade-offs may exist between these two sets of costs, and decisions about them require operational knowledge of the state of the third subsystem, the reach of river, which links the effluent discharge to the raw water abstraction. The nitrate problem must, of course, be managed under day-to-day meteorological variations, which affect both surface runoff additions of nitrate-nitrogen and the river's sedimentation and dilution characteristics.

In short, it is difficult to isolate the nitrate problem, for it affects many components of the water quality system. It also affects and is affected by operational decisions that are, superficially at least, related to the management of other problems.

We shall consider the nitrate problem in greater depth in Section 6. While this problem suggests desirable practical developments, it has much to do with the new theoretical potential for operational management.

5

The Approach: New Potential for Operational Management

Given the current and prospective problems discussed in Section 3 and the recent developments in practice examined in Section 4, this section looks at the advances in analysis and understanding that will shape and facilitate future applications of operational water quality management. Integration, coordination, and adaptability, which we found generally absent from current practice, will form the background of our discussion; however, our primary concern here is more detailed topics. We identify six principal constituents of an approach to operational water quality management – not solutions, but rather a program for problem solving. The first three components of the approach deal with procedures for analyzing problems before operational management is implemented in practice. They relate to the planning and design stages of management and are aimed at changing the conditions that have so far prevented or hampered wider application of operational management. The other three constituents focus on problems of day-to-day practice; they are a response to the challenge of providing solutions that will succeed in spite of practical constraints.

These six constituents of the approach are

1. Advances in economic analysis, which can now accommodate joint considerations of fixed and variable (operating) costs and can incorporate assessments of the effects of transient crises, failures, uncertainties, and meteorological variability
2. Analysis of interactions and reliability (in the sense of achieving multiple objectives within a complex infrastructure of activities), including the sensitivity of operational management to accidents and failures
3. Process control system synthesis, with special reference to analyzing subsequent operating policies in the planning and design phases of management (i.e., design–operation interactions)
4. Use of support services in operational decision making, including mathematical models

5. On-line monitoring, estimation, and forecasting, in the context of operational water quality monitoring networks

6. Computing and on-line control, where we focus on microprocessor-based developments and on the appropriate deployment of both conventional and unconventional control system applications

We give particular attention to accepting, and even exploiting, the human element in the operational control loop and to solutions in which economic analysis can incorporate more of the detailed, subtle features of operational management. An important objective is to bridge the gap between the macroscopic requirements of economic analysis and the microscopic details of operational control system synthesis.

The state of our knowledge

For many, applied systems analysis may be synonymous with mathematical modeling, yet this is not entirely true. An applied systems analysis does often resort to the use of a mathematical model; there may also be a growing tendency to formalize understanding in terms of a mathematical model and to believe that it contributes to a better understanding of the way a system behaves (especially if the model is complex and apparently comprehensive). The mathematical model has become a useful tool; in one form or another, it pervades this section of our report. We cannot, however, equate a complex model with improved understanding.

Models are a key feature of current and expected developments; their role, however, is functional, as they serve management. Table 6 offers an evaluation of the state of our knowledge, where knowledge refers to the availability of a model describing short-term (i.e., hourly or daily) variations in process behavior. The qualifications given are, of course, both relative and subjective: the gradation from "relatively poor" to "relatively good" covers judgments about the existence of a hypothetical model, its qualitative confirmation by experimental observations, and the completion of more systematic studies of model calibration and verification.

Advances in economic analysis

More than a decade ago, seasonal waste treatment was proposed as a source of substantial economic savings; permission

TABLE 6 Relative qualification of models available for use in analyses, where the qualifications 1 to 4 express a gradation from relatively good (1) to relatively poor (4).

Process	Relative qualifications	
	Wastewater treatment	River
Nitrogen removal		
a. Nitrification	1	2
b. Denitrification	3	3
BOD removal (easily degradable organic material)	2	–
Suspended solids removal	3	–
Phosphorus removal	3	–
Effects of toxic spillages	4	4
Interactions		
a. Between nitrogen removal and suspended solids removal	4	–
b. Between nitrogen removal and phosphorus removal	4	–
DO-BOD interaction	–	1
Phytoplankton growth	–	2
Sediment transport/desposition (adsorption of toxic substances)	–	4

for variable waste control was suggested for allowing trade-offs between capital-intensive treatment facilities and facilities with high operating and maintenance costs. Neither suggestion appears to have been seriously considered, doubtless because, as we have indicated, the time was not ripe. Such suggestions may also have been unattractive because of theoretical and computational difficulties in applying optimization algorithms able to handle the inevitable complexities of these issues. Since the earliest attempts (in the mid- to late-1960s) to obtain optimal solutions to water quality management (that is, to minimize fixed costs), the development of applicable methods of optimization has been remarkable.

Following the problems described in Section 3, we argue here that the balance between design and construction costs, on one hand, and operational costs, on the other hand, is shifting notably toward the latter. This shift is also increasing the relative importance of variable operating cost considerations. The benefits to be gained from operational water quality management depend on the recognition that nothing remains constant with time, either in the short term (for example, transient crises) or in the long term (for example, the changing role of treatment facilities). A framework for economic analysis and planning that addresses *jointly* both fixed and variable costs and that recognizes the inherent time-variable and unpredictable character of the receiving water body and local meteorology would represent substantial progress, and such a framework is indeed emerging. As long as analysis of the economics of water quality management has remained bound to fixed cost considerations and average performance indices, it has been impossible to explore fairly and properly the advantages of operational policies. The emergence now of a broader economic framework greatly enlarges the scope of planning options. There are thus economic choices to be made between either changing the operation and design of existing facilities or constructing new facilities.

Other factors easily accommodated within such a framework include uncertainty about the behavior of the receiving water body; extreme or abnormal operational events, such as spillages of toxic substances or treatment plant overflows; and (to extend our closing point in Section 4) coordination of pollutant removal facilities with low-flow augmentation, for example. The statistical, or probabilistic, nature of this new economic analysis also permits cost minimization subject to the satisfaction of probabilistic water quality standards (no longer an unreality, according to Price and Pearson 1979), such as the frequency of excessive nitrate-nitrogen concentrations persisting for a given period of time. These are all issues prominent among the problems of Section 3.

Analysis of interactions and reliability

Returning to the nitrate problem, we see in Figure 6 a deliberate indication of a growing amplitude (and frequency) of oscillation in the stream nitrate-nitrogen concentrations deriving from direct sources. These increasingly larger fluctuations might be caused by a combination of higher nitrate concentrations in surface runoff and by a more widespread use of fully nitrifying biological wastewater treatment processes. With respect to the latter, the grounds for suggesting an oscillatory behavior lie in two generally accepted observations. The first is that (in an activated sludge unit, for example) either full nitrification or virtually no nitrification occurs, depending on operating conditions. The second is that sudden loss of nitrification can be precipitated by any change in operating conditions – the effects of a storm, for example. Can we reasonably determine, however, the probability of a transient excess of stream nitrate-nitrogen concentration of a given magnitude and duration? More generally, can we determine the probability of occurrence of the transient crises shown in Figure 4 and the sensitivity of overall system performance to these crises? To broaden the basis for discussion, we might suppose that a crisis could result from a computer or instrument failure, a recycle pump failure, a bulking sludge condition in the wastewater treatment plant, or some other cause.

Many of the problems discussed in Section 3 (the growing complexity of river basin management, the move toward preventive strategies, and the possibility of transient crises, for example) point toward an increasingly urgent need to answer questions such as these. They require, in particular, the analysis of interactions – both among the components of the water quality system and among the means for satisfying various multiple objectives. As the activities of the river basin become more deeply intertwined, it becomes more important to assess the relative degree of dependence (or independence) of the effects of (and prospective operational management responses to) failures and accidents. To what extent, for example, does the design and configuration of the system permit operational management to coordinate individual activities in order to confine and localize the effects of a failure? Such questions are ultimately concerned with reliability.

Yet Table 6 suggests that our understanding is weakest with respect to the interactions among processes, including the effects of toxic spillages. While it may have been established that nitrification and denitrification affect the conditions for phosphorus removal suspended solids settling and removal (bulking and rising sludges included) these interactions are by no means well understood. Subsequent operational management will have to address the resolution of "imponderable" trade-offs among multiple objectives (the removal of BOD, nitrogen, phosphorus, and suspended solids, for instance). We are certainly in a better position to undertake such analyses now than we were 10 to 15 years ago. The study of transient violations of nitrate-nitrogen standards is a promising example of how understanding (and analysis) is gradually becoming more integrated.

Process control system synthesis

Process control system synthesis is equally limited by the levels of understanding indicated in Table 6; as we observed in Section 2, its successful application depends on a valid and accurate model of process dynamic behavior. Control system synthesis may be a matter of designing a control scheme for an existing facility or of developing a control scheme simultaneously with the design of a new facility prior to construction. Traditionally, the latter approach has been decidedly unconventional and this, too, has been a limiting factor.

In Section 3 we noted the differential rates of electronic engineering and civil engineering innovations and the conventional separation of design and operational considerations. It is unfortunate, because innovation is concerned with change, that a rather robust circular argument exists, militating against such possibly desirable change. Operational control systems implemented on process designs that were conceived without due consideration of subsequent operating practice would seem to have a relatively high probability of not being demonstrably beneficial. This situation may be used to reinforce the conclusion that operational control is not feasible for *any* process design. Such a circular argument must be interrupted at a certain point; it becomes progressively less tenable in the face of the problems mentioned in Section 3, especially where the adaptability of operational policies assumes greater importance.

The key point from which we may begin to dismantle this circular argument concerns the systematic study of design–operation interactions. For example, how sensitive is the flexibility of plant operation to the design of a facility? Can the influence of design parameters on operational performance be quantified, and to which design parameters is this performance most sensitive? How sensitive is the design of a facility to prospective changes in water quality standards and management objectives? The study of design–operation interactions addresses such questions. Yet however flexible the design of the facility, such advantages can be exploited only by adequate operating performance. Given current models for wastewater treatment plant design, it is possible to analyze the sensitivity of a design solution to such factors as influent variability, the enhancement of methane production, and the specification of desired effluent characteristics. These factors are admittedly more closely associated with the macroscopic questions that follow from economic analyses. They are being addressed, however, and this is a step toward both systematic study of design–operation interactions and flexible performance capability.

Use of support services in operational decision making

We discussed briefly in Section 2 the prerequisites for the successful application of process control. The areas in which these conditions are largely satisfied (for example, the aerospace, nuclear power, chemical process, and paper and pulp industries) have enjoyed the benefits of significant advances in the application of process control systems. Looking at these as "conventional" control applications, we can (for the reasons outlined in Section 2) argue that conventional approaches to control are of limited relevance to operational water quality management. The real challenge, where the prerequisites are not met, is either to promote changes in order to bring about these conditions (our concern earlier in this section) or to seek less conventional ways of achieving the desired objectives of operational water quality management.

A first response is to relinquish the idea of eliminating the human element in the control loop, a customary objective of conventional process control system synthesis. As we stated in Section 2, this response is an integral component of the observed convergence between theory and practice; in Section 4 we drew attention to the practice of man–machine interaction in operational water quality management. Suppose, therefore, that we retain the human element in the control loop. How much more effective would a manager's control decisions be if the information retrieved from on-line sensors were restructured? Assuming the availability of a computing facility, what is the potential for using on-line mathematical models and information processing algorithms in

1. Rapid evaluation of the short-term consequences of various control actions
2. Prediction of events
3. Statistical estimation of process performance from error-corrupted measurements and reconstruction of information about process variables that may be important for the control function but are not directly measured by instruments?

The importance of the human element in the control loop is underscored by the findings of a recent survey of factors limiting the performance of wastewater treatment plants. Hegg et al. (1978) report that "The highest ranking factor contributing to poor plant performance was operator application of concepts and testing to process control." They also conclude that ". . . present plant personnel are an untapped source for achieving improved plant performance."

This brings us to a point of transition in this part of our report: from a concern with promoting changes to satisfy the prerequisites for implementing operational management to a concern for tackling existing problems in day-to-day operating practice. Poor operation and maintenance is perhaps the most important problem bearing on the second group of components in our approach. In the context of Figure 2, which illustrates the component functions of the basic management system, we deal in the remainder of this section with data retrieval, information processing, and the determination and implementation of control actions.

A simple example serves as our point of departure. A model of process behavior programmed on a computer, together with a manager who wishes to have access to the model for generating scenarios that reflect the possible consequences of operational decisions, is a good example of the use of support services in decision making and of man–machine interaction. In the Bedford-Ouse river system (see Figures 9 and 10), suppose that the manager of the water treatment plant for community U_2 (Bedford, say) announces an expected excessive nitrate-nitrogen or ammonium-nitrogen episode and requests a temporary change in the removal of waste nitrogenous material at the upstream wastewater treatment plant. A host of questions relevant to operational decisions would follow from this request for action. For example, how independent is the action to change the level of nitrification? Does it compromise BOD removal? Can denitrification be achieved temporarily? How long will it take to re-establish nitrification of the wastewater? What is the status of the nitrifying population in the river? Will the effects of control action be nullified by the river's natural response? Is an additional (nitrogenous) BOD load to the river acceptable?

Thus support services in decision making assume an important role when operational management requires cross-coordination of effort among the individual subsystems – when the plant manager has to think beyond the straightforward characteristics of the plant effluent. In this and similar situations, complexity is likely to overpower logical thought, and imponderable trade-offs between multiple objectives must be resolved by experienced (possibly empirical) but well-supported judgment. Such situations are a consequence especially of the increasingly complex nature of river basin management discussed in Section 3.

On-line monitoring, estimation, and forecasting

On-line estimation and forecasting are concerned with processing field data and restructuring the information thus derived. We cannot consider them, however, without questioning the kind of information required for operational decision making – and hence the purpose of a monitoring network in terms of operational water quality management.

We may make the proposition that an operational monitoring network must satisfy objectives different from those satisfied by a network designed for monitoring compliance with a standard and for acquiring basic understanding. An operational network should be capable of:

- Providing unambiguous and reliable measurements of short-term rates of change. (The primary concerns of operational management are typically problems associated with diurnal variations, accidental events, and meteorological variability)
- Measuring reliably what will be called "surrogate" variables, supplemented by data processing algorithms. (Such a combination exploits fully all the opportunities to convert reliable data into useful information. As a typical example, knowledge of the state of biological activity is often desirable for the control of the activated sludge process; it could, in principle, be reconstructed through the combination of a model and processed data on the surrogate variables of substrate and metabolic end-product concentrations in the influent and effluent streams.)

Our proposition, therefore, is based on three important principles: (1) while we cannot measure all variables of possible interest, what we can measure should, above all, be measured reliably; (2) what we wish to know for operational purposes is not necessarily the same as what we can measure; and (3) the potential to derive more useful information from existing monitoring systems has not been fully explored. Monitoring legal compliance with a standard and acquiring basic knowledge about the state of water quality seem to rest fundamentally on direct measurement of a variable or group of variables; a law defining acceptable performance in any other terms would be virtually unenforceable. Operational decision making, in contrast, does not have to be similarly restricted to information about directly measured variables.

What kind of information, then, is required for operational decision making? To answer this question we must reconsider the gap between the capacity to observe accurately and the present capacity to implement control actions that will bring about only rather crude changes in performance. There must be some degree of consistency between the information provided and the use to which it is put. The likelihood of an incompatibility between the accuracy of observation and the accuracy of control is a logical consequence of the differential rates of electronic and civil engineering innovations. As a function of working within the present limitations on control accuracy we therefore emphasize here the reliability, rather than the accuracy, of monitoring systems; this clearly has implications for the development of measuring devices. Reliability is also important when considering questions about detection and management of the transient crises discussed in Section 3. This is part of the broader issue of information requirements for surveying "ideal" performance (or behavior) and for detecting "nonideal" operating conditions, where a transient crisis would clearly be an extremely "nonideal" situation.

In operational decision making, we must also determine whether operating performance is as desired. Acquiring this knowledge rests on the ability to specify a set of conditions defining a "normal" state of affairs. The simplest definition of "normal" would be that a given measured variable remains within certain bounded values. Yet a transient crisis may not manifest itself so simply; its perceived effects may occur as a more subtle combination or sequence of changes in the values of two or more variables. When this is so, a more complex definition of the term is needed – possibly by means of a logical or mathematical model, which is an operational definition of normal or ideal behavior. Given the high probability, however, that the causes of any transient crises are difficult to detect, it is especially important to define "normal" in terms of relationships among the reliably and easily measured variables, which we call "surrogate" variables. The most useful such variables will be those that are integrative, in the sense of being responsive to many types of pollutant effects. Inferring the causes of transient crises or of other aspects of nonideal operating conditions depends on interpreting the changes in these responsive variables.

The essence of the approach to monitoring, estimation, and forecasting in operational management is therefore the idea of drawing reliable inferences about system performance. Suppose, for example, that a transient pollution event occurs in a stretch of river; what information is required for operational management? Two concerns are how quickly the pollutant will travel downstream and to what extent the peak loading will be attenuated. These factors are determined by the transport and dispersive properties of the stream, which in turn can be reconstructed from (for example) conductivity measurements at two or more locations along the river. In a simple sense, therefore, the measurements of conductivity act as a surrogate for direct measurement of the actual substances involved in the pollution event. Such an event, in this case of partially known character, occurred recently in the Bedford-Ouse.* It was possible to make a forecast (four days ahead of time) of the timing of the peak downstream BOD and ammonium-N loadings which turned out (in the event) to be incorrect by only a few hours.

The theoretical development of estimation and forecasting algorithms has already been more than adequate: the algorithms can be programmed on a microprocessor chip. Their potential (for supervising and detecting "failures", for example) has yet to be explored more fully, and this depends on acceptance of the principles outlined in this section.

Computing and on-line control

We have already mentioned the challenge for conventional control approaches in accommodating the sometimes unconventional demands of operational water quality management. This does not imply, however, that control theory does not offer solutions to the problems discussed here, or that it has not adapted to the changing needs of new applications. In this subsection we therefore discuss some conventional control techniques, the nature of whose potential implementation in practice may be markedly altered by such recent developments in small-scale computing facilities as microprocessors. We also discuss new approaches to process control that are currently evolving within control theory.

The first of these topics necessarily involves a broader examination of computer applications. Thus we start our discussion at

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* P. G. Whitehead (Institute of Hydrology, Wallingford, UK 1981), personal communication.

this point, bearing in mind our statements from Section 2 concerning the radically expanded scope for operational data retrieval. Present computer installations for process control reveal two major trends. The previously dominant preference for a single, large-scale, central computer is being superseded by the emerging philosophy of dividing the computational burden among many small subunits (each of which is designed to carry out a specific set of tasks), whose basic component is the microprocessor. Extremes in both directions should be avoided. With the former, a failure in the central computer would be fatal for the entire system of operational management – a point of obvious relevance to the question of reliability. With the latter, a rigid computer system architecture might result – one that is not easily amenable to subsequent modifications and unable to perform complex computational tasks, given the inherent limitations of the decentralized microprocessor.

Essentially, however, we can look at microprocessors as low-cost, flexible computing power that can be installed along a decentralized network. They can support a variety of activities: data acquisition and instrument management, data exchange with the central computer and communication line management, peripheral process control and (control) actuator management. In addition to these administrative and supervisory functions, possibilities for applying microprocessors include, as we have noted, various tasks of estimation, forecasting, and control. A task may be as simple as detecting and compensating for instrument drift, which would be important for avoiding incorrect operating information (a point that extends our notion of a reliable monitoring network). It may be as complex as reconstructing estimates of biological activity using a simple model of substrate/biomass interaction; this task could in turn be embedded in a fully closed-loop process controller – where, again, the controller component could be programmed on a microprocessor. Preliminary research and development work has already been carried out on such applications (Holmberg et al. 1980), and the area shows substantial potential.

What are the implications of the second topic, new and less conventional approaches to control system design? If we relinquish the idea of "eliminating the human element in the control loop," are there ways to exploit the human element in the loop? It is often said, for example, that an experienced manager can control the performance of his treatment plant more capably than an automatic controller. (In Section 4 we made observations to this effect in discussing the coordination of individual automatic control loops.) Conventional applications of control to a complex process such as an activated sludge unit have largely been restricted to individual loops that essentially regulate subcomponents of the overall behavior. Coordinating these individual loops to determine the ambient operating environment, controlling responses to bulking sludge and rising sludge conditions, and using qualitative observations of performance all require the involvement of the plant manager. Indeed, how does one translate a control rule such as "Recycle sludge color and odor observed to be 'poor' (mixed liquor is underaerated); therefore, increase aeration (increase dissolved oxygen set-point)" into the precise quantitative terms needed for conventional control system design?

Underlying such a control rule is a qualitative mental model of process relationships founded on accumulated empirical operating experience. Here, then, is the point at which we can begin to exploit the human element in the control loop; the notion of fuzzy control – a relatively recent development in control theory – addresses this point. In principle, then, a formal means exists for codifying empirical operating experience in the linguistic terms in which it is recorded and subsequently recalled for application. However, this is not a vehicle for dispensing with managerial decision making, for a fuzzy controller can be used as a support service in operational management. The accumulation of empirical operating experience is a continuous process, which in turn should encourage adaptation and enrichment of the previous experience crystallized in the rules of the fuzzy controller.

The essence of problem solving is that the technique used should match the nature of the problem. If certain conventional problems of operational water quality management can be solved by conventional control designs, this is all well and good. It is even better if such solutions release more of the plant manager's time for solving the less conventional, but increasingly important problems of coordination, compliance with complex standards, and evaluation of trade-offs among conflicting operational objectives.

In retrospect

This report deals with change. In this section, we have looked at changes in theory and understanding that are not yet visible in practice. If our solutions appear unconventional, two examples may provide perspective. First, discharges of storm water into a major European estuary have been observed to cause severe temporary depletion of dissolved oxygen. The operational control system designed to regulate this behavior comprises a launch (for detecting the DO sag), a radio link, and a barge equipped with oxygenation equipment. Second, physicists examining the application of recent advances in radio science to remote environmental sensing propose that distributions of various algal populations in water can be monitored by a tunable laser system that exploits knowledge of specific molecular absorption mechanisms. Who, ten years ago, would have thought this possible?

6

Guidelines for the Future

Throughout this report we have been particularly concerned with change, arguing that nothing remains constant with time. Against the background of long-term trends, we look at the present as a pivotal point in the development and application of operational water quality management.

What, then, does our analysis lead us to expect of water quality management in the future? How can operational management help us to respond to the problems currently, or about to be, experienced, and what are the implications of these responses for overall policy? In order to draw conclusions and make recommendations about such questions, we must first bring together the threads of the arguments made in earlier sections of this report. Figure 11 summarizes the principal interactions among the problems, the approach, and the policy implications; we shall also briefly recapitulate our discussion of the problems and, to a lesser extent, the approach. We can then draw some general conclusions about the desirable attributes of water quality management and make some more specific recommendations for realizing the full potential of operational management. (These conclusions and recommendations were summarized in Section 1.) In making conclusions about the desirable attributes of water quality management, we take a last look at the problem of nitrate pollution.

The problems

Let us begin by looking again at the *problems.** Taking a broad historical perspective, we see that, as a river basin becomes

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*The key words from Figure 11 are in italics.

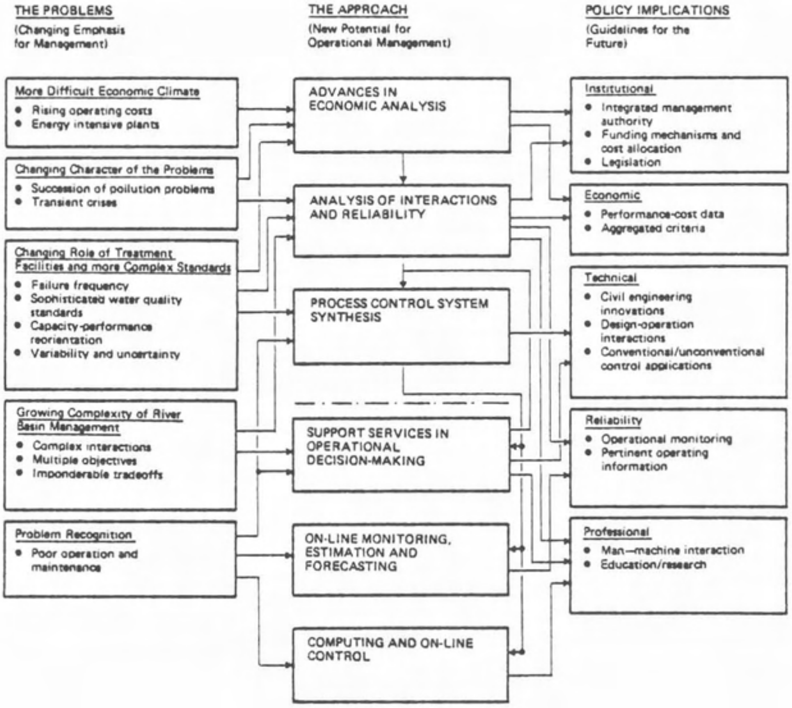

Figure 11. Principal interactions among the problems, approach, and policy implications of operational water quality management.

highly developed, the interactions between activities affecting and affected by water quality become more subtle and complex *(complex interactions)*. Simultaneously, a gradual loss of independence in managing the activities of the basin – a kind of implosion of interactions – takes place. The objectives of management become more complex. For example, the traditional, singular focus on easily degradable organic wastes and their effects on dissolved oxygen is compromised. Inevitably, conflicts among *multiple objectives* lead to decisions that must be made on the basis of more or less *imponderable trade-offs*.

From a different perspective, however, the increasing implementation of strategies for management changes to some extent the nature of the problems to be solved over the long term *(succession of pollution problems)*. Different categories of pollutants and problems – from "easily degradable wastes," from "point sources," to "nonpoint sources," to "eutrophication," to "toxics," and so forth – assume dominance in our perception of which problems require the most urgent management attention. The increasing level of interaction, however, prevents the simple treatment of problems as linear and successive; apparently retrograde steps may be advisable from time to time. If management has been successful in the past, average levels of water quality may well be improving. If the thrust of legislation concerning toxic substances is to prevent the release of these substances to the environment, the probability increases that such substances will be discharged to rivers, not in steady, small amounts, but in accidental, discontinuous, large amounts. Assuming, further, that the public is increasingly aware of improving average water quality, *transient crises* are likely to be much more apparent and damaging.

Past management strategies have led to a progressively complex infrastructure of existing civil engineering facilities in river basins. The essential objectives may thus no longer be to cure the ills of the past, but to prevent the problems of the future. Accordingly, the burden of management can shift toward maintaining adequate performance of existing facilities in the face of equipment and other failures. The *frequency of failure* (in absoute terms) is likely to rise simply because of an ever-growing number of installed facilities. Given, then, an existing system of facilities and an (initial) set of enforceable, operative standards for stream or effluent quality, what is the next step for water quality management? During the past decade there has been a remarkable rate of innovation of electronic engineering equipment. Most of it has been used to improve the capacity to observe in water quality management, with significant direct consequences – principally in creating a monitoring system consistent with the needs of operational management. The indirect consequences may be even more significant. If the behavior of the environment can be observed in ever more detailed terms and on shorter time scales, there is increasing scope for specifying and surveying compliance with *more sophisticated water quality standards.* If the tendency is therefore to change the standards of the present to meet the different problems of the future, the important questions will center less on determining how much more waste to treat and more on how to treat it differently *(capacity--performance reorientation)*. Coupled inextricably with these developments is the capacity to monitor the performance of water quality management on a time scale consistent with the *variability and uncertainty* of meteorological events. Factors previously submerged in yearly average statistics might no longer be allowed to remain so obscure; perhaps even the temptation to specify probabilistic water quality standards will become irresistible.

Hence we move finally to problems associated with the economics of water quality management, and to recognizing the problem of operational management itself. With respect to economics, the dominant issue has become the rapid rise to significance (from virtual obscurity) of the operating costs of wastewater treatment *(rising operating costs)*. This has been the most immediate effect of the oil price rises of 1973 and the subsequent perception of an energy problem. Less immediate, but exacerbating the first problem, are the delayed effects of commissioning pre-1973 energy-intensive wastewater treatment plant designs *(energy-intensive plants)*. In some countries enormous sums of capital have been invested in constructing facilities (a fact much on the minds of those responsible for water quality management), yet the objectives conceived in the planning process are not being achieved because of *poor operation and maintenance*.

These, then, are the problems germane to assessing operational water quality management. They are, or should be, the driving forces of change and innovation. Of course, we could have discussed additional problems; similarly, the ones we examined may be amenable to solutions other than operational management.

Defining the problems is really an act of *analysis*. In that sense, Sections 2, 3, and 4 represent our analysis, while Section 5 deals with the *synthesis* of a new approach and with the potential solutions that approach offers. Including a review of current practice under the rubric of analysis may require some justification. The current practice of operational water quality management is not widespread; examples of it illustrate essentially individual solutions to individual problems. In other words, the initiative to apply solutions has not been integrated and coordinated with a broader view of past, present, and future trends in water pollution problems. This is not to belittle these pioneering applications; on the contrary, the analytical observation of a lack of integration provides direction for future progress. An analysis of current practice points to promising lines of innovation, reveals areas where applications have been rare or nonexistent, and indicates the major innovative changes of the recent past – innovations related to engineering, basic knowledge, and professional education.

A new approach

Figure 11 shows the six principal components of a new approach to operational management: advances in economic analysis; analysis of interactions and reliability; process control system synthesis; use of support services in operational decision making; on-line monitoring, estimation, and forecasting; and computing and on-line control. Across this spectrum, we have focused on developing potential solutions that lie between the previous extremes of economic analyses dominated by fixed cost considerations (principally for design and construction) and exclusively technical studies of on-line, automatic, control schemes.

In broad terms, there is a conceptual division between the constituents. The first three concern procedures for analyzing problems before operational management is implemented in practice; they relate directly to the planning and design stages of management and attempt to alter the conditions that have so far prevented or hampered applications of operational management. The second three components of the approach deal with problems of day-to-day operating practice; an important element here is recognizing and responding to the challenge of generating solutions that will work in spite of ever-present constraints.

Advances in economic analysis serve as our point of departure. Problems to be handled by such analysis include considerations of rising operating costs and energy-intensive treatment plants. The primary analytical (mathematical) development permitting quantitative treatment of such problems is the ability to handle fixed and variable costs jointly. In principle, solutions accounting for aspects of variability and uncertainty (and thereby transient crises and failures), together with solutions for the economics of adapting existing facilities (capacity–performance reorientation), are also possible.

From this various problems and their solutions, at the level of *analysis of interactions and reliability*, follow directly. As the activities of the river basin become more deeply intertwined, it becomes more important to assess and exploit the relative degree of dependence (or independence) of the effects of (and prospective operational management responses to) failures and accidents. There will thus be growing concern with the reliability of managerial performance. This part of the approach clearly addresses the problems of satisfying the increasingly multiple objectives of water quality management. It also has important implications for the tactical procedures inherent in planning for managing operational contingencies (i.e., for the second group of three potential solutions).

Process control system synthesis is less directly associated with the problems discussed in Section 3 than are the two preceding constituents of the approach. Largely defined by the systematic study of design–operation interactions, it deals with questions concerning the flexibility of plant operational performance, which in turn is dictated by the probable changes in water quality standards and the changing role of treatment facilities. The problem of poor operation and maintenance, however, has an obvious and more direct relevance to this part of the approach. Including control system design in the first group of potential solutions places the consideration of subsequent operating policies firmly in the domain of planning and design procedures. Consistent oversight of this point has forced us to recognize the problem of poor operation and maintenance.

The second group of potential solutions to the problems includes the *use of support services in operational decision making.* As opposed to other, more conventional applications of process control, operational water quality management seeks to exploit the advantages of retaining a human element in the control loop. The two subsequent constituents, *on-line monitoring, estimation, and forecasting* and *computing and on-line control,* concern management's capacity to observe and capacity to act. Poor operation and maintenance are probably the most important problems bearing directly on these parts of the approach.

Policy implications: conclusions and recommendations

What, then, does our analysis lead us to expect of water quality management in the future? We first draw some general conclusions about the desirable attributes of water quality management. Then we make specific recommendations on steps toward achieving the full potential of the approach summarized above and discussed in Section 5.

The analysis described in this report is intentionally broad in perspective. Restricting discussion to a single country with its own institutional structures, to a single type of pollution problem, or to a specific part of the water and wastewater industry would have been counterproductive.

Our conclusions are consistent with the broad sweep of the analysis. In general, operational water quality management is, and must be, feasible. In some cases, the problems themselves – whether transient crises or defining water quality standards by reference to shorter time scales – will force the pace of the change toward operational management. In other cases, the desired changes – especially those related to electronic engineering innovations – are likely to occur at such a rate that further stimulation will be unnecessary, while cautionary recommendations may be needed. In yet other cases, for which most of our recommendations will be relevant, we can perceive undesirable constraints on developing and implementing operational management.

In presenting our first conclusion about the primary desirable attributes of water quality management we run the risk of stating the obvious. Nevertheless, to ignore this conclusion would be to lose sight of the objectives of operational management. Good management, then, should be:

- Adaptable, flexible, integrated, and coordinated. These attributes will be required increasingly in managing the complex problems discussed in Section 3. They may seem self-evident; however, the current restrictions on management's capacity to act are evidence of limited flexibility, while the review of current practice in Section 4 indicates a lack of integration and coordination.

There are, in addition, two secondary desirable attributes of water quality management:

- An understanding of the trade-offs between and interactions among multiple objectives and problems. In other words, we need to recognize and classify the advantages and disadvantages of interactions among the components and management activities of the water quality system shown in Figure 8.
- Safe failure and contingency planning. Failures (of many different kinds) will certainly occur; hence we must plan for corresponding operational measures that will minimize their damaging effects.

We must add to these desirable attributes a qualification: there is clearly a great difference between advocating such ideal objectives and achieving them in practice. Indeed, how does one determine, except in the most specific cases, whether the practice of management is "adaptable," "flexible," and "coordinated"? In general, we can only illustrate in detail the kind of problem that calls for these qualities in management. For this purpose we turn again to the nitrate problem. Like all "good" problems amenable to systems analysis, it has many facets, even from the restricted perspective of operational management.

The historical perspective provides a useful starting point. The nitrate problem has emerged at the end of the BOD problem for two reasons. First, we have begun to manage the point-source BOD problem successfully, which in turn has led to perception of the rising profile of nonpoint sources. Second, nitrate production in treatment plants has been encouraged, at least in part, to reduce potential nitrogenous oxidation demand on receiving waters. Nitrate pollution is a central feature of the nonpoint and eutrophication problems and, because of its public health effects, could be argued to be at the beginning of the toxics problem.

Responsibility for managing the problem can be located in more than one of the traditional subdivisions of the water quality sytem: in the wastewater treatment plant, in the river, and in the water purification plant. Moreover, management of the nitrate problem cannot be treated independently of other objectives. In the wastewater treatment plant, for instance, nitrate production (that is, nitrification) interacts with the processes of BOD removal, phosphorus removal, and chlorination, where each of these processes is tied to a different management objective.

Operational management of nitrate levels cannot be summarily dismissed as a typical pollution problem that is economically "uninteresting". Nitrification of wastewater generally requires higher rates of aeration and thus more energy for operation. As nitrification affects pH and alkalinity conditions, it may influence the amount of chemicals required for precipitating phosphorus compounds. There is also a cost associated with "blending" nitrate-rich raw water with other waters for potable supply. Clearly, trade-offs, both in economic terms and in the achievement (or lack of achievement) of multiple objectives, may exist.

The production and removal of nitrate-nitrogen is affected, in principle, by operational decisions: decisions such as not to nitrify, to nitrify, or to nitrify and denitrify. The capacity to implement these decisions now, however, may already have been prohibited years ago by an inappropriately designed treatment plant. Indeed, the freedom to choose to suppress nitrification – as an operating decision – may have become heavily circumscribed by longer-term changes quite outside the confines of the treatment plant. While BOD might no longer be perceived as the principal problem (in which case suppression of nitrification might not be such a retrograde step), there have been parallel developments in the successive impoundment of river sections, with consequent modifications of the reaeration and sedimentation characteristics of the receiving stream.

Finally, the nitrate problem is sensitive to uncertainty and variability: the storm that disturbs the operation of the treatment process, increases agricultural runoff, and scours the nitrifying population of bacteria from the bed of the receiving river; failure of a recycle pump or air blower; or spillage of toxic material into the sewer network.

Adaptability of management is a primary asset in solving such problems. Despite its appearance of concern with short-term problems, operational management enhances the adaptability of water quality management over the long-term. The problems discussed in Section 3 and the review of Section 4 point toward the desirability of the previously mentioned attributes of good management practice.

The recommendations arising from the analysis can be characterized as institutional, economic, technical, reliability, and professional. The *institutional* recommendations concern:

- *An integrated, regional water management authority.* Without such a body, coordinated operational management is unlikely to be as effective as it could be (see Okun 1977).
- *Funding mechanisms and cost allocation.* Separating the sources of funds for design and construction costs from that for operating costs obstructs meaningful translation of the results of a fixed/variable-cost economic analysis into practice. Construction and operating costs cannot be traded against each other.
- *Legislation.* Not all innovative changes – particularly not those related to changes in management practice – are stimulated by economic analysis. It may also be counterproductive from the point of view of innovation to enforce legal requirements that continually place management in the predicament of operating at the limits of technical capabilities. This is the implication of the ever-increasing ability to monitor compliance with more detailed standards: rather than stimulating innovation, it could instead remove the freedom to experiment (and to make mistakes). We might adopt the maxim "innovation with spare capacity."

The *economic* constraints on the more rapid development and justification of operational water quality management must also be relaxed if the full potential of Section 5 is to be fairly assessed. These pertain to:

- *Performance–cost data.* Economic analysis geared to operational management relies on data on operating costs as a function of various pollutant removal efficiencies (for example, costs of operating at 75 percent, 80 percent, and 85 percent BOD removal rates). Such data are generally unavailable because of the constraints firmly established by a circular argument. This argument maintains that treatment processes are operated at fixed efficiencies because technically they cannot be operated otherwise; there has been no legal or economic incentive to operate them in any other way. Thus relevant performance–cost data are unavailable, and realistic economic analysis is impossible. This confirms the notion that all processes should be operated at a fixed, immutable efficiency. Yet, when more than one type of pollutant must be removed, not all pollutants can be removed at maximum efficiency, and trade-offs among operations at less-than-maximum efficiencies must be evaluated.
- *Aggregated criteria.* New criteria for assessing the benefits of operational control must be developed if we are to evaluate these benefits within a broad economic framework. Most operational control studies justify themselves in terms of one criterion – that the controller is able to match actual performance with desired performance within some tolerable level of error (deviation) over a short period of time. But if such technical details are to be matched with the scale of an economic analysis of the type discussed here, the details must be aggregated into quite different criteria. For instance, how will the operational control scheme perform in a wet or dry season? How will it cope with a long-term increase in sewage loads? How does it change the probability of occurrence of a transient crises? Although these are important questions, they are as yet apparently unanswered.

With respect to *technical* recommendations, we are concerned partly with removing constraints and partly with stimulating the rate of innovation of a civil engineering nature to match that of electronic engineering innovations. Our *technical* recommendations thus relate to:

- *Civil engineering innovations.* These improve management's "capacity to act" and to implement control decisions, while electronic innovations that facilitate communication and information retrieval improve the complementary "capacity to observe." In broad terms, we may be approaching a situation in which management will be able to observe in splendid detail what is going wrong with a system, yet will be powerless to implement corrective action because the slower rate of civil engineering innovations dominates the capacity to act. Given the stimulus expected from development of biotechnology in other fields, the required civil engineering innovations may be imminent.

- *Design–operation interactions.* We need to assess the influence of process designs (both new and old) on operating policies.
- *Conventional/unconventional control applications.* The primary aim of conventional control applications in operational water quality management should be to free the manager from routine business to enable him to concentrate on coordinating, evaluating trade-offs, and managing contingencies. In particular, we can then use less conventional approaches to assist the manager in achieving these aims.

The problems of communication and information retrieval have been much alleviated by the innovation of electronic engineering equipment, as already noted. There are both advantages to be exploited and pitfalls to be avoided as a result of these developments. These developments have raised questions of *reliability,* particularly with respect to the following:

- *Operational monitoring.* The information requirements of operational decision making differ from those of planning and of supervising compliance with standards. The needs of operational monitoring should be defined according to the three principles discussed in Section 5: (1) Because all variables of possible interest cannot be measured, those that can be measured should be measured reliably; (2) what we wish to know for operational purposes is not necessarily the same as what can be measured; (3) the potential for deriving more useful information from existing monitoring systems has not been fully explored. To some extent, these principles shift the burden of providing operating information away from relying on sensor hardware and toward relying on computing-device software. In addition, a rapid response to a wide variety of transient crises may be necessary (at least initially); from the point of view of reliability, it is better to cast a "coarse-mesh" monitoring system over a broad spectrum of pollutant categories than to use an accurate "fine-mesh" system that results in detecting just one or two specific pollutants.
- *Pertinent operating information.* An operational monitoring network is ultimately only as effective as the managerial response to the information provided. A monitoring system that encourages too great a dependence on the infallibility of instru-

ments and computers and that submerges pertinent details of operation in an excess of irrelevant information is certainly unreliable.

These recommendations do not cover requirements for personnel responsible for operational management, yet this, too, is a crucial topic. Two recent feature articles in the Journal of the US Water Pollution Control Federation have highlighted the problem. Wubbena (1979) noted that "Billions of dollars are spent on complex facilities to ensure safe drinking water and to treat wastewater, but recruiting, training, and retention of competent operators has not kept pace with advancing technology." Sherrard and Sherrard (1979) argued that "One of the most pressing and immediate problems facing the water pollution control field is the recruitment, employment, training, and retention of a highly motivated and dedicated work force." Our *professional* recommendations therefore deal with:

- *Man–machine interaction.* The convergence between theory and practice, our review of current practice, and the new potential for operational water quality management all point toward the critical importance of man–machine interaction. Plant automation and computerization should neither merely assume the passive role of recording plant performance nor aim toward eliminating the human element from the control function. Rather, technological innovations should be used to encourage active interaction between man and computer in operational management.
- *Education and research.* To the list of recommendations concerning operator training given eleswhere, we merely add that man–machine interaction implies an increasing demand for skilled personnel who are familiar with the use of computerized support services for operational decision making. With respect to research (and with important implications for education), two areas merit more concerted effort. First, we should improve our understanding and classification of interactions among components of the water quality system, interactions among pollutant problems, and the control actions taken to resolve these problems. This will accelerate satisfying the need for integration and will increase appreciation of the interdisciplinary character of water quality management. Second, we should study design–operation interactions systematically. Such study will add a wider appreciation of process dynamics to existing strengths in civil engineering research.

A final remark

Optimal use of operational water quality management depends initially on it being an acceptable concept. The studies on which this report is based provided ample opportunity for critical self-appraisal, directed ultimately at this question of acceptability. Two such critical comments follow:

> The concept of time-variable (operational) water quality management seems to induce one of two reactions in those who are currently involved in water quality management. Either they think that, while it has no relevance in their situation, they can appreciate its conceptual niceties, or alternatively, they claim that perhaps with slight extensions, it is no more than setting out formally what they practice intuitively or have arrived at through long years of experience. Either reaction amounts to a display of resistance to the acceptance of the different perspectives suggested in the total systems approach. This can only be overcome by patience and persistence (but not annoyance) and a readiness to seize any opportunity to implement the concept when the occasion arises. (Newsome 1980.)
>
> Technical readiness to utilize more advanced monitoring and control systems in treatment plants is in general good (only the motivation is lacking). . . . the realization of integrated real-time systems for regional water quality management seems to be a matter for the next century. (Halme 1980.)

Perhaps Halme's prediction will be accurate, but this may not be so discouraging; after all, the past twenty years have produced some remarkable changes in attitude, and the next century is less than twenty years away.

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